

Influence of mapping resolution on assessments of stream and streamside conditions: lessons from coastal Oregon, USA

KEN VANCE--BORLAND^{a,*}, KELLY BURNETT^b and SHARON CLARKE^c

^a*Department of Forest Science, Oregon State University, Corvallis, OR 97331, USA*

^b*USFS Pacific Northwest Research Station, Forestry Sciences Lab, 3200 S.W. Jefferson Way, Corvallis, OR 97331, USA*

^c*Roaring Fork Conservancy, Basalt, CO 81621, USA*

ABSTRACT

1. Digital hydrographic data are commonly employed in research, planning, and monitoring for freshwater conservation, but hydrographic data sets differ in spatial resolution and accuracy of spatial representation, possibly leading to inaccurate conclusions or unsuitable policies for streams and streamside areas.

2. To examine and illustrate the potential for different hydrographic datasets to influence in-channel and streamside characterizations, a study area in the US Pacific Northwest was chosen because 1:100 000, 1:24 000, and densified 1:24 000 hydrography are available and widely used in research and management for several species of Pacific salmon and trout at risk. The potential was examined for differences among the digital hydrographic datasets in: (1) spatial extent to influence estimated abundances of fish habitat, streamside buffer conditions, and fish distributions; and (2) spatial position to influence estimated streamside buffer conditions and estimated stream gradient.

3. The analysis of spatial extent found the total stream length represented by the 1:100 000 hydrography was approximately one half that of 1:24 000 hydrography and only one fifth that of densified 1:24 000 hydrography. The 1:100 000 and 1:24 000 networks differed significantly for 13 out of 18 fish habitat attributes, and the three hydrographic datasets differed significantly for many characteristics in streamside buffers; fish distributions mapped at 1:24 000 added 6-14% of stream length to 1:100 000 distributions. The analysis of spatial position found few differences between the 1:100 000 and 1:24 000 hydrography in streamside buffer characteristics but significant differences in channel gradient.

4. Overall, hydrographic datasets differed only slightly in spatial position but differed in spatial extent to the point of representing different populations of streams. If species inhabiting larger streams (greater mean annual discharge) are of interest, then results derived from studies based on 1:100 000 hydrography should prove useful. However, higher-resolution hydrography can be critical when designing and implementing strategies to protect fish and other aquatic species at risk in smaller streams.

Copyright © 2008 John Wiley & Sons, Ltd.

Received 13 June 2007; Revised 30 November 2007; Accepted 20 January 2008

KEY WORDS: freshwater conservation; stream analysis; streamside conditions; fish distribution; spatial extent; spatial position; spatial resolution; cartographic scale

INTRODUCTION

Freshwater ecosystems have been severely affected by human activities globally, leading to declining populations or extinctions of numerous aquatic species (Revenge *et al.*, 2000). In North America, freshwater fauna are becoming extinct at five times the rate of terrestrial fauna (Ricciardi and Rasmussen, 1999). As human populations grow, water quality

declines in many areas of the world due to point-source pollution from municipalities and industry and non-point source pollution from land uses such as agriculture (Cosgrove and Rijsberman, 2000). Increasing water withdrawals for municipal, industrial, and agricultural uses often keep surface flows from reaching the sea in major rivers, including the Yellow River in China, the Colorado River in the USA, and the Indus River between India and Pakistan (Cosgrove

*Correspondence to: Ken Vance-Borland, Forestry Sciences Lab, 3200 SW Jefferson Way, Corvallis, OR 97331-4401, USA.

E-mail: ken.vance-borland@oregonstate.edu

The contribution of Ken Vance - Borland and Kelly Burnett to this article was prepared as part of their duties as a United States Federal Government Employee.

Table 1. Selected aquatic research (R) and management (M) studies and the cartographic scale of source maps upon which digital hydrographic data are based

Reference	Country	General topic	Source data scale
Nel <i>et al.</i> , 2007 Smith <i>et al.</i> , 1997	South Africa United States	Biodiversity M Water quality R	1:500 000
Wantzen <i>et al.</i> , 2006 Higgins <i>et al.</i> , 2005	Brazil Bolivia, Brazil, Paraguay, US	Impact assessment M Conservation M	1:250 000 1:250 000 and 100 000
Filipe <i>et al.</i> , 2004	Portugal	Conservation M	1:100 000
Herlihy <i>et al.</i> , 2000 Iverson <i>et al.</i> , 2001 Larsen <i>et al.</i> , 2004 Moglen and Beighley, 2000 Richards <i>et al.</i> , 1996 Turner and List, 2007 Wing and Skaugset, 2002	United States	Ecological condition R Riparian habitat R Salmon habitat M Hydrology R Stream habitat R Conservation M Salmon habitat R	1:100 000
Leathwick <i>et al.</i> , 2005	New Zealand	Fish distribution R	1:50 000
Burnett <i>et al.</i> , 2007 Clarke and Burnett, 2003 Lunetta <i>et al.</i> , 1997 Torgersen <i>et al.</i> , 2004	United States	Salmon habitat R Aquatic data R Salmon habitat M Fish distribution R	1:24 000

and Rijsberman, 2000). More than half the world's large river systems are affected by dams, resulting in ecosystem fragmentation, habitat loss, modified flow regimes, and reduced sediment flux (Nilsson *et al.*, 2005; Syvitski *et al.*, 2005). Overfishing in inland waters, particularly acute in Asia and Africa, can eliminate top aquatic predators and alter food webs, primary productivity, and nutrient dynamics (Allan *et al.*, 2005). Presence of exotic species also causes major impacts on freshwater systems (Vitousek *et al.*, 1997).

Characterizations of freshwater species and ecosystems over the broader spatial extents necessary to address conservation issues typically rely on maps of streams and lakes (hydrography) in a geographic information system (GIS). Digital hydrographic data are produced from printed maps available at different cartographic scales, for example 1:24 000 (1 cm on map represents 0.24 km on the ground) or 1:500 000 (1 cm on map represents 5 km on the ground). Such data are commonly employed in research and management for conservation (Table 1). For example, the Nature Conservancy has developed an aquatic ecosystem classification method for freshwater conservation planning using digital hydrography at a variety of scales including 1:100 000 for the 31 000 km² Willamette River Basin in Oregon and 1:250 000 for the 600 000 km² Upper Paraguay River Basin in Brazil, Paraguay, and Bolivia (Higgins *et al.*, 2005).

Digital hydrographic data produced from source maps at different cartographic scales differ in spatial resolution, or size of the smallest feature represented (Johnson *et al.*, 1989), and in the accuracy of spatial representation. The Australian GEODATA TOPO 250K hydrographic data, digitized from 1:250 000-scale printed maps, include only streams longer than 2.5 km and water bodies wider than 250 m with areas greater than 62.5 ha (Geoscience Australia, 2003). The 1:100 000-scale National Hydrography Dataset (NHD) for the continental USA includes streams longer than 1.6 km and lakes or ponds larger than 2.4 ha (USGS, 2005). The locations of stream channels are generally more accurately represented by higher-than lower-resolution digital hydrography. For example, the

United States Geological Survey (USGS) standard for horizontal positional accuracy in 1:24 000 data is that 90% of mapped streams lie within approximately 12 m of their true positions, but for 1:100 000 data the standard is 50 m (USGS, 2005). Although the 1:100 000 hydrography depicts many fewer streams and depicts streams less accurately than 1:24 000 hydrography (Lunetta *et al.*, 1997; Moglen and Beighley, 2000; Hansen, 2001), the higher-resolution dataset has not yet been completed for the entire USA (Moglen and Beighley, 2000; USGS, 2004). Even 1:24 000 data may not represent all perennial streams in an area and probably represent only a few of the intermittent (wet season flow) or ephemeral (flow during and after precipitation) streams (Hansen, 2001; Meyer and Wallace, 2001).

Where available data are of insufficient resolution to meet research and management needs, several options are possible for developing new digital hydrography. Adding stream lines (densifying) to existing hydrography based on aerial photographs (WDFW, 2006), digital orthophotos (USFS, 2003), or topographic map contour crenulations is one option. These methods are time consuming and costly and so are generally undertaken only for small areas. Another option for representing more of the stream network is to generate hydrography from Digital Elevation Models (DEMs) (Miller, 2003; Burnett *et al.*, 2007; WWF, 2007; Clarke *et al.*, 2008), but results depend upon DEM resolution and quality as well as stream-delineation algorithms. The World Wildlife Fund (WWF) and partners in the HydroSHEDS project have delineated streams for Latin America, Africa, and much of Asia comparable in detail with those represented on 1:250 000-scale printed maps (WWF, 2007). These efforts used digital elevation data from the Shuttle Radar Topography Mission (SRTM) imagery. The SRTM digital elevation data are at 90 m resolution and limited to areas between 60° north and 60° south latitude. Other space-borne platforms use a polar orbit to produce digital elevation data at higher resolutions (10 m) for non-forested areas over the entire planet (e.g. ALOS, 2007). Airborne laser mapping, such as red waveform light

detection and ranging (lidar), can penetrate forest canopies and generate very high-resolution (<1 m) digital elevation data (Lefsky *et al.*, 2001, 2002). Despite key advantages, such data are relatively expensive to obtain, process, and store for large areas.

Because digital hydrographic data for much of the world may be available or developed at different spatial resolutions, conservation workers must choose which of these best meets their needs in each situation. Choice of map scale depends on matching the geographic extent and grain (i.e. fine to coarse) desired for analyses with that of any existing or prospective hydrographic data. Just as for digital road data (Hawbaker and Radeloff, 2004), this choice may affect analytical outcomes, possibly leading to inaccurate conclusions or unsuitable policies for streams and streamside areas (Hansen, 2001; Meyer and Wallace, 2001). How different hydrographic datasets may influence characterizations that are essential to conservation of stream ecosystems has seldom been rigorously evaluated (but see Lunetta *et al.*, 1997; Hansen, 2001; Rosenfeld *et al.*, 2002; Stoddard *et al.*, 2005).

To examine and illustrate the potential for different hydrographic datasets to influence in-channel and streamside characterizations, a study area in the US Pacific Northwest was identified. This area was chosen because 1:100 000, 1:24 000, and densified 1:24 060 hydrography are available and are widely used in research and management for several species of Pacific salmon and trout at risk. The objectives of this study were to compare differences among the hydrographic datasets in: (1) spatial extent to influence estimated stream lengths, streamside buffer conditions, characteristics of fish habitat, and fish distributions; and (2) spatial position to influence streamside buffer conditions and estimated stream gradient. Although analysis targeted streams that provide habitat for Oregon coastal coho salmon *Oncorhynchus kisutch* (US Endangered Species Act [ESA] threatened species) and steelhead *O. mykiss* (US ESA species of concern), results that demonstrate the influence of map resolution on stream and streamside assessments should be relevant for informing aquatic conservation beyond the Pacific Northwestern USA.

METHODS

The study area was the 255 000 ha Siuslaw National Forest in the Coastal Province of Oregon, USA. It is underlain by shallow-water marine sedimentary rocks and scattered basaltic volcanics and intrusives (Orr *et al.*, 1992). The resulting landscape is of relatively low relief (elevations range from sea level to >1250 m) but highly dissected, with soil-mantled ridge-and-valley terrain of steep slopes expressing a variety of drainage patterns (Figure 1). The climate is maritime, with wet winters (up to 250 cm precipitation per year), dry summers, and a moderate temperature regime. The natural vegetation is coastal temperate rainforest, with an overstory of conifers (especially Douglas-fir *Pseudotsuga menziesii*, western hemlock *Tsuga heterophylla*, western redcedar *Thuja plicata*, grand fir *Abies grandis*, and Sitka spruce *Picea sitchensis*) and hardwoods (especially red alder *Alnus rubra* and bigleaf maple *Acer macrophyllum*) in riparian areas. Most of the current forestland is in relatively young seral stands, and the large, flat river valleys have been cleared for agriculture. In

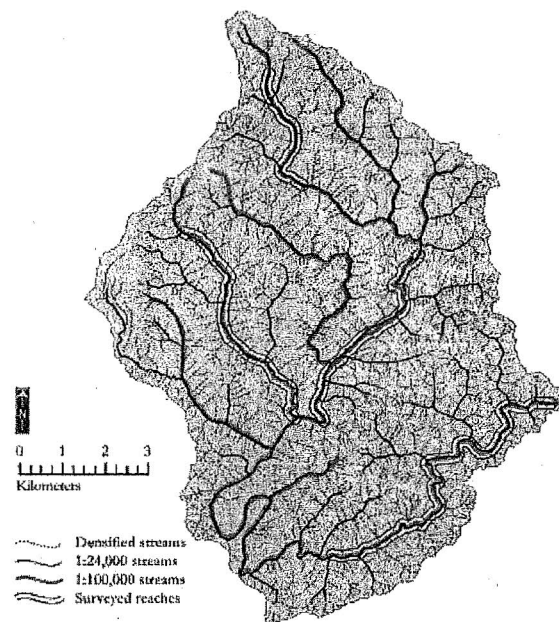


Figure 1. Study catchment showing 1:100 000, 1:24 000, and densified 1:24 000 hydrography, and the four surveyed reaches in the catchment.

addition to coho salmon and steelhead, the study area also supports populations of Chinook salmon *O. tshawytscha*, chum salmon *O. keta*, and coastal cutthroat trout *O. clarkii clarkii*; none of the latter is ESA listed.

Hydrographic datasets

Three digital hydrographic datasets (Figure 1) that are free and publicly available for the study area were compared: (1) 1:100 000 Pacific Northwest River Reach Files (Stream Net, 2001); (2) 1:24 000 US Forest Service (USFS) Cartographic Feature Files (e.g. USFS, 2003b); and (3) 1:24 000 Siuslaw National Forest densified streams (USFS, 2003a). River Reach Files were created by federal, state, and tribal agencies in the early 1990s from streams on 1:100 000 USGS topographic maps, are maintained by the Stream Net program (StreamNet, 2003), and are part of the 1:100 000 National Hydrography Dataset. Cartographic Feature File (CFF) streams were digitized by the USFS Geospatial Service and Technology Center from USFS Primary Base Series maps, which are 1:24 000 USGS topographic maps that have been modified or updated to satisfy Forest Service needs. Most reaches in the 1:100 000 and 1:24 000 hydrographic datasets are coded as having perennial or intermittent flow. The Siuslaw National Forest began to densify their CFF data in 1992 by digitizing streams visible on 1:40 000 black-and-white aerial photographs and more recently by digitizing from contour crenulations on 1:24 000 topographic maps and streams visible on 1:24 000 digital orthophotos (USGS, 1996).

Characteristics compared among hydrographic datasets

To evaluate implications for catchment-level and reach-level applications, hydrographic datasets were compared relative to

Table 2. Digital hydrographic datasets used to compare differences in spatial extent and spatial position based on in-channel and streamside characteristics

Comparison characteristic	1:100 000	1:24 000	Densified 1:24 000	See Table
Spatial extent				
Stream length	X	X	X	3
Streamside buffer	X	X	X	4
Fish habitat	X	X		5
Fish distributions	X	X		6
Spatial position				
Streamside buffer	X	X		7
Channel gradient	X	X		7

spatial extent and spatial position (Table 2), using a variety of in-channel (e.g. fish habitat, stream gradient, and fish distribution) and streamside (land cover and topography) characteristics. Reach as used here, generally, is a relatively short section of stream, but has been variously defined, for example, as a stream length that is of fixed distance, 20-times the active channel width, or homogeneous with respect to hydrogeomorphic characteristics (e.g. mean annual flow, gradient, and valley constraint).

Land cover and topography

Characteristics of forest cover, hill-slope, and road density were tabulated for buffers created in the GIS for each hydrographic dataset. The characteristics were selected based on the potential to influence freshwater habitat conditions. Buffers incorporated the area within 100m on either side of a mapped channel because this is the distance within which aquatic conservation receives highest priority along fish-bearing streams on federal lands (USDA and USDI, 1994). Also, most functions that riparian forests provide to streams (e.g. large-wood delivery, shade, bank stability) are fully met within 100m of a channel in much of the US Pacific coastal region (FEMAT, 1993).

Forest-cover characteristics were obtained from a classification based on satellite imagery along with topographic, climatic, geologic, and extensive field-plot data (Ohmann and Gregory, 2002). Forest-cover classes were identified based on composition of dominant and co-dominant trees, quadratic mean diameter (QMD), and vegetation density as measured by basal area (BA). Percentage of the buffered area was estimated for six cover classes: non-forest, open ($<5\text{m}^2\text{ha}^{-1}$ BA and QMD $<50\text{cm}$ or $<10\text{m}^2\text{ha}^{-1}$ BA and QMD $>50\text{cm}$), hardwood forest ($>1.5\text{m}^2\text{ha}^{-1}$ BA, $>65\%$ of the BA in hardwood forest), and mixed forests of conifer (BA $>1.5\text{m}^2\text{ha}^{-1}$) and hardwood (BA $<65\%$) with a small (2.5–25.4 cm), medium (25.5–50.4 cm), or large ($>50.5\text{cm}$) QMD. Percentage of streamside buffers in six hill-slope classes was estimated from 10m DEMs. Road densities (km km^{-2}) were calculated from the US Bureau of Land Management 1:24 000 General Transportation Roads Network (GTRN, BLM, 2004).

Fish habitat

These data were from an ongoing programme by the Siuslaw National Forest to create an opportunistic inventory of fish habitat (i.e. in non-randomly selected stream reaches). Reaches

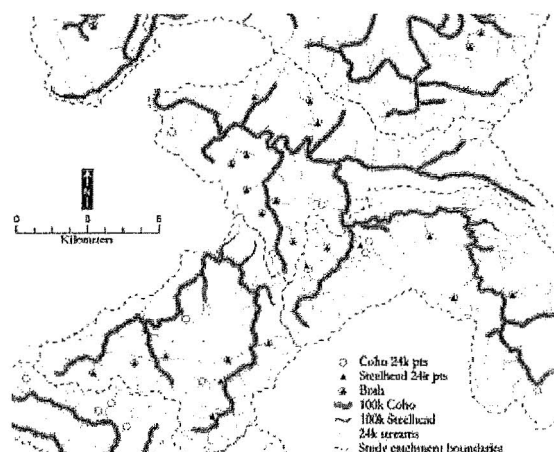


Figure 2. An example of coho salmon and steelhead distribution data available as continuous lines at 1:100 000 and as isolated points denoting the most upstream extent of fish use at 1:24 000.

in the Siuslaw National Forest data were defined to be homogeneous with respect to hydrogeomorphic characteristics (USFS, 1995). Information on a variety of stream attributes (e.g. channel morphology and large wood abundance) that are typical of fish habitat inventories was collected between 1993 and 1995 with standardized protocols (USFS, 1995). The inventory data were attached in a GIS (ESRI, 2000) to the 1:100 000 and 1:24 000 hydrographic datasets.

Channel gradient

Percentage channel gradient was calculated for each reach inventoried by the Siuslaw National Forest through dividing the change in elevation from the upstream to downstream end of the reach by the reach length and multiplying by 100. Elevations were obtained from a 10m DEM (Underwood and Crystal, 2002; Clarke and Burnett, 2003).

Fish distribution

The Oregon Department of Fish and Wildlife (ODFW) identified streams on 1:100 000 and 1:24 000 hydrography that were accessible to coho salmon and to winter steelhead (ODFW, 2004). The distribution maps are based on stream surveys and the professional judgement of fish biologists with field knowledge of the mapped area. Distributions of each species are represented as continuous lines at 1:100 000 but as isolated points at 1:24 000, which denote the most upstream extent of fish use (Figure 2). The total length of fish distribution for each species was estimated at 1:100 000 directly from the hydrography and at 1:24 000 by summing the length determined at 1:100 000 and the distance between the end of distribution at 1:100 000 and the point indicating the end of distribution at 1:24 000.

Comparing hydrographic datasets

Stream networks were compared in a fixed set of catchments when examining the effects of spatial extent and a fixed set of reaches when examining the effects of spatial position. Consequently, observations were paired by stream networks in all statistical comparisons. Nonparametric Wilcoxon's

signed-rank tests (Sokal and Rohlf, 1995) were used because differences between paired observations for most variables were not normally distributed. Densified 1:24 000 streams were compared only for spatial extent and only regarding stream length and streamside buffer characteristics because the added streams were not associated with fish habitat, gradient, fish distribution, or any other attributes.

Spatial extent

The potential for differences in spatial extent among the hydrographic datasets to influence in-channel and streamside characterizations was examined. Analysis was limited to the 34 catchments containing at least 2 km of stream in the Siuslaw National Forest inventories. For each of the three hydrographic datasets in the 34 catchments, the total stream length, stream density, number of stream reaches inventoried, and percentage of stream length inventoried was calculated. For 100 m buffers in the 34 catchments, differences among the three hydrographic datasets were compared pairwise for the percentage area of each forest-cover class, percentage area of each hill-slope class, and road density. The difference between the 1:100 000 and 1:24 000 hydrographic data for the percentage of stream length coded as perennial and the length-weighted average of each attribute in the Siuslaw National Forest fish habitat inventories was also evaluated.

The 1:100 000 and 1:24 000 hydrographic datasets were compared relative to the total length of stream mapped by ODF&W as accessible to coho salmon and to winter steelhead in the 34 catchments. The 1:24 000 fish distribution mapping effort varied greatly among catchments: density of mapped distribution points ranged from one point per 460 ha to one point per 9217 ha. Therefore, comparisons were also made for catchments determined to have more complete mapping efforts at 1:24 000, based on the criterion of at least one mapped distribution point per 1000 ha.

Spatial position

The potential was examined for differences in spatial position between the 1:100 000 and 1:24 000 hydrographic data to influence land-cover and topographic characteristics in and around all 264 reaches in the Siuslaw National Forest fish habitat inventories. Differences in the percentage area of each forest-cover class, the percentage area of each hill-slope class, and road density were compared between the 1:100 000 and 1:24 000 hydrography in 100 m buffers for those reaches. The potential for differences in spatial position between these

hydrographic data sets to influence estimated channel gradients for the reaches was also examined.

RESULTS

Spatial extent

For the 34 catchments studied, stream length, stream density, and the proportion of inventoried streams differed significantly ($\alpha=0.05$) among the three hydrographic datasets (Table 3). The total stream length represented by the 1:100 000 hydrography (1758 km) was approximately one-half that of the 1:24 000 hydrography (3517 km) and only one-fifth that of the densified 1:24 000 hydrography (8988 km); stream densities followed the same pattern. Consistent with this, the Siuslaw National Forest field crews inventoried a much greater proportion of the stream network represented at 1:100 000 than at the two higher resolutions. However, one-third of the inventoried reaches were not represented on the 1:100 000 hydrography: of 397 reaches mapped at 1:24 000, only 264 (67%) were shown at 1:100 000. In only seven of the 34 catchments were all inventoried reaches represented at 1:24 000 also represented at 1:100 000.

The three hydrographic datasets differed significantly ($\alpha=0.05$) for many characteristics in streamside buffers (Table 4). Whereas buffers on the lower-resolution hydrography generally contained the greatest percentage of area in non-forested land, broadleaf forests, and lower hill-slope classes, buffers on the higher resolution hydrography contained the greatest percentage of area in open land, in mixed conifer/hardwood forests with small, medium, and large diameter trees, and in higher hill-slope classes (20–40% and 40–65%). The percentage area of the highest hill-slope class was greater, but road densities were less, in buffers on the 1:24 000 than on either of the other hydrographic datasets.

The 1:100 000 and 1:24 000 hydrographic datasets differed significantly ($\alpha=0.05$) for 13 out of 18 fish habitat attributes (Table 5). Based on catchment medians, inventoried reaches represented at 1:100 000 had lower gradients, primary channel lengths, pool frequency, and percentage gravel substrate in riffles, but higher flows, active channel depths, active channel widths, width to depth ratios, sinuosity, percentage of reach area in pools, number of deep pools per kilometre, number of complex pools per kilometre, and percentage bedrock substrate than those represented at 1:24 000. Approximately 78% of the total mapped length in the 1:100 000 hydrography and 90% in the 1:24 000 hydrography was coded as perennial stream.

Table 3. Differences between hydrographic datasets in stream length, stream density, and proportion of stream length inventoried by the Siuslaw National Forest in the 34 catchments studied

Hydrography	Mapped stream length (km)		Stream density (km km ⁻²)		Proportion of mapped length inventoried	
	Median	Range	Median	Range	Median	Range
1:100 000	45	29–105	0.77	0.55–1.01	0.21	0.04–0.61
1:24 000	97	49–210	1.54	1.11–1.95	0.13	0.02–0.43
Densified 1:24 000	240	98–605	3.91	1.92–6.20	0.05	0.01–0.17

The median and range express variation among catchments; differences in medians are all significant ($\alpha=0.05$) using Bonferroni adjusted signed-rank tests.

Table 4. Results of paired signed-rank tests of differences in forest cover (as defined in the text), hill-slope, and road density within 100 m buffers around all mapped 1:100 000, 1:24 000, and densified (dens) 1:24 000 streams, summarized by catchments ($n = 34$)

Characteristic	Signed-rank test P -values (Bonferroni adjusted)			Median difference		
	1:100 000– 1:24 000	1:100 000– dens 1:24 000	1:24 000–dens 1:24 000	Value at 1:100 000– value at 1:24 000	Value at 1:100 000– value at dens 1:24 000	Value at 1:24 000– value at dens 1:24 000
Forest cover (%)						
Non-forest	<0.001	<0.001	<0.001	3.4	7.3	3.6
Open	0.05	0.002	0.066	−0.4	−0.6	−0.5
Broadleaf	<0.001	<0.001	<0.001	2.9	10.1	6.2
Small	<0.001	<0.001	<0.001	−1.7	−6.4	−4.7
Medium	<0.001	<0.001	<0.001	−1.6	−4.0	−3.1
Large	0.012	<0.001	0.002	−2.1	−3.5	−2.2
Hill-slope (%)						
0–3%	<0.001	<0.001	<0.001	2.3	5.1	2.2
3–6%	<0.001	<0.001	<0.001	1.9	3.4	1.6
6–20%	<0.001	0.002	0.04	3.4	4.9	1.5
20–40%	<0.001	<0.001	<0.001	−1.6	−6.9	−5.1
40–65%	<0.001	<0.001	<0.001	−3.4	−6.2	−2.0
>65%	0.003	1	0.007	−1.7	−0.3	0.9
Road density (km km^{-2})	0.005	0.002	<0.001	0.3	−0.3	−0.7

A negative median difference for an attribute indicates the value was greater for the higher resolution hydrography.

Table 5. Results of paired signed-rank tests for in-channel differences between 1:100 000 and 1:24 000 hydrographic datasets in the 34 catchments with ≥ 2 km of Siuslaw National Forest fish habitat inventories

Fish habitat attributes	Signed-rank test P -value	Difference (value at 1:100 000 minus value at 1:24 000)	
		Median	Range
Primary channel length (m)	<0.001	−4530	−39529–1019
Active channel depth (m)	<0.001	0.01	−0.01–0.1
Active channel width (m)	<0.001	0.35	−0.1–1.9
Width–depth ratio	<0.001	0.45	−0.5–16.4
Discharge ($\text{m}^3 \text{s}^{-1}$)	<0.001	0.005	−0.003–0.116
Channel gradient (%)	<0.001	−0.3	−4.4–0.3
Sinuosity	<0.001	0.008	−0.7–0.2
Number of habitat units/100 m	0.169	−0.008	−0.7–2.0
Percentage area in pools	<0.001	0.01	−0.03–0.2
Number of pools/km	0.959	0.05	−3.7–12.4
Number of deep (> 1 m) pools/km	0.003	0.08	−0.5–1.8
Number of complex pools/km	<0.001	0.08	−0.2–1.2
Pool frequency	<0.001	−0.5	−23.7–0.1
Percentage area in bedrock	0.02	0.01	−2.3–4.3
Percentage of riffle area in gravel	0.006	−0.5	−6.8–2.8
Percentage of riffle area in sand and fine organic matter	0.33	−0.005	−3.8–4.2
Number of large wood pieces/100 m	0.241	−0.04	−0.6–0.5
Number of key large wood pieces/100 m	0.758	−0.005	−0.4–0.2

A negative median difference for an attribute indicates that value was greater at 1:24 000 than at 1:100 000. Active channel is defined by the 'bank full' or annual high flow line; width–depth ratio is based on active channel.

Table 6. Mapped fish distributions from 1:100 000 (100 k) and 1:24 000 (24 k) hydrography in the 34 catchments with ≥ 2 km of Siuslaw National Forest fish habitat inventories

Species	Number of catchments with 24 k distribution limit points	No. of points	Length (km) of 100 k distribution lines in catchments with points	Distance (km) from 100 k lines to 24 k points	Distance as % of 100 k line length	Number of catchments with at least one 24 k point per 1000 ha	Line-to-point distance as % of 100 k line length in catchments with at least one 24 k point per 1000 ha
<i>O. kisutch</i>	21	123	760.2	67.4	8.9	10	14.3
<i>O. mykiss</i>	22	95	835.7	50.7	6.1	6	10.9

About two-thirds of the 34 catchments contained points representing the upstream distribution of coho salmon and winter steelhead mapped at 1:24 000 (Table 6). In those

catchments, the distance from the ends of fish distribution at 1:100 000 to 1:24 000 points added 9% to the distribution for coho salmon and 6% for steelhead. For catchments where the

Table 7. Results of paired signed-rank tests of differences in forest cover, hill-slope, and road density within 100m buffers around the inventoried reaches in the Siuslaw National Forest data that are represented at both 1:100 000 and 1:24 000, and also of channel gradient

Characteristic	Signed-rank test <i>P</i> -value (df = 263)	Median difference	Range
Forest cover (%)			
Non-forest	0.377	0.0	-6.2-3.3
Open	0.453	0.0	-9.0-9.4
Broadleaf	0.522	0.0	-29.9-21.0
Small	0.785	0.0	-9.0-15.7
Medium	0.348	-0.2	-14.5-14.7
Large	0.334	0.0	-28.4-34.6
Hill-slope (%)			
0-3%	0.478	0.0	-9.3-11.5
3-6%	0.160	0.0	-8.4-6.0
6-20%	0.267	0.1	-20.5-7.8
20-40%	<0.001	0.5	-19.6-18.4
40-65%	0.293	-0.03	-11.9-15.9
> 65%	<0.001	-0.1	-21.7-16.0
Road density (km km ⁻²)	0.241	-0.01	-4.2-2.6
Channel gradient (%)	<0.001	0.14	-6.5-23.8

The road density comparison was limited to the 131 reaches with roads in the buffers. A negative difference for an attribute indicates the value was greater at 1:24 000 than at 1:100 000.

mapping effort for fish distribution at 1:24 000 was considered more complete, 14% was added for coho and 11% for steelhead.

Spatial position

No significant ($\alpha=0.05$) differences were found between the 1:100 000 and 1:24 000 hydrographic datasets in the percentage area of any forest-cover class or in road density for buffers on inventoried reaches. For hill-slope classes, significant differences were found between the percentage buffered area in classes of 20-40% and > 65% (Table 7). The percentage channel gradient also differed significantly ($P<0.001$) between the two hydrographic datasets. Paired differences between the 1:100 000 and 1:24 000 hydrography in gradient ranged from -6.5% (3.1% versus 9.6%) to 23.8% (28.2% versus 4.4%), with a median difference of 0.14%. Estimated channel gradients were negative for five reaches at 1:100 000 and for one reach at 1:24 000.

DISCUSSION

Spatial extent

Catchment-level comparisons identified differences among the three hydrographic datasets for length as well as for in-channel and streamside characteristics that were attributable to differences in spatial extent.

Differences in length

Differences were expressed simply in terms of stream length, stream density, and percentage of stream length inventoried for fish habitat. Results for stream length are consistent with those from studies in which topographic maps, ranging from

1:20 000 to 1:100 000, all greatly under-represented field-mapped stream lengths but did so increasingly as map resolution coarsened (Hansen, 2001; Rosenfeld *et al.*, 2002). Identical to the finding from this study for the Oregon Coast Range, Lunetta *et al.* (1997) determined that a 1:24 000 air-photo densified stream network was five times longer than the 1:100 000 stream network for western Washington, USA. For areas with less topographic relief or precipitation, the 1:100 000 hydrography may more closely represent actual stream lengths. However, coding of perennial and intermittent streams may be less accurate in arid than in humid, montane regions (Stoddard *et al.*, 2005).

Differences in stream length translated into differences in stream density (km km⁻²) that may have implications for freshwater research and conservation. Stream density was an important predictor variable for assessing the status and distribution of several salmonid species in the interior Columbia River basin, USA (Lee *et al.*, 1999). More complete hydrography showing higher stream densities may have greater utility for characterizing aquatic ecosystem heterogeneity and for finding specific sites, such as tributary junctions, that are potential aquatic biodiversity hotspots (Benda *et al.*, 2004; Fernandez *et al.*, 2004; Kiffney *et al.*, 2006; Rice *et al.*, 2006). Thorough mapping of stream density is critical for accurately determining stream order, which reflects the number of tributaries upstream of a point and thus stream size. Streams are often stratified based on order for monitoring, research, and conservation purposes (Filipe *et al.*, 2004; Schmera and Eröst, 2004), but digital hydrography that does not represent smaller streams will underestimate true stream order (Wing and Skaugset, 2002). This emphasizes the need to state map scale when giving estimates of stream order.

The percentage of total stream length in this study coded as perennial conflicts with findings in other areas and raises questions about the utility of information on duration of annual flow associated with the 1:100 000 and 1:24 000 hydrographic datasets. At the 1:100 000 scale, Stoddard *et al.* (2005) identified 28% of mapped stream length for the entire western USA as being perennial versus 78% in the present study for western Oregon. Numerous errors in coding of perennial and intermittent streams in the 1:100 000 hydrography were identified through field evaluation (Stoddard *et al.*, 2005). Drainage areas determined in the field as necessary to sustain perennial flow in western Oregon (Clarke *et al.*, 2008) lead us to conclude that both the 1:100 000 and 1:24 000 hydrography under-represent the extent of the perennial network in the study area. Thus, some of the length added by densification of the 1:24 000 hydrography is in perennial streams, despite the majority being in intermittent streams. Although the true spatial extent of streams can vary seasonally and yearly with discharge, an accurate map of the perennial network is important for broad-scale conservation planning and management of most aquatic species. For other aquatic species, a good approximation of the intermittent network may also be necessary.

Although the additional streams mapped at resolutions higher than 1:100 000 are relatively small, many support fish and may help sustain their populations across large spatial extents. Once the 1:24 000 fish distribution maps are completed for western Oregon, it is expected that the length of the 1:100 000 distributions will be augmented considerably more

than the 9% and 6% found, respectively, for coho salmon and winter steelhead; this expectation is supported by the finding of greater added distribution length in catchments with more complete 1:24 000 mapping effort. These additional lengths may represent non-trivial amounts of habitat for ESA listed and at-risk fish species. Results of this study agree with those of previous studies quantifying salmonid distributions in small, unmapped streams (Brown *et al.*, 1996; Rosenfeld *et al.*, 2002). These studies indicate that all salmonid-bearing streams are unlikely to be mapped even at 1:24 000. Habitats supplied by small streams may contribute to basin-wide persistence of fish populations. For example, juvenile coho salmon that emigrated from mainstem habitats to rear over winter in small tributaries grew faster, and survived better, possibly contributing more to recruitment, than juveniles that overwintered in the mainstem (Ebersole *et al.*, 2006; Wigington *et al.*, 2006). The importance to stream fish of different habitat types and connectivity among these is increasingly recognized (Kocik and Ferreri, 1998; Pichon *et al.*, 2006; Gresswell and Hendricks, 2007).

Small, headwater streams are unique ecosystems that can sustain numerous species other than fish and are tightly coupled to downstream ecosystems. Headwater riparian areas and streams provide habitat for native amphibians (Sheridan and Olson, 2003; Olson and Weaver, 2007) and macroinvertebrates (Meyer and Wallace, 2001; Progar and Moldenke, 2002), including recently discovered species (Dieterich and Anderson, 2000) and endemics (Adams and Bury, 2002). Storage, processing, and transport in headwater channels influences biophysical conditions onsite (Richardson and Daney, 2007) as well as the delivery of water, wood, sediment, nutrients, and organisms to downstream channels (MacDonald and Coe, 2007). Surface and subsurface hydrologic flows connect headwater and larger streams (Winter *et al.*, 1998; Nadeau and Rains, 2007). Fish habitat in larger rivers can be shaped by sediment (Benda and Dunne, 1997a,b; Zimmerman and Church, 2001; Benda *et al.*, 2005) and wood (Reeves *et al.*, 2003; Hassan *et al.*, 2005; Bigelow *et al.*, 2007) transported from small, fishless headwater streams. Such small streams can also affect productivity and biodiversity in fish-bearing streams by supplying nutrients, organic matter, and organisms, including macroinvertebrate prey (Wallace *et al.*, 1995; Webster *et al.*, 1999; Kiffney *et al.*, 2000; Wipfli and Gregovich, 2002; Meyer *et al.*, 2007; Wipfli *et al.*, 2007).

Conservation of many aquatic species may depend on the integrity of smaller streams and connections between these and larger rivers. Physical and biological characteristics of small streams warn of ecosystem changes that can eventually affect larger streams, but these small streams are generally the least protected by management regulations and the most sensitive to degradation (Meyer and Wallace, 2001; Rosenfeld *et al.*, 2002). Proper management of small streams and their links to larger rivers can be important in maintaining and restoring downstream ecosystem quality (Gomi *et al.*, 2002; Cummins and Wilzbach, 2005; Meyer *et al.*, 2007).

Differences in characteristics

Catchment-level comparisons regarding spatial extent also indicated that the hydrographic datasets differed for in-channel and streamside characteristics and thus represented

different populations of streams. Differences between the 1:100 000 and 1:24 000 hydrography in fish-habitat attributes reflected that field-inventoried reaches selected at 1:100 000 regularly excluded smaller streams higher in the channel network. For example, inventoried reaches at 1:100 000 tended to be wider, deeper, and have lower gradients than inventoried reaches at 1:24 000. The 1:100 000 and 1:24 000 data differed in some important measures of habitat complexity (e.g. number of complex pools per kilometre) but not in others (e.g. number of large wood pieces per kilometre).

Because higher-resolution hydrography typically extends streams further up into a catchment, landscape characteristics at 1:24 000 differed from those adjacent to larger streams represented at 1:100 000. Findings that 1:100 000 streamside buffers contained greater percentages of non-forested area and lower hill-slope classes than 1:24 000 buffers are consistent with the distribution of private non-industrial lands throughout the Oregon Coast Range, including private holdings within the boundary of the Siuslaw National Forest. These private lands occur primarily in low gradient, wide valleys along larger rivers and tend to be in agricultural and rural residential uses (Burnett *et al.*, 2007). The greater percentage of broadleaf forests found along the lower-resolution hydrography reflects a higher likelihood of red alder in wetter and more frequently disturbed areas near larger streams (Pabst and Spies, 1999). In contrast, areas along smaller streams have environmental conditions that foster conifers and greater percentages of recently harvested, open areas generated by federal and private industrial forestry (Young, 2000).

Road density results can be understood in the context of differences in road type and position, and the potential to evaluate effects of roads near the different hydrographic datasets. Road densities were relatively high along the 1:100 000 hydrography because the primary transportation corridors represented were commonly built in valleys parallel to large rivers (Jones *et al.*, 2000). Road densities were also high along the densified 1:24 000 hydrography but for different reasons; roads in these areas include extensive secondary transportation corridors and routes for accessing and hauling timber. Roads can generate a variety of negative effects in both terrestrial and aquatic ecosystems (Trombulak and Frissell, 2000). Effects of non-primary roads may be of particular concern for aquatic ecosystems because these roads often occur in mid-slope locations and regularly cross small streams (Jones *et al.*, 2000), typically were built to lower construction standards than primary roads, and may not be accurately mapped (Hawbaker and Radeloff, 2004). The potential to assess many of the aquatic effects (e.g. delivery of road-associated landslides to small streams or blocking of fish passage by culverts on minor roads), depends on the availability of accurate maps across broad spatial extents for both streams and roads.

That different hydrographic datasets may represent different populations of streams can have implications for aquatic conservation beyond western Oregon. For example, in a study of agricultural impacts to streams in the Tenente Amaral River catchment of Brazil, located in the highly threatened Cerrado biome, Wantzen *et al.* (2006) added numerous streams visible on satellite imagery to the available 1:250 000 hydrography. Field visits indicated that all streams were not resolved in the satellite imagery. The small streams that were added to the available hydrography influenced study findings and potential

conservation options because unimpaired channels were detected only in headwaters unmapped at 1:250 000. All other channels were either moderately or strongly impaired.

Spatial position

Differences in spatial position between hydrographic datasets had little effect on streamside characteristics examined at the reach scale. Thus, we expect that the publicly available 1:100 000 and 1:24 000 hydrography will yield similar results in future reach-scale characterizations when, as in this study, streamside data are of relatively low resolution and reaches are relatively constrained by adjacent hill-slopes. The choice of hydrography may influence buffer characteristics more when streamside data are at a higher resolution or where channels can meander across a wide floodplain and thus positional differences between the 1:100 000 and 1:24 000 hydrography are likely to be greater. Findings of this study support the first proposition but shed little light on the second. The only significant differences found between hydrographic datasets were with the highest-resolution data (hill-slope classes from 10m DEMs), but these differences were identified with a dataset containing a small proportion of unconstrained reaches. A dataset with more unconstrained reaches than were available for the Siuslaw National Forest is necessary to examine thoroughly how channel constraint may affect reach-scale streamside characterizations.

The differences detected in channel gradient suggest that the choice of hydrography may influence reach-level characterizations of stream channels. The generally higher gradients and more reaches with estimated negative channel gradients at 1:100 000 compared to 1:24 000 indicate the lower-resolution hydrography may present problems when characterizing gradient or other topographic attributes of stream channels. Although a physical impossibility, negative reach gradients can be estimated from DEMs when the elevation at the downstream end exceeds that at the upstream end. This indicates that the digital hydrography is not accurately positioned relative to the DEM (FitzHugh, 2005). Drainage enforcement had been done on the DEM with the 1:24 000 digital hydrography, but not the 1:100 000; this may partly explain differences found in this study. Consistent with these findings, Lunetta *et al.* (1997) chose to use 1:24 000 rather than 1:100 000 hydrography because the superior 'absolute stream orientation' (i.e. positional accuracy) was essential for their analyses. They found 50% greater length of low-gradient reaches (representing potential salmon habitat) in 1:24 000 than in 1:100 000 streams and attributed that difference in part to the poor positional accuracy of 1:100 000 streams relative to the DEM used to measure reach gradients.

CONCLUSIONS

Differences between digital hydrographic datasets in spatial resolution were found to influence in-channel and streamside characterizations at both catchment and reach scales. However, differences in resolution appeared to affect catchment-scale characterizations more than reach-scale characterizations. This is because the hydrographic datasets differed only slightly in the spatial position of examined reaches but differed in spatial extent to the point of

representing different populations of streams. Higher resolution hydrography includes more streams, and streams that extend further into a catchment, and thus differs from lower-resolution hydrography in biophysical characteristics.

Whether or not differences in spatial extent among hydrographic datasets produce differences that matter to conservation depends on the particular application. If a species inhabiting larger (greater mean annual discharge), wadeable streams is of interest (Lee *et al.*, 1999; Flitcroft *et al.*, 2002; Wing and Skaugset, 2002), then results derived from fish habitat inventories based on a 1:100 000 digital hydrography should prove useful. However, such a dataset can omit up to four-fifths of the stream length in an area and provide little information on one or more categories of stream, including headwater streams that have received much recent attention from researchers and policy makers (Naiman and Latterell, 2005; Danehy and Ice, 2007; Freeman *et al.*, 2007; Nadeau and Rains, 2007). Higher resolution hydrography can be critical when designing and implementing strategies to protect small streams from possible negative effects of common management practices, such as timber harvest or road building, and to restore habitat and functions of small streams for fish and other aquatic species at risk.

It is rare in the freshwater literature to find references to exactly what hydrography was used in studies, and rarer to find discussions of the advantages and disadvantages of hydrographic options that are available for research or management applications. We hope that these findings will motivate others to consider carefully and report the choice of hydrography used. This choice may influence analytical outcomes, the scope of inference for analyses, and the ability to compare results among studies. Consequently, it is critical to report details about the chosen hydrography, including a full citation, so potential implications to study results of mapping attributes such as duration of annual flow, cartographic scale, horizontal accuracy, and method of development can be considered.

ACKNOWLEDGEMENTS

Funding was provided by the USDA Forest Service. Shaun McKinney assisted with developing study objectives. Manuela Huso provided statistical assistance. Kelly Christiansen created the figures. We thank Philip Kaufmann, Jeanne Nel, and Philip Boon for thoughtful comments on an earlier draft that greatly improved the manuscript.

REFERENCES

- Adams MJ, Bury RB. 2002. The endemic headwater stream amphibians of the American Northwest: associations with environmental gradients in a large forested preserve. *Global Ecological Biogeography* 11: 169-178.
- Advanced Land Observing Satellite (ALOS). 2007. *The Four Major Missions of ALOS*. Japan Aerospace Exploration Agency. Available from <http://alos.nasda.go.jp/2/alos.mission-e.html> (accessed April 2007).
- Allan JD, Abell R, Hogan Z, Revenga C, Taylor BW, Welcomme RL, Winemiller K. 2005. Overfishing of inland waters. *BioScience* 55: 1041-1051.

- Benda LE, Dunne T. 1997a. Stochastic forcing of sediment routing and storage in channel networks. *Water Resources Research* 33: 2865-2880.
- Benda LE, Dunne T. 1997b. Stochastic forcing of sediment supply to the channel networks from landsliding and debris flows. *Water Resources Research* 33: 2849-2863.
- Benda L, Poff NL, 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.
- Benda L, Hassan MA, Church M, May CL. 2005. Geomorphology of steepheadwaters: the transition from hillslopes to channels. *Journal of the American Water Resources Association* 41: 835-851.
- Bigelow P, Benda LE, Miller DJ, Burnett KM. 2007. On debris flows, river networks, and the spatial structure of channel morphology. *Forest Science* 53: 220-238.
- Brown TG, Barton L, Langford G. 1996. The use of a geographic information system to evaluate Terrain Resource Information Management (TRIM) maps and to measure land use patterns for Black Creek, Vancouver Island. Canadian Manuscript Report of Fisheries and Aquatic Sciences 2395.
- Bureau of Land Management (BLM). 2004. *GTRN (Roads-BLM 24k)*. BLM Oregon State Office, Portland, Oregon. Available from <ftp://ftp.blm.gov/pub/OR/gisweb/download/Regional/groun<LtransportatiolLpub.zip> (accessed April 2008).
- Burnett KM, Reeves GH, Miller DJ, Clarke S, Vance-Borland K, Christiansen K. 2007. Distribution of salmon-habitat potential relative to landscape characteristics and implications for conservation. *Ecological Applications* 17: 66-80.
- Clarke S, Burnett K. 2003. Comparison of digital elevation models for aquatic data development. *Photogrammetric Engineering and Remote Sensing* 68: 1367-1375.
- Clarke SE, Burnett KM, Miller DJ. 2008. Modeling streams and hydrogeomorphic attributes in Oregon from digital and field data. *Journal of the American Water Resources Association* 44: 459-477.
- Cosgrove WJ, Rijsberman FR. 2000. *World Water Vision: Making Water Everybody's Business*. Earthscan Publications: London.
- Cummins KW, Wilzbach MA. 2005. The inadequacy of the fish-bearing criterion for stream management. *Aquatic Sciences* 67: 486-491.
- Danehy RJ, Ice GG. 2007. Introduction to special issue on headwater streams. *Forest Science* 53: 101-103.
- Dieterich M, Anderson NH. 2000. The invertebrate fauna of summer-dry streams in western Oregon. *Archiv für Hydrobiologie* 147: 273-295.
- Ebersole JL, Wigington Jr PJ, Baker JP, Cairns MA, Church MR, Hansen B, Miller B, LaVigne HR, Compton, JE, Leibowitz SG. 2006. Juvenile coho salmon growth and survival across stream network seasonal habitats. *American Fisheries Society* 135: 1681-1697.
- Environmental Systems Research Institute (ESRI). 2000. *ArcInfo User's Manual*. ESRI: Redlands, California.
- Forest Ecosystem Management Assessment Team (FEMAT). 1993. Forest ecosystem management: an ecological, economic, and social assessment. Report of the Forest Ecosystem Management Assessment Team. United States Department of Agriculture, Forest Service; United States Department of the Interior [and others], Portland, Oregon.
- Fernandez CC, Podos J, Lundberg JG. 2004. Amazonian ecology: tributaries enhance the diversity of electric fishes. *Science* 305: 1960-1962.
- Filipe AF, Marques TA, Seabra S, Tiago P, Ribeiro F, Moreira da Costa L, Cowx IG, Collares-Pereira MJ. 2004. Selection of priority areas for fish conservation in Guadiana River basin, Iberian Peninsula. *Conservation Biology* 18: 189-200.
- FitzHugh TW. 2005. GIS tools for freshwater biodiversity conservation planning. *Transactions in GIS* 9: 247-263.
- Flitcroft RL, Jones KK, Reis KEM, Thom BA. 2002. Year 2000 stream habitat conditions in western Oregon. Monitoring Program Report Number OPSW-ODFW-2001-05, Oregon Department of Fish and Wildlife, Portland.
- Freeman MC, Pringle CM, Jackson CR. 2007. Hydrologic connectivity and the contribution of stream headwaters to ecological integrity at regional scales. *Journal of the American Water Resources Association* 43: 5-14.
- Geoscience Australia. 2003. *GEODATA TOPO 250 K Series 2: Product User Guide*. National Mapping Division, Geoscience Australia: Canberra.
- Gomi T, Sidle RC, Richardson JS. 2002. Understanding processes and downstream linkages of headwater systems. *Bioscience* 52: 905-916.
- Gresswell RE, Hendricks SR. 2007. Population-scale movement of coastal cutthroat trout in a naturally isolated stream network. *Transactions of the American Fisheries Society* 136: 238-253.
- Hansen WF. 2001. Identifying stream types and management implications. *Forest Ecology and Management* 143: 39-46.
- Hassan M, Hogan DL, Bird SA, May CL, Gomi T, Campbell D. 2005. Spatial and temporal dynamics of wood in headwater streams of the Pacific Northwest. *Journal of the American Water Resources Association* 41: 899-919.
- Hawbaker TJ, Radeloff ve. 2004. Roads and landscape pattern in northern Wisconsin based on a comparison of four road data sources. *Conservation Biology* 18: 1233-1244.
- Herlihy AT, Larsen DP, Paulsen SG, Urquhart NS, Rosenbaum BJ. 2000. Designing a spatially balanced, randomized site selection process for regional stream surveys: the EMAP Mid-Atlantic pilot study. *Environmental Monitoring and Assessment* 63: 95-113.
- Higgins N, Bryer MT, Khoury ML, Fitzhugh TW. 2005. A freshwater classification approach for biodiversity conservation planning. *Conservation Biology* 19: 432-445.
- Iverson LR, Szafoni DL, Baum SE, Cook EA. 2001. A riparian wildlife habitat evaluation scheme developed using GIS. *Environmental Management* 28: 639-654.
- Johnson CB, Sullivan TJ, Blick DJ. 1989. Defining regional populations of lakes for the assessment of surface water quality. *Water Resource Bulletin* 25: 565-572.
- Jones JA, Swanson FJ, Wemple BC, Snyder KU. 2000. Effects of roads on hydrology, geomorphology, and disturbance patches in stream networks. *Conservation Biology* 14: 76-85.
- Kiffney PM, Richardson JS, Feller Me. 2000. Fluvial and epilithic organic material dynamics of headwater streams of southwestern British Columbia, Canada. *Archiv für Hydrobiologie* 148: 109-129.
- Kiffney PM, Greene CM, Hall JE, Davies JR. 2006. Tributary streams create spatial discontinuities in habitat, biological productivity and diversity in main stem rivers. *Canadian Journal of Fisheries and Aquatic Sciences* 63: 2518-2530.
- Kocik JF, Ferreri CP. 1998. Juvenile production variation in salmonids: population-dynamics, habitat, and the role of spatial relationships. *Canadian Journal of Fisheries and Aquatic Sciences* 55: 191-200.
- Larsen DP, Kaufmann PR, Kincaid TM, Urquhart NS. 2004. Detecting persistent change in the habitat of salmon-bearing streams in the Pacific Northwest. *Canadian Journal of Fisheries and Aquatic Sciences* 61: 283-291.

- Leathwick JR, Rowe D, Richardson J, Elith J, Hastie T. 2005. Using multivariate adaptive regression splines to predict the distributions of New Zealand's freshwater diadromous fish. *Freshwater Biology* 50: 2034-2052.
- Lee DC, Sedell JR, Rieman BE, Thurow RF, Williams JE, and others. 1999. Broad-scale assessment of aquatic species and habitats. In *The Interior Columbia Basin Ecosystem Management Project: Scientific Assessment*, Quigley TM et al. (eds). USDA Forest Service, Pacific Northwest Research Station: Portland, Oregon; Volume III, Chapter 4.
- Lefsky M, Cohen W, Spies T. 2001. An evaluation of alternate remote sensing products for forest inventory, monitoring, and mapping of Douglas-fir forests in western Oregon. *Canadian Journal of Forest Research* 31: 78-87.
- Lefsky MA, Cohen WB, Parker GG, Harding DJ. 2002. Lidar remote sensing for ecosystem studies. *BioScience* 52: 19-30.
- Lunetta RS, Cosentino BL, Montgomery DR, Beamer EM, Beechie TJ. 1997. GIS-based evaluation of salmon habitat in the Pacific Northwest. *Photogrammetric Engineering and Remote Sensing* 63: 1219-1229.
- MacDonald LH, Coe D. 2007. Influence of headwater streams on downstream reaches in forested areas. *Forest Science* 53: 148-168.
- Meyer JL, Wallace JB. 2001. Lost linkages in lotic ecology: rediscovering small streams. In *Ecology: Achievement and Challenge*, Press MC, Huntly NJ, Levin S (eds). Blackwell Science: Oxford; 295-317.
- Meyer JL, Strayer DL, Wallace JB, Eggert SL, Helfman GS, Leonard NE. 2007. The contribution of headwater streams to biodiversity in river networks. *Journal of the American Water Resources Association* 43: 86-103.
- Miller DJ. 2003. Programs for DEM analysis. In *Landscape Dynamics and Forest Management*. General Technical Report RMRS-GTR-101CD, USDA Forest Service, Rocky Mountain Research Station, Fort Collins, Colorado. CD-ROM.
- Moglen GE, Beighley RE. 2000. Using GIS to determine extent of gauged streams in a region. *Journal of Hydrologic Engineering* 5: 190-196.
- Nadeau TL, Rains MC. 2007. Hydrological connectivity between headwater streams and downstream waters: how science can inform policy. *Journal of the American Water Resources Association* 43: 118-133.
- Naiman RJ, Latterell P. 2005. Principles for linking fish habitat to fisheries management and conservation. *Journal of Fish Biology* 67(sB): 166-185.
- Nel JL, Roux DJ, Maree G, Kleynhans CJ, Moolman J, Reyers B, Rouget M, Cowling RM. 2007. Rivers in peril inside and outside protected areas: a systematic approach to conservation assessment of river ecosystems. *Diversity and Distributions* 13: 341-352.
- Nilsson C, Reidy CA, Dynesius M, Revenga C. 2005. Fragmentation and flow regulation of the world's large river systems. *Science* 308: 405-408.
- Ohmann JL, Gregory MJ. 2002. Predictive mapping of forest composition and structure with direct gradient analysis and nearest neighbor imputation in coastal Oregon, USA. *Canadian Journal of Forest Research* 32: 725-741.
- Olson DH, Weaver G. 2007. Vertebrate assemblages associated with headwater hydrology in western Oregon managed forests. *Forest Science* 53: 343-355.
- Oregon Department of Fish and Wildlife (ODFW). 2004. Fish Distribution/Habitat GIS Data. ODFW, Salem, Oregon. Available from <http://rainbow.dfw.state.or.us/nrimp/information/fishdistdata.htm> (accessed April 2007).
- Orr EL, Orr WN, Baldwin EM. 1992. *Geology of Oregon*, 4th edn. Kendall/Hunt: Dubuque, Iowa.
- Pabst RJ, Spies TA. 1999. Structure and composition of unmanaged riparian forests in the coastal mountains of Oregon, USA. *Canadian Journal of Forest Research* 29: 1557-1573.
- Pichon CL, Gorges G, Boet P, Baudry J, Goreaud F, Faure T. 2006. A spatially explicit resource-based approach for managing stream fishes in riverscapes. *Environmental Management* 37: 322-335. DOI: 10.1007/s00267-005-0027-3.
- Progar RA, Moldenke AR. 2002. Insect production from temporary and perennially flowing headwater streams in western Oregon. *Journal of Freshwater Ecology* 17: 391-407.
- Reeves GH, Burnett KM, McGarry EV. 2003. Sources of large wood in a pristine watershed in coastal Oregon. *Canadian Journal of Forest Research* 33: 1363-1370.
- Revenga C, Brunner J, Henninger N, Kassem K, Payne R. 2000. *Pilot Analysis of Global Ecosystems: Freshwater Ecosystems*. World Resources Institute: Washington, DC.
- Ricciardi A, Rasmussen JB. 1999. Extinction rates of North American freshwater fauna. *Conservation Biology* 13: 1220-1222.
- Rice SP, Ferguson RI, Hoey TB. 2006. Tributary control of physical heterogeneity and biological diversity at river confluences. *Canadian Journal of Fisheries and Aquatic Sciences* 63: 2553-2566.
- Richards C, Johnson LB, Host GE. 1996. Landscape-scale influences on stream habitats and biota. *Canadian Journal of Fisheries and Aquatic Sciences* 53(Suppl. 1): 295-311.
- Richardson JS, Danehy RJ. 2007. A synthesis of the ecology of headwater streams and their riparian zones in temperate forests. *Forest Science* 53: 131-147.
- Rosenfeld JS, MacDonald S, Foster D, Amrhein S, Bales B, Williams T, Race F, Livingstone T. 2002. Importance of small streams as rearing habitat for coastal cutthroat trout. *North American Journal of Fisheries Management* 22: 177-187.
- Schmera D, Eroost T. 2004. Effect of riverbed morphology, stream order and season on the structural and functional attributes of caddisfly assemblages (Insecta: Trichoptera). *Annals of Limnology* 40: 193-200.
- Sheridan CD, Olson DH. 2003. Amphibian assemblages in zero-order basins in the Oregon Coast Range. *Canadian Journal of Forest Research* 33: 1452-1477.
- Smith RA, Schwarz GE, Alexander RA. 1997. Regional interpretation of water-quality monitoring data. *Water Resources Research* 33: 2781-2798.
- Sokal RR, Rohlf FJ. 1995. *Biometry*. W. H. Freeman: New York.
- Stoddard JL, Peck DV, Olsen AR, Larsen DP, VanSickle J, Hawkins CP, Hughes RM, Whittier TR, Lomnický G, Herlihy AT et al. 2005. *Environmental Monitoring and Assessment Program (EMAP) Western Streams and Rivers Statistical Summary*, EPA 620/R-05/006. US Environmental Protection Agency, Washington, DC.
- StreamNet. 2001. *PNW River Reach File Documentation*. StreamNet, Portland, Oregon. Available from <http://www.streamnet.org/pnw/PNWNAR.html> (accessed April 2007).
- StreamNet. 2003. *Dist.Anadromous*. StreamNet, Portland, Oregon. Available from <ftp://ftp.streamnet.org/pub/streamnet/gisdata/Distribution/Anadromous/MetaData/Meta.Anadromous.htm> (accessed April 2007).
- Syvitski JPM, Viirismarty CI, Kettner AJ, Green P. 2005. Impact of humans on the flux of terrestrial sediment to the global coastal ocean. *Science* 308: 376-380.
- Torgersen CE, Gresswell RE, Bateman DS. 2004. Pattern detection in stream networks: quantifying spatial variability in fish distribution. In *GIS Spatial Analyses in Fishery and Aquatic Sciences*, Vol. 2, Nishida T, Kailola PJ,

- Hollingsworth CE (eds). Fishery-Aquatic GIS Research Group: Kawagoe, Saitama, Japan; 405-420.
- Trombulak SC, Frissell CA. 2000. Review of ecological effects of roads on terrestrial and aquatic communities. *Conservation Biology* 14: 18-30.
- Turner DS, List MD. 2007. Habitat mapping and conservation analysis to identify critical streams for Arizona's native fish. *Aquatic Conservation: Marine and Freshwater Ecosystems* 17: 737-748.
- Underwood J, Crystal RE. 2002. *Hydrologically enhanced, high-resolution DEMs*. A Supplement to Geospatial Solutions, April 1, 2002: 8-14. Available from <http://www.geospatial-solutions.com> (accessed April 2007).
- USDA Forest Service and USD} Bureau of Land Management (USDA and USDI). 1994. Record of decision for amendments to Forest Service and Bureau of Land Management planning documents within the range of the northern spotted owl. Portland, Oregon.
- United States Forest Service (USFS). 1995. *Stream Inventory Handbook*. Pacific Northwest Region Fisheries Program, Portland, Oregon. Available from <http://www.fs.fed.us/r6/water/fhr/sida/index.htm> (accessed April 2007).
- United States Forest Service (USFS). 2003a. *Streams*. Siuslaw National Forest, Corvallis, Oregon. Available from <http://www.fs.fed.us/r6/data-library/gis/siuslaw/stream.htm> (accessed April 2007).
- United States Forest Service (USFS). 2003b. Cartographic Feature Files. Forest Service Geospatial Service and Technology Center, Salt Lake City, Utah. Available from <http://fsgeodata.fs.fed.us/metadata/CFE.htm> (accessed April 2007).
- United States Geological Survey (USGS). 1996. *National mapping program standards; Digital orthophoto standards; Part 1: General*. USGS, Reston, Virginia. Available from <http://rockyweb.cr.usgs.gov/nmpstds/doqstds.html> (accessed April 2007).
- United States Geological Survey (USGS). 2004. *The National Hydrography Dataset (NHD) - High-resolution*. USGS, Reston, Virginia. Available from <http://nhdgeo.usgs.gov/metadata/nhd.Jrigh.html> (accessed April 2007).
- United States Geological Survey (USGS). 2005. *The National Hydrography Dataset: Concepts and Contents*. USGS, Reston, Virginia. Available from <http://nhd.usgs.gov/chapter1/index.html> (accessed April 2007).
- Vitousek PM, D'Antonio CAM, Loope LL, Rejmanek M, Westbrooks R. 1997. Introduced species: a significant component of human-caused global change. *Nell' Zealand Journal of Ecology* 21: 1-16.
- Wallace JB, Webster JR, Meyer JL. 1995. Influence of log additions on physical and biotic characteristics of a mountain stream. *Canadian Journal of Fisheries and Aquatic Sciences* 52: 2120-2137.
- Wantzen KM, Siqueira A, da Cunha CN, de SA MDP. 2006. Stream-valley systems of the Brazilian Cerrado: impact assessment and conservation scheme. *Aquatic Conservation: Marine and Freshwater Ecosystems* 16: 713-732.
- Washington Department of Fish and Wildlife (WDFW). 2006. *Fish and wildlife geographic information system digital data documentation*. WDFW, Olympia, Washington. Available from <http://wdfw.wa.gov/hab/digital/doc.pdf> (accessed April 2007).
- Webster JR, Benfield EF, Ehrman TP, Schaeffer MA, Tank IL, Hutchens JJ, D'Angelo DJ. 1999. What happens to allochthonous material that falls into streams? A synthesis of new and published information from Coweeta. *Freshwater Biology* 41: 687-705.
- Wigington Jr PJ, Ebersole IL, Colvin ME, Leibowitz SO, Miller B, Hansen B, Lavigne HR, White D, Baker IP, Church MR *et al.* 2006. Coho salmon dependence on intermittent streams. *Frontiers in Ecology and the Environment* 4: 513-518.
- Wing MO, Skaugset A. 2002. Relationships of channel characteristics, land ownership, and land use patterns to large woody debris in western Oregon streams. *Canadian Journal of Fisheries and Aquatic Sciences* 59: 796-807.
- Winter TC, Harvey IW, Lehn Franke O, Alley WM. 1998. *Ground Water and Surface Water: A Single Resource*. US Geological Survey Circular 1139.
- Wipfli MS, Gregovich DP. 2002. Export of invertebrates and detritus from fishless headwater streams in southeastern Alaska: implications for downstream salmonid production. *Freshwater Biology* 47: 957-969.
- Wipfli MS, Richardson IS, Naiman RI. 2007. Ecological linkages between headwaters and downstream ecosystems: transport of organic matter, invertebrates, and wood down headwater channels. *Journal of the American Water Resources Association* 43: 72-85.
- World Wildlife Fund (WWF). 2007. HydroSHEDS. Available from <http://www.worldwildlife.org/freshwater/hydrosheds.cfm> (accessed April 2007).
- Young K. 2000. Riparian zone management in the Pacific Northwest: who's cutting what? *Environmental Management* 26: 131-144.
- Zimmerman A, Church M. 2001. Channel morphology, gradient profiles and bed stresses during flood in a step-pool channel. *Geomorphology* 40: 311-327.