Tier 3 Nominations

Provided by Lindsey Bloom

CHILKAT INDIAN VILLAGE
"Yee gu.aa yax x'wan."

An Indian Reorganization Act Village
Under Act of Congress June 15th 1935
32 Chilkat Avenue Klukwan, Alaska
HC60 Box 2207 Haines, Alaska 99827
PH: (907) 767-5505
FX: (907) 767-5518
Email: klukwan@chilkat-nsn.gov

February 22, 2017

The Honorable
Governor Bill Walker
Alaska State Capital, 3rd Floor
P.O. Box 110001
Juneau, Alaska 99801

RE: Request for ecological protection of water quality

Dear Governor Walker,

Governor Walker, in the absence of a state process for designating the Chilkat River as an "Outstanding National Resource Water's" (ONRW)/ Tier 3 river, we ask you to use your executive power as our Governor to make the designation. The Constantine North Inc.'s (AKA: Palmer Mine) has been in the exploration stage for many years and their ongoing progress to establishing the mine is a clear environmental threat to the Chilkat River. The Tier 3 statute has been federal law for 20 years. The interim guidelines were approved 10 years ago but the Alaska Department of Environmental Conservation (DEC) refuses to make any Tier 3 designations. We cannot wait another year or 10 – 20 years for DEC's decision, we need your help now. Please use your authority to either designate the Chilkat River as a Tier 3 or consider protecting the Chilkat River as if it is a Tier 3 until DEC can establish a process.

Our Tribe nominated the Chilkat River as a "Tier 3 Outstanding National Resource Waters" for our children's, children. It has been established that the Chilkat Tlingit's did not merely subsist but actually thrived in the Chilkat Valley because of the abundance of salmon in the Chilkat River. The variety of fish in the Chilkat River continue to feed our people through the subsistence process as it has for centuries. The Chilkat River is a tremendously valuable resource. Our ancestors named the River "Jilkaat Heeni" – Translated means "Storage container for Salmon" because all five species of wild Pacific Salmon, as well as Steel Head, and Dolly Varden Trout inhabit the Chilkat River. The Chilkat River wild stock salmon also supports a robust commercial fishing industry that is central to the economies of the Upper Lynn Canal communities as well as the other communities in South East Alaska. Further, the abundant, late run of Chum Salmon in the Chilkat River attracts the American Bald Eagle by the thousands and led to the establishment of the Alaska Chilkat Bald Eagle Preserve. "The preserve was established to protect and perpetuate the world's largest concentration of Bald Eagles and their critical habitat. It also sustains and protects the natural salmon runs and allows for traditional uses; provided such uses do not adversely affect the preserve resources." http://dnr.alaska.gov/parks/units/eagleprv.htm. The abundance of eagles has given the communities of Haines and Klukwan opportunity to extend the visitor season well into late fall and early winter and the impact of contaminated water from mining operations would undoubtedly impact the eagle population and, in turn, the visitor industry which we have worked so hard to develop in the communities of the upper Lynn Canal.

Suffice it to say, Governor Walker, there is a lot at stake here and time is of the essence. The Palmer/Constantine mine is moving towards full scale operation and we have no other recourse to protect the waters of the Chilkat River from their mining operation runoff. I appreciated, in your State of the State Address you mentioned "Environmental Stewardship", and we are now asking you to consider the Tier 3 status as part of our environmental stewardship responsibility. You also mentioned in your State Address the "Transboundary Working Group" and the progress they have made in protecting our state's rich water resources that are connected to Canadian boundaries. The fish that swim up the Chilkat also swim upstream to Canada's rivers establishing it as transboundary water that needs our state's protection.

The continued delays by the DEC to implement a Tier 3 process is detrimental to our survival. Governor with no other option available to us, we ask again, please use your Executive Authority as Governor to designate Tier 3 status to the Chilkat River.

Thank you for your consideration to our request and we look forward to your response.

Sincerely,

Kimberley Strong
President

Venetie Village Council
General Delivery
Venetie, AK 99781

RECEIVED BY:
Division of Water
AUG 18 2016
Department of
Environmental Conservation

July 23, 2016

Michelle Hale
Alaska Dept. of Environmental Conservation
Division of Water
410 Willoughby Ave., Ste. 303
Juneau, AK 99811-1800

Dear Michelle,

We, the Venetie Village Council, request the designation of the Chandlar River to be an Outstanding National Resource Water (Tier 3), as it fulfills state regulatory requirements: it is located within the Yukon Flats Wildlife Refuge and the village lies below the confluence of the Chandlar and East Fork River. This place holds the spawning bed for the chum salmon and thus, provides a great ecological significance for the whole area.

Venetie has had a long-time concern about the Chandlar Mine and its possible impacts to the Chandlar River and the land, especially the chum salmon, but also, grayling, King Salmon, and the whole area is a gateway for waterfowl, which we rely heavily upon to survive.

Therefore, after a discussion of the matter in a village council meeting, it was determined by the Venetie village council to request the designation of the Chandlar River to be an Outstanding Natural Resource (Tier 3).

1st Chief of Venetie

Jerry Frank

Jerry Frank

RECEIVED BY:
Division of Water
AUG 18 2016
Department of
Environmental Conservation

8-16-16

Hello michelle,

My name is Matt Gilbert I coordinated Jerry Frost in writing the Letter for Nomination. I know it's him you would prefer to speak to, since he's on the hurdling but if you need to speak to someone, please don't hesitate to contact me, email is the best way: mattgak35@gmail.com

Sincerely,
Matt Gilbert

ONE PEOPLE-ONE RIVER

YUKON RIVER INTER-TRIBAL WATERSHED COUNCIL

725 CHRISTENSEN DRIVE, SUITE 3
ANCHORAGE, AK 99501
PHONE: (907) 258-3337
FAX: (907) 258-3339
TOLL FREE: (844) 730-3337

WHITEHORSE OFFICE: PO BOX 3123-211
WHITEHORSE, YUKON TERRITORY CANADA
Y1A-5P7

November 30, 2017

Andrew Sayers-Fay, Director
Division of Water
Alaska Dept. of Environmental Conservation
410 Willoughby Ave., Ste. 303
P.O. Box 111800
Juneau, AK 99811-1800

Dear Director Sayers-Fay,

On behalf of the Yukon River Inter-Tribal Watershed Council (YRITWC), I am writing in support of the nomination by the Gwichyaa Zhee Gwich'in Tribal Government and Chalkyitsik Village Council of the Draanjik River (Black River) for Tier 3 Outstanding National Resource Waters under the terms of the Clean Water Act, 40 CFR 131.12 and Alaska regulation 18 AAC 70.015. The 255 miles of the Draanjik River are the home to species of aquatic life unique to the area, particularly several species of salmon which spawn there, and is one of the few spawning areas in the Yukon Basin for sheefish. The river to date has been protected from the impacts of human-caused pollution due to its remote location; this designation would ensure that it remains in its pristine condition.

Beyond its role as essential fish habitat, the Draanjik River is an important buffering waterway for aquatic and terrestrial species stressed by climate change, an increasing threat to the Yukon River Basin. Warming temperatures have led to permafrost degradation, causing wetlands and ponds to be displaced by scrub and grasses. Protecting the Draanjik River from human-caused degradation supports a resilient landscape able to host robust levels of biodiversity. The acceleration of climate change makes the role of the Draanjik in resiliency critical.

In addition to threats posed by climate change, the nomination identifies several other pending or possible human-caused threats to the Draanjik River. We are deeply concerned that the current state fiscal climate may open lands to mining and development which would destroy this unique and unspoiled area. Tier 3 protections would allow the Draanjik to maintain its natural integrity free of human-caused contamination.

The nominating tribes, Gwichyaa Zhee Gwich'in Tribal Government and Chalkyitsik Village Council, are signatory members of The Accord, which is the treaty agreement between the Council's 73 Tribes and First Nations. The organizing principle of the Accord is an agreement that each sovereign indigenous government does what it can to protect the Yukon River, its tributaries, and lands, which all support indigenous ways of life. The tribes nominating the Draanjik River for Tier 3 status are taking an action consistent with the Accord and we are happy to support that effort.

GUIDING PRINCIPLES
Be Good Listeners ~*~ Be Respectful ~*~ Be Flexible ~*~ Have Integrity ~*~ Be Honest ~*~ Be Timely ~*~ Be Non judgmental
Share Wisdom ~*~ Be Consensual ~*~ Be Unifying ~*~ Be Fair & Equal ~*~ Be Tenacious ~*~ Be Trustworthy ~*~ Be Patient
Be Bold ~*~ Be Inclusive

During the YRITWC Executive Committee meeting on October 11, 2017, a resolution supporting this nomination was passed unanimously. Protecting waterways and lands central to indigenous ways of life is a key part of the YRITWC mission, and Tier 3 designation for the Draanjik River provides the necessary regulatory protections to allow it to continue to support a vibrant and diverse landscape.

We understand the gravity of this designation and appreciate the weight of the State's decision. If there is any other information that the YRITWC can provide to assist in your determination, please let me know. We look forward to your decision.

Respectfully,

Kelly Donnelly, MPA
AK Executive Director

GWICHYAA ZHEE GWICH'IN TRIBAL GOVERNMENT and CHALKYITSIK VILLAGE COUNCIL

November 7, 2017

Via U.S. Mail and Email to:
Michelle Hale, Director, Division of Water
Alaska Department of Environmental Conservation
410 Willoughby Ave , Suite 303
Juneau, Alaska 99801

Dear Ms. Hale,
The Gwichyaa Zhee Gwich'in Tribal Government and the Chalkyitsik Village Council (hereinafter referred to as "Tribes") welcome this opportunity to nominate the Draanjik River and all of its tributaries for designation as Tier 3 Outstanding National Resource Waters under the terms of the Clean Water Act, 40 CFR 131.12 and Alaska regulation 18 AAC 70.015.

The federally recognized[1] Tribes serve the Gwich'in people of Fort Yukon and Chalkyitsik. They exercise sovereign governmental authority to protect the health and welfare of tribal citizens and their homelands. The Draanjik River system constitutes the landscape upon which depend their health, identity, food security, municipal water source (for Chalkyitsik), and cultural continuity. The water is pristine, has exceptional and sensitive ecological value, offers remarkable recreational uses, and sustains rich resources that support a traditional indigenous culture.

LOCATION AND DESCRIPTION

The Draanjik River, located in northeastern Alaska, is a tributary of the Porcupine River and is approximately 300 miles long.[2] It heads on land administered by the Bureau of Land Management (BLM) 35 miles southeast of Fanny Mountain at 65°33'33"N, 141°51'19"W, then flows north-northwest into the Yukon Flats National Wildlife Refuge (YFNWR), where it turns west to join the Black River Slough (an anabranch of the Porcupine River) 16 miles northeast of the community of Fort Yukon. Its two major tributaries are the Salmon Fork and the Grayling Fork. The headwaters of the Salmon Fork are in the Ogilvie Mountains in Yukon Territory, Canada, at 66° 53' 4"N, 139° 57' 2"W. It flows southwest to the international border, then another 74 miles in a general westerly direction until it enters the Draanjik River. The entire Canadian portion of the Salmon Fork is designated the Salmon Fork Chinook Salmon Conservation Unit, CK 77. In Alaska the Salmon Fork watershed is either managed as the Salmon Fork Area of Critical Environmental Concern (ACEC) by the BLM, or is part of the

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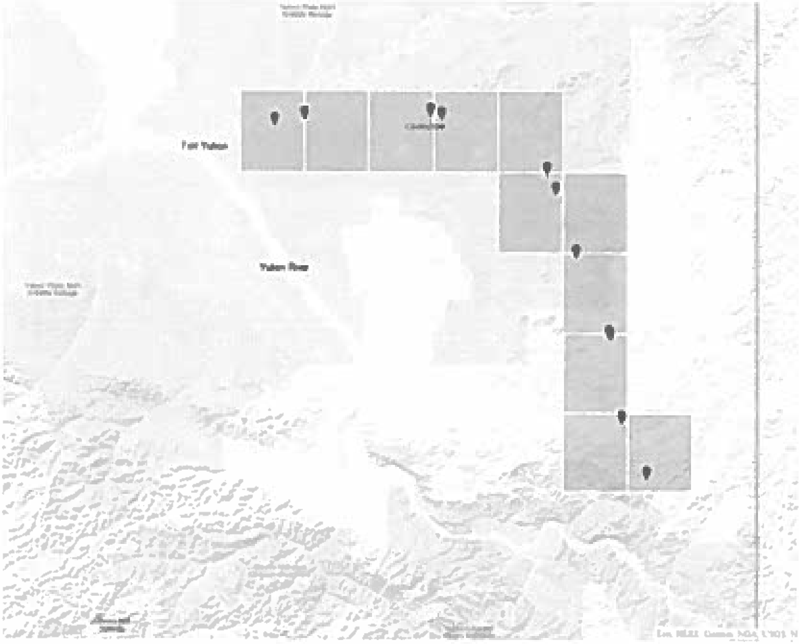
[1] *Federal Register*, Volume 74, Number 183 dated August 11, 2009 (74 FR 40218) "Indian Entities Recognized and Eligible to Receive Services from the United States Bureau of Indian Affairs" (August 11, 2009).

[2] For an overview of the Draanjik River's physical character, see C. M. Brown to Chief, Division of Resources, March 28, 1980, file FF-09320, Alaska State Office, BLM.

YFNWR. The Grayling Fork also heads in the Ogilvie Mountains in Canada at 65° 52' 22"N, 140° 27' 35"W. The Alaskan portion is almost entirely within lands administered by the BLM. The village of Chalkyitsik is the only community located within the drainage of Draanjik River, and is the home of the Draanjik Gwich'in tribe. The name of the river is of Gwich'in Athabascan origin and translates to "caches along the river." Formerly, the name "Black River" was used, but in 2014 the U.S. Board on Geographic Names officially restored the original name.[3]

Coordinates (One point per USGS topographic map containing the feature, NAD83)

Sequence	Latitude(DEC)	Longitude(DEC)	Latitude(DMS)	Longitude(DMS)	Map Name
1	66.6641667	-144.7277778	663951N	1444340W	Fort Yukon C-2
2	66.6797222	-144.4991667	664047N	1442957W	Fort Yukon C-1
3	66.6917194	-143.5259638	664130N	1433133W	Black River C-6
4	66.6817912	-143.4417730	664054N	1432630W	Black River C-5
5	66.5138234	-142.6286085	663050N	1423743W	Black River C-4
6	66.4510659	-142.5596339	662704N	1423335W	Black River B-4
7	66.2578806	-142.4031690	661528N	1422411W	Black River B-3
8	66.0065647	-142.1491608	660024N	1420857W	Black River A-3
9	65.9994444	-142.1366667	655958N	1420812W	Charley River D-3
10	65.7374787	-142.0487081	654415N	1420255W	Charley River C-3
11	65.5591667	-141.8552778	653333N	1415119W	Charley River C-2



Source: USGS Geographic Names Information System (GNIS): ID 1399160

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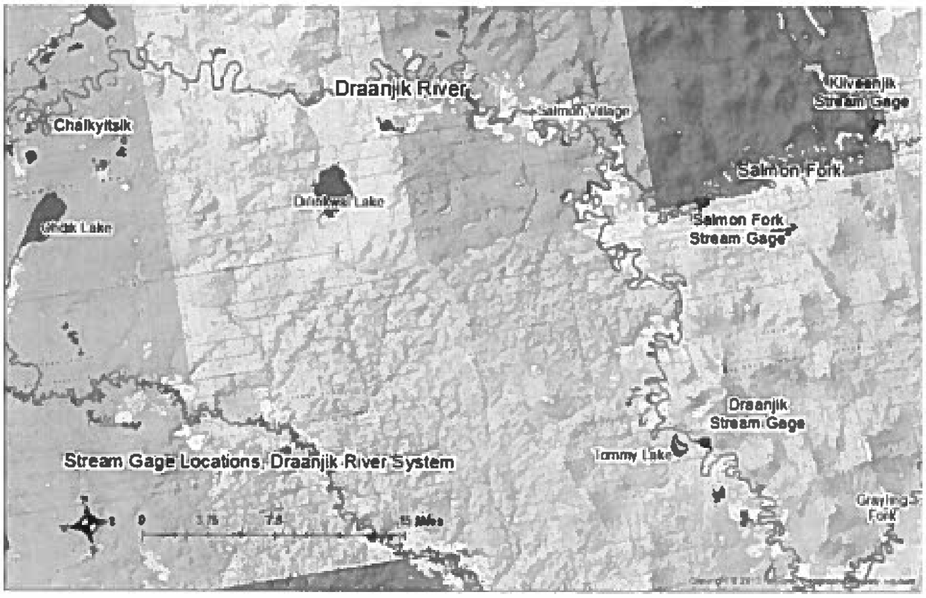
[3] https://geonames.usgs.gov/apex/f?p=138:3:0::NO::P3_FID,P3_TITLE:1399160,Draanjik%20River

In 1991 the BLM performed a reconnaissance level aquatic resource investigation on the Salmon Fork from the international boundary to Kiiveenjik Creek, which included some preliminary hydrologic data.[4] More complete streamflow data is available from the US Fish and Wildlife Service, which operated three continuous recording discharge gages from 1993 to 1998, on the Draanjik River near Tommy Lake, on the Salmon Fork and on Kiiveenjik Creek:[5]



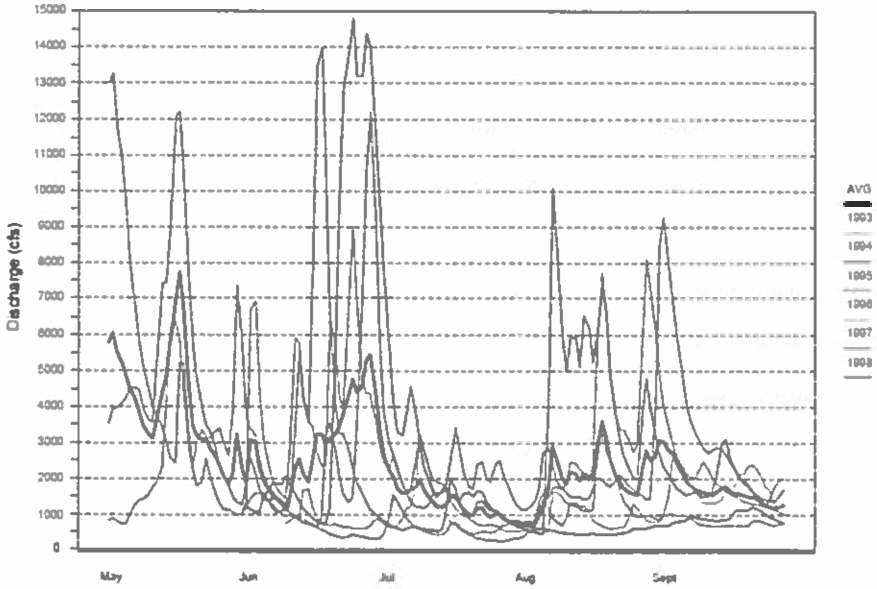


Figure 2 - Annual and average hydrographs for the Black River (1993-1998). Yukon Flats National Wildlife Refuge, Alaska

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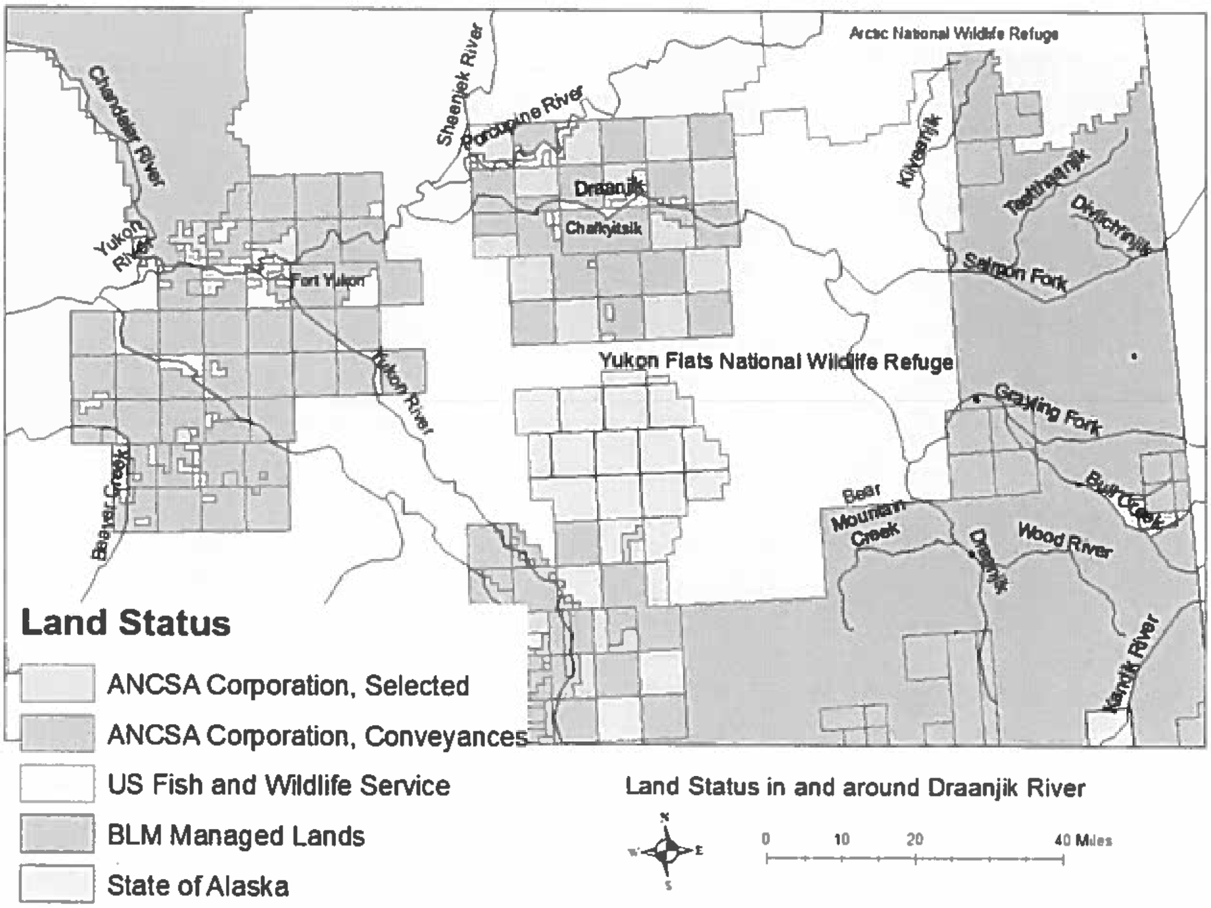
[4] Kostohrys, J., Lubinski, B., and Collin, N. 1991. Aquatic Resources of the Salmon Fork Black River, Alaska. Bureau of Land Management Open File Report No. 51

[5] John Trawicki, "Water Resources Inventory and Assessment, Yukon Flats National Wildlife Refuge (Water Years 1993-1998): Final Report," WRB 00-04 (Water Resources Branch, U.S. Fish and Wildlife Service, April 2000), 7

LAND OWNERSHIP



Land Status in and around Draanjik River

From the mouth of Wood River, the Draanjik River flows through 32 townships before emptying into the Porcupine River. The upper river and its headwaters tributaries flow broadly across BLM lands before entering the YFNWR. The remainder of the river is located in the Refuge. Of that portion, land in nearly eight townships has been conveyed to the Chalkyitsik Native Corporation and Doyon, Ltd. Some parcels are selected but not yet conveyed under the provisions of the Alaska Native Claims Settlement Act. The river and stream bed below mean high water mark were not include in the conveyances.[6] The Grayling Fork flows mostly across BLM lands. It crosses Doyon, Ltd, lands in two townships, which were conveyed by Interim Conveyance Nos. 331 and 432. In both townships, the Grayling Fork itself was excluded from the conveyances as a navigable waterway. Grayling Fork then flows through three townships in the YFNWR before it empties into the Draanjik River. The Salmon Fork and its tributaries are located on land managed by the BLM or by the YFNWR.

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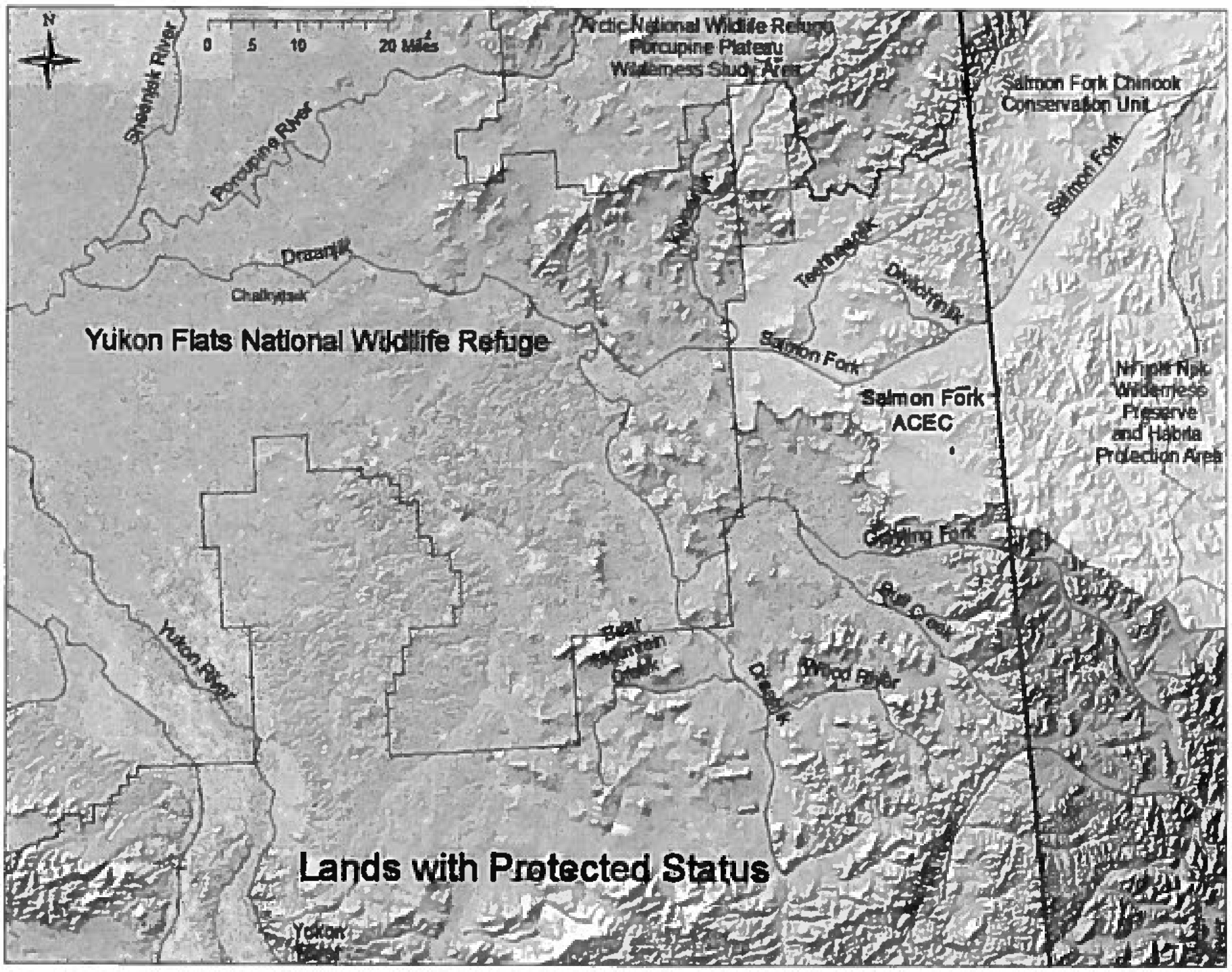
[6] Robert W. Faithful to Assistant Deputy State Director for Conveyance Management, July 22, 1983, file F-14846-A, Alaska Native Claims Settlement Act files, Northern Field Office, Bureau of Land Management, Fairbanks

On February 14, 2003, the State of Alaska applied to the BLM for a Recordable Disclaimer of Interest (RDI) to provide finality on the navigability on Draanjik River and its tributaries. On October 24, 2003, the BLM issued an RDI determining that the Draanjik River as far upriver as the mouth of Grayling Fork, Salmon Fork to the international border, Grayling Fork for the first 54 river miles, and Bull Creek for 16 miles are navigable, and the underlying lands therefore are the property of the State.[7] Alaska owns the lands underlying navigable waters by virtue of the equal footing doctrine, under which new states are admitted to the Union with all of the powers of sovereignty and jurisdiction that pertained to the original states, and ownership of lands underlying navigable waters is an essential attribute of state sovereignty. When Alaska became a state, title to lands underlying navigable waters within its boundaries passed to it automatically. The bed of most of Draanjik River up to mean high water mark therefore is State property.

PROTECTED AREAS



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[7] Recordable Disclaimer of Interest, Serial Number F-93920. BLM, Anchorage. http://www.dnr.state.ak.us/mlw/nav/rdi/blackgroup/blackgroup_rdi.pdf

In 2008, Chalkyitsik Village Council recommended the portion of the Draanjik River watershed within BLM managed lands for designation as an ACEC. The 1991 BLM study, *Aquatic Resources of the Salmon Fork Black River, Alaska*,[8] stated that:

> Given the high quality and diversity of this ecosystem, the areas of critical spawning and rearing habitat for anadromous and resident fish populations, and the high potential for future recreational and subsistence use, we should consider giving parts or all of the area a special land designation, such as naming it an Area of Critical Environmental Concern...

In 2016, the BLM designated approximately 623,000 acres within the Salmon Fork watershed as the Salmon Fork ACEC, to protect relevant and important values including bald eagle nesting habitat, priority fish habitat, and rare flora.[9] The goals of the ACEC include the maintenance of stream channel integrity, ensuring the proper functioning of riparian habitat, and preserving water quality for fish and aquatic resources. The ACEC is a right-of-way avoidance area, limiting winter use to snowmobiles weighing 1,000 pounds and less, and prohibiting summer use of off-highway vehicles Along with 28 Riparian Conservation Units and the upper Draanjik River headwaters area, the ACEC is closed to locatable mineral entry and leasable minerals.

The Porcupine Plateau Wilderness Study Area (WSA) in the Arctic National Wildlife Refuge extends along the northern boundary of the Draanjik River watershed. Its 4.4 million acres are exemplary in the degree to which they meet the criteria of the Wilderness Act. Comprising about 23 percent of the Refuge, the Porcupine Plateau WSA is sufficiently large, protected, and distant from substantial threats to enable it to be managed as wilderness. This WSA was determined to be highly suitable for wilderness designation and was recommended as such in the 2015 Arctic National Wildlife Refuge Comprehensive Conservation Plan.[10] President Obama proposed wilderness designation to Congress in 1915.

To the east, the entire watershed of the Salmon Fork on the Canadian side of the international boundary is designated Chinook Salmon Conservation Unit, CK-77. The Canadian Department of Fisheries and Oceans establishes Conservation Units in order to delineate important units of salmon diversity, to provide the basis of current and future salmon production, and to protect stocks that have unique adaptations that are genetically encoded and are geographically isolated. Additionally, the Canadian Government and the Vuntut Gwich'in First Nation have established the Ni'iinlii Njik Habitat Protection Area, the Ni'iinlii Njik Ecological Reserve, and the Ni'iinlii Njik Wilderness Preserve. The purposes of this combined Wilderness Preserve and Habitat Protection Area are to protect in its natural state a representative example of the North Ogilvie Mountains from development, to protect numerous streams including the headwaters of the Salmon Fork of Draanjik River, and to provide a buffer to mitigate human activities that could adversely affect the wilderness characteristics of the area.

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[8] Kostohrys, J., Lubinski, B., and Collin, N. 1991. Aquatic Resources of the Salmon Fork Black River, Alaska. Bureau of Land Management Open File Report No. 51

[9] *Eastern Interior, Draanjik Record of Decision and Approved Resource Management Plan*, 2016. BLM, Fairbanks.

[10] Arctic National Wildlife Refuge Comprehensive Conservation Plan and Final Environmental Impact Statement (CCP/FEIS). 2015.

WATER QUALITY

40 CFR 131.12(a)(3): "Where high quality waters constitute an outstanding National resource, such as waters of the National and State parks and wildlife refuges and waters of exceptional recreational or ecological significance, that water quality shall be maintained and protected."

By far most of Draanjik River flows within the Yukon Flats National Wildlife Refuge. According to Trawicki, "The chemical water quality of surface water on and adjacent to the Refuge is considered good. Dissolved solids average less than 200 milligrams per liter."[11] The Refuge comprises approximately 10.9 million acres and is bisected by the Yukon River. The purposes for which Congress established the Refuge in 1980 include ensuring water quality in a manner consistent with conserving fish and wildlife populations and habitats in their natural diversity. The Refuge is particularly rich in waterfowl. The number of breeding ducks averages between 1 and 2 million, the highest density in the state. More canvasbacks nest on the Refuge than in the rest of Alaska combined. With some 20,000 wetlands, the Refuge provides thousands of miles of shoreline and cover for nesting. Water quality in the Yukon Flats is of national interest, as waterfowl banded on the Yukon Flats have been recovered in 11 foreign countries, eight Canadian Provinces, and 45 of the 50 United States. Numerous other water birds and shorebirds, including some 15,000 common, Pacific and red-throated loons, spend summers among the lakes, rivers and wetlands on the Refuge. Discharge into the Yukon Flats from Draanjik River is crucial to maintaining the pristine water quality necessary to achieve the purposes of the Refuge.

Draanjik River is of exceptional ecological significance, with more than just local importance. Three species of salmon spawn in its waters, providing subsistence opportunity to Alaskans living along 800 miles of the Yukon River. The uniqueness of Draanjik River salmon stocks is part of nature's strategy of genetic diversity. The upper reaches of different river systems, like Draanjik River and Porcupine River, can be in the same ecological zone, but the salmon in them are geographically isolated from each other and are genetically distinct. Groups of wild salmon living in an area sufficiently isolated from other groups, if extirpated, are very unlikely to be recolonized naturally within an acceptable time frame (e.g. a human life time). Maintenance of genetic diversity lends a species a degree of adaptivity and resilience, and is very important to the future of salmon because of the impacts that climate change is expected to have in the north.

The Yukon River Chinook salmon stocks are currently classified as a yield concern. Draanjik River supports a valuable spawning population of Chinook salmon. Redds and spawning activity have been documented in the main stem of the Salmon Fork from its mouth to about 10 miles into Canada.[12] Since 2015 the Alaska Department of Fish and Game and Tanana Chiefs Conference have been collecting tissue samples of spawning Chinook in Salmon Fork for genetic analysis.

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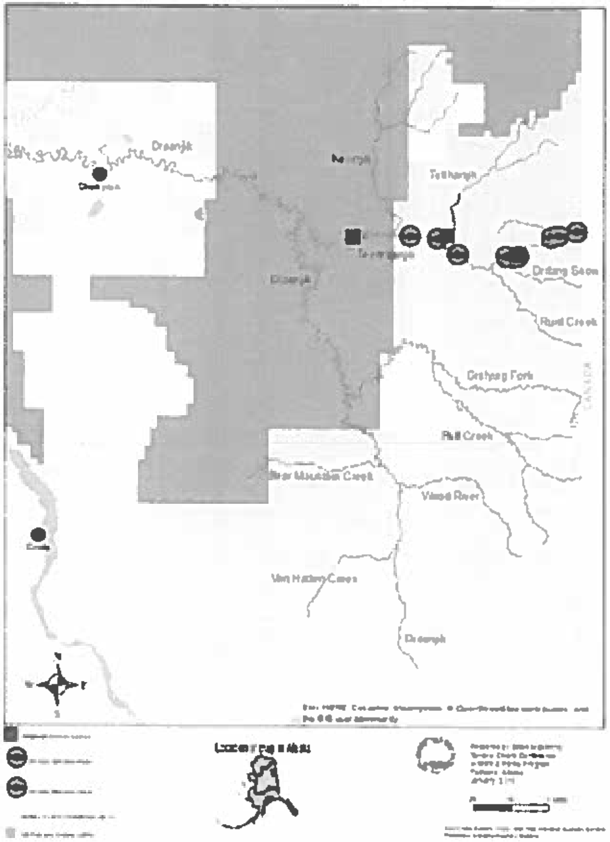
[11] John Trawicki, "Water Resources Inventory and Assessment, Yukon Flats National Wildlife Refuge (Water Years 1993-1998): Final Report," WRB 00-04 (Water Resources Branch, U.S. Fish and Wildlife Service, April 2000), 7

[12] McKenna, Brian, 2017. Personal communication.

2015 Chinook Salmon Tissue Sample Collections



Map illustrating the location of Chinook salmon tissue samples collected in the Salmon Fork in 2015. Fifty samples were collected during 2015. Another forty eight were collected in 2017. Adding to and improving the Yukon River salmon genetic baselines database is an ongoing process which will ultimately result in more accurate and timely management decisions.

Source: McKenna, Brian and Nick DeCovich, 2015. Chinook Salmon Tissue Sample Collections for the Analysis of Yukon River DNA Baseline Samples in Alaska. Yukon River Panel Project CRE-78-14B. Tanana Chiefs Conference, Fairbanks, Alaska

Draanjik River supports significant runs of fall chum and coho salmon. The watershed's spawning and rearing habitat and water quality are important contributors to the success of the Yukon River's commercial, sport and subsistence fisheries. Spawning mostly occurs in the mainstem of Salmon Fork and in tributaries, especially at locations where water wells up through the eroded limestone karst substrate and maintains constant water temperatures. Karst ecosystems are rare and are more productive than ecosystems based on other substrates. Karst is formed by the dissolving action of water on bedrock (usually carbonates). This geological process occurs over thousands of years and results in unusual surface and subsurface features including sinkholes, vertical shafts, disappearing streams, springs, complex underground drainage systems and caves. The numerous areas of upwelling water make Kiiveenjik and Teetthąąnjik Creeks prime spawning habitat for fall chum and coho salmon. The most significant such location, both biologically and culturally for the Draanjik Gwich'in, is Nee'inlįį, located on a side tributary of Kiiveenjik Creek. Nee'inlįį translates literally as "fish swim there repeatedly," and has the more general meaning of "salmon spawning place." Although on the Arctic Circle, upwelling groundwater keeps the stream open throughout the year. This phenomenon creates its own microclimate which affects vegetation, opportunities for habitat use and consequent biological diversity and abundance. Every year thousands of salmon travel from the Bering Sea to spawn and die in this "salmon hole." The resulting nutrient load, and warm upwelling water of this system, sustains an unusually diverse ecosystem for this latitude and location. Grizzly bears congregate around Nee'inlįį and along the river each fall to feed on the spawning salmon. The integrity of the watershed is critical to the maintenance of these natural processes and biological relationships – including the salmon spawning areas and the grizzly bear-salmon interaction.

The Draanjik River also supports a resident spawning population of sheefish.[13] Brown describes this population as a smaller-maturing, upper drainage stock with little or no anadromy which restricts its migrations to freshwater habitats.[14] This is significant because Draanjik River is one of only six sheefish spawning areas which have been identified or verified in the Yukon River drainage.[15] Arctic grayling are found in good numbers throughout the Draanjik River and were the most abundant of all fish species sampled during a fisheries inventory conducted in 1991.[16]

Nee'inlįį, located on a small tributary of Draanjik River. (Photo credit: Brian McKenna, TCC)

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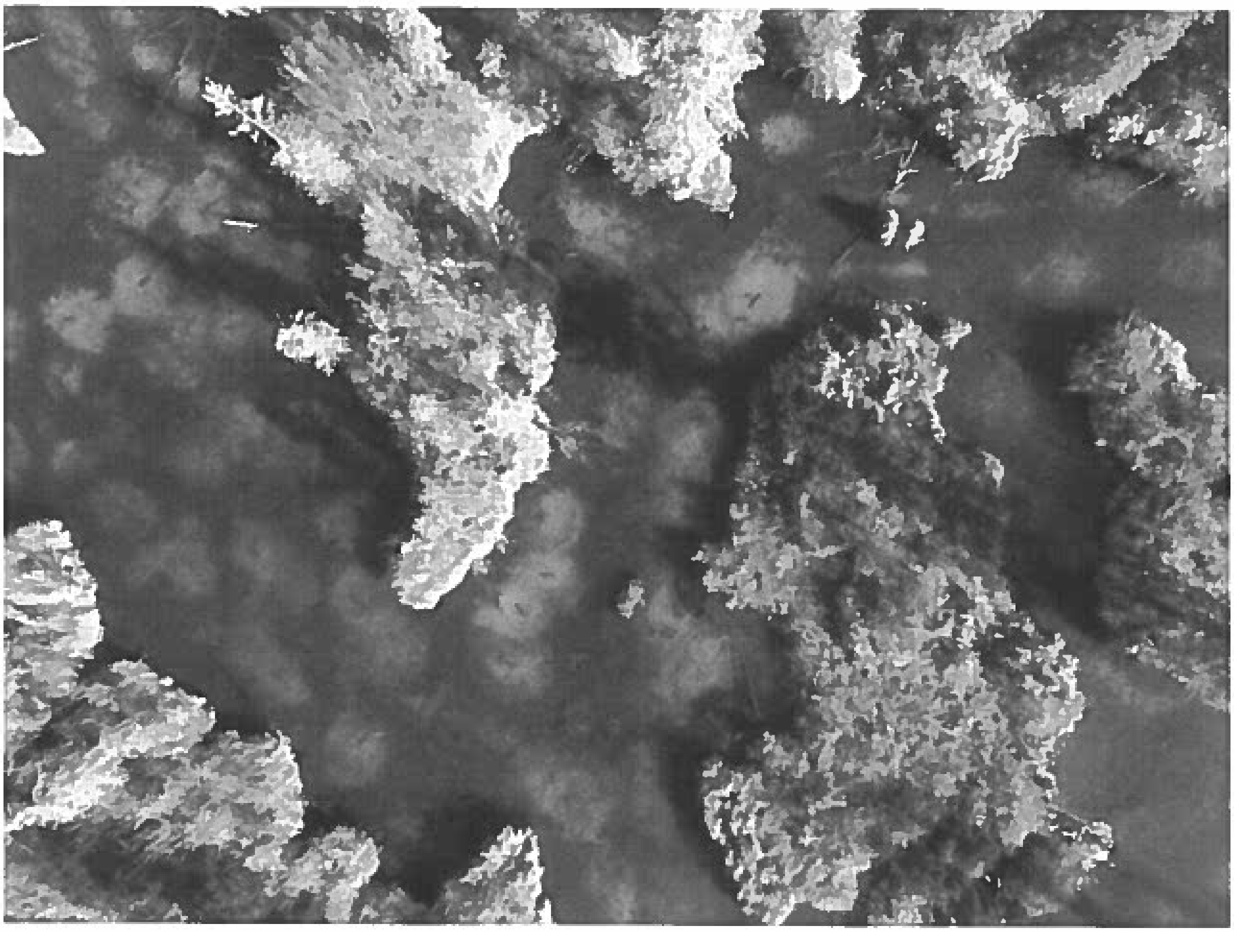
[13] Alt, K. T. 1978. A life history and study of sheefish and whitefish in Alaska. Alaska Department of Fish and Game, Division of Sport Fish, Annual Performance Report, 1977–1978, Federal Aid in Fish Restoration, Project F-9-10, Vol. 19:1–22, R-II, Juneau.

[14] Brown, R. J., C. Brown, N. M. Braem, W. K. Carter III, N. Legere, and L. Slayton. 2012. Whitefish biology, distribution, and fisheries in the Yukon and Kuskokwim River drainages in Alaska: a synthesis of available information. U.S. Fish and Wildlife Service, Alaska Fisheries Data Series 2012–4, Fairbanks, Alaska.

[15] Brown, R.J., and J.M. Burr. 2012. A radiotelemetry investigation of the spawning origins of Innoko River inconnu (sheefish). Alaska Department of Fish and Game. Fishery Data Series No. 12-54.

[16] Kostohrys, J., Lubinski, B., and Collin, N. 1991. Aquatic Resources of the Salmon Fork Black River, Alaska. Bureau of Land Management Open File Report No. 51



Nee'inlįį. The light blue areas are redds. Numerous individual chum salmon are visible.
(Photo credit: Brian McKenna, TCC)

WATER CHEMISTRY

In the mid-1970's, the U.S. Geological Survey[17] conducted a water geochemical survey in the Draanjik River hydrologic unit. A total of 627 water samples were collected from locations in the Black River quadrangle. Not all samples from this quadrangle come from the Draanjik River drainage, as small portions of other streams (e.g. Little Black River and Porcupine River) are included. Samples were collected during September of 1978. Draanjik River also lies on the Charley River quadrangle. Altogether, the USGS obtained water sample geochemistry for 1,148 sample locations within the Draanjik River hydrologic unit.

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[17] U.S. Geological Survey, 1997, Geochemistry of Alaska--National Uranium Resource Evaluation, Hydrogeochemical and Stream Sediment Reconnaissance Program: U.S. Geological Survey Open-File Report 97-492.

Summary of Black River quadrangle sample types.

Sediment Sample Type	Number of Samples	Water Sample Type	Number of Samples
Wet Streams	142	Streams	137
Dry Streams	7	Lakes	490
Wet Lakes	489		
Total Sediments	**638**	**Total Waters**	**627**

The 627 water samples from the Black River quadrangle were sent to the Oak Ridge Gaseous Diffusion Plant (ORGDP) for analysis. These samples were analyzed for uranium and up to 27 additional elements and the results were released by ORGDP in the GJBX-339(81) report. Maps and data for the Black River quadrangle are available online at: https://mrdata.usgs.gov/nure/water/select.php?place=q67144&div=quad&map=on

All 1,148 records from the Draanjik River watershed can be found at: https://mrdata.usgs.gov/nure/water/select.php?place=h19040204&div=fips

The highest anomaly is for naturally occurring zinc in Bull Creek, about three miles west of Midnight Mountain. Water at that sample site contains up to 1,584 ppb zinc, along with elevated barium, cobalt, chromium, iron, magnesium, manganese, and vanadium. The area which Bull Creek drains includes Midnight Mountain, the summit of which is about one mile east of a mineral prospect containing deposits of zinc, and lesser amounts of silver, copper and lead. These prospects are located on land conveyed to Doyon, Ltd.[18]

CONTINUING THREATS TO WATER QUALITY

Midnight Hill; North Midnight

Doyon, Ltd, selected and received conveyance for land which contains deposits of zinc, along with smaller concentrations of lead, silver and copper, located about one mile west of the top of Midnight Hill, in the Bull Creek drainage. The prospects occur along an east-west trending gossan, about 250 feet wide, that extends for about 900 feet. Another, smaller, gossan is located approximately 1000 feet to the northeast.[19][20][21] Commercial development of this prospect, with associated transportation infrastructure, could pose serious threats to water quality in Draanjik River.

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[18] Alaska Resource Data File, Open-File Report 03-53. Black River Quadrangle.

[19] Doyon Limited, 1987, Mines, prospects, and geochemical anomalies on Doyon, Ltd. regional overselection lands, Alaska, Blocks 1-8: Fairbanks, Alaska, WGM, Inc., Doyon Limited Report 86-01A, 150 p. (volume 1 of 2).

[20] Bright, M.J., 1989, Mineral potential of Doyon, Ltd. overselection block VII, east-central Alaska: Fairbanks, Alaska, WGM Inc., Doyon Limited Report 90-35, 29 p.

[21] Jirik, D., Rishel, J., Yinger, M., and Ruzicka, J., 1979, 1978 Annual progress report, Midnight Hill area report: Fairbanks, Alaska, WGM Inc., Doyon Limited Report 79-09.

Existing mineral claims at Rusty Springs property

The Rusty Springs Property is located in the Salmon Fork drainage in Yukon Territory, Canada, 29 km east of the Alaska border. It was first staked in 1975 after investigation of the deep red-orange colored springs and seeps in the valley of Carrol Creek, a tributary of Salmon Fork. Over a 40 year period Rusty Springs has had nearly $5 million in exploration, including 123 drill holes, targeting high-grade silver, lead, copper and zinc mineralization. An all-weather, 600 meter airstrip was completed in 1996 and a 193 kilometer winter road accesses the property from the Dempster Highway. The claims are 100 % owned by Eagle Plains Resources Ltd, which has made Rusty Springs available for option to joint-venture partners.[22] Economic development of this prospect poses complex problems concerning environmental controls, because the effects of mining in Canada could have profound ecological repercussions in Alaska.

Climate change

Changes in habitat within and beyond the Draanjik River system are predicted to stress all of the wildlife, waterfowl and fish populations that serve as subsistence resources. Some populations may increase in abundance while others may alter their migration and become unavailable. The State of Alaska's Department of Commerce stated in its letter to the Alaska Impact Assessment Commission that:

> 'Continued thawing of permafrost, and the retreat and thinning of sea ice is likely to cause widespread alterations to the lifecycles, habitats and health of ecosystems of subsistence resources. As habitats change, these populations are likely to undergo dramatic shifts in range and abundance, which in turn will affect communities that are dependent upon subsistence resources.'
>
> 'Anticipated rural community impacts include:
>
> - Impaired dietary and economic well-being of subsistence based way of life.
> - Loss of traditional meat ice cellars in several northern villages to thaw, making them useless.
> - Reduced quality of life.'

As sovereign governments with the duty to ensure the future wellbeing of their citizens, the Tribes strive to mitigate these impacts, and recognize not only challenges from climate change but consider the compounding of impacts when reviewing potential development that could promote damage to subsistence resources. The Tribes consider the maintenance of water quality to be key to the environmental health of the watershed as a whole, and an indicator of inchoate changes that may have negative and wide ranging impacts. The governing councils of the Tribes have concluded that Tier 3 designation of the Draanjik River is required in order to maintain the watershed's high water quality in the face of these changes.

Changes to the BLM Eastern Interior Resource Management Plan

In early January of 2017, the BLM approved the Draanjik Resource Management Plan (RMP)[23] for the BLM-managed portion of the Draanjik watershed after eight years of effort. The Plan

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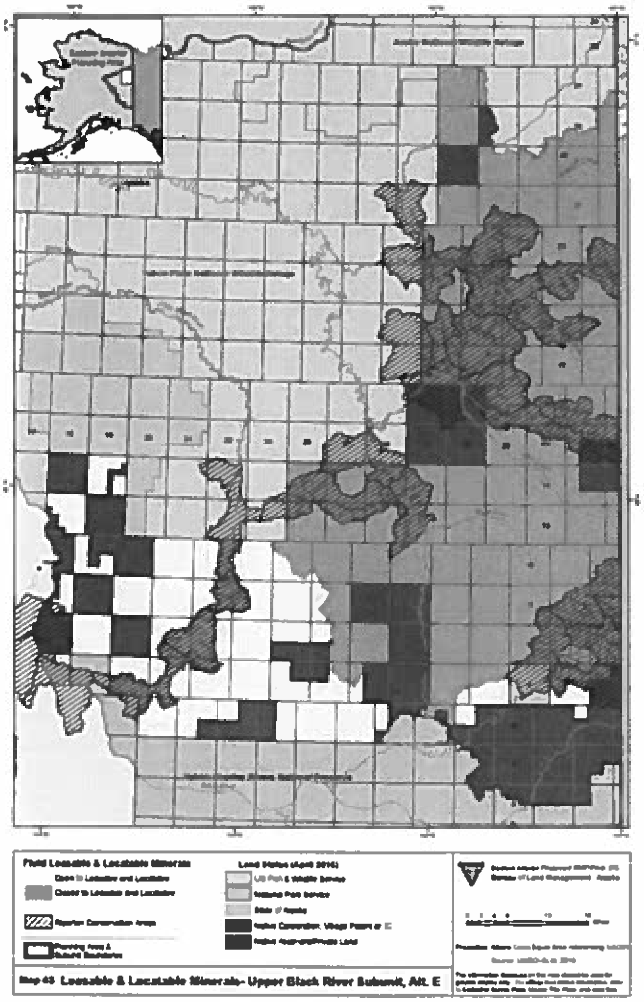
[22] http://www.eagleplains.com/projects/rusty-springs

[23] https://eplanning.blm.gov/epl-front-office/eplanning/docset_view.do?projectId=1100&currentPageId=10151&documentId=94622

closes 77 percent of the lands in its planning area to both mineral leasing and mineral entry, including the Salmon Fork ACEC and the upper Draanjik watershed.

The Tribes and the State of Alaska were Cooperating Agencies during the development of the Plan. The BLM also engaged in extensive government-to-government consultation with the Tribes, who acknowledge that the plan is a compromise that strikes an appropriate balance between the protection of important areas of traditional use and development in conformity with the BLM's multiple use mandate. The approved RMP recognizes the important cultural link between the Tribes and the Draanjik Planning Area, and seeks to protect values important to the Tribes such as water quality. It is designed to protect and maintain the natural chemical, physical, and biological quality of surface and ground waters, wetlands, and floodplains, as well as the natural flow regime, water levels and integrity of surface and ground waters.



The mechanism which the RMP employs to achieve these protections is to recommend to the Secretary of the Interior that existing ANCSA 17(d)(1) withdrawals (public land order 5173 and others as applicable) be maintained until the establishment of new withdrawals under the authority of the Federal Land Policy and Management Act (FLPMA). The new withdrawals would be established on 1,813,000 acres in the following areas for the purposes of protecting sensitive resources, and would withdraw lands from locatable mineral entry and location:

- Approximately 623,000 acres in the Salmon Fork ACEC.
- Approximately 491,000 acres in Riparian Conservation Areas.
- Approximately 699,000 acres in the upper Draanjik River watershed.

The Secretary of the Interior, however, can revoke the current ANCSA 17(d)(1) withdrawals at any time without new FLPMA withdrawals in place, and indeed such revocation has been proposed and is under consideration by the Department of the Interior. If this were to occur it would allow development of placer and hardrock mining in the Draanjik watershed with profound negative impacts on water quality. Therefore, in addition to the protections for water quality written into the current version of the RMP, Tier 3 designation is required to mitigate anticipated risks to the exceptional characteristics of the water.

Karst aquifers require increased protection

> Ground-water flow in karst aquifers is very different from flow in granular or fractured aquifers. Karst ground-water flow is often turbulent within discrete conduits that are convergent in their upper reaches and may be divergent in their very lower reaches, simulating the flow pattern of surface water streams that are dendritic or trellised but with discharge to one or more springs. Significant precipitation events tend to flood karst aquifers quickly, causing a rapid rise in the potentiometric surface that may flood older, higher levels which discharge to a different set of springs. The epikarstic zone in karst terranes stores and directs infiltrating water down discrete percolation points. Chemical contamination may be fed directly to a karst aquifer via overland flow to a sinkhole with little or no attenuation and may contaminate downgradient wells, springs, and sinkholes within a few hours or a few days. Contaminants may also become temporarily stored in the epikarstic zone for eventual release to the aquifer. Flood pulses may flush the contaminants to cause transiently higher levels of contamination in the aquifer and discharge points. The convergent nature of flow in karst aquifers may result in contaminants becoming concentrated in conduits. Once contaminants have reached the subsurface conduits, they are likely to be rapidly transported to spring outlets. Traditional aquifer remediation techniques for contaminated aquifers are less applicable to karst aquifers.[24]

The exceptional productivity of Draanjik River as a salmon spawning stream is due in large part to the fact that it is a karst aquifer type. The biological richness comes with a price: high sensitivity to contamination. Disturbing the hydrogeography through mining activities or petroleum extraction can have wide ranging and unpredictable consequences for critical spawning sites such as Nee'inlįį. When oil is spilled it can have an immediate, acute, negative effect on fish and other aquatic organisms, killing or impairing them through direct contact that may block oxygen uptake, or ingestion, which may compromise other physiological functions.[25] Oil contamination has a much greater impact on the survival and fitness of eggs, larvae, and juvenile fish than on adult fish. When developing salmon embryos are exposed to very low levels of dissolved hydrocarbon (5.4 ppb) they experience reduced growth and survival compared to control groups of unexposed fish.[26] Many studies clearly indicate that oil in the environment is never a positive ecological attribute. The headwaters and uppermost tributaries of Draanjik River extend into a potential gas and oil bearing formation known as the Kandik Basin. With an eye to future oil and gas development in the Kandik Basin, large tracts of upper Draanjik land have been conveyed to Doyon, Ltd, which feels optimistic about the commercial potential of hydrocarbon extraction there.[27] Should development occur, Tier 3 designation will be necessary to ensure stringent controls for the protection of ground and surface water.

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[24] Field, M. KARST HYDROLOGY AND CHEMICAL CONTAMINATION. U.S. Environmental Protection Agency, Washington, D.C., EPA/600/J-93/510 (NTIS PB94135134).

[25] Law, R. J., and J. Hellou. 1999. *Contamination of fish and shellfish following oil spill incidents*. Environmental Geosciences 6(2):90–98.

[26] Heintz, R. A., S. D. Rice, A. C. Wertheimer, R. F. Bradshaw, F. P. Thrower, J. E. Joyce, and J. W. Short. 2000. Delayed effects on growth and marine survival of pink salmon *Oncorhynchus gorbuscha* after exposure to crude oil during embryonic development. Marine Ecology Progress Series 208:205–216.

[27] Hite, David. *A Native Corporation Evaluates Potential of Alaska's Kandik Area*. Oil and Gas Journal, Nov. 17, 1997.

SUMMARY

The water of Draanjik River is exceptional. It is in pristine condition, largely absent of human sources of degradation. Because of its outstanding biological significance, it is valuable to the State of Alaska as a key component to the productivity and ecology of the Yukon River system. Salmon spawning and rearing in Draanjik River provide subsistence opportunity to Alaskans living in 30 communities. It is also a route of migration for Chinook salmon which spawn in Canada.

Draanjik River occupies a karst landscape, atypical in Alaska, and has significant portions characterized by a karst aquifer type. These aquifers include valuable freshwater resources of exceptional quality, but are almost always vulnerable to contamination, due to their specific hydrogeologic properties.[28] Contaminants can easily enter karst aquifers through thin soils or via swallow holes (sinks). Inside the aquifer, contaminants can quickly spread over large distances, due to rapid and turbulent flow in the conduit network. Natural attenuation processes, such as filtration and retardation, are often less effective than in other aquifers.[29] Therefore, karst aquifers require increased protection.

In addition to having exceptional characteristics relative to other State of Alaska water, Draanjik River is a major component of a National Wildlife Refuge, which in itself qualifies the water for designation as Outstanding National Resource Water.

The Draanjik River basin is in one of the most remote corners of Alaska. Many of its headwater tributaries originate in the North Ogilvie Mountains Ecoregion, in protected wilderness areas in Canada. After traversing the Porcupine Plateau, the river ends up as a major contributor to the hydrologic regime of the Yukon Flats. This is a part of North America remarkable for its untrammeled, natural wilderness. It is not, however, uninhabited. For millennia it has been the homeland of the Draanjik Gwich'in, which means "people who dwell along Draanjik River." The river is so central to their identity that they name themselves after it. Under their stewardship the watershed has remained an intact ecosystem which continues today to support a vibrant, productive subsistence economy. The river provides food security, municipal water supply, and transportation to important subsistence resources. Many families in Fort Yukon are of Draanjik Gwich'in origin. They have a favorite story they like to tell about loading up the boat for a return to Draanjik, to visit or to go hunting. Leaving Fort Yukon, the route goes up Porcupine River about 20 miles to the mouth of Draanjik River. Once in the mouth, the boat stops, and everyone pulls out a cup to dip into river for a good drink of delicious, pure Draanjik River water.

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[28] Drew D, Hötzl H (1999) *Karst Hydrogeology and Human Activities. Impacts, Consequences and Implications*. Balkema, Rotterdam.

[29] Ford D, Williams P (2007) *Karst Hydrogeology and Geomorphology*. Wiley

Respectfully Submitted,

Woodie Salmon
First Chief, Chalkyitsik Village Council and Chairman, Council of Athabascan Tribal Governments

Nancy James
First Chief, Gwichyaa Zhee Gwich'in Tribal Government; Vice Chair, Council of Athabascan Tribal Governments

Yakutat Tlingit Tribe
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Phone (907) 784-3238 * Fax (907) 784-3595 * www.ytttribe.org

December 9, 2010

Lynn Kent, Director
Division of Water
Alaska Department of Environmental Conservation
410 Willoughby Ave., Ste. 303
P.O. Box 111800
Juneau, AK 99811-1800

Re: Nomination for Tier 3 Outstanding Natural Resource Water (ONRW) Designation

Ms. Kent,

As a representative's of the Yakutat Tlingit Tribe we nominate the Yakutat Forelands for ONRW status and protection under 18 AAC 70.015(a)(3). Under these criteria, the Yakutat Forelands qualify as both an exceptional recreational area and as having special ecological significance. Additionally, these lands contain many historic, traditional, sacred and cultural sites vital to the Tlingit Tribe.

Furthermore, we find that the entire area is comprised of an interconnected wetland that functionally serves as one watershed. The entirety of this wetland is critical anadromous fish habitat. The surrounding riparian vegetation plays a crucial role in fish habitat and channel stability: shade, cover, food, stream energy dissipation, and habitat complexity, are critical to the maintaining the functions of anadromous wetlands. Wetlands are described as part of essential fish habitat in the Pacific Coast Salmon Plan (1999). Tier 3 designation will uphold the public interest as described in the Alaska Wetlands Initiative (EPA, May 1994).

Area Boundaries

The area nominated is comprised of the Land Use Development (LUD) II area and Semi-remote Recreation LUD named as the Yakutat Forelands in the Tongass Land and Resource Management Plan (TLMP), 2008. A map is available in the published Forest Plan. The goal of this LUD as stated in TLMP is to "***maintain the wild land characteristics of these congressionally designated unroaded areas, permit fish and wildlife improvements and primitive recreational facilities***." The protections afforded under a Tier 3 designation are consistent with this goal.. The area is already under congressionally mandated protection.

To preserve, maintain and protect the unique culture, land & resources of Yakutat Tlingit people;
to maximize our social, health & well being while creating economic development benefits to all tribal members.

Area Characteristics

The Yakutat Forelands comprise a diverse array of wetlands that possess a variety of functions and values that contribute substantially to the States and Nation's economy and well-being. These estuarine vegetated wetlands are considered to be among Alaska's most valuable. The area includes moist and wet marshes, kettle ponds, palustrine emergent marshes, sitka spruce/ hemlock forested wetlands, riparian shrub communities, littoral wetlands, and temperate rainforest wetlands. This area serves as valuable habitat to wildlife and fisheries. All of the activities, either natural or by man on the Forelands are dependent on the natural quality and abundance of the water. The interconnectedness between hydrology, fisheries, wildlife and people in this area demands the highest level of protection by the State of Alaska.

Reasons Tier 3 Protections

Fish Habitat

These coastal and riverine wetlands are important to commercial, sport and subsistence fishing economies. The Yakutat Forelands are an interconnected wetland/estuarine complex that serve as critical spawning and rearing areas for all five salmon species, cutthroat, dolly varden trout and significant runs of eulachon. Included in this area are the Italito, Akwe and Alsek Rivers. According to the West Foreland Hydrologic Condition Assessment (2005);

> "These streams collectively have the highest values for both spawning and rearing habitats. They are also among the most sensitive to both natural and human-caused disturbances. Some have developed complex life cycles uniquely adapted to their watersheds. The Situk River alone is considered one of the most productive rivers in Southeast Alaska due to its high fish species diversity and population density (Thedinga et al 1993)."

These world-class recreational fishing rivers attract thousands of sport fishermen per year from throughout the world. The revenue generated by sport fishing is vital to the economy of Yakutat and Southeast Alaska.

The Yakutat Forelands have been a vital subsistence fishery for over a millenium. These wetlands support subsistence fisheries for Native and rural non-Native Alaskans, as well as big game hunting. Resident households in Yakutat consume over 1000 pounds of wild foods, annually, from the forelands alleviating the high cost of grocery bills (Alaska Dept. of Fish and Game Subsistence Division Report, 1999).

Wildlife Habitat

The Yakutat Forelands comprise a valuable habitat for black and brown bear, moose, waterfowl, trumpeter swans, sandhill cranes, shorebirds, wolves, marbled murrelets, and various neotroppical migrants for reproduction ,winter habitat and migration resting areas. Over 500,000 shorebirds utilize the foreland estuaries during migration (Alaska's Key Costal Wetlands, U.S. Forest Service Report)

Importance to Tlingit Culture

The area contains numerous archeologically sensitive areas sacred to the Tlingit peoples. Much of their culture and identity are dependent on the continued health of the Forelands. Large sections of the area are currently being assessed for eligibility for the National Historic Register.

Local Economy

Tlingit people are known as people of the Salmon, the majority of the monetary economy of Yakutat is derived from the Forelands in the form of commercial fishing, guided hunting and fishing, tourism, and remote recreation. All of these activities depend on the pristine quality of the wetland resource.

Therefore we ask the Alaska State Department of Environmental Conservation to acknowledge the exceptional ecological significance and outstanding recreational opportunities of the Yakutat Forelands and protect the dependent relationship between the surface and subsurface water quality, soils, fish and wildlife, economy and culture and designate this area a Tier 3 Outstanding Natural Resource Water afforded the highest level of protection.

Thank you for your assistance in helping us to attain this.

Yakutat Tlingit Tribe Council

Name:______________________________ Title:_Tribal President_______________
Victoria L. Demmert

Signature:_____________________________ Date:__________________________

Nomination of the Koktuli River
(North Fork, South Fork, Main Fork)

Alaska's First Outstanding National Resource Water

Petitioners:
Trout Unlimited, Inc. – Alaska Program
Nushagak-Mulchatna Wood-Tikchik Land Trust
Alaska Alpine Adventures, LLC (Dan Oberlatz)
SnoPac Products, Inc.
Alaska Independent Fishermen's Marketing Association
Renewable Resources Coalition
Nunamta Aulukestai

Table of Contents

Executive Summary

On behalf of Trout Unlimited, Inc. – Alaska Program, the Nushagak-Mulchatna Wood-Tikchik Land Trust, Alaska Alpine Adventures, LLC (Dan Oberlatz), SnoPac Products, Inc., Alaska Independent Fishermen's Marketing Association, Renewable Resources Coalition, and Nunamta Aulukestai (collectively "Petitioners"), we submit the following nomination to designate the Koktuli River as Alaska's first Outstanding National Resource Water (ONRW).

The Koktuli River is legendary even by Alaska standards. Its meandering route across the rolling tundra of Southwest Alaska beckons to anglers and backcountry recreationists from around the globe - drawing outdoor enthusiasts of all kinds to the its clean sparkling water, world-class wildlife viewing and hunting opportunities, and trophy trout and salmon.

The Koktuli River system, an ecological powerhouse located in the heart of the Bristol Bay watershed, is the headwaters to the most productive sockeye salmon fishery in the world. It is one of Alaska's highest valued waters – a source of pristine water sustaining critical fish and wildlife habitat in one of the most intact watersheds left on the planet. The Koktuli River drainage supports over a dozen species of fish, including all five Pacific salmon species, and serves as prime spawning, rearing, and migration habitat. The Koktuli's remote nature and pristine water quality are crucial factors that sustain the millions of salmon that are born, grow, migrate and return to spawn its gravels every year – upholding a large part of the world renowned Bristol Bay salmon population.

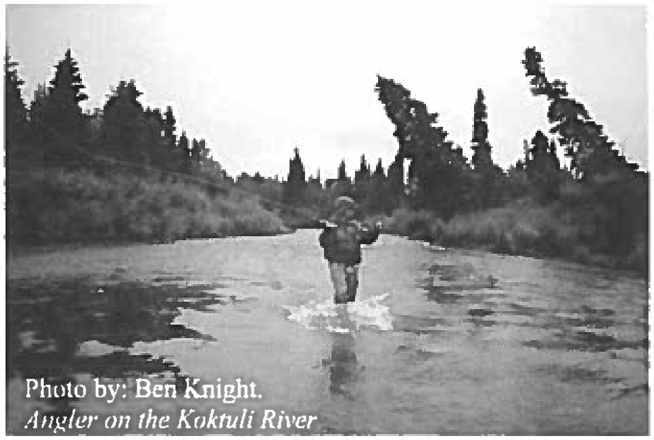

Photo by: Ben Knight.
Angler on the Koktuli River

In addition to its outstanding ecological capacity the Koktuli River is well known across the state, the nation, and the world, for the exceptional recreation opportunities that exist because of its pristine water quality, and bountiful wildlife and fishery resources. Anglers from all over the world travel to the Koktuli River each year to experience some of the best backcountry fishing opportunities Alaska has to offer. In addition, the Koktuli River system and the larger Bristol Bay watershed is a critical component to the local lifestyle – it supports the world's largest sustainable commercial sockeye salmon fishery and generations of subsistence users.

While the Bristol Bay region is remarkable by all standards and has many exceptional waters, the Koktuli River is truly outstanding. Protecting the Koktuli River system's pristine water quality for its recreational, commercial and subsistence values is an important part of maintaining the integrity of this unique world-class watershed. This nomination reflects a widespread desire to protect its outstanding qualities and to recognize an important class of streams of which the Koktuli River so exemplifies through the designation of Alaska's first ONRW.

I. BACKGROUND

A. Nominated Waterbody: The Koktuli River (North Fork, South Fork, Mainstem)

The waterbody nominated for Outstanding National Resource Water designation comprises all of the tributaries of the Koktuli River, its associated sloughs and floodplains, as well as the North and South Forks from their sources, to where the mainstem Koktuli meets the Mulchatna River. [1]

The three maps (Figures 1-3) and two appendices (Appendix I and II) detail the location of the waterbody, as well as current land status.

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[1] The system nominated as Alaska's Outstanding National Resource Water includes Mainstem, North and South Forks of the Koktuli River, from the North Fork headwaters near Latitude 59.95 N and Longitude -155.323 W and the South Fork headwaters near Latitude 59.896 N and Longitude -155.278 W, to where the mainstem discharges into the Mulchatna River at Latitude 59.933 N and Longitude -156.428 W

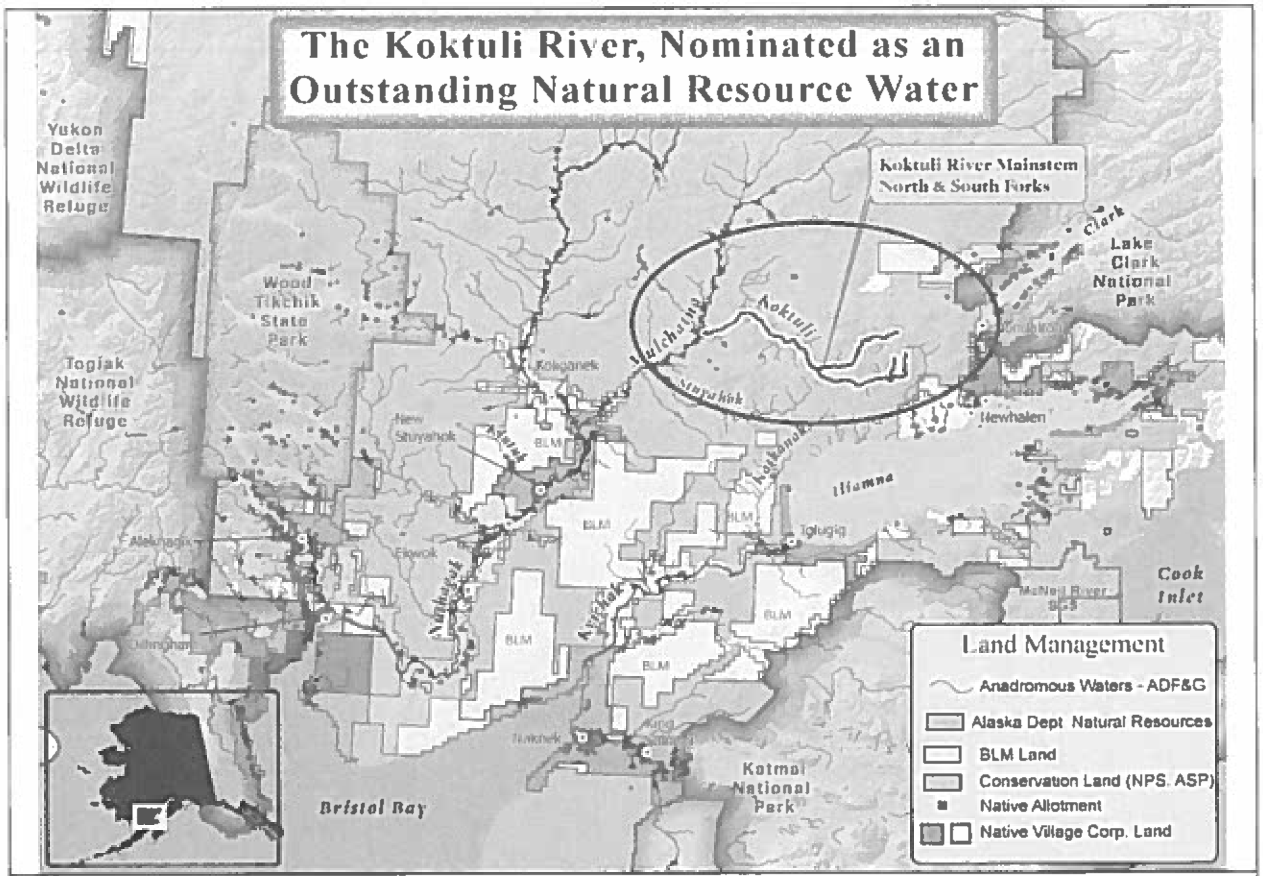

Figure 1: Overview map showing general location of the Koktuli River. The map also provides land status information of surrounding area.

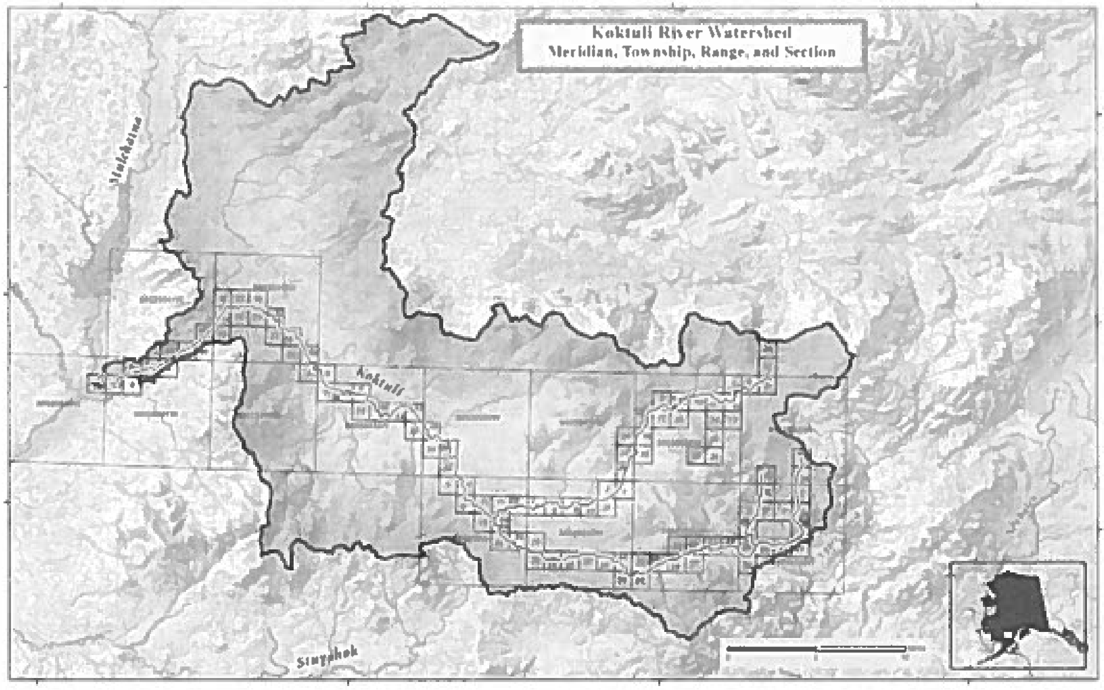

Figure 2. Map of Koktuli River Drainage (Mainstem, North and South Forks) delineated in blue outline. The system nominated as Outstanding National Resource Waters includes Mainstem, North and South Forks, from the North Fork headwaters near Latitude 59.95 N and Longitude -155.323 W and the South Fork headwaters near Latitude 59.896 N and Longitude -155.278 W, to where the mainstem discharges into the Mulchatna River at Latitude 59.933 N and Longitude -156.428 W. Boxes illustrate precise location of river system by Meridian, Township, Range, and Section. (See Appendix I and II for full listing of Meridian, Township, Range and Section information)

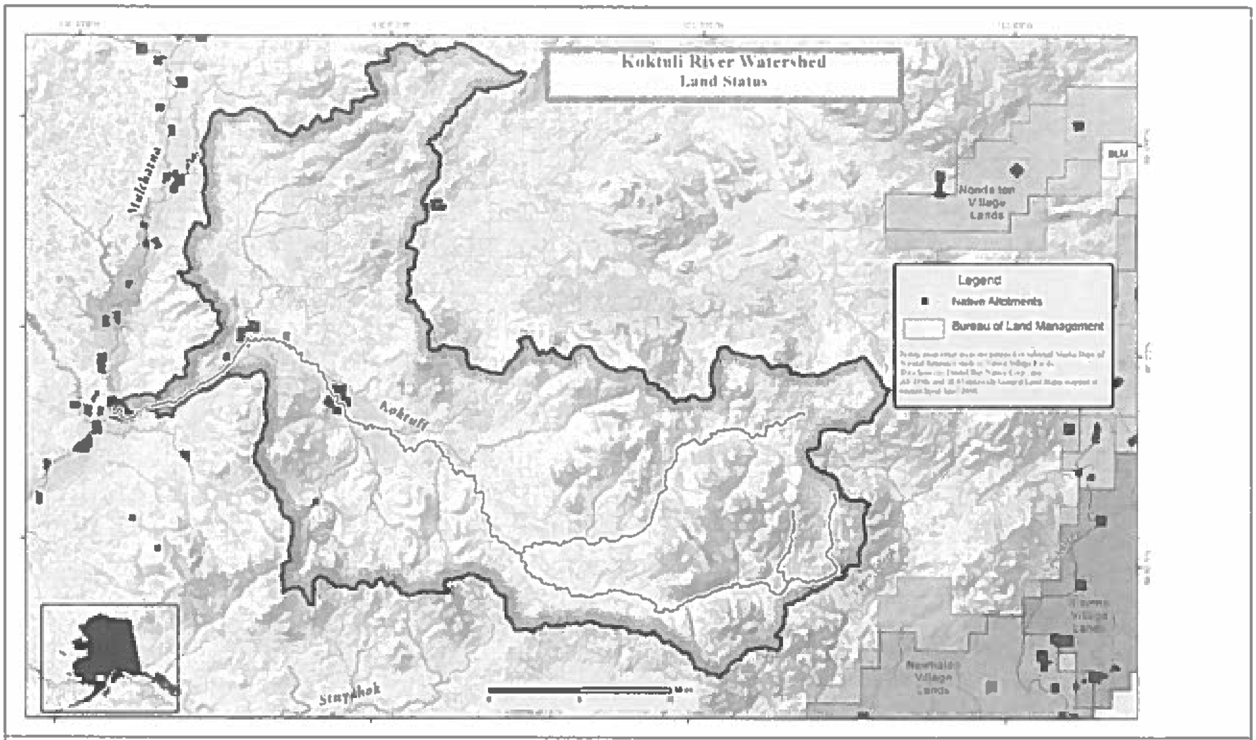

Figure 3: Koktuli River Watershed showing State Land Status and Native Allotments

B. Legal Background

This rule-making petition is filed under Alaska Statute (AS) 44.62.220, which allows any interested person or group to petition an agency for the adoption or repeal of a regulation. Under AS 44.62.230, within thirty days after receipt of the petition the Alaska Department of Environmental Conservation (ADEC) must either deny the petition in writing or schedule the matter for a public hearing under AS 44.62.190 - 44.62.215. In this instance, should ADEC need additional time to consider the petition, under appropriate circumstances the petitioners would be willing to waive the thirty day deadline.

The Clean Water Act ("CWA") is the nation's most important water quality protection statute, and one of its primary goals is to restore and maintain "the chemical, physical, and biological integrity of the Nation's waters." 33 U.S.C. § 1251(a). The Act seeks to achieve this goal in several ways, one of which is the promulgation of water quality standards. Under section 303(c), 33 U.S.C. § 1313(c), the state promulgates water quality standards ("WQS") not only to establish water quality goals for the nation's waters, but also to provide a regulatory mechanism when technology-based standards prove inadequate. *See* Water Quality Standards Handbook: Second Edition ("Handbook"), EPA-823-B94-005a, p. INT-1 (1994). Generally, WQS define the water quality goals for a waterbody by designating the permissible uses of the waterbody, setting criteria to protect the designated uses, and using antidegradation requirements to prevent any worsening of water quality. 40 C.F.R. § 131.6. As a result, WQS are a critical and necessary part of the CWA's mandate to enhance and maintain water quality in order to protect public health and welfare, especially when technology-based standards under the National Pollutant Discharge Elimination System ("NPDES") permit system do not achieve established water quality protections.

Antidegradation is a WQS requirement found in section 303(d) of the CWA and further detailed in federal regulations. The goals of antidegradation are to: (1) ensure that no activity will degrade water quality so as not to support existing uses; and (2) maintain and protect high quality waters. 33 U.S.C. § 1313(d); 40 C.F.R. § 131.12. The federal antidegradation policy requires states to develop rules and implementation procedures to protect existing uses and to prevent clean waters from being unnecessarily degraded, while giving very stringent protection to the highest quality waters in the state. Federal regulations specify that each state must adopt an antidegradation policy "consistent with the following":

> (1) Existing instream water uses and the level of water quality necessary to protect the existing uses shall be maintained and protected.
> (2) Where the quality of the waters exceed levels necessary to support propagation of fish, shellfish, and wildlife and recreation in and on the water, that quality shall be maintained and protected unless the State finds, after full satisfaction of the intergovernmental coordination and public participation provisions of the State's continuing planning process, that allowing lower water quality is necessary to accommodate important

> economic or social development in the area in which the waters are located. In allowing such degradation or lower water quality, the State shall assure water quality adequate to protect existing uses fully. Further, the State shall assure that there shall be achieved the highest statutory and regulatory requirements for all new and existing point sources and all cost-effective and reasonable best management practices for nonpoint source control.
>
> (3) Where high quality waters constitute an outstanding National resource, such as waters of National and State parks and wildlife refuges and waters of exceptional recreational or ecological significance, that water quality shall be maintained and protected.

40 C.F.R. § 131.12.[2] In 1997, Alaska adopted this three "tier" approach almost word for word, although the state's policy specifies, under (2), that the state may allow "the reduction of water quality for a short-term variance under 18 AAC 70.200, a zone of deposit under 18 AAC 70.210, a mixing zone under 18 AAC 70.240, or another purpose as authorized in a department permit, certification, or approval." 18 AAC 70.015(a). This exemption can be granted only after an applicant submits an application and the department finds that the exemption is necessary for social or economic reasons, that certain water quality criteria will not be violated, and that certain methods of pollution control will be implemented. 18 AAC 70.015(a)(2).

EPA's antidegradation regulation also requires the State to "identify the methods for implementing such policy. . . ." 40 C.F.R. § 131.12(a). For enforcement purposes, this is the most important part of the antidegradation requirement. The procedures developed to implement the antidegradation policy must be designed to: (1) prohibit any degradation in some waters; (2) minimize the impacts of degrading activities in others; and (3) assure that in <u>every</u> case, existing uses are protected. *See* Handbook, pp. 4-1 – 4-2.

<u>To date, the Alaska Department of Environmental Conservation ("DEC") has not established implementation procedures for its antidegradation policy, as required by EPA</u>. Those procedures would specify the process and criteria used to determine when waters are degraded by discharges or nonpoint sources of pollution, and what social and economic benefit to the state would be necessary to justify any degradation. They would also establish a process for nomination and designation of ONRWs.

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[2] *See also* Handbook, p. 4-10:

- Tier 1: <u>Protect Existing Uses</u>. Permit no activity that would eliminate, interfere with or lower water quality necessary to support existing uses.
- Tier 2: <u>Maintain "High Quality" Waters</u>. Avoid – or at least hold to an absolute minimum – any lowering of the water quality of waters that meet or exceed standards. In order to allow additional pollution loading, it must be shown that the increase is necessary, there are no alternatives to increasing the pollution, and the activity generating the pollution provides important economic or social development to the community (i.e. jobs, sanitary services, etc.).
- Tier 3: <u>Protect "Outstanding" Waters</u>. Give the most ecologically significant and sensitive, the cleanest, and the most recreationally popular waters the strict protection they need and deserve (i.e., no degradation allowed).

Even though the State has no antidegradation policy implementation procedures, the federal antidegradation policy provides guidance for Petitioners. Guidance for developing implementation methods for antidegradation policies is to be provided through EPA's Regional Offices.[3] While there is no published antidegradation guidance from Region X, Region VIII provides the following guidance on factors to consider when designating ONRWs:

> The factors to be considered in determining whether to assign an ONRW designation may include the following: (a) location (e.g., on federal lands such as national parks, national wilderness areas, or national wildlife refuges), (b) previous special designations (e.g., wild and scenic river), (c) existing water quality (e.g., pristine or naturally-occurring), (d) ecological value (e.g., presence of threatened or endangered species during one or more life stages), (e) recreational or aesthetic value (e.g., presence of an outstanding recreational fishery), and (f) other factors that indicate outstanding ecological or recreational resource value (e.g., rare or valuable wildlife habitat).[4]

Other guidance is also helpful in identifying relevant criteria for designating ONRWs. For example, the Great Lakes Initiative ("GLI") identifies the following criteria:

> Waters that may be considered for designation as Outstanding National Resource Waters include, but are not limited to, water bodies that are recognized as: Important because of protection through official action, such as Federal or State law, Presidential or secretarial action, international treaty, or interstate compact; Having exceptional recreational significance; Having exceptional ecological significance; Having other special environmental, recreational, or ecological attributes; or waters whose designation as Outstanding National Resource Waters is reasonably necessary for the protection of other waters so designated.[5]

Other states, such as New Mexico, provide a detailed list of the materials that must be submitted to nominate surface waters for ONRW designation. Any person may nominate a surface water of the state for designation as an ONRW by filing a petition with the New Mexico water quality control commission pursuant to petition guidelines.[6] A petition to classify a surface water of the state as an ONRW must include: (1) a map of the proposed surface water area; (2) a written statement based on scientific principles to support the nomination; (3) supporting scientific evidence demonstrating that one or more of ONRW criteria has been met; (4) water quality data to establish a baseline for the proposed ONRW; (5) a discussion of activities that might contribute to the reduction of water quality in the proposed ONRW; (6) any additional evidence to substantiate the designation, including an analysis of

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[3] Water Quality Standards Regulation, 63 Fed. Reg. at 36,781.

[4] U.S. Envtl. Prot. Agency, Region VIII, EPA Region VIII Guidance: Antidegradation Implementation 9 (1993), http://www2.rivernetwork.org/cleanwater/Region8_ch2_pg5-20.pdf

[5] Final Water Quality Guidance for the Great Lakes System, 60 Fed. Reg. 15,366, 15,413 (1995).

[6] N.M. Code R. § 20.6.4.8 (2000).

the economic impact of the designation; and (7) an affidavit of publication of notice for the petition.[7] However, no specific ONRW criteria are included in the New Mexico petition requirements.

Similarly, Virginia adopted a nomination process that requires petitioners to justify an ONRW designation based on specified factors.[8] In Virginia, the State may classify unique and special surface waters of the state as an ONRW upon finding that such waters have (1) exceptional environmental settings and (2) *either* exceptional recreational *or* aquatic community significance. The factors are further broken down to include the following:

1) **Exceptional Environmental Settings**: This category lists those features that singly or in combination make a water body physically attractive. To meet this mandatory requirement, one or more of the following factors must apply:
    a) The water possesses outstanding scenic beauty resulting from the natural features of the basin such as its topography, geology, ecology or physiography; or
    b) The water has already received designation as a national wild and scenic river; or
    c) The water represents an important component of a state or national park, forest, or wildlife refuge; or
    d) The water includes remote, primitive or relatively undeveloped areas with public access by motorized vehicle restricted or unavailable.
2) **Exceptional Recreational Significance**: In order to demonstrate the nominated water body exhibits exceptional recreational opportunities, the water must support recreational activities which do not require modification of the existing natural setting such as fishing, canoeing, rafting, kayaking, tubing, birding, hiking, backpacking with primitive camping, or the like.
3) **Exceptional Aquatic Community Significance**: To demonstrate that a water body nominated for ONRW status contains an "exceptional aquatic community," one or more of the following factors must apply:
    a) The water supports an exceptional wild or natural fishery, or
    b) The water contains an exceptional high diversity of aquatic species (fish or benthic macroinvertebrate) as categorized by the appropriate protocol for that water body type and species, such as the 95th percentile of the EPA's Rapid Bioassessment Protocol II method for measuring macroinvertebrate diversity in streams[9] or the 95th percentile of biological metrics provided in more recent EPA

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[7] *Id.*

[8] Memorandum from Ellen Gilinsky, Director, Virginia Department of Environmental Quality, on Guidance for Exceptional State Waters Designations in Antidegradation Policy Section of Virginia Water Quality Standards Regulation to Regional Directors (November 15, 2004), http://www.deq.state.va.us/export/sites/default/waterguidance/pdf/042021.pdf.

[9] Plafkin, James L., Michael T. Barbour, Kimberly D. Porter, Sharon K. Gross and Robert M. Hughes, *Rapid Bioassessment Protocols For Use in Streams and Rivers: Benthic Macroinvertebrates and Fish*, United States Environmental Protection Agency; Office of Water; Washington, D.C. (1989).

bioassessment technical support guidance documents for wadeable streams and rivers,[10] lakes and reservoirs[11] and estuarine and coastal marine waters.[12]

Because DEC has yet to develop antidegradation policy implementation procedures, this Petition follows the established criteria from Region VIII and other states as a basis to petition DEC for a rulemaking to designate ONRWs in the Bristol Bay region, namely the Koktuli River, North and South Forks and Mainstem. **Based upon the following detailed information provided in this Petition, DEC should classify Koktuli River, its associated sloughs and floodplains, the tributaries of the Koktuli River, as well as the North and South Forks from their sources to where the mainstem discharges into the Mulchatna River, as Alaska's first Outstanding National Resource Water.**

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[10] Barbour, M.T., J. Gerritsen, B.D. Snyder, and J.B. Stribling, *Rapid Bioassessment Protocols for Use in Wadeable Streams and Rivers: Periphyton, Benthic Macroinvertebrates, and Fish*, Second Edition, U.S. Environmental Protection Agency (1999), http://www.epa.gov/owow/monitoring/rbp.

[11] Gerritsen, Jeroen, Robert E. Carlson, Donald L. Dycus, Chris Faulkner, George R. Gibson, John Harcum, and S. Abby Markowitz, *Lake and Reservoir Bioassessment and Biocriteria. Technical Guidance Document*, United States Environmental Protection Agency (1998), http://www.epa.gov/owow/monitoring/tech/lakes.html.

[12] Bowman, Michael L., George R. Gibson, Jr., Jeroen Gerritsen, and Blaine Synder, *Estuarine and Coastal Marine Waters: Bioassessment and Biocriteria Technical Guidance*, United States Environmental Protection Agency, 2000, http://www.epa.gov/ost/biocriteria/States/estuaries/estuaries1.html.

II. RATIONALE FOR THE NOMINATION OF THE KOKTULI RIVER

The Koktuli River is part of the larger Bristol Bay watershed - an intricate system of rivers, lakes, and streams, 250 miles southwest of Anchorage, Alaska. Five major rivers (the Nushagak, Kvichak, Naknek, Egegik, and Ugashik rivers) draining into Bristol Bay produce: (1) one third of the world's sockeye salmon (the most important commercial stock), (2) the world's most famous indigenous trout fisheries, (3) tremendous commercial, subsistence and sport fishing economic value (contributing over $440 million to Alaska's economy each year), and (4) because of the fish, one third of the U.S. grizzly bear population. The Koktuli River system stands as a crucial component of this intricate web of habitat sustaining the biocomplexity of fisheries, especially salmon, populations within the watershed.

The headwaters of the Koktuli River are located approximately 120 miles northeast of the community of Dillingham, Alaska. The Koktuli flows approximately 75 miles from its headwaters to the confluence of the mainstem with the Mulchatna River, which then flows into the Nushagak River and into Bristol Bay. The Nushagak River (including the Koktuli) hosts the largest king salmon run in Alaska; in 2006 ADF&G counted 125,000 into the system. In 2008, the Alaska Department of Fish and Game documented an inshore run of over 10 million sockeye salmon in the Nushagak system (ADF & G, 2008).

Though it is clear under federal regulations that in designating ONRWs "water quality shall be maintained and protected", neither the federal regulations nor the State of Alaska DEC spells out definitive criteria for ONRW designation beyond the suggestion that candidate waterbodies should be "waters of exceptional recreational or ecological standards" or ones already recognized under a park, refuge or Wild and Scenic Designation. But in the words of past member of the Alaska Board of Fisheries Rupe Andrews, who spoke to the value of the Koktuli River, and its nearby Upper and Lower Talarik Creeks, we believe that "Extraordinary places deserve extraordinary protections." (Board of Fish Meeting – December 2006)

Petitioners nominate the Koktuli River system as Alaska's first ONRW for several reasons. First, it has already been recognized by stakeholders (ranging from back country recreationists to commercial fisherman and local businesses to the Alaska state legislature) as an important area through existing "special designations." Second, the Koktuli River holds extraordinary ecological significance both because of its own unique ecosystem and as a major support system for the larger region . Third, the recreation opportunities are outstanding, setting the gold-standard for Alaska backcountry floating and fishing opportunities.

A. *Previous/Existing Special Designations*

The Kokuli watershed is already recognized as having exceptional ecologic, historic, and recreational value to the state of Alaska and beyond. As world salmon resources decline the value of Bristol Bay's salmon resources continues to grow. As early as the 1970's the state recognized the importance of the fishery and the watershed that supports it and determined it was in the best interest of the state to provide heightened protection for the Bristol Bay area, its wild salmon and the superb existing recreational, subsistence, commercial and ecological values within and connected to the area. In 1972 the Bristol Bay Fisheries Reserve was created - the Koktuli River lies in the heart of this Reserve Area..[13] These reasons for protection continue to be relevant and support the need for additional protective measures in the Bristol Bay region, especially in the Koktuli watershed.

There is wide-ranging support from a diverse stake-holder group that the Koktuli River system is extremely important to Alaskans and special recognition and protection of the Koktuli river system re-emerged as a priority amongst fisheries stakeholders over two years ago, when the Board of Fisheries (BOF) reviewed Proposal 121 which would provide additional protections for the watersheds in the region. The proposal received the most public testimony recorded in the history of the BOF in favor of a proposal. As a result of the meetings, the Board of Fisheries acknowledged the Koktuli River and the larger Bristol Bay watershed as outstanding fisheries resources by establishing a Habitat Committee to further address the potential need for additional protective measures. Testimonies of support for these waters to be protected as a Fisheries Refuge came from local Natives, commercial and sport fisherman, as well as attorneys and scientists. **(See Section on *Community Support and Testimony* on pg. 48)**

During the following legislative session, two bills, Senate Bill 67 and House Bill 134, were introduced to offer higher standards of protection for the Koktuli River and other key systems in Bristol Bay. Senate Bill 134, the *Wild Salmon Protection Act*, aimed for protection of water used by salmon or for human consumption.[14] The Bill passed out of the Fisheries Committee of the 25th legislature. As introduced, it provided that subject to exceptions for most current uses of water, a person would not be able to "withdraw, obstruct, divert, inject, pollute or pump" surface or ground water or "alter, destroy, displace, relocate, channel, damn [or] convert to dry land" any water body in the Nushagak River drainage and other rivers which flow into Bristol Bay.[15] The Bill received the most hearings held in one committee in

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[13] This determination prohibited the issuance of a surface entry permit or an exploration license to develop an oil and gas lease until the legislature found that the entry would not constitute a danger to the fishery. However, this provision did not include provision on mining, which now stands at the greatest potential risk to these waters. **(See Section on *Potential Risks to the Reduction of Water Quality and Existing Values* at pg. 35)**

[14] H.B. 134, 25th Leg. (Feb. 2007), *available at* http://www.legis.state.ak.us/PDF/25/Bills/HB0134A.PDF (last checked Mar. 24, 2008). While S.B. 67 primarily seeks to protect fish, game, habitat, and public uses of these resources, and would be implemented by ADF&G and DNR, H.B. 134 would add a new section to the Alaska Code, Alaska Stat. § 16.10.015, and would be implemented by the Alaska Department of Environmental Conservation (DEC).

[15] See H.B. 134, 2007 Leg., 25th Sess. § (Alaska 2007).

Alaskan history and had an astounding level of public support, however it didn't get passed into law. In essence, the Bill would have offered many of the same antidegradation policies that the designation of as an Outstanding National Resource Water would enact. Recognizing the time required and the political process of passing a such a Bill in the State legislature, the immediate threats to the Koktuli River, the mission of the Water Department of Alaska's Department of Environmental Conservation to improve and protect the State's water resources, and the intent of the federal law governing Outstanding National Resource Waters, the petitioners believe ONRW designation best ensures continuation of the pristine water quality of the Koktuli River system.

B. Exceptional Ecological Value

The Koktuli River watershed is one of the most intact watersheds left on the planet. Characterized by healthy meandering rivers, clean clear cold water and a haven for fish and wildlife alike – it deserves special protection for its pristine, intact ecological conditions.

As previously discussed, the federal Clean Water Act and accompanying federal regulations require States to develop water quality standards[16], which must include an antidegradation policy.[17] Ultimately, the state must develop policy consistent with the federal antidegradation policy. Clearly under federal antidegradation regulations, "exceptional recreational or ecological significance" is a central criterion for designating ONRWs, as well as formal recognition that the water body is of high quality, in this case, recognition previously granted by the Alaska State Legislature (as discussed in above Previous/Existing Special Designations Section).

Supporting Scientific Evidence Demonstrating ONRW Criteria

1. Healthy fish populations

The pristine water, intact river beds, and relatively untouched uplands of the Koktuli River sustain one of the most productive trout and salmon fisheries in the world. These fish support other aquatic life in the system as well as many terrestrial species.

The rivers and streams of the Koktuli watershed provide some of the best coldwater fish habitat in the region. The Koktuli salmon are of particular importance because they significantly contribute to the genetic diversity of Bristol Bay's salmon fisheries. Escapement[18] into the Koktuli's North and South forks is historically strong for coho, sockeye, and Chinook salmon. Historic aerial escapement index counts of Chinook salmon, conducted by the Department of Fish and Game between 1967 to 1999, show the Koktuli River to have the highest mean of

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[16] 33 U.S.C. s. 1313(a); 40 C.F.R. s.131

[17] 40 C.F.R. s.131.12

[18] It must be noted that any measure of escapement is probably an underestimate of the actual and that escapement estimates are made after harvests; and, therefore, are a very poor representation of the production.

streams selected by salmon (out of the Stuyahok River, Nushagak River, Mulchatna River, King Salmon River, Klutuspak River, Kokwok River, Iowithla River, and Koktuli River, all within the Nushagak and Mulchatna drainages).[19] The South Fork is particularly important for Chinook salmon. An estimated 13,900 Chinook salmon escaped into the South Fork Koktuli in 2005.[20] State biologists estimate that on average, nearly ¼ of the king salmon that return to the Nushagak drainage each year spawn within the Koktuli river system (Dye and Schwanke, *In Prep).* Despite the limitation that escapement numbers give when compared to actual production numbers, the Koktuli River system remains comparatively high, emphasizing the exceptional importance of this system to fisheries production within the larger Bristol Bay watershed.

In addition to the many salmon that use the drainage, the Koktuli River system lies within an area specially managed for its exceptional rainbow trout fishery resources. Designed to protect the biological integrity of the region's world famous wild rainbow trout stocks as well as to ensure recreational benefit to all users, the regulations for the Southwest Alaska Rainbow Trout Management Plan (SWARTMP) were adopted by the Alaska BOF in 1990. The BOF established eight catch and release areas, six fly-fishing catch and release only areas, and eleven single-bait artificial lure areas (including the Koktuli River system) to protect rainbow trout stocks.[21]

The outstanding qualities of the rainbow trout fisheries of the Koktuli River system are further emphasized by field research conducted by the Department of Fish and Game during the 1970's. Demonstrating the remarkable size of many of the fish found within the Koktuli river system, the length frequencies documented for rainbow trout were highest for the Koktuli with a mean[22] of 399 millimeters (rivers surveyed include the Koktuli, Chilikildrotna, Chilchitna, and Stuyahok).[23] In addition to rainbow trout, researchers captured grayling, dolly varden, northern pike, as well as round whitefish during their surveys. The mean length for grayling within the Koktuli River system was also higher than in the Stuyahok, Chilchitna, and Chilikadrotna Rivers.

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[19] Dunaway, Dan and Sonnichsen, Sandra, *Area Management Report for the Recreational Fisheries of Southwest Alaska Sport Fish Management Area*, Fishery Management Report No. 01-06, 1999, http://www.sf.adfg.state.ak.us/sfPubsComplete/Fmr01-06.pdf.

[20] Northern Dynasty Mines, Inc. 2006d. Pebble Project. Baseline Environmental Team Agency Meetings. November 28 to December 1, 2006. Anchorage, Alaska.

[21] Alaska Dept. of Fish & Game, Division of Sport Fish, *Southwest Alaska Alaska Rainbow Trout Management Plan*, Alaska Board of Fisheries, Feb. 1990, at pages 1, 5, 8-9, http://www.sf.adfg.state.ak.us/region1/trout/wildtrout/rbtmgt1990bof.pdf

[22] Range of fork length for rainbow trout was between 262-519 mm; 203-436mm for grayling; 37-495 for dolly varden; 559- for Northern Pike; and 115- for round whitefish.

[23] Russell, Richard, and Gwartney, Louis A., Annual Report for Inventory and Catologing of Sport Fish and Sport Fish Waters of the Bristol Bay Area, Alaska Department of Fish and Game, 1978. Available online at http://www.sf.adfg.state.ak.us/FedAidPDFs/fredF-9-10(19)G-I-E.pdf.

Although there is a lot of evidence supports the outstanding ecological significance of the Koktuli river, there is a lot left to be learned. Stream surveys conducted by The Nature Conservancy in 2008, indicated that data regarding presence and absence of anadromous fish in the Koktuli River system still remains understudied. Working in partnership with the Department of Fish and Game, 27 streams were studied to determine the presence or absence of anadromous fish - anadromous rearing Chinook and/or coho salmon were documented in 20 streams, 13 of which were tributaries to the Koktuli totaling over 17 miles .[24] Recent research conducted by the Alaska Department of Fish and Game further updates historic studies and documents fish distribution, resident fish size composition, as well as water quality in the Koktuli River. The report *Koktuli River Fish Distribution Assessment* is included in full in Appendix III. However, excerpts from the discussion are selected below to further detail the outstanding fishery resources and water quality in this section of the nomination.

> The float trips provided documentation of the size distribution, presence, and distribution fish species in the lower 52 miles of the river. Size distributions of fish captured with hook and line can be used for future comparisons of samples collected in a similar manner. The similarity of rainbow trout length distributions during the 3 months of the project provides evidence that there may be a resident population in the river during the summer… The length distributions of Arctic grayling were significantly different due to slightly larger fish captured in June. With Arctic grayling present upstream of the float survey area, the difference in length distributions may be explained by the larger grayling being located father upriver later in the summer…
>
> Although not an index of abundance, the CPUE of resident species does provide a means of documenting fish distribution in the survey area. Rainbow trout were most common in the lower half of the survey area and Arctic grayling were more common in the upper half of the survey area and are common above the survey area…The distribution of rainbow trout throughout the river did not appear to be change significantly over the course of the three float trips. Dolly Varden appeared in the lower half of the river between June and July and exhibited an upstream movement between July and August. This is likely an anadromous population, similar to those observed in the Togiak River drainage west of the Nushagak River, that enter the system to feed on salmon spawn during late summer and to spawn in the fall. Although spawning locations are unknown, some of the Dolly Varden sampled in August were developing sexual characteristics such as spawning colors…
>
> Adult salmon were present throughout the survey area seasonally and appeared abundant. Spawning was observed by Chinook, chum, and sockeye salmon beginning in the upper section of the float, and aerial surveys indicate that spawning occurs above this location as well. Juvenile and Chinook and coho salmon were captured at three of the four water quality sampling sites and salmon fry were commonly observed throughout the area.[25]

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[24] Johnson, J., and Klein, Kimberly, Special Publication No. 09-05 Catalog of Waters Important for Spawning, Rearing, or Migration of Anadromous Fishes – Southwestern Region, Effective June 1, 2009Available online at http://www.sf.adfg.state.ak.us/SARR/AWC/index.cfm/FA/data.AWCData

[25] Craig J. Schwanke, *Koktuli River Fish Distribution Assessment,* Alaska Department of Fish and Game, Fishery Data Series No. 07-78, December 2007, 14 at http://www.sf.adfg.state.ak.us/FedAidPDFs/fds07-78.pdf.

Each year more data is collected and more is learned about the importance of the Koktuli river to healthy trout and salmon populations.

2. *Koktuli River salmon support regional populations.*

The Koktuli River system makes significant contributions to the sustainability of salmon populations in the larger river systems within the Bristol Bay watershed by providing critical spawning habitat and genetic diversity to our world's salmon populations.

In 2004, estimates of more than 14,000 Chinook and 12,000 sockeye spawned in the Koktuli drainage (McLarnon 2006). The Koktuli River drainage supports a variety of important fish species and serves as a fish passage corridor between portions of the watershed used for fish production. Chinook salmon (*Oncorhynchus tshawytscha*), chum salmon (*Oncorhynchus keta*), coho salmon (*Oncorhynchus kisutch*), sockeye salmon (*Onchorhynchus nerka*), round whitefish (*Prosopium cylindraceum*), Pygmy whitefish (*Prosopium coulteri*), Arctic grayling (*Thymallus arcticus*), Dolly Varden (*Salvelinus malma*), Arctic char (Salvelinus alpinus), rainbow trout (*Osmerus mordax*), slimy sculpin (*Cottus cognatus*), and Alaskan brook lamprey rely on the Koktuli system for a portion of, or all of their spawning, incubation, rearing, and passage life phases. These species contribute to sport, commercial, and subsistence fishing in the area (Wiedmer, 2006) (Table 3). The calendar of when many of these species use the Koktuli River system is available in the periodicity charts in Appendix IV.

In her written testimony to the Alaska Board of Fisheries in favor of Proposal 121, Dr. Carol Ann Woody, fisheries biologist and regional expert, spoke on the importance of preserving the Koktuli River system because of the critical role it plays in maintaining the biodiversity which sustain the world-renowned fisheries of Bristol Bay. She explained the complexity of one system in the context of the larger watershed and the global relevance for salmon conservation and habitat management:

> Throughout the world, once productive commercial fishery stocks are no longer viable, (e.g., Atlantic salmon and cod, Pacific sardine, Peruvian anchoveta etc.). In contrast, the Bristol Bay salmon fishery is extraordinary because it is considered a rare example of a sustainable fishery. This is due primarily to unaltered habitat, good management, and unparalleled stock biodiversity - several hundred smaller spawning populations, comprise the whole, or the metapopulation (Hilborn et al. 2003). This salmon biodiversity tempers effects of unpredictable environmental change because different stocks perform better under different environmental conditions. Because future environmental variation is unpredictable, and because development can adversely affect fish production, it is important to understand and conserve biodiversity... Bristol Bay provides the world with a rare and valuable natural laboratory, annually revealing how salmon naturally colonize, adapt and flourish in a relatively unaltered state. Because Bristol Bay contains the greatest sockeye salmon genetic and habitat diversity documented to date (Habicht et al. 2004, Ramstad et al. 2004, Ramstad et al. 2006), studies here provide a valuable template for

> rehabilitation of the more than 300 endangered salmonid stocks in the Pacific Northwest (Nehlsen et al. 1991, Allendorf et al. 1997).[26]

Dr. Woody's assertions are further supported by the research of Dr. Daniel Schindler, H. Mason Keeler Professor of Aquatic and Fishery Sciences at University of Washington and Dr. Jack Stanford, Professor of Ecology, at the University of Montana. Their testimony on the ecological significance of the Koktuli River system is included in Appendix V to provide scientific support for this nomination. In addition Jack Williams, Trout Unlimited's Senior Scientist and leader in the fisheries ecology field, recently testified on behalf of salmon before the House Subcommittee on Insular Affairs, Oceans, and Wildlife, in his testimony he emphasized the importance of protecting salmon strongholds, such as those that exist in the Koktuli river drainage:

> Protecting the best remaining stronghold populations has long been recognized as the First Principle of conservation biology. The concept of protecting salmon strongholds has been promoted as a scientifically sound and cost effective approach to anchor wild salmon populations (Rahr and Augerot 2006). Additionally, scientists have argued for a large, watershed scale approach to fisheries conservation that would protect entire healthy watersheds and the native fish communities contained therein (Moyle and Yoshiyama 1992).[27]

The Koktuli river is a salmon stronghold not only for the Bristol Bay region but for the entire West coast. By protecting the Koktuli spawning populations of salmon we can help ensure that the Bristol Bay fishery continues as a world leader and can strengthen the existing model of sustainable salmon management.

3. Koktuli salmon as a keystone species

The return of anadromous fish maintains stream productivity as decomposing carcasses release nutrients to the food chain to provide food for rearing salmon, resident species, terrestrial animals and vegetation. Salmon are considered a "keystone" species because of the myrid of species that depend on them for survival. Salmon runs function as huge conveyor belts that transport life-supporting marine nutrients into upstream habitats. As salmon move upstream, spawn and die their decaying carcasses are the primary food source for aquatic invertebrates and fish. They also are eaten by birds and terrestrial mammals which transfer some of those nutrients to nearby marshes and upland plant communities. For example sockeye salmon runs in southwest Alaska add up to 170 tons of phosphorous per year to Lake Illiamna[28], and the number of salmon carcasses carried by brown bears to within 100 meters of

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[26] Dr. Carol Ann Woody, Written Testimony Submitted to the Alaska Board of Fisheries, December 2006.

[27] Dr. Jack Williams, Written Testimony Submitted to the US House Subcommittee on Insular Affairs, Oceans, and Wildlife, June 2009

[28] Hartman and Burggner 1972 in Mary F. Willson, Scott M. Gende, and Brian H. Marston. 1998. Fishes and the Forest. *Bioscience*. 48(6):455-462).

streams adds phosphorous to terrestrial systems at a rate of 6.77 kg/ha -- the equivalent application rate of commercial fertilizers for evergreen trees[29],[30].

Many terrestrial wildlife species found in the region use the Koktuli drainage and often take advantage of the abundant salmon resources there. Marten may be present in low numbers restricted to areas of extensive mature forest. Moose populate forested and riparian areas of the drainage. Caribou of the Mulchatna Caribou Herd frequently travel through the Koktuli Drainage. Upper portions of the Koktuli river drainage are important Caribou calving habitat and other areas see heavy use during the post-calving aggregation period in late June and early July.[31] Large numbers of caribou periodically winter throughout the drainage, but population counts are highly variable. Brown bears, wolves, and coyotes roam throughout the drainage. Beaver, mink, muskrat, and river otters use the wetland and riparian areas. Waterfowl, water birds, and ptarmigan use the areas of the drainage that provide habitat needs of specific species (Woolington, 2006).

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[29] Mary F. Willson, Scott M. Gende, and Brian H. Marston. 1998. Fishes and the Forest. *Bioscience*. 48(6): 455-462).

[30] http://www.wildsalmoncenter.org/about/whySalmon.php

[31] Alaska Department of Natural Resources, Division of Mining, Land and Water, *Nushagak & Mulchatna Rivers Recreation Management Plan (2005 Revision)*, Adopted April 2005.

4. Water quality throughout the watershed is consistently pristine[32] [33]

The Koktuli River watershed, including the mainstem, the North and South forks and their respective watershed areas, are currently roadless, which further protects the system from eroded sediment and damaging hydrograph changes that roads often contribute. Access in the upper areas of the Koktuli drainage is limited to a few small lakes suitable for the landing of small float planes. Most travel is by raft or on foot. Although there have been mineral exploration activities within the headwater drainages of the Koktuli River in recent years, consisting of drilling activity and temporary water use, which the Department of Natural Resources asserts to be "negligible," we can assume that the riparian ecology and stream habitat is currently largely intact.

Conductivity is exceedingly low, indicating low concentrations of dissolved minerals and ions. It qualifies under the most stringent water quality criteria supporting drinking water and aquatic life uses, and supports the healthy diversity of fish species and genetic diversity of salmon stocks.

The chemical and physical water quality of natural riverine systems is affected by changes in seasonal discharge (Doyle et al., 2005). Thus it will change when break-up arrives. Dirt and dust entrain in snow and ice. As snow and ice melt, metals bound within dirt particles are released in drips and freshets. As the new fresh water sinks into the ground, it replenishes

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[32] This section was compiled by Kendra Zanzow of the Center for Science in Public Participation.

[33] Summary of data collection. Data from a current study of discharge and water quality on the mainstem Koktuli River has been ongoing since 2005, conducted by hydrologist Cathy Flanagan with support from the Bristol Bay Native Association (BBNA). Data on stream water and sediment have also been collected by the Environmental Natural Resources Institute (ENRI) of the University of Alaska, Anchorage on the mainstem and North and South Fork Koktuli Rivers (2008) and by the Nature Conservancy along the North and South Forks and its tributaries (2009). Additionally the Pebble Limited Partnership has released preliminary data on surface water quality from the main stem, north fork and south fork of the Koktuli River and associated tributaries (2004-2008). This baseline data is supplemented by research conducted by Craig Schwanke under the Department of Fish and Game and data collected by Dr. Carol Ann Woody, cataloging many new miles of stream in the Anadromous Waters Catalog. It is believed that these data provide an adequate baseline for the proposed Koktuli River ONRW, however many studies are currently in progress and we hope that new scientific info that becomes available can further supplement existing data.

Cathy Flanagan's data details water quality (temperature, specific conductivity, dissolved oxygen, pH, turbidity, water color), and water chemistry (nutrients, major elements, and trace elements) at a station on the Koktuli River below the confluence with the Swan River. These are included on Page 13 of the *Koktuli River Fish Distribution Assessment, 2007* in the Appendix VI. Data from ENRI and The Nature Conservancy of water quality sampling on the North and South Fork Koktuli's and associated tributaries have not been released to the public. Both field data (pH, specific conductivity, dissolved oxygen, temperature) and analytical data (nutrients, major metals, trace metals, anions, cations) were collected. Preliminary data from the Pebble Limited Partnership's , with one station on the main stem of the Koktuli River and several on the North and South Forks and associated tributaries, is available at website http://www.pebblepartnership.com/pages/environment/environment-pre-permitting.php#Report_Series_F. Analytical data (nutrients, major and trace elements, cations and anions) is available but field parameter data is not. Cathy Flanagan's water quality data collection protocols are available in Appendix , and Quality Assurance Project Plans (QAPPs) and field study plans from the Pebble Limited Partnership are available at http://www.pebblepartnership.com/pages/environment/environmental-documents.php.

groundwater. Groundwater travels under streams and pushes up through the streambed sediments, flushing out metals that have sequestered in sediment pore water and sorbed to sediment surfaces. Between snow melt releasing dust particles and pushing dirt and rock along with it, and the groundwater pulsing from beneath streams, the metals entering the stream water column increase in a sharp pulse. This starts as melting begins, and continues until discharge – the volume of fresh water rushing into the streams – dilutes the incoming metals. As melting slows and trickles to a stop, the concentration of minerals dissolved in the water column stabilizes, with only occasional, localized spikes as rainstorms erode rock and push sediment into streams, increasing the concentrations of metals commonly found in surface geology, such as iron, aluminum, and manganese. Conversely, cations such as calcium, magnesium, and sodium are transported by groundwater to streams, and are in highest concentration when discharges are very low and groundwater makes up a significant part of the stream base flow. A large body of research has shown that a range of flow levels is important for different ecological processes (Poff, 1997) and that certain discharges are more important for the maintenance of nutrient transport rates, nutrient retention levels, and temperature regime maintenance (Doyle et al., 2005, Doyle, 2005, Emmett et al., 2001).

Therefore, we can expect the median water quality to be consistent, but with occasional spikes in erosional material and cations consistent with seasonal events such as melting, rains, and fluctuating stream discharge volumes. When the full data is graphed as a box plot, occasional unusually high concentrations observed are shown as outliers.

Based on the available data, all trace and major elements, as well as ammonia, pH, and other parameters set out in the State of Alaska Water Quality Criteria Manual for Toxic and Other Deleterious Organic and Inorganic Substances[34] meet or exceed State of Alaska water quality criteria for drinking water or aquatic life criteria, whichever is the most stringent for the parameter, when based on the median of surface water chemistry to date.

Tributaries of the South Fork Koktuli located near the headwaters generally have the highest mineral content. The range of concentrations observed for erosional material (aluminum, iron, manganese, copper, lead) exceeds the most stringent State water quality standards, but the medians all meet these standards; that is, the range reflects short-term increases in minerals due to rain or melt events while the median defines the pristine water chemistry of the streams. Graphs representing examples of ranges and medians for common minerals are found in Appendix VII.

The streams of the Koktuli watershed are generally below the state-recommended alkalinity standard and therefore have little buffering capacity, and are susceptible to changes in pH – these streams will find it harder to recover from introduction of acid in the water than streams that have higher alkalinity and higher buffering capacity. The median alkalinity reaches the State of Alaska recommendation on the main stem of the Koktuli River.

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[34] Draft, as amended December 12 2008

The maintenance of the nutrients, water chemistry, and temperature regimes of a system become extremely important when we begin to consider the effects that changes in these parameters could have on the health of the resident and anadromous fish species that use Koktuli River system and the outstanding habitat that ultimately supports outstanding commercial, recreational, and subsistence benefits. By preventing degradation to the Koktuli's pristine water quality, ONRW designation would preserve and protect fish habitat and the recreational and ecosystem function dependent on them. Altering the functions of a natural riverine system so that the optimal conditions are not attained or do not coincide with the needs of different periods of species life cycles, may cause adverse effect on aquatic species.[35]

C. Exceptional Recreational and Social Values

The pristine, free flowing waters of the Koktuli drainage contribute to the extraordinary sport, and subsistence fishing opportunities in the region and also play a significant role in the success and sustainability of the regional commercial fishing industry, the primary source of employment and income in the region.

1. Recreation: Value of current use and potential impacts

The Koktuli River is well known across the state, the nation, and the world, for the outstanding recreational capacity of its water quality, ecology, and perhaps above all, fishery resources. The very fact that this river system resides in such a remote region, with very little public access and infrastructure development, makes recreation on the Koktuli River an unparalleled experience. Recreation and tourism spending in Bristol Bay brings $90 million to the state in the form of taxes and licenses each year. In addition, it is estimated that anglers that come to the Bristol Bay area spend about $117 million within the local economy.

The Koktuli River offers world-renowned sport-fishing opportunities for anglers visiting from around the globe. While other areas in the Bristol Bay watershed may receive more pressure due to easier access, the remoteness and pristine nature of this system offers an unparalleled fishing experience within the Bristol Bay Fisheries Reserve. For example, the South Fork flowing into the mainstem of the Koktuli River is a popular float for anglers seeking a multi-day, remote wilderness experience in the larger Bristol Bay watershed. As

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[35] Example of natural riverine system functions that might cause adverse effects on aquatic species if altered:

- altering optimal water temperature, pH, dissolved oxygen, and chemical composition;
- altering optimal water velocity and depth;
- altering optimal stream morphology;
- increasing suspended organic or mineral material;
- altering chemical/physical character of bottom sediments;
- increasing sedimentation and reduction in permeability of substrate;
- reducing food supply; and
- reducing protective cover (e.g., overhanging stream banks or vegetation).

part of the *Economics of Wild Salmon Watersheds: Bristol Bay, Alaska* report, anglers coming to the Bristol Bay region were surveyed and 70% of those surveyed said the most important attribute of the recreational experience was "[f]ishing in a remote, off-the-road locations." It was also noted in the survey that if a road were built that provided easier access to the area, 45.5% of non-residents and 30.4% of residents felt that they would stop fishing in this area and potentially stop coming to Alaska to fish entirely."[36] (Duffield et al, 2006, p. 45-63).

Angler on the Koktuli River. Photograph by Ben Knight.

Although specific economic studies haven't been done for the Koktuli River, by taking a look at the the role recreation plays in the regional economy we can see that salmon and the waters that support them are critical to maintaining this exemplary recreation area. Sport fishermen spend some $60 million a year to experience the Bristol Bay watershed. Over 65,000 people visit the Bristol Bay region each year to fish and recreate. Near the major communities, local roads provide sport fishermen with limited access. Clients of remote lodges pay up to $8000/week to fish in the pristine waters of the Bristol Bay watershed. Whether it is fishing for a giant 30 inch rainbow, Chinook or sockeye salmon, or grayling, sport-fishing opportunities in Bristol Bay are currently endless. The Alaska Department of Fish and Game recently published a study examining the impact and contributions of sport fishing in Alaska, which also breaks down the regional significance of the Bristol Bay watershed.

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[36] John Duffield and Chris Neher et al, Duffield, *The Economics of Wild Salmon Watersheds: Bristol Bay, Alaska*, 2007 at 45-63.

Anglers fishing in Alaska spent nearly $1.4 billion on fishing trips, equipment, and development and maintenance of land use primarily for the pursuit of sport fishing in Alaska. Resident spending was $733 million and nonresident spending was $652 million. A total number of 15,879 full and part-time jobs were supported by money spent on sport fishing in 2007 and accounted for $545 million in total wages and benefits paid to employees and proprietors. South central Alaska, including Bristol Bay, was by far the most popular angling region in Alaska.[37] While the actual use of the Koktuli River contributes only a fraction to this economy, its outstanding ecological significance sustaining the biocomplexity needed to maintain the world renowned fisheries of the Bristol Bay watershed is a vital component to Alaska's sport fishing tourism industry.

John Duffield, one of the nation's top natural resource economists, has studied the region extensively. In a recent economic study, he concluded: "It is apparent that the private sector basic employment [harvesting, processing, recreation, government and health] in this economy is essentially 100% dependent on Bristol Bay's wild salmon ecosystems…The only other basic driver is government employment including hospitals, which are publicly funded. As a share of basic employment, the salmon ecosystem dependent sectors account for 63.6 % of all the basic employment that essential drives the Bristol Bay economy."[38] (Duffield et al, 2006, p. 16). Duffield's research further documents concern for maintaining the Bristol Bay sport fishing industry at its current level if there were larger infrastructure changes to the region, such as road development. Survey results of non-resident and resident anglers fishing in Bristol Bay show that 45.4% of non-residents and 30.5% of residents who had fished in the watershed felt that increased road access would cause them to stop fishing in the region.[39]

Although the Department of Fish and Game asserts that the sport-fish log books significantly underestimate actual use, the logs from 2005-2007 document usage patterns in the Koktuli River System. Regional Sport-Fish Biologist Craig J. Schwanke details usage of the system, as well as concerns of impacts from future mining development:

> The Nushagak/Mulchatna River drainage is a popular drainage for sport fishing in the BBMA [Bristol Bay Management Area] with 18,420 angler-days from 1999-2003 (Howe et al. 2001; Jennings et al. 2004, 2006a, b; Walker et al. 2003). The average effort for the Koktuli River during the same 5-year period was 519 angler-days (Howe et al. 2001; Jennings et al. 2004, 2006a, b; Walker et al. 2003). Potential mineral resource development at the headwaters of the Koktuli River may increase access and angling pressure on the river. Increased use and mineral development may also have the potential to negatively affect the river's water quality to the detriment of fish populations.[40]

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[37] Alaska Department of Fish and Game, *Economic Impacts and Contributions of Sportfishing in Alaska*, 2009, at http://www.sf.adfg.state.ak.us/statewide/economics.

[38] John Duffield and Chris Neher et al, Duffield, *The Economics of Wild Salmon Watersheds: Bristol Bay, Alaska*, 2007 at 16.

[39] John Duffield, *Supra* note 52 at 58.

[40] Craig J. Schwanke, *Koktuli River Fish Distribution Assessment*, Alaska Department of Fish and Game, Fishery Data Series No. 07-78, December 2007, 1 at http://www.sf.adfg.state.ak.us/FedAidPDFs/fds07-78.pdf.

It is evident, through both data on the use of the Koktuli River, as well as testimony in support of the fishing experience, that these waters support an exceptional fishery that greatly contributes to the larger tourism industry in the Bristol Bay watershed.

2. *Subsistence: Value of current use and potential impacts.*

The Koktuli River's renewable resources also contribute to the subsistence lifestyles of Alaska Natives in the area. Locals rely heavily upon these pristine waters and the fishery resources they sustain, to feed their families throughout the year. The Koktuli River system makes significant contributions to the sustainability of the salmon populations in the larger river systems within Bristol Bay, by providing critical spawning habitat. In 2004, estimates of more than 14,000 Chinook and 12,000 sockeye spawned in the Koktuli drainage (McLarnon 2006).

Residents of native allotments along the Koktuli, as well as residents of Ekwok, New Stuyahok, Dillingham, and adjacent inland areas of the Nushagak and Mulchatna River drainages have relied on the Koktuli River area as a place of subsistence harvest. Residents of these areas hunt for both moose and caribou and trap fur bearers from this area, the Koktuli River provides riparian habitat zones for movement corridors, cover and forage. Salmon harvest occurs more intensively near communities, although the Koktuli River and its tributaries are known to be important spawning and rearing habitat for the species previously listed in the periodicity tables (Appendix IV).

While there is certainly individual value of the Koktuli watershed for subsistence use, as previously discussed, the health of these waters directly contribute to the larger Bristol Bay watershed and related subsistence use. There are 25 communities in the region with a resident population of about 8000. Major communities located within the region include Naknek, King Salmon, Dillingham, Togiak, Nondalton, Newhalen, and Iliamna. In addition, the smaller communities of Ekwok, New Stuyahok and Koliganek are the primary users of the subsistence resources in the Nushagak drainage. About 70% of the population is Alaska Native, relatively high compared to the rest of the state which is estimated at about 16%. Alaska Natives likely followed salmon runs after the last ice age ended (~10,000 – 15,000 years ago) and settled in regions with abundant dependable food resources. In Bristol Bay more than 50% of the subsistence resource is from salmon dependant upon clean water and healthy habitat. Approximately one third of the subsistence harvest comes from land mammals (31%); and non-salmon fish comprise another 10% of the subsistence harvest. Alaskans in Bristol Bay harvest some 2.4 million pounds of salmon (or ~315 lbs per person) for subsistence each year from tributaries of Bristol Bay.[41]

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[41] John Duffied, *Supre* note 52 at 11.

Specific subsistence use of the Koktuli watershed was recently documented in a study conducted by The Nature Conservancy. The primary product of the ecoregional assessment was to term a portfolio of areas of biological significance as well as collect traditional ecological knowledge of use patterns. Figures 4-6 show documented subsistence use of the Koktuli watershed for harvesting moose, sockeye, Chinook, coho, chum, and pink salmon. The study identifies the Nushagak drainage as one of the richest areas in the state in terms of its abundance of natural resources.

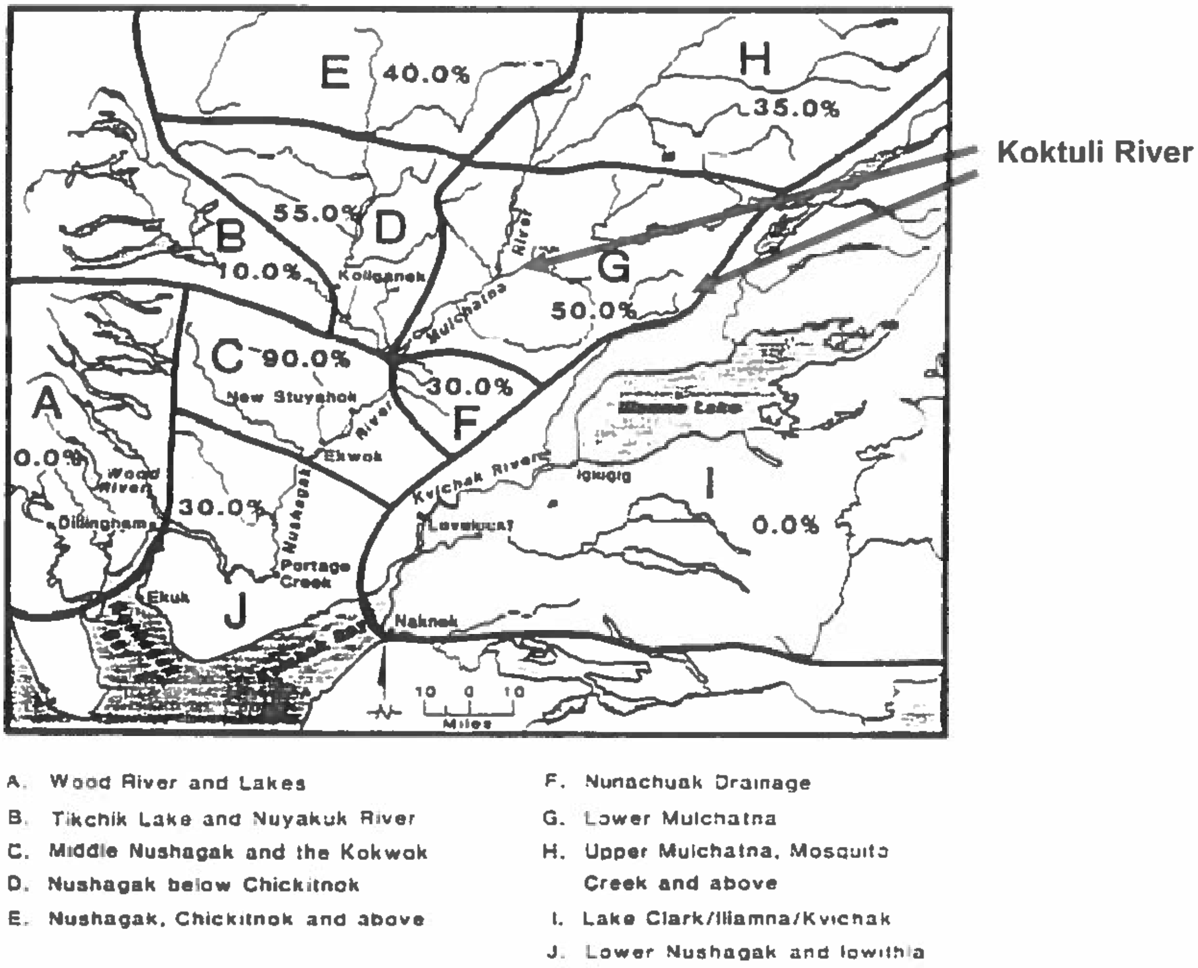

Figure 4: Illustrates 30% of Ekwok households which used the Koktuli River watershed for Moose Hunting.

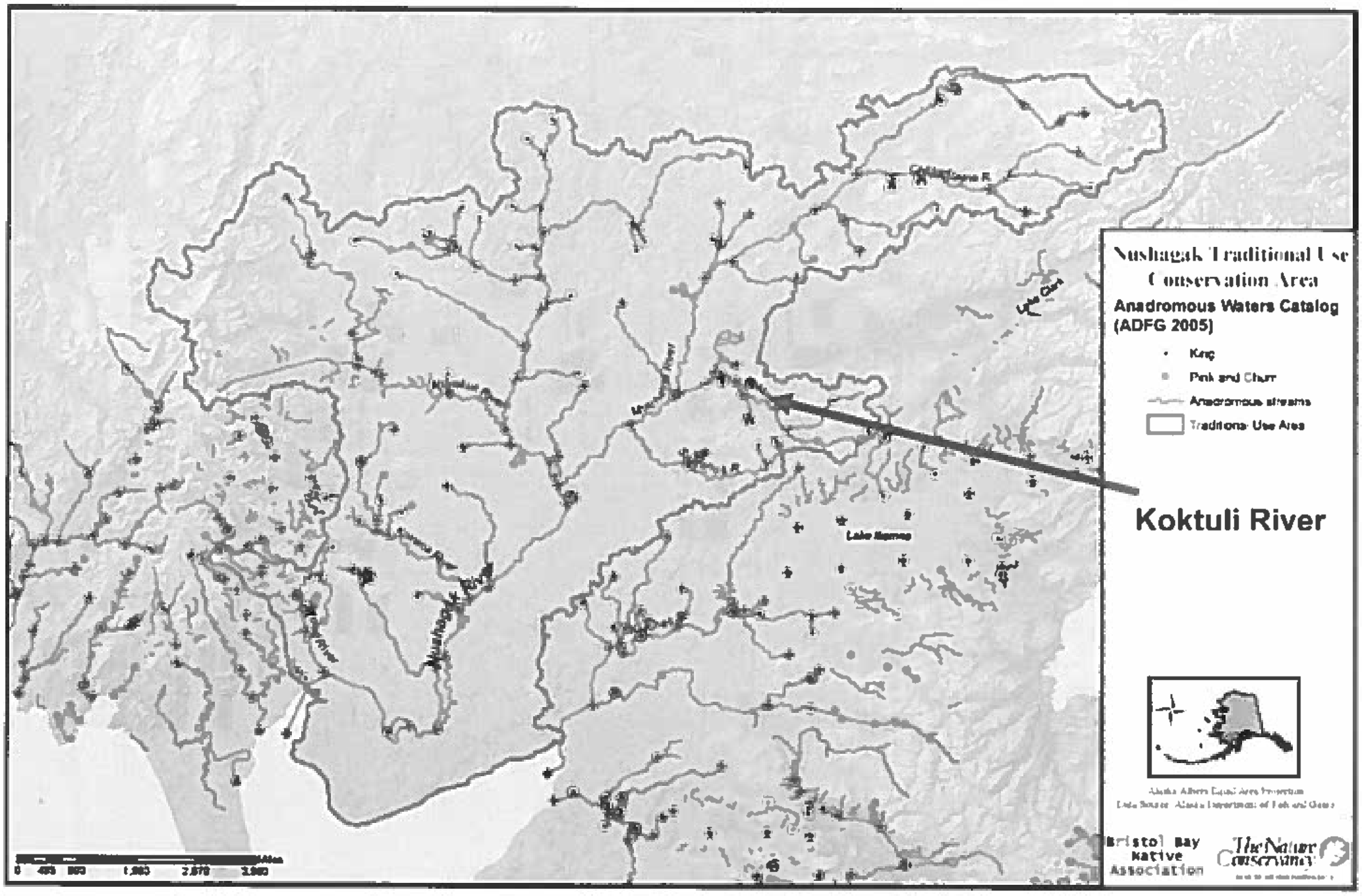

Figure 5: The map illustrates traditional ecological use within the Nushagak drainage. Data shows subsistence use for harvesting coho, pink and chum within the Koktuli River watershed (mainstem, North and South Forks.)

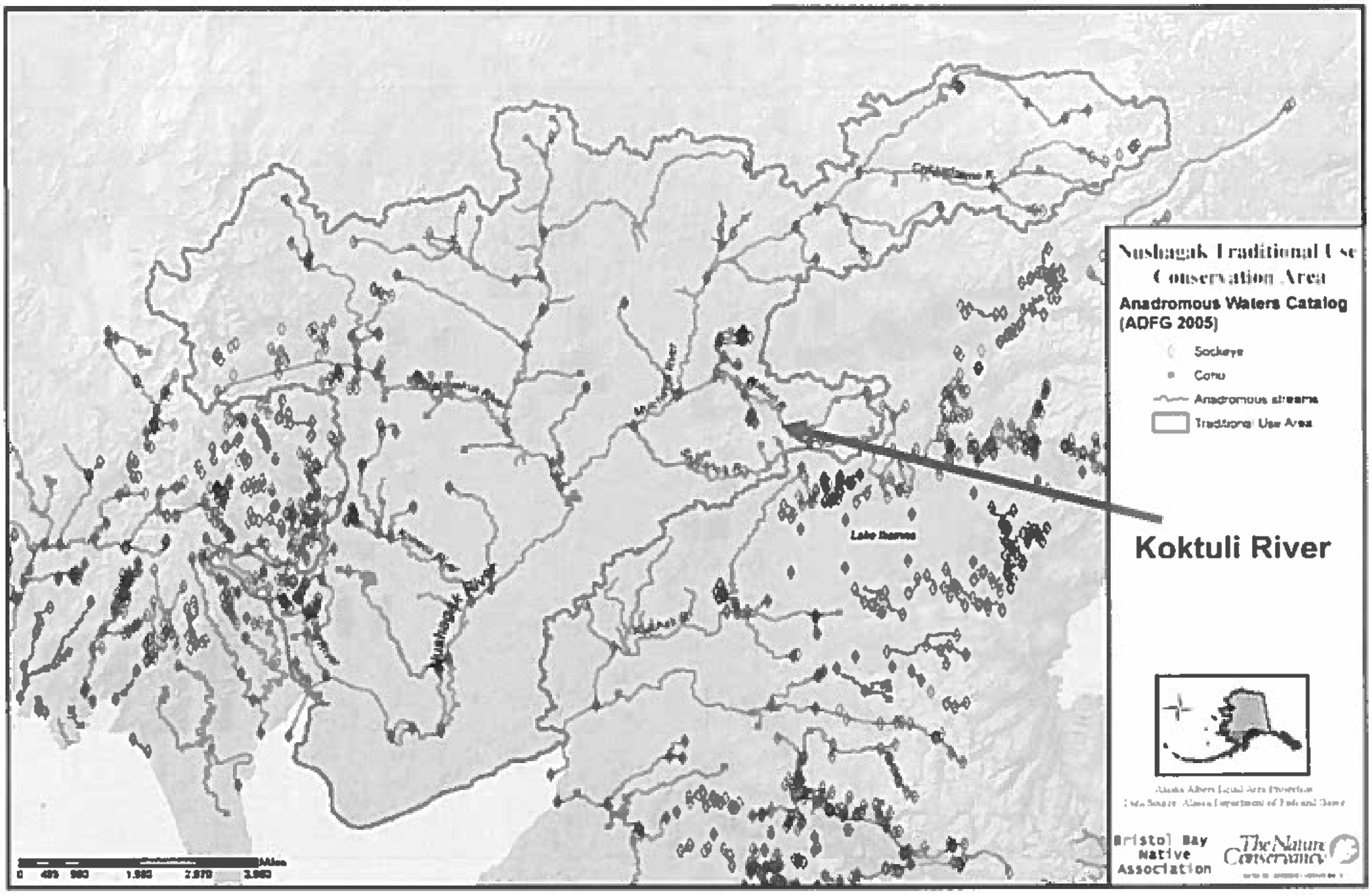

Figure 6: The map illustrates traditional ecological use within the Nushagak River drainage. Data shows subsistence use for harvesting sockeye and coho within the Koktuli River (mainstem, North and South Forks.

3. Commercial Fishing: Value of current use and potential impacts.

While no commercial fishing occurs directly within the Koktuli River system, the scientific arguments presented in this report support the fact that Koktuli waters serve a vital role in the health of the larger watershed and its associated commercial fishing industry. A report recently completed by Northern Economics details the role of commercial fisheries in Alaska's economy. The report determined that if Alaska were a nation, it would place 9th among seafood producing countries. Alaska's seafood industry has played a major role in the state's history, and it remains a major part of the economy today, with more jobs that any other private sector. The Bristol Bay fishery plays a large role in Alaska's seafood industry and provides a substantial number of jobs year after year. In 2008, the salmon fishing industry in Bristol Bay employed nearly 11,500 people.[42]

The Bristol Bay commercial fisheries management area includes eight major river systems: Naknek, Kvichak, Egegig, Ugashik, Wood, Nushagak, Igushik, and Togiak, with the Kvichak and Nushagak (of which the Koktuli is part of) as the largest producers. Bristol Bay's commercial salmon harvest accounts for nearly 33% of Alaska's total harvest earnings each year. Harvest and processing of Bristol Bay fish generates nearly $320 million a year. Annual commercial catches between 1984 and 2003 averaged nearly 24 million sockeye salmon, 69,000 Chinook, 971,000 chum, 133,000 coho, and 593,000 pink salmon.[43]

Bristol Bay accounted for a significant portion of Alaska's seafood harvesting jobs due to the large salmon fisheries occurring in the region. Bristol Bay has about 13 percent of Alaska's total seafood processing jobs, 26.1 percent of the state's total seafood harvesting jobs, and about 19.9 percent of the state's workforce in seafood harvesting and seafood processing combined. [44]

The Bristol Bay salmon fishery is considered well managed and categorized as one of the only sustainable commercial fisheries in the world. The salmon that return to the Bristol Bay region offer an invaluable renewable resource for Alaska if current, relatively pristine habitat is maintained through the Koktuli River watershed, as well as the larger Bristol Bay watershed. By designating the Koktuli River as an ONRW it will be protecting a large portion of the headwaters of the largest sockeye salmon run on earth – a stronghold for the species and a way of life.

Through these recreation, economic and social arguments, it is evident that nearly the entire private economy of the Bristol Bay region is dependent on a healthy functioning ecosystem: local, Alaskan, and non-Alaskan commercial fishers, processors, sport anglers, sport hunters and wildlife viewers sustain the private economy when fish and game are available. However, the value of these renewable resources extends far beyond any year-by-year economical analysis of jobs, industry income and subsistence harvest. Maintaining the pristine habitat of the Koktuli River through designation as an ONRW will undoubtedly help sustain the truly exceptional ecological value of this watershed, the way of life for many Alaskans, and the outstanding recreational opportunities in perpetuity.

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[42] Northern Economics, Inc. *The Seafood Industry in Alaska's Economy*, January, 2009, 9, at http://www.marineconservationalliance.org/docs/SIAE_Jan09.pdf.

[43] John Duffield, *Supra* note 52 at 13.

[44] Northern Economics, Inc., *Supra* note 56 at 50.

III. Potential Risks[45] to the Reduction of Water Quantity, Quality and Existing Values

The petitioners believe that avoiding certain activities that have historically proven high risk to water quality and pristine fish habitat is necessary to protecting these outstanding national resources for the best, long-term ecological and recreational public interest.

At the time of filing this application, the reasonably foreseeable threats to the water quantity and quality of the Koktuli River are extractive water use as well as potential contamination from proposed hard-rock mining activities; mainly development of the Pebble Mine and associated human-caused impacts. Metal mines throughout the world have degraded water quality and require enormous volumes of water. According to the Environmental Protection Agency (EPA), the hard-rock mining industry is the single largest source of toxic releases in the US. This industry has already caused enormous damage to rivers and fisheries around the world. More than 70% of mines in the United States have exceeded the water quality standards which they promised to upkeep during their permitting process (Kuipers and Maest, 2006).

Under the proposed plans of the Pebble Partnership, the Pebble project will create two tailings dams, one at the headwaters of the South Fork of the Koktuli River.[46]Given the

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[45] The petitioners interpret this section of the nomination packet to refer to *reasonably foreseeable human activities* which could cause reduction in existing water quality or habitat – or cause *increased* pollution, above the existing baseline, which the ONRW is intended to prevent.

[46] Geoffrey Y. Parker and Frances M. Raskin, et al, *Pebble Mine: Fish, Minerals, and Testing the Limits of Alaska's "Large Mine Permitting Process,* "Alaska Law Review Vol XXV, 17, (June 2008).
The Pebble Mine likely would include most of the following facilities:

1. An open pit mine at Pebble West that may be about 2000 feet deep and cover about two square miles and an underground mine at Pebble East that may be of comparable size and 5000 feet deep.
2. Various stream diversion channels, wells and devices to: (a) prevent water from filling the open pit, (b) extract water that would be used for processing the ore, (c) transport ore concentrate in a slurry via pipelines, and (d) transport wastes in a slurry via pipelines.
3. A mill to crush, process, and concentrate the ore extracted from the open pit and underground mines.
4. Five dams or embankments composed of waste rock and earthen-fill material that together would span about nine linear miles. The three largest dams would be 740 feet high and 3 miles long, 700 feet high and 2.9 miles long, and 710 feet high and 1.3 miles long.70 These dams and embankments would create and contain ponds that would cover at least 10 square miles and store chemically reactive, ore-processing wastes known as "tailings."
5. A deep-water port in marine waters on the west side of Cook Inlet (about 200 miles southwest of Anchorage) to load the ore concentrate on ocean freighters.
6. A 104-mile road to provide a transportation corridor from the mine facilities to the port.
7. Two 100-mile-long, fifteen inch-diameter pipelines that would run parallel to the road. One pipeline would be used to transport a slurry of copper ore concentrate from the mill to the port, where the slurry would be de-watered. The other pipeline would return the slurry water to the mine area.
8. Four 54-inch-diameter pipelines. Three of the pipelines, totaling 70,000 feet (13.25 miles), would transport mine wastes from the mill to the waste storage facilities. The fourth pipeline, totaling 17,000 feet (3.2 miles), would reclaim water from the waste facilities and transport it to the mill.

immediate threats to the waters of the Koktuli River system, the main goals of protections offered by ONRW designation would ensure that the development of any large-scale metallic sulfide mine would not directly, indirectly, or cumulatively have any adverse effect on: wild salmon and other fish; wildlife; commercial, subsistence, and sport-fishing; and guiding and tourism activities, within this watershed that is already part of the Bristol Bay Fisheries Reserve.

The breadth of political leaders concerned about the future of the Koktuli river system in the face of mining development extends to the very memorable words of the late Jay Hammond, the popular Republican governor of Alaska from 1976 to 1982. He made his home on the shores of Lake Clark in the Bristol Bay drainages, just 30 miles from the Koktuli River and the Proposed Pebble Mine.[47] On July 11, 2005, two weeks before his death, he expressed his views:

> When I was first asked about the Pebble Mine… I expressed this concern: that if I were asked where in Alaska would I least rather see the largest open-pit mine in the world, I can think of no more less appropriate spot than the headwaters of the Talarik Creek and Koktuli River, the drainages of two of the finest trout streams and salmon spawning in Alaska. But I have since modified that to where if asked that question again, I'd say there is one place I'd even less rather see it, and that's in my living room here at Lake Clark.[48]

The following sections explain how mining affects water quantity and quality as well as critical fish habitat, and ways in which the Koktuli River system may be vulnerable should the Pebble Mine, or any other large-scale metallic sulfide mine, be developed.

A. *Water Quantity*[49]

A key reason the Koktuli River supports such a robust population of fish and therefore outstanding recreational opportunities is that the river's natural hydrology remains largely intact. Water flows are sufficient to maintain cool water temperatures, flush silt, and support other ecological functions. They also allow for exceptional backcountry floating and fishing opportunities.

Modern hard-rock metallic sulfide mining requires massive volumes of water, which are typically diverted from fisheries, domestic, recreational, and agricultural uses, thus

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9. A 300-megawatt power plant that would be located on the Kenai Peninsula, across Cook Inlet.
10. More than 100 miles of transmission lines and undersea cables to transmit electricity from the power plant on the Kenai Peninsula to the mine site.

[47] Jay S. Hammond, Tales of Alaska's Bush Rat Governor: The Extraordinary Biography of Jay S. Hammond, 294 (1994).

[48] Interview by Lance Holter with Jay S. Hammond, former Governor of Alaska, in Port Alsworth, Alaska (July 11, 2005) available upon request by Geoffrey Y. Parker and Frances M. Raskin.

[49] Sections on water quality and quantity compiled by Robert Moran, hydrogeologist and international mining consultant. (Moran, R. 2007. Pebble hydrogeology and geochemistry issues.)

increasing competition for water .Water use in metals mining ranges between 100 and 8,000 liters of water per ton of ore extracted. In 2000, mines in the US alone withdrew about 518,000 m^3 per day.[50] The *EPA and Hardrock Mining: A Source book for industry in the Northwest and Alaska* describes some of the effects from mining water withdrawal from a watershed:

> A proposed mining project can impact the quantity and velocity of surface water flow by altering natural drainage patterns and the infiltration/runoff relationships in a watershed; discharging storm water and wastewater; impounding water; changing the character of gaining and losing stream reaches through mine dewatering; mining through stream channels and flood plains; and by diverting, re-routing, and channelizing streams. Importantly, many mining activities have the potential to alter the equilibrium balance between flow and sediment transport in streams (Johnson, 1997). Altering this equilibrium causes stream gradients, channel geometries, channel patterns, and stream banks to adjust to new equilibrium conditions that reflect new erosion and sediment transport characteristics (Johnson, 1997). Such changes can disrupt aquatic habitats both upstream and downstream of a mine. The creation of waste dumps, tailings impoundments, mine pits and other facilities that become permanent features of the post-mining landscape can cause fundamental changes in the physical characteristics of a watershed (O'Hearn, 1997).[51]

Developing and operating the Pebble Mine would require billions of gallons of water each year of mine operation. Northern Dynasty Mines, Inc. (NDM) applied to the State of Alaska in July of 2006 for water rights in the following amounts, in gallons per year (Table 1):

Location	**Surface Water (GPY)**	**Groundwater (GPY)**
South Fork Koktuli	12.03 billion	2.8 billion
North Fork Koktuli	8.02 billion	0.2 billion
Upper Talarik Creek	6.84 billion	1.7 billion

Table 1: Water requested by Northern Dynasty Mines, Inc. (NDM) in water rights applications to the Department of Natural Resources, 6/2006. (GPY = gallons per year)

This amount of proposed water use by the Pebble Mine developers is nearly 35 billion gallons of water a year, more than annual water consumption rates in Anchorage.[52]

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[50] Global Equity Research, Watching water: A guide to evaluating corporate risks in a thirsty world. March 2008 at http://www.pebblescience.org/pdfs/jpmorgan_watching_water.pdf

[51] U.S. Environmental Protection Agency, Region 10. 2003. *EPA and Hardrock Mining: A Source book for industry in the Northwest and Alaska.* Found at pg 46 at http://yosemite.epa.gov/R10/WATER.NSF/840a5de5d0a8d1418825650f00715a27/e4ba15715e97ef2188256d2c00783a8e/$FILE/Maintext.pdf

[52] USGS. 2006. Anchorage Water Use. Fact Sheet 2006-3148. USGS Anchorage, AK

1. Water quantity and impacts on fish

Water quantity is an extremely critical component of healthy salmon populations at all portions of their life cycle. The chemical and physical water quality of natural riverine systems is affected by changes in seasonal discharge (Doyle et al., 2005). Because the greatest natural mortality of salmonids occurs during early life stages while they are still in fresh water, the aquatic environment greatly influences rates of natural mortality. Sufficient water velocity and depth are also needed to allow the movement of water over, within and through gravel that transports dissolved oxygen to eggs and newly hatched salmon, and removes metabolic wastes. Stream velocity is particularly important to distribute aquatic invertebrates – a primary food source that juveniles depend upon for growth.

A large body of research has shown that a range of flow levels is important for different ecological processes (Poff, 1997) and that certain discharges are more important for the maintenance of nutrient transport rates, nutrient retention levels, and temperature regime maintenance (Doyle et al., 2005, Doyle, 2005, Emmett et al., 2001). The maintenance of the nutrients, water chemistry, and temperature regimes of a system becomes extremely important when we begin to consider the effects that changes in these parameters could have on the health of resident and anadromous fish species that use the system and provide commercial, recreational, and subsistence benefits to the Bristol Bay Region. Altering the natural stream flow patterns that could cause extended periods of low discharge can lead to the desiccation of eggs, low oxygen levels, high temperatures during warm weather, freezing during low temperatures, and high embryo mortality. Artificially low flows and shallow water depth can ultimately block upstream migration of adults (ADF&G 1985a, Reiser and Bjornn 1979). Any of these changes could have significant impacts on the salmon that depend on the Koktuli River to complete their life cycle.

B. Water Quality

Hard rock mining has a poor track record when it comes to water contamination – especially in areas where the mine site is close to ground or surface water. A study that provided in-depth comparison of predictions of water pollution vs. actual water pollution found that 85% of the mines near surface water with elevated potential for acid drainage or contaminant leaching exceeded water quality standards; 93% of the mines near groundwater with elevated potential for acid drainage or contaminant leaching exceeded water quality standards, and of the sites that did develop acid drainage, 89% predicted that they would not.[53] The 2007 EPA Toxins Release Inventory (TRI) showed that the hardrock mining industry was

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[53] Kuipers, J.R., Maest, A.S., MacHardy, K.A., and Lawson, G. 2006. Comparison of Predicted and Actual Water Quality at Hardrock Mines: The reliability of predictions in Environmental Impact Statements.

again the leader in the release of toxins into the environment producing over 1.1 billion pounds. The below graph is from the EPA TRI website:[54]

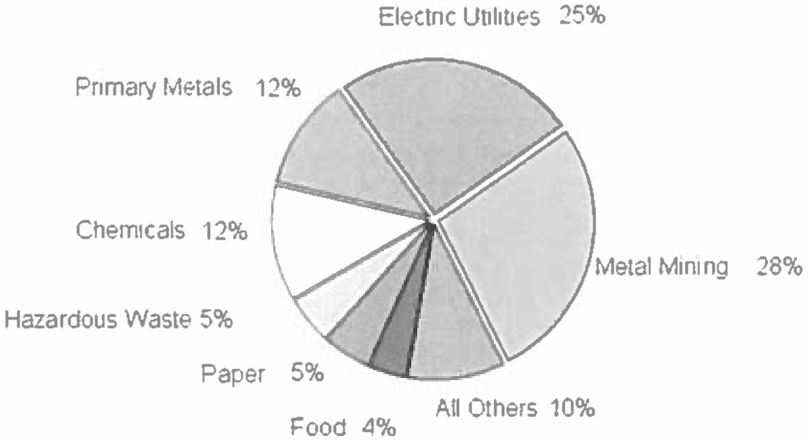

Figure 7: TRI Total Disposal or Other Releases 4.09 billion pounds (Source: http://www.epa.gov/tri/tridata/tri07/brochure/brochure.htm)

The EPA estimates in a 2004 report that the hardrock mining industry (including gold) is responsible for polluting 3,400 miles of streams and 440,000 acres of land.[55] Similarly, the U.S. Forest Service (USFS) estimates that approximately 10,000 miles of rivers and streams may have been contaminated by acid mine drainage from the metal mining industry.[56] The National Academy of Science, in their review of hardrock mines on federal lands found that at individual facilities, hardrock mining operations may disturb thousands of acres of land and impact watersheds including, to varying degrees, effects on groundwater, surface water, aquatic biota, aquatic and terrestrial vegetation, wetlands, wildlife, soils, air, cultural resources, and humans that use these resources recreationally or for subsistence. [57]

For example, like the proposed Pebble Mine, the Bingham Canyon Mine is a copper/gold/molybdenum mine, currently the largest in North America with an ore body roughly half the size of Pebble. Pollution from the mine has contaminated 60 square miles of groundwater near Salt Lake City, making water unusable for at least 4,300 households. Kennecott Utah Copper Corp., a subsidiary of Rio Tinto, built a multi-million dollar water treatment facility, the largest of its kind in the United States, to treat an estimated 2.7 billion gallons of polluted water annually for at least the next 40 years.

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[54] http://www.epa.gov/tri/tridata/tri07/brochure/brochure.htm

[55] U.S. EPA. 2004. "Cleaning Up the Nation's Wast Sites: Markets and Technology Trends." EPA 542-R-04-015. Accessed at http://www.epa.gov/tio/pubisd.htm

[56] U.S. EPA 2004. "Nationwid Identification of Hardrock Mining Sites." Office of Inspector General. Report No. 2004-P-00005. Accessed at: http://epa.gov/oig/reports/2004/20040331-2004-p-00005.pdf

[57] National Research Council. 1999. *Hardrock Mining on Federal Lands*. National Academies Press. Washington, DC.

Figure 8. Kennecott Bingham Canyon Mine in Utah. (Left) Tailings impoundment (roughly 9,000 acres) with the Great Salt Lake at the top left. The pit is 0.75 miles deep, 2.5 miles wide, and covers 1,900 acres. (Right) Tailings are shown in the foreground (grey) with Salt Lake City in the background. Operations produced a 60 square-mile groundwater plume under valley to right, mostly from waste rock seepage. As of 2006, Kennecott had spent $370 million on cleanup and source control, and will be required to pump and treat aquifer water for at least the next 40 years. By 2009, 2.7 billion gallons of water will be treated annually to supply homes unable to use the aquifer.

Byproducts are created throughout the various stages of mining. Some of these can be relatively non-toxic, others must be carefully taken care of to prevent damage to human health or the ecosystem. Pollution at mine sites can primarily happen through the mishandling of site operation chemicals, tailings creation and storage, acid mine drainage, and metals leaching all of which could have downstream effects on the Koktuli River's fish and ecosystem functions.

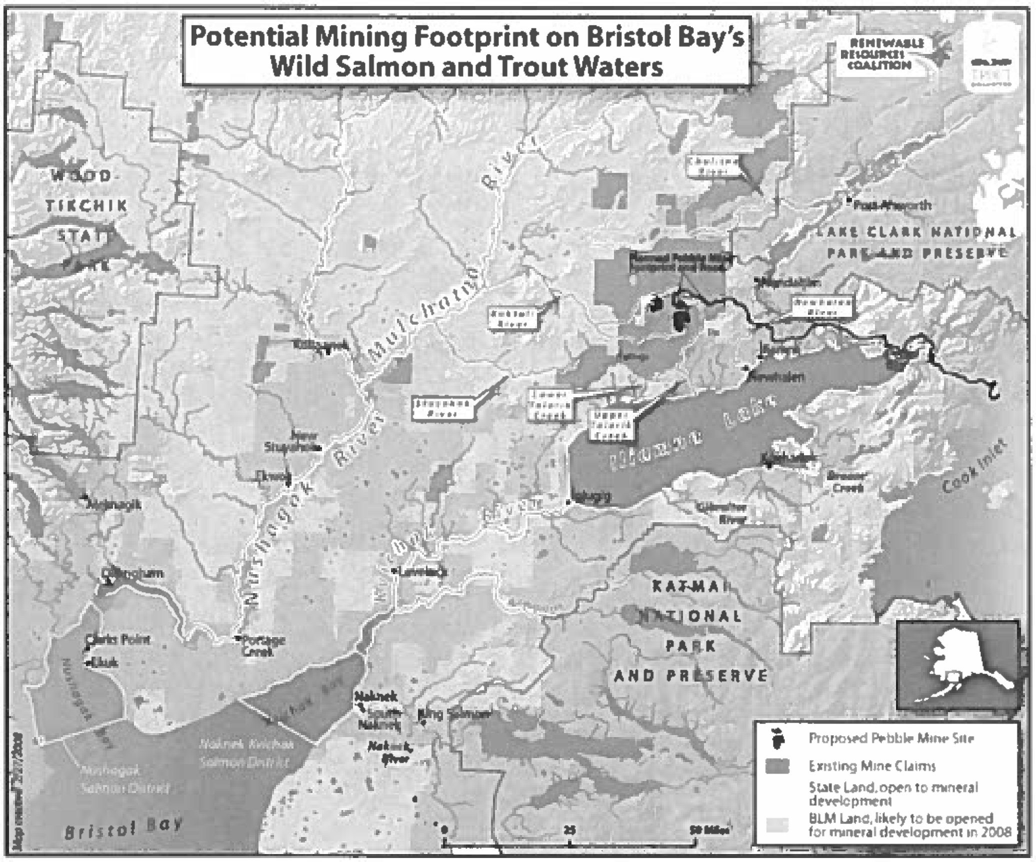

Figure 9: Existing mining claims and the proposed Pebble Mine shown in relation to the Koktuli River system. The mine site lies directly in between the North and South Fork of the Koktuli River, which feeds the Mainstem, all nominated as Alaska's first Outstanding National Resource Waters.

1. Site operation chemicals

Mine operations use tremendous amounts of chemicals– explosives, fuels, oils, greases, antifreeze, water treatment chemicals, herbicides, pesticides, and road de-icing compounds – that may be released into local surface and groundwater and can be toxic to fish and wildlife. A large part of the Pebble mining activities would take place within the Koktuli River watershed using ground and surface water.

One of the most common chemicals used in mining to separate the gold from the other minerals and rocks removed from the site is cyanide. About 1.4 million tons of hydrogen cyanide is produced throughout the world, about 13% of this goes towards the production of cyanide related chemicals used to process gold. Cyanide is typically transferred and stored at mining sites in one of two ways: 1) in liquid form, transported by tanker truck or railcar and then offloaded to an onsite storage tank; 2) in briquette or flake form, transported via truck or railcar in drums, plastic bags, bins, boxes or ISO-containers. The cyanide is then mixed with the ore to remove the gold via leaching. When the recoverable gold is removed the cyanide laced ore is either dewatered to recover the solution, treated to neutralize or recover cyanide, or is sent to the tailing storage facility. [58]

Although cyanide in minute amounts occurs naturally and is produced by some plants, a small amount can be highly toxic to humans and wildlife. A teaspoon full of two-percent solution of cyanide can kill a human adult.[59] Fish and aquatic invertebrates are extremely sensitive to cyanide, just 5.0 to 7.2 micrograms per liter of free cyanide in aquatic systems can effect a fish's movement and prevent successful reproduction. Higher amounts can cause additional physical effects and death.[60]

Cyanide is just one of the many chemicals that will be used at the proposed Pebble Mine site that has a chance to contaminate the currently pristine, life-supporting waters of the Koktuli River.

2. *Tailings*

During mining operations ore is removed from the ground and mixed with water and chemicals separate copper, gold and other metals from the rock. More than 99 percent of processed ore becomes a solid-water-chemical waste called tailings that are usually permanently stored within large impoundments. Tailings contain process chemicals and elements from natural rock that can harm humans and wildlife. For example, 2 parts per billion concentrations of copper above background may negatively affect the ability of salmon to locate their spawning grounds.[61] Other natural rock elements may include aluminum, antimony, arsenic, barium, cadmium, chromium, cobalt, iron, lead, manganese, mercury, molybdenum, nickel, selenium, silver, thallium, zinc, sulfides, and natural radioactive constituents (uranium, thorium, potassium-40).

Process chemicals in tailings may include lime, sodium isopropyl xanthate (e.g. SF-113), dithiophosphate and thionocarbamate (e.g. Aeropromotor AC 6682), methyl isobutylcarbinol (MIBC), and polypropylene glycol methyl ether (Dowfroth 250). Some of these chemicals are recycled but most are discharged with the tailings.

Copper mines frequently operate for 50 years or more. Tailings impoundments must hold the waste forever and are vulnerable to natural forces such as erosion, landslides and earthquakes. Seepage is collected and returned to the impoundment during operations, but this

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[58] From the International Cyanide Management Institute website: http://www.cyanidecode.org/cyanide_use.php

[59] http://montanakids.com/agriculture_and_business/mining/Future_of_Mining.htm

[60] From the International Cyanide Management Institute website: http://www.cyanidecode.org/cyanide_environmental.php

[61] Hecht, S.A. and 5 coauthors. 2007. An overview of sensory effects on juvenile salmonids exposed to dissolved copper. Technical White Paper. NMFS, Seattle, WA.

process usually stops when mining ceases. Inevitably, some of the "chemical soup" seeps out into the surrounding ground and surface waters.

If developed the proposed Pebble Mine would be the largest open pit mine in North America. The pit would stretch to 2 miles wide, and be dug as much as 2,000 feet deep. The 8 billion tons of waste rock removed from the mine would require two giant tailings ponds enclosed by four earthen dams, the largest measuring 4.3 miles long and 740 feet high (far bigger than Grand Coulee Dam). The other dams would be 700, 400 and 175 feet tall. Each of these dams would put two valleys under water, one of which is in the Koktuli river watershed. The area is also an active earthquake zone which leads to an elevated risk of structure damage and pollution.[62]

3. *Risk of Acid Mine Drainage and Metals Leaching* [63]

The reasonably foreseeable human activities of mining development in the Koktuli River watershed, makes Acid Mine Drainage (AMD) another potential risk that would degrade water quality. Acid drainage and metal leaching occur because the metals developers want from mines commonly exist as complex chemical compounds in the rock. The entire mineral makeup of the rock, not just the copper or gold, determines how excavating and storing rock affects the environment.

Three processes can lead to contamination. First, rain and snow falling on crushed or broken rock can turn the water acidic (low pH) or alkaline (high pH). Second, rain or snow on rock may leach metal salts (readily dissolved compounds) into water. Third, processing chemicals can leak or spill.

Iron sulfide is a major contributor to AMD. Iron sulfide often occurs with gold and other valuable minerals. Rain, snowmelt, or water moving over iron sulfide forms sulfuric acid. The acid dissolves metals in the rock like copper, zinc, nickel, and lead. Acid and metals are washed downstream into clean watersheds where aquatic plants and animals are exposed. It can occur in tunnels, open pits, waste rock piles, and mill waste (tailings) (Figure 10).

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[62] http://ourbristolbay.com/the-risk-factsheet.html

[63] This section compiled by Dr. Kendra Zamzow of CSP2, http://www.csp2.org. References are included at the bottom of: http://ourbristolbay.com/acid-rock-drainage.html

Figure 10: Acid Drainage photo. Acid drainage is red or orange because of the iron in it. Dissolved oxidized iron gives acid drainage its distinctive red color. These processes occur naturally, but are more extreme when rock is crushed and more rock surface is exposed. Acid on tunnel walls at Kensington gold mine (Southeast Alaska). Photo - D. Chambers.

While sulfide makes acid, carbonate in rock buffers acid. The ratio of sulfides to neutralizing rock like carbonate influences the overall acidity of mine drainage. With enough buffering minerals, drainage may not be acid; however, neutralizing minerals often break down more quickly than sulfides, so even if there is plenty of neutralization initially, acid drainage may develop in the future. Acid mine drainage may take decades to develop.

Acid mine drainage may contain copper, zinc, cadmium and other minerals to which salmon are very sensitive. As little as a 2-8 parts per billion increases in copper above natural stream levels damages the ability of salmon to smell and it becomes harder to avoid predators, find mates, and return to spawning grounds.

When acid drainage enters clean streams, the acid is diluted, but "yellowboy" forms as red dissolved iron becomes solid. Yellowboy is a classic orange color (Figure 11) and acts like cement, smothering species that live on stream bottoms.

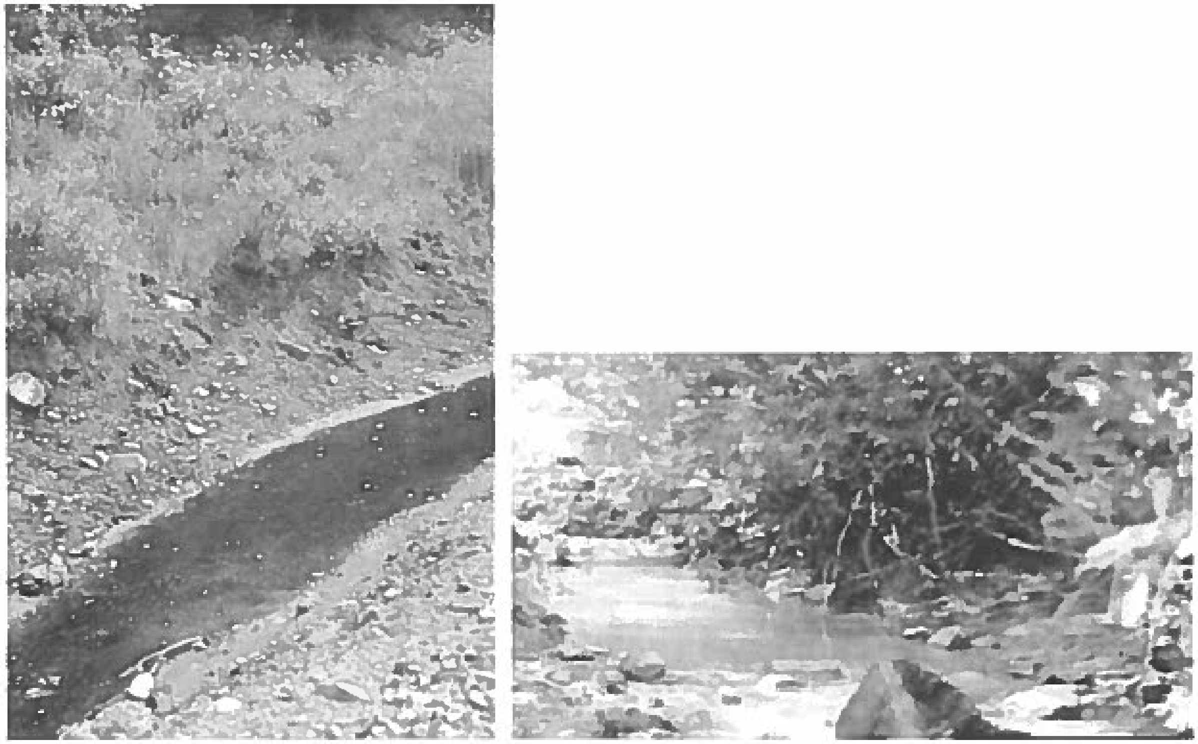

Figure 11: Red dissolved iron and yellowboy. The red iron (top) and yellowboy (bottom) near the closed Leviathan copper mine in California. Top photo G. Miller. Bottom photo Lahontan Regional Water Quality Board.

Dissolved aluminum also becomes solid in natural waters, forming mucus-like streamers that clog fish gills and cause fish to suffocate.

Acid drainage is irreversible. Placing sulfide rock underwater or burying it can slow acid formation by removing oxygen, but it won't stop completely if certain forms of iron are present. Since it cannot be stopped, the contaminated water must be treated in perpetuity, for hundreds or thousands of years. [64]

Preliminary geochemical data indicates significant acid mine drainage potential at the Pebble Mine site. If water treatment is required, expensive lime treatment may be necessary, possibly

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[64] Mining companies post bonds to pay for water treatment, but regulators often underestimate the cost, leaving taxpayers to pay. For example, when Montana and the US Environmental Protection Agency (EPA) requested Pegasus Gold to clean up water pollution in 1998, Pegasus filed for bankruptcy and left Montana with millions of dollars in water treatment costs.

in perpetuity. Lime products form sludge that will require on site disposal. Treated discharge has low metals but high total dissolved solids (tds).

Authorizing a mine where it is known that water treatment in perpetuity will be required poses significant long term financial and/or environmental risks to the public.

In addition to acid mine drainage, other mining byproducts can have effects on the watershed. Metals and metal-like elements don't need acid to dissolve – they can dissolve at neutral or alkaline pH. This is called "metal leaching". Alkaline pH can occur in two ways: if the rock contains a lot of carbonate, or if ore processing requires the pH of process water to be very high. For instance, when cyanide is used to extract gold, the pH must be kept high to avoid forming cyanide gas that can kill people. Alkaline water causes arsenic, cadmium and selenium to dissolve. These toxins can reduce growth, cause physical deformities and kill fish.

4. *Impacts to Fish*

Given the location of the deposit (See Figure 9) the proposed Pebble Mine has potential to contaminate surface water of the Koktuli River system, a direct threat to the characteristics of an Outstanding National Resource Water. In addition to surface water contamination, the extensive glacial gravel deposits of the Koktuli area are highly permeable; a characteristic that contributes to salmon productivity but also provides pathways for water and potentially for mine wastes to move between surface and groundwater and between river basins.

Salmon have adapted to the local surface water, naturally pure with extremely low concentrations of dissolved minerals; even minute amounts of contaminants beyond what these salmon have adapted can potentially cause harm. Salmon and organisms comprising freshwater food chains are very sensitive to heavy metals, trace elements, and other contaminants found in mine wastes.[65] Pollution from mines can degrade habitat and other ecosystem functions including[66]:

> *Acid Mine Drainage* - Acid mine drainage harms respiratory function of fish, and low PH can impact reproduction rates and rearing success. Low PH can also kill aquatic plants and macroinvertebrates, thereby diminishing important food sources and disrupting the natural food chain.
>
> *Heavy metals contamination* - Dissolve heavy metals can bioaccumulate in trout and salmon and collect on their gills, causing respiratory problems. Some metals have been shown to severely impact the juvenile salmon life cycle and limit growth rates. High metal concentrations in water can be toxic to plants and wildlife. They can also

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[65] Elsa M. Sorensen, *Metal Poisoning In Fish*, 235-84 (1991); A. Dennis Lemly, *Mining in Northern Canada: Expanding the Industry While Protecting Arctic Fishes – A Review*, 29 Ecotoxicology and Envtl. Safety 229, 230-34 (1994); Ronald Eisler, *Handbook of Chemical Risk Assessment: Hazards to Humans, Plants, and Animals: Metals, 144-73 (2000).*

[66] http://www.tu.org/conservation/abandoned-mines-western-us

bioaccumulate in fish tissues and can be passed on to humans and other animals through the food chain. Open-pit mines, tunnels, and other mine workings can also be a direct threat to groundwater contamination when they extend below the water table. When these areas fill up with water, they can lower the water table and contribute to dewatered streams, springs, and wells.

- *Sedimentation* - . As soil particles are washed into a stream, sedimentation occurs as they drop to the streambed and cover rocks and vegetation Sediment from waste rock and tailings piles can cover spawning beds, impair the growth of other aquatic organisms and smother juvenile trout. Sediment can also raise the water temperature, decrease oxygen supplies, fill pools, destroy stream channels, and lead to greater risks of flooding.

Some examples:

- In Colorado, there are 20,299 abandoned mine sites and 1,300 miles of adversely affected streams! As one example, mining waste has killed 20 miles of the Animas River fishery in southwest Colorado from the nearby molybdenum mine.
- In New Mexico, at least eight miles of the Red River's aquatic life (including its trout) have been decimated by heavy metal waste associated with the nearby molybdenum mine.
- In Montana, a tailings dam in the headwaters of the Blackfoot River breached in 1975 and sent sever thousand tons of mine waste into the river. The toxic material has been traced as far as 16 miles downstream and killed all aquatic life in the first ten miles of the river.

Of particular concern to the outstanding natural waters of the Koktuli River system is potential contamination from: low pH or an unusually high pH; metals/metalloids (elevated concentrations of many potentially toxic constituents such as: aluminum, antimony, arsenic, barium, cadmium, copper, chromium, cobalt, iron, lead, manganese, mercury, molybdenum, nickel, selenium, silver, thallium, vanadium, zinc); together with elevated concentrations of the major metals (calcium, magnesium, sodium and potassium); of nonmetals (sulfate, nitrate, ammonia, boron, phosphorus, fluoride, chloride); and of natural radioactive constituents (uranium, thorium, potassium-40, gross alpha and beta, in general), all of which are associated with natural rock in place. Two recent papers document the presence of these constituents in the Red Dog mine rocks (Kotzebue area), and it is of similar concern in the Bristol Bay watershed (Slack et al., 2004a and b). Moreover, interactions among metals, can produce more than additive effects. Mixtures of metals can cause higher rates of mortality in fish than would be expected by simply adding the effects of each element alone.[67] Once inside an organism, metallic elements exist in a specific form and ratio to other elements and will interact directly

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[67] J.B. Sprague & B.A. Ramsay, *Lethal Levels of Mixed Copper-Zinc Solutions for Juvenile Salmon*, 22 J. of the Fisheries Red. Bd. Of Can. 425 (1965); Sorenson, *Supra* note 26, 335-39; Eisler, *supra* note 26 at 335.

or indirectly based on a multitude of parameters.[68] For example, survival from egg to hatch of catfish (*Ictalurus* spp.) treated with a 1:1 ratio of Cu:Zn declined predictably under an additive model up to a concentration of ~1 ppm. With increasing concentrations, mortality rates increased synergistically at higher that predicted rates.[69] However, relatively few studies of synergistic effects exist, and the scientific understanding of such effects is still developing.[70]

Short-term fluctuations in water quality are caused by diurnal variation in natural conditions, especially light exposure. For example, this has been documented in a small system in Colorado that receives acid mine drainage; photoreduction of ferric iron results in a well-defined increase in dissolved ferrous iron during the day. There is greater variability in dissolved iron concentrations during the day, indicative of photoreduction. (McKnight, 1988). To understand the chemical and physical nature of this system, baseline water quality data collected at specific time intervals is needed, as is long-term monitoring for diel cycle variations. A full understanding of natural systems requires that we understand complex ways in which seemingly unrelated processes such as photosynthesis and sorption are coupled. (Fuller, 1989). Diurnal fluctuations in concentrations of metals such as cadmium and zinc also have documented impacts on trout survival. (Nimick et al., 2007). Seasonal fluctuations can bring much larger changes in concentration than diurnal changes - particularly during break up when snow is melting. This causes metals sequestered in sediment and sediment pore-water to flush up into the water column and sharply increase metal concentrations in water.

There are potential effects on fish of from copper concentration increases [2-10 ppb (µg/L)] over natural levels in the aquatic environment.[71] Minute increases of dissolved copper above natural water levels can impair a salmon's sense of smell, and thus survival, as salmon use smell to find spawning grounds and to distinguish among predators, prey, kin, and mates (Woody, 2007; Hecht et al. 2007). Increased levels of copper can stress salmon and impair their ability to fight disease, breathe, or maintain cell fluid and electrolyte balance (osmoregulation), and can impair brain function (Eisler 2001; Woody, 2007). Additionally, increased levels of copper may delay or accelerate natural hatch rates, which can reduce salmon survival rates and kill or harm salmon food sources, including algae, zooplankton, aquatic insects and fish (Woody, 2007). The following excerpt from the Alaska Law Review[72] further explains these potential threats to the Koktuli River system and its fisheries habitat:

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[68] H.H. Sanstead, *Effects and Does-Response Relationships of Toxic Metals* (1976); SORENSEN, *supra* note 26, at 335.

[69] Wesley J. Birge & Jeffrey A. Black, *Effects of Copper on Embryonic and Juvenile Stages of Aquatic Animals*, *in* Jerome O. Nriagu, ed., *Copper in the Environment: Health Effects Part II*, 373 and 386–88.

[70] Geoffrey Y. Parker and Frances M. Raskin et al, *Pebble Mine: Fish, Minerals, and Testing the Limits of Alaska's "Large Mine Permitting Process*, Alaska Law Review, Volume XXV, No. 1, June 2008, 19.

[71] The proposed Pebble Mine would be a large-scale (2007 Northern Dynasty Mines plans show ~2.6 mi long X 1.6 mi wide X 1 – 5 thousand ft deep copper-gold-molybdenum) mine similar to mines (e.g. Butte, MT) that increased copper and other pollutants harmful to fish in the surrounding environment (USEPA 1994; Woody, 2007). The exact Pebble Mine plan is undefined at present. It is expected to include both open-pit and underground operations.

[72] Geoffrey Y. Parker and Frances M. Raskin, et al, *Pebble Mine: Fish, Minerals, and Testing the Limits of Alaska's "Large Mine PermittingProcess.* "Alaska Law Review Vol XXV, 17, (June 2008).

Both lethal and sublethal effects of copper (Cu) on salmon and their food chains have been demonstrated[73] at concentrations below the Alaska state water quality criterion for protection of freshwater species (9 micrograms Cu per liter (µg Cu/L) calculated on 100 mg/L hardness (CaCO3)), and well below the human drinking water criterion of 1,300 µg Cu/L.[74] Copper has sublethal effects on salmon that can reduce the viability of populations.[75] Concentrations below the accepted criterion for aquatic life in Alaska (< 9 µg Cu/L) have produced the following documented effects on fish:

1. impairment of sense of smell (olfaction);[76]
2. interference with normal migration;[77]
3. impairment of their ability to fight disease (immune response);[78]
4. difficulties in breathing;[79]
5. disruption of osmoregulation (ability to control internal salinity of body fluids);[80]
6. impairment of ability to sense vibrations via their lateral line canals (a sensory system that helps fish avoid predators);[81]
7. impairment of brain function;[82]
8. changes in enzyme activity, blood chemistry and metabolism;[83] and
9. delay or acceleration of natural hatch rates;[84]

Many metals toxic to aquatic life are commonly released at hard rock mining sites, and interactive effects on salmon and aquatic systems are not well studied.[85] Few studies exist on the "cocktail" effects that multiple metals have on fish and aquatic food chains. Combined effects can be more toxic than any single element.[86]

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[73] Eisler, *supra* note 21, at 144–173, TABLE 3.5 144–161.

[74] Alaska Admin. Code tit. 18 § 70.020(b) (2007) incorporates by reference the *Alaska Water Quality Criteria for Toxic and Other Deleterious Substances*, *available at* http://dec.alaska.gov/water/wqsar/wqs/pdfs/70wqsmanual.pdf (stating copper criteria for freshwater aquatic life and for human health).

[75] David H. Baldwin et al., *Sublethal Effects of Copper on Coho Salmon: Impacts on Nonoverlapping Receptor Pathways in the Peripheral Olfactory Nervous System*, 22 Envt'l Toxicology and Chemistry 2273 (2003); Eisler, *supra* note 21, at 163–166. SORENSEN, *supra* note 19, at 269–276.

[76] J. Raloff, *Aquatic Non-Scents: Repercussions Of Water Pollutants That Mute Smell*, SCIENCE NEWS, Jan. 27, 2007, at 59.

[77] J.N. Goldstein, D. F. Woodward and A. M. Farag, *Movements of Adult Chinook Salmon During Spawning Migration in a Metals-Contaminated System, Coeur d'Alene River, Idaho*, TRANSACTIONS OF THE AMERICAN FISHERIES SOCIETY 128, 121–129 (1999); D.F. Woodward et al., *Brown Trout Avoidance of Metals in Water Characteristic of the Clark Fork River, Montana*, CANADIAN JOURNAL OF FISHERIES AND AQUATIC SCIENCES 52:2031–2037 (1995); SORENSEN, *supra* note 105, at 264.

[78] R.J. Baker, M.D. Knittel , and J.L. Fryer, *Susceptibility of Chinook Salmon,* Oncorhynchus tshawytscha *(Walbaum), and Rainbow Trout,* Salmo gairdneri. *Richardson, to Infection with* Vibrio anguillarum *Following Sublethal Copper Exposure*, Journal of Fish Diseases 3:267–275 (1983).

[79] Sorensen, *supra* 27 at 266–269.

[80] *Id.* at 256–262; Eisler, *supra* note 21, at 180.

[81] Sorensen, *supra* note 27, at 253.

[82] Eisler, *supra* note 27, at 163.

[83] Sorensen, *supra* note 27, at 256–262. EISLER, *supra* note 104, at 180.

[84] Sorensen, *supra* note 27, at 271.

[85] Eisler, *supra* note 27, at 102–105.

[86] Carol Ann Woody, *Copper: Effects on Freshwater Food Chains and Salmon: A Review*, 14 *at* http://fish4thefuture.com/pdfs/Woody_Copper_Effects_to_Fish%20-%20FINAL2007.pdf. (Sept. 21, 2007).

The Pebble Partnership asserts that about ninety-five percent of the metal that the mine would produce is copper.[87] Given the location of the deposit, the type of deposit and mine proposed, increased levels of copper are reasonable and foreseeable changes from human activities that would cause reduction in existing water quality within the Koktuli River watershed and have a significant effect on its trout and salmon populations.

Of additional concern are contaminants generated in the processing of ore, and these are of toxic concern to fish and fish habitat. The following chemical agents are some of the potentially-toxic processing compounds generally added in mineral processing: methyl isobutyl carbinol, potassium ethyl xanthate, sodium ethyl ether, potassium amyl xanthate, sodium isobutyl xanthate, sodium metabisulfite, zinc sulfate, copper sulfate, sodium cyanide, sodium sulfide, lime, sodium hydroxide, organic antiscalents and flocculents (Personal Communication between Robert Moran and Lauren Oakes, 11/2007). Moreover, interactions among metals, such as copper and zinc, can produce more than additive affects. Mixtures of metals cause higher rates of mortality in fish than would be expected by simply adding the effects of each element alone.[88]

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[87] Elizabeth Bluemink, *Jewelers Announce Opposition to Pebble Prospect's 'Dirty Gold:' Companies Call for Protection of River Drainages*, Anchorage Daily News, Feb. 13, 2008, at A1, *available at* http://www.adn.com/money/industries/mining/story/313462.html.

[87] Eisler, *supra* note 27, at 163–166 at 138.

[88] J. B. Sprague and B.A. Ramsay, *Lethal Levels of Mixed Copper-Zinc Solutions for Juvenile Salmon, 22* J. of the Fisheries Red. Bd. Of Can. 425 (1965); Sorenson, *supra* note 105, 335-39; Eisler *supra* note 104, at 104.

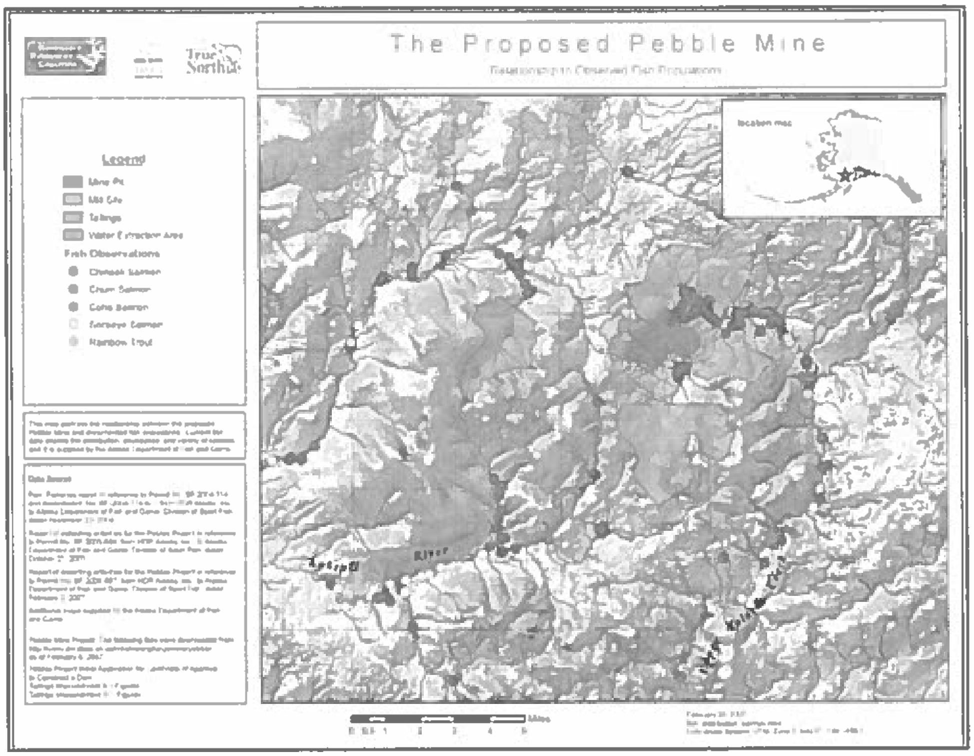

Figure 12: illustrates the proposed Pebble Mine in proximity to the Koktuli Rivers and details observed anadromous fish populations.

Once copper and other heavy metals enter a system, they generally remain and are constantly recycled due to floods, lake turnover, and benthic feeding organisms (e.g., snails, clams, whitefish). Such effects on salmon and aquatic food chains of the Koktuli River system could cause significant declines in salmon populations, and the cumulative long term effects of copper and other pollution on salmon warrant the protection and maintenance of existing water quality of the Koktuli River system.

IV. Community Support and Testimony

Local Support, Testimony, and Additional Evidence to Substantiate ONRW Designation

Anglers, recreationists, scientists, and local Natives, recognize the Koktuli River system is well known as one of the most beautiful and outstanding waters in the state, supporting a larger ecosystem like none other on the planet.

Flyfishing lodge owner Chuck Ash is a native Alaskan who has guided wilderness and fly fishing trips since 1975. As owner of Brightwater Alaska, a guided fishing company, he has floated, hiked, and fished the Koktuli River and surrounding area since 1985.

> Over the years I have watched as rivers diminish in wilderness value due to greatly increased human use, especially by float planes and river boats. The Koktuli however has remained by and large unaffected. It has no headwaters lake from which it can be easily accessed by plane and the river is too small and too interdicted by natural logjams and sweepers to be easily navigated by river boats.
>
> There are a number of rivers in Bristol Bay where I can float and find good fishing. The Koktuli is one of the last two remaining rivers where I can take customers to find true wilderness and real solitude. All of Alaska was once this way.
>
> The ecosystem over the length of the river is unique and defines the experience. The upper third of the river is through upland tundra, which abruptly changes to a riparian spruce-birch forest at the confluence of the north and main forks. This forest continues in a narrow but widening band, closely contained by the tundra on the uplands surrounding it, and descends into the broader floodplain of the Mulchatna River.
>
> Because of the wide variety of habitat along its entirety, the Koktuli is unusual in the mix of species it contains. Vegetation, birds and mammals on the upper end are those that require the open and more arid conditions of tundra. Further downriver are found the species that require the coolness and shelter of the forest. All the species present on the Koktuli require fresh and clean water for their existence.
>
> Moose, wolves, wolverines and foxes are the resident large mammal species here, but many of the other mammalian, avian and piscine species are migratory. Birds migrate from North America, South America, Asia and the Pacific islands to nest here or on their way to nesting grounds further north. Caribou migrate through the Koktuli valley on their annual peregrinations. The migrating salmon, however, are the linchpin to the strength and diversity of this ecosystem.
>
> Salmon come annually from the sea to spawn, transferring energy and minerals from the ocean to the waters and land of the Koktuli in the process. Rainbow trout and Dolly Varden migrate upstream to feed on the roe and decaying flesh of these spawning salmon, returning to the larger waters of the Mulchatna in the late summer. Grayling descend from their own spawn in the upper river to take advantage of the salmon spawn, as well. Bears migrate seasonally both to and through the Koktuli in search of spawning salmon. The people who reside in the

Bristol Bay area are also economically and culturally dependent on these returning salmon. Without the salmon the fabric of life here is weakened and the richness of this ecosystem and all it supports wanes.

My concern for the protection of the Koktuli River sysytem is not personal, but rather for the sanctity of what was once both unique and common, and is now scarce and precious.

Chuck Ash
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briteh2o@alaska.net

<u>Nature writers and photographers, Erin McKittrick and Bretwood Higman (Hig)</u> have walked over 7000 miles all over Alaska. They have studied the wilderness of Alaska not only as fuel for their writing and photography but to gain awareness about these last remaining wilderness locations. Hig and Erin visited the Koktuli and Iliamna region in the summer of 2006, upon completion of there epic 3000 mile journey, this was said,

> When I visited the Koktuli River in 2006 along with my wife and a friend, we had been living in Washington. In many ways this framed our impressions. In Washington, there are beautiful mountains, but if you visit the rivers, they are crowded by development, framed by young forests, and sport a fraction of the fish that once crowded their waters. In contrast, the Koktuli wanders free across a broad wild valley.
>
> We passed a USGS river gage, but no other evidence that humankind existed. Starting at the headwaters in Frying Pan Lake, we walked and floated first through tundra speckled with spring flowers and roaming bears. At lower elevations willow and cottonwood forests crowded the river, providing browse for moose. We caught rainbow trout and arctic grayling. Even after a winter, the signs of last season's salmon runs were apparent—bear scat filled with fish bones. On the lower river we passed into spruce forests. These gallery forests are confined to the floodplain, and are bounded by broad plains of rich tundra feeding caribou and providing nesting for migratory birds such as the arctic tern and sandhill crane.

> Everywhere in salmon country rivers are the biological center of the universe. It is only on the river banks that you see the animals and plants at their full diversity and density. Along the Koktuli, that ecosystem is particularly broad and diverse. Because the valley is broad and low, and because the river crosses through transitions between tundra and forest, there is diverse habitat to support plants and animals. When the salmon come, providing a huge boost in nutrients, the ecosystem benefits for miles to either side of the river.
>
> The Koktuli is alive. In Washington, most large animal tracks are rare—there we would react with excitement at even one bear print. The banks of the Koktuli are crisscrossed with tracks of bear, caribou, moose, beaver, porcupine, ground squirrel, wolverine, river otter, and innumerable birds. My wife and I moved to Alaska a little over a year ago, in part because of the Koktuli Valley and places like it.

In a recent poll, which is the most in-depth survey of local Alaska Natives' opinion, determined that only 8 percent of survey respondents supported the Pebble mine project. The survey also found that 79 percent of respondents believe the Pebble Mine, located in the headwaters of two of the region's largest salmon-spawning rivers, would damage Bristol Bay's wild salmon fishery – a key resource that many residents depend on for income and food.

Designate the Koktuli River as Alaska's First ONRW

The Koktuli River is a gem even amongst Alaska's most stunning landscapes and deserves the protection that Outstanding National Resource Water status awards. Its trout and salmon populations have sustained decades of anglers and other recreationists in their quest to experience some of the best backcountry travel left in the country. In addition, healthy runs of salmon have supported a vibrant and well-functioning ecosystem for centuries, which in turn has shaped a subsistence way of life for Alaska Natives and other residents who depend on the land for their survival and way of life. We, the petitioners of this nomination, can think of no watershed more worthy of becoming Alaska's first Outstanding National Resource Water than the Koktuli River system.

Additional References

Alaska Department of Fish and Game, 2008 Bristol Bay Salmon Season Summary, Alaska Department of Fish and Game Division of Commercial Fisheries Summary. Accessed at http://www.cf.adfg.state.ak.us/region2/finfish/salmon/bbay/brbpos08.pdf

Alaska Department of Fish and Game, Division of Sport Fish. January, 2009. Economic Impacts and Contributions of Sportfishing in Alaska, Summary Report 2007. Anchorage, Alaska.

Alaska Department of Fish and Game. Coho Salmon Life History and Habitat Requirements: Southwest, Southcentral, Arctic, Western and Interior Regions. Available at http://www.sf.adfg.state.ak.us/Static/AWC/PDFs/coho_salmon.pdf

Doyle, M. W. 2005. Incorporating hydrologic variability into nutrient spiraling. Journal of Geophysical Research, Vol 110: 1-11.

Doyle, M. W., Stanley, E. H., Strayer, D. L., Jacobson, R. B., and Schmidt, J. C. 2005. Effective discharge analysis of ecological processes in streams. Water Resources Research. Vol 41: 1-14.

Duffield, J., Patterson, D., Neher, C. (2007), The Economics of Wild Salmon Watersheds: Bristol Bay, Alaska.

Emmett, W. W., and Wolman, M. G. 2001. Effective discharge and gravel-bed rivers. Earth Surface Processes and Landforms, Vol 26:1369-1380.

Fuller, Christopher and Davis, James. 1989. Influence of coupling of sorption and photosynthetic processes on trace element cycles in natural waters. Nature. Vol. 340., No. 6228., pp. 52-54, 6th July 1989.

Hauser, William. 2007. Potential Impacts of the Proposed Pebble Mine on Fish Habitat and Fishery Resources of Bristol Bay. Available at http://www.savebristolbay.org/atf/cf/%7BE729E68D-22F3-4596-9503-54FE676F2264%7D/HauserSep07.pdf

Hecht, Scott A, et al. 2007. An overview of sensory effects on juvenile salmonids exposed to dissolved copper: Applying a benchmark concentration approach to evaluate sublethal neurobehavioral Toxicity. Technical White Paper. National Marine Fisheries Service (NMFS), Office of Protected Resources, Endangered Species Division, 510 Desmond Drive SE., Lacey, WA 98506 USA.

Howe, A. L., and R. J. walker, C. Olnes, K. Sudnet, and A. E. Bingham. 2001. Participation, catch, and harvest in Alaska sport fisheries during 1999. Alaska Department of Fish and Game, Fishery Data Series No. 01-8, Anchorage. http://www.sf.adfg.state.ak.us/FedAidPDFs/fds01-08.pdf

Jennings, G. B., K. Sundent, A. E. Bingham, and D. Sigurdsson. 2004. Participation, catch and harvest in Alaska sport fisheries during 2001. Alaska Department of Fish and Game, Fishery Data Series No. 04-11, Anchorage. http://www.sf.adfg.state.ak.us/FedAidPDFs/fds04-11.pdf

Jennings, G. B., K. Sudent, A. E. Bingham, and D. Sigurdsson. 2006a. Participation, catch and harvest in Alaska sport fisheries during 2002. Alaska Department of Fish and Game, Fishery Data Series No. 06-34, Anchorage. http://www.sf.adfg.state.ak.us/FedAidPDFs/fds06-34.pdf

Jennings, G. B., K. Sudent, A. E. Bingham, and D. Sigurdsson. 2006a. Participation, catch and harvest in Alaska sport fisheries during 2003. Alaska Department of Fish and Game, Fishery Data Series No. 06-44, Anchorage. http://www.sf.adfg.state.ak.us/FedAidPDFs/fds06-44.pdf

McKnight, D.M. and Bencala, Kenneth. Diel variations in iron chemistry in an acidic stream in the Colorado Rocky Mountains, U.S.A. Arctic and Alpine Research, Vol. 20., No. 4, (Nov. 1988), pp. 492-500.

McKnight, D.M. and Kimball, B.A. et al. 1988. Iron Photoreduction and oxidation in an acidic mountain stream. Science. Vol. 240, Pages 577-692, April 29,1988.

Nimick, D.A., Harper, D.D., Farag, A.M., Cleasby, T.E., MacConnell, E., and Skaar, D., 2007, Influence of in-stream diel concentration cycles of dissolved trace metals on acute toxicity to one-year-old cutthroat trout (Oncorhynchus clarki lewisi): Environmental Toxicology and Chemistry, v. 26, p. 2667-2678.

Poff, N. L., J. D. Allan, M. B. Bain, J. R. Karr, K. L. Prestegaard, B. D. Richter, R. E. Sparks, and J. C. Stromberg (1997), The Natural Flow Regime, BioSience, 47, 769-784.

Reiser, D.W., and Bjornn, T.C. 1979. Influence of Forest and Rangeland Management on Anadromous Fish Habitat inWestern North America: Habitat Requirements of Anadromous Salmonids. U.S. Forest Service, Pacific Northwest Forest and Range Experiment Station.

Slack, J.F., J.A. Dumoulin, J.M. Schmidt, L.E. Young, C.S. Rombach, 2004a, Paleozoic Sedimentary Rocks in the Red Dog Zn-Pb-Ag District and Vicinity, Western Brooks Range, Alaska: Provenance, Deposition, and Metallogenic Significance. Economic Geology, Vol. 99, pg. 1385-1414.

Slack, J.F., K.D. Kelley, V. M. Anderson, J.L. Clark, R. A. Ayuso, 2004b, Multistage Hydrothermal Silicification and Fe-Tl-As-Sb-Ge-REE Enrichment in the Red Dog Zn-Pb-Ag District, Northern Alaska: Geochemistry, Origin, and Exploration Applications. Economic Geology, Vol. 99, pg. 1481-1508.

Wiedmer, M., 2006. Fish Periodicity Charts for the upper Mulchatna and Koktuli Rivers. Alaska, Department of Fish and Game, Anchorage, AK.

Woody, C. A. 2007 Copper: Effects on Freshwater Food Chains and Salmon. A Literature Review. American Fisheries Society.

Woolington, J. Email correspondence with Cathy Flanagan regarding biologic species use of the upland and riparian portions of the Koktuli River drainage area on November 6, 2006. GMU 17 Area Management Biologist5, Alaska Department of Fish and Game, Anchorage, Alaska.

Personal Communication

Moran, Robert E., Michael Moran Associates. 2007. Email correspondence with Lauren Oakes regarding legal opinions related to on-going Red Dog mine litigation and geochemical background re: Pebble aquatic toxicity issues. Moran references correspondence with James Kulas, Teck Cominco to Enoch Adams, Jr., Oct. 11 and 13, 2007.

Appendices

Appendix I

Location of South Fork and Mainstem Koktuli River by Meridian, Township, Range, Section

MTR	MERIDIAN	TWP	TWP_DIR	RNG	RNG_DIR	SEC_NO
S002S040W18	S	2	S	40	W	18
S002S040W17	S	2	S	40	W	17
S002S040W16	S	2	S	40	W	16
S002S040W19	S	2	S	40	W	19
S002S040W20	S	2	S	40	W	20
S002S040W21	S	2	S	40	W	21
S002S040W22	S	2	S	40	W	22
S002S041W25	S	2	S	41	W	25
S002S040W30	S	2	S	40	W	30
S002S040W27	S	2	S	40	W	27
S002S040W26	S	2	S	40	W	26
S002S041W34	S	2	S	41	W	34
S002S041W35	S	2	S	41	W	35
S002S041W36	S	2	S	41	W	36
S002S040W35	S	2	S	40	W	35
S002S040W36	S	2	S	40	W	36
S003S041W05	S	3	S	41	W	5
S003S041W04	S	3	S	41	W	4
S003S041W03	S	3	S	41	W	3
S003S040W01	S	3	S	40	W	1
S003S039W06	S	3	S	39	W	6
S003S042W12	S	3	S	42	W	12
S003S041W07	S	3	S	41	W	7
S003S041W08	S	3	S	41	W	8
S003S039W07	S	3	S	39	W	7
S003S039W08	S	3	S	39	W	8
S003S039W09	S	3	S	39	W	9
S003S039W16	S	3	S	39	W	16
S003S039W15	S	3	S	39	W	15
S003S039W14	S	3	S	39	W	14
S003S039W13	S	3	S	39	W	13
S003S039W24	S	3	S	39	W	24
S003S038W19	S	3	S	38	W	19
S003S038W30	S	3	S	38	W	30
S003S038W29	S	3	S	38	W	29
S003S035W27	S	3	S	35	W	27
S003S038W32	S	3	S	38	W	32
S003S035W32	S	3	S	35	W	32
S003S035W34	S	3	S	35	W	34
S004S038W05	S	4	S	38	W	5
S004S038W04	S	4	S	38	W	4

S004S035W05	S	4	S	35	W	5
S004S035W03	S	4	S	35	W	3
S004S038W09	S	4	S	38	W	9
S004S038W10	S	4	S	38	W	10
S004S035W07	S	4	S	35	W	7
S004S035W08	S	4	S	35	W	8
S004S035W09	S	4	S	35	W	9
S004S035W10	S	4	S	35	W	10
S004S038W15	S	4	S	38	W	15
S004S038W14	S	4	S	38	W	14
S004S035W18	S	4	S	35	W	18
S004S035W15	S	4	S	35	W	15
S004S038W23	S	4	S	38	W	23
S004S038W24	S	4	S	38	W	24
S004S037W19	S	4	S	37	W	19
S004S036W21	S	4	S	36	W	21
S004S036W22	S	4	S	36	W	22
S004S036W23	S	4	S	36	W	23
S004S036W24	S	4	S	36	W	24
S004S035W19	S	4	S	35	W	19
S004S035W20	S	4	S	35	W	20
S004S035W21	S	4	S	35	W	21
S004S035W22	S	4	S	35	W	22
S004S037W30	S	4	S	37	W	30
S004S037W29	S	4	S	37	W	29
S004S037W28	S	4	S	37	W	28
S004S037W27	S	4	S	37	W	27
S004S037W26	S	4	S	37	W	26
S004S037W25	S	4	S	37	W	25
S004S036W30	S	4	S	36	W	30
S004S036W29	S	4	S	36	W	29
S004S036W28	S	4	S	36	W	28
S004S036W27	S	4	S	36	W	27
S004S035W30	S	4	S	35	W	30
S004S037W36	S	4	S	37	W	36
S004S036W31	S	4	S	36	W	31

Appendix II

Location of North Fork Koktuli River by Meridian, Township, Range, Section

MTR	MERIDIAN	TWP	TWP_DIR	RNG	RNG_DIR	SEC_NO
S002S035W29	S	2	S	35	W	29
S002S035W32	S	2	S	35	W	32
S003S036W01	S	3	S	36	W	1
S003S035W06	S	3	S	35	W	6
S003S035W05	S	3	S	35	W	5
S003S036W08	S	3	S	36	W	8
S003S036W09	S	3	S	36	W	9
S003S036W10	S	3	S	36	W	10
S003S036W11	S	3	S	36	W	11
S003S036W12	S	3	S	36	W	12
S003S036W18	S	3	S	36	W	18
S003S036W17	S	3	S	36	W	17
S003S036W16	S	3	S	36	W	16
S003S036W14	S	3	S	36	W	14
S003S036W13	S	3	S	36	W	13
S003S037W24	S	3	S	37	W	24
S003S036W19	S	3	S	36	W	19
S003S036W23	S	3	S	36	W	23
S003S037W25	S	3	S	37	W	25
S003S036W30	S	3	S	36	W	30
S003S036W27	S	3	S	36	W	27
S003S036W26	S	3	S	36	W	26
S003S037W36	S	3	S	37	W	36
S004S037W02	S	4	S	37	W	2
S004S037W01	S	4	S	37	W	1
S004S038W11	S	4	S	38	W	11
S004S038W12	S	4	S	38	W	12
S004S037W07	S	4	S	37	W	7
S004S037W08	S	4	S	37	W	8
S004S037W09	S	4	S	37	W	9
S004S037W10	S	4	S	37	W	10
S004S037W11	S	4	S	37	W	11
S004S038W14	S	4	S	38	W	14

Appendix III

Koktuli River Fish Distribution Assessment

Fishery Data Series No. 07-78

Kokturi River Fish Distribution Assessment

by

Craig J. Schwanke

December 2007

Alaska Department of Fish and Game
Divisions of Sport Fish and Commercial Fisheries

Symbols and Abbreviations

The following symbols and abbreviations, and others approved for the Système International d'Unités (SI), are used without definition in the following reports by the Divisions of Sport Fish and of Commercial Fisheries: Fishery Manuscripts, Fishery Data Series Reports, Fishery Management Reports, and Special Publications. All others, including deviations from definitions listed below, are noted in the text at first mention, as well as in the titles or footnotes of tables, and in figure or figure captions.

Weights and measures (metric)

centimeter	cm
deciliter	dL
gram	g
hectare	ha
kilogram	kg
kilometer	km
liter	L
meter	m
milliliter	mL
millimeter	mm

Weights and measures (English)

cubic feet per second	ft^3/s
foot	ft
gallon	gal
inch	in
mile	mi
nautical mile	nmi
ounce	oz
pound	lb
quart	qt
yard	yd

Time and temperature

day	d
degrees Celsius	°C
degrees Fahrenheit	°F
degrees kelvin	K
hour	h
minute	min
second	s

Physics and chemistry

all atomic symbols	
alternating current	AC
ampere	A
calorie	cal
direct current	DC
hertz	Hz
horsepower	hp
hydrogen ion activity (negative log of)	pH
parts per million	ppm
parts per thousand	ppt, ‰
volts	V
watts	W

General

Alaska Administrative Code	AAC
all commonly accepted abbreviations	e.g., Mr., Mrs., AM, PM, etc.
all commonly accepted professional titles	e.g., Dr., Ph.D., R.N., etc.
at	@
compass directions:	
east	E
north	N
south	S
west	W
copyright	©
corporate suffixes:	
Company	Co.
Corporation	Corp.
Incorporated	Inc.
Limited	Ltd.
District of Columbia	D.C.
et alii (and others)	et al.
et cetera (and so forth)	etc.
exempli gratia (for example)	e.g.
Federal Information Code	FIC
id est (that is)	i.e.
latitude or longitude	lat. or long.
monetary symbols (U.S.)	$, ¢
months (tables and figures): first three letters	Jan,...,Dec
registered trademark	®
trademark	™
United States (adjective)	U.S.
United States of America (noun)	USA
U.S.C.	United States Code
U.S. state	use two-letter abbreviations (e.g., AK, WA)

Measures (fisheries)

fork length	FL
mideye-to-fork	MEF
mideye-to-tail-fork	METF
standard length	SL
total length	TL

Mathematics, statistics

all standard mathematical signs, symbols and abbreviations	
alternate hypothesis	H_A
base of natural logarithm	e
catch per unit effort	CPUE
coefficient of variation	CV
common test statistics	(F, t, χ^2, etc.)
confidence interval	CI
correlation coefficient (multiple)	R
correlation coefficient (simple)	r
covariance	cov
degree (angular)	°
degrees of freedom	df
expected value	E
greater than	>
greater than or equal to	≥
harvest per unit effort	HPUE
less than	<
less than or equal to	≤
logarithm (natural)	ln
logarithm (base 10)	log
logarithm (specify base)	$\log_2$, etc.
minute (angular)	'
not significant	NS
null hypothesis	H_0
percent	%
probability	P
probability of a type I error (rejection of the null hypothesis when true)	α
probability of a type II error (acceptance of the null hypothesis when false)	β
second (angular)	"
standard deviation	SD
standard error	SE
variance	
population	Var
sample	var

FISHERY DATA SERIES NO. 07-78

KOKTULI RIVER FISH DISTRIBUTION ASSESSMENT

by
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Alaska Department of Fish and Game, Division of Sport Fish, Dillingham

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Division of Sport Fish, Research and Technical Services
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December 2007

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The Division of Sport Fish Fishery Data Series was established in 1987 for the publication of technically oriented results for a single project or group of closely related projects. Since 2004, the Division of Commercial Fisheries has also used the Fishery Data Series. Fishery Data Series reports are intended for fishery and other technical professionals. Fishery Data Series reports are available through the Alaska State Library and on the Internet: http://www.sf.adfg.state.ak.us/statewide/divreports/html/intersearch.cfm This publication has undergone editorial and peer review.

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ABSTRACT

Float trips were conducted on the lower 52 miles of Koktuli River in the Nushagak River drainage during June, July and August 2005 to document the size distribution of resident fish species and observe the distribution of resident fish and salmon species in the river. Water quality parameters were documented at four sites on each float trip. Hook and line sampling was conducted from two rafts on each float trip. A total of 183 rainbow trout *Oncorhynchus mykiss*, 291 Arctic grayling *Thymallus arcticus*, and 70 Dolly Varden *Salvelinus malma* were captured. The mean fork length and weight of rainbow trout was 406 mm and 880 g. The mean fork length and weight of Arctic Grayling and Dolly Varden were 311 mm and 364 g and 448 mm and 993 g, respectively. A total of 193.3 hours was spent angling. The mean catch per unit effort (fish/hour) of rainbow trout, Arctic grayling and Dolly Varden were 0.95, 1.50, and 0.55, respectively. Adult Chinook *O. tshawytscha*, chum *O. keta*, sockeye *O. nerka* and coho salmon *O. kisutch* were observed throughout the river over the course of the study. Juvenile Chinook and coho were captured in minnow traps at most sites sampled.

Key words: Koktuli River, Nushagak River, float trips, water quality, rainbow trout, *Oncorhynchus mykiss*, Arctic grayling, *Thymallus arcticus*, Dolly Varden, *Salvelinus malma*, catch per unit effort.

INTRODUCTION

The Koktuli River flows into the Mulchatna River of the Nushagak River system in southwest Alaska (Figure 1). A lack of rapids and a diversity of anadromous and resident fish species, most notably rainbow trout *Oncorhynchus mykiss*, make the river a popular choice for float trips in the Bristol Bay Management Area (BBMA). Float and wheel equipped aircraft access the river's headwaters, and the lower river is accessible by power boat from Mulchatna River. Three float trips were conducted on Koktuli River to document the presence and distribution of anadromous and resident fish species in the drainage. In addition, water quality and aquatic habitat parameters were documented. This information will be used as a reference for evaluating the potential future impacts of development and increased use in the drainage.

The headwaters of Koktuli River are located approximately 120 miles northeast of the community of Dillingham. The Koktuli River is comprised of a north and south fork (Figure 2). The south fork is a larger, wider river conducive to float trip activities and flows approximately 75 miles to its confluence with the Mulchatna River. The Koktuli River supports all five species of Pacific salmon *Oncorhynchus*, rainbow trout, Arctic grayling *Thymallus arcticus*, round whitefish *Prosopium cylindraceum*, Dolly Varden *Salvelinus malma*, and northern pike *Esox lucius*. Aerial index surveys to enumerate Chinook salmon *O. tshawytscha* spawning in the Nushagak River drainage indicate that Koktuli River supports approximately 24% of the drainage's spawning population (Dye and Schwanke *In prep*).

The Nushagak/Mulchatna River drainage is a popular drainage for sport fishing in the BBMA with 18,420 angler-days of effort from 1999 to 2003 (Howe et al. 2001; Jennings et al. 2004, 2006a, b; Walker et al. 2003). The average effort for the Koktuli River during the same 5-year period was 519 angler-days (Howe et al. 2001; Jennings et al. 2004, 2006a, b; Walker et al. 2003). Potential mineral resource development at the headwaters of Koktuli River may increase access and angling pressure on the river. Increased use and mineral development also have the potential to negatively affect the river's water quality to the detriment of fish populations. Documenting fish distribution, resident fish size composition and water quality in Koktuli River provides information to assess potential effects of development and increased use.

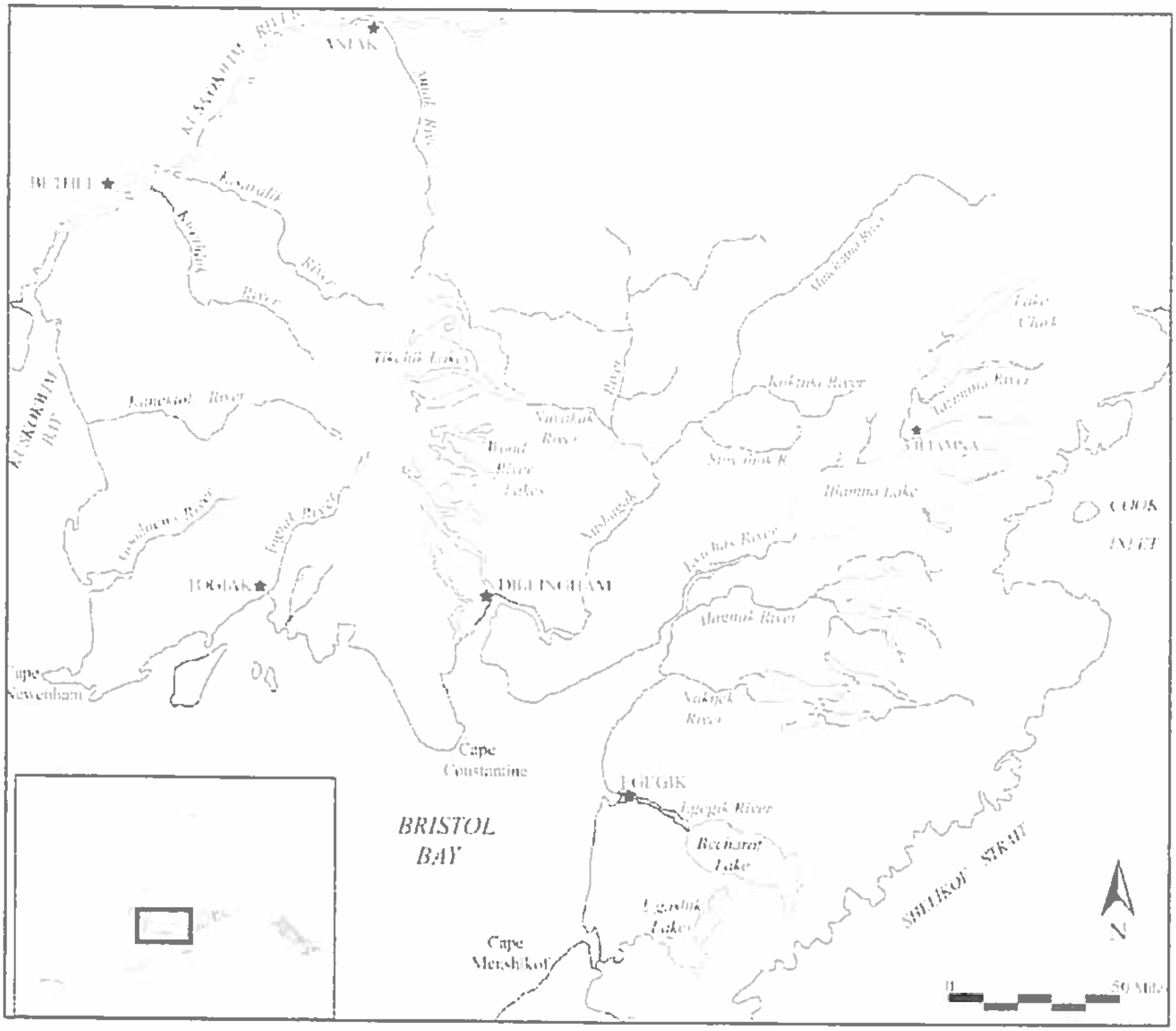

Figure 1.–Bristol Bay area showing the location of Koktuli River in Nushagak River drainage.

OBJECTIVES

The objective of this study was to:

1. Estimate the size distribution of resident fish species susceptible to hook and line sampling in the upper south fork of the Koktuli River to its confluence with Mulchatna River.

Addition project tasks were to:

1. Calculate the mean catch per unit effort (CPUE) (number of rainbow trout, Arctic grayling and Dolly Varden captured per hour) with hook and line gear in Koktuli River between the upper south fork and its confluence with Mulchatna River;

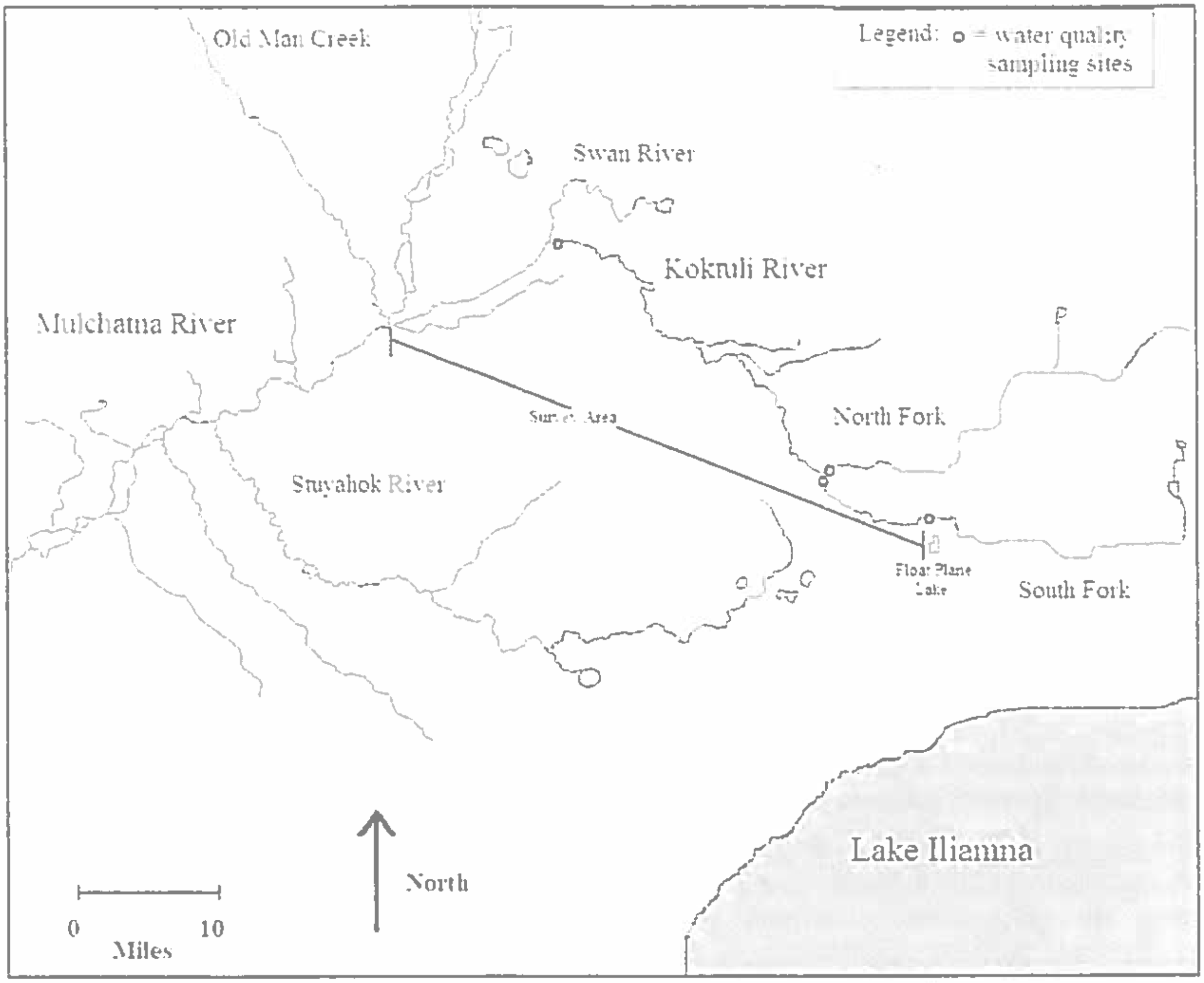

Figure 2.–Koktuli River showing the survey area, water quality sampling sites, and a float plane accessible lake near the upper end of the survey area.

2. Document water quality and aquatic habitat parameters from four locations on Koktuli River;
3. Document distribution of resident fish species in Koktuli River between the upper south fork and its mainstem confluence with Mulchatna River;
4. Document the upper reaches of the river where anadromous salmon are observed spawning; and
5. Document the upper reaches of the river where juvenile anadromous salmon are captured with minnow traps.

METHODS

STUDY DESIGN

Float trips on Koktuli River were conducted in June, July and August of 2005. A trip scheduled for September was not possible due to low water preventing float plane access. The study area was a 52-mile stretch of river from the upper south fork of Koktuli River to its mainstem confluence with Mulchatna River (Figure 2). A combination of visual observation, angling and minnow trapping was used to determine the presence and distribution of fish in the river. Water quality was assessed at four locations on each trip.

Float trips began on the upper south fork of Koktuli River near a tundra lake that was large enough to accommodate a float equipped airplane (Figure 2). Float trips were conducted by four technicians in two 10-foot rafts and took 5 days. Terminal gear used largely consisted of size two and three spinners of various colors and brands. Sampling was conducted in 2-mile stretches using a "leap frog" strategy. One raft floated (without sampling) through a 2 mile section of river as indicated by a global positioning system (GPS) while the other raft sampled the 2 miles that the previous raft floated through. Once the primary raft floated 2 miles, its occupants sampled the next 2-mile section. The start and ending location of each 2-mile river section were recorded with a global positioning system. These points defined the sections of river to be floated and fished during subsequent trips. The technician not oaring angled over the entire course of each section. The other technician angled when productive habitat (i.e. deep pools, deep runs, woody debris) was encountered and the raft was stopped. Time spent angling in each section by each technician was recorded to estimate CPUE of resident species. Each technician's independently recorded catch and effort were combined to estimate CPUE in each section.

Water quality and aquatic habitat parameters sampling sites were recorded with GPS coordinates on the first float trip and subsequent samples were taken at the same location. The locations were: the starting point of the float trip, immediately above the confluence with the north fork, on the north fork immediately above its confluence with the south fork, and on Koktuli River immediately above the confluence with the Swan River (Figure 2). Parameters measured were: water and air temperature, pH, specific conductivity, turbidity, dissolved oxygen level, water color, stream stage, substrate type, channel width, water depth and riparian plant community. In addition, wire mesh minnow traps baited with salmon eggs were set at each location and soaked while water quality data were gathered (approximately 1 hour). After the water quality data were collected the minnow traps were retrieved and the number of each species captured was recorded.

DATA COLLECTION AND REDUCTION

All resident fish species captured with hook and line gear were measured for fork length (FL) to the nearest millimeter and weighed to the nearest 10 grams. The terminal gear used to capture the fish was recorded. Each rainbow trout over 250 mm FL received an individually numbered Floy-T-Anchor^{TM} tag placed on the left side near the posterior base of the dorsal fin. No secondary mark was used. All fish captured in minnow traps were identified and counted. The first encounter of any resident or anadromous species was documented with GPS to indicate the upper range of that species' distribution within the survey area. Each technician recorded the number of hours fished per 2-mile section and the number of fish caught in each section.

At each of the water quality and habitat assessment sites a transect was selected crossing a straight section of the river channel. Channel width and thalweg depth were measured at the ordinary high water level and wetted levels. A YSI[1] 556 MPS multi- parameter meter was used to measure several water quality parameters. Measurements were taken in slow water by inserting the probe directly in the channel near the thalweg, or 12 liters of stream water were collected in a bucket and immediately analyzed. The probe was gently agitated to ensure proper mixing and the water chemistry readings were allowed to stabilize before recording values. Specific conductivity, pH, turbidity, dissolved oxygen and temperature were measured with the meter.

Water color (clear, ferric, humic or muddy), stream stage (dry, low, medium, high), three dominant substrate classes (Wentworth scale, Wentworth 1922), and Rosgen channel type (Rosgen 1996) were visually assessed. The dominant riparian vegetation community along each bank was visually assessed (Viereck et al. 1982). A photograph of an upstream and downstream view was taken along the banks connecting a transect.

A log was maintained to summarize data collected each day. The log summarized the daily catch of all fish species, weather conditions, estimated number of each salmon species observed spawning, water temperature, observations of any subsistence and sport fish activity, and miles of river covered.

DATA ANALYSIS

Biological Composition

Mean length and weight and their associated variances were calculated for each resident fish species caught. The proportion of a particular species s, in weight or length class i (p_{si}), was estimated as:

$$\hat{p}_{si} = \frac{x_{si}}{n_s}, \qquad (1)$$

with x_{si} being the number of fish of species s in weight category i and n_s being the total number of fish species s sampled for length or weight.

The associated variance was estimated as:

$$\hat{V}(\hat{p}_{si}) = \frac{\hat{p}_{si}(1 - \hat{p}_{si})}{n_s - 1}. \qquad (2)$$

In addition, Anderson-Darling tests (Scholz and Stephens 1987) were used to assess differences in the length frequency distributions for each resident species captured among float trips.

Catch per Unit Effort

CPUE was estimated by river section to provide an impression of relative fish density in Koktuli River.

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[1] YSI Incorporated, Yellow Springs, Ohio. Use of this company name does not constitute endorsement, but is included for scientific completeness.

Average CPUE for the study area was estimated as a ratio (Thompson 1992):

$$\overline{CPUE} = \sum_{i=1}^{n} c_i \Big/ \sum_{i=1}^{n} e_i ; \qquad (3)$$

and its variance estimated as:

$$\hat{V}(\overline{CPUE}) = \frac{\sum_{i=1}^{n} \left(c_i - \overline{CPUE} \times e_i\right)^2}{\bar{e}^2 n(n-1)} . \qquad (4)$$

where:

c_i = catch of each fish species in section i;

e_i = effort expended in section i;

n = number of sections in study area;

and

$$\bar{e} = \sum_{i=1}^{n} \frac{e_i}{n} .$$

RESULTS

Float trips were conducted from 13-16 June, 11-15 July and 16-19 August. A total of 183 rainbow trout were captured on the three float trips, of which 181 were measured for length and 177 were weighed. Two hundred and ninety-one Arctic grayling were captured of which 290 were measured for length and 272 were weighed. Seventy Dolly Varden were captured, all of which were measured for length and 65 were weighed.

The length distribution of rainbow trout captured during the float trips ranged from 269 to 557 mm FL (Figure 3) with a mean length of 406 mm (SE = 5.01) and fish in the 350 to 450 mm range dominated the sample (Table 1). No significant difference ($D = 1.32$, $n_{trip1} = 55$, $n_{trip2} = 67$, $n_{trip3} = 59$, $P = 0.10$) was detected in the cumulative length frequency distributions of rainbow trout captured among float trips. The weight distribution ranged from 100 to 2,200 g with a mean of 880 g (SE = 33.96).

The length distribution of Arctic grayling captured ranged from 210 to 405 mm FL (Figure 4) with a mean length of 311 mm (SE = 2.53) and fish in the 250 to 350 mm range dominated the sample (Table 1). There was a significant difference ($D = 6.01$, $n_{trip1} = 114$, $n_{trip2} = 95$, $n_{trip3} = 81$, $P < 0.001$) in the cumulative length frequency distributions of Arctic grayling captured among float trips. The weight distribution of Arctic grayling ranged from 100 to 805 g with a mean weight of 364 g (SE = 9.08).

The length distribution of Dolly Varden ranged from 181 to 571 mm FL (Figure 5) with a mean length of 448 mm (SE = 8.01) and fish in the 400 to 500 mm range dominated the sample (Table 1). No significant difference ($D = 0.553$, $n_{trip2} = 25$, $n_{trip3} = 45$, $P = 0.573$) was detected for the cumulative length frequency distributions of Dolly Varden on the two trips they were captured.

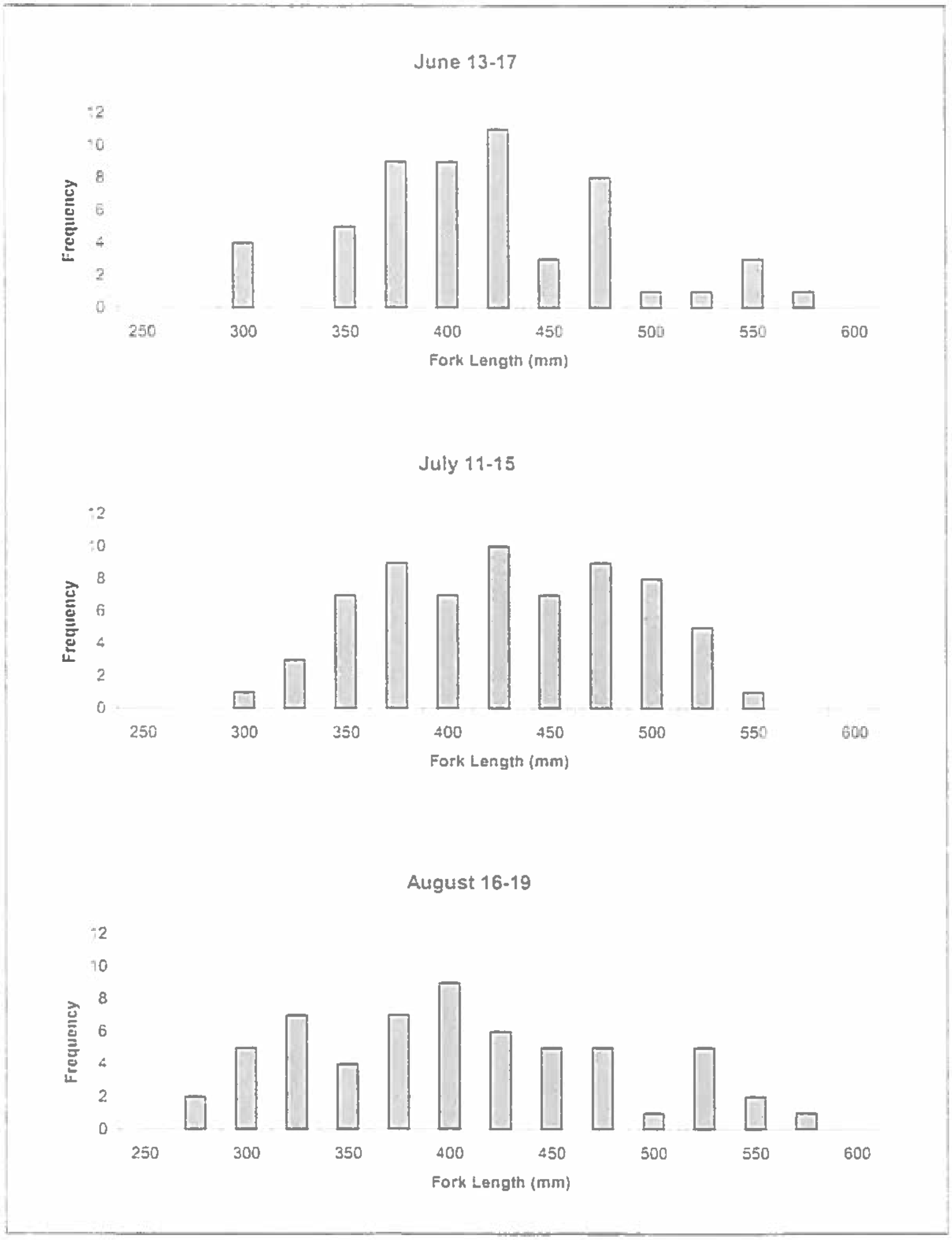

Figure 3.–Length frequency distribution of rainbow trout captured during each of three float trips on Koktuli River, 2005.

Table 1.–Proportions of resident fish species by length with estimated standard error from Koktuli River, 2005.

		Length (FL, millimeters) [a]								
		150-199	200-249	250-299	300-349	350-399	400-449	450-499	500-549	550-599
Rainbow Trout										
	Proportion	0	0	0.07	0.14	0.27	0.24	0.18	0.09	0.01
	Standard Error	0	0	0.019	0.026	0.033	0.032	0.029	0.022	0.008
Arctic Grayling										
	Proportion	0	0.08	0.32	0.38	0.21	0.01	0	0	0
	Standard Error	0	0.016	0.027	0.028	0.024	0.006	0	0	0
Dolly Varden										
	Proportion	0.03	0	0	0.01	0.07	0.37	0.36	0.11	0.04
	Standard Error	0.020	0	0	0.014	0.031	0.058	0.058	0.038	0.024

[a] FL = fork length

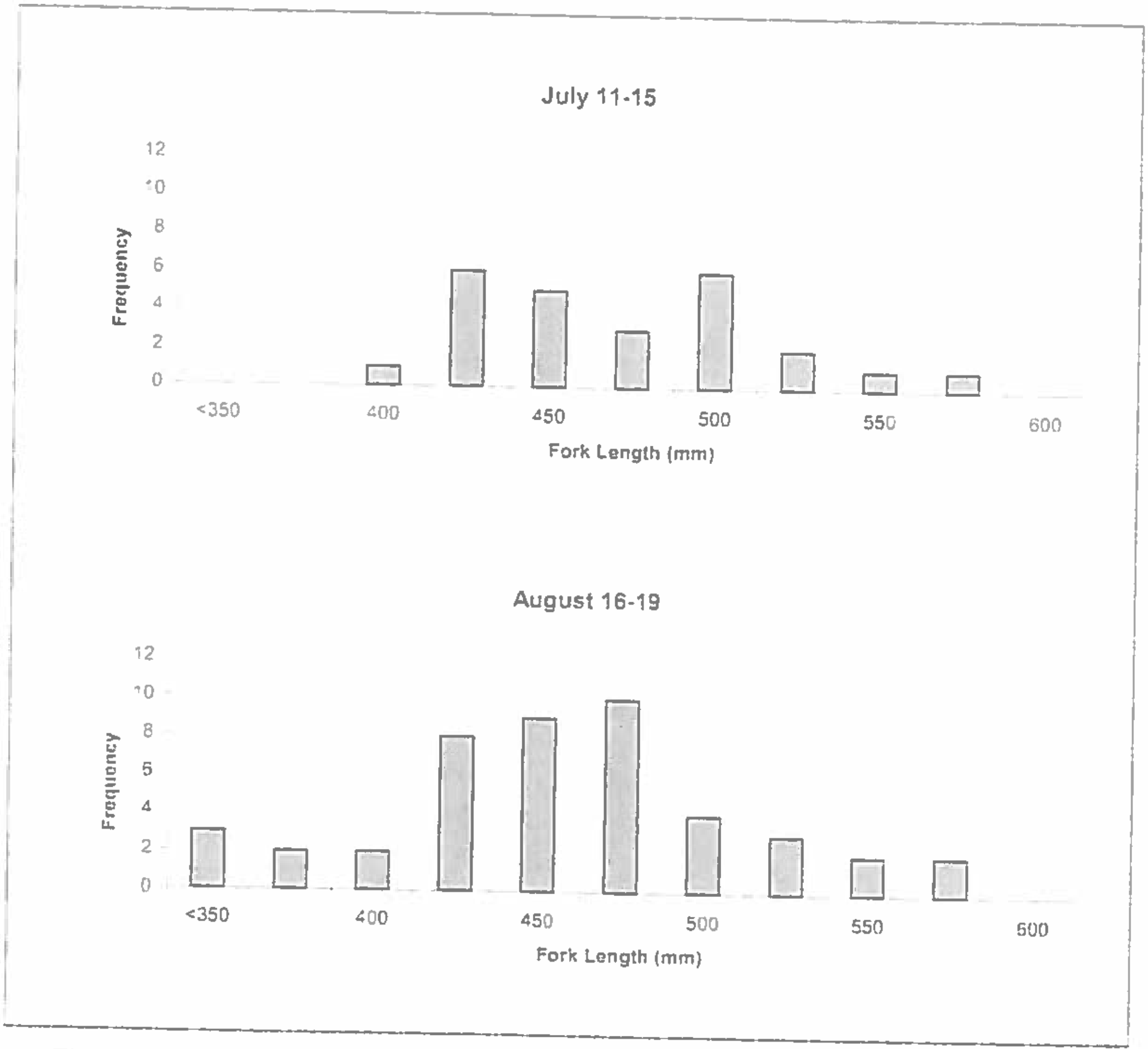

Figure 5.–Length frequency distribution of Dolly Varden captured during float trips on Koktuli River, 2005.

The weight distribution of Dolly Varden ranged from 100 to 2,080 g with a mean weight of 993 g (SE = 43.12).

A total of 193.3 hours was spent rod and reel sampling during the three float trips with a mean time spent angling of 64.4 hours (SE = 1.65) (Table 2). The total catch from the three float trips was 544 resident fish with a mean of 181 (SE = 6.17) fish caught per float trip. The average CPUE of rainbow trout per float trip fluctuated between 0.82 and 1.11 fish/hour with a mean average CPUE of 0.95 fish/hour (SE = 0.12) (Table 2). The average CPUE of Arctic grayling decreased each subsequent trip from 1.70 to 1.26 fish/hour with a mean average CPUE of 1.50 fish/hour (SE = 0.15) (Table 2). The average CPUE of Dolly Varden increased from zero in June to 0.69 fish/hour in August with an average CPUE of 0.55 fish/hour (SE = 0.11) for the two trips they were captured (Table 2).

Table 2.–Summary of hours sampled with hook and line, the number and catch per unit effort (CPUE) of resident fish species during each of three float trips on Koktuli River, 2005.

			Catch [a]				Mean CPUE [b]		
Trip	Dates	Hours sampled	Rainbow Trout	Arctic Grayling	Dolly Varden	Total	Rainbow Trout	Arctic Grayling	Dolly Varden
1	13-17 June	67.0	55	114	0	169	0.82	1.70	0.00
2	11-15 July	61.4	68	95	25	188	1.11	1.40	0.26
3	16-19 August	64.9	60	82	45	187	0.93	1.26	0.69
	Total:	193.3	183	291	70	544			
	Mean (SE):	64.4 (1.65)	61 (3.8)	97 (9.29)	23 (13.02)	181 (6.17)	0.95 (0.12)	1.50 (0.15)	0.55 (0.11)

[a] Number of fish.

[b] CPUE = catch per unit effort (fish/hour).

Water quality information was collected at the four designated sampling sites on each of the float trips. The location of each site was recorded with GPS coordinates and all water quality data were collected with the exception of turbidity during the June float trip (Table 3). All sampling sites were sampled at the medium stream stage and had clear, well oxygenated water. Minnow traps were set at each water quality sampling site during the first float trip and only at site four during the rest of the float trips. Forty-nine juvenile Chinook and coho salmon *O. kisutch* were captured at three of the four water quality and habitat assessment sites (Table 3).

Hours spent angling and the catch and CPUE of resident species in addition to the number of adult salmon observed in each river section for each float trip are summarized in Appendices A1-A3. Rainbow trout were found throughout the river on each of the float trips, but were most concentrated in sections 14 through 22 with 65% of the total catch therein and a mean average CPUE of 1.65 fish/hour (SE = 0.20). Arctic grayling were most concentrated in the upper half of each float trip. Sections 1 through 14 comprised 81% of the total catch and an average CPUE of 2.24 fish/hour (SE = 0.19). In July, the majority of Dolly Varden (76%) was captured in the lower sections 14 through 26. In August, Dolly Varden were captured with a higher frequency (62%) in the upper sections 1 through 13.

Four adult species of Pacific salmon (Chinook salmon, chum salmon *O. keta*, sockeye salmon *O. nerka* and coho salmon) were observed over the course of the three float trips (Appendices A1-A3). In June, only two Chinook salmon were observed in the lower river. In July, approximately 3,354 Chinook salmon were observed throughout the majority of sections. Chum and sockeye salmon were also observed in most sections throughout the river in July. In August the majority of Chinook and chum salmon had completed spawning and carcasses were common throughout the float trip. Sockeye salmon were also present throughout the river in August with the majority of the fish in the upper sections either spawning or dead. The remaining sockeye salmon in the lower sections were in prespawning aggregations. The first coho salmon was captured in section 2 during the August trip. Seven additional coho salmon were subsequently captured in other sections.

Biological data files are archived with ADF&G, Research and Technical Services (Appendix B1).

DISCUSSION

The float trips provided documentation of the size distributions, presence, and distribution of resident fish species in the lower 52 miles of the river. Size distributions of fish captured with hook and line can be used for future comparisons of samples collected in a similar manner. The similarity of rainbow trout length distributions during the 3 months of the project provides evidence that there may be a resident population in the river during the summer. However, this observation must be considered with caution since no life history studies of rainbow trout have been conducted in Mulchatna River drainage and the extent of movement between tributaries is unknown. The length distributions of Arctic grayling were significantly different due to slightly larger fish captured in June. Another research project on Arctic grayling in Koktuli River found Arctic grayling to be common upriver of the survey area during the summer (P. McLarnon, Fishery Biologist, HDR Inc., Anchorage, personal communication). With Arctic grayling present upstream of the float trip survey area, the difference in length distributions may be explained by the larger grayling being located farther upriver later in the summer. Arctic grayling have been found to segregate by size within a drainage during the summer with the

Table 3.–Location, vegetation and substrate dominant classification, dates, water quality data and juvenile salmon minnow trapped during float trips on Koktuli River, 2005.

											Channel					
											Width (m)		Depth (m)			
			Date	Water Temp (°C)	Specific Conductivity (µS/cm)	Dissolved Oxygen (% & mg/L)	pH	Turbidity (NTU)[a]	Water Color	Stream Stage	OHW[b]	Wetted	OHW[b]	Wetted Thalweg[c]	Minnow Trap Catch[d] Chinook	Coho
Site 1																
General Location		Start of float trip	13-Jun	15.4	45	95%, 9.05	6.70	ND	Clear	Medium	19.0	17.8	[illegible]	0.8	4	1
GPS Coordinates		59° 48.251 N latitude 155° 35.690 W longitude	14-Jul	15.0	38	76%, 7.65	7.88	1.19	Clear	Medium	19.0	[illegible]	1.6	[illegible]	ND	ND
Vegetation Classification	Right bank Left bank	IIIA2d (Closed tundra) IIC1b (Closed low willow shrub)	16-Aug	11.1	[illegible]	104%, 11.30	7.26	0.51	Clear	Low, continuous surface flow	19.0	16.2	1.3	0.9	ND	ND
Dominant Substrates		Small cobble, large pebble, coarse gravel														
Rosgen Channel Code, Stream Type:		C3 (slightly entrenched channel, cobble dominated substrate, with a low width to depth ratio and high sinuosity)														
Site 2																
General Location		South fork above confluence with North fork	14-Jun	16.6	41	90%, 8.83	6.86	ND	Clear	Medium	31.1	14.7	1.1	0.6	[illegible]	[illegible]
GPS Coordinates		59° 50.030 N latitude 155° 46.534 W longitude	12-Jul	12.1	31	70%, 7.55	7.58	1.26	Clear	Medium	31.1	31.9	1.1	0.6	ND	ND
Vegetation Classification	Right bank Left bank	IC2 (Open mixed forest) IIC1b (Closed low willow shrub)	17-Aug	10.7	15	91%, 10.34	6.40	0.05	Clear	Low, surface flow discontinuous	31.1	23.6	1.1	0.5	ND	ND
Dominant Substrates		Small cobble, large pebble, coarse gravel														
Rosgen Channel Code, Stream Type:		C4 (slightly entrenched channel, gravel dominated substrate, with a low width to depth ratio and high sinuosity)														
Site 3																
General Location		North fork above confluence with South fork	14-Jun	15.5	42	86%, 8.58	6.70	ND	Clear	Medium	33.8	11.1	1.5	0.9	1	8
GPS Coordinates		59° 50.036 N latitude 155° 46.350 W longitude	15-Jul	12.3	31	71%, 7.43	7.46	2.75	Clear, slightly brown	Medium	33.8	32.7	1.5	0.9	ND	ND
Vegetation Classification	Right bank Left bank	IC2a (Open spruce-paper birch forest) IIC1b (Closed low willow shrub)	17-Aug	11.2	66	94%, 10.37	6.40	1.35	Clear, slightly brown	Low, continuous surface flow	33.8	ND	1.5	0.6	ND	ND
Dominant Substrates		Large pebble, small cobble, coarse gravel														
Rosgen Channel Code, Stream Type:		C4 (slightly entrenched channel, gravel dominated substrate, with a low width to depth ratio and high sinuosity)														
Site 4																
General Location		Above confluence with Swan River	17-Jun	12.9	43	85.4%, 9.03	6.90	ND	Clear	Medium	51.2	29.1	2.1	1.0	4	[illegible]
GPS Coordinates		59° 39.826 N latitude 156° 12.932 W longitude	15-Jul	13.7	37	68.4%, 7.67	7.48	1.37	Clear	Medium	51.2	12.1	2.1	1.2	17	4
Vegetation Classification	Right bank Left bank	IIC1b (Closed low willow shrub) IC2a (Open spruce-paper birch forest)	19-Aug	11.5	48	97%, 10.55	7.30	3.51	Clear	Medium	51.5	[illegible]	2.1	1.1	[illegible]	[illegible]
Dominant Substrates		Coarse sand, small pebble, small cobble														
Rosgen Channel Code, Stream Type:		C5 (slightly entrenched channel, sand dominated substrate, with a low width to depth ratio and high sinuosity)														

[a] Nephelometric turbidity unit.

[b] OHW = ordinary high water level.

[c] Thalweg = the deepest channel in the river bed, almost always the area with the fastest flowing water.

[d] Numbers of juvenile salmon. ND = no data, minnow traps not set.

largest fish migrating to the upper reaches of the drainage (Armstrong 1986; Vincent-Lang and Alexandersdottir 1990).

Although not an index of abundance, the CPUE of resident species does provide a means of documenting fish distribution in the survey area. Rainbow trout were most common in the lower half of the survey area and Arctic grayling were more common in the upper half of the survey area and are common above the survey area. Very little additional insight regarding the life history and movements of rainbow trout and Arctic grayling was obtained during this study. The distribution of rainbow trout throughout the river did not appear to change significantly over the course of the three float trips. Only one rainbow trout was recaptured. It was tagged during June in section 15 and recaptured approximately 10 miles upriver in July. Dolly Varden appeared in the lower half of the river between June and July and exhibited an upstream movement between July and August. This is likely an anadromous population, similar to those observed in the Togiak River drainage west of the Nushagak River, that enter the system to feed on salmon spawn during late summer and to spawn in the fall (M. Lisac, Fishery Biologist, USFWS, Dillingham, personal communication). Although spawning locations are unknown, some of the Dolly Varden sampled in August were developing sexual characteristics such as spawning colors.

Water quality data were collected over the course of the project to document a number of parameters. Turbidity was not collected during the June float trip due to a malfunction with sampling equipment. The location of each of the four sites that data were documented allow for the direct comparison of future samples from the same sites at the medium stream stage. Koktuli River water quality appears to be relatively pristine and supports a healthy diversity of salmonid species.

Adult salmon were present throughout the survey area seasonally and appeared abundant. Spawning was observed by Chinook, chum and sockeye salmon beginning in the upper section of the float, and aerial surveys indicate that spawning occurs above this location as well. Juvenile Chinook and coho salmon were captured at three of the four water quality sampling sites and salmon fry were commonly observed throughout the survey area.

In light of potential mineral resource development, additional studies are occurring in Koktuli River drainage by other research entities to document environmental parameters and assess fish populations. This study in conjunction with these other studies provides a means of documenting current conditions to assist in monitoring the impacts of potential development in the drainage. A basic understanding of fish distribution throughout the survey area was garnered from this research. However, very little information is available regarding the life history of rainbow trout or other resident species in the Nushagak and Mulchatna River drainages. Future research should examine the life history of the drainages' resident species for the documentation of spawning and other seasonal critical habitat areas.

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REFERENCES CITED

Armstrong, R. H. 1986. A review of Arctic grayling studies in Alaska, 1952 - 1982. Biological Papers of the University of Alaska No. 23.

Dye, J., and C. Schwanke. *In prep.* Area management report for the recreational fisheries of the Bristol Bay Sport Fish Management Area of Alaska, 2000 and 2001. Alaska Department of Fish and Game, Fishery Management Report, Anchorage.

Howe, A. L., R. J. Walker, C. Olnes, K. Sundet, and A. E. Bingham. 2001. Participation, catch, and harvest in Alaska sport fisheries during 1999. Alaska Department of Fish and Game, Fishery Data Series No. 01-8, Anchorage. http://www.sf.adfg.state.ak.us/FedAidPDFs/fds01-08.pdf

Jennings, G. B., K. Sundet, A. E. Bingham, and D. Sigurdsson. 2004. Participation, catch, and harvest in Alaska sport fisheries during 2001. Alaska Department of Fish and Game, Fishery Data Series No. 04-11, Anchorage. http://www.sf.adfg.state.ak.us/FedAidPDFs/fds04-11.pdf

Jennings, G. B., K. Sundet, A. E. Bingham, and D. Sigurdsson. 2006a. Participation, catch, and harvest in Alaska sport fisheries during 2002. Alaska Department of Fish and Game, Fishery Data Series No. 06-34, Anchorage. http://www.sf.adfg.state.ak.us/FedAidpdfs/fds06-34.pdf

Jennings, G. B., K. Sundet, A. E. Bingham, and D. Sigurdsson. 2006b. Participation, catch, and harvest in Alaska sport fisheries during 2003. Alaska Department of Fish and Game, Fishery Data Series No. 06-44, Anchorage. http://www.sf.adfg.state.ak.us/FedAidpdfs/fds06-44.pdf

Rosgen, D. L. 1996. Applied river morphology. Wildland Hydrology Books, Pagosa Springs, CO.

Scholz, F. W., and M. A. Stephens. 1987. K-sample Anderson-Darling tests. Journal of the American Statistical Association 82:918-924.

Thompson, S. K. 1992. Sampling. John Wiley and Sons, New York.

Viereck, L. A., C. T. Dyrness, and A. R. Batten. 1982. 1982 Revision of preliminary classification for vegetation of Alaska. USDA Forest Service, Institute of Northern Forestry, Pacific Northwest Forest and Range Experiment, Fairbanks.

Vincent-Lang, D., and M. Alexandersdottir. 1990. Assessment of the migrational habits, growth, and abundance of the Arctic grayling stocks of the Gulkana River during 1989. Alaska Department of Fish and Game, Fishery Data Series No. 90-10, Anchorage. http://www.sf.adfg.state.ak.us/FedAidPDFs/fds90-10.pdf

Walker, R. J., C. Olnes, K. Sundet, A. L. Howe, and A. E. Bingham. 2003. Participation, catch, and harvest in Alaska sport fisheries during 2000. Alaska Department of Fish and Game, Fishery Data Series No. 03-05, Anchorage. http://www.sf.adfg.state.ak.us/FedAidPDFs/fds03-05.pdf

Wentworth, C. K. 1922. A scale of grade and class terms for clastic sediments. Journal of Geology 30:377-392.

APPENDIX A. HOURS FISHED, CATCH, EFFORT, AND OBSERVATIONS

Appendix A1.–The number of hours angled by 2-mile river sections with the number and catch per unit effort of each resident fish species captured and the number of adult salmon observed on the June 13-17 float trip, 2005.

			Catch [a]			CPUE [b]			Adult Salmon Observed/Present			
2-Mile Section	Date	Hours Angled	Rainbow Trout	Arctic Grayling	Dolly Varden	Rainbow Trout	Arctic Grayling	Dolly Varden	Chinook	Chum	Sockeye	Coho
1	13-Jun	4.37	0	16	0	0	3.66	0	0	0	0	0
2	13-Jun	5.72	0	3	0	0	0.52	0	0	0	0	0
3	14-Jun	5.78	0	16	0	0	2.77	0	0	0	0	0
4	14-Jun	5.50	1	13	0	0.18	2.36	0	0	0	0	0
5	14-Jun	3.98	1	8	0	0.25	2.01	0	0	0	0	0
6	14-Jun	1.97	1	6	0	0.51	3.05	0	0	0	0	0
7	15-Jun	1.42	0	2	0	0	1.41	0	0	0	0	0
8	15-Jun	1.67	1	3	0	0.60	1.80	0	0	0	0	0
9	15-Jun	1.55	1	2	0	0.65	1.29	0	0	0	0	0
10	15-Jun	1.88	0	2	0	0	1.06	0	0	0	0	0
11	15-Jun	1.53	1	4	0	0.65	2.61	0	0	0	0	0
12	15-Jun	1.83	1	1	0	0.55	0.55	0	0	0	0	0
13	15-Jun	1.52	2	0	0	1.32	0	0	0	0	0	0
14	15-Jun	1.45	2	4	0	1.38	2.76	0	0	0	0	0
15	16-Jun	2.77	4	11	0	1.45	3.98	0	0	0	0	0
16	16-Jun	2.08	2	4	0	0.96	1.92	0	0	0	0	0
17	16-Jun	2.02	3	0	0	1.49	0	0	0	0	0	0
18	16-Jun	3.02	2	3	0	0.66	0.99	0	0	0	0	0
19	16-Jun	4.32	8	4	0	1.85	0.93	0	0	0	0	0
20	16-Jun	1.13	4	2	0	3.53	1.76	0	0	0	0	0
21	17-Jun	5.45	12	6	0	2.20	1.10	0	0	0	0	0
22	17-Jun	0.83	0	2	0	0	2.40	0	0	0	0	0
23	17-Jun	1.58	4	0	0	2.53	0	0	2	0	0	0
24	17-Jun	1.67	2	2	0	1.20	1.20	0	0	0	0	0
25	17-Jun	1.28	3	0	0	2.34	0	0	0	0	0	0
26	17-Jun	0.70	0	0	0	0	0	0	0	0	0	0
	Total	67.02	55	114	0				2	0	0	0

[a] Number of fish.

[b] CPUE = catch per unit effort (fish/hour).

Appendix A2.–The number of hours angled by 2-mile river sections with the number and catch per unit effort of each resident fish species captured and the number of adult salmon observed on the July 11-15 float trip, 2005.

2-Mile Section	Date	Hours Angled	Catch [a] Rainbow Trout	Catch [a] Arctic Grayling	Catch [a] Dolly Varden	CPUE [b] Rainbow Trout	CPUE [b] Arctic Grayling	CPUE [b] Dolly Varden	Adult Salmon Observed/Present [c] Chinook	Chum	Sockeye	Coho
1	11-Jul	2.28	1	5	0	0.44	2.19	0	180	5	ND	0
2	12-Jul	1.78	0	8	0	0	4.49	0	80	21	35	0
3	12-Jul	2.17	1	2	0	0.46	0.92	0	67	20	100	0
4	12-Jul	2.40	1	5	0	0.42	2.08	0	105	20	20	0
5	12-Jul	1.80	2	8	0	1.11	4.44	0	ND	ND	ND	0
6	13-Jul	2.62	3	5	3	1.15	1.91	1.15	300	35	110	0
7	13-Jul	2.13	1	8	1	0.47	3.75	0.47	381	80	ND	0
8	13-Jul	1.87	0	7	0	0	3.75	0	225	25	50	0
9	13-Jul	2.15	0	6	0	0	2.79	0	ND	ND	ND	0
10	13-Jul	1.88	1	9	0	0.53	4.78	0	255	80	50	0
11	13-Jul	2.12	0	5	0	0	2.36	0	371	ND	ND	0
12	13-Jul	2.18	1	0	1	0.46	0	0.46	141	60	40	0
13	13-Jul	2.00	1	6	1	0.50	3.00	0.50	79	ND	ND	0
14	14-Jul	2.10	3	7	0	1.43	3.33	0	23	60	5	0
15	14-Jul	2.92	10	2	6	3.43	0.69	2.06	200	160	ND	0
16	14-Jul	2.98	3	2	0	1.01	0.67	0	201	265	97	0
17	14-Jul	2.08	2	2	2	0.96	0.96	0.96	ND	ND	ND	0
18	14-Jul	3.00	6	2	4	2.00	0.67	1.33	201	100	147	0
19	14-Jul	2.40	4	0	1	1.67	0	0.42	105	ND	ND	0
20	15-Jul	3.08	6	0	3	1.95	0	0.97	10	50	3	0
21	15-Jul	3.67	8	1	2	2.18	0.27	0.55	167	ND	ND	0
22	15-Jul	2.58	3	2	0	1.16	0.77	0	90	135	200	0
23	15-Jul	1.98	0	1	0	0	0.50	0	123	ND	ND	0
24	15-Jul	2.18	2	0	0	0.92	0	0	50	30	20	0
25	15-Jul	2.42	7	2	1	2.90	0.83	0.41	ND	ND	ND	0
26	15-Jul	2.60	2	0	0	0.77	0	0	ND	ND	ND	0
	Total	61.38	68	95	25				3354	1146	877	0

[a] Number of fish.

[b] CPUE = catch per unit effort (fish/hour).

[c] ND = no data, not counted by field staff.

Appendix A3.–The number of hours angled by 2-mile river sections with the number and catch per unit effort of each resident fish species captured and the number of adult salmon observed on the August 16-19 float trip, 2005.

			Catch[a]			CPUE[b]			Adult Salmon Observed/Present[c]			
2-Mile Section	Date	Hours Angled	Rainbow Trout	Arctic Grayling	Dolly Varden	Rainbow Trout	Arctic Grayling	Dolly Varden	Chinook	Chum	Sockeye	Coho
1	16-Aug	3.1	1	9	0	0.32	2.90	0	12	ND	ND	0
2	16-Aug	2.8	1	9	2	0.36	3.20	0.71	ND	ND	Yes	1
3	16-Aug	2.4	1	4	2	0.41	1.66	0.83	ND	ND	ND	0
4	16-Aug	2.7	0	4	0	0	1.51	0	ND	ND	Yes	0
5	16-Aug	1.9	0	3	0	0	1.57	0	ND	ND	Yes	0
6	17-Aug	3.3	3	4	11	0.91	1.22	3.35	ND	ND	ND	2
7	17-Aug	3.5	4	5	5	1.16	1.45	1.45	Yes	ND	ND	0
8	17-Aug	2.1	0	7	1	0	3.39	0.48	ND	ND	ND	0
9	17-Aug	1.9	1	5	0	0.52	2.61	0	ND	ND	ND	0
10	17-Aug	1.8	0	5	1	0	2.75	0.55	ND	ND	ND	0
11	17-Aug	1.9	2	4	0	1.06	2.12	0	5	ND	100	1
12	17-Aug	2.2	1	5	1	0.45	2.27	0.45	ND	ND	ND	0
13	18-Aug	2.5	2	8	5	0.80	3.20	2	ND	ND	Yes	0
14	18-Aug	3.3	3	2	5	0.90	0.60	1.5	ND	ND	ND	0
15	18-Aug	3.7	4	0	0	1.10	0	0	ND	ND	500	0
16	18-Aug	2.5	3	4	3	1.22	1.63	1.22	ND	ND	ND	1
17	18-Aug	2.3	4	1	2	1.74	0.43	0.87	ND	ND	ND	30
18	18-Aug	3.1	1	2	2	0.33	0.65	0.65	ND	ND	ND	0
19	18-Aug	1.7	4	0	1	2.35	0	0.59	ND	ND	ND	0
20	19-Aug	2.4	0	1	0	0	0.43	0	ND	ND	ND	0
21	19-Aug	2.2	4	0	0	1.79	0	0	ND	ND	200	1
22	19-Aug	3.1	14	0	1	4.47	0	0.32	ND	ND	ND	0
23	19-Aug	2.2	0	0	0	0	0	0	ND	ND	ND	0
24	19-Aug	2.3	5	0	3	2.22	0	1.33	ND	ND	ND	0
25	19-Aug	2.8	2	0	0	0.71	0	0	ND	ND	ND	0
26	19-Aug	1.4	0	0	0	0	0	0	ND	ND	ND	0
	Total	64.9	60	82	45				17	ND	800	36

[a] Number of fish.

[b] CPUE = catch per unit effort (fish/hour).

[c] ND = no data, not counted by field staff.

APPENDIX B. LIST OF ARCHIVED BIOLOGICAL DATA FILES

Appendix B1.–List of archived biological data files for resident fish species captured by hook and line sampling at Koktuli River, 2005.

File Name [a]	Description (location, species, captured technique, data collected, dates sampled)
t-000500b012005	Koktuli R: rainbow trout: hook & line; sex, length, weight & tag data, 13-17 Jun
t-000500b032005	Koktuli R: rainbow trout: hook & line: sex, length, weight & tag data, 11-15 Jul
t-000500b062005	Koktuli R: rainbow trout: hook & line: sex, length, weight & tag data, 16-19 Aug
t-000500b022005	Koktuli R: Arctic grayling: hook & line: sex, length, weight & tag data, 13-17 Jun
t-000500b042005	Koktuli R: Arctic grayling: hook & line: sex, length, weight & tag data, 11-15 Jul
t-000500b072005	Koktuli R: Arctic grayling: hook & line: sex, length, weight & tag data, 16-19 Aug
t-000500b052005	Koktuli R: Dolly Varden: hook & line: sex, length, weight & tag data, 13-17 Jun
t-000500b082005	Koktuli R: Dolly Varden: hook & line: sex, length, weight & tag data, 11-15 Jul

Note: Archived at the Alaska Department of Fish and Game (ADF&G), Division of Sport Fish, Research and Technical Services at 333 Raspberry Road, Anchorage, AK 99518-1565.

[a] Text files of data scanned from mark-sense forms (ADF&G, Standard Age Weight Length, Form Version 1.2).

Appendix IV

Periodicity Chart for Koktuli Rivers and upper Mulchatna River (Wiedmer, 2006).

Chinook Salmon	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Smolt Passage ?				??	????	????	????	----	----			
Adult Passage						??XX	XXXX	XX??				
Spawning ?							??XX	XXXX	??			
Incubation ?	XXXX	XXXX	????	????	????		???X	XXXX	XXXX	XXXX	XXXX	XXXX
Rearing ?	XXXX	XXXX	XXXX	XXXX	XXXX	XXXX	XXXX	XXXX	XXXX	XXXX	XXXX	XXXX

Sockeye Salmon	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Smolt Passage				??	XXXX	XXXX	XX??	----	----			
Adult Passage					??	??XX	XXXX	XXXX	????			
Spawning							?XXXX	XXXX	XXXX	?		
Incubation	XXXX	XXXX	XXXX	XXXX	XXXX		?XXX	XXXX	XXXX	XXXX	XXXX	XXXX
Rearing	XXXX	XXXX	XXXX	XXXX	XXXX	XXXX	XXXX	XXXX	XXXX	XXXX	XXXX	XXXX

Chum Salmon	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Smolt Passage			????	????	????	????	????	????	????			
Adult Passage						??XX	XXXX	XXXX	????	????	????	
Spawning							??XX	XXXX	????			
Incubation	????	????	????	????			????	????	????	????	????	????
Rearing			????	????	????	????						

Coho Salmon	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Smolt Passage			????	XXXX	XXXX	XXXX	XXXX	XXXX	????			
Adult Passage						??	???X	XXXX	XXXX	XXXX	????	????
Spawning									XXXX	XXXX	????	????
Incubation	XXXX	XXXX	XXXX	XXXX	XXXX	????	?		XXXX	XXXX	XXXX	XXXX
Rearing	XXXX	XXXX	XXXX	XXXX	XXXX	XXXX	XXXX	XXXX	XXXX	XXXX	XXXX	XXXX

Rainbow Trout	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Adult Passage	XXXX	XXXX	XXXX	XXXX	XXXX	XXXX	XXXX	XXXX	XXXX	XXXX	XXXX	????

Spawning				??XX	XXXX	XXXX						
Incubation				??XX	XXXX	XXXX	XXXX	?				
Rearing	XXXX	XXXX	XXXX	XXXX	XXXX	XXXX	XXXX	XXXX	XXXX	XXXX	XXXX	XXXX

Based upon professional judgment of ADF&G biologists

Smolt passage is for juvenile emigration to estuarine/marine environment

Adult passage: for salmon is immigration; for trout, char, and other species, immigration and emigration.

Incubation life phase includes time of egg deposition to fry emergence

? = Data not available or timing is incomplete

Arctic Grayling	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Adult Passage	XXXX	XXXX	XXXX	XXXX	XXXX	XXXX	XXXX	XXXX	XXXX	XXXX	????	????
Spawning				XXXX	XXXX	XXXX						
Incubation				XXXX	XXXX	XXXX	????					
Rearing	XXXX	XXXX	XXXX	XXXX	XXXX	XXXX	XXXX	XXXX	XXXX	XXXX	XXXX	XXXX

Arctic Char	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Smolt Passage?	????	????	????	????	????	????	????					
Adult Passage	????	????	????	????	????	????	????	????	????	????	????	????
Spawning ?										????	????	
Incubation ?	????	????	????	????						????	????	????
Rearing ?	????	????	????	????	????	????	????	????	????	????	????	????

Dolly Varden	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Smolt Passage?	????	????	????	????	????	????	????					
Adult Passage	XXXX	XXXX	XXXX	XXXX	XXXX	XXXX	XXXX	XXXX	XXXX	XXXX	XXXX	XXXX
Spawning ?										????	????	
Incubation ?	????	????	????	????						????	????	????
Rearing ?	XXXX	XXXX	XXXX	XXXX	XXXX	XXXX	XXXX	XXXX	XXXX	XXXX	XXXX	XXXX

Round Whitefish	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Adult Passage	XXXX	XXXX	XXXX	XXXX	XXXX	XXXX	XXXX	XXXX	XXXX	XXXX	XXXX	XXXX
Spawning ?									????	????	????	
Incubation ?	????	????	????	????						????	????	????
Rearing	????	????	????	????	????	????	????	????	????	????	????	????

Longnose Sucker	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Adult Passage	????	????	????	????	????	????	XXXX	XXXX	XXXX	????	????	????
Spawning				????	??XX	????	????					
Incubation				????	????	????	????					

Rearing	????	????	????	????	????	????	????	????	????	????	????	????

Arctic Lamprey	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Adult Passage?	????	????	????	????	????	????	????	????	????	????	????	????
Spawning ?				????	????	????						
Incubation ?				????	????	????	????					
Rearing ?	XXXX	XXXX	XXXX	XXXX	XXXX	XXXX	XXXX	XXXX	XXXX	XXXX	XXXX	XXXX

Based upon professional judgment of ADF&G biologists

Smolt passage is for juvenile emigration to estuarine/marine environment

Adult passage: for salmon is immigration: for trout, char, and other species, immigration and emigration.

Incubation life phase includes time of egg deposition to fry emergence

? = Data not available or timing is incomplete

Pygmy Whitefish	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Adult Passage	????	????								????	????	????
Spawning ?	????										????	????
Incubation ?	????	????	????	????	????							
Rearing		????	????	????	????	????	????	????	????	????	????	????

Slimy Sculpin	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Adult Passage	XXXX	XXXX	XXXX	XXXX	XXXX	XXXX	XXXX	XXXX	XXXX	XXXX	XXXX	XXXX
Spawning				XXXX	XXXX	XXXX						
Incubation				XXXX	XXXX	XXXX	XXXX					
Rearing	XXXX	XXXX	XXXX	XXXX	XXXX	XXXX	XXXX	XXXX	XXXX	XXXX	XXXX	XXXX

Based upon professional judgment of ADF&G biologists

Smolt passage is for juvenile emigration to estuarine/marine environment

Adult passage: for salmon is immigration: for trout, char, and other species, immigration and emigration.

Incubation life phase includes time of egg deposition to fry emergence

? = Data not available or timing is incomplete

Appendix V

Daniel Schindler/Jack Stanford Testimony Letter with References

February 8, 2009

RE: Koktuli River nomination as an Outstanding National Resource Water

To: Trout Unlimited, Alaska

We are responding to your request for us to comment on the scientific rationale to petition the Koktuli River for establishment as an Outstanding National Resource Water. The Koktuli is a major tributary of the Mulchatna River that, in turn, is one of the major tributaries of the Nushagak River of Bristol Bay. This river network provides habitat for one of the most diverse fish communities in Alaska, dominated by five species of culturally and economically valuable Pacific salmon. The Chinook ("king") salmon stock in the Nushagak is one of the largest in the world and supports a huge sport and commercial fishery. Nushagak sockeye salmon populations contribute to the world's largest sockeye fishery in Bristol Bay. Included in the Nushagak sockeye population complex is a relatively rare strain that does not rely on lakes as nursery habitats but rather migrates directly to the marine environment (i.e., river-type sockeye). Pink salmon, chum salmon, coho salmon, rainbow trout, arctic char, and arctic grayling are also extremely abundant throughout the river network. It is arguable that the Nushagak River system harbors one of the most biodiverse and productive fish communities in Alaska.

The Koktuli River is a significant component of the vast Nushagak River watershed based on its contributions to the hydrologic and geomorphic diversity of this system, characteristics important for ecosystem functioning. Diverse geomorphic and hydrologic attributes within river systems make them more resilient to changes in regional climatic conditions. The complexity of river systems is maintained by the continuous erosional processes that generate the mosaic of habitat types that characterize free-flowing rivers[i]. Through time, this mosaic of habitat types shifts throughout the river basin as changes in climatic conditions alter the hydrology and, therefore, the erosional processes that maintain river habitat[ii]. Thus, human development of watersheds can alter the productivity and diversity of rivers because the opportunities for the habitat mosaic to shift through space and time becomes increasingly constrained as more habitat is used for human purposes.

Healthy fish stocks are critically dependent on the shifting habitat mosaic of natural river systems. Diverse habitat buffers fish populations from extreme climatic conditions because this habitat diversity provides refuges to fish from the variety of climatic stresses associated with warm summer temperature, fall flooding, winter freezing, etc., that are common to northern rivers. The invaluable sockeye salmon fisheries of Bristol Bay have been sustainable for over a century largely because the habitat for sockeye salmon across western Alaska has been maintained in near-pristine condition, and sockeye production has been allowed to vary across space and time as the habitat mosaic used by sockeye salmon has adapted in response to climate change[iii]. Indeed, as we look to the future and think about the possible consequences of ongoing climate change for salmon stocks, the best action we can take now is to aggressively protect the diverse network of salmon habitats in Bristol Bay[iv]. The Koktuli River represents a key component of this habitat network and maintaining its current water quality and quantity, without risking degradation, is critical to the integrity of the system. Establishing it as an Outstanding National Resource Water is an important first step towards protecting the invaluable natural heritage of this region of Alaska.

Sincerely,

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[i] Stanford, J. A., M.S. Lorang, and F.R. Hauer. 2005. The shifting habitat mosaic of river ecosystems. International Association of Theoretical and Applied Limnology. 29: 123–136.

[ii] Whited, D.C., M.S. Lorang, M.J. Harner, F.R. Hauer, J.S. Kimball, and J.A. Stanford. 2007. Climate, hydrologic disturbance, and succession: Drivers of floodplain pattern. Ecology 88: 940–953.

[iii] Hilborn, R., T.P. Quinn, D.E. Schindler, and D.E. Rogers. 2003. Biocomplexity and fisheries sustainability. Proceedings of the National Academy of Sciences, USA. 100: 6564–6568.

[iv] Schindler, D.E., X. Augerot, E. Fleishman, N.J. Mantua, B. Riddell, M. Ruckelshaus, J. Seeb, and M. Webster. 2008. Climate change, ecosystem impacts, and management for Pacific salmon. Fisheries 33: 502–506.

Verh. Internat. Verein. Limnol. 29 123–136 Stuttgart, March 2005

Plenary lecture

The shifting habitat mosaic of river ecosystems

J. A. Stanford, M. S. Lorang, and F. R. Hauer

Introduction

The essence of ecology is to understand the distribution and abundance of biota (Andrewartha & Birch 1954). In the same vein, a cornerstone of ecology is quantifying how and why organisms are dependent on specific biophysical space (habitat) to complete one stage or another in their life cycles (Southwood 1977). On the one hand, phenotypic plasticity promotes successful growth and reproduction in variable habitats, but on the other hand habitat fidelity over several to many generations may constrain (adapt) the species or life stage to a habitat with quite specific spatial or functional attributes. Conservation biologists sometimes refer to these locally adapted populations with habitat-specific life cycles as ecologically significant units. Such populations have been accorded special protection and management if they are rare or declining in numbers. However, habitat intrinsically is not static, owing to constantly changing successional (or gradient) states as landscape is mediated by interactive physical (e.g. flood, drought, fire) and biological (e.g. disease, predation, invasion) drivers. Thus, physical and biological attributes vary in time and space and interact to determine quantity and quality of specific habitat per life stage. Sufficient quality habitat is required to permit a positive life history energy balance to sustain a population over the long term, otherwise extinction occurs (Hall et al. 1992). Particular species, and even particular populations of species, either adapt to the dynamic nature of habitat or they fail to persist in that landscape. Of course, a given landscape is composed of n-dimensional gradients and species responses, and feedbacks are complex and nonlinear, making habitat per life stage of each species in the landscape very difficult to define. Nonetheless, quantifying habitat for species in very specific spatial and temporal terms is fundamental to conservation of biodiversity world wide.

A useful way to examine the problem of defining habitat per life stage is to think of landscapes as being composed of habitat mosaics (Likens & Bormann 1974). Indeed, landscape ecology in theory and practice attempts to define species (or population) distributions, abundances and productivity in context of patches or mosaics of biophysical space used by those species (or populations). The dynamics of habitat mosaics and species responses to them, including complex biophysical feedbacks, perhaps is the essence of landscape ecology.

Herein we examine river ecosystems in this dynamic habitat context. We present a general typology of floodplain structures or elements as a basis for habitat delineation. We argue that while the elements that define riverine habitats tend to persist in natural river systems (and are constrained or eliminated by human alteration), the distribution of the habitat patches (mosaics) changes spatially over time due to primary drivers, particularly flooding, channel avulsion, cut and fill alluviation (erosion and deposition of fine and coarse sediments), deposition of wood recruitment and regeneration of riparian vegetation.

We call this phenomenon the ***shifting habitat mosaic*** and argue it is a fundamental process attribute of river ecosystems. We propose that the rather wide array of contemporary theories about river ecosystem structure and function are substantially unified by thinking of river ecosystems as a continuum of 3-dimensional shifting habitat mosaics from headwaters to the ocean.

Key words: river ecology, shifting habitat mosaics, biodiversity, landscape ecology, river networks

Ecological connectivity along the river corridor: the floodplain catena

The theory of river ecosystems has developed from a longitudinal, stream-in-the-valley view, to a dynamic three-dimensional construct that interconnects the aquatic and terrestrial landscapes as expanding and contracting mosaics of habitat patches from headwaters to the ocean (Fig. 1). Whether viewed as a continuum of habitats (Vannote et al. 1980) or in various alternative models as dynamic channel networks

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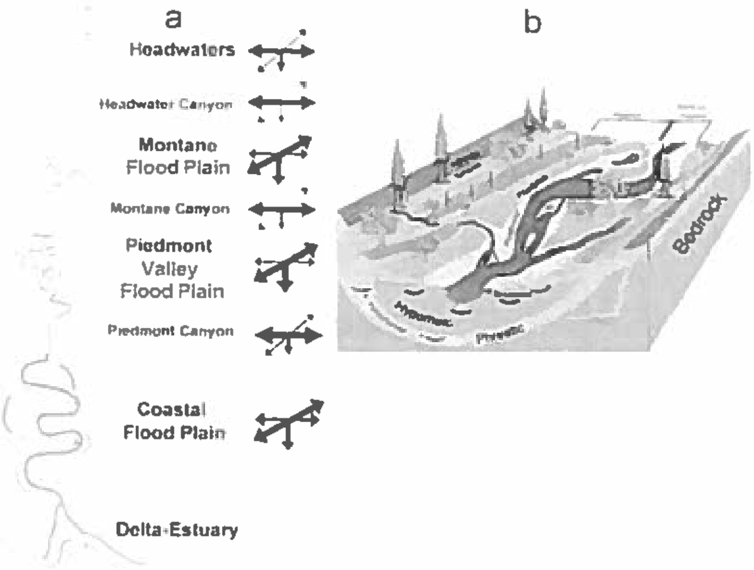
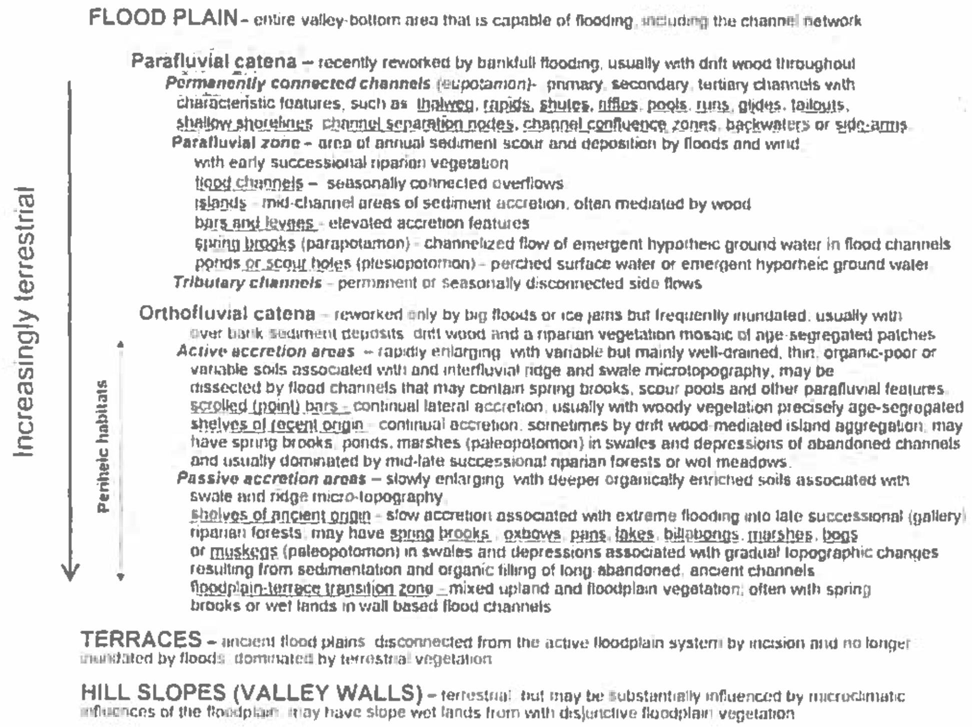


Fig. 1. Idealized view of (a) the longitudinal distribution of flood plains and canyons ("beads on a string") within a river ecosystem from headwaters to the ocean and (b) the 3-D structure of alluvial the flood plains (beads), emphasizing dynamic longitudinal, lateral and vertical dimensions and recruitment of wood debris. The groups of arrows in (a) indicate the expected strength of ground- and surfacewater exchange (vertical), channel and flood plain (lateral) interactions and upstream to downstream or longitudinal (horizontal) connectivity in the context of (b). The floodplain landscape contains a suite of structures (Fig. 2) produced by the legacy of cut and fill alluviation as influenced by position within the natural-cultural setting of the catchment. The hyporheic zone is defined by penetration of river water into the alluvium and may mix with phreatic ground water from hillslope or other aquifers not directly recharged by the river. Alluvial aquifers usually have complex bed sediments with interstitial zones of preferential groundwater flow (paleochannels – see text). Modified from STANFORD (1998), WARD et al (2002).

(BENDA et al. 2004) or discrete patchworks (POOLE 2002), river ecosystems are undeniably corridors composed of highland to lowland landscapes in which the strength of connectivity between the main channel and the terrestrial environment varies in relation to hydrogeomorphic controls on downstream flux of water and materials (dissolved and particulate matter).

Organisms are distributed along this corridor in complex and often seasonally dynamic patterns related to life history energetics, moving from one habitat patch to another as may be advantageous for successful reproduction. For example, salmon migrate into river systems to spawn, often with great fidelity to specific locations, such as groundwater effluent areas. However, juvenile salmon may rear far from the natal sites, such as in shallow water nurseries provided by shoreline, backwater or spring channel areas of flood plains. Entrainment of neonates of fish and other species in low velocity patches, where they can grow into strong swimmers or crawlers able to deal with the vagaries of water flow in the main channels, is a fundamental, but too often overlooked, aspect of river and stream ecology. Moreover, geomorphic barriers may constrain movement or isolate species, producing variation in trophic (food web) relations adding further complexity to biotic patterns and interactions (HERSHEY et al. 1999). Issues of scale can complicate matters even more. Species or even aggregations of species may live continuously in habitats the size of a rock or log in a stream, whereas, the salmon life history ecosystem includes entire river systems for spawning and rearing, estuaries for adapting to salt water and a large portion of the ocean for maturation. Thus, habitat must be viewed hierarchically (FRISSELL et al. 1986) and in a life history context.

Our ecosystem view in Fig. 1 is dependent on interactions among dynamic, nonlinear physical and biological processes linking water, heat and materials (biota, sediment, plant-growth nutrients) flux and retention to fluvial landscape (riverscape) change (see also FAUSCH et al. 2002). In this context certain physical attributes or elements of "riverscapes" are evident. The main channel and its side channels and side arms are interconnected by the parafluvial (the area of the flood plain that is annually scoured by flooding) and hyporheic (volume of the alluvial aquifer fed by penetration of river water) zones in three dimensions. The parafluvial is the erosional domain, whereas, the orthofluvial is the depositional domain of the flood plain in terms of sediment mass balance, although localized areas of erosion and deposition may occur across the entire catena. Indeed, channel migration and/or avulsion (sometimes called channel capture) is a fundamental process that increases complexity and in braided, anastomosing or meandering systems (LEOPOLD et al. 1992) leads to creation of an array of channels of different age. The parafluvial zone clearly is a harsh environment that on one hand limits vegetation encroachment by flood scour, but on the other hand provides the substratum conditions that stimulate seedlings of riparian forests to germinate, allowing succession to eventuate. The seedlings will persist only if scour locally abates and they can grow fast enough to root in juxtaposition with the annual maximum and minimum water table elevations of the alluvial aquifer. Too dry or too wet for too long and they cannot survive (ROOD & MAHONEY 1990). Once a pole stand (e.g. of juvenile cottonwoods) has established on a gravel



FLOOD PLAIN – entire valley-bottom area that is capable of flooding, including the channel network

Parafluvial catena – recently reworked by bankfull flooding, usually with drift wood throughout
  Permenently connected channels (eupotamon)- primary, secondary, tertiary channels with characteristic features, such as thalweg, rapids, shutes, riffles, pools, runs, glides, tailouts, shallow shorelines, channel separation nodes, channel confluence zones, backwaters or side-arms
  Parafluvial zone – area of annual sediment scour and deposition by floods and wind with early successional riparian vegetation
    flood channels – seasonally connected overflows
    islands – mid-channel areas of sediment accretion, often mediated by wood
    bars and levees – elevated accretion features
    spring brooks (parapotamon) – channelized flow of emergent hypotheic ground water in flood channels
    ponds or scour holes (plesiopotomon) – perched surface water or emergent hyporheic ground water
  Tributary channels – permnnent or seasonally disconnected side flows

Orthofluvial catena – reworked only by big floods or ice jams but frequently inundated, usually with over bank sediment deposits, drift wood and a riparian vegetation mosaic of age-segregated patches
  Active accretion areas – rapidly enlarging with variable but mainly well-drained, thin, organic-poor or variable soils associated with and interfluvial ridge and swale microtopography, may be dissected by flood channels that may contain spring brooks, scour pools and other parafluvial features
    scrolled (point) bars – continual lateral accretion, usually with woody vegetation precisely age-segregated
    shelves of recent origin – continual accretion, sometimes by drift wood-mediated island aggregation, may have spring brooks, ponds, marshes (paleopotomon) in swales and depressions of abandoned channels and usually dominated by mid-late successional riparian forests or wet meadows
  Passive accretion areas – slowly enlarging with deeper organically enriched soils associated with swale and ridge micro-topography
    shelves of ancient origin – slow accretion associated with extreme flooding into late successional (gallery) riparian forests, may have spring brooks, oxbows, pans, lakes, billabongs, marshes, bogs or muskegs (paleopotomon) in swales and depressions associated with gradual topographic changes resulting from sedimentation and organic filling of long abandoned, ancient channels
    floodplain-terrace transition zone – mixed upland and floodplain vegetation, often with spring brooks or wet lands in wall based flood channels

TERRACES – ancient flood plains disconnected from the active floodplain system by incision and no longer inundated by floods, dominated by terrestrial vegetation

HILL SLOPES (VALLEY WALLS) – terrestrial, but may be substantially influenced by microclimatic influences of the floodplain, may have slope wet lands from with disjunctive floodplain vegetation

Fig. 2. Linked structural (habitat) elements of floodplain river landscapes. Channel and floodplain elements overlap spatially and interact temporally but time frames differ among rivers. Periheic habitats are lateral lakes and ponds fed by ground water that occur on the flood plains of large tropical rivers as described by MERTES (1997).

bar, it becomes a trap for sediments and organic matter by greatly decreasing flow competence, thereby gradually building up and forming depositional shelves allowing a mature gallery forest to develop over the long term. Channel avulsion can result in large areas of the parafluvial zone being removed from annual scour processes, setting the stage for a depositional process shift that turns the suite of parafluvial features (Fig. 2) into a depositional shelf. Many variations on this general theme may occur (GURNELL et al. 2002). Moreover, the evolution of recruitment requirements of cottonwoods and other tree species of river riparia is but one of many cases of biotic adaptation to disturbance that eventually leads to dependence on certain dynamic habitat conditions. Since habitat shape and location change in relation to changes in the system state, organisms must have the capacity to find them.

The hydrography, that is, the drainage network and its flow pattern, is an obviously fundamental system attribute. Headwater channels drain small catchments and/or originate from melting snowfields or glaciers or as portals from aquifers embedded in the massifs of the river basin (Fig. 1). Flow varies with precipitation or snow, and ice melt and flow patterns may have long (climatic) and short (seasonal or event) term periodicities or flood pulses that mediate the dynamic nature of river ecosystems (JUNK et al. 1989). Channel confluences build larger streams that transport progressively more water and materials downstream. Mass wasting in the steep gradient reaches provides sediment loads. Aggradation facilitates sedimentation and floodplain development, with primary controllers being climate, valley morphometry, drift wood, plant succession and water and sediment budgets.

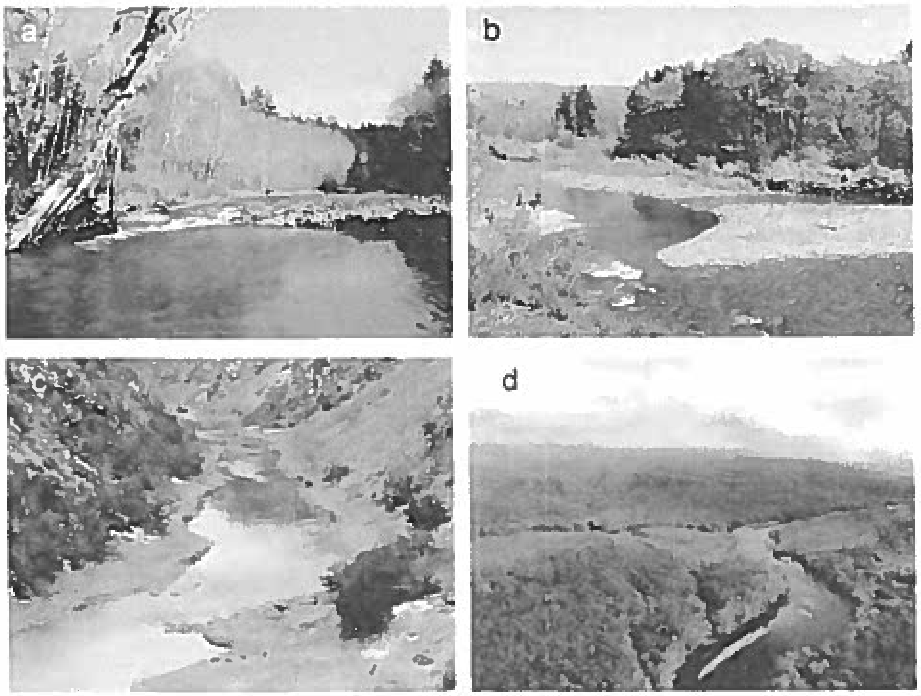
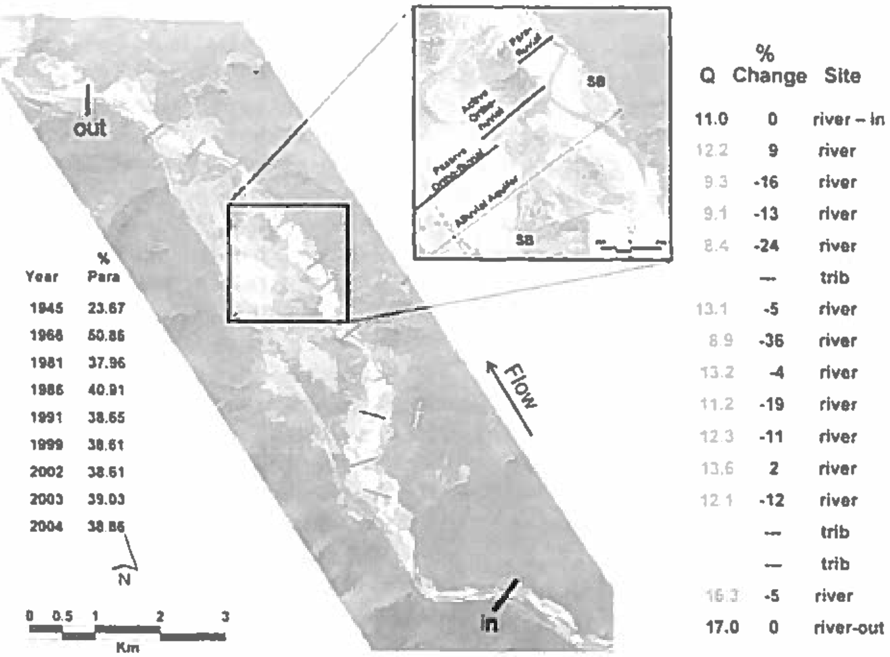


Fig. 3. Examples of river landscapes in which floodplain elements vary: (a) tailout-rapid-pool-eddy sequence associated with a point bar and vegetation chronosequences from early successional stages in the parafluvial zone to the gallery forest of red alder (*Alnus rubra*) and Sitka spruce (*Picea sitchensis*) on an orthofluvial shelf along an Oregon coastal stream, Tenmile Creek (Lane County); (b) a similar scene on a prairie reach of the Two Medicine River, Montana (Glacier County) but with plains cottonwood (*Populus deltoides*) as the primary gallery species on the orthofluvial shelf; (c) a montane canyon reach of the Gunnison River, Colorado (Montrose County) with extremely compressed floodplain elements; and (d) Krutogorova River, Kamchatka, Russian Federation, an 8th order river with a complex channel network and age chronosequences of cottonwood (*Populus suaveolens*), willow (*Chosenia arbutifolia*) and alder (*Alnus* sp.) trees arrayed across the 8 km wide floodplain catena.



Year	% Para
1945	23.67
1966	50.86
1981	37.96
1986	40.91
1991	38.65
1999	38.61
2002	38.61
2003	39.03
2004	38.86

Q	% Change	Site
11.0	0	river – in
12.2	9	river
9.3	-16	river
9.1	-13	river
8.4	-24	river
	—	trib
13.1	-5	river
8.9	-36	river
13.2	-4	river
11.2	-19	river
12.3	-11	river
13.6	2	river
12.1	-12	river
	—	trib
	—	trib
16.3	-5	river
17.0	0	river-out

Fig. 4. Satellite multi-spectral image of the Nyack Flood Plain of the Middle Flathead River, Montana (USA), showing the habitat mosaic in late summer, 2004. Inset enlarges the floodplain catena described in Fig. 2, although in this case the orthofluvial gallery forest has been partially cleared for hay farming. Data on the left demonstrate the gradual riparian reforestation of the parafluvial zone after the flood of record in 1964. Water mass balance data on the right (mean discharge, Q, in m^3/sec, sd = 0.05–0.30 per site) were obtained synoptically with an acoustic Doppler depth and velocity profiler during a base flow period and show longitudinal change in down-welling (red) and up-welling (green). Percent change refers to Q measured in the channel at each river site relative to Q at the top of the flood plain (river in) and equals zero (Qin = Qout) at the bottom of the flood plain (river out) when tributary flow is included in the accounting (refer to text for more explanation).

Biophysical complexity increases with floodplain development; therefore, location and complexity of flood plains in the river corridor also are fundamental system attributes that compliment and interact with the system-wide influence of the stream network. In theory, the most complex flood plains are expected in the middle or piedmont reaches where lateral dispersion of maximum stream power may be expected, but this has not been documented clearly. Moreover, some minimum geomorphic unit to systematically classify and link reaches, segments and the geomorphic domains in Fig. 1 is required for such an analysis. However, all rivers are alluvial to some extent, and their flood plains clearly are retention structures having characteristic habitat elements or units that are linked as a catena (Fig. 2). By virtue of this natural tendency of rivers to carry sediments, wood and other materials downstream in spiraling fashion (alternately storing and exporting water and materials in relation to system drivers described above), all rivers and all river reaches have some of these elements (e.g. as in Fig. 3).

Habitat mosaics: formative processes on the Nyack Flood Plain

Our research is focused on the montane Nyack Flood Plain in the middle Rocky Mountains of North America (Fig. 4). This much-studied system on the 5th order Middle Fork of the Flathead River in northwestern Montana (USA) at the southern boundary of Glacier National Park has been fully instrumented, including a dense network of groundwater monitoring wells, to document and model water, heat and nutrient flux and influences on biotic productivity above and below ground in the context of Fig. 1b. These studies focus on floodplain biocomplexity, with current emphasis on 3-D process modeling and the microbial ecology of the massive hyporheic zone (www.umt.edu/flbs/Research/Biocomplexity.htm). We use satellite and airborne remote sensing tools, calibrated by on the ground measures, to document distribution and abundance of many habitat attributes (Fig. 2) in a spatially explicit fashion over time. The work is in progress but some conclusions are germane to a general description of the causes and consequences of the shifting habitat mosaic in a river ecosystem context.

Cut and fill alluviation coupled with channel avulsion driven by flooding and moderated by driftwood deposition and woody vegetation succession are the primary habitat forming processes. Note in Fig. 4 the parafluvial zone changes area in relation to the intensity of flooding. Far more (~24 %) of the flood plain is vegetated today than 50 years ago because native woody vegetation has colonized the areas scoured during big flood years. Such oscillations in the riverscape underscore the utility of the shifting habitat mosaic in describing the patterns of biotic responses to cut and fill alluviation.

Obviously the area, depth and velocity in the suite of habitat elements in permanently connected channels (e.g. riffle-pool-glide-tailouts; Fig. 2) also change size and character in relation to discharge pattern. But what is not so obvious, and too often overlooked in a river management context, is the substantial influence of surface and ground water exchange on the character (habitability) of these structures.

Indeed, flux of water through the alluvial aquifer is another fundamental riverscape forming process. At Nyack, the alluvial aquifer extends from valley wall to valley wall owing to the characteristics of the bed sediments that are over 150 deep at the upstream end. Flow through the aquifer at the floodplain scale follows the slope of the valley, from lower right to upper left in Fig. 4. There is a bedrock basement with layers of increasing hydraulic conductivity above. Surface layers derive from the legacy of fluvial activity over perhaps the last 5000 years or more, since the last valley glacier melted. River water penetrates the alluvium and returns to the river in a longitudinal pattern (Fig. 4). Water loss rate from the channel is rapid over short spatial scales as shown by the data in Fig. 4 and corroborated by piezometer surveys that documented steep vertical hydraulic gradients in localities denoted by red slashes in Fig. 4. Unsaturated vertical flow has been repeatedly documented at the upstream end of the flood plain when the river approaches minimum discharge. This means that during periods of low river discharge the water table is much deeper than the river channel at the upstream end of the flood plain, and therefore river water descends as particle boundary flow vertically in proportion to the hydraulic conductivity of the sediments. The river would dry up at the surface for some distance if flow was reduced below the threshold where the vertical hydraulic gradient exceeds the longitudinal (in-channel) hydraulic gradient. Surface flow would resume at some point downstream where the river channel and water table elevations intersect. Dewatering of the river by total loss of surface flow into the alluvium does not occur at Nyack, but has been observed elsewhere in the catchment where in-channel deposits of cobble and gravel are quite extensive relative to base flow. This phenomenon, of course, occurs in rivers world wide, especially in arid areas where runoff is episodic and release from storage in floodplain alluvial aquifers maintains in-channel flow.

Flux of water in and out of the aquifer at Nyack is controlled by river flow, the slope of the flood plain and local hydraulic conductivity of the bed sediments. In consequence, the river loses and gains water longitudinally in a complex pattern that balances near bedrock canyon at the downstream end of the flood plain (Fig. 4). Presence and persistence of water at the surface depends on depth of scour during flooding and the elevation of the water table as discharge declines from peak to base flows. Water emerges into abandoned flood channels as spring brooks or fluxes through scour holes.

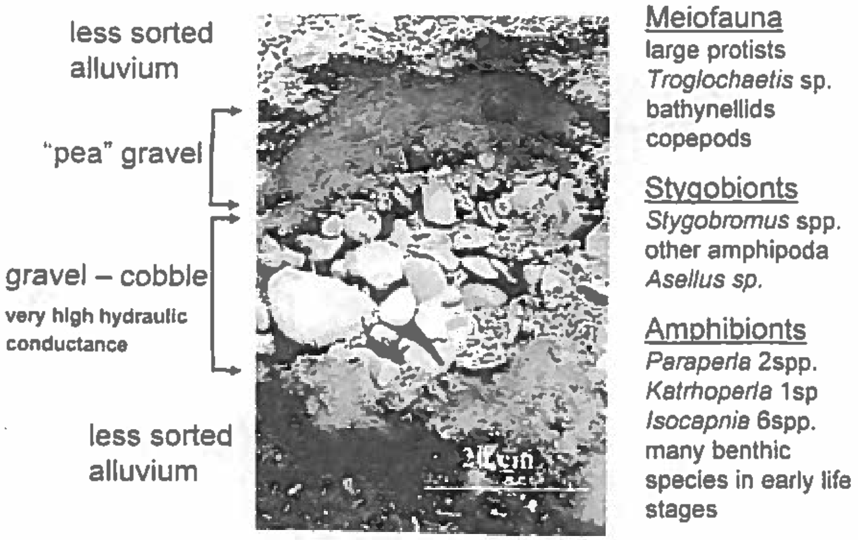


Fig. 5. Typical physical structure and primary fauna of the zones of preferential flow (buried paleochannels, see Fig. 1) within the alluvial aquifers of gravel-bed rivers, in this case from the Nyack Flood Plain (photo by B. Reid, Flathead Lake Biological Station, Polson, Montana).

creating a patchwork or mosaic of aquatic habitats that may be seasonally ephemeral or persist through the base flow period depending on local topography.

Likewise, a habitat mosaic exists in the subsurface owing to the differential sorting of the bed sediments as they are deposited over the milieu. Based on slug tests, tracer movement and other measures of hydraulic conductivity in the well grid at Nyack, we have documented that zones of preferential flow exist throughout the aquifer. We originally conceived these as the lenses of highly sorted remnants of the thalwegs of ancient channels (i.e. paleochannels in Fig. 1) buried by decades of alluviation. Paleochannels are very evident as ridge (bank) and swale (thalweg) topography of the orthofluvial shelves, and wells drilled into swales areas almost uniformly have higher hydraulic conductivity than adjacent areas. Other researchers have noted the tendency for channel backfilling in gravel-bed rivers to assume a bimodal particle size distribution, with the coarse material being the more hydraulically conductive (Huggenberger et al. 1998).

We have observed the structure of zones of preferential flow in cut banks (Fig. 5 and 6a) and at various elevations in wells cased with clear plastic, allowing us to video tape the vertical distribution of sediment size as well as dye-tracer entry patterns. Certainly the well drilling process alters the natural character of the bed sediments to some extent, but this is minimized by use of a geoprobe that vibrates the casing into the bed sediments, as opposed to an auger-type drill. In any case, large interstices must exist throughout the aquifer because large-bodied organisms including a several species of stoneflies (Plecoptera) and amphipods (Crustacea) are routinely present in well samples and are the top consumers in a complex ground-water food web containing some 50 metazoan species (Stanford et al. 1994, Case 1995). The food web is powered by epilithic microbial production (Ellis et al. 1998). Presence of abundant biota in riverine alluvial aquifers is well documented at Nyack and elsewhere in the Flathead River system, and in many other rivers worldwide, and presents fascinating ecological implications (Ward et al. 1998).

We have been unable, however, to demonstrate connectivity of zones of preferential flow (e.g. in a network context) beyond the fact that large-bodied groundwater organisms are found throughout the aquifer system, apparently able

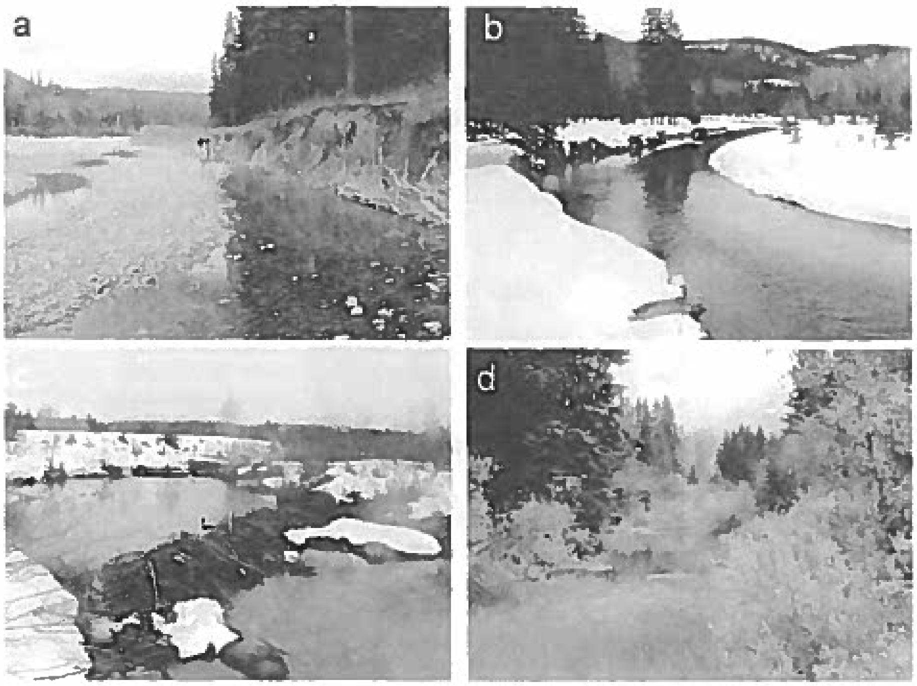


Fig. 6. Aquatic habitats of Nyack Flood Plain: (a) parafluvial spring brooks emerging from a lateral bar (river is in background) in a flood channel adjacent to an eroding orthofluvial shelf with a gallery cottonwood (*Populus balsamifera spp. trichocarpa*) and spruce (*Picea engelmannii*) forest; (b) large orthofluvial spring brook; c) orthofluvial spring brook with beaver dams; and (d) orthofluvial pond and marsh in an ancient channel within the gallery forest.

to move from place to place with ease. It appears the zones of preferential flow, while much like gravel-filled pipes (Fig. 5), are more intricate than we previously thought, and we have no firm understanding of how the high hydraulic conductivity is maintained given the volume of fine sediments and organic matter in the system. We speculate this subsurface habitat mosaic is maintained, if not created, by a combination of bioturbation by the large organisms living in the interstitial space and a physical process known as sapping flow or seepage erosion (SCHORGHOFER et al. 2004). However, large organism abundance is low relative to aquifer volume; bioturbation, therefore, seems a bit of a stretch. As for sapping flow, our idea is that higher head pressures occur in zones of well-sorted alluvium, creating enough flow competence for fine particles to move downgradient to surface portals (spring heads) and hence out of the aquifer, leaving progressively larger interstitial spaces behind. This hypothesis is not consistent with the literature on seepage erosion, however, and much remains to be learned. In any case, it is safe to say that zones of preferential flow delineate a subsurface shifting habitat mosaic because we know they are present throughout the near surface bed sediments at least, and these deposits are constantly moved and reshaped by cut and fill alluviation that mediates gravel bar migration and channel avulsions.

Shifting habitat mosaics and distribution of biota at Nyack

The consequence of strong lateral and vertical forces in the flood plain is the formation and maintenance of the shifting habitat mosaic. Many habitat types are readily apparent (Figs. 6 and 7). Cut banks reveal vertical chronosequences on the shelves (Fig. 6a), with the ripar-

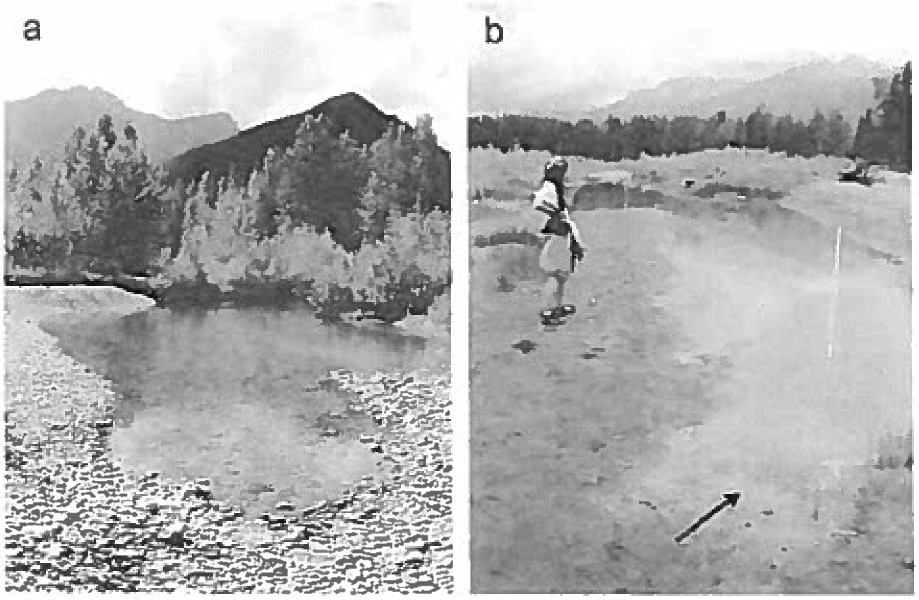


Fig. 7. Parafluvial ponds on the Nyack Flood Plain: (a) cobble-bottom scour pool with high groundwater flux; (b) scour pool, back-filled with fine sediments, resulting in relatively lower groundwater flux compared to Pond A. Arrow points to an aggregation of boreal toad (*Bufo boreas*) tadpoles in warm shallows of Pond B.

ian rhizosphere embedded in silty, sandy soils on orthofluvial shelves, underlain by gravel and cobble strata. Availability of groundwater to the rhizosphere depends on elevation of the shelf relative to the seasonally changing water table, and the pattern may be altered by channel degradation. Higher elevation shelves (relative to the stream channel network) and areas at the top of the flood plain can be very dry, whereas swales in the mid- and lower reaches of the flood plain can be permanently saturated, thereby greatly influencing plant assemblages and associated species at the floodplain scale.

Spring brooks are warm in the winter and cool in the summer relative to the channel (Fig. 8) and as influenced by the length of the groundwater flow path that feeds them. The longer the ground water flow path the greater the moderation of the annual temperature pattern toward the mean annual air temperature (6 °C at Nyack; note the spring head temperatures in Fig. 8 are uniformly cold but the spring brook warms downstream during the day). River water may penetrate a gravel bar and reemerge down slope in a flood channel (Fig. 6a) with heat and ion content similar to the river. Thus upwelling ground water may be only hours or days in the alluvium (young), but in other areas, emerging ground water may be much older and substantially more loaded with ions than water in the river channel. Often, these more moderated spring heads occur in deeply scoured channels below cut banks of the orthofluvial shelves (Fig. 6a). Spring brooks generally reflect more stable conditions than the channel: lower velocity flows, moderated temperatures and elevated plant available nutrients owing to microbial metabolism of organic matter in the aquifer.

Side channels and floodplain spring brooks may be substantially modified by large animals, particularly beavers (Fig. 6c), whose dams accelerate water and sediment retention and alter vegetation patterns. Hippos and crocodiles, for example, function similarly in tropical systems (Naiman 1988).

Scour holes created by flooding (Figs. 7 and 9) provide lentic habitats embedded in a predominately lotic ecosystem. In the parafluvial zone, these ponds may be re-scoured annually or more

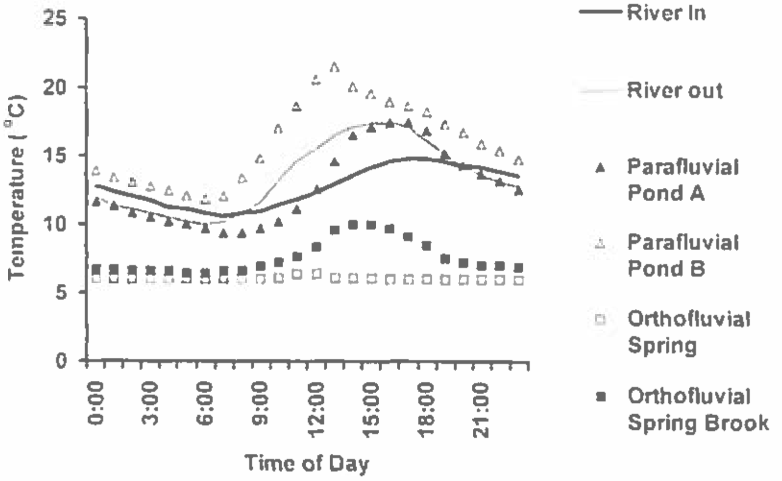


Fig. 8. Diel temperature patterns for various aquatic habitats during a hot summer day on the Nyack Flood Plain. River-in refers to the main channel at the upstream end of the flood plain, whereas, river-out is at the downstream end (see Fig. 4). Ponds and spring brooks also are as in Fig. 4.

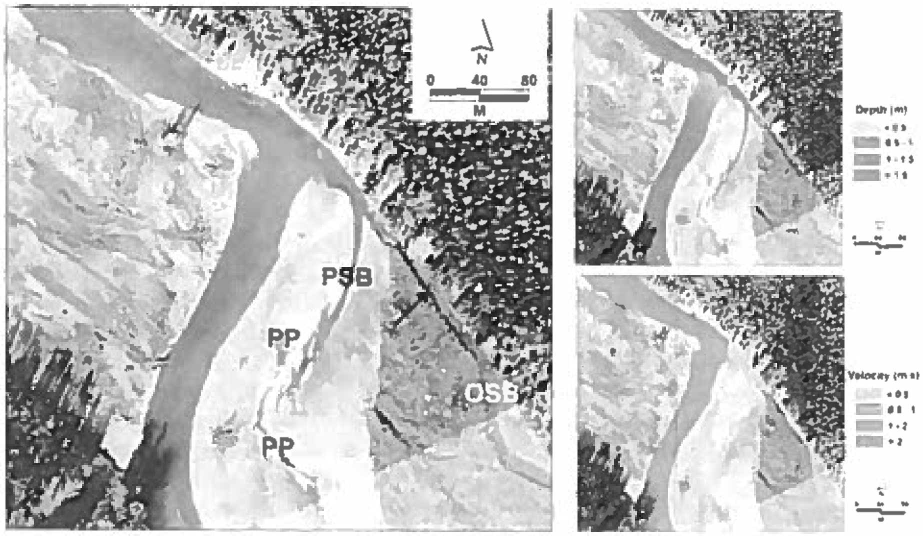


Fig. 9. High resolution (5 × 5 cm m pixel) digital image obtained from aircraft of a reach of the Nyack Flood Plain showing orthofluvial (OSB) and parafluvial (PSB) spring brooks, parafluvial ponds (PP), drift wood, actively growing vegetation patches, channel substratum gradients and other floodplain characters (see Fig. 2). In the panels on the right, water depth and velocity were mapped using a spatially explicit GIS pixel classification derived from ground truth information obtained with automated acoustic Doppler velocity and depth profiler linked to a survey grade global positioning system. Classification accuracy was 70% with $0.5 m^2$ resolution (WHITED et al. 2003). Arrow indicates a beaver dam that reduced velocity and increased depth of the spring brook (same SB occurs at the top of the inset in Fig. 4).

often by flooding, thereby preventing colonization by rooted plants, and in many cases providing little or no hiding cover for organisms. Nonetheless, parafluvial ponds are inhabitated by over 100 species invertebrates, three amphibians and several fish species, including invasive brook trout that are able to competitively exclude native trout (CHILCOTE 2004). Ponds often are more marsh-like (Fig. 6d), and in time become wetlands in the depositional environment of the orthofluvial. Thus, floodplain ponds and wetlands are important habitat types that allow colonization by organisms not usually viewed as riverine, substantially increasing biodiversity of the river corridor. Pond temperatures vary with volume, canopy cover and groundwater flux rate; summer and winter temperature stratification is usual (Chilcote 2004).

We are able to precisely measure habitat using a combination of remote sensing tools, including multi and hyperspectral sensors, infrared sensors and high resolution digital photography. Spectral and, more recently, digital imagery provide effective classification of key aquatic habitat variables such as plant cover, substratum type, wood debris and water depth and velocity (Lorang et al. 2005), whereas, temperature patterns can be obtained with infrared sensors. In Fig. 9, the habitat mosaic of a portion of the Nyack Flood Plain is clearly apparent in a high resolution digital image with enough pixel contrast to allow accurate classification of water depth and velocity. At this location the river channel strikes the hill slope, increasing the local velocity and eroding sediments to create a deep pool below a rapid. During flooding, obstruction of the channel by the hill slope reduces velocity of the upstream reach, allowing substantial alluviation and the formation of a huge transverse gravel bar with a variety of habitat types and various stages of plant succession, in some places mediated by deposition of drift wood. Note the repeating chronosequences of channel habitat (rapid, riffle, pool, glide and tailout) and associated differential sorting of bed sediments. These habitat elements shift in position and character as discharge and associated stream power changes in short (daily-seasonal) to long (annual-decadal) time steps.

High resolution imagery data can be used to help explain complex distributions of biota determined on the ground. For example, juvenile fish abundance is 2X and 10X higher respectively in the orthofluvial and parafluvial spring brooks than in similar depth areas of main channel areas, owing to lower velocities, better food resources and better hiding cover in the spring brooks (M. Anderson, Flathead Lake Biological Station, unpublished data).

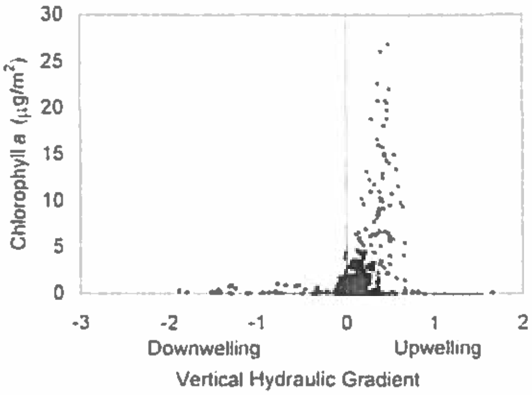


Fig. 10. Standing crop biomass of periphyton during late summer on rocks of channel and spring-brook habitats in relation to vertical hydraulic gradient, where positive and negative values show relative strength of ground water upwelling or downwelling respectively at each sampling site on the Nyack Flood Plain. Diamonds are sites in the main channel; whereas, x indicates values for sites in parafluvial spring brooks.

Across the flood plain we consistently observe strong biotic responses to groundwater upwelling (aquifer effluent) in contrast to the downwelling (aquifer influent) areas. Periphyton blooms occur in relation to higher dissolved solids content in spring brooks and gaining reaches of the channel (Fig. 10). Greater stability of substratum and temperatures in spring brooks may also promote periphyton growth. Benthos species compositions in spring brooks differ from channel assemblages, and standing crop biomass is often much higher (Case 1995). In response to greater food resources, growth rates of some aquatic insects are significantly greater in groundwater effluent areas of the main channel than in losing reaches (Pepin & Hauer 2002). Growth of cottonwood trees and leaf nitrogen content (relative to carbon) is significantly higher in the regional upwelling areas of the downstream quarter of the flood plain compared to the strongly influent areas at the upstream end (Harner & Stanford 2003).

The Nyack Flood Plain is a biodiversity hot spot. Over 500 species of aquatic macroinvertebrates have been documented, and some habitats have not been inventoried. All but one of the 12 native fishes and most of the commonly

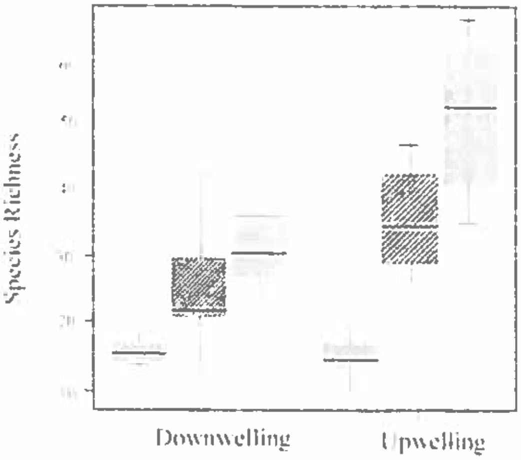


Fig. 11. Comparative species richness of vascular plants in 100 m^2 plots on parafluvial gravel bars (stippled, n = 50 plots), in cottonwood pole stands on parafluvial shelves (slashed, n = 60) and in gallery forests on orthofluvial shelves (barred, n = 63) in regional areas where river water was either influent into (downwelling) or effluent from (upwelling) the alluvial aquifer of the Nyack Flood Plain. Data from Mouw (2001).

occurring wildlife species in the Flathead Basin-Glacier National Park area, including grizzly bears (*Ursus arctos*) and mountain goats (*Oreamnos americanus*), are occasional or permanent residents, and the flood plain is a primary regional wintering and calving area for elk (*Cervus elaphus nelsoni*). Sixty eight percent of the regional vascular flora is found at Nyack (Mouw & Alaback 2003), a plant richness coherent with the flood disturbance and groundwater-flux domaines of the flood plain (Fig. 11). We attribute the notably rich species assemblages to the diversity of niches associated with the shifting habitat mosaic and strong linkages between aquatic and terrestrial habitats above and below ground.

Conclusion: importance of the shifting habitat mosaic

The central tenet of our work is that dynamic, nonlinear physical and biological processes linking water, heat and materials (biota, sediment, plant-growth nutrients) flux and retention to fluvial landscape change maximize on the flood plains of river ecosystems. The key processes driving life cycles of biota, their productivity and other biogeochemical patterns and cycles include flood-caused scour and sedimentation (cut and fill alluviation), routing of river water and nutrients above and below ground, channel movement (avulsion) and production and entrainment of large wood. Ground water routing through gravel bars and flood plain aquifers and upwelling back to the surface involves penetration of river water into zones of high hydraulic conductivity within the bed sediments that are created by channel scour and subsequent filling with sorted gravel and cobbles. Strong interactions between short-duration, high stream-power floods, channel and sediment movement, increased roughness due to presence of vegetation and dead wood and upwelling of ground water coupled with riparian regeneration creates a complex, dynamic distribution of resource patches and associated biota: *the shifting habitat mosaic (SHM)*. Emergent properties of large flood plains derive from energy dispersion and materials retention and cycling, as moderated by external drivers (e.g. marine derived organic matter, invasive species, flow regulation). We believe the SHM is the proximate emergent property of river ecosystems that underscores the importance of flood plains, arrayed like beads on a string from headwaters to the ocean, as primary organizing elements of the regional landscape in which the river network is embedded.

Our ideas about river biocomplexity in the context of the SHM and its universal applicability perhaps may be biased by our long-term focus on the Nyack Flood Plain and the Flathead River system. Moreover, we have not clearly shown that the processes driving the SHM at Nyack, a montane flood plain, occur in the same ways and with similar outcomes throughout the stream corridor (as in Fig. 1). High elevation or meandering coastal flood plains may differ in process, although doubtless the SHM is present in some form. The importance of the SHM also may differ in rivers that receive substantial marine or other natural nutrient subsidies, for example from salmon runs.

Therefore, in cooperation with a large multidisciplinary and multinational team, we have established a network of observatory river ecosystems in western North America and the Russian Far East to examine flood plain processes more synthetically. These are among the most pristine salmon rivers of the Pacific Rim. The species composition and biomass of returning salmon vary among the rivers, as does the arrangement of flood plains within the stream network. A standardized cross-site sampling protocol has been implemented to allow the water, sediment and nutrient flux data and process modeling outputs developed at Nyack to be compared and contrasted across the network. We view Nyack and the Flathead system as the control in a natural experiment, with hydrography and marine nutrient subsidy as the treatments among network river ecosystems. The SHM and associated life history diversity of salmon and other keystone biota are the primary response variables. This long-term ecological research is called the Salmonid Rivers Observatory Network (www.umt.edu/biology/flbs/Research/SaRON.htm). Our preliminary results strongly support the conclusions and wider applicability of the Nyack studies.

As usual in ecological studies, we have focused conceptually on natural, non-anthropogenic processes and interactions. But, of course humans have grossly modified most river corridors with dams, revetments and water diversions, creating discontinuities that have characteristic recovery trajectories depending on the scope of the alternation (Ward & Stanford 1995). Inundation of flood plains by damming the canyons downstream is a universal practice that clearly is effective for flood control and facilitates the plethora of water management objectives associated with stream regulation. Natural ecosystem structure and function is substantially altered by flow regulation and human encroachments on many flood plains downstream from water storage dams (Stanford et al. 1996, Poff et al. 1997). For example, discharge pattern in the river shown in Fig. 3c is regulated by dams upstream, and the effects of lost flow seasonality are apparent. The ribbons of grasses and deciduous trees (appearing brown due to winter senescence in this photo) filling the compressed parafluvial zone between the channel and historic maximum flood elevation (indicated by lineal border of hillslope juniper trees, *Juniperus scopulorum*) on both sides of the river did not exist in the pre-regulation condition owing to extreme flood scour. Invasion of non-native plants and senescence of native riparian trees is a pervasive and well-documented impact of flow regulation (Rood & Mahoney 1990, Johnson 2002).

Owing to human domination of river corridors worldwide, alluvial flood plains are among the most endangered landscapes on earth (Tockner & Stanford 2002), which has alarming implications for the long-term integrity of fresh waters. The challenge is to leverage better conservation and restoration practices from the robust emerging view of natural rivers as riverscapes composed of shifting mosaics of habitat patches (Fausch et al. 2002, Hauer et al. 2003). New tools such as high resolution imagery from remote sensing and high speed computations to create user-friendly visualizations of the SHM and predicted outcomes of restoration scenarios should empower this more synthetic view of rivers for nonscientists. The goal is to restore lost biodiversity, bioproductivity and, hence, the natural storage and cleansing functions that sustain the strategically important natural goods and services of river ecosystems.

Acknowledgements

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References

Andrewartha, H.G. & Birch, L.C., 1954: The Distribution and Abundance of Animals. – University of Chicago Press, Chicago, Illinois, 782 pp.

Benda, L., Poff, N.L., Miller, D., Dunne, T., Reeves, G., Pess, G., & Pollock, M., 2004: The network dynamics hypothesis: how channel networks structure riverine habitats. – BioScience **54**: 413–427.

Case, G.L., 1995: Distribution and abundance of zoobenthos in channel, springbrook and hyporheic habitats of an alluvial floodplain. – M.A. Thesis, Univ. of Montana, Missoula, Montana.

Chilcote, S., 2004: Ecology of Parafluvial Ponds. – Ph.D. Diss., Univ. of Montana, Missoula, Montana.

Ellis, B.K., Stanford, J.A. & Ward, J.V., 1998: Microbial assemblages and production in alluvial aquifers of the Flathead River, Montana, USA. – J. N. Am. Benthol. Soc. **17**: 382–402.

Fausch, K.D., Torgersen, C.E., Baxter, C.V. & Li, H.W., 2002: Landscapes to riverscapes: Bridging the gap between research and conservation of stream fishes. – BioScience **52**: 483–498.

Frissell, C.A., Liss, W.J., Warren, C.E. & Hurley, M.D., 1986: A hierarchical framework for stream habitat classification: Viewing streams in a watershed context. – Environ. Manag. **10**: 199–214.

Gurnell, A.M., Piegay, H., Swanson, F.J. & Gregory, S.V., 2002: Large wood and fluvial processes. – Freshw. Biol. **47**: 601–619.

Hall, C.A.S., Stanford, J.A. & Hauer, F.R., 1992: The distribution and abundance of organisms as a consequence of energy balances along multiple environmental gradients. – Oikos **65**: 377–390.

Harner, M.J. & Stanford, J.A., 2003: Differences in cottonwood growth between a losing and a gaining reach of an alluvial flood plain. – Ecology **84**: 1453–1458

Hauer, F.R., Dahm, C.N., Lamberti, G.A. & Stanford, J.A., 2003: Landscapes and ecological variability of rivers in North America: Factors affecting restoration strategies. – In: Wissmar, R.C. & Bisson, P.A. (Eds.): Strategies for Restoring River Ecosystems: Sources of Variability and Uncertainty in Natural and Managed Systems: 81–105. American Fisheries Soc., Bethesda, Maryland.

Hershey, A.E., Gettel, G.M. & McDonald, M.E., 1999: A geomorphic-trophic model for landscape control of arctic lake food webs. – BioScience 49: 887–897.

Huggenberger, P., Hoehn, E., Beschta, R. & Woessner, W., 1998: Abiotic aspects of channels and floodplains in riparian ecology. – Freshw. Biol. 40: 407–425.

Johnson, W.C., 2002: Riparian vegetation diversity along regulated rivers: Contribution of novel and relict habitats. – Freshw. Biol. 47: 749–759.

Junk, W.J., Bayley, P.B. & Sparks, R.E., 1989: The flood pulse concept in river-floodplain systems. – In: Dodge, D.P. (Ed.): Proceedings of the International Large River Symposium: 110–127. Canadian Spec. Publ. of Fisheries and Aquatic Sciences 106.

Leopold, L., Wolman, M.G. & Miller, J.P., 1992: Fluvial Processes in Geomorphology. 2nd ed.. – Dover Publications, Inc., New York, New York. 535 pp.

Likens, G.E. & Bormann, F.H., 1974: Linkages between terrestrial and aquatic ecosystems. – BioScience 24: 447–456.

Lorang, M.S., Whited, D.C., Hauer, F.R., Kimball, J.S. & Stanford, J.A., 2005: Using airborne multispectral imagery to evaluate geomorphic work across flood plains of gravel-bed rivers. – Ecol. Applic. (in press).

Mertes, L.A.K., 1997: Documentation of the significance of the perirheic zone on inundated floodplains. – Water Resour. Res. 33: 1749–1762.

Mouw, J.E.B., 2001: Floodplain plant diversity and conservation in regional and local contexts. – Ph.D. diss., The University of Montana, Missoula.

Mouw, J.E.B. & Alaback, P.B., 2003: Putting floodplain hyperdiversity in a regional context: An assessment of terrestrial-floodplain connectivity in a montane environment. – J. Biogeogr. 30: 87–103.

Naiman, R.J., 1988: Animal influences on ecosystem dynamics. – BioScience 38: 750–752.

Pepin, D.M. & Hauer, F.R., 2002: Benthic responses to groundwater-surface water exchange in two alluvial rivers in northwestern Montana. – J. N. Am. Benthol. Soc. 21: 370–383.

Poff, N.L., Allan, J.D., Bain, M.B., Karr, J.R., Prestegaard, K.L., Richter, B.D., Sparks, R.E. & Stromberg, J.C., 1997: The natural flow regime: A paradigm for river conservation and restoration. – BioScience 47: 769–784.

Poole, G.C., 2002: Fluvial landscape ecology: Addressing uniqueness within the river discontinuum. – Freshw. Biol. 47: 641–660.

Rood, S.B. & Mahoney, J.M., 1990: Collapse of riparian poplar forests downstream from dams in western prairies: probable causes and prospects for mitigation. – Environ. Manag. 14: 451–464.

Schorghofer, N., Jensen, B., Kudrolli, A. & Rothman, D.H., 2004: Spontaneous channelization in permeable ground: Theory, experiment, and observation. – J. Fluid Mechanics 503: 357–374.

Southwood, T.R.E., 1977: Habitat, the templet for ecological strategies? – J. Anim. Ecol. 46: 337–365.

Stanford, J.A., 1998: Rivers in the landscape: introduction to the special issue on riparian and groundwater ecology. – Freshw. Biol. 40: 402–406.

Stanford, J.A., Ward, J.V., Liss, W.J., Frissell, C.A., Williams, R.N., Lichatowich, J.A., & Coutant, C.C., 1996: A general protocol for restoration of regulated rivers. – Regul. Rivers: Res. and Manag. 12: 391–413.

Stanford, J.A., Ward, J.V. & Ellis, B.K., 1994: Ecology of the alluvial aquifers of the Flathead River, Montana. – In: Gibert, J., Danielopol, D.L. & Stanford, J.A. (Eds.): Groundwater Ecology: 367–390. Academic Press, Inc., San Diego, California.

Tockner, K. & Stanford, J.A., 2002: Riverine flood plains: present state and future trends. – Environ. Conserv. 29: 308–330.

Vannote, R.L., Minshall, G.W., Cummins, K.W., Sedell, J.R. & Cushing, C.-E., 1980: The river continuum concept. – Can. J. Fish. Aquat. Sci. 37: 130–137.

Ward, J.V., Bretschko, G., Brunke, M., Danielopol, D., Gibert, J., Gonser, T. & Hildrew, A.G., 1998: The boundaries of river systems: the metazoan perspective. – Freshw. Biol. 40: 531–569.

Ward, J.V. & Stanford, J.A., 1995: The serial discontinuity concept: extending the model to floodplain rivers. – Regul. Rivers: Res. and Manag. 10: 159–168.

Ward, J.V., Tockner, K., Arscott, D.B. & Claret, C., 2002: Riverine landscape diversity. – Freshw. Biol. 47: 517–539.

Whited, D.C., Stanford, J.A. & Kimball, J.S., 2003: Application of airborne multispectral digital imagery to characterize the riverine habitat. – Verh. Internat. Verein. Limnol. 28: 1373–1380.

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A GENERAL PROTOCOL FOR RESTORATION OF REGULATED RIVERS

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ABSTRACT

Large catchment basins may be viewed as ecosystems in which natural and cultural attributes interact. Contemporary river ecology emphasizes the four-dimensional nature of the river continuum and the propensity for riverine biodiversity and bioproduction to be largely controlled by habitat maintenance processes, such as cut and fill alluviation mediated by catchment water yield. Stream regulation reduces annual flow amplitude, increases baseflow variation and changes temperature, mass transport and other important biophysical patterns and attributes. As a result, ecological connectivity between upstream and downstream reaches and between channels, ground waters and floodplains may be severed. Native biodiversity and bioproduction usually are reduced or changed and non-native biota proliferate.

Regulated rivers regain normative attributes as distance from the dam increases and in relation to the mode of dam operation. Therefore, dam operations can be used to restructure altered temperature and flow regimes which, coupled with pollution abatement and management of non-native biota, enables natural processes to restore damaged habitats along the river's course. The expectation is recovery of depressed populations of native species. The protocol requires: restoring peak flows needed to reconnect and periodically reconfigure channel and floodplain habitats; stabilizing baseflows to revitalize food-webs in shallow water habitats; reconstituting seasonal temperature patterns (e.g. by construction of depth selective withdrawal systems on storage dams); maximizing dam passage to allow recovery of fish metapopulation structure; instituting a management belief system that relies upon natural habitat restoration and maintenance, as opposed to artificial propagation, installation of artificial instream structures (river engineering) and predator control; and, practising adaptive ecosystem management.

Our restoration protocol should be viewed as an hypothesis derived from the principles of river ecology. Although restoration to aboriginal state is not expected, nor necessarily desired, recovering some large portion of the lost capacity to sustain native biodiversity and bioproduction is possible by management for processes that maintain normative habitat conditions. The cost may be less than expected because the river can do most of the work.

KEY WORDS: restoration; general protocol

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INTRODUCTION

Flow regulation is perhaps the most pervasive change wrought by humans on rivers world-wide. Dynesius and Nilsson (1994) recently showed that all of the larger rivers in the northern third of the world are regulated; flow in most is totally controlled by dams and diversions, except for some free-flowing reaches and during extreme floods.

Much research in stream ecology world-wide is now devoted to understanding and mitigating flow regulation and the interactive effects of land and water use by humans within catchment basins. A primary goal of 'The Freshwater Imperative', a recent synthesis of research direction by limnologists in the USA, is understanding and predicting the influences of flow regulation on the integrity (e.g. long-term maintenance of native species diversity) and resiliency (e.g. natural recovery from human-mediated environmental change) of epicontinental aquatic ecosystems (Naiman *et al.*, 1995a; summarized in Naiman *et al.*, 1995b).

River corridors were the arteries for the development of ancient civilizations and modern societies and they remain central to local and global economies. Quality of life in all countries can be assessed in terms of quality and quantity of environmental goods (e.g. potable and irrigable water, fisheries) and services (e.g. sustained discharge and bioproduction) that humans are able to obtain from river ecosystems (*sensu* Lubchenco *et al.*, 1991). Conservation and restoration of rivers clearly should be a national priority for responsible governments and a wide array of actions have been proposed or discussed (e.g. Gore, 1985; Toth *et al.*, 1993; Gore and F. D. Shields, 1995; Shuman, 1995; Van Dijk *et al.*, 1995).

However, governments struggle with the designation of the specific elements of river environments that need to be conserved or restored, because of conflict between human use of riverine goods and services and different perceptions of how those finite resources can be sustained as human populations burgeon. Moreover, management actions targeted at a particular segment or species too often fail to meet objectives because rivers are not viewed as interconnected ecosystems from headwaters to ocean confluence.

Indeed, a strong tendency has emerged to focus river conservation and restoration on charismatic or economically important fauna, such as trout and salmon, without thorough consideration of the attributes and processes of the catchment that control biodiversity and bioproduction (Sparks, 1995). In the USA, federal legislation aimed at recovery of species deemed in danger of extinction has fostered management and research emphasis on the biology of particular organisms rather than on the ecosystem processes that control their survival within diverse assemblages of native biota (Minckley and Deacon, 1991). For example, the decade-old restoration programme for anadromous salmon runs in the Columbia River has cost well over $1 billion dollars; yet, native populations are rapidly approaching non-viable levels (Nehlsen *et al.*, 1991, Huntington *et al.*, 1996) because restoration focused on hatchery production as mitigation for lost or damaged habitat (National Research Council, 1995).

To be successful, river restoration plans must be based not only on the biology of organisms, but also on a thorough understanding of the biogeochemical processes that control the distribution and production of biota, and the human influences on those processes. In this paper we examine the general principles of river ecology and stream regulation in an ecosystem context and we use these principles as the basis for the proposition of a general protocol for restoration of entire catchments.

NATURAL–CULTURAL ELEMENTS OF CATCHMENT ECOSYSTEMS

Rivers cannot be separated in theory or practice from the lands they drain (Hynes, 1975). Hence, the catchment basin (often referred to as watershed in the USA) defines the spatial dimensions of river ecosystems. Understanding the linkages between terrestrial and aquatic components and processes within the catchment is essential to river protection and restoration.

The catchment landscape is composed of interactive, biophysical resources (e.g. water, minerals, nutrients, habitats, food-webs) that are used by the assemblage of animals and plants (biodiversity) that live within the ecosystem. Biodiversity encompasses such phenomena as genetic variation, morphological variation, life history variation within species and the richness, distributions, biomass and productivity of populations, species, guilds and other taxonomic and trophic categories across the landscape. It also encompasses the myriad of biophysical processes (functional attributes) that control these phenomena (Hall *et al.*, 1992; Doppelt *et al.*, 1993; Noss and Cooperrider, 1994; and many others). However, the salient features of biodiversity, species numbers (alpha diversity) and distribution (beta diversity), are determined by the availability of the resources that are needed by animals and plants in order to reproduce successfully (i.e. complete their life cycle) (Andrewartha and Birch, 1954) and thereby sustain ecosystem integrity (Frissell and Bayles, 1996; Ward, in press). Life history stages are determined by the genome of each species as derived from its legacy of genetic responses to changes in the availability of resources. Hence, the dynamic biophysical components of the landscape are controlled in space and time by environmental changes (e.g. forest fires, spates, drought, disease, earthquakes) that vary in intensity and duration.

Similarly, human societies within catchments usually are derived from a mix of cultures (e.g. natives, immigrants) that use or market goods and services to produce wealth or some other measure of the quality of life desired by individuals. Desires and perceptions that individuals have about life-style are dynamic and influenced by heritage, education, earning power, shortages and surpluses of goods such as fossil fuels, laws, taxes and natural resource management policies, among many other social and economic concerns.

The point is, that both natural and cultural components of catchments are complex and highly interactive. Humans change catchment landscapes by using or extracting environmental goods and services; whereas, societies change in relation to the quality or ecological integrity of landscapes in which they reside (Blikie and Brookfield, 1987; Schnberg and Gould, 1994; and many others in the rapidly expanding environmental sociology and ecological economics literature).

Within this natural–cultural framework, we recognize that river ecosystems have a certain natural capacity to maintain biota and produce biomass (Warren *et al.*, 1979; Frissell *et al.* 1996; Ebersole *et al.*, in press) and that biodiversity and bioproduction are dynamic in time and space in relation to availability of resources (Benke *et al.*, 1988). Biotic dynamics derive from natural variation in the environmental setting; equilibrium conditions (e.g. logistic relationship between resources and bioproduction) rarely exist for very long because environmental changes are constantly reconfiguring resource availability. Periodic constraints on species-specific productivity increases opportunities for other species to use resources, inferring that levels of ecosystem biodiversity and bioproduction generally are related to the intensity, frequency and duration of disturbance events (Huston, 1979; Resh *et al.*, 1988; Pimm, 1991; Huston, 1994; Reice, 1994).

Ecological capacity, therefore, varies from place to place and higher levels of biological richness (speciosity) and bioproduction are most likely to occur in ecosystems with a long legacy of high spatial and temporal environmental heterogeneity (Connell, 1978; Ward and Stanford, 1983; Salo *et al.*, 1986; Poff and Ward, 1990; Ward, in press). In contrast, total unit area biomass (standing crop) of a few species, while also constrained by inherent ecosystem capacity, may be high under sustained conditions of environmental constancy owing to slow turnover rates. For example, a few species are often extremely abundant and persistent in spring-brooks, lake outlets and reservoir tailwaters, where disturbance events are relatively benign (e.g. scouring floods, very dynamic diel and annual temperature patterns and rapid changes in transport of particulate matter do not occur because of the buffering effect of the lake or reservior) (Ward and Dufford, 1979; Gislason, 1985; Perry and Sheldon, 1986; Valett and Stanford, 1987; Wooton, 1987; Shannon *et al.*, 1994).

Humans tend to dominate ecosystems, thereby superimposing pervasive, continual perturbation on the natural disturbance regimes that sustain habitats and biotic communities. The result is suppression, and in some cases permanent loss, of environmental heterogeneity and biodiversity, fundamentally reducing the productive capacity of biotic resources (Warren and Liss, 1980; Frissell *et al.*, 1993; Frissell *et al.*, in press; Ebersole *et al.*, in press). The goal of river restoration should be to minimize human-mediated constraints, thereby allowing natural re-expression of productive capacity. In some, if not most, intensely regulated rivers, human-mediated constraints may have progressed to the point that full re-expression of capacity is neither desired nor possible. Nonetheless, the implication is that basic ecological principles applied to rivers in a natural–cultural context can lead to restoration of biodiversity and bioproduction in space and time; but, the constraints must be removed, not mitigated.

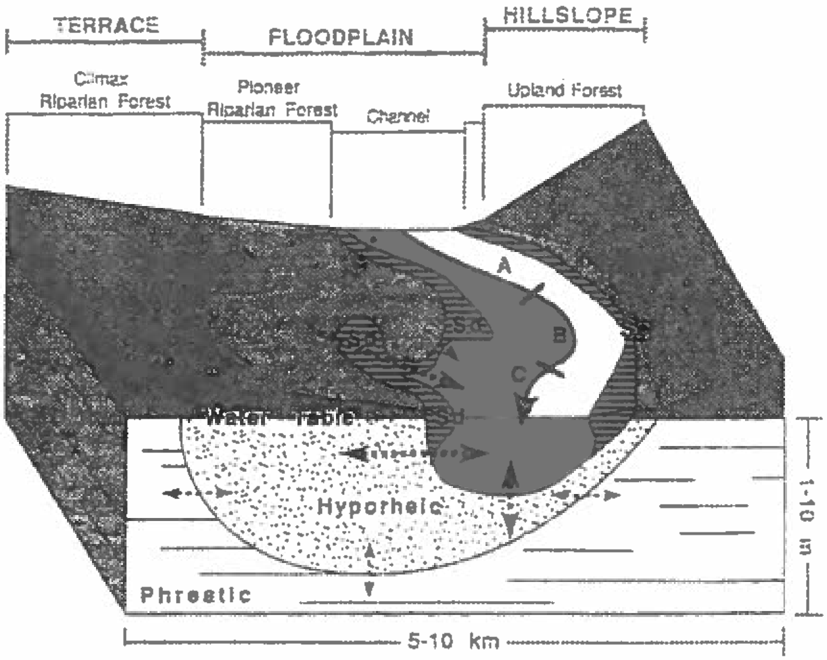

Figure 1. Major landscape features of a montane floodplain river, showing the three primary spatial dimensions (lateral, longitudinal or altitudinal, and vertical) that are dynamically molded through time (the fourth dimension) by fluvial processes. Biota may reside in all three spatial dimensions: riparos (streamside or riparian), benthos (channel), hyporheos (river-influenced groundwater) and phreatos (deep groundwater). The hatched area is the varial zone or the area of the channel that is periodically dewatered as a consequence of the average amplitude of the discharge regime. Major channel features include a run (A), riffle (B) and pool (C): Sd refers to sites of sediment deposition and Se refers to a major site of bank erosion. The heavy solid line is the thalweg and broken lines conceptualize circulation of water between benthic, hyporheic and phreatic habitats (after Stanford, 1996; see also Stanford and Ward, 1992)

GENERAL PRINCIPLES OF RIVER ECOLOGY

Conservation and management strategies for large rivers must have a solid conceptual basis or they will likely fail to sustain biodiversity and bioproduction. Contemporary river ecology is guided by a number of intertwined concepts or principles derived from empirical studies. No two rivers are exactly alike and no single theory encompasses the myriad of biophysical interactions and responses to natural and human disturbances that make each river unique. However, fundamental principles do apply; many conservation and restoration efforts become myopic, costly and too often fail because plans and actions overlook ecological fundamentals.

Unregulated rivers exist as geohydraulic continua from continental divides to the oceans. They are networks of surface and groundwater flow paths that drain catchment landscapes (Gibert *et al.*, 1990). The energy of flowing water constantly reconfigures the physical form of these interconnected flow pathways, primarily by the process of cut and fill alluviation (Leopold *et al.*, 1964) although dissolution can dominate in limestone massifs (Mangin, 1994) and a few other situations. Inorganic and organic materials are eroded upstream and deposited downstream primarily in relation to: (a) long- and short-term flow dynamics; (b) the resistivity of geological formations to erosion and dissolution; (c) instream retention structures (e.g. eddies, wood debris); and, (d) the geometry of the catchment.

Channel morphologies are determined by the legacy of flooding. Big floods fill channels with inorganic and organic materials eroded laterally and vertically at upstream locations, thereby producing a continuum of instream structures (pools, runs, riffles, gravel bars, avulsion channels, islands, debris jams) and lateral floodplain terraces in many sizes and shapes. Local morphologies resulting from infrequent, very large floods may persist in the same general form (quasi-equilibrium) for long time periods until the next big flood, even

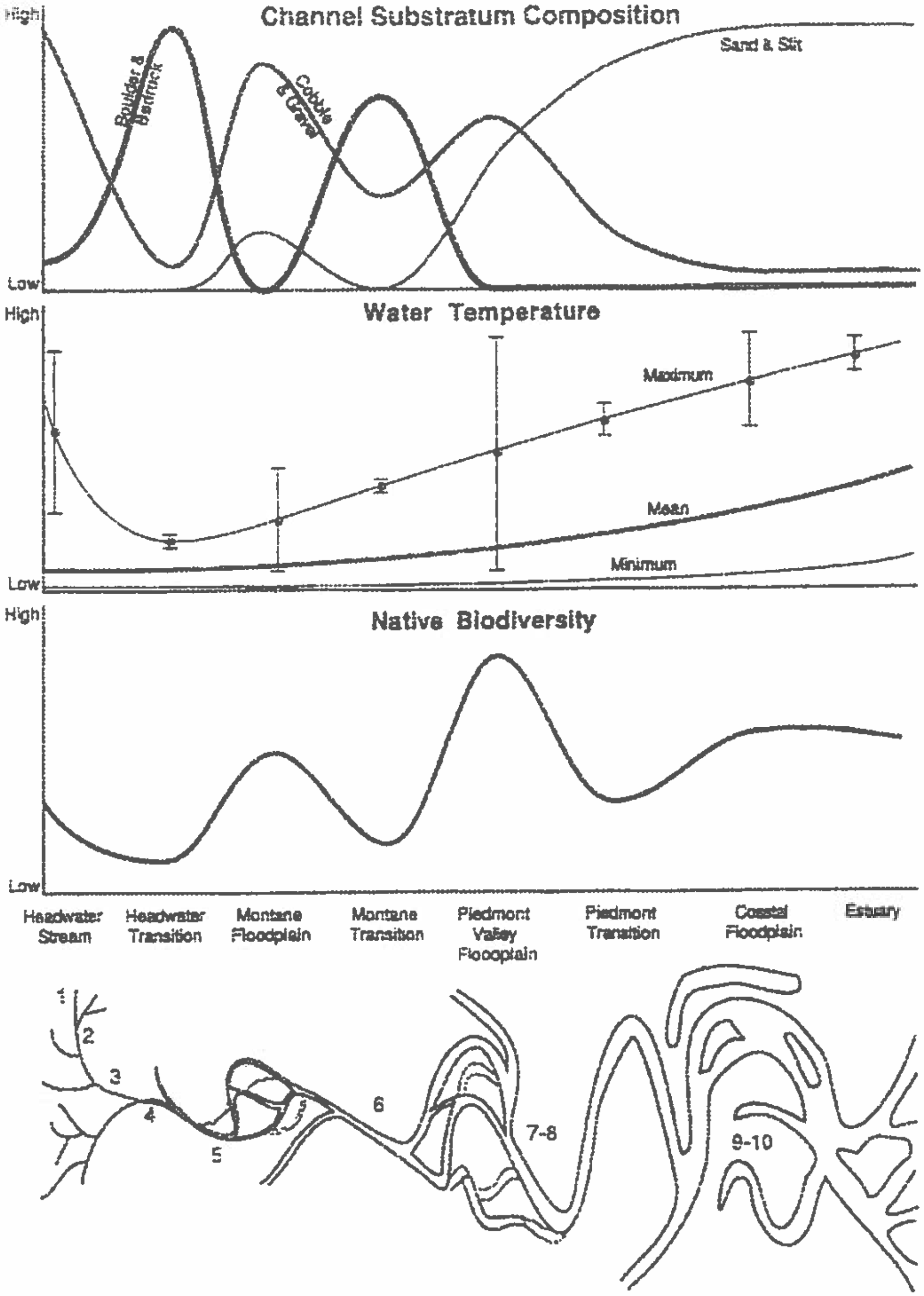

Figure 2. Conceptualized continuum of a large unregulated river showing biophysical gradients and nodes of environmental heterogeneity (centres of organization) of the major alluvial reaches. Vertical bars on the plot of maximum temperature represent the annual range of annual maximum temperature across all habitats at any point in the river continuum. Numbers indicate stream order. The figure is not drawn to scale; transition reaches are often much longer than inferred

though interim flow dynamics gradually and subtly reconfigure instream structures and features (Schumm and Lichty, 1956). For example, the channel of the Snake River upstream from Hells Canyon, Idaho, USA, persists as an incised gravelbed channel containing a chain of elevated, mid-channel islands that have not been overtopped since the cataclysmic glacial flood that formed them receded over 8000 years ago (Connor, 1993). Other river channels with a greater sediment supply and frequent overbank flooding are constantly shifting, braiding or meandering on the valley bottom from year to year as the channel fills with material in one place causing the flow pathway to avulse and downcut (Best and Bristow, 1993).

All rivers are fundamentally alluvial in nature as a consequence of cut and fill alluviation mediated by flooding. Most rivers have deeply bedded and expansive floodplains interspersed between constrained and often incised reaches (canyons), where the bedrock may be very near or exposed on the stream bottom. Hence, river ecosystems have three important spatial dimensions that are temporally dynamic (Figure 1). The longitudinal (upstream–downstream) dimension is described in detail in the ecological literature, including the occurrence and ecological significance (discussed below) of streamside (riparian) vegetation and associated faunal assemblages in the surficial transition zone from riverine to terrestrial environments. However, critically important lateral and vertical attributes and connections are often overlooked or ignored. Owing to the high porosity of the bed sediments in gravel bed rivers, river water penetrates the bottom and saturates the alluvial bedding of the channel and floodplain down to the less porous bedrock, thereby creating complex groundwater (hyporheic) habitats. As the valley constricts, or owing to changes in the local bedrock geometry, the water table may intersect the surface creating floodplain (riparian) wetlands; permanent spring-brooks and ponds in up-welling areas may be observed at the downstream end of flood plains. Indeed, a prominent feature of alluvial rivers is sequential down- and up-welling of river water into and out of the bed sediments, which interacts with overland flooding to create complex habitat mosaics on the floodplain surface. The floodplain, with its hyporheic and riparian habitats, is therefore the transition zone or ecotone linking aquatic and terrestrial components of the river ecosystem above and below ground level. Also, groundwater flowing from uplands may mix with river water flowing within the hyporheic zone, creating yet another important lateral ecotone. These lateral and vertical transition zones alternate in juxtaposition with the channel from headwaters to mouth, forming hyporheic and riparian corridors (Naiman *et al.*, 1988; Stanford and Ward, 1993; Ward and Weins, in press).

The mosaic of channel and floodplain structures creates a constantly changing habitat template (*sensu* Southwood, 1977, 1978) for a myriad of plants and animals that comprise riverine food-webs. Resources needed by particular life history stages of organisms have discrete or 'patchy' distributions within this heterogeneous landscape. As flows change, not only does the ability of the river to move substratum change, but the way in which water moves around and/or over instream structures, such as boulders and gravel bars, also changes. Hence, biota must adapt to resources arrayed as dynamic patches that manifest from local (e.g., a single rock on a single riffle in a particular river reach; Townsend, 1989) to catchment scale. Moreover, as biota attempt to find and utilize these patches to sustain growth and reproduction over the long term, they must also adapt to the physical forces of water movement (Statzner *et al.*, 1988). Therefore, biota are often arrayed in precise locations within the river channel and along the river continuum (Poff and Allan, 1995). For example, a large, behaviourally dominant trout may occupy the optimal position within an eddy for capturing drifting insects; if that fish is removed, the next fish in the pecking order will move into that foraging location (Bachman, 1983). Salmonids are generally confined to the colder, rocky reaches (rhithron) of the stream continuum and are replaced by warm water species (e.g. cyprinids, ictalurids) in the slow moving, sandy and often turbid reaches downstream (potamon) (Illies, 1956; Illies and Botosaneanu, 1963).

The river continuum is a complex, dynamic gradient of habitat types from headwaters to oceanic confluence, and flora and fauna are usually distributed rather predictably along that gradient (Figure 2) according to the requirements specified by each stage in their life cycle (Vannote *et al.*, 1980). Each species or unique life history type (stock or population) is most abundant where the resources they require are most abundant and/or most efficiently obtained. They will be present (locally adapted) wherever they can maintain a positive energy balance, that is, they have enough resources to sustain growth and reproduction and thereby sustain the presence of the species or stock in the river food-web at that location (Hall *et al.*, 1992). For some species, a positive life history energy balance can be maintained without much movement and suites of organisms appear to occur in zones along the river continuum: others must move long distances in search of resources needed for each life stage, sometimes involving migrations into the lakes (e.g. adfluvial bull charr, *Salvelinus confluentus*) or the ocean (e.g. anadromous salmon and trout: *Onchorynchus* spp., *Salmo salar and S. trutta*; *Salvelinus* spp.)

Widely dispersed species often exist as metapopulations because local populations are linked by dispersal and gene flow into larger regional populations that may encompass the entire catchment (Hanski, 1991; Hanski and Gilpin, 1991). For example, metapopulation structure is thought to be particularly evident in many salmonid populations (Reisenbichler *et al.*, 1992; Rieman and McIntyre, 1993) and most likely influences the probability of persistence for a species (Stacy and Taper, 1992). Metapopulation linkages allow for local extinction of populations, which can be re-established via colonization from adjacent populations (Leider, 1989; Milner and Bailey, 1989). The spatial arrangement of large- and small-scale habitat features within a catchment may serve as a template for metapopulation organization of fishes (Schlosser and Angermeier, 1995). The mosaic of floodplain reaches and constrained segments (Figure 2) within the mainstem and tributaries influences size, spatial distribution and proximity of local spawning populations. Proximity of populations and favourability of connecting habitats can affect exchange of individuals between local populations (Reiman and McIntyre, 1993, Li *et al.*, 1995; Schlosser and Angermeier, 1995) and thus influence potential for recolonization of habitats where local extinction has occurred.

Since most river fauna are ectotherms, growth and reproduction is also vitally influenced by river temperature. Most organisms adapted to the cold climes of the headwater reaches simply cannot survive in warmer reaches downstream, and vice versa. Indeed, species found in a particular thermal environment in one river generally will be found in very similar environments in other rivers within the geographical range of that species, if all other resource needs are also met. Because growth of ectotherms is strictly temperature dependent, temperature is a critical habitat attribute (Ward, 1985; Hall *et al.*, 1992). Stream insects and fish will be found in areas of the stream where their thermal needs are met and substratum, food and other resources are marginal, but rarely the inverse, at least for individuals that ultimately reproduce successfully. This is because of the basic thermal energetics of growth and the fact that many life history stages, such as insect emergence (ecdysis) and fish spawning are initiated by precise temperature cues (Brett, 1971; Vannote and Sweeney, 1980; Ward and Stanford, 1982). In addition, because few riverine organisms have highly specialized food requirements, food limitation may be less prevalent than thermal limitation most of the time.

For plants of the river food-web, availability of light and nutrients is crucial. In headwater streams shaded by riparian plants, decomposition of allochthonous (terrestrially derived) coarse particulate organic matter (leaves, grasses) usually drives instream bioproduction (Cummins *et al.*, 1984, 1989). Plant growth nutrients are released into transport by the decomposition of particulate organic matter entrained on the bottom, and are utilized by aquatic plants in better light environments downstream where the stream channel is wider and the riparian canopy opens. Of course, nutrients and other dissolved solids are also derived from dissolution of the bedrock and other geochemical reactions. Indeed, streams with high alkalinity from limestone dissolution generally are more productive than streams draining more inert bedrocks, such as granite massifs (Kruger *et al.*, 1983; Waters *et al.*, 1990). Dissolved solids that are required for growth by algae and macrophytes spiral downstream, alternatively retained and released into transport by the river food-webs (Newbold *et al.*, 1981, 1982). Conditions may shift back to heterotrophy in turbid, slow moving reaches near the river mouth as a consequence of planktonic microbial decomposition of organic matter transported from upstream reaches, reduced light reaching the bottom owing to deep and often turbid water and shifting substratum (Vannote and Sweeney, 1980; Minshall *et al.*, 1983; Naiman *et al.*, 1987).

All of this underscores the complex linkages between the spatial dimensions of river ecosystems (Figure 1). These interactive components and attributes are repeated throughout the river course, from headwaters to mouth. Floods maintain channel and floodplain habitats and pulse nutrient-enriched waters laterally into backwaters and on to floodplains, as well as downstream into the estuary. Because it is a continual habitat-forming process, river biota are adapted to frequency and duration of flood pulses (Copp, 1989; Junk *et al.*, 1989). Rivers that flood frequently (annually or more often) maintain different species and food-webs than systems that are more ecologically benign by rarely or never experiencing scouring floods (e.g. spring-brooks and lake outlet streams). Food-webs are complex and change predictably along the stream

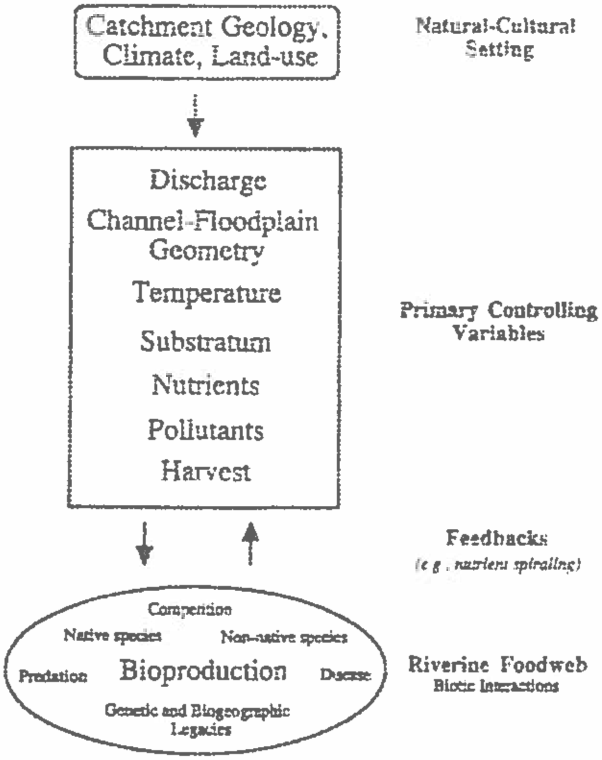

Figure 3. Primary controlling variables and biophysical interactions of river ecosystems

continuum in direct response to variations in the strength of interconnections between channel, groundwater, floodplain and upland elements of the catchment (Ward and Stanford, 1995a).

In our view the primary variables driving the distribution and abundance of animals and plants in flood prone rivers are usually abiotic and primarily determined by the geological and climatic setting of the catchment basin (Figure 3). Biotic interactions (e.g. competition, predation, parasitism), while they obviously continually occur within food-webs in all habitats, may become progressively more important and apparent as the time between abiotic disturbances increases, and hence are most pronounced in spring-brooks and lake outlet streams where abiotic drivers are comparatively non-variable (Ward and Stanford, 1983b; McAuliffe, 1983, 1984; Reice, 1994). All big rivers that are not influenced by large on-channel lakes are naturally flood prone, and ultimately biophysical structure is controlled by the inexorable, but highly dynamic, scouring process of cut and fill alluviation.

Environmental heterogeneity (complexity) maximizes in the alluvial (aggraded) reaches of the river continuum. Owing to the energetics of materials transport through large catchment basins from high elevation to sea level, alluvial reaches are arrayed along the stream continuum between canyon segments like beads on a string (Figure 2). The hyporheic and riparian corridor is expansive on alluvial reaches and seasonal temperature patterns vary within the wide array of aquatic habitats that exist laterally from the channel across the floodplain (Ward, 1984). Large floodplains appear to function as centres of biophysical organization within the river continuum (*sensu* Regier *et al.*, 1989). They are likely to be 'hot spots' of biodiversity and bioproduction that are structurally and functionally linked by the river corridor (Copp, 1989; Gregory *et al.*, 1991; Zwick, 1992; Stanford and Ward, 1993; Ward and Stanford, 1995a,b). Indeed, intermountain and piedmont valley floodplains world-wide are characterized by nutrient-rich floodplain soils and diverse and productive backwater and mainstem fisheries (Welcomme, 1979; Davies and Walker, 1986; Lowe-McConnell, 1987; Sparks *et al.*, 1990; Junk and Piedade, 1994; Welcomme, 1995). These reaches are also foci for human activities within the catchment basin (Amoros *et al.*, 1987; Petts *et al.*, 1989; Wissmar *et al.*, 1994).

Additional data are needed to confirm explicitly the pattern of biodiversity hypothesized in Figure 2 for a spectrum of rivers world-wide, but the importance of alluvial zones as biological 'hot spots' within river continua is very clear (e.g. riparian plants: Junk *et al.*, 1989; Gregory *et al.*, 1991; benthic insects: Zwick, 1992; Roth *et al.*, in press; fishes: Welcomme, 1979; Rieman and McIntyre, 1995). Moreover, metapopulation theory suggests that core populations are critical for persistence of metapopulations with core-satellite structures (Schoener 1991; Harrison 1991, 1994). Core populations are relatively large populations occupying high quality habitat. In rivers, large alluvial reaches may support core populations of fishes (Lichatowich and Mobrand, 1995). These productive populations can serve as stable sources of dispersers that can recolonize peripheral habitats where less productive satellite populations have undergone local extinctions (Harrison, 1991, 1994; Reiman and McIntyre 1993; Li *et al.*, 1995; Schlosser and Angermeier, 1995); or, core populations may 'rescue' from extinction satellite populations whose abundance has been severely reduced (Brown and Kodrick-Brown, 1977; Gotelli 1991; Stacey and Taper, 1992). Thus, core populations can buffer metapopulations against environmental change and contribute to resiliency of regional fish production. Certain riparian plant species also appear to exist as metapopulations with cores on alluvial floodplains (Decamps and Tabacchi, 1994). Therefore, we propose that alluvial reaches should also be foci for large river conservation and restoration.

THE RIVER DISCONTINUUM: HUMAN ALTERATION OF LARGE RIVER ECOSYSTEMS

Humans vastly reduce the capacity of river ecosystems to sustain natural biodiversity and bioproduction by severing or compromising the dynamic interactive pathways of the river continuum. As described above, native biota of rivers display life history traits that allow populations to survive within a certain range of environmental variation that characterizes a particular river. If this range of variation changes, organisms must locally adapt to the new range of environmental conditions or be extirpated. Recolonization of extirpated areas may occur over time as environmental constraints ameliorate and/or as a consequence of immigration of suitably adapted populations. However, human-mediated environmental change can be so rapid and so severe as to exceed the ability of biota to adapt. The interactive pathways of the river continuum too often are permanently severed by human activities, and native biodiversity and bioproduction decline.

Pervasive human perturbations that uncouple important ecological processes linking ecosystem components in large river basins can be lumped into three broad classes: (a) water pollution of all types; (b) food-web manipulation by harvest, stocking and exotic invasions; and (c) alteration of water, temperature and materials flux by dams, diversions and revetment. Human land use creates direct and diffuse inputs of water-borne wastes from the catchment and its airshed (Hynes, 1966; Warren, 1971), accelerates erosion and sediment loading related to deforestation and road building (Waters, 1995), alters flux rates of materials in rivers (e.g. eutrophication, acidification) and uncouples lotic food-webs by toxic effects. Harvest of fishes and invertebrates, and the purposeful and accidental introduction of non-native species, induces strong interactions that alter food-webs by causing biomass and bioproduction shifts, species replacements and other trophic effects (Mooney, 1986) that may cascade through all trophic levels and even involve terrestrial species that feed on aquatic biota (Spencer *et al.*, 1991). Pollution and food-web manipulation are interactive with stream regulation effects in most catchments. However, alteration of flow regimes and associated severing of connectivity in the three spatial dimensions of riverine ecosytems perhaps are the most strikingly pervasive influence of humans on river landscapes world-wide (Dynesius and Nilsson, 1994).

Three first principles of the ecology of stream regulation

At least three fundamental commonalties emerge from the large literature on the ecology of regulated rivers (reviewed by Baxter, 1977; Ward and Stanford, 1979, 1987; Lillehammer and Saltveit, 1984; Petts, 1989; Calow and Petts, 1992). These principles must be recognized in the derivation of large river restoration strategies.

1. Habitat diversity is substantially reduced. Large storage dams world-wide inundate piedmont or

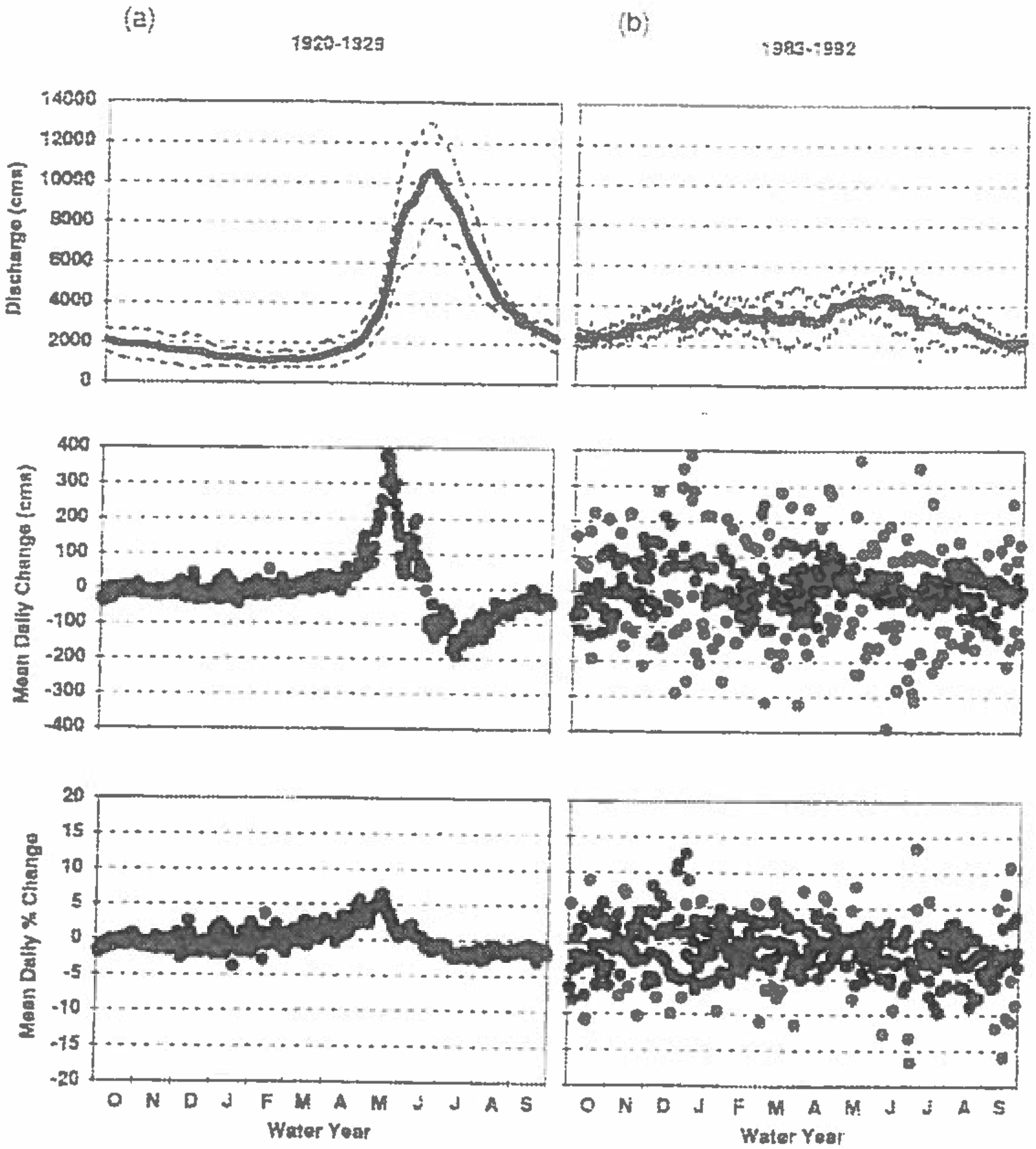

Figure 4. (a) Discharge of the Columbia River, USA, in the Hanford Reach, an eighth-order segment in the piedmont transition (see Figure 2) between Priest Rapids and the confluence of the Snake River, for the period 1920–1929 when no large storage dams were present upstream. In the top panel the solid line is mean daily discharge plotted for each day of the water year beginning 1 October and ending 30 September, and the broken line plots standard error. These data were used to calculate average daily change in discharge (middle panel) and average percentage daily change (bottom panel) (b) Same as (a), except data are for the period 1983–1992, when the flow of the Columbia River in this reach was regulated by Priest Rapids and other dams upstream (derived from US Geological Survey data, Reston, Virginia, USA)

mountain valley floodplains, thereby severing the river continuum. Mass transport dynamics that create instream and floodplain habitats for riverine biota are drastically altered. Flood peaks are eliminated, daily discharges are more variable (e.g. Figure 4) and temperature seasonality may be reduced or lost (Stanford and Hauer, 1992; Blinn *et al.*, 1995).

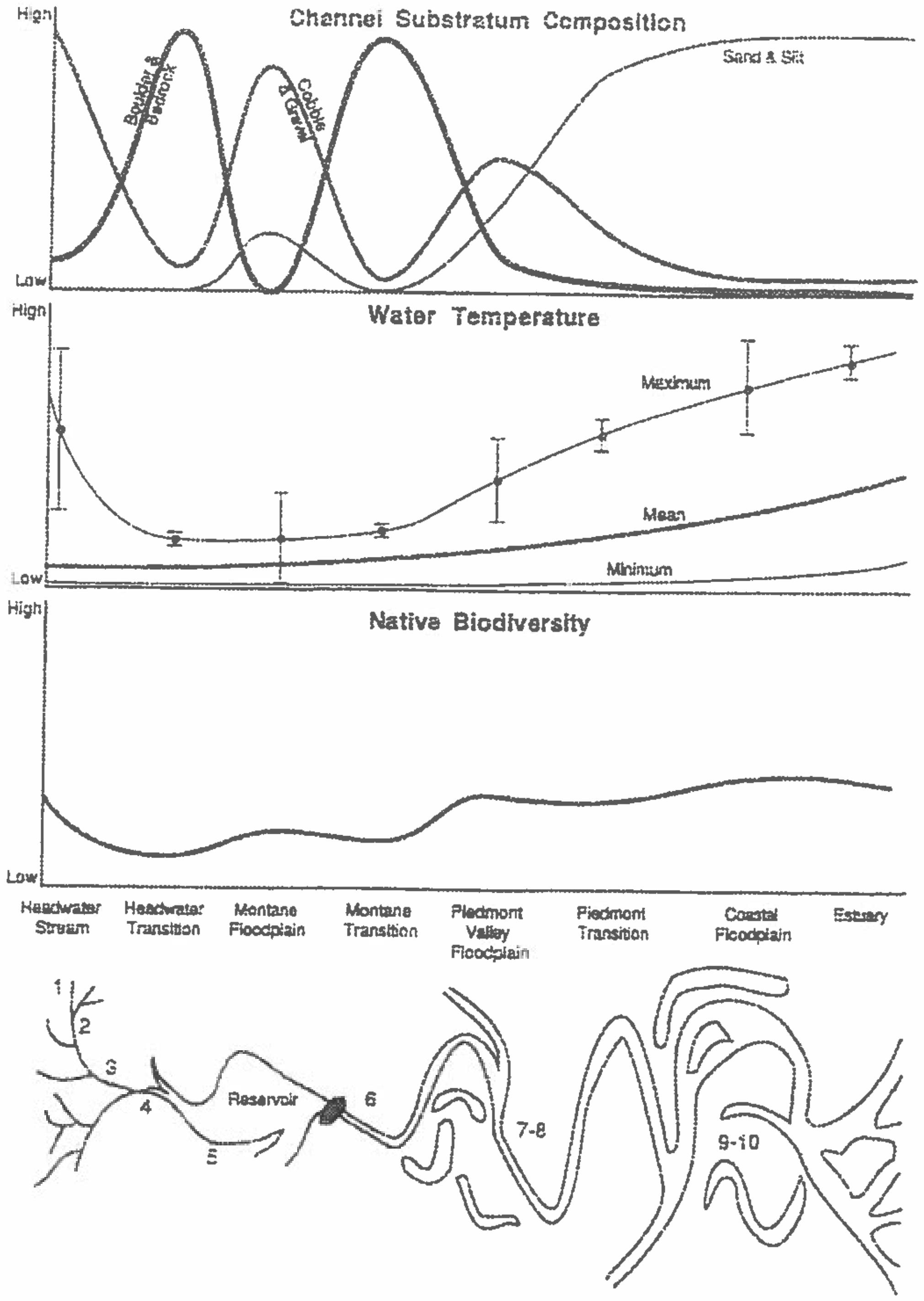

Figure 5. Conceptualized continuum of a large river after regulation by a high volume, high head storage dam in the montane transition (compare with Figure 2). Tributaries downstream from the dam are assumed to be unregulated. Vertical bars on the plot of maximum temperature represent the annual range of annual maximum temperature across all habitats at any point in the river continuum. Numbers indicate stream order. The figure is not drawn to scale; transition reaches are often much longer than inferred

As a consequence of reservoir storage of peak flows for flood control, navigation, irrigation and hydropower production, baseflows increase substantially and often fluctuate so erratically that aquatic biota cannot survive in shallow, near-shore habitats. The varial zone, shown in Figure 1, constricts owing to loss of peak flows and is depopulated by cyclic dewatering and rewatering that occurs on weekly, daily or even hourly schedules (Cushman, 1985; Jourdonnais and Hauer, 1993). In stark contrast, a natural river pulses water on to often expansive floodplains within a range of variation that allows a diversity of aquatic and riparian biota to exist in multiple successional stages in a complex array of habitats. Persistent shallow or slack water habitats are especially important for the survival of early life history stages of fishes that cannot survive in the strong currents of the channel thalweg. Storage of bedload in the reservoir and constant clear water flushing downstream artificially depletes gravel and finer sediments in the tailwaters, causing armouring of the bed with large cobble and boulder substratum (Simons, 1979). Large rocks eroded from the canyon walls and coarse bedload from tributaries jam the channel and increase the size of rapids over time, because peak flows are insufficient to scour and transport the largest materials downstream (Dolan *et al.*, 1978). Channel constrictions and habitat simplification occur as the channel downcuts and riparian vegetation invades to the top of the varial zone in aggraded reaches, owing to loss of upstream sediment supply and loss of scouring flood flows (Johnson, 1994; Church, 1995).

The general conclusion is that regulation creates a discontinuum of environmental conditions and severs the connectivity of channel, groundwater, floodplain and upland components of the catchment ecosystem; habitats for riverine biota become spatially homogenous, limited to the permanently wetted portion of the channel thalweg that is dominated by conditions dictated by operations of upstream storage reservoirs (Figure 5). Indeed, serial construction of low-head dams has converted virtually all the mainstems of the largest rivers in USA, Europe, Sweden and Finland into shallow reservoir habitat that is neither truly lacustrine nor riverine.

2. *Native biodiversity decreases and non-native species proliferate.* Native biodiversity almost always decreases after regulation (Minckley and Deacon, 1991; Ward and Stanford, 1991; Moyle and Leidy, 1992; Stevens *et al.*, in press), as conceptualized in Figure 5 compared with Figure 2. Vital core populations may be extirpated and satellite populations may become increasingly isolated by regulation schemes. Moreover, for anadromous species of fish mortality resulting from passage through dams and reservoirs on the mainstem may be selective for certain of the geographically diverse populations that use the mainstem as a common migratory pathway, thereby reducing biodiversity and increasing the probability of metapopulation extinction (Harrison and Quinn, 1989; Reiman and McIntyre, 1993).

Altered temperature patterns and continual export of very fine organic matter and dissolved nutrients, coupled with simplification of the channel, stabilization of bottom substratum and loss of floodplain inundation, promotes environmental conditions to which native species are poorly adapted, opening opportunities for non-native plants and animals to establish robust populations (Stanford and Ward, 1986; Li *et al.*, 1987; Pflieger and Grace, 1987; Bain *et al.*, 1988; Shannon *et al.*, 1994). In some cases one or a few native species are more abundant than they were before regulation (e.g. Poe *et al.*, 1991). But, the most pervasive result of habitat change produced by regulation is the proliferation of non-native species. Non-native invertebrates and fishes are consistently more abundant in regulated compared with unregulated river reaches (Li *et al.*, 1987; Bain *et al.*, 1988). Native riparian plants cannot exist on dewatered floodplains, which opens niches for exotic, dryland plants. Moreover, owing to loss of scouring flows, exotic and some native riparian plants choke the periodically saturated area of the shoreline above the narrowed varial zone and exotic hydrophytes usually invade and quickly dominate shallow water habitats (Decamps and Tabacchi, 1994; Johnson, 1994). Explicit reasons for non-native proliferation in regulated rivers vary, but, in general, non-natives are simply better competitors in the homogenous habitats of regulated rivers, plus the fact that a wide array of non-natives have been purposely introduced into regulated rivers.

3. *Biophysical conditions reset predictably in relation to influences of tributaries and as distance downstream from the dam increases.* The serial discontinuity concept (SDC) (Ward and Stanford, 1983, 1985b) explicitly acknowledges the inherent connectivity of the river continuum and predicts that the conditions described above will ameliorate downstream as a natural consequence of the biophysical energetics of rivers. The spatial rate at which reset occurs and its manifestation relative to position within the river continuum (Figure 5) is related to the limnological attributes (depth, volume, water retention time, trophic state) of

the reservoir, the mechanics of water release (surface, bottom or depth selective), the mode of dam operations and the influence of tributaries entering downstream from the dam. If the tributaries are large and unregulated, they may substantially mediate the reset (Stanford and Hauer, 1992). In any case, conditions at some point downstream from the dam will closely approximate conditions elsewhere in the continuum. Thus, upstream or downstream shifts in biophysical conditions mediated by dams manifest as predictable discontinuities in the river continuum. For example, biophysical conditions at some predictable point downstream from a large bottom release (hypolimnial) dam in the montane transition of a temperate latitude river will be very similar to pristine conditions far upstream, because of the cool, clear water released from the resevior. In rivers that are free flowing for long distances downstream from large dams in the montane reaches, the position of the rhithron–potomon transition can be predicted from the operational mode of the dams relative to the influence of tributaries.

The predictions of the SDC along the longitudinal dimension have been largely substantiated (Stanford *et al.*, 1988; Ward and Voelz, 1988; Hauer *et al.*, 1989; Stanford and Ward, 1989; Ward and Stanford, 1990, 1991; Munn and Brusven, 1991; Sabater *et al.*, in press), although recent incorporation of responses of large floodplains (Ward and Stanford, 1995b) require additional resolution. The main point is that the ecological consequences of specific regulation schemes are largely predictable, and environmental degradation associated with regulation can be ameliorated. We recognize that uncertainties derive from interactions with pollution and the introduction of exotic biota. However, pollution can be curtailed or eliminated, and non-native biota are likely to be substantially less successful as invaders when dams are operated in ways that maximize resets of environmental heterogeneity.

RESTORATION PROTOCOL

The era of dam building may be over in much of the world because high efficiency and affordable dam sites are already developed. Loss of biodiversity and bioproduction, especially riverine and anadromous fisheries (Frissell, 1993; Welcomme 1995), underscores the need for restoration of regulated rivers and enormously expensive reconstructions are underway or are being planned (Dahm *et al.*, 1995; Gore and Shields, 1995). Even removal of large dams on large rivers is included in some restoration plans because the costs of damage to fisheries and other attributes of riverine integrity in some instances far exceed the commercial value of the dams. Removal of large dams is obviously problematic in a variety of ways, such as the mobilization of large volumes of fine sediments stored in the reservoir basin, and methods for evaluating removal strategies have been proposed (Shuman, 1995). A variety of approaches exist for restoring small streams with substantial emphasis on engineered structures such as weirs, off-channel ponds, rock gardens (Gore and Shields, 1995) and many other artificial habitat structures (Hunter, 1991). Commercial operations advertise engineering expertise for bulldozing damaged streams back to pre-regulation channel configurations and stories of restored fisheries and improved water quality abound in the popular literature, although scientific, long-term evaluations of such schemes are much less available (Sear, 1994). Structures placed instream are often washed out, fail to restore biodiversity or produce unanticipated negative responses, such as increased bank erosion or accelerated deposition of fine sediments (Frissell and Nawa, 1992) and increased water temperatures (C. Frissell, unpublished data) associated with weirs and rock gardens. Such problems largely derive from lack of attention to the conceptual foundations of river ecology and the first principles of the ecology of regulated streams.

Formalize the problem at catchment scale

Restoration of large, regulated rivers begins with recognition of the river continuum and evaluation of the loss of ecosystem capacity to sustain biodiversity and bioproduction. Biological (e.g. past and present distribution of native biota) *and* physical (e.g. channel configuration) indices of ecosystem resilience are needed (Frissell *et al.*, 1993); measures of biological integrity as defined by Angermeier and Karr (1994) may be more useful than biodiversity *per se* because of the difficulty of accurately determining the distribution and abundance of benthos, fish and other river organisms. Habitat requirements for all life history stages and generation times (turnover rates) of native, keystone species (i.e., top carnivores and other strong interactors capable of structuring food-webs: Power *et al.*, 1995) may clarify spatial and temporal scales in large river restorations.

In general, the entire catchment, from headwaters to the ocean, is relevant. In the case of rivers that support anadromous fisheries, estuarine and ocean habitats connect functionally to the riverine components. Mathematical models can be used very effectively to formalize understanding of the effects of regulation and interactions with pollution and food-web manipulation within the river continuum, but models should not be used *exclusively* to define a restoration strategy (Hall, 1988b). The process must be inferential from the entire body of quantitative and qualitative information about how river regulation and interactive effects have altered ecosystem capacity.

Restore environmental (habitat) heterogeneity but let the river do the work

The main goal is to reduce the range of human disturbances so that interconnected riverine habitats (Figures 1 and 2) can support diverse and productive food-webs, including species of special social and economic interest. Management should strive to restore environmental heterogeneity and reduce or eliminate sources of mortality from pollution and overharvest. Keep in mind that riverine biodiversity and bioproduction are largely controlled by abiotic drivers (Figure 3) and that density-dependent relationships, such as the stock-recruitment relations often used to determine fisheries harvest prescriptions, rarely manifest predictably owing to natural abiotic variation (Hall, 1986; Hall, 1988a; Pimm, 1991; Huston, 1994).

Owing to the importance of flow to habitat maintenance, and temperature to food-web energetics, highly significant restoration is possible simply by reregulation to allow more natural seasonality of flow and temperature. We call this restoration of normative habitat conditions, where the norm or standard is established from what is possible in a natural–cultural context as opposed to striving for pristine conditions which are difficult, if not impossible, to define or achieve, at least for entire catchments. Removal of dams certainly should be considered and, where possible, done; but, restoration of normative habitat conditions is possible in many if not most regulated rivers without taking dams out. However, channel revetments are problematic because the objective is to reconnect channels and floodplains.

Peak flows are needed to scour and rearrange substratum and reconnect floodplain habitats with the channel; spatial and temporal temperature variability promotes re-establishment of native biodiversity (Figures 2 and 5). Peak flows needed to re-establish cut and fill alluviation (called effective flows by geomorphologists) may or may not be equal to bank-full, and gravel supply may be limiting owing to storage of bedload in the reservoirs (Ligon *et al.*, 1995). Effective flows can rapidly degrade (downcut) entire segments when sediment mass balance relations change as a consequence of regulation (Andrews and Nelson, 1989). Adding sediments to regulated rivers (e.g. using slurry pipelines from reservoir deltas) should not be out of the realm of consideration in situations where instream sediment supply is limited by years of regulation. However, overbank flows in many cases will initiate cut and fill alluviation in an ecologically effective manner, supplying sufficient sediment from lateral erosion.

We emphasize that reregulation of flows requires careful evaluation of channel morphometry, bed-sediment size distribution and shear stress in relation to the range of possible flows. A great deal of geomorphological study and modelling has been devoted to this problem in recent years (Andrews, 1980; Andrews and Nelson, 1989; Kellerhals and Church, 1989; Deitrich *et al.*, 1993; Church, 1995) and more work is needed. In general, flows that mobilize substrata of median particle diameter will build bars, cut overflow channels and dig pools. Determination of peak flows is complicated by dense, often senescent, thickets of riparian vegetation on the floodplains of regulated rivers. Repeated scouring flows will most likely restore riparian successional vitality. Annual temperature patterns similar to pre-regulation conditions, which will directly mediate restoration of biota, can often be attained by depth selective withdrawal structures on the dams (Gore, 1985).

Of course, restoration of overbank flows may be problematic in many rivers where humans have colonized the floodplains. In these cases, revetments have often been extensively built to restrain flood flows. Reregulation to produce overbank flows may not be practical. However, floods of record will most likely result in overbank flow even in intensely regulated rivers, because natural storage on floodplains throughout the continuum has been drastically diminished. Revetments tend to act as dams during very large floods on

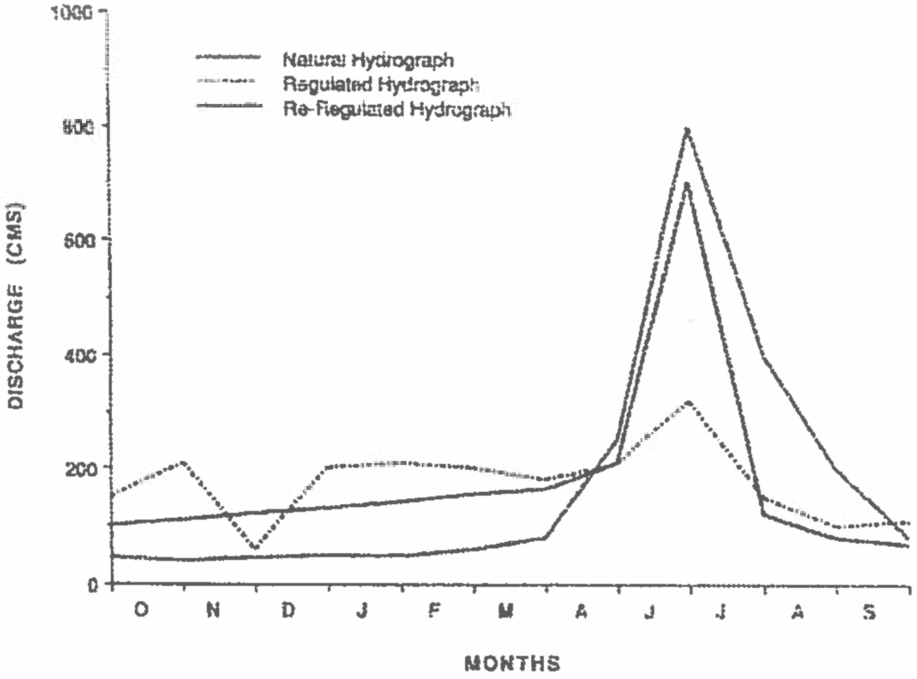

Figure 6. Simulated annual discharge ($m^3/s \times 10$, mean monthly flow) patterns in the Hanford Reach of the Columbia River, USA. The same volume of water passed through the reach in each of the three scenarios (derived from US Geological Survey data, Reston, Virginia, USA)

aggraded rivers and extensive scouring of floodplain surfaces occurs if revetments are breached. Recent floods (1993–1995) of such magnitude in large rivers of western Europe, southern Scandinavia, Bangladesh and the USA provided evidence of the value of vacating floodplains to reduce the human costs and exploit natural flood pulsing (Sparks, 1995)

The strong inference for management is to protect uncolonized floodplains by re-establishing periodic overbank flooding, allowing the river to rebuild habitats. Elsewhere, incentives will be needed to get people to vacate floodplains so that revetments can be removed allowing reconnection of channels and floodplains. If that is not practical or desired by stakeholders, development of strategies for reconnecting severed lowland floodplain wetlands and backwaters by use of lateral flow control structures may be useful (Gore, 1985; Gore and Shields, 1995). In situations where alluvial areas have been inundated, it may be possible to lower permanently the full pool level of the reservoir, allowing riverine cut and fill alluviation to reconfigure and restore drowned floodplains. As in dam removal, this scenario requires careful evaluation because sediment transport dynamics may be different from those that occurred prior to regulation.

Whereas peak flows are needed to restore natural habitat heterogeneity, usually stabilization of baseflow fluctuations will also be needed to revitalize the varial zone of the channel (Figure 1). Establishment of sustained baseflows restores biodiversity and bioproduction in shallow water habitats, which are critically important to benthic insects that must emerge from the shorelines of rivers, and small fishes that must reside on or near substratum in low velocity habitats (Perry and Perry, 1986; Weisberg *et al.*, 1990; Travnichek *et al.*, 1995).

Reregulation in most rivers can be accomplished without substantially compromising storage or hydropower (Figure 6). Peak flows are built from storage and runoff and released in concert with natural runoff timing in the catchment (Figure 4). In wet years, peaks can be reregulated to approach floods of record, depending on the release capability of the dam. Very high flows are not needed every year to maintain instream and floodplain habitats nor is the historical duration of floods likely to be required because most of the sediment is moved on the rising limb of the hydrograph. In years of average catchment water yield, a modest peak flow can be generated, while also elevating baseflow to accomplish the purposes for which the dams were built. In dry years, peak flows can be minimal or non-existent (Figure 4). The strategy is simply to lower the baseflow a little to build peaks in relation to catchment runoff. In all years it is essential to prevent massive dewatering of the varial zone during baseflow periods; explicitly, this means that daily changes in flow (ramping rates) should not exceed the range of variation that occurred before regulation (Figure 4).

Operators of hydroelectric dams may object to reregulation recommendations as depicted in Figure 6, because of the potential constraints on generation of peak power and concern often exists that the legal requirements for electrical load control cannot be met. On the contrary, load control can be performed without ramping flow beyond the range of variation observed in pre-regulation periods (Jourdonnais and Hauer, 1993). Loss of peaking is problematic. However, most large dams are part of large electrical marketing grids and alternatives to hydropower peaking exist today that were not available a decade ago. For example, modern fuel turbines are very effective peaking units, natural gas reserves are large world-wide and local utilities are finding gas-powered turbines to be preferred alternatives to the purchase of regional hydropower. The need for hydropower peaking may wane in the next decade, particularly if the cost of, and public desire for, downstream environmental mitigation increases.

Maximize passage efficiency to allow recovery of metapopulations

Maintenance of instream and floodplain habitats by restoration of peak flows and revitalization of shallow and slack water habitats by stabilization of baseflows will increase ecological connectivitiy along all three spatial dimensions. However, in the absence of dam and reservoir removal, optimization of dam and reservoir passage efficiency for biota is required to reconnect the longitudinal dimension (Figure 2). Mechanisms for significantly reducing mortality of juvenile and adult fish as they pass hydroelectric dams include flowing ladders, travelling screens, surface-release attractors and other bypass devices (Gore, 1985). The main point is that dams with no, or very inefficient, bypass systems maintain the discontinuum and isolate populations, thereby limiting the gene flow that may be needed to restore and maintain metapopulations. On the other hand, the presence of impassable dams in some cases has prevented immigration of non-native species into native food-webs and effectively isolated viable native populations (Stanford and Hauer, 1992).

In many large, regulated rivers, viable populations of native species remain in segments isolated by dams. Restoration of flow and temperature seasonality and reconnection of these refugia may restore critically important core areas, revitalize metapopulation structure and rapidly lead to recovery of genetically and numerically depressed populations (Sedell *et al.*, 1990; DeVore *et al.*, 1995). Indeed, a primary strategy of large river restoration should be to identify, stabilize, restore and reconnect river segments to core areas containing native food-webs. The expectation is that native species will recolonize restored habitat from the core area (Lichatowich *et al.*, 1995; Frissell and Bayles, 1996). The process can be mediated by artificial supplementation (replanting) of the vestigial stock if the native gene pool is properly cultured. However, this strategy is fraught with risk owing to the complexity of locally adapted stocks (Lichatowich *et al.*, 1995). Perhaps a better strategy is to reconnect the beads and allow the biota to adapt. How long this will take is a key question; biology itself can be limiting. Time frames for recovery will probably vary from years to decades depending on the degree of habitat degradation, the strength of normative conditions and the species involved. We note that biota in the rivers devastated by the eruption of Mount St. Helens, Washington, USA, in 1980 returned much sooner than expected (Anderson and Wisseman, 1987; Lamberti *et al.*, 1992; Leider, 1989) and chinook salmon in New Zealand rivers developed locally adapted life histories within 50 years after initial introduction (Quinn and Unwin, 1993).

Minimize planting of cultured stocks

Contemporary fisheries management is based on a belief system that embraces the concept that loss of bioproduction and biodiversity from stream regulation can be mitigated by construction and operation of artificial culture systems. In other words, the belief is that habitat loss caused by stream regulation can be replaced, if not enhanced, by artificial propagation. Perhaps no greater myth exists in ecology. While economically important, non-native salmonid and other fisheries have been established from cultured stocks in river segments world-wide, in almost every case this practice has failed miserably to meet its objective of replacing lost fisheries (Lichatowich, in press). Stocking of native and non-native fish has irresponsibly compromised native food-webs around the world and is rightfully called the Frankenstein Effect (Moyle *et al.*, 1986). A large body of literature debates this problem; the bottom line is that culture operations should be avoided unless native biota are clearly headed for extinction as a consequence of habitat loss (Minckley and Deacon, 1991; Hilborn, 1992). Even then, cultured stocks cannot be expected to re-establish if they are simply released back into the same degraded habitats. Ecological bottlenecks that compromised endangered species in the first place have to be rectified, and the only way to do that in large river systems is to restore habitat in a continuum context.

Be wary of management actions that attempt to control riverine food webs

Perhaps the greatest uncertainty in reregulating river systems to restore hot spot connectivity (Figure 2) is the unexpected consequence of the inexorable proliferation of non-native biota. Wendell Minckley and James Deacon, the sages of fish ecology in the species-rich American Southwest often rightly noted that locally adapted fish of the desert are clearly able to deal with extreme environmental variation, but natives are quickly depressed or driven to extinction by food-web change associated with invasions of non-native species (e.g. Minckley and Douglas, 1991). However, restoration of natural flow and temperature dynamics compromises the ability of non-native species to sustain viable populations and promotes native species (Li *et al.*, 1987; Meffe and Minckley, 1987; Bain *et al.*, 1988). Even with restoration of the full range of natural flow variation, interactions with non-native plants and animals will most likely continue to be a problem for native biodiversity management and conservation.

One alternative is to control non-native populations by aggressive harvest. However, it is very difficult to do this without also affecting natives, and prediction of the influence of the food-web structure is tenuous at best. Moreover, in some cases one or a few native species have become very abundant in regulated rivers along with non-natives. For example, native squawfish (*Ptychocheilus oregonensis*) in the Columbia River, USA, are thought to be a major source of predation mortality for juvenile salmon, which exist in very depressed populations (Poe *et al.*, 1991; Rieman *et al.*, 1991) and a very aggressive control programme has been initiated by paying fishermen a bounty for each squawfish caught. However, food-web structure in the lower Columbia River is poorly known, a wide variety of non-native predators are present and predicting food-web responses as well as influences on salmon mortality is tenuous. A congener (*P. lucius*) in the Colorado River is listed as endangered and a very expensive recovery program has been initiated. For many people these strategies seem at cross-purposes, even though the ecology of the two species is very different.

In general, the effectiveness of predator control programmes is minimal or poorly demonstrated even though it is a very popular management strategy. We agree with Goodrich and Buskirk (1995) that population control of abundant native vertebrates should be a strategy of last resort for conservation of rare natives. Columbia River salmon evolved with squawfish predation and restoration of proper habitats for salmon smolts clearly should reduce smolt mortality. However, constraining proliferation of non-native plants and animals is an obvious need for conservation of native biodiversity.

Again, the preferred approach may be to implement reregulation to restore lost habitat and allow the food-web to adjust as it will. The available body of information suggests that natives will fare better than non-natives. Clearly, it is advisable to document and monitor food-web dynamics carefully from a community ecology perspective.

Use adaptive ecosystem management

Any strategy to remediate the effects of large river regulation will require an adaptive approach. Scientists can be relied upon to document ecological problems by research and synthesis of empirical information on cause and effect, but the solution of problems must involve knowledge of human perceptions and desires, which are often different from that inferred by the strict interpretation of the science (Ludwig *et al.*, 1993). In most cases, inefficient information transfer between science, management, policy makers (government) and the general public hinders the attainment of common ground.

Adaptive ecosystem management (Lee and Lawrence, 1986) is a useful process for solving the catchment-scale problems discussed herein. We agree with Stanford and Poole (1996) who advocate an iterative, step-wise approach that involves synthesis of available information in an ecosystem context to define the problem, public participation in goal setting (e.g. protection and restoration of native biodiversity), research and peer review to define science-based management actions (e.g., reregulation), effective monitoring and evaluation of management actions and adaptive revision of actions based on new information from scientific research.

CONCLUSIONS

Reregulation of large river systems from headwaters to mouth for the purpose of restoring and reconnecting hot spots of native biodiversity and bioproduction has not been accomplished anywhere to date. Our protocol should be viewed as an hypothesis in need of an experimental catchment. Many candidate rivers exist. We recognize that this analysis has not adequately considered the economic and social ramifications of our protocol. A fundamental problem is that the metrics for linking natural and cultural elements of ecosystems remain elusive. Perhaps that shortcoming can be solved through multidisciplinary examination of large river ecosystems using adaptive management. However, the reality is that sustainability of natural attributes of large river ecosystems is vastly compromised by regulation. Site-specific mitigation activities that ignore the biophysical continuum hold little promise and can be very costly when continued without evaluation year after year. The logical alternative is to try restoring biophysical connectivity of an entire regulated river ecosystem using the protocol proposed herein and adapted to the specifics of the selected river. Restoration of some large portion of lost capacity to sustain native biodiversity and bioproduction seems possible, especially in large rivers with a substantial portion of the continuum remaining in a free-flowing state. The cost may be less than expected because the river can do the most of the work.

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REFERENCES

Amoros, C., A. Roux, L., Reygrobellet, J. L., Bravard, J. P. and Pautou, G. 1987. 'A method for applied ecological studies of fluvial hydrosystems', *Regul. Riv.*, 1, 17–36.

Anderson, N. H. and Wisseman, R. W. 1987. 'Recovery of the Trichoptera fauna near Mt. St. Helens five years after the 1980 eruption', in Bournaud, M. and Tachet, H. (Eds), *Proceedings of the 5th International Society on Trichoptera, Junk, Dordrecht, The Netherlands*. pp. 367–373.

Andrewartha, H. G. and Birch, L. C. 1954. *The Distribution and Abundance of Animals*. University of Chicago Press, Chicago. 281 pp.

Andrews, E. D. 1980. 'Effective and bankfull discharges in the Yampa River Basin, Colorado and Wyoming', *J. Hydrol.*, 43, 311–330.

Andrews, E. D. and Nelson, J. M. 1989. 'Topographic response of a bar in the Green River, Utah to variation in discharge', in Ikeda, S. and Parker, G. (Eds), *River Meandering*. American Geophysical Union. pp. 463–485.

Angermeier, P. L. and Karr, J. R. 994. 'Biological integrity versus biological diversity as policy directives', *BioScience*, 44(10), 690–697.

Bachman, R. A. 1983. 'Foraging behavior of free-ranging wild brown trout (*Salmo trutta*) in a stream', *Trans. Am. Fish. Soc.*, 113, 1–32.

Bain, M. B., Finn, J. T. and Booke, H. E. 1988. 'Stream-flow regulation and fish community structure', *Ecology* 69, 382–392.

Baxter, R. M. 1977. 'Environmental effects of dams and impoundments', *Ann. Rev. Ecol. System.*, 8, 255–283.

Benke, A. C., Hall, C. A. S., Hawkins, C. P., Lowe-McConnell, R. H., Stanford, J. A., Suberkropp K. and Ward, J. V. 1988. 'Bioenergetic considerations in the analyses of stream ecosystems', *J. North Am. Benthol. Soc.*, ,7(4), 480–502.

Best, J. L. and Bristow, C. S. (Ed.). 1993. *Braided Rivers*. Geological Society Special Publications The Geological Society, London. 419 pp.

Blikie, P. and Brookfield, H. 1987. *Land Degradation and Society*. Methuen, New York. 453 pp.

Blinn, D. W., Shannon, J. P., Stevens L. E. and Carder, J. P. 1995. 'Consequences of fluctuating discharge for lotic communities', *J. North Am. Benthol. Soc.*, 14, 233–248.

Brett, J. R. 1971. 'Energetic responses of salmon to temperature. A study of some thermal relations in the physiology and freshwater ecology of sockeye salmon (*Oncorhynchus nerka*)'. *Am. Zool.*, 11, 99–113.

Brown, J.H. and Kodric-Brown, A. 1977. 'Turnover rates in insular biogeography: effects of immigration on extinction', *Ecology*, 58, 445–449.

Calow, P. and Petts, G. E. (Eds), 1992. *The Rivers Handbook. Volume 1, Hydrological and Ecological Principles*. Blackwell Scientific, Oxford.

Church, M. 1995. 'Geomorphic response to river flow regulation: case studies and time-scales', *Reg. Riv.*, 11(1), 3–22.

Connell, J. H. 1978. Diversity in tropical rain forests and coral reefs', *Science*, 199, 1302–1310.

Connor, J. E. 1993. *Hydrology, Hydraulics and Geomorphology of the Bonneville Flood*. US Geological Survey Special Paper 274. US Govt. Printing Office, Washington.

Copp, G. H. 1989. 'The habitat diversity and fish reproductive function of floodplain ecosystems', *Environ. Biol. Fishes*, 26, 1–27.

Cummins, K. W., Minshall, G. W., Sedell, J. R., Cushing, C. E. and Petersen, R. C. 1984. 'Stream ecosystem theory', *Verh. Internat. Verein. Theor. Angew. Limnol.*, 22, 1818–1827.

Cummins, K. W., Wilzbach, M. A., Gates, D. M., Perry, J. B. and Taliaferro, W. B. 1989. 'Shredders and riparian vegetation. Leaf litter that falls into streams influences communities of stream invertebrates', *BioScience*, 39(1), 24–30.

Cushman, R. M. 1985. 'Review of ecological effects of rapidly varying flows downstream of hydroelectric facilities', *North Am. J. Fisheries Man.*, 5, 330–339.

Dahm, C. N., Cummins, K. W., Valett, H. M. and Coleman, R. L. 1995. 'An ecosystem view of the restoration of the Kissimmee River', *Restoration Ecol.*, 3(3), 225–238.

Davies, B. R. and Walker, K. F. (Ed.), 1986. *The Ecology of River Systems*. Dr. W. Junk, Dordrecht, The Netherlands. 793 pp.

Decamps, H. and Tabacchi, E. 1994. 'Species richness in vegetation along river margins', in Giller, P. S., Hildrew, A. G. and Raffaelli, D. G. (Eds), *Aquatic Ecology: Scale, Pattern and Process*. Blackwell Scientific Publications, London.

DeVore, J. D., James, B. W., Tracy, C. A. and Hale, D. A. 1995. 'Dynamics and potential production of white sturgeon in the unimpounded Lower Columbia River', *Trans. Am. Fish. Soc.*, 124(6), 845–856.

Dolan, R., Howard, A. and Trimble, D. 1978. 'Structural control of the rapids and pools of the Colorado River in the Grand Canyon', *Science*, 202, 629–631.

Doppelt, B., Scurlock, M., Frissell, C. and Karr, J. 1993. *Entering the Watershed*. Island Press, Washington, D.C. 462 pp.

Dynesius, M. and Nilsson, C. 1994. 'Fragmentation and flow regulation of river systems in the northern third of the world', *Science*, 266, 753–762.

Ebersole, J.L., Liss, W.J. and Frissell, C.A. In press. 'Restoration of stream habitats in managed landscapes in the western USA: restoration as re-expression of habitat capacity', *Environ. Manage.*

Frissell, C. A. 1993. 'Topology of extinction and endangerment of native fishes in the Pacific northwest and California (U.S.A.)', *Conservation Biol.*, 7(2), 342–354.

Frissell, C. A. and Bayles, D. 1996. Ecosystem management and the conservation of aquatic biodiversity and ecological integrity', *Wat. Res. Bull.*, 32, 229–240.

Frissell, C. A. and Nawa R. K. 1992. 'Incidence and causes of physical failure of artificial habitat structures in streams of western Oregon and Washington', *North Am. J. Fish. Manage.*, 12, 182–197.

Frissell, C. A., Liss W. J. and Bayles, D. 1993. 'An integrated, biophysical strategy for ecological restoration of large watersheds', in Spangenborg, N. E. and Potts, D. E. (Ed.), *Proceedings of the Symposium on Changing Roles in Water Resources Management and Policy*. American Water Resources Association, Bethesda. pp. 449–456.

Frissell, C. A., Liss, W. J., Gresswell, R. E., Nawa, R. K. and Ebersole, J. L. In press. 'A resource in crisis: changing the measure of salmon management', in Stouder, D. J., Bisson, P. A. and Naiman, R. J. (Eds). *Pacific Salmon and their Ecosystems: Status and Future Options*. Chapman & Hall, New York.

Gibert, J., Dole-Olivier, M. J., Marmonier, P. and Vervier, P. 1990. 'Surface water-groundwater ecotones', in Naiman, R. J. and Decamps, H. (Eds), *Ecology and Management of Aquatic-Terrestrial Ecotones*. Partenon Publ., London. pp. 199–255.

Gislason, G. M. 1985. 'The life cycle and production of *Simulium vittatum* Zett. in the River Laxa, North-East Iceland', *North Am. J. Fish. Manage.*, 22, 3281–3287.

Goodrich, J. M. and Buskirk, S. W. 1995. 'Control of abundant native vertebrates for conservation of endangered species', *Conservation Biol.*, 9(6), 1357–1364.

Gore, J. A., (Ed.), 1985. *The Restoration of Rivers and Streams. Theories and Experience*. Butterworth Publishers, Stoneham. 280 pp.

Gore, J. A. and Shields, J. F. D. 1995. 'Can large rivers be restored?', *BioScience*, 45(3), 142–152.

Gotelli, N.J. 1991. 'Metapopulation models: the rescue effect, the propagule rain, and the core-satellite hypothesis', *American Naturalist*, 138, 768–776.

Gregory, S. V., Swanson, F. J., McKee, W. A. and Cummins, K. W. 1991. 'An ecosystem perspective of riparian zones', *BioScience*, 41(8), 540–551.

Hall, C. A. S. 1986. 'The changing intellectual climate of fisheries management', *Environ. Manage.*, 10(3), 331–334.

Hall, C. A. S. 1988a. 'An assessment of several of the historically most influential theoretical models used in ecology and of the data provided in their support', *Ecol. Model.*, 43, 5–31.

Hall, C. A. S. 1988b. 'What constitutes a good model and by whose criteria?', *Ecol. Model.*, 43, 125–127.

Hall, C. A. S., Stanford, J. A. and Hauer, F. R. 1992. 'The distribution and abundance of organisms as a consequence of energy balances along multiple environmental gradients', *Oikos*, 65, 377–390.

Hanski, I. 1991. 'Single species metapopulation dynamics' concepts, models and observations', *Biol. J. Linnean Soc.*, 42, 17–38.

Hanski, I. and Gilpin, M. 1991. 'Metapopulation dynamics: brief history and conceptual domain', *Biol. J. Linnean Soc.*, 42, 3–16.

Harmon, J. R. and Park, D. L. 1980. 'Evaluation of a bypass sytem for juvenile salmonids at Little Goose Dam', *Marine Fish. Rev.*, June, 25–28.

Harrison, S. 1991. 'Local extinction in a metapopulation context: an empirical evaluation', *Biol. J. Linnean Soc.*, 42, 73–88.

Harrison, S. 1994. 'Metapopulations and conservation', in Edwards, P. J., May, R.M. and Webb, N.R. (Eds), *Large-scale Ecology and Conservation Biology*. Blackwell Scientific Publications, Oxford. 375 pp.

Harrison, S. and Quinn, J.F. 1989. 'Correlated environments and the persistence of metapopulations'. *Oikos*, **56**, 293–298.

Hauer, F. R., Stanford, J. A. and Ward, J. V. 1989. 'Serial discontinuities in a Rocky Mountain river. II. Distribution and abundance of Trichoptera'. *Regul. Riv. Res.*, **3**, 177–182.

Hilborn, R. 1992. 'Hatcheries and the future of salmon in the Northwest'. *Fisheries*, **17**(1), 5.

Hunter, C. J. 1991. *Better Trout Habitat: A Guide to Stream Restoration and Management*. Island Press, Washington, D.C. 320 pp.

Huntington, C., Nehlsen, W. and Bowers, J. 1996. 'A survey of healthy native stocks of anadromous salmonids in the Pacific Northwest and California'. *Fisheries*, **21**, 6–14.

Huston, M. 1979. 'A general hypothesis of diversity', *American Naturalist*, **113**, 81–101.

Huston, M. A. 1994. *Biological Diversity. The Coexistence of Species on Changing Landscapes*. Cambridge University Press, Cambridge. 681 pp.

Hynes, H. B. N. 1966. *The Biology of Polluted Waters*. Liverpool University Press, Liverpool. 202 pp.

Hynes, H. B. N. 1975. 'The stream and its valley', *Verh. Intern. Verein. Theor. Angew. Limnol.*, **19**, 1–15.

Illies, J. 1956. 'Seeausfluss-Biozönosen lappländischer Waldbäche', *Ent. Tidskr.*, **77**, 138–153.

Illies, J. and Botosaneanu, L. 1963. 'Problemes et methodes de la classification et de la zonation ecologique des eaux courantes, considerees surtout du point de vue faunistique', *Mitteil. Internat. Verein. Theor. Angew. Limnol.*, **12**, 1–57.

Johnson, W. C. 1994. 'Woodland expansion in the Platte River, Nebraska: patterns and causes', *Ecol. Monographs*, **64**(1), 45–84.

Jourdonnais, J. H. and F. R. Hauer. 1993. 'Electrical frequency control and its effects on flow and river ecology in the lower Flathead River, Montana', *Rivers*, **4**(2), 132–145.

Junk, W. J. and Piedade M. T. F. 1994. 'Species diversity and distribution of herbaceous plants in the floodplain of the middle Amazon', *Verh. Internat. Verein. Theor. Angew. Limnol.*, **25**, 1862–1865.

Junk, W. J., Bayley, P. B. and Sparks, R. E. 1989. 'The flood pulse concept in river-floodplain systems' in Dodge, D. P. (Ed.), *Proc. Int. Large River Symposuim, Can. Spec. Publ. Fish. Aquat. Sci.*, **106**, 110–127.

Heiler, G., Hein, T., Schiemer, F. and Bornette, G. 1995. 'Hydrological connectivity and flood pulses as the central aspects for the integrity of a river–floodplain system'. *Regul. Riv*, **11**(3/4), 351–361.

Kellerhals, R. and Church, M. 1989. 'The morphology of large rivers: characterization and management', *Can. Spec. Publ. Fish. Aquat. Sci.*, **106**, 31–48.

Kondolf, G. M. and Larson, M. 1995. 'Historical channel analysis and its application to riparian and aquatic habitat restoration', *Aqua. Conserv. Mar. Freshwater Ecosystems*, **5**(2), 109–126.

Krueger, C. C. and Waters, T. F. 1983. 'Annual production of macroinvertebrates in three streams of different water quality', *Ecology*, **64**, 840–850.

Lamberti, G. A., Gregory, S. V., Hawkins, C. P., Wildman, R. C., Ashkenas, L. R. and Denicola, D. M. 1992. 'Plant herbivore interactions in streams near Mount St Helens', *Freshwater Biol.*, **27**, 237–247.

Lee, K. N. and Lawrence J. 1986. 'Adaptive management: learning from the Columbia River Basin fish and wildlife program', *Environ. Law*, **16**, 431–460.

Leider, S. A. 1989. 'Increased straying by adult steelhead trout, *Salmo gairdneri*, following the 1980 eruption of Mount St. Helens', *Environ. Biol. Fishes*, **24**, 219–229.

Leopold, L. B., Wolman, M. G. and Miller, J. P. 1964. *Fluvial Processes in Geomorphology*. W. H. Freeman and Co., San Francisco. 522 pp.

Li, H. W., Schreck, C. B., Bond, C. E. and Rexstad, E. 1987. 'Factors influencing changes in fish assemblages of Pacific Northwest streams', in Matthews, W. J. and Heins, D. C. (Eds), *Community and Evolutionary Ecology of North American Stream Fishes*. University of Oklahoma Press, Norman. pp. 193–202.

Li, H. Currens, W., K., Bottom, D., Clarke, S., Dambacher, J., Frissell, C., Harris, P., Hughes, R. M., McCullough, D., McGie, A., Moore, K. and Thiel, S. in press. 'Safe havens: refuges and evolutionarily significant units', *Am. Fish. Soc. Symp.*, **17**.

Lichatowich, J. in press. 'Evaluating the performance of salmon management institutions: the importance of performance measures, temporal scales and production cycles', in Stouder, D. J., Bisson, P. A. and R. J. Naiman (Eds), *Pacific Salmon and Their Ecosystems*. Chapman & Hall, New York.

Lichatowich, J. A. and Mobrand, L. E. 1995. Analysis of Chinook salmon in Columbia River from an Ecosystem Perspective. US Department of Energy, Banneville Power Administration, Portland, Oregon. 102 pp.

Lichatowich, J., Mobrand, L., Lestelle, L. and Vogel, T. 1995. 'An approach to the diagnosis and treatment of depleted Pacific salmon populations in Pacific Northwest watersheds', *Fisheries*, **20**(1), 10–18.

Ligon, F. K., Dietrich, W. E. and Trush, W. J. 1995. 'Downstream ecological effects of dam', *BioScience*, **45**(3), 183–192.

Lillehammer, A. and Saltveit, S. J. (Eds). 1984. *Regulated Rivers*. Oslo University Press, Oslo. 540 pp.

Lowe-McConnell, R. H. 1987. *Ecological Studies in Tropical Fish Communities*. Cambridge University Press, Cambridge.

Lubchenco, J., Olson, A. M., Brubaker, L. B., Carpenter, S. R., Holland, M. M., Hubbell, S. P., Levin, S. A., MacMahon, J. A., Matson, P. A., Melillo, J. M., Mooney, H. A., Peterson, C. H., Pulliam, H. R., Real, L. A., Regal, P. J. and Risser, P. G. 1991. 'The sustainable biosphere initiative: An ecological research agenda', *Ecology*, **72**(2), 371–412.

Ludwig, D., Hillborn R. and Walters, C. 1993. 'Uncertainty, resource exploitation and conservation: Lessons from history', *Science* **260**, 17–36.

Mangin, A. 1994. 'Karst hydrogeology', in Gibert, J., Danielopol, D. L. and Stanford, J. A. (Eds), *Groundwater Ecology*. Academic Press, Inc., San Diego, California. pp. 43-68.

McAuliffe, J. R. 1983. 'Competition, colonization patterns and disturbance in stream benthic communities', in Barnes, J. R. and Minshall, G. W. (Eds.), *Stream Ecology: Application and Testing of General Ecological Theory*. Plenum Press, New York. 399 pp.

McAuliffe, J. R. 1984. 'Competition for space, disturbance, and the structure of a benthic stream community', *Ecology*, **65**, 894–908.

Meffe, G. K. and Minckley W. L. 1987. 'Persistence and stability of fish and invertebrate assemblages in a repeatedly disturbed Sonoran Desert stream', *Am. Midland Naturalist*, **117**, 177–191.

Milner, A. M. and Bailey, R. G. 1989. 'Salmonid colonization of new streams in Glacier Bay National Park, Alaska', *Aquaculture Fish Manage.*, **20**, 179–192.

Minckley, W. L. and Deacon, J. E. (Eds). 1991. *Battle Against Extinction. Native Fish Management in the American West*. University of Arizona Press, Tucson. 535 pp.

Minckley, W. L. and Douglas, M. E. 1991. 'Discovery and extinction of western fishes: a blink of the eye in geologic time', in Minckley, W. L. and Deacon, J. E. (Eds), *Battle Against Extinction: Native Fish Management in the American West*. University of Arizona Press, Tucson. pp. 7-17.

Minshall, G. W. 1978. 'Autotrophy in stream ecosystems', *BioScience*, 28(12), 767–771.

Minshall, G. W., Petersen, R. C., Cummins, K. W., Bott, T. L., Sedell, J. R., Cushing, C. E. and Vannote, R. L. 1983. 'Interbiome comparison of stream ecosystem dynamics' *Ecol. Monographs.*, 53, 1–25.

Mooney, H. A. and Drake, J. A. (Eds). 1986. *Ecology of Biological Invasions of North America and Hawaii*, Springer-Verlag, New York.

Moyle, P. B. and Leidy, R. A. 1992. 'Loss of biodiversity in aquatic ecosystems: evidence from fish faunas', in Fielder, P. L. and Jain, S. K. (Ed.), *Conservation Biology: The Theory and Practice of Nature, Conservation, Preservation and Management*. Chapman and Hall, New York. pp. 128–169.

Moyle, P. B., Li H. W. and Barton, B. A. 1986. 'The Frankenstein effect: Impact of introduced fishes on native fishes in North America', in Stroud, R. H. (Ed.), *Fish Culture in Fisheries Manag.*. Am. Fish. Soc., Maryland. pp. 415–426.

Munn, M. and Brusven, M. A. 1991. 'Benthic macroinvertebrate communities in nonregulated and regulated waters of the Clearwater River, Idaho', *Regul. Riv.*, 6, 1–11.

Naiman, R. J., Melillo, J. M., Lock, M. A., Ford, T. E. and Reice, S. R. 1987. 'Longitudinal patterns of ecosystem processes and community structure in a subarctic river continuum', *Ecology*, 68, 1139–1156.

Naiman, R. J., Decamps, H., Pastor, J. and Johnston, C. A. 1988. 'The potential importance of boundaries to fluvial ecosystems', *J. North Am. Benthol. Soc.*, 7(4), 289–306.

Naiman, R. J., Magnuson, J. J., McKnight, D. M. and Stanford, J. A. (Eds). 1995a. *Freshwater Imperative: A Research Agenda*, 1st edn., Island Press, Washington, D.C. 165 pp.

Naiman, R. J., Magnuson, J. J., McKnight, D. M., Stanford, J. A. and Karr, J. R. 1995b. 'Freshwater ecosystems and their management: a national initiative', *Science*, 270(5236), 584–585.

National Research Council. 1995. *Upstream: Salmon and Society in the Pacific Northwest*. National Academy of Sciences, Washington, D.C. 388 pp.

Nehlsen, W., Williams, J. E. and Lichatowich, J. A. 1991. 'Pacific salmon at the crossroads: stocks at risk from California, Oregon, Idaho, and Washington', *Fisheries*, 16(2), 4–21.

Newbold, J. D., Elwood, J. W., O'Neill, R. V. and Van Winkle, W. 1981. 'Measuring nutrient spiralling in streams', *Can. J. Fish. Aquat. Sci.*, 38(7), 860–863.

Newbold, J. D., O'Neill, R. V., Elwood, J. W. and Van Winkle, W. 1982. 'Nutrient spiralling in streams: implications for nutrient limitation and invertebrate activity', *American Naturalist*, 120(5), 628–652.

Noss, R. F. and Cooperrider, A. Y. 1994. *Saving Nature's Legacy: Protecting and Restoring Biodiversity*. Island Press, Washington, D.C.

Perry, S. A. and Perry, W. B. 1986. 'Effects of experimental flow regulation on invertebrate drift and stranding in the Flathead and Kootenai Rivers, Montana, USA', *Hydrobiologia*, 134, 171–182.

Perry, S. A. and Sheldon, A. L. 1986. 'Effects of exported seston on aquatic insect faunal similarity and species richness in lake outlet streams in Montana, USA', *Hydrobiologia*, 137, 65–77.

Petts, G. E. and Wood, R. (Eds). 1988. 'River regulation in the United Kingdom', *Regul. Riv.*, 2(3).

Petts, G. E., Moller, H. and Roux, A. L. (Ed.). 1989. *Historical Change of Large Alluvial Rivers: Western Europe*. John Wiley & Sons, Chichester. 355 pp.

Pflieger, W. L. and Grace, T. B. 1987. 'Changes in the fish fauna of the Lower Missouri River, 1940–1983', in Matthews, W. J. and Heins, D. C. (Eds), *Community and Evolutionary Ecology of North American Stream Fishes*. University of Oklahoma Press, Norman. pp. 166–177.

Pimm, S. L. 1991. *The Balance of Nature? Ecological Issues in the Conservation of Species and Communities*. University of Chicago Press, Chicago. 447 pp.

Poe, T. P., Hansel, H. C., Vigg, S., Palmer, D. E. and Prendergast, L. A. 1991. 'Feeding of predaceous fishes on out-migrating salmonids in John Day Reservoir, Columbia River', *Trans. Am. Fish. Soc.*, 120(4), 405–420.

Poff, N. L. and Allan, J. D. 1995. 'Functional organization of stream fish assemblages in relation to hydrological variability', *Ecology*, 76(2), 606–627.

Poff, N. L. and Ward, J. V. 1990. 'Physical habitat template of lotic systems: recovery in the context of historical pattern of spatiotemporal heterogeneity', *Environ. Manage.*, 14, 629–645.

Power, M. E., Sun, A., Parker, G., Dietrich, W. E. and Wootton, J. T. 1995. 'Hydraulic food-chain models', *BioScience*, 45(3), 159–167.

Quinn, T. P. and Unwin, M. J. 1993. 'Variation in life history patterns among New Zealand chinook salmon (*Oncorhynchus tshawytscha*) populations', *Can. J. Fish. Aquat. Sci.*, 50, 1414–1421.

Regier, H. A., Welcomme, R. L., Stedman, R. J. and Henderson, H. F. 1989. 'Rehabilitation of degraded river ecosystems', in *Proceedings, of the International Large River Symposium*. Can. Spec. Publ. Fish. Aquat. Sci., pp. 86-89.

Reice, S. R. 1994. 'Nonequilibrium determinants of biological community structure', *American Scientist*, 82(5), 424–435.

Reisenbichler, R. R., McIntyre, J. D., Solazzi, M. F. and Landino, S. W. 1992. 'Genetic variation in steelhead of Oregon and Northern California', *Trans. Am. Fish. Soc.*, 121, 158–169.

Resh, V. H., Brown, A. V.,ACovich, . P., Gurtz, M. E., Li, H. W., Minshall, G. W., Reice, S. R., Sheldon, A. L., Wallace, J. B. and Wissmar, R. C. 1988. 'The role of disturbance in stream ecology', *J. North Am. Benthol. Soc.*, 7, 433–455.

Rieman, B. E. and McIntyre, J. D. 1993. 'Demographic and habitat requirements for conservation of bull trout', *Report number INT-308*, US Forest Service, Intermountain Research Station, Boise, Idaho, USA. 38 pp.

Rieman, B. E. and McIntyre, J. D. 1995. 'Occurrence of bull trout in naturally fragmented habitat patches of varies size', *Trans. Am. Fish. Soc.*, 124(3), 285–296.

Rieman, B. E., Beamesderfer, R. C., Vigg, S. and Poe, T. P. 1991. 'Estimated loss of juvenile salmonids to predation by northern squawfish, walleyes, and smallmouth bass in John Day reservoir, Columbia River', *Trans. Am. Fish. Soc.*, 120, 448–458.

Roth, N. E., Allan, J. D. and Erickson, D. L. in press. 'Landscape influences on stream biotic integrity assessed at multiple spatial scales', *Landscape Ecol.*

Sabater, F., Armengol, J. and Sabater, S. 1989. 'Measuring discontinuities in the Ter River', *Regul. Riv.* 3, 133–142.

Salo, J., Kalliola, R., Häkkinen, I., Mäkinen, P., Niemelä, Puhakka, M. and Coley, P. D. 1986. 'River dynamics and the diversity of Amazon lowland forest', *Nature*, 322, 254–258.

Schinberg, A. and Gould, K. A. 1994. *Environment and Society: the Enduring Conflict*. St. Martins Press, New York. 324 pp.

Schlosser, I. J. and Angermeier, P. L. 1995. 'Spatial variation in demographic processes of lotic fishes: conceptual models, empirical evidence, and implications for conservation', *Am. Fish. Soc. Symp.*, 17, 392–401.

Schoener, T. 1991. 'Extinction and the nature of the metapopulation', *Acta Oecologia*, 12, 53–75.

Schumm, S. A. and Lichty, R. W. 1956. 'Time, space and causality in geomorphology', *Am. J. Sci.*, 263, 110–119.

Sear, D. A. 1994. 'River restoration and geomorphology', *Aquat. Conserv. Marine Freshwater Ecosystems*, 4, 169–177.

Sedell, J. R., Reeves, G. H., Hauer, F. R., Stanford, J. A. and Hawkins, C. P. 1990. 'Role of refugia in recovery from disturbances: modern fragmented and disconnected river systems', *Environ. Manage.*, 14(5) 711–724.

Shannon, J. P., Blinn, D. W. and Stevens, L. E. 1994. 'Trophic interactions and benthic animal community structure in the Colorado River, Arizona, U.S.A.', *Freshwater Biol.*, 31, 213–220.

Shuman, J. R. 1995. 'Environmental considerations for assessing dam removal alternatives for river restoration', *Regul. Riv.*, 11(3/4), 249–261.

Simons, D. B. 1979. 'Effects of stream regulation on channel morphology', in Ward, J. V. and Stanford, J. A. (Eds), *The Ecology of Regulated Streams*. Plenum Press, New York. pp. 95-111.

Southwood, T. R. E. 1977. 'Habitat, the templet for ecological strategies?', *J. Animal Ecol.*, 46, 337–365.

Southwood, T. R. E. 1978. *Ecological Methods*, 2nd edn., Chapman & Hall, London. 524 pp.

Sparks, R. E. 1995. 'Need for ecosystem management of large rivers and their floodplains', *BioScience*, 45(3), 168–182.

Sparks, R. E., Bayley, P. B., Kohler, S. L. and Osborne, L. L. 1990. 'Disturbance and recovery of large floodplain rivers', *Environ. Manage.*, 14, 699–709.

Spencer, C. N., McClelland, B. R. and Stanford, J. A. 1991. 'Shrimp stocking, salmon collapse, and eagle displacement: cascading interactions in the food-web of a large aquatic ecosystem', *BioScience*, 41(1), 14–21.

Stacy, P. B. and Taper, M. 1992. 'Environmental variation and the persistence of small populations', *Ecol. Appl.*, 2, 18–29.

Stanford, J. A. 1996. 'Landscapes and catchment basins', in Hauer, F. R. and Lamberti, G. A. (Eds), *Methods in Stream Ecology*. Academic Press, San Diego. pp. 3–22.

Stanford, J. A. and Hauer, F. R. 1992. 'Mitigating the impacts of stream and lake regulation in the Flathead River Catchment, Montana, USA: an ecosystem perspective', *Aquat. Conserv.*, 2, 35–63.

Stanford, J. A. and Hauer, F. R. (Eds) 1993. 'Fifth International Symposium on Regulated Streams', *Regul. Riv.*, 8(1/2).

Stanford, J. A., Hauer, F. R. and Ward, J. V. 1988. 'Serial discontinuity in a large river system', *Verh. Internat. Verein. Theor. Angewa. Limnol.*, 23, 1114–1118.

Stanford, J. A. and Poole, G. C. in press. 'A protocol for ecosystem management', *Ecol. Applic.*

Stanford, J. A. and Ward, J. V. 1986. 'Fish of the Colorado system', in Davies, B. R. and Walker, K. F. (Eds), *The Ecology of River Systems*. Dr. W. Junk Publishers, Dordrecht, The Netherlands. pp. 385–402.

Stanford, J. A. and Ward, J. V. 1989. 'Serial discontinuities in a Rocky Mountain river. I. Distribution and abundance of Plecoptera', *Regul. Riv.*, 3, 169–175.

Stanford, J. A. and Ward, J. V. 1992. 'Management of aquatic resources in large catchments: Recognizing interactions between ecosystem connectivity and environmental disturbance', in Naiman, R. J. (Ed.), *Watershed Management*. Springer-Verlag, New York. pp. 91–124.

Stanford, J. A. and Ward, J. V. 1993. 'An ecosystem perspective of alluvial rivers: connectivity and the hyporheic corridor', *J. North Am. Benthol. Soc.*, 12(1), 48–60.

Statzner, B., Gore, J. A. and Resh, V. H. 1988. 'Hydraulic stream ecology: Observed patterns and potential applications', *J. North Am. Benthol. Soc.*, 7(4), 307–360.

Stevens, L. E., Shannon, J. P. and Blinn, D. W. in press. 'Colorado River benthic ecology in Grand Canyon, Arizona: dam, tributary and geomorphic influences', *Reg. Riv.*

Taylor, E.B. 1991. 'A review of local adaptation in Salmonidae, with particular reference to Pacific and Atlantic salmon', *Aquaculture*, 98, 185–207.

Toth, L. A., Obeysekera, J. T. B., Perkin, W. A. and Loftin, M. K. 1993. 'Flow regulation and restoration of Florida's Kissimmee River', *Reg. Riv.*, 8(1/2), 155–166.

Townsend, C. R. 1989. 'The patch dynamics concept of stream community ecology', *J. North Am. Benthol. Soc.*, 8, 36–50.

Travnichek, V. H., Bain, M. B. and Maceina, M. J. 1995. 'Recovery of a warmwater fish assemblage after the initiation of a minimum-flow release downstream from a hydroelectric dam', *Trans. Am. Fish. Soc.*, 124(6), 836–844.

Valett, H. M. and Stanford, J. A. 1987. 'Food quality and hydropsychid caddisfly density in a lake outlet stream in Glacier National Park, Montana, USA', *Can. J. Fish. Aquat. Sci.*, 44, 77–82.

Van Dijk, G. M., Marteijn, E. C. L. and Schulte-Wülwer-Leidig, A. 1995. 'Ecological rehabilitation of the River Rhine: plans, progress and perspectives', *Regul. Riv.*, 11(34), 377–388.

Vannote, R. L. and Sweeney, B. W. 1980. 'Geographic analysis of thermal equilibria: a conceptual model for evaluating the effect of natural and modified thermal regimes on aquatic insect communities', *American Naturalist*, 115(5), 667–695.

Vannote, R. L., Minshall, G. W., Cummins, K. W., Sedell, J. R. and Cushing, C. E. 1980. 'The river continuum concept', *Can. J. Fish. Aquat. Sci.*, 37(1), 130–137.

Ward, J. V. 1984. 'Stream regulation of the upper Colorado River: Channel configuration and thermal heterogeneity', *Verh. Int. Verein. Theor. Angew. Limnol.*, 22, 1862–1866.

Ward, J. V. 1985. 'Thermal characteristics of running waters', *Hydrobiologia*, 125, 31–46.

Ward, J. V. in press. 'Riverine landscapes: biodiversity patterns, disturbance regimes and aquatic conservation', *Biol. Conserv.*

Ward, J. V. and Dufford, R. G. 1979. 'Longitudinal and seasonal distribution of macroinvertebrates and epilithic algae in a Colorado springbrook-pond system', *Arch. Hydrobiologia*, 86(3), 284–321.

Ward, J. V. and Stanford, J. A. (Ed). 1979. *The Ecology of Regulated Streams*. Plenum Press, New York. 398 pp.

Ward, J. V. and Stanford, J. A. 1982. 'Thermal responses in the evolutionary ecology of aquatic insects', *Ann. Rev. Entomol.*, 27, 97–117.

Ward, J. V. and Stanford, J. A. 1983a. 'The serial discontinuity concept of lotic ecosystems', in Fontaine III, T. D. I. and Bartell, S. M. (Eds), *Dynamics of Lotic Ecosystems*. Ann Arbor Science Publishers, Ann Arbor. pp. 29–42.

Ward, J. V. and Stanford, J. A. 1983b. 'The intermediate-disturbance hypothesis: An explanation for biotic diversity patterns in lotic ecosystems', in Fontaine III, T. D. and Bartell, S. M. (Eds), *Dynamics of Lotic Ecosystems*. Butterworth, Kent.

Ward, J. V. and Stanford, J. A. 1987. 'The ecology of regulated streams: Past accomplishments and directions for future research', in Craig, J. F. and Kemper, J. B. (Eds.), *Regulated Streams-Advances in Ecology*. Plenum, New York.

Ward, J. V. and Stanford, J. A. 1991. 'Benthic faunal patterns along the longitudinal gradient of a Rocky Mountain river system', *Verh. Intern. Verein. Theor. Angew. Limnol.*, 24, 3087–3094.

Ward, J. V. and Stanford, J. A. 1995a. 'Ecological connectivity in alluvial river ecosystems and its disruption by flow regulation', *Regul. Riv.*, 11, 105–120.

Ward, J. V. and Stanford, J. A. 1995b. 'The serial discontinuity concept: extending the model to floodplain rivers', *Regul. Riv.*, 10, 159–168.

Ward, J. V. and Voelz, N. J. 1988. 'Downstream effects of a large, deep-release, high mountain reservoir on lotic zoobenthos', *Verh. Internat. Verein. Theor. Angew. Limnol.*, 23, 1174–1178.

Ward, J. V. and Wiens, J. A. in press. 'Ecotones of riverine ecosystems: role and typology, spatio-temporal dynamics, and river regulation', in Zalewksi, M., F. Schiemer and Thorpe, J. (Eds), *Inland Water Ecotones*. Cambridge University Press, Cambridge.

Warren, C. E. 1971. *Biology and Water Pollution Control*. W. B. Saunders, Philadelphia. 434 pp.

Warren, C.E., Allen, M.J. and Haefner, J.W. 1979. 'Conceptual frameworks and the philisophical foundations of general living systems theory', *Behavioral Science*, 24, 296–310.

Waters, T. F. 1995. *Sediment in Streams: Sources, Biological Effects and Control*. American Fisheries Society, Bethesda. 251 pp.

Waters, T. F., Doherty, M. T. and Krueger, C. C. 1990. 'Annual production and production: biomass ratios for three species of stream trout in Lake Superior tributaries', *Trans. Am. Fish. Soc.*, 119, 470–474.

Weisberg, S. B., Janicki, A. J., Gerritsen, J. and Wilson, H. T. 1990. 'Enhancement of benthic macroinvertebrates by minimum flow from a hydroelectric dam', *Regul. Riv.*, 5, 265–277.

Welcomme, R. L. 1979. *Fisheries Ecology of Floodplain Rivers*. Longman. 317 pp.

Welcomme, R. L. 1995. 'Relationships between fisheries and the integrity of river systems', *Reg. Riv.*, 11(1), 121–136.

Wissmar, R. C., Smith, J. E., McIntosh, B. A., Li, H. W., Reeves, G. H. and Sedell, J. R. 1994. 'A history of resource use and disturbance in riverine basins of eastern Oregon and Washington (early 1800s–1990s)', *Northwest Sci.*, 68, 1–35.

Wooton, R. S. 1987. 'The ecology of lake-outlet black flies', in Kim, K. C. and Merritt, R. W. (Eds), *Black Flies*. The Pennsylvania State University, University Park, Pennsylvania. pp. 146–154.

Zwick, P. 1992. 'Stream habitat fragmentation – a threat to biodiversity', *Biodiversity Conservation*, 1, 80–97.

Biocomplexity and fisheries sustainability

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A classic example of a sustainable fishery is that targeting sockeye salmon in Bristol Bay, Alaska, where record catches have occurred during the last 20 years. The *stock complex* is an amalgamation of several hundred discrete spawning populations. Structured within lake systems, individual populations display diverse life history characteristics and local adaptations to the variation in spawning and rearing habitats. This biocomplexity has enabled the aggregate of populations to sustain its productivity despite major changes in climatic conditions affecting the freshwater and marine environments during the last century. Different geographic and life history components that were minor producers during one climatic regime have dominated during others, emphasizing that the biocomplexity of fish stocks is critical for maintaining their resilience to environmental change.

climate change | resilience | Pacific salmon | endangered species | biodiversity

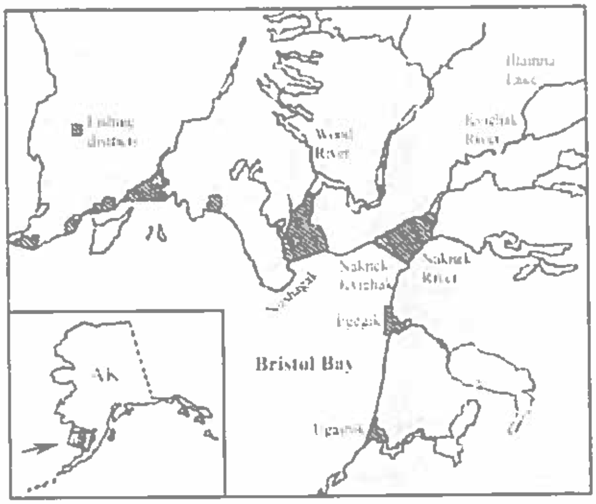

Fig. 1. Map of Bristol Bay, Alaska, showing the major lake systems producing sockeye salmon and the associated fishing districts. Figure is adapted from Minard and Meacham (37), which also gives an overview of Bristol Bay sockeye management practices.

At a time of growing concern about the sustainability of many of the world's fisheries, several stand out as providing long-term sustainable yield. Among the most prominent successes are the fisheries for sockeye salmon in Bristol Bay, Alaska (Fig. 1), that have seen record returns and catches in the last two decades. This success is due in part to several factors including (*i*) favorable ocean conditions in recent decades, (*ii*) a single, accountable management agency, and (*iii*) a well established program of limited entry to the fishery. However, the biocomplexity of the stock structure has also played an critical role in providing stability and sustainability. Here we provide evidence for the effects of biocomplexity on sustainability and emphasize that conserving biocomplexity within fish stocks is important for maintaining their resilience to future environmental change.

The Biodiversity Of Bristol Bay Sockeye

Homing of Pacific salmon (*Oncorhynchus* spp.) to their natal sites results in reproductive isolation of populations, allowing natural selection to operate on heritable phenotypic traits, and the result is a wealth of distinct, locally adapted populations (1, 2). Sockeye salmon (*Oncorhynchus nerka*), for example, display a wide variety of life history types, each associated predictably with certain breeding and rearing habitats (3). The diversity of phenotypes thus reflects the adaptation of populations to the diversity of suitable habitats. Spawning by salmonid fishes generally takes place in lotic habitats, and Bristol Bay sockeye salmon spawn in streams and rivers ranging from 10 cm to several meters deep, and in substrate ranging from small gravel to cobble (4, 5). Some creeks have spring-fed ponds with much finer substrate and deeper, slowly flowing water, and these too are used for spawning. Sockeye also spawn in groundwater-fed beaches at the outwash areas of rivers and along hillsides with substantial groundwater inputs. In these habitats, sockeye may spawn from the shoreline to depths of several meters. Finally, sockeye may also spawn on the rocky beaches of low-lying islands that are too flat to develop groundwater but where wind-driven surface currents are sufficient to deliver highly oxygenated water to developing embryos buried in the coarse gravel (6).

Adult sockeye display a suite of adaptations to the diversity of spawning and incubation environments, seen repeatedly from one site to another (Table 1). First, the date of spawning reflects the long-term average thermal regime experienced by incubating eggs and the timing of food production for juvenile salmon in the spring. Simply put, the adults spawn at a date that, given the average thermal regime, will allow the embryos to complete embryonic development and emerge in time to feed on aquatic insects and zooplankton the following spring (7). Salmon spawn early (late July to mid-August) in small streams that experience cold temperatures during incubation but spawn later (late August to October) in large rivers and lakes that have substantial heat storage capacity (8).

Not only the timing of spawning but also the average size of the eggs reflects the habitat-specific features of the incubation environment. In general, salmon have very large eggs compared with other teleost fishes (9). The development of such large embryos is possible because the cold, highly oxygenated water counters the surface-to-volume constraint against large eggs and because size-selective predation (10) and competition favor large juveniles (11). Larger adult salmon have both larger and more numerous eggs than smaller salmon, but the energetic constraints on the female result in tradeoffs between egg size and egg number that are population-specific. Sockeye spawning in rocky island beaches have unusually large eggs (12). This takes advantage of the well oxygenated water and large interstitial spaces among the rocks to provide the offspring with abundant yolk to help survive the prolonged posthatching period that results from early spawning. In addition, large eggs may be less vulnerable to size-selective predation by sculpins (*Cottus* spp.) (13). In contrast to the island spawners, the eggs of females spawning in streams and rivers are of intermediate size (match-

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Abbreviations: ENSO, El Niño Southern Oscillation; PDO, Pacific Decadal Oscillation.

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Table 1. A summary of life history variation within the Bristol Bay stock complex of sockeye salmon

Element of biocomplexity	Range of traits or options found
Watershed location within Bristol Bay complex	Seven different major watersheds, ranging from maritime-influenced systems on the Alaskan Peninsula to more continental systems
Time of adult return to freshwater	June–September
Time of spawning	July–November
Spawning habitat	Major rivers, small streams, spring fed ponds, mainland beaches, island beaches
Body size and shape of adults	130–190 mm body depth at 450 mm male length; sleek, fusiform to very deep-bodied, with exaggerated humps and jaws
Egg size	88–116 mg at 450 mm female length
Energetic allocation within spawning period	Time between entry into spawning habitat and death ranges from 1–3 days to several weeks
Time spent rearing in freshwater	0–3 years
Time spent at sea	1–4 years

ing the size of incubation substrates), and those of females spawning in ponds and mainland beaches are very small, apparently an adaptation to the lower oxygen levels and reduced water circulation in the finer substrates that characterize these environments (12).

In addition to the adaptations of salmon for egg incubation the adults show habitat-specific tradeoffs between the pressures of sexual and natural selection. In the absence of intervening selection, large and deep-bodied male salmon have more opportunities to mate than smaller, less deep-bodied individuals (14). Large females have more and larger eggs (12) and can bury them deeper (15) than smaller females. However, size-selective predation by bears (16–18) and physical access to shallow streams (18, 19) favor smaller fish in the evolution of body size and morphology. The result is that salmon spawning on mainland and island beaches, where there is little predation and no difficulty of access, are deep-bodied for their length compared with sockeye spawning in rivers and creeks (19). In addition, the average age at maturity is greater for sockeye spawning in larger rivers than in smaller creeks (19, 20).

The dimensions of biocomplexity in Bristol Bay sockeye are summarized in Table 1. Because it is relatively easy to study salmon during their spawning period, we understand the diversity of life history strategies during this life stage better than for the freshwater rearing or marine portion of the life history. However, there is variation among lakes and populations within lakes in the proportion of salmon spending 1 or 2 years in freshwater before seaward migration and in the average size of smolts (21), and in the degree of diurnal predator avoidance exhibited by juveniles (22). Such variation, combined with variation in size after a fixed period of ocean residence (18), suggests far more diversity in foraging and survival strategies during these later two periods than we yet understand. This mixture of life history strategies and local adaptations within the Bristol Bay sockeye is likely what buffers the stock complex to large-scale changes in environmental conditions, and thus, provides its long-term stability.

Changes in Freshwater and Ocean Environments

Environmental conditions in both the freshwater and marine systems of the North Pacific Ocean have shown several substantial and important modes of variability relevant to the ecology and evolution of sockeye salmon. Time-series analyses of salmon catches and climatic conditions during the last century demonstrate that salmon populations have responded to climate variability across wide spatial and temporal scales (23). The dominant modes of temporal variability in atmospheric–oceanic conditions are attributable to subdecadal patterns associated with the El Niño Southern Oscillation (ENSO) and to the 50- to 70-year (interdecadal) climate oscillations that have operated over the North Pacific Basin for at least 300 years (24).

The interdecadal changes in marine–atmospheric conditions that appear to be linked to oscillations in the strength of the winter Aleutian Low pressure cell have received particular attention recently. This Pacific Decadal Oscillation (PDO) (25) is a pan-Pacific phenomenon that is distinct from other sources of climate variability in the Pacific (26). Positive phases of both the ENSO and the PDO are associated with warmer than average winter temperatures along the North American coast, cooler than average temperatures in the central North Pacific, and low atmospheric sea level pressure over much of the North Pacific basin (23, 26). However, whereas ENSO events last from 12–18 months and occur every 2–7 years, the PDO involves abrupt transitions in atmospheric–marine physical conditions that are stable and persist for 20–35 years (24, 25).

Marine ecosystems appear to respond in a strong, nonlinear manner to apparently subtle changes in the marine physical conditions associated with the PDO. Many biological features of the North Pacific show prominent changes between interdecadal phases of the PDO. These prolonged modifications in ecosystem organization associated with changes in atmospheric–oceanic coupling have been termed regimes (27). The productivity of Alaskan sockeye salmon populations appears to be among the more sensitive biological systems that respond to interdecadal climate shifts and is strongly coherent with changes in the PDO (23, 26). Biological responses to the PDO seem to be related to changes in marine phytoplankton productivity that are transmitted through zooplankton to fishes (28–30). Although the exact mechanisms for the linkage between ocean physical processes and salmon production are not understood, the largest effects appear to occur early in the marine life history of salmon, possibly as they move from their freshwater nursery habitats through nearshore marine systems (23).

The terrestrial ecosystems of Alaska have also experienced substantial changes in climate during the last century that appear to be related to the same shifts in atmospheric conditions that drive variation in marine systems. For example, the length of the annual growing season in interior Alaska has increased from ≈130 days to ≈145 days since the 1950s (31). This lengthening of the growing season is also apparent in the timing of the spring thaw in sockeye nursery lakes in Bristol Bay (unpublished data). Much of the shift in growing season occurred during the late 1970s, at a time when the marine environment was exhibiting substantial, ecosystem-wide responses to a shift in the PDO (23). In general, interior Alaska has had relatively warm and wet conditions in the last two decades since the 1977/78 PDO shift (25). Time-series comparisons between coastal river flows and the PDO index demonstrate significant temporal coherence between atmospheric conditions associated with the PDO and

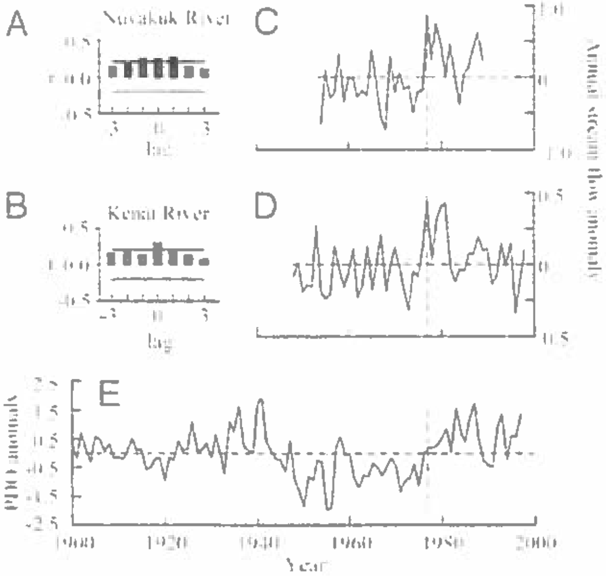

Fig. 2. Comparisons of the average annual PDO index for 1900–1998 (*E*) (ref 26 and http://tao.atmos.washington.edu/pdo) and annual streamflow for two coastal rivers in southwestern Alaska. All time series have been normalized to the long-term mean. (*A* and *B*) The cross correlation plots (CCF) between normalized annual flow for each of the two rivers and the annual average PDO index. Lags are shown for 1-year increments. Horizontal lines on *A* and *B* mark the significance bounds ($P = 0.05$). Historical streamflow (annual $ft^3 \cdot s^{-1}$) is shown for the Nuyakuk River (59°56′08″ N, 158°11′16″ W, *C*) in the Upper Nushagak drainage near Dillingham, Alaska (1954–1989) and for the Kenai River at Cooper Landing, Alaska (60°29′34″ N, 149°48′28″ W, *D*) for 1948–1998.

the hydrologic conditions in sockeye spawning and nursery habitats (Fig. 2). When we use the Kenai River and the Nuyakuk River as examples, we see that climate regimes associated with positive phases of the PDO are characterized by relatively high stream flows, whereas negative phases of the PDO are associated with below-average flows (23, 25).

Temporal and spatial variation in the hydrology of spawning and nursery habitats have important implications for both the spawning success of adult sockeye and for growth and survival of juveniles during their freshwater residency. For example, access to small spawning streams by adults is impeded during years with low flows (19) whereas access to spawning habitat on lake beaches may be much less dependent on hydrologic patterns. Survival of smolts during their seaward migration may also be enhanced during periods with high flow because of reduced vulnerability to freshwater predators. In general, years with high stream flows coincide with years of favorable near-shore marine conditions such that sockeye productivity may be enhanced at several stages of their life history (25).

There is apparent coordination among several critical physical and biological conditions important to sockeye salmon biology. Nevertheless, an outstanding characteristic of the responses of Bristol Bay sockeye to climate variation is that not all populations appear to respond coherently to documented shifts in the environment. We argue that this population-specific variability in response to climate fluctuations is ultimately responsible for the resilience of the entire Bristol Bay sockeye stock.

Historical Patterns of Stock Productivity

To illustrate the importance of biocomplexity of the Bristol Bay stock complex, we have broken down the historical sockeye catch into the contributions from the three major fishing districts (Naknek/Kvichak, Egegik, and Nushagak) (Fig. 3). Before the 1950s, we do not have estimates of the number of fish spawning in each river system and must use fishery catch as a surrogate for total run, but all major fisheries were already well developed by the early 20th century and catch is an excellent metric of total run size. We see that initially the Naknek/Kvichak was responsible for most of the sockeye production, with the Nushagak a close second and Egegik a small contributor. In the middle part of the 20th century, the importance of the Nushagak diminished, whereas Egegik remained roughly steady, and the Naknek/Kvichak dominated, driven almost exclusively by the Iliamna Lake populations. During that period, the Bristol Bay fishery was essentially a Naknek/Kvichak fishery. With the PDO regime shift of 1977 the Egegik run expanded greatly, so it was often at least as big than the Naknek/Kvichak, and the Nushagak system remained a small but steady contributor to the total fishery. In the 1990s the Naknek/Kvichak contribution declined dramatically. Egegik diminished, whereas Nushagak increased slightly to become, in some recent years, the most important fishery in Bristol Bay. Even within the Naknek/Kvichak district, the contribution of Iliamna Lake is now so small that it requires special protective fishery management to allow fishing on the Naknek populations.

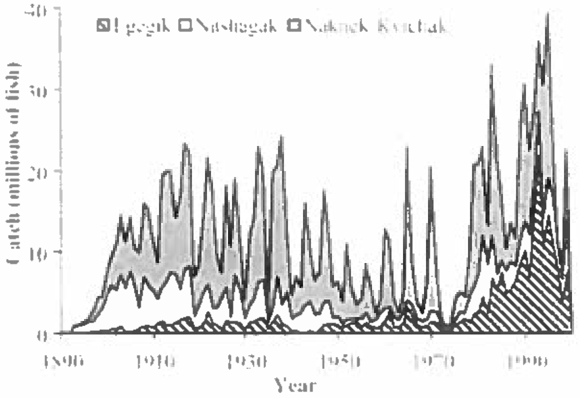

Fig. 3. Catch history of the three major fishing areas within Bristol Bay, Alaska. Contributions of the minor districts, Ugashik and Togiak, have averaged 4.6% since 1955.

Since the 1950s, visual counting towers on the major rivers leading into the lake systems have provided reliable counts of the number of fish passing through the fishery *en route* to their spawning sites. The number of recruits per spawner is the total number of adult returns from a spawning year divided by the number of fish that spawned in that brood year, and is a measure of per capita reproductive success. We calculated this for individual systems within fishing districts associated with each of the major rivers in Bristol Bay to demonstrate the temporal changes in their productivity (Fig. 4). In Fig. 4 we see the Naknek/Kvichak broken into its two dominant components: the Kvichak River–Lake Iliamna system and the Naknek River system. The Nushagak fishing district consists of three distinct lake/river systems: the Igushik, the Wood, and the Nushagak (not shown in Fig. 4). Finally the Ugashik system is the most remote of Bristol Bay's systems, located on the Alaska Peninsula.

Two features are important in Fig. 4, the absolute number of recruits per spawner and the temporal trends. The Kvichak and Wood systems have produced the fewest recruits per spawner, generally 2–4, whereas the Naknek averages ≈4, and the Egegik, Ugashik and Igushik show considerable variability but average more than Kvichak and Wood. Egegik showed the largest increase after the 1977 regime shift. This rise in survival was largely responsible for the upsurge in abundance of Egegik sockeye after the shift. The Ugashik system also showed a

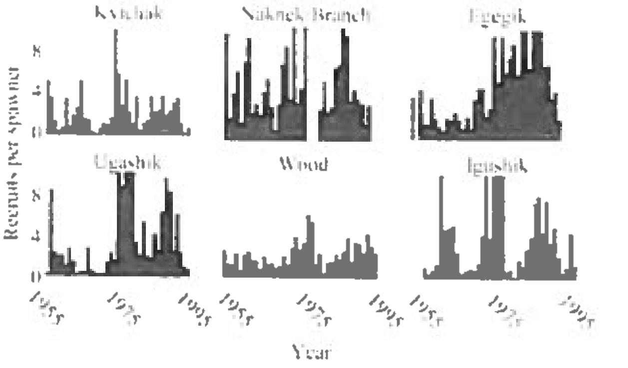

Fig. 4. Number of recruits per spawner for different Bristol Bay sockeye salmon stocks. Values >10 were truncated; the maximum was 27.4 for the Ugashik River in 1978.

dramatic increase in survival around the regime shift, whereas the Kvichak, Naknek, and Wood systems showed little response. Indeed, the Kvichak system has shown a dramatic reduction in productivity fewer than one recruit per spawner (i.e., below replacement even without fishing) since the mid-1990s. It is important to emphasize that none of these lake systems have been affected by habitat degradation from logging, mining, agriculture, hydroelectric development, or urbanization prevalent elsewhere, nor have they been colonized by non-native species. Thus we are able to attribute the changes in productivity to natural ecological processes rather than any direct anthropogenic ones.

These changes in productivity are not a response to changes in escapement and consequent compensatory mortality (32). The dramatic increase in Egegik productivity from brood years 1976–1988 coincided with a slight increase in average escapement, rather than a decrease, which would be required to generate higher recruits per spawner due to compensation. Similarly, the decline in Kvichak/Naknek productivity in the 1990s did not correspond to a significant change in average escapement, nor did the increase in Nushagak system productivity (particularly the Wood River) correspond to any significant change in escapement levels. In all cases the trends in escapement were subtle and in the opposite direction required for compensation to have been responsible for the observed dynamics.

Within the Kvichak/Iliamna system we have aerial surveys of ≈100 different spawning locations. We have classified these locations into three types: ponds and creeks, large rivers, and lake beaches. Fig. 5 shows the historical trend in the aerial counts of these sites, emphasizing strong contributions from river-spawning fish in the late 1970s and 1980s, overlaid on a sustained decline in the proportion of fish spawning on beaches. The life history patterns of beach spawners are quite different from pond/creek and river spawners, and changes in lake level, ice cover, and temperature associated with regime shifts may affect salmon using these habitat types differently. This suggests that shifts we have seen between Naknek/Kvichak, Egegik, and Nushagak may well be taking place on a much finer scale within individual systems.

The biocomplexity of Bristol Bay sockeye involves coarse-scale geographic structure organized at the scale of lake and river systems, fine-scale geographic structure associated with distinct spawning streams, beaches, and ponds, and several dimensions of life history variation within this geographic structure. The maintenance of the salmon runs appears to be caused by all of these levels of biocomplexity, with the strongest evidence being for the coarse-scale geographic structure responding differently over time. The evidence that the local adaptations have been the cause of differential response to environmental change is circumstantial, but it is unarguable that the biocomplexity in all its dimensions has buffered the stock from environmental changes. The fixed escapement management policy, which closes harvesting when stocks are low, undoubtedly protects stocks during periods of poor productivity and is the single most important management tool available to protect biocomplexity. Within major river and lake systems we generally do not have sufficient data to determine whether the fine-scale structure of biocomplexity has been maintained during the last century of commercial exploitation, and such monitoring should be made a high priority.

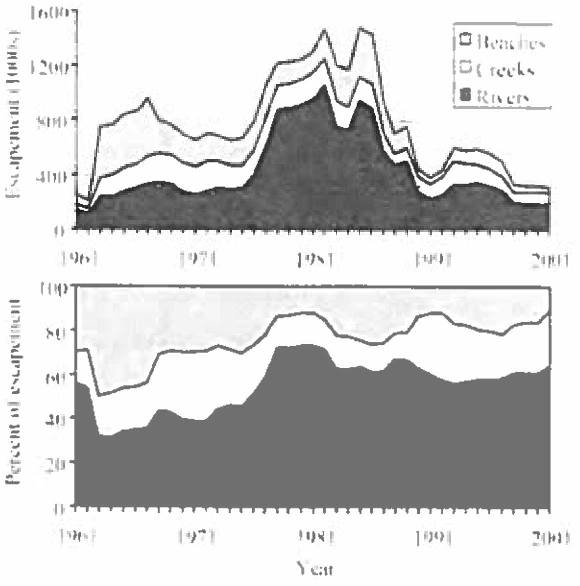

Fig. 5. The absolute (*Upper*) and relative (*Lower*) contributions of sockeye salmon using three types of spawning habitats within the Iliamna Lake system since 1961. Data have been smoothed with a 5-year running mean to emphasize the long-term trends.

Conclusions

The stability and sustainability of Bristol Bay sockeye salmon have been greatly influenced by different populations performing well at different times during the last century. Indeed, no one associated with the fishery in the 1950s and 1960s could have imagined that Egegik would produce over 20 million fish in 1 year, nor could they imagine that the Nushagak would produce more than the Kvichak, as it has in the last 4 years. It appears that the resilience of Bristol Bay sockeye is due in large part to the maintenance of all of the diverse life history strategies and geographic locations that comprise the stock. At different times, different geographic regions and different life history strategies have been the major producers. If managers in earlier times had decided to focus management on the most productive runs at the time and had neglected the less productive runs, the biocomplexity that later proved important could have been lost. Such loss of biocomplexity is a characteristic of the salmon situation in the Pacific Northwest, where many stock components were lost because of dams or deliberate overharvesting in an attempt to maximize catch from hatcheries (33). Similarly, in British Columbia there has been a focus on commercially important populations such as Fraser River sockeye salmon and neglect of the numerous smaller populations (34). In the 1950s, managers could have chosen to overlook the Egegik or Nushagak systems, and at the time the cost would have appeared to be low.

We have emphasized the importance of biocomplexity on the larger geographic scale, but similar patterns exist on ever-smaller scales within each lake system over the range of habitats and life history strategies described earlier. Within lakes, tributaries show asynchronous shifts in density and productivity, and even within tributaries we have seen habitat units affected by selective predation by bears, blockage by beaver dams, and other local processes. Our ability to measure changes in contribution at this level of biocomplexity is limited by our ability to assign the fishery catch to fine scale locations. Advances in genetic stock identification may pave the way for a high resolution analysis of the role of biocomplexity in maintenance of sustainability.

This work has lessons beyond the conservation of Pacific salmon. There is growing recognition that many marine fish stocks consist of amalgamations of several geographic components (35, 36). It would seem prudent to try to prevent loss of such stock components, including those that appear, at present, to be unproductive. This might necessitate a much finer scale of management than that which is the current norm. We believe that long-term sustainability is derived in large part from complementary patterns of productivity in different stock components. Defining the entire stock as healthy simply because a large component is doing well might lead to decline and extinction if the conditions that fostered the success of the healthy component disappear and the alternate strategy, which would have done well in the new environmental conditions, has been lost.

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1. Taylor, E. B. (1991) *Aquaculture* **98**, 185–207.
2. Dittman, A. H. & Quinn, T. P. (1996) *J. Exp. Biol.* **199**, 83–91.
3. Wood, C. C. (1995) in *Evolution and the Aquatic Ecosystem: Defining Unique Units in Population Conservation*, ed. Neilsen, J. L. (Am. Fisheries Soc., Bethesda), pp. 195–216.
4. Demory, R. L., Orrell, R. F. & Heinle, D. R. (1964) *Spawning Ground Catalog of the Kvichak River System, Bristol Bay, Alaska* (U. S. Fish and Wildlife Service, Washington, DC), Special Science Report, Fisheries No. 488.
5. Marriott, R. A. (1964) *Stream Catalog of the Wood River Lake System, Bristol Bay, Alaska* (U. S. Fish and Wildlife Service, Washington, DC), Special Science Report, Fisheries No. 494.
6. Leonetti, F. E. (1997) *N. Am. J. Fish. Manage.* **17**, 194–201.
7. Burgner, R. L. (1991) in *Pacific Salmon Life Histories*, eds. Groot, C. & Margolis, L. (Univ. of British Columbia Press, Vancouver), pp. 1–118.
8. Olsen, J. C. (1968) in *Further Studies of Alaska Sockeye Salmon*, ed. Burgner, R. L. (Univ. of Washington, Seattle), pp. 169–197.
9. Winemiller, K. O. & Rose, K. A. (1993) *Am. Nat.* **142**, 585–603.
10. West, C. J. & Larkin, P. A. (1987) *Can. J. Fish. Aquat. Sci.* **44**, 712–721.
11. Abbott, J. C., Dunbrack, R. L. & Orr, C. D. (1985) *Anim. Behav.* **92**, 241–253.
12. Quinn, T. P., Hendry, A. P. & Wetzel, L. A. (1995) *Oikos* **74**, 425–438.
13. Foote, C. J. & Brown, G. S. (1998) *Can. J. Fish. Aquat. Sci.* **55**, 1524–1533.
14. Quinn, T. P. & Foote, C. J. (1994) *Anim. Behav.* **48**, 751–761.
15. Steen, R. P. & Quinn, T. P. (1999) *Can. J. Zool.* **77**, 836–841.
16. Quinn, T. P. & Kinnison, M. T. (1999) *Oecologia* **121**, 273–282.
17. Ruggerone, G. T., Hanson, R. & Rogers, D. E. (2000) *Can. J. Zool.* **78**, 974–981.
18. Quinn, T. P. & Buck, G. B. (2001) *Trans. Am. Fish. Soc.* **130**, 995–1005.
19. Quinn, T. P., Wetzel, L., Bishop, S., Overberg, K. & Rogers, D. E. (2001) *Can. J. Zool.* **79**, 1782–1793.
20. Rogers, D. E. (1987) *Can. Spec. Pub. Fish. Aquat. Sci.* **96**, 78–89.
21. Crawford, D. L. (2000) *Bristol Bay Sockeye Salmon Smolt Studies for 1999* (Alaska Department of Fish and Game, Anchorage, AK).
22. Scheuerell, M. D. & Schindler, D. E. (2003) *Ecology*, in press.
23. Hare, S. R. & Mantua, N. J. (2000) *Prog. Oceanogr.* **47**, 103–145.
24. Minobe, S. (1999) *Geophys. Res. Lett.* **26**, 855–858.
25. Mantua, N. J., Hare, S. R., Zhang, Y., Wallace, J. M. & Francis, R. C. (1997) *Bull. Am. Meteorol. Soc.* **78**, 1069–1079.
26. Hare, S. R., Mantua, N. J. & Francis, R. C. (1999) *Fisheries* **24**, 6–14.
27. Beamish, R. J., Noakes, D., McFarlane, G. A., Klyashtorin, L., Ivanov, V. V. & Kurashov, V. (1999) *Can. J. Fish. Aquat. Sci.* **56**, 516–526.
28. Polovina, J. J., Mitchum, G. T., Graham, N. E., Craig, M. P., DeMartini, E. E. & Flint, E. N. (1994) *Fish. Oceanogr.* **3**, 15–21.
29. Brodeur, R. D., Mills, C. E., Overland, J. E. & Schumacher, J. D. (1999) *Fish. Oceanogr.* **8**, 296–306.
30. McGowan, J. A., Cayan, D. R. & Dorman, L. M. (1998) *Science* **281**, 210–217.
31. Running, S. W., Way, J. B., McDonald, K. C., Kimball, J. S., Frolking, S., Keyser, A. R. & Zimmerman, R. (1999) *Trans. Am. Geophys. Union* **80**, 213–221.
32. Hilborn, R. & Walters, C. J. (1992) *Quantitative Fisheries Stock Assessment: Choice, Dynamics & Uncertainty* (Chapman & Hall, New York).
33. Council, N. R. (1996) *Upstream: Salmon and Society in the Pacific Northwest* (Natl. Acad. Press, Washington, DC).
34. Hyatt, K. D. & Riddell, B. E. (2000) in *Sustainable Fisheries Management: Pacific Salmon*, eds. Knutson, E. E., Steward, C. R., MacDonald, D., Williams, J. E. & Reiser, D. W. (CRC Press, Boca Raton, FL), pp. 51–62.
35. Ruzzante, D. E., Taggart, C. T., Lang, S. & Cook, D. (2000) *Ecol. Appl.* **10**, 1090–1109.
36. Lage, C., Purcell, M., Fogarty, M. & Kornfield, I. (2001) *Can. J. Fish. Aquat. Sci.* **58**, 982–990.
37. Minard, R. E. & Meacham, C. P. (1987) *Spec. Pub. Fish. Aquat. Sci.* **96**, 336.

PERSPECTIVE:
FISHERIES MANAGEMENT

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Climate Change, Ecosystem Impacts, and Management for Pacific Salmon

ABSTRACT: As climate change intensifies, there is increasing interest in developing models that reduce uncertainties in projections of global climate and refine these projections to finer spatial scales. Forecasts of climate impacts on ecosystems are far more challenging and their uncertainties even larger because of a limited understanding of physical controls on biological systems. Management and conservation plans that explicitly account for changing climate are rare and even those generally rely on retrospective analyses rather than future scenarios of climatic conditions and associated responses of specific ecosystems. Using past biophysical relationships as a guide to predicting the impacts of future climate change assumes that the observed relationships will remain constant. However, this assumption involves a long chain of uncertainty about future greenhouse gas emissions, climate sensitivity to changes in greenhouse gases, and the ecological consequences of climate change. These uncertainties in forecasting biological responses to changing climate highlight the need for resource management and conservation policies that are robust to unknowns and responsive to change. We suggest how policy might develop despite substantial uncertainties about the future state of salmon ecosystems.

Cambio climático, impactos a nivel ecosistema y manejo del salmón del Pacífico

RESUMEN: A medida que el cambio climático se intensifica, existe un creciente interés en desarrollar modelos que reduzcan la incertidumbre en las proyecciones del clima global, y llevar estas proyecciones a escalas más finas. El pronóstico de los impactos del clima sobre los ecosistemas es más difícil de abordar y la incertidumbre asociada es aun mayor porque se tiene un entendimiento rudimentario sobre los controles físicos en sistemas biológicos. Son pocos los sistemas de manejo y conservación que consideran explícitamente el papel del clima, e incluso éstos se basan en análisis retrospectivos más que en escenarios futuros de condiciones climáticas y las correspondientes respuestas a nivel ecosistema. Al utilizar relaciones biofísicas preestablecidas como guía para predecir los impactos de cambio climáticos, se asume que dichas relaciones permanecerán constantes. Sin embargo, esta suposición implica una larga cadena de imprecisiones con respecto a la intensidad de futuras emisiones de gases de invernadero, sensibilidad climática a los cambios en estos gases, y las consecuencias ecológicas del cambio climático. La incertidumbre del pronóstico de las respuestas biológicas a un clima cambiante, resaltan la necesidad de políticas de manejo y conservación que sean suficientemente robustas a esas incógnitas y sensibles al cambio. Se sugiere cómo pueden desarrollarse tales políticas a pesar de la importante incertidumbre que existe en torno al estado futuro de los ecosistemas que albergan al salmón.

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OVERVIEW OF SALMON RESPONSES TO CHANGING CLIMATE

Pacific salmon are icons of the natural and cultural heritage of coastal nations throughout the subarctic North Pacific Ocean (SNPO). Since the 1960s, scientists across all nations of the SNPO have greatly advanced understanding of Pacific salmon and their habitats. During this time period, environmental conditions of the SNPO also have shifted substantially in response to inter-decadal climate variability and longer-term warming trends (e.g., Schindler et al. 2005). Initial syntheses of these data have begun to shed light on how salmon and their ecosystems respond to changing climate.

Pacific salmon are affected by climate change across a hierarchy of coarse and fine spatial and temporal scales; each of these scales has distinct implications for development of policy that will be robust to future climate change. At the scale of the entire SNPO (Figure 1), biomass of Pacific salmon has increased substantially over the last century (Figure 2; Eggers 2009 in press), coincident with increases in global temperatures (IPCC 2007). This increased salmon production has been especially pronounced since the mid-1970s (Mantua et al. 1997; Beamish et al. 2008). However, trends in both climatic conditions and salmon production have not been uniform across the SNPO. In western North America, inter-decadal patterns of salmon production in northeastern stocks (i.e., Alaska) are out of phase with production regimes for stocks in the conterminous United States and Canada (Figure 3). This variation in production coincides with warming trends in salmon watersheds and nearshore marine waters in western North America, but cooling trends in the open waters of the interior North Pacific Ocean where most salmon feed and mature (Mantua et al. 1997; Hare et al. 1999).

Figure 1. Map of the distribution of salmon in the Subarctic North Pacific Ocean (SNPO). Letters and corresponding arrows depict the location and rough spatial scales over which data from Figures 3 and 4 were summarized

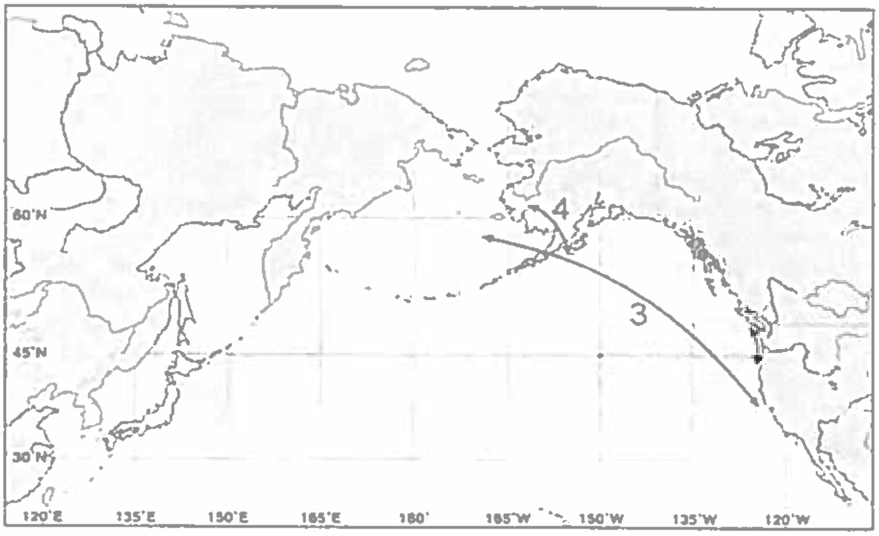
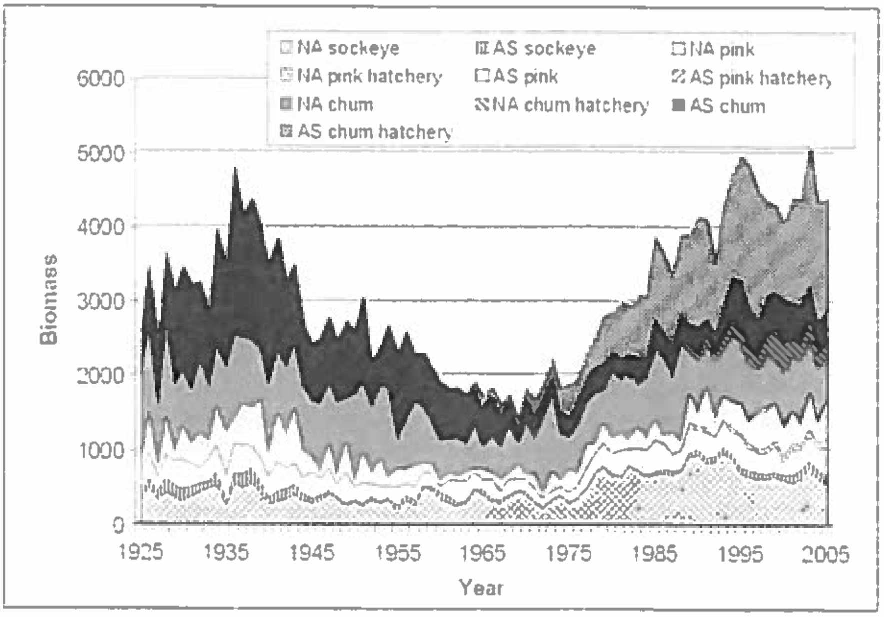


Figure 2. Total biomass (thousands of metric tons) of chum (*Oncorhynchus keta*), sockeye (*O. nerka*), and pink salmon (*O. gorbuscha*) inhabiting the SNPO (stippled area in Figure 1) from 1925–2005. Data are separated by species, continent of origin (North America [NA] versus Asia (AS), and hatchery versus wild stocks). Not all hatchery contributions are known with high certainty (e.g., Russian pink salmon) so these are combined with the wild components. Data are from Eggers (2009 in press)



At still finer spatial scales, stocks entering the ocean within 500-800 km of one another have weakly coherent responses to changes in local oceanographic conditions (Mueter et al. 2002; Pyper et al. 2005). This regional coherence in productivity is most correlated with regional variation in sea surface temperatures (Mueter et al. 2002). However, at the scale of individual populations, responses to regional shifts in climatic conditions are diverse (Figure 4; Peterman et al. 1998; Hilborn et al. 2003; Crozier and Zabel 2006; Rogers and Schindler 2008). Further, salmon species vary considerably in their responses to regional climate changes (Hare et al. 1999). Identifying features of the environment and of salmon populations that produce the diversity of salmon responses to regional climate forcing is critical because these are the scales at which most management and conservation activities operate.

Policies for managing salmon in the face of climate change must change if we hope to meet our conservation and management goals. Our ability to accurately predict climate impacts on salmon ecosystems is incomplete and unlikely to improve to the point of accounting for the regional response diversity noted above. Policies must be robust to these uncertainties rather than reliant upon prescriptive forecasts of climate and associated ecological conditions. Some such management strategies have been suggested as ways to account for climatically-driven changes in salmon production, without the need to understand the intricacies of climate impacts on salmon ecosystems (e.g., Walters and Parma 1996; Peterman et al. 2000). For example, Walters and Parma (1996) showed that a constant harvest strategy (i.e., one that exploits a constant proportion of stock each year) performs remarkably well at tracking long-term fluctuations in stock productivity, as would be caused by climate change. The information needed to develop such a strategy relies heavily on our ability to forecast year-to-year variation in abundance but does not necessarily rely on an intricate understanding of the processes causing climatically-driven variation. Given our limited predictive capacity, what information about the links between salmon and climate is useful to current policy? In particular, how might policy to address climate impacts on salmon embrace the hierarchy of spatial and temporal scales that characterize salmon responses to a changing environment?

Figure 3. Standardized anomalies of salmon harvests along the North American west coast from 1925–2005. Data were smoothed with a 5-year running mean. Abbreviations are: ch = Chinook salmon (O. *tshawytscha*), co = coho salmon, so = sockeye salmon, pi = pink salmon. BC = catch from British Columbia, US = catch from US lower 48 states, AK = catch from Alaska)

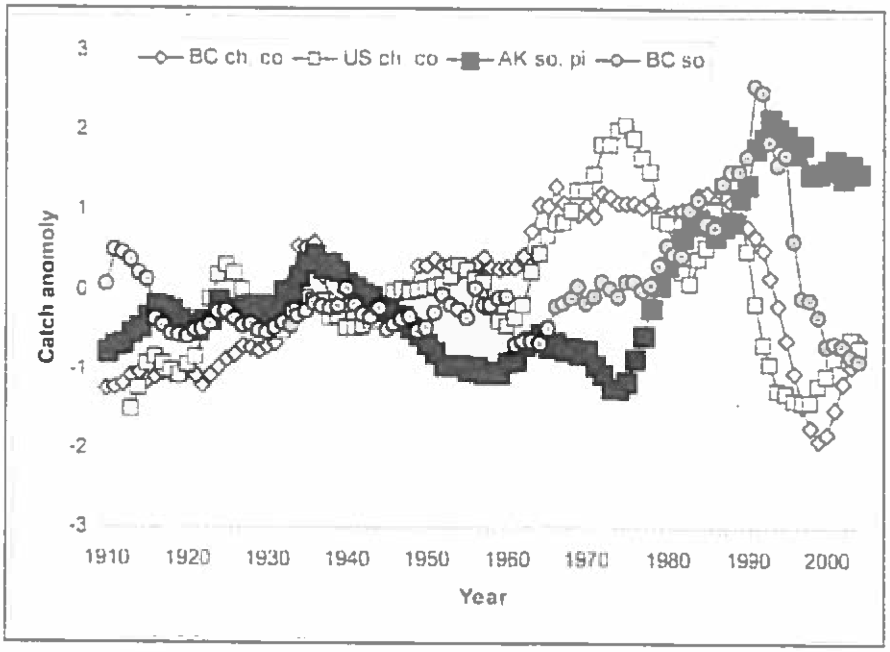
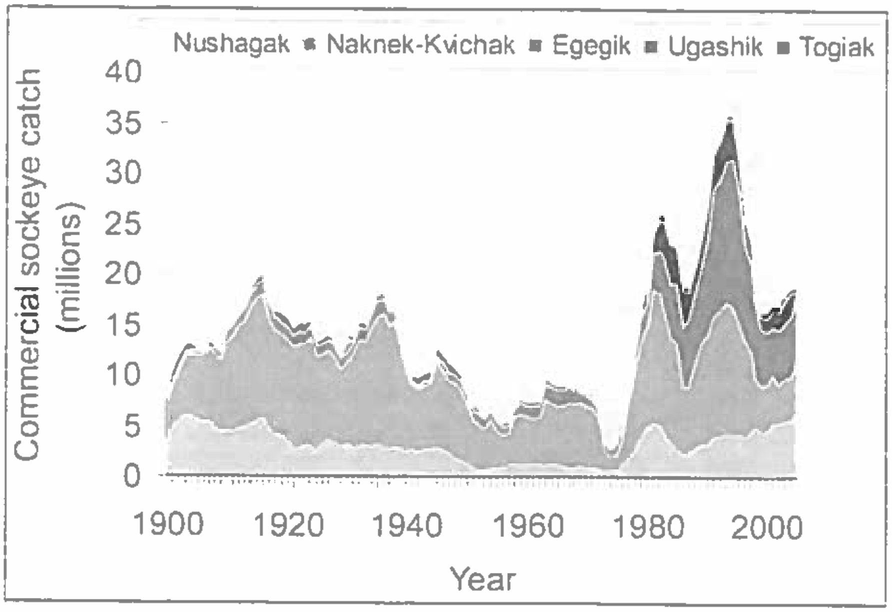


Figure 4. Sockeye salmon (*O. nerka*) commercial catch (millions of fish) from Bristol Bay, Alaska, from 1893–2006, apportioned to five fishing districts associated with the major rivers of this region (updated from Hilborn et al. 2003). Data are smoothed with a 5-year running mean.



The need for SNPO-wide salmon-climate policy

Improved salmon-climate policy is needed at all of the spatial scales described above. First, we believe that proactive policy development at the scale of the entire SNPO is needed to help minimize future climate-induced political conflicts over the use of limited prey resources by salmon from different nations of the SNPO. At the scale of the entire SNPO, increases in salmon biomass largely reflect increasing numbers of hatchery-released salmon from Eurasia (Figure 2, Eggers 2009 in press) that compete with salmon from North American rivers when they overlap in international waters (Kaeriyama and Edpalina 2004; Ruggerone et al. 2005). This surge in salmon production was concurrent with a general cooling of North Pacific offshore habitat where salmon achieve most of their growth (Mantua et al. 1997; Hare et al. 1999). If the increasing trend in biomass is dependent upon the cooling trends in this offshore ecosystem, it is not likely to persist with ongoing climate warming. Thus, the institutional expectation of the SNPO's capacity to produce salmon that has developed during the last few decades may prove overly optimistic as global atmospheric and upper-ocean temperatures continue to increase. In fact, capacity may decline if thermal characteristics of offshore habitat eventually switch trajectories and, consistent with global climate model projections, the upper ocean begins warming. More extensive use of the Arctic Ocean by Pacific salmon may partially offset any diminished capacity of the SNPO. Nevertheless, international coordination of management of the open-ocean commons used by Pacific salmon needs refinement to address potential climate-driven changes in productivity. There is currently no coordinated vision for use of the SNPO (Holt et al. 2008).

Climate policy at regional scales

At intermediate (regional) spatial scales, policies that govern maintenance of habitat quality and harvest strategies could be modified to more appropriately account for complex stock structure and variation in climate impacts on different habitats used by salmon. Multi-decadal regimes of high salmon production (Beamish et al. 1999) due to favorable ocean conditions may mask the erosion of freshwater and estuarine habitat quality, and within-stock biodiversity, that only become evident once productivity in the ocean decreases. For example, fisheries for Oregon coho salmon (*Oncorhynchus kisutch*) appeared to be robust and sustainable from the 1950s into the mid-1970s. During this period, hatchery programs grew rapidly and replaced wild stocks as the principal producers of juvenile coho salmon (Pearcy 1992). Intense harvest rates that seemed appropriate for hatchery stocks during periods of exceptionally high marine survival proved too high for the long-term sustainability of wild stocks. In 1977, a shift in the state of the Pacific Decadal Oscillation generated a 20-year period of unfavorable ocean conditions for Oregon coho salmon. The abundance of both hatchery and wild coho salmon adults plummeted, sending coho salmon populations and their fisheries into a decline from which they may be only beginning to recover. Accordingly, despite their knowledge that hatcheries were eroding the complex stock structure of wild coho salmon that had evolved for millennia, a 20-year period of high marine survival rates led fishery managers to mistakenly believe that large-scale hatchery production could sustain intense fisheries (Lichatowich 1999).

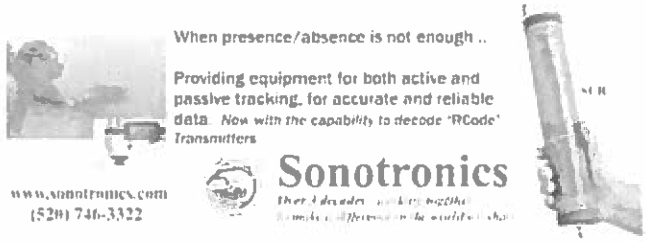
Further, Oregon coho salmon provide a compelling example of situations where favorable climatic conditions and high survival in one habitat (e.g., ocean) can obscure the degradation of other habitats (e.g., freshwater systems). For example, degradation of freshwater habitats can occur during periods of favorable ocean conditions that produce high marine survival rates. The degradation of freshwater habitats is only detectable once marine conditions switch back to a low productivity regime and salmon populations are more dependent on high quality freshwater habitat. Consequently, a ratchet effect can develop on population size and stock diversity as climatically-driven conditions in the ocean oscillate between periods of high and low quality (Lawson 1993).

Although within-stock diversity hinders the development of accurate and generalizable long-term forecasts of climate impacts on salmon at watershed scales, policies that protect diverse landscapes and their potential for diverse ecological responses are likely an effective means to hedge bets against future climate changes. Ecosystem and population sensitivity to changes in temperature and precipitation varies substantially across the entire latitudinal gradient that salmon occupy. The ecological and climatic factors that produce intraregional variation in population responses to changing climate (e.g., Hilborn et al. 2003; Crozier and Zabel 2006; Rogers and Schindler 2008) are poorly understood. It is useful to think of salmon landscapes as heterogeneous "filters" of climate. The environmental conditions experienced by any individual population are produced from how the overriding climate signal is expressed in their habitat, as influenced by its geomorphic, hydrologic, and ecological characteristics. We currently have a poor understanding of how landscapes filter climate signals, and how these in turn affect salmon populations. This lack of knowledge is an impediment to developing accurate predictions about the future status of specific salmon populations. However, to some extent, the regional diversity of population responses to climate change appears to derive from local adaptations of salmon populations to heterogeneity in landform and hydrologic conditions (Hilborn et al. 2003; Beechie et al. 2006; Crozier and Zabel 2006; Rogers and Schindler 2008). This response diversity imparts resilience to human social systems, such as fisheries, because they integrate across this ecological heterogeneity (Hilborn et al. 2003). Focusing regional policy on "salmon landscapes" will also be necessary to account for the range of habitats used by salmon over the course of their lives, including migratory corridors (Martin 2006). In the Pacific Northwest, where salmon landscapes are being developed most quickly, such protection of habitat may have to be especially aggressive to counteract ongoing effects of climate change (Ashley 2006).

What science can do to improve salmon-climate policy

Science can play an important role in reducing key uncertainties about climate impacts to which future policy can adapt. Areas that are particularly ripe for study and application to policy include:

- Developing quantitative models that allow projections for temperature, precipitation, and hydrologic conditions to be reliably downscaled to the watershed level. These models will facilitate exploration of the probability that regional conditions will support salmon in specific locations as climate continues to warm (Battin et al. 2007).
- Developing models that allow for integration of multiple factors influencing salmon ecosystems, including the cumulative impacts of climate change, land use, and water use on habitat, fishery harvest, and hatchery effects.
- Exploring the extent to which salmon and co-occurring organisms might adapt to ongoing climate change, thus affecting the direction and magnitude of overall ecosystem response. The role of evolution in ecological responses to anthropogenic change of Earth systems has been essentially ignored in conservation planning (Smith and Bernatchez 2007). This knowledge would inform policy decisions to invest or divest in salmon fisheries, salmon recovery, and hatchery production around the North Pacific.
- Exploring scenarios of future ocean productivity, linkages among ocean and freshwater or terrestrial conditions, and effects of changes in ocean, freshwater, or terrestrial conditions on salmon production at local, regional, and SNPO scales. This knowledge will be important for creating a management regime for cooperative use of the ecosystem services of the SNPO.
- Improving our understanding of how climate change affects the metapopulation processes important to salmon evolutionary and ecological dynamics.
- Refining genetic techniques to identify stocks, and ways to efficiently implement the data generated by those techniques, in harvest management to protect stock diversity in fisheries.



CONCLUSIONS

Predictions of the scope and exact nature of biological responses to future climatic and habitat conditions will always be subject to considerable uncertainty. However, we can be certain that climate will continue to change and biological responses will be heterogeneous across a variety of spatial and temporal scales. We face the challenge of developing management and conservation approaches that are robust to substantial uncertainties about future conditions and capable of responding to change. Simultaneously, we must hone our ability to identify a realistic range of alternative futures. While we have focused on Pacific salmon, the issues we raise are not unique to these species. Many of these same issues will challenge policy to achieve sustained production and conservation of any wide-ranging species as global and regional climate continue to change. ⚓

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REFERENCES

Ashley, K. 2006. Wild salmon in the 21st century: energy, triage, and choices. Pages 71-88 *in* R. T. Lackey, D. H. Lach, and S. L. Duncan, eds. Salmon 2100: the future of wild Pacific salmon. American Fisheries Society. Bethesda, Maryland.

Battin, J., M. W. Wiley, M. H. Ruckelshaus, N. Palmer, E. Korb, K. K. Bartz, and H. Imaki. 2007. Projected impacts of climate change on salmon habitat restoration. Proceedings of the National Academy of Sciences 104:6720-6725.

Beamish, R. J., D. J. Noakes, G. A. McFarlane, L. Klyashtorin, V. V. Ivanov, and V. Kurashov. 1999. The regime concept and natural trends in the production of Pacific salmon. Canadian Journal of Fisheries and Aquatic Sciences 56:516-526.

Beamish, R. J., R. M. Sweeting, and C. M. Neville. 2008. Changing climate and the need to change our thinking about the management of Pacific salmon. American Fisheries Society Special Publications, in press.

Beechie, T., E. Buhle, M. Ruckelshaus, A. Fullerton, and L. Holsinger. 2006. Hydrologic regime and the conservation of salmon life history diversity. Biological Conservation 130:560-572.

Crozier, L., and R. W. Zabel. 2006. Climate impacts at multiple scales: evidence for differential population responses in juvenile Chinook salmon. Journal of Animal Ecology 75: 1100-1109.

Eggers, D. M. 2009. In press. Sustainability of the Arctic-Yukon-Kuskokwim salmon fisheries. *In* C. Krueger, C. Zimmerman, eds. American Fisheries Society, Bethesda, Maryland.

Hare, S. R., N. J. Matua, and R. C. Francis. 1999. Inverse production regimes: Alaska and West Coast Pacific salmon. Fisheries 24(1): 6-14.

Hilborn, R., T. P.Quinn, D. E. Schindler, and D. E. Rogers. 2003. Biocomplexity and fisheries sustainability. Proceedings of the National Acadamy of Sciences 100:6564-6568.

Holt, C. A., M. B. Rutherford, and R. M. Peterman. 2008. International cooperation among nation-states of the North Pacific Ocean on the problem of competition among salmon for a common pool of prey resources. Marine Policy 32:607-617.

IPCC (Intergovernmental Panel on Climate Change). 2007. The science basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge.

Kaeriyama, M., and R. R. Edpalina. 2004. Evaluation of biological interaction between wild and hatchery population for sustainable fisheries management of Pacific salmon. Pages 247-259 *in* K. M. Leber, S. Kitada, H. L. Blankenship, T. Svåsand, eds. Stock enhancement and sea ranching: developments, pitfalls and opportunities. 2nd Edition, Blackwell, Oxford.

Lawson, P. W. 1993. Cycles in ocean productivity, trends in habitat quality, and the restoration of salmon runs in Oregon. Fisheries 18(8):6-10.

Lichatowich, J. 1999. Salmon without rivers. a history of the Pacific salmon crisis. Island Press. Washington, DC

Mantua, N. J., S. R. Hare, Y. Zhang, J. M. Wallace, and R.C. Francis. 1997. A Pacific interdecadal climate oscillation with impacts on salmon production. Bulletin of the American Meteorological Society 78:1069-1079.

Martin, J. T. 2006. Salmon caught in the squeeze. Pages 411-424 *in* R. T. Lackey, D. H. Lach, and S. L. Duncan, eds. Salmon 2100: the future of wild Pacific salmon. American Fisheries Society. Bethesda, Maryland.

Mueter, F. J., D. M. Ware, and R. M. Peterman. 2002. Spatial correlation patterns in coastal environmental variables and survival rates of salmon in the north-east Pacific Ocean. Fisheries Oceanography 11:205-218.

Pearcy, W. G. 1992. Ocean ecology of North Pacific salmonids. Washington Sea Grant, University of Washington Press, Seattle.

Peterman, R. M., B. J. Pyper, M. F. Lapointe, M. D. Adkison, and C. J. Walters. 1998. Patterns of covariation in survival rates of British Columbian and Alaskan sockeye salmon (*Oncorhynchus nerka*) stocks. Canadian Journal of Fisheries and Aquatic Sciences 55:2503-2517.

Peterman, R. M., B. J. Pyper, and J. A. Grout. 2000. Comparison of parameter estimation methods for detecting climate-induced changes in productivity of Pacific salmon (*Oncorhynchus* spp.) Canadian Journal of Fisheries and Aquatic Sciences 57:181-191.

Pyper, B. J., F. J. Mueter, and R. M. Peterman. 2005. Across-species comparisons of spatial scales of environmental effects on survival rates of northeast Pacific salmon. Transactions of the American Fisheries Society 134:86-104.

Rogers, L. A., and D. E. Schindler. 2008. Asynchrony in population dynamics of sockeye salmon in southwestern Alaska. Oikos 117:1578-1586.

Ruggerone, G. T., E. Farley, J. Neilsen, and P. Hagen. 2005. Seasonal marine growth of Bristol Bay sockeye salmon (*Oncorhynchus nerka*) in relation to competition with Asian pink salmon (*O. gorbuscha*) and the 1977 regime shift. Fisheries Bulletin 103:355-370.

Schindler, D. E., D. E. Rogers, M. D. Scheuerell, and C. A. Abrey. 2005. Effects of changing climate on zooplankton and juvenile sockeye salmon growth in southwestern Alaska. Ecology 86:198-209.

Smith, T. B., and L. Bernatchez. 2007. Evolutionary change in human-altered environments. Molecular Ecology 17:1-8.

Walters, C. J., and A. M. Parma. 1996. Fixed exploitation rate strategies for coping with effects of climate change. Canadian Journal of Fisheries and Aquatic Sciences 53:148-158.

Appendix VI

BBNA Study: Water Quality Data Collection and Research Specifics

Project/Task Descriptions

The Koktuli River Baseline Discharge and Water Quality Study was designed to provide a recorded baseline of the river's physical and chemical characteristics. The collection of water quality data occurred at discharge-stream gages installed to quantify the amount and distribution of surface water at different locations throughout the watershed. The three gage sites employed in this study were located at points along the mainstem of the Koktuli (2) and Swan (1) Rivers to provide an accurate accounting of discharge within the entire Koktuli Watershed. The sites were located far enough from the confluence of streams to avoid backwater flows and incomplete mixing of contamination from the joining stream. Complete mixing at samples sites were verified along the discharge cross-section with physical parameters measured at a variety of stage heights. The physical properties were recorded along with the occurrence and distribution of nutrients, major ions, and trace metals and their relationship to hydrologic conditions. The study employed most USGS standard operating procedures for collecting and processing water quality samples and discharge/gage datasets. Quality assurance procedures provided support for the deviations from standard USGS procedures.

Collection and Processing

Guidelines for sampling can be found in the USGS "National Field Manual for the Collection of Water-Quality Data" (USGS, 1997 to Present) and the EPA "Method 1669: Sampling Ambient Water for Trace Metals at EPA Water Quality Criteria Levels" (EPA, 1996). Additional sources of water quality field techniques can be found in USGS publications by Horowitz (1994) and Shelton (1994).

Equipment Cleaning and Preparation

Powderless, latex gloves were worn to clean any equipment that would contact the sample. The sampling equipment was rinsed initially with tap water to remove dirt and particles picked up in the field. If the equipment was new or excessively dirty, it was then washed in a 0.2-percent solution of phosphate-free soap and rinsed with tap water before going on to the next step. A 5% hydrochloric acid solution was then used before the final rinse with deionized water. The clean equipment was then placed in sealed plastic bags for storage and/or transport to the field.

Equipment sets for each site were precleaned to minimize sampling time in the field. The data collection sample bottles were pre-rinsed 3 times with deionized water and filled to 1/3rd their total volume. The prepared sample bottles were sealed in a clean, sealable plastic bag for transport to the sampling site.

Sample Collection, Filtration, Preservation, and Shipping

Samples were collected through the entire depth of the water column and at multiple verticals across the river using the equal-width increment (EWI) method. This provided a flow-weighted, depth and width integrated representative sample. Multimeter measurements were taken at varying depth to determine the level of mixing along the cross section. Well-mixed cross sections were sampled with a minimum of five equal width stations. Ten verticals were used if the cross section is poorly mixed. If environmental conditions or safety concerns prevent the use of the standard EWI method, a detailed account of the equipment and methods used was completed.

In normal circumstances the EWI, method was performed using a sampler designed by the USGS for water quality sampling. The sampler consisted of a DH81 sampler with shrink-wrapped rod that held a 1-liter plastic bottle that was fitted with a D77 cap and a Teflon nozzle. Sample water collected at equal intervals was combined in a churn splitter. When the cross section had been sampled, well-mixed, unfiltered water was withdrawn from the churn splitter to fill sample bottles for laboratory analysis. Filtered samples were withdrawn from the churn splitter by a peristaltic pump via a C Flex hose and filtered through a 0.45 m membrane capsule or a disk filter. Nitric acid (HNO_3) was added to cation and trace metals sample bottle to preserve the water for laboratory analysis. Sulfuric acid (H_2SO_4) was added to samples for the preservation of water for nutrients analysis. Specific bottles were used to deter the deterioration of the samples.

The samples were processed in the field just after collection. To reduce/eliminate potential contamination, the work surface was covered with plastic sheeting. The filtered samples were process in a portable processing chamber frame covered with disposable plastic cover. Powderless, latex gloves were worn for each step by both dirty and clean hands samplers.

The processed samples were shipped by overnight delivery to Manchester Environmental Laboratory in Port Orchard, Washington in an ice-filled cooler as soon as possible. Due to logistics, this usually occurred at the in the office following the field trip. The lab verified temperature upon receipt to assure proper sample handling. The temperatures should have been within a range just above freezing to 6°C (Maloney, 2004). An Analytical Services Requests (ASR) form specifying the sample analysis to be performed was mailed with the samples. Copies of the ASRs were filed in the water quality station folders with the water quality field forms to provide a record of the requested analysis.

Inspection and Acceptance Requirements for Supplies

The quality of data can be significantly affected by the type of equipment used. The supplies and equipment used to collect, process, and preserve inorganic water samples were purchased from a variety of suppliers identified by the Federal Interagency Sedimentation Project in Vicksburg, MS. The equipment was purchased from supplier identified by FIDS to assure products to the microgram per liter level required for trace metals sampling.

Data Quality Objectives for Measurement Data

The data quality objectives (DQOs) were established to ensure that the baseline water quality data was representative of the systems under study. In order to insure representative samples a variety of quality control samples were collected throughout the study. These quality control samples included site field blanks, equipment blanks, split replicates, and concurrent replicates. At least one set of each quality control sample was collected at each water quality collection site over the course of the project.

Blanks were used to test for contamination arising from collection, processing, preservation, and shipping procedures using quality assured inorganic blank water (IBW) (Mueller, 1997; Horowitz 1994). Field blanks were obtained at the field site before processing a stream sample. One field blank was collected at each water quality site per year. Equipment blanks were performed in a clean, non-field environment once a season prior to the collection of samples or when equipment was used for the first time.

Quality control replicate samples were collected to produce statistically meaningful evaluations of data. Replicate samples insured the accuracy and precision of measurements. Split replicate samples were used to determine variability introduced during sample processing and analysis (Mueller, 1997; Horowitz 1994). A split replicate is a single, large volume of sample water that is divided into identical sub samples (a primary and duplicate). Split samples were collected several times a year at each water quality station to insure the accuracy of the data being collected. Accuracy is a measure of confidence that describes how close a measurement is to its "true" value.

Concurrent replicate samples comprise the maximum imprecision of the data by incorporating variability measured from split replicates plus variability introduced by sample collection. A concurrent replicate is two separate samples collected closely together in time at the same location. In this way, concurrent replicates insure the precision of the sampling process by testing both the consistency of the sampling methods and the agreement among repeated measurements of the same characteristics or parameters. Concurrent samples were collected once a year at each water quality station.

Standardized sampling, analytical methods and units of reporting that compare to other sample studies were used to ensure the comparability of the collected data with the data produced by similar studies. Comparability is the degree to which data can be compared directly to similar studies. This project employed testing methods that are comparable to methods employed by the National Water Quality Analysis (NWQA) Program and employed by other water quality monitoring programs throughout the country.

The sampling schedule of this project was constructed to assure representative water quality conditions through seasonal flow variations over time. A completeness measure was used to ensure that the data does represent seasonal variation. Completeness is the comparison between the amounts of usable data collected versus the amount of data called for in the sampling plan. Completeness is measured as the percentage of total samples collected and analyzed as a whole and for individual parameters and sites as compared to the goals set out by the project design. A complete data set was initially set at 75% of the target number. All efforts were then made to not miss two consecutive scheduled sampling events for any one site. If less than 75% samples were taken from a site in a given year data from that site was not qualified when considering trend analysis in annual reports.

Training Requirements
Adequate training in methods and procedures is necessary to improve knowledge, avoid potential error, ensure the quality of the data, and lends legal credibility to the data. Employees participating in water quality sampling were trained accordingly. Employee training included self-education, work experience, in-house instruction, and formal courses. Individuals were fully trained in the proper protocols before collecting water quality data.

Documentation and Records
All data gathered was recorded on site at the time sampling occurs using a data sheet. Original copies of all data sheets are kept on file at the indefinitely. Copies of the data sheets were shipped with the water sample to the water quality-testing lab immediately upon return to Anchorage so any data collection concerns could be addressed as quickly as possible.

SAMPLING PROCESS DESIGN

Sample Site Selection
The two gage sites employed in this study were located at points along the mainstem of the Koktuli and Swan Rivers to provide an accurate accounting of discharge within the entire Koktuli Watershed. The sites were located far enough from the confluence of streams to avoid backwater flows and incomplete mixing of contamination from the joining stream. Complete mixing at samples sites was verified along the discharge cross-section with physical parameters measured at a variety of stage heights. The physical properties were recorded along with the occurrence and distribution of nutrients, major ions, and trace metals and their relationship to hydrologic conditions.

Sampling Sites, Parameters, & Collection Frequency
Sampling occurred at the two stream gage sites that were located on the Koktuli and Swan Rivers. The first site was located on the Swan River above the confluence with the Koktuli River. The next water quality-monitoring site was located at the stream gage on the main stem of the Koktuli River below its confluence with the Swan River and above the confluence with the Mulchatna River.

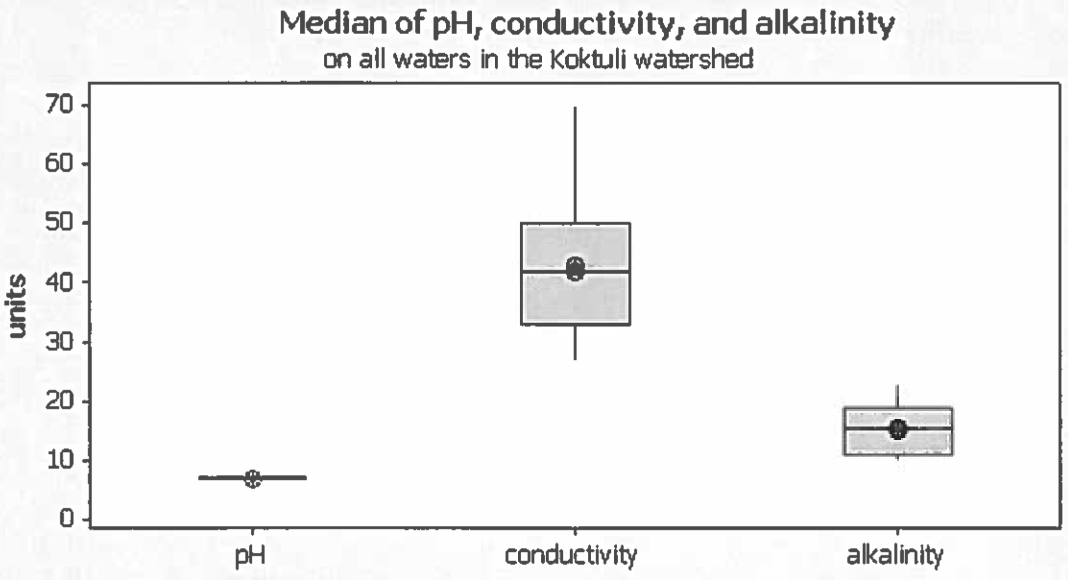
Physical properties were recorded along with the occurrence and distribution of nutrients, major ions, and trace metals and their relationship to hydrologic conditions. More specifically, measurements of pH, specific conductivity, water temperature, and salinity were recorded at all stream gage stations when discharge measurements are made. Readings were taken in mid-depth at five or more equally spaced points in the river cross-section. In addition, water samples were collected for laboratory analysis at gages one and three over a range of flows. Samples were collected three or four times in open water from May to October. Periodically one sample was collected in March when partial or total ice cover may be present. Sample collection will continue for a minimum of three consecutive years.

Appendix VII

Water Quality Data Analysis

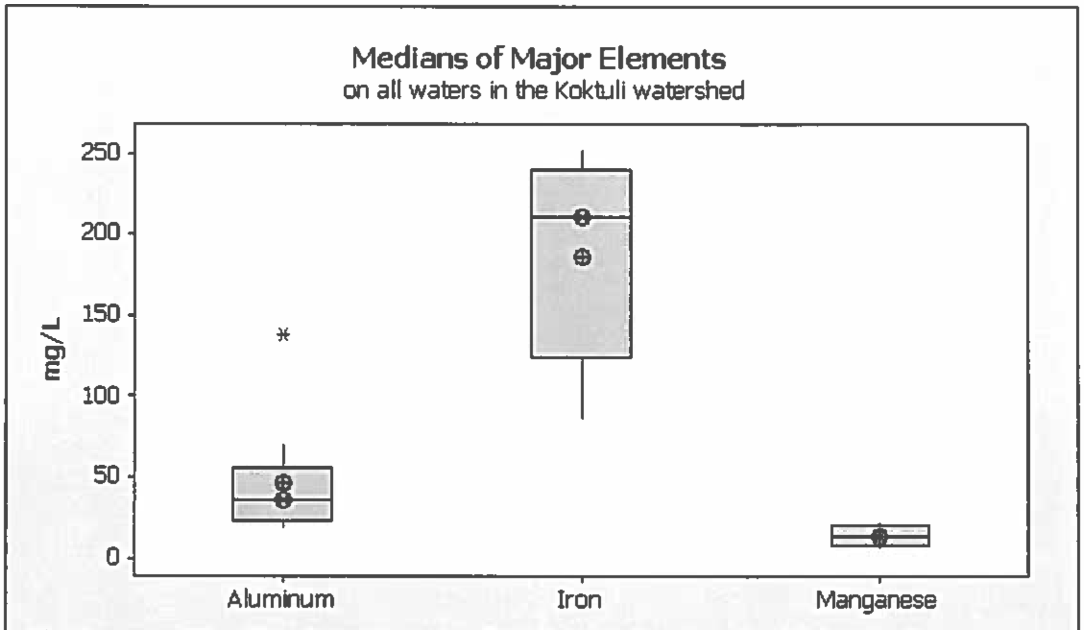
By Kendra Zanzow

The following series of box plots was created by assembling the medians as calculated by different research groups (BBNA, ENRI, the Natue Conservancy, and PLP) for each parameter for all surface water bodies in the Koktuli watershed for which data was available, including the main stem Koktuli River, the North Fork Koktuli, the South Fork Koktuli, tributaries of the North Fork Koktuli, and tributaries of the South Fork Koktuli. For instance, the median alkalinity of the main stem Koktuli (Cathy Flanagan and PLP), North Fork Koktuli main stem, South Fork Koktuli main stem (Nature Conservancy, ENRI and PLP), and North Fork Koktuli tributaries and South Fork Koktuli tributaries (Nature Conservancy and PLP) are all included in the box plot of alkalinity. Data includes preliminary data presented by the Pebble Limited Partnership (PLP), but removing PLP data does not significantly change the results. The pH is not available from PLP, but field pH published by Northern Dynasty Minerals is included in the pH graphs. Vertical lines represent the range of medians, shaded box represents the interquartile range, horizontal lines represent the median of assembled medians, and the circle without a horizontal line represents the mean of medians.



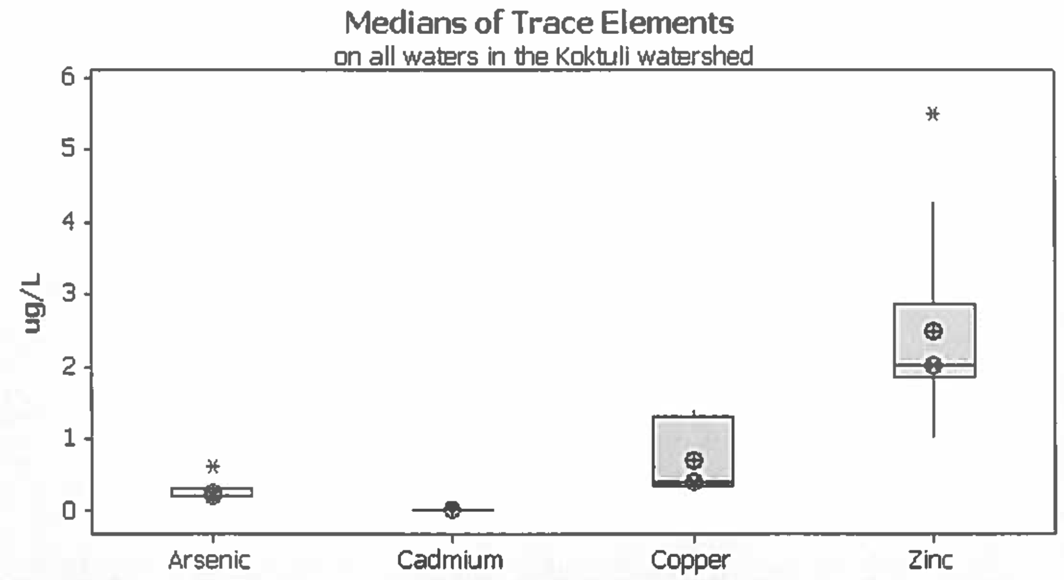
conductivity in uS/cm; alkalinity in mg/L
pH median of medians and mean of medians is 7.0
conductivity median of medians and mean of medians is 43
alkalinity median of medians and mean of medians is 16 mg/L

Note the neutral pH, very low conductivity, and very low alkalinity. Low conductivity is only found in very pure waters. The low alkalinity means water pH will drop quickly if acid enters it.



Aluminum: median of medians 36, mean of medians 49, benchmark criteria 87 ug/L
Iron: median of medians 211; mean of medians 198; benchmark 300 ug/L
Manganese: median of medians 13; mean of medians 17; benchmark 50 ug/L

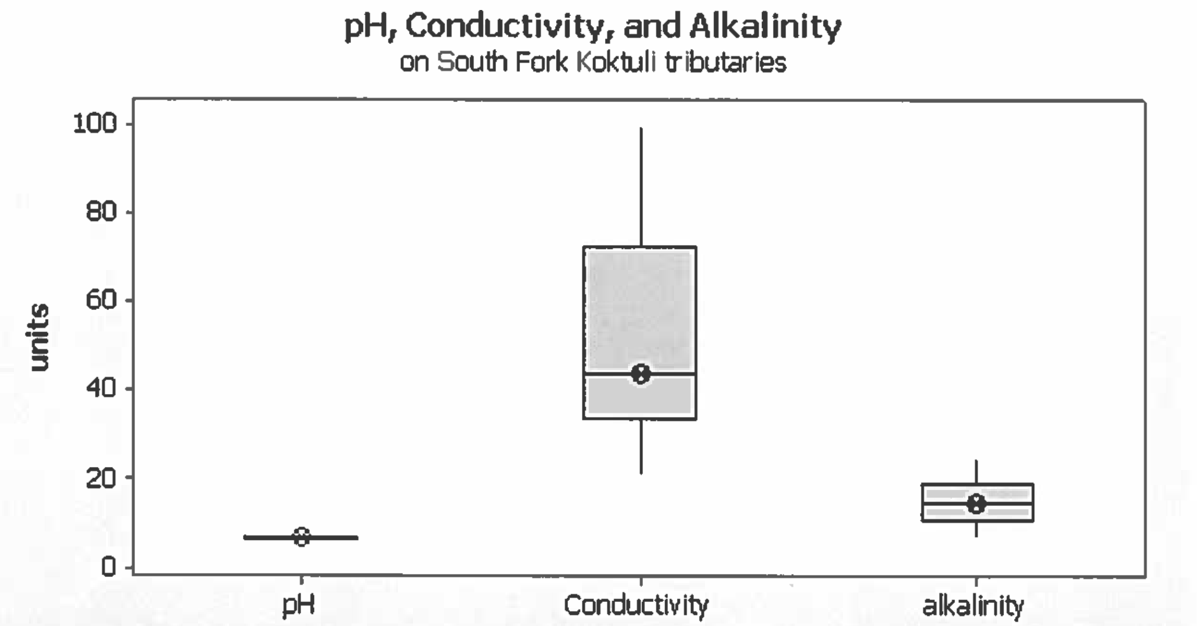
Except for the one outlier in aluminum, the entire range of medians of data for aluminum, iron, and manganese exceed State of Alaska most stringent water quality standards.



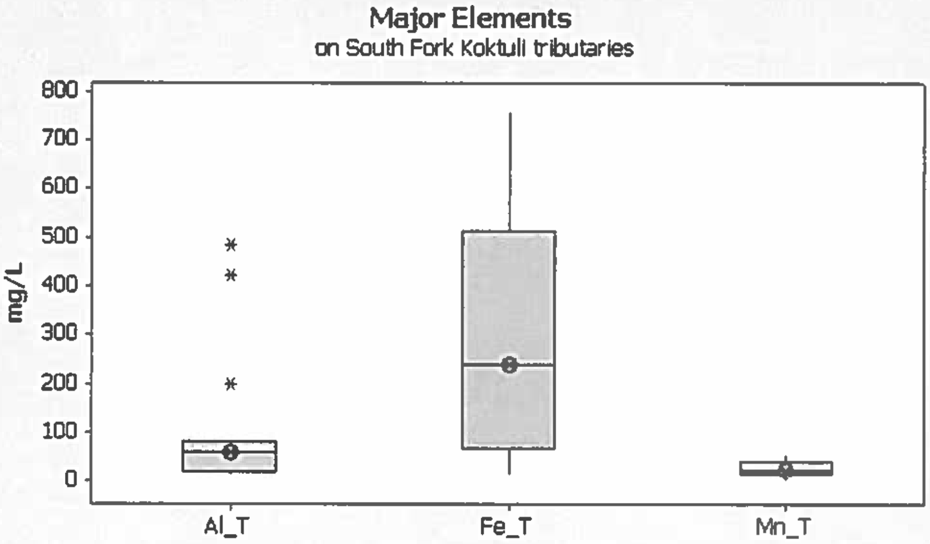
Copper median of medians is 0.4; mean of medians is 0.8; benchmark is 2.7 ug/L
Arsenic median of medians is 0.2; mean of medians 1.1; benchmark 10 ug/L
Cadmium median of medians is 0.01; mean of medians 0.02; benchmark 0.1 ug/L
Zinc median of medians is 2; mean of medians is 5; benchmark is 36 ug/L

All trace elements exceed State of Alaska most stringent water quality standards when summed as the median or mean of all waters.

Tributaries at the headwaters of the South Fork Koktuli represent the most mineralized waters in the watershed, and therefore the "worst case scenario" of watershed waters. Grapsh below show that while the full range of data exceeds most stringent water quality standards, the medians meet them. The previous set of graphs represented summaries of medians. The graphs below are a summary of individual raw data points on several different tributaries of the South Fork Koktuli. While they do not represent the median of a parameter at a single station, they provide a picture of headwater tributaries as a whole.

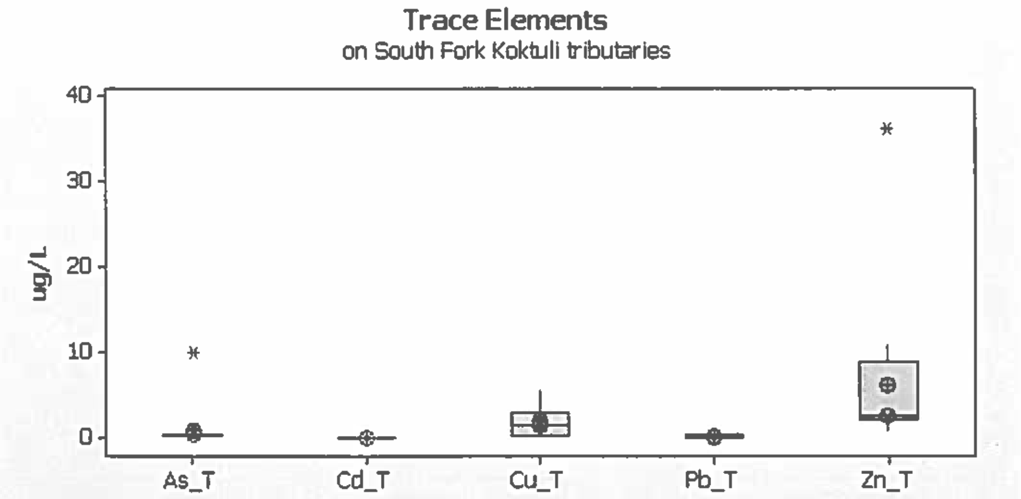


pH in pH units; conductivity as uS/cm; alkalinity in mg/L
pH median 6.9; mean 6.8
conductivity median 44; mean 50 uS/cm
alkalinity median and mean 15 mg/L



Aluminum median 60; mean 101; benchmark 87 ug/L
Iron median 237; mean 277; benchmark 300 ug/L
Manganese median 24; mean 26; benchmark 50 ug/L

Aluminum and iron have individual data points exceeding most stringent criteria – representing influxes of minerals during rain and melt events – but medians remain below the most stringent water quality use standards. This indicates that even in tributaries where mineralization is observed, water quality is very good.



Arsenic median 0.3; mean 0.9; benchmark 10 ug/L
Cadmium median 0.01; mean 0.03; benchmark 0.1 ug/L
Copper median 1.4; mean 1.9; benchmark 2.7 ug/L (varies with hardness)
Lead median 0.05; mean 0.23; benchmark 0.54 ug/L
Zinc median 3; mean 6; benchmark 36 ug/L

All trace elements fall well within most stringent water use quality standards.