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Lee Benda, Daniel Miller, Jason C. Leppi, Bernard Romey & Kevin Andras

BUILDING NEW HYDROGRAPHY AND VIRTUAL WATERSHEDS TO CONSERVE FRESHWATER FISHERIES

Lee Benda*[1], Daniel Miller[1], Jason C. Leppi[2], Bernard Romey[3], Kevin Andras[1]

[1] TerrainWorks, Mt. Shasta, California, USA

[2] The Wilderness Society, Anchorage, Alaska, USA

[3] Romey Riverscape Science, Longview, Washington, USA

* Corresponding author (leebenda@terrainworks.com)

ABSTRACT: The increasing availability of high-resolution digital elevation data is enhancing the mapping of hydrography across Earth's surface. As pressures on fluvial ecosystems grow, digital maps of river networks should include a data structure necessary to assess aquatic habitats and the environmental threats to them from resource development and climate change. Using examples from across Alaska, USA, we demonstrate how newly available radar and laser digital elevation products are being used to discover thousands of kilometers of previously unmapped channels, ranging from headwater to valley bottom streams. This comprehensive and attributed high-resolution hydrography that connects lentic, lotic, and terrestrial systems—a virtual watershed—has resulted in tens to hundreds of percent increases in potential salmonid habitats across landscapes ranging from the Arctic tundra to southeast rainforests. Our findings show how virtual watersheds enhance understanding of freshwater and diadromous fish habitats and serve as a model for supporting conservation efforts and environmental problem-solving in other regions globally.

1.0 Introduction

Freshwater biodiversity continues to decline across the planet due to anthropogenic impacts[1-3]. Fish species in many regions face extinction and their loss will have far-reaching implications for human well-being[4]. Environmental impacts that include pollution, land uses, flow regulation, and climate change[5,6] accumulate within hierarchical river networks[7-9]. The resulting degraded and fragmented habitats[10-12] are causing declines in many freshwater and diadromous fish populations worldwide[3,13,14].

Addressing the challenges that fish species face within freshwater ecosystems in the 21st-century depends on knowing how physical and biological features in watersheds interact to create habitats in river networks and knowing where those habitats are located at the scale of entire basins to regions[15,16]. Fish habitats are strongly influenced by the longitudinal sequence of channel morphologies[17-19]; channel interactions with floodplains, valley floors, and hillsides[20,21]; and the density and characteristics of tributary confluences[22-26]. Food resources and thermal regulation mediated by riparian vegetation, lakes and wetlands, and groundwater and hyporheic processes also influence the spatial distribution and diversity of freshwater habitats[27-30]. Thus, features of freshwater ecosystems that influence fish habitats have been studied at varying levels of detail and scale over the last several decades[31-33].

At the most fundamental level of mapping, a geography of rivers and their tributaries is required to identify locations of aquatic habitats. Throughout the twentieth century, paper topographic maps depicted rivers, streams, and other water bodies using stereoscopy— a technique that combines overlapping pairs of aerial imagery to produce three-dimensional representations of topography, including streams and rivers. More recently, geographies of stream channels were computer-digitized into digital hydrography databases for use in geographic information system software (GIS). These cartographically derived stream layers commonly omit many kilometers of headwater and valley bottom streams and inaccurately locate streams, particularly in areas of dense vegetation cover and in subtle, low-relief topography[34-37]. Despite their incompleteness and marginal accuracy, these riverine spatial datasets remain authoritative hydrography for government agencies, universities, nongovernmental organizations, private sectors, and the public[38,39]. In this paper, we refer to this era of river network mapping as “cartographic” to differentiate it from more recent computerized delineation of hydrography.

Increasing availability of high-resolution digital elevation models (DEM) is greatly improving the ability to more accurately delineate streams and rivers[40,41]. Beginning in 2010, the U.S. Geological Survey's (USGS) 3D digital elevation program began acquiring 5 m DEMs statewide in Alaska using Interferometric Synthetic Aperture Radar (IFSAR).This elevation data are now being used to create more accurate and complete hydrography to update the National Map of river networks[42-46]. In certain areas in Alaska, Light Detection and Ranging (LiDAR) DEMs at one-meter resolutions are being used to delineate streams previously obscured under vegetative cover[47-49]. We refer to river networks that are extracted directly from digital elevation models as "algorithmic" to differentiate them from earlier cartographic-derived networks.

Accurate and more complete algorithmic hydrography can be used for generalized mapping of fish habitats by specifying threshold environmental attributes that govern the upstream extent of fish occupancy, like drainage area, flow, and gradient[50-52]. More recently, analysis and modeling of fish habitats have focused on spatial variations in habitat quality, complexity and abundance, reflecting different life cycle requirements for spawning, rearing, foraging, and refugia. This more detailed analysis of fish habitats relies on longitudinal sequences of hydro-geomorphic features that include channel widths, depths, gradients (over varying length scales); streamflow; tributary confluence effects; topographic confinement; proximity and connectedness to floodplains, lakes and wetlands; turbidity; solar insolation; water temperature; sinuosity; and stream power; among others[15,17-19,53-57]. But most algorithmic stream networks, including those being created using higher-resolution DEMs, typically lack many of those hydro-geomorphic attributes and connectivity among them[35-36,41]. However, the increasing availability of numerical algorithms to generate these attributes, among others, is allowing practitioners to better delineate and characterize habitats for fish and other aquatic species[58,59].

Resource managers in Alaska are tasked with maintaining sustainable salmonid populations across thousands of miles of streams in remote and rugged landscapes. Accurate information about the extent and quality of habitat is essential for informing management decisions and for evaluating potential impacts of resource development and climate change on wild salmonid abundance[60-62]. Alaskan fisheries biologists from state and federal agencies, tribal entities, universities, NGOs, and private organizations have long worked to gather critical data on salmonid habitats, movement patterns, and occupancy across life stages. Programs like the Alaska Department of Fish and Game’s (ADFG) Freshwater Fish Inventory have significantly expanded knowledge of anadromous and resident freshwater fish distribution[63]. This vital field data cover only a fraction of species, is sparse in remote areas, and is limited spatially across a large state of more than one million square kilometers, limiting its utility for large-scale habitat assessments needed by land managers and conservation planners. Thus, improved methods for assessing salmon habitats are particularly important for conservation planning and restoration.

In this paper, we describe a methodology for delineating hydrography using recently available digital elevation models. Fortran computer programs were used in combination with high resolution IFSAR and LIDAR digital elevation models in four physiographic areas in Alaska. The newly created hydrography was compared and contrasted with older cartographic hydrography in the National Hydrography Dataset (NHD). A comparison of stream densities among the IfSAR, LiDAR, and NHD digital hydrography was used to evaluate the comprehensiveness of the modeled river networks. Using the new hydrography, we developed new fish habitat models to predict potential habitats for several species of salmon, ranging from the Arctic tundra to southeastern rainforests. Thus, our study describes an evolution in science and technology where low resolution, incomplete hydrography with limited attributes and analysis potential are being replaced by higher resolution, more comprehensive river networks. Additionally, highly-resolved hydrography can be used to connect lentic, lotic, and terrestrial systems—a virtual watershed—to inform conservation efforts[39,64]. Addressing the geographical and analytical limitations of national-level hydrography presents a global challenge[35-36]. The approach developed in Alaska serves as a model for updating national-level hydrography with analytical capabilities for identifying critical aquatic habitats, supporting environmental problem solving, and enhancing conservation efforts worldwide.

2.0 Methods

2.1 Study Areas and Data Sources

Alaska, the largest U.S. state (1,718,000 km^2), extends from latitude 51º15' south to 71º23' north and encompasses a wide range of physiographic provinces from maritime conifer rainforests in the southeast Alexander Archipelago to the taiga forests of the Yukon-Tanana watersheds in the interior to the tundra of the Brooks Range and Arctic coastal plain (Figure 1). Climate ranges from humid temperate in the south to arid cold in the north. The state is home to all five species of North American Pacific salmon: Chinook (*Oncorhynchus tshawytscha*), sockeye (*O. nerka*), coho (*O. kisutch*), chum (*O. keta*), and pink (*O.gorbuscha*). Other freshwater and diadromous species include Steelhead trout (*O. mykiss*), Arctic Char (*Salvelinus alpinus*), Dolly Varden (*S. malma*), Grayling (*Thymallus arcticus*) and Whitefish (Coregonus spp.).

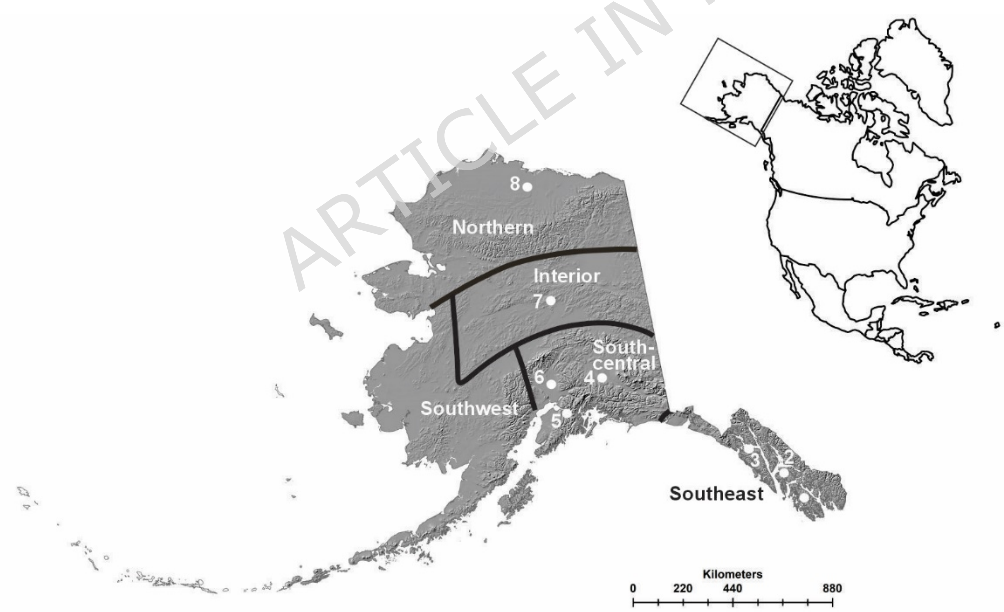

Figure 1. White circles show the locations of new algorithmic river networks and virtual watersheds within four physiographic regions in Alaska. 1-Prince of Wales Island; 2-Kupreanof/Kuiu Islands; 3-Chichagof Island; 4-Copper River; 5-Kenai Peninsula (Southcentral Region); 6-Matanuska-Susitna River; 7-Yukon River tributaries; 8-Colville River. Map was created using ESRI ArcMap 10.6 software using

publicly available data; USGS Alaka hillshade and Alaska Department of Natural Resources, Alaska Coastline data layers (https://www.arcgis.com/sharing/rest/content/items/24bb1a5332894893bf9a305d9f6c6696/info/metadata/metadata.xml?format=default&output=html).

For decades, topographic maps in Alaska were of low resolution because of the state's remoteness, size, lack of ground survey controls, and little cloud-free photogrammetry[43]. Alaska quadrangle maps were produced at 1:63,360 (1 inch = 1 mile), compared to the rest of the U.S. that had maps of 1:24,000. Alaska quadrangles were also inaccurate, never achieving national map standards at any scale, where mountains could be offset by more than one mile, leading to numerous controlled flights into terrain (CFIT) aviation accidents[43].

The National Hydrography Dataset (NHD) in Alaska, a digital vector library of streams, rivers and other waterbodies within the National Map, was created cartographically using the 1950s era U.S.G.S. topographic maps (1:63,360 scale) and existing aerial photography. The NHD was completed in 2008.

The advent of computer technologies in the latter 20th century led to creation of digital elevation products. A bare earth DEM contains point elevations arranged at regularly spaced intervals across an x and y grid in units of feet or meters. Elevations in a DEM represent terrain heights relative to a vertical datum. The National Elevation Database DEMs for Alaska were initially created by digitizing 100-foot (30.48m) contours on the available 1:63,360-scale paper topographic maps that yielded DEM resolutions mostly in the range of 1 to 2 arc-seconds, or approximately a grid resolution of 30 to 60 meters.

In the early 2000s, the Space Shuttle Mapping Mission employed C and X band synthetic aperture radar to generate digital surface models (DSM) across Alaska at 1-arc-second (approximately 30 m) resolution (DSMs include buildings and vegetation). Beginning in 2010 and running through 2020, the USGS contracted with private vendors to collect IFSAR data using aircraft. These data were used to create a DSM and a DEM for Alaska at a resolution of approximately 5 m. In the last decade, one-meter LiDAR elevation data have been collected using aircraft in select locations across Alaska by agencies including the USGS, U. S. Forest Service (USFS), and National Resources Conservation Service (NRCS).

Alaska uses the NHD cartographic streams as the base layer to maintain a catalogue of all channels across the state that are known to contain salmon, called the Anadromous Waters Catalog (AWC)[64]. Based on the ADFG policy, the occupancy of salmon in any stream channel requires on-the-ground visual confirmation of at least two fish. The AWC underestimates salmon habitats across the state because of incomplete NHD hydrography and the field validation component[17,56,65]. In addition, the AWC is also limited by non-detection bias, where lack of records does not accurately indicate absence of habitats and fish.

Beginning in 2016, the USGS initiated a program to update and improve the NHD using newly available IFSAR DEMs across the State of Alaska (3D Elevation Program or 3DEP). That effort to create more complete and accurate algorithmic networks is currently ongoing. The 3DEP and subsequent 3D Hydrography Programs (3DHP) that create new hydrography and subbasin boundaries have specific protocols for numerical precision, channel delineation, and waterbody classification[45,66].

2.2 Building Virtual Watersheds

A virtual watershed couples algorithmic hydrography, represented at the DEM-cell (node) scale, to other terrestrial and lentic landscape elements, including hillsides, valley floors, floodplains, riparian zones, wetlands, lakes, alluvial fans, and erosion sources, among others[38,39,44,67,68]. The data structures, methods, and algorithms described below for creating virtual watersheds have grown out of studies that explored temporal and spatial patterns of landscape dynamics over the last couple decades[69-72], that included creating digital hydrography from DEMs[67,73-77].

The numerical analyses used to build algorithmic hydrography in Alaska are implemented in a set of Fortran programs[44,78]. The programs have been incorporated into a user interface for ArcGIS and ArcPro called NetMap[38,39,67]. Six steps are required. First, DEMs of the highest resolution are merged into a single, contiguous elevation model for entire catchments. DEMs from different data sources are warped along edges to match the mean focal elevations, calculated over a radius of 50 m or more[79]. The resulting contiguous DEM is resampled to the desired resolution. Second, a hydrologically conditioned surface is created using a combination of depression filling and carving[80] to ensure spatially continuous, single direction water flow across terrain. The DEM itself is not modified and is the base from which the channel network is extracted and other landforms delineated (floodplains, wetlands, riparian areas, and steep slope erosion areas) and connected to the network.

Delineating a channel network requires identifying the upstream extent of headwater channels—where channels begin. The third step defines channel initiation using: a) threshold for contributing area multiplied by gradient squared[66], which is representative of fluvial erosion potential[81]; b) threshold plan curvature measured over a length scale for resolving fluvial topography; and c) the hillslope length scale over which (a) and (b) are met. An appropriate length scale typically spans tens of meters and separate initiation values are specified for high and low gradient areas. The D-infinity algorithm[82] is used to calculate flow accumulation and direction within contiguous watershed boundaries.

Once channels are initiated, the fourth step traces the down-gravity flow uses D-8 directions guided by terrain indicators of channel locations, including surface gradient, plan curvature, and fluvial geomorphic features[83,84]. A path-based analysis is used to correct for the limited choice of eight flow directions[85]. Fifth, drainage enforcement is used to guide flow directions and to specify channel locations. These include: a) polygons of open water digitized from imagery; b) reflected intensity from LiDAR and IFSAR data indicating open water; c) GIS vector line files of channel centerlines from accurate field surveys; d) line segments indicating culvert locations at road-stream crossings; and e) points of known channel initiation. Lastly, channel traces are smoothed to provide optimal channel centerlines to more accurately estimate channel lengths and gradients.

The resulting algorithmic network is represented digitally as a set of linked nodes, one node for each DEM cell. This data structure maintains information at the smallest spatial grain available from the elevation data. Channel attributes for each node, such as gradient and valley confinement, are calculated from the unmodified

DEM. A nodal data structure that represents channel gradient at any length scale is used to evaluate gradient-related thresholds to fish movement, including the occurrence of migration-blocking waterfalls. Flow routing and accumulation rasters are spatially registered to the fluvial nodes to couple the terrestrial and lentic landscape features to the lotic ecosystem. Various algorithms are used to delineate the other features of a virtual watershed including floodplains, wetlands, riparian processes, thermal refugia, and sediment and organic material sources to the network, including by mass wasting[44,74,86-88]. See also citations in Discussion.

2.3 Delineating Fish Habitats

To address the limitations of field-based studies, GIS-based modeling of fish habitats within virtual watersheds has focused on immutable geophysical riverine features as reliable predictors of habitat suitability and spatial distribution[15,18,19,54,56,57,73,89,90]. Such fish habitat models, called Intrinsic Potential (IP), a modified version of resource selection functions[91], have used various combinations of channel gradient, valley confinement, and mean annual flow as predictors of habitat suitability for coho, steelhead, and Chinook salmon in Oregon[16]. In southcentral Alaska, Bidlack et al.[15] used a combination of channel gradient, confinement, and spatial coverage of glaciers as a proxy for water turbidity to create an IP model for Chinook in the Copper River. On the eastern Kenai Peninsula, a sockeye salmon IP model used a combination of proximity to lakes, gravel availability below lakes, and channel confinement related to floodplains[57]. In southeast Alaska, IP models for coho, chum, and pink salmon have used gradient, confinement, and flow[50]. The southeast Alaska Chinook and coho salmon IP models link reach scale (100 m) habitat attributes to summer juvenile fish density[15,50]. The chum and pink salmon models in southeast Alaska are based on redd density[56] . A Broad Whitefish (*Coregonus nasus*) IP model was developed for the Colville River in Arctic Alaska using bankfull channel width, degree of channel braiding, and gravel sediment size[15]. All of the studies cited above used the algorithmic hydrography-virtual watershed data structure described in Section 2.2.

There is increasing interest in predicting the upstream extent of fish migration for resident and anadromous fish species, including in Alaska[19,53,92-95]. While IP models focus on spatial patterns of habitat quality, end of habitat models identify the upper boundaries of fish populations across riverscapes. LiDAR-derived virtual watersheds, in conjunction with fish occurrence data from tribal, state, and federal agencies, are being used to develop end-of-habitat models in southeast Alaska[96].

We developed virtual watersheds, inclusive of algorithmic networks, in eight study areas in Alaska, including four in southeast, two in southcentral, one in the interior, and one in the Arctic (Figure 1). The study area watersheds were selected based on the needs of funding organizations, including North Chichagof Island (NRCS), full Chichagof Island (USFS), Kupreanof/Kuiu Islands (NRCS), Prince of Wales Island (USFS), Copper River (Ecotrust), Kenai Peninsula (USFS), Matanuska/Susitna (The Nature Conservancy), Yukon-Chena/Tanana/Chatanika/Goodpaster/Salcha Rivers (University of Alaska), and Colville River (The Wilderness Society). The upstream extents of the digital networks and network density (km per km^2) were based on the method of channel delineation described in Section 2.2 and on conferring with local agency and NGO personnel. IfSAR and LiDAR DEMs were used as available across study areas, except in the Copper River watershed in the southcentral region where only 20 and 30 m DEMs existed.

In the eight study areas, we compared the cumulative lengths of channels in the algorithmic networks to the cartographic NHD channel lengths and compared the predicted IP-modeled fish habitat lengths to the lengths of anadromous fish habitats in the AWC in each of the watersheds and islands (Table 1). We applied fish habitat models for coho, Chinook, sockeye, and Broad Whitefish within seven of the watersheds. Salmon IP models that were applied to the algorithmic river networks included coho[56] in southeast Alaska (study sites 1-3), Chinook[17] in the Copper River in southcentral (site 4), sockeye[57] in the Kenai Peninsula in southcentral (site 5), coho[56] and Chinook[17] in the Matanuska-Susitna River in southcentral (site 6), and Broad Whitefish[15] in the Colville River (site 8) in the Arctic. In the Yukon area watersheds (site 7), a generic end-of-fish channel gradient threshold of 10% was applied, above which salmon were assumed to be absent or in minimal numbers[49].

3.0 Results

Lengths of IFSAR and LiDAR derived algorithmic river networks always exceeded the cartographic NHD lenghts by tens to hundreds of percent (Table 1). The increase in IFSAR derived networks ranged from 2% to 53% and average 28%. The 2% increase occurred in the Colville River watershed in the Arctic. The increase in LiDAR derived algorithmic network lengths ranged from 84% to 203% and averaged 144%. The Copper River algorithmic network was derived from 20 m and 30 m DEMs and the total channel length was 23% less than the NHD length. The largest increases in LiDAR derived channel length occurred in the forested areas of southeast Alaska (84% to 146%) where it has been difficult to detect channels cartographically using imagery alone. In three watersheds that had both IFSAR and LiDAR DEMs, they were merged and combined, as described in Section 2.2. The increase in LiDAR/IFSAR combined algorithmic network lengths, over the cartographic NHD, ranged from 19% to 124% and averaged 67%. The higher resolution DEMs (LiDAR, IFSAR/LiDAR combinations) had the greatest increase in channel lengths, particularly in the heavily forested southeast region (Table 1). Proportional increases in channel length led to very large increases in net length of channels in any watershed or island. For example, in the Matanuska Susitna watershed in southcentral Alaska with a drainage area of 64,806 km^2, the net increase in algorithmic channel length over that of the NHD is 50,292 km. In the 5,657 km^2 Prince of Wales Island in southeast Alaska, the net increase in delineated channels is 8,910 km.

Table 1. NHD cartographic stream lengths are compared to the lengths of algorithmic networks extracted from digital elevation models (DEMs). Cumulative lengths of predicted fish habitats by individual species are compared to the lengths of fish occupied channels in the Anadromous Waters Catalog (AWC). DEM types and resolutions are indicated.

Location	Area (km^2)	DEM Type/ Resolution	NHD Length (km) [km km^{-2}][1]	Algorithmic channel length (km) in virtual watersheds	AWC[3](km)	Model Habitat Length (km) (% increase[4])

				(% increase[2]) [km km^{-2}][1]		
North Chichagof Island[5] (Portion of) (Southeast)	1,074	IFSAR LiDAR	1,244 [1.1] 1,244	1,899 (53%) [1.8] 3,055 (146%) [2.8]	189 (coho) 189 (coho)	402[6] (115%) 930[6] (392%)
Full Chichagof Isand[5] (Southeast)	5,273	LiDAR/ IFSAR combo	10,620 [2.0]	16,884 (59%) [3.2]	938 (coho)	1,275[6] (36%)
Kupreanof/Kuiu Islands[5] (Portions of) (Southeast)	744	LiDAR	1,936 [2.6]	5,866 (203%) [7.8]	166 (coho)	1,343[6] (708%)
Prince of Wales Island[5] (Southeast)	5,657	LiDAR	10,619 [1.9]	19,529 (84%) [3.5]	1,523 (coho)	4,838[6] (218%)
Copper River[7] (Southcentral)	20,275	20 m/30 m[8]	72,869 [3.6]	56,111 (-23%) [2.8]	3,553 (Chinook)	12,500[9] (252%)
Kenai Peninsula[8] (Portion of) (Southcentral)	10,310	IFSAR/ LiDAR combo	9,902 [1.0]	11,763 (19%) [1.1]	352 (sockeye)	1,477[10] (311%)
Matanuska-Susitna[7] (Southcentral)	64,806	LiDAR/ IFSAR combo	40,635 [0.6]	90,927 (124%) [1.4]	4,988 (Chinook) 6,356 (coho)	18,507[9] (270%) 25,910[5] (308%)
Yukon-Chena/Tanana/ Chatanika/Goodpaster/ Salcha Rivers[11] (Portions of) (Interior)	19,669	IFSAR	15,092 [0.8]	19,536 (29%) [1.0]	1,262 (generic salmon)	11,411[12] (804%)
Colville River[13] (Arctic)	60,255	IFSAR	74,489 [1.2]	75,834 (2%) [1.3]	470 (Broad Whitefish)	1,548[14] (229%)

1 Drainage density (total channel length/watershed area)
2 ((algorithmic – NHD)/NHD) * 100
3 Alaska Anadromous Waters Catalog (AWC)[64]
4 ((Predicted – AWC)/AWC) * 100
5 Southeast Alaska, Alexander Archipelago region

6 Coho IP[56]
7 Southcentral Alaska
8 ASTER and SPOT satellite data (Geographic Information Network of Alaska (GINA; www.gina.alaska.edu/)
9 Chinook IP[17]
10 Sockeye IP[57]
11 Interior Alaska
12 Generic gradient barrier, salmon 10%[52]
13 Arctic Alaska
14 Broad Whitefish IP[15]

The lengths of additional anadromous fish habitats predicted in all algorithmic networks over those contained within the AWC ranged from 36% to 804% and averaged 332% (Table 1). The increase in predicted habitat length in the IFSAR derived networks ranged from 115% to 804% and averaged 383%. The increase in predicted fish habitat lengths in the LIDAR derived networks ranged from 218% to 708% and averaged 439%. The increase in predicted fish habitat lengths in the IFSAR/LiDAR combination ranged from 36% to 311% and averaged 230%. The largest predicted increases in lengths of salmonid habitats (392%, 708%, Table 1) occurred within the forested southeast region. Similar to the increase in total channel lengths, the model predicted increases in salmonid habitat lengths resulted in very large increases in net habitats. For example, in watersheds of the North Chichagof Island in southeast Alaska (1,074 km^2), we predicted 930 km of coho habitats using LiDAR-derived river networks compared to the AWC habitat length of 189 km, for an increase of 741 km of coho salmon habitat. In the 64,806 km^2 Matanuska Susitna watershed the model predicted 18,507 km of chinook habitat using LiDAR river networks compared to the AWC length of 4,988 km, for an increase of 13,519 km. In the same watershed, we predicted 25,910 km of coho habitat compared to the AWC coho habitat length of 6,356 km, for an increase of 19,554 km. Large increases in projected fish habitats over the AWC is expected because the AWC requires field validation of fish occupancy in remote river systems and is subject to nondetection bias.

A visual comparison among the NHD cartographic and the IFSAR and LiDAR algorithmic networks reveals an increasing length of channels within virtual watersheds that is concentrated in the headwaters and that extend down to wider valley floors (Figure 2). Increasing channel length also occurs within the wider valley floors in braided channel networks, as illustrated in the Matanuska-Susitna River watershed (Figure 2).

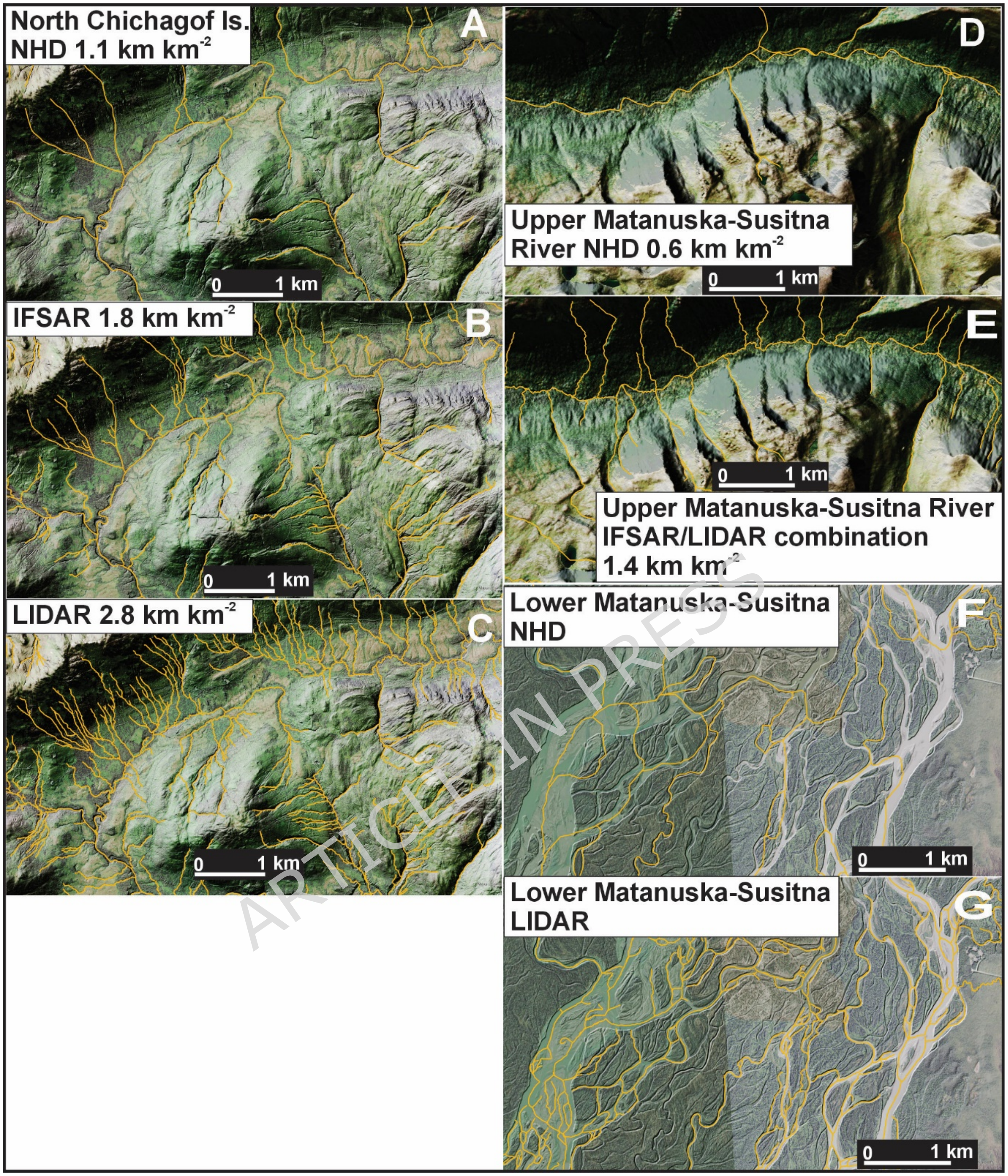

Figure 2. (Left panel) The density of channel networks in northern Chichagof Island in southeast Alaska increases from the cartographic NHD to the algorithmic networks delineated from IFSAR and LiDAR DEMs (A-C, using LIDAR shaded relief). (Right panel) The increase in river network density is illustrated in the Matanuska-Susitna River watershed (D-E, using IFSAR shaded relief). The network delineated from the IFSAR/LiDAR combination occurs in both the upper valleys as headwater

tributaries and along the wider valley floors with braided channels (F-G, using LIDAR shaded relief). Software: ArcGIS Pro 3.5. Data Source: ArcGIS Map Service; Server: https://services.arcgisonline.com/ArcGIS/rest/services/World_Imagery/MapServer

The modeled increases in coho habitats in the North Chichagof Island in southeast Alaska are predicted to occur along the wider valley floors where newly delineated headwater tributaries join with the mainstem (Figure 3). Predicted increases in coho salmon channel length also occurs as upriver extensions of networks (Figure 3).

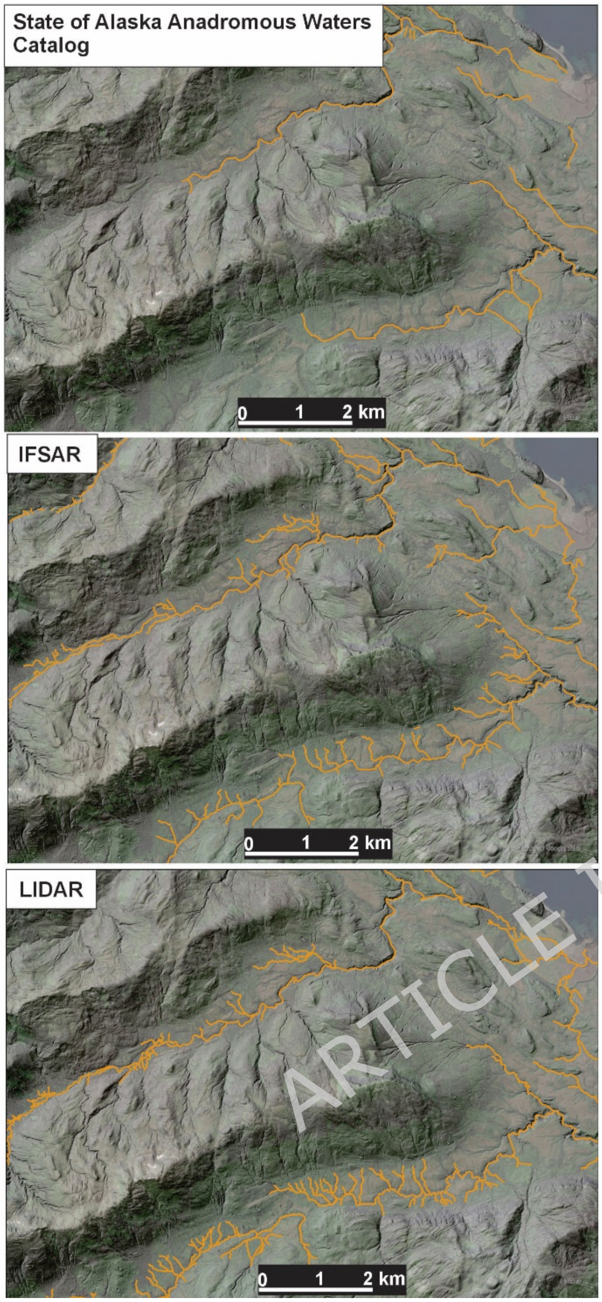

Figure 3. Predicted coho salmon habitat[56] in the North Chichagof Island increased in the more densified channel networks that were delineated in IFSAR and LiDAR networks, compared to Alaska’s anadromous watershed catalog that is based on the cartographic NHD. The predicted increase in fish habitat occurs mainly in low gradient channels within wider valley floors that are extensions of newly delineated headwater tributaries (Figure 2). Predicted increases in modeled fish habitats also occurs as upriver extensions higher in the watershed. Map data source is same as Figure 2.

4.0 Discussion

There is a general pattern of higher drainage densities of the algorithmic networks compared to the cartographic NHD (Table 1). In the North Chichagof Island, Yukon tributaries, and the Colville River watershed the NHD densities (km km^{-2}) ranged from 0.8 to 1.2 (average 1.0) compared to the IFSAR network densities of 1.0 to 1.8 (average 1.4). In the North Chichagof, Kupreanof/Kuiu, and Prince of Wales Islands, NHD densities ranged from 1.1 to 2.6 (average 1.9) compared to the LIDAR network densities of 2.8 to 7.8 (average 4.7). The network densities in the IFSAR-LIDAR combinations in the full Chichagof Island, Kenai Peninsula, and the Matanuska-Susitna watershed ranged from 1.1 to 3.2 (average 1.9) compared to the NHD densities of 0.6 to 2.0 (average 1.2). Algorithmic channel networks created using LIDAR had the highest average density (4.7), followed by IFSAR-LIDAR combinations (1.9), with IFSAR networks having the lowest density (1.4)

The relative change in channel density and in the absolute increase in new channel length are sensitive to the channel initiation thresholds as described in Section 2.2. Threshold criteria include a minimum drainage area (multiplied by gradient squared), plan curvature, and the length scales associated with these. Fluvial erosion features, as reflected in the channel threshold criteria, that are detectable on DEMs particularly using LIDAR, can extend high on hillslopes (Figure 4). The inclusion of these features depends on the objectives of natural resource applications, including physical and biological functions. High densities of headwater channels that encompass ephemeral hydrography may be of interest to hydrologists as sources of flow to larger, fish-bearing channels. Additionally, the merger of small ephemeral channels downslope creates larger tributaries that traverse valley floors that are predicted salmon habitats (Figure 3). Small ephemeral channels on steep terrain are also sources of landslide and debris flow potential[86] and are of interest to geologists for hazard mitigation.

Algorithmic hydrography could overpredict or underpredict the density of channel networks, depending on the channel initiation criteria that is used. One issue in underpredicting or overprediction is the definition of a channel. Are declivities that only run water for a few days a year, during high precipitation events or during snowmelt runoff, a channel? Or, must a channel have flowing water year-round? As discussed above, ephemeral channels that have flow only during big storms can be corridors of channelized debris flows. If characterizing debris flow potential is important, then small declivities should be included that would increase stream density (Figure 4). If ephemeral channels are excluded, channel densities would be lower. But the confluencing of several ephemeral channels can lead to larger channels downstream and the potential for fish habitats. We used channel initiation thresholds necessary to capture most headwater channels that appear to be eroded by fluvial or debris flow processes. Initiation criteria vary based on the resolution of the DEM and the objectives of the modeler.

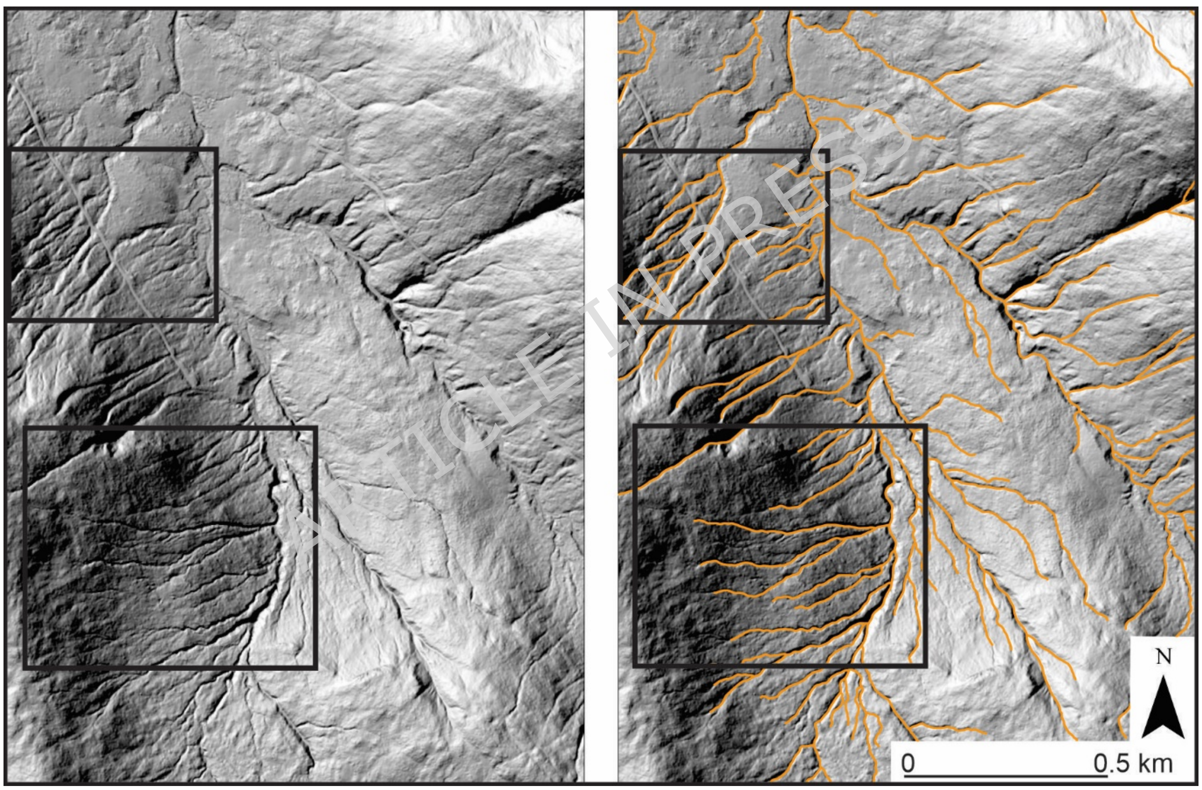

Figure 4. (Left panel) One meter LiDAR DEM (resampled to two meters) reveals the high density of ephemeral channels in a watershed on Kupreanof Island in southeast Alaska. (Right panel) Channel network initiation criteria were defined to capture the high density of ephemeral channels that are prone to landslides and debris flows and to identify the small valley floor streams that are formed from them that are predicted salmon habitats (e.g., Figure 3). Hence, target channel densities are

defined by hydrogeomorphic and biological functions. Map data source is same as Figure 2.

An important control on variation in delineated channel densities is the difference between IFSAR and LIDAR technologies. IFSAR is a radar product, and it characterizes the ground elevation surface that includes variation in vegetation height. Variations in vegetation height, whether natural (muskeg versus dense conifer forests) or human modified (forest versus clearcut), are reflected in the ground surface, complicating detection of channel features. Thus, poor resolution of topography using IFSAR DEMs can lead to incomplete channel delineation, particularly in forests of southeast and southcentral Alaska (Figure 2). Network completeness using IFSAR is greater in areas of low relief vegetation (shrubs and grasses), such as in the Colville River in the Arctic region where the NHD density of 1.2 is similar to the new IFSAR-based channel density of 1.3 (Table 1). In contrast, LIDAR penetrates vegetation depending on plant basal area and laser point density and thereby allows for greater accuracy of bare ground surface elevations and hence the detection of subtle fluvial erosion features.

Even in watersheds with similar cartographic and algorithmic river densities, hydrography delineated from digital elevation data is spatially more accurate. For example, in Arctic regions like the Colville River, IFSAR-based algorithmic river networks provide higher resolved hydrography in braided parts of networks compared to cartographic-based hydrography, similar to the lower Matanuska-Susitna River (e.g., Figure 2F-G). In addition, headwater first-order streams in the Arctic often appear more abundant and extend further upslope in the NHD than they exist on the ground. Our field observations of the upward extent of headwater streams in that landscape are consistent with the IFSAR river networks. It appears that cartographers, using aerial imagery, can mischaracterize linear wetland and muskeg features as channels, whereas algorithmic delineation of channels using digital elevation data requires detection of fluvial erosion in the form of declivities, however subtle.

Multiple geology, vegetation, modeling, and human factors also influence the detection of hydrographic features. For the cartographic NHD, the degree of conspicuous fluvial erosion, density of obscuring vegetation, and objective and skill of the cartographer will influence the completeness of the mapped networks. Channel density using LIDAR DEMs can vary significantly based on the threshold channel initiation criteria that are selected based on natural science objectives (encompassing ephemeral channels, identifying fish habitats, predicting landslide potential etc.) and the natural density of fluvial erosion features. For example, a high drainage density of 7.8 km km^{-2} in the LIDAR-based Kupreanof/Kuiu Island networks in southeast Alaska (Figure 4) resulted from a high density (closely spaced) of headwater ephemeral channels and the objectives of defining landslide and debris flow potential and of delineating valley bottom tributaries that are salmon habitats. Further determining the role of lithology, geological structure, glacial history, and erosion mechanisms on the variations in natural drainage density across Alaska would require additional modeling over larger areas to encompass greater variation in physiographic conditions.

The additional length of previously unidentified channels on valley floors as extensions of ephemeral headwaters and of additional braids and secondary channels of mainstem rivers (Figures 2 and 3), greatly increase abundance of predicted anadromous fish habitats (Table 1). The proportional increases in fish habitat length over the lengths of salmon habitats documented within the Anadromous Waters Catalog are substantial and average hundreds of percent. Presumably, Intrinsic Potential salmon models if applied to the NHD networks would also reveal increased lengths of predictive habitats, although not to the extent revealed by IFSAR and LIDAR networks. But the NHD data structure (channel lengths of kilometers and lack of channel gradients and drainage area attributes) limits direct applications of existing salmon models in the NHD. Predictions of new fish habitats could be used by federal and state agencies, and NGOs, to guide new field surveys to verify accessible fish habitats and fish occupancy across the state of Alaska. However, if the AWC continues to require on-the-ground confirmation of fish biomass in streams (field documentation of at least two fish), then the utility of model-predicted mapping of salmon habitats to guide resource management, in the absence of field validation, will be limited.

Creating an accurate and complete algorithmic stream network for Alaska will be key to protecting diadromous fish and freshwater biodiversity. Fish move across riverscapes in response to shifting conditions and select a variety of habitats over their lives to maximize fitness and survival. Salmonid species use a suite of permanent and temporary aquatic habitats[97] that is influenced by landscape complementation[98] and neighborhood effects. For example, coho salmon often spawn in small headwater streams in southeast Alaska and juveniles often move into wetland complexes, small lakes, or first- order tributaries to rear prior to heading to sea[99,100]. Many of these productive rearing habitats (and connectivity corridors between habitats) may not currently be mapped and therefore they are at risk from development activities such as logging and mining.

Higher resolution and more comprehensive stream networks are valuable on their own. But more spatially extensive and accurate stream networks that are embedded within a virtual watershed data structure can be used to evaluate the full range of hydro-geomorphic processes in river ecosystems and the effects of human activities on them[35,36,41]. Such virtual watersheds have five analytical features as outlined in Section 2.2: 1) channel delineation using a node-based data structure that supports variable channel length scales; 2) lotic-lentic-terrestrial connectivity and landscape discretization using flow directions and accumulation; 3) channel nodes or channel reaches attributed with watershed and channel information; 4) landform characterization, including floodplains, wetlands, and erosion sources, among others; and 5) downstream-upstream routing and data aggregation. This data structure supports a suite of analyses including characterizing and identifying critical habitats and supporting conservation and restoration problem solving[38,39]. For example, the Keex' Kwáan Community Forest Partnership used virtual watersheds in portions of Kupreanof/Kuiu Island to conduct an analysis of effects of forest roads on salmon habitat[101]. LiDAR-based algorithmic networks within virtual watersheds allowed ranking of all road-stream crossings by the length of habitats that could be restored by upgrading the crossings.

In practice, virtual watersheds have been used to characterize geomorphic attributes of channel networks in Oregon[74,75], Washington[102], Alaska[17,56], Spain[36,103,104], and Uruguay[105]; identify fish habitats and floodplains in the Pacific

Northwest[15,17,53,56,106,107]; quantify ecological effects of tributary confluence in the western U.S.[68,108-110]; forecast post-wildfire impacts on fisheries in Washington[111]; predict shade and wood recruitment to streams in Spain[112,113]; create channel classification models in Alberta[114,115]; predict forest road erosion in China[116]; evaluate effects of climate change on fish habitat in Alaska[117]; evaluate potential for landslides and debris flows in Oregon[86,87,110]; and create ecosystem evaluation models on the Iberian Peninsula[38].

The virtual watersheds and their algorithmic networks described in this paper in the four Alaska physiographic regions are distinct from the USGS 3DHP program that is being used to update the National Map of waterbodies in Alaska. The USGS 3DHP program uses IFSAR and to a lesser extent LIDAR DEMs to create more spatially accurate digital hydrography. 3DHP hydrography doesn't include the physical attributes necessary to readily predict salmon habitats or to support other natural resource applications of virtual watersheds. However, virtual watersheds in Alaska could contribute to the 3DHP program by providing value-added features[118], including watershed and channel attributes. Conversely, updated hydrography created by the 3DHP program could be used as the network template to create virtual watersheds, thus promoting spatial consistency across the National Map and virtual watersheds at regional scales.

The analytical limitations of existing digital hydrography in Alaska described here is a problem that exists worldwide. In 2015, network completeness and analytical capabilities of official country-wide digital hydrography were evaluated in five countries—Canada, China, Russia, Spain, and the U. S.[39] All national-level hydrography lacked in network completeness and analytical capabilities (to conduct the types of studies cited above). The incidence of low resolution and incomplete hydrography with few channel and watershed attributes and with limited analysis potential is thus common globally. The Alaska project that describes the evolution of channel network and watershed geospatial capabilities through the incorporation of algorithmic networks within virtual watersheds offers a guide to other countries, provinces, states, and regions for updating their own geospatial resources to advance environmental problem solving, including the conservation of aquatic habitats[38,39].

5.0 Conclusions

We present a new approach for delineating hydrography using newly available IFSAR and LIDAR digital elevation models in four physiographic regions of Alaska. A comparison of stream densities among the newly developed algorithmic hydrography and the older cartographically derived hydrography in the National Hydrography Dataset revealed that the State of Alaska has had incompletely mapped river networks. Our analysis illustrates that many headwater and valley streams are missing from existing federal and state maps of Alaskan hydrography. Application of computer-based algorithms using IFSAR and LiDAR DEMs led to detection of thousands of kilometers of newly identified channels, ranging from headwaters to valley bottom streams. These newly delineated streams on maps represent hundreds of percent increases in cumulative channel lengths across multiple watersheds and islands.

The existing incomplete cartographic hydrography of the original NHD provides the base layer for Alaska's Anadromous Waters Catalog which consequently underestimates the spatial extent of salmon habitats. Application of salmon models using attributed algorithmic hydrography in virtual watersheds has led to hundreds of percent increases in predicted habitats across the four physiographic regions. Existing state hydrography also lacks the data structure for evaluating resource development and conservation activities, including identifying the extent of fish habitats and potential impacts from mining, logging, urban development, and hydropower. The new science and technology of virtual watersheds described here has the potential to increase the state of Alaska's ability to identify and protect salmon habitats.

Newly available statewide IFSAR digital elevation data are supporting the creation of more complete and higher resolution digital hydrography by the USGS. Being a radar product, the use of IFSAR for network extraction is most appropriate in areas of limited vegetation cover (north of southcentral Alaska). LiDAR DEMs are coming online in southcentral and southeast Alaska in areas of dense vegetation cover. The

USGS 3DEP and 3DHP programs in Alaska that are being used to update the National Map of streams and other waterbodies lack the numerical data structure necessary to build virtual watersheds. However, the 3DEP and 3DHP networks can be integrated within virtual watersheds, including the node-based and attributed networks, to create value-added geospatial products[119].

Incomplete hydrography and its limitations in analytical capabilities extend beyond Alaska to other regions, provinces, states, and countries. The Alaska project described here presents a model on how national hydrography can be updated and given analytical capabilities to enhance understanding of freshwater and diadromous fish habitats. Virtual watersheds can be used to plan strategic conservation to combat freshwater fish biodiversity loss and address 21st century challenges in other areas globally[119].

Data and Program Availability

The datasets and the Fortran code that were used during this study are available on request from the authors.

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