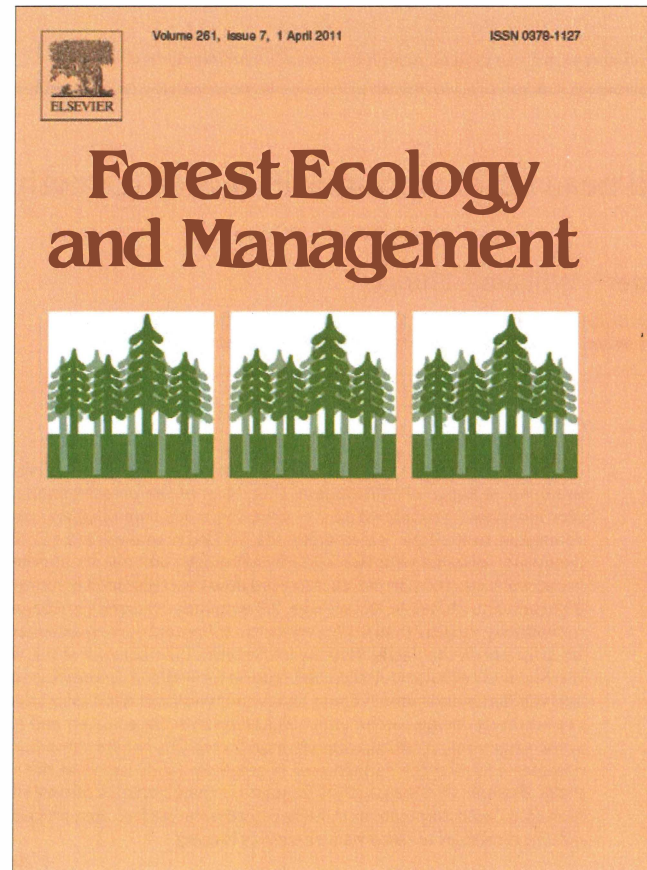


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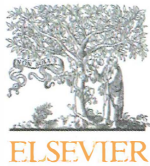


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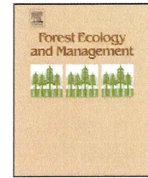
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Characteristics of small headwater wetlands in second-growth forests of Washington, USA

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ABSTRACT

In 2002, we initiated a study to clarify the response of headwater catchments to logging on timberlands in the Coast Range of Washington, USA. Most of the predominantly first-order streams studied (summer low flows typically $< 0.3 \text{ L s}^{-1}$) were hydrologically complex, consisting of a main surface channel connected to multiple, small wetlands. To better understand the forest management implications of headwater systems with two surface hydrology components of potentially differing areal extents (i.e., broad wetlands and narrow, channelized flow), we examined in more detail the wetlands associated with 30 headwater channels. On average, 2.3 wetlands occurred per channel. All 68 surveyed wetlands were, individually, smaller than 0.1 ha, which is a minimum survey-and-manage size criterion for forested wetlands in use in the Pacific Northwest. Seventy-nine percent of the wetlands surveyed by the full-triad method met regional wetland triad criteria for wetland delineation (qualifying wetland soils, hydrology, and vegetation indicators). These headwater wetlands were associated with several landscape variables: (1) northerly-facing catchments, (2) perennial surface water, and (3) down, channel-associated large wood originating from adjacent riparian forest. Our results show that small forested wetlands are quite common and that the surface area of small wetlands can rival the surface area of the associated first-order streams. This initial effort to quantify characteristics of small headwater wetlands suggests small wetlands could dominate or influence headwater surface area processes including those associated with stream responses to disturbances such as logging.

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1. Introduction

Wet areas characterized by gley soils and obligate wetland vegetation are often associated with small, forested, headwater streams in the US Pacific Northwest. Status of these areas as actual wetlands, however, is unclear—that is, do their affinities lie more with seeps or channel reaches expressing some degree of wetland character? Or, do such areas have a spatial presence and wetland character distinct from the channel, as well as from surrounding uplands? Either way, such areas, referred to here as headwater wetlands, develop and persist in the streamside zone of channels which are frequently steep (typically $> 20\%$), narrow (bankfull width typically $< 1.5 \text{ m}$), and short (usually $< 500 \text{ m}$), where decomposing logs and exposed tree roots are dominant structural elements (Dietrich and Dunne, 1993). We define such channels here as headwaters, to include both zero-order catchments directly above the “chan-

nel head” (Dietrich et al., 1987), as well as the first-order channel below the channel head, where active deposition and scour occur. On steep slopes commonly associated with headwaters, channel initiation is often located at the convergence of shallow sub-surface flows where seepage may be apparent (Montgomery and Dietrich, 1989). Within these areas, wetlands often develop as perennial, localized saturation of substrates maintained by piped channels, seeps, and springs.

Reasons for studying the frequency and characteristics of small headwater wetlands include their influence on both physical and biological processes. For example, interpreting the thermal sensitivity of headwater streams to logging is not straightforward (Johnson, 2003). Riparian shade, as well as geology, substrate, gradient, wood in the channel, and riparian stand density can correlate with stream temperature (Dent et al., 2008). Cool groundwater inputs have been identified as a possible confounding factor, potentially exerting a larger influence on stream temperature than canopy cover (Mellina et al., 2002). Headwater wetlands may also confound interpretation, as they are often associated with groundwater (e.g., Cole et al., 1997; Stein et al., 2004), and small forested wetlands have been observed as a factor in headwater stream temperature in response to logging (Kreutzweiser et al., 2009). Bio-

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logically, headwater-associated seeps or wetlands are important to the management of rare endemic taxa. Wetlands provide nursery or refugia habitat for populations of amphibians of federal concern (e.g., Nordstrom, 1997; Olson et al., 2007) in areas that are typically too steep to support fish (Davic and Welsh, 2004). Amphibian habitats are a key consideration for management practices in forested headwater catchments, where many of these species are declining (i.e., Corn and Bury, 1989; Kiesecker et al., 2001). Also, unique headwater-associated taxa assemblages, diversity, and habitats around headwater streams and wetlands are not found on adjacent upslope areas, the result of close uplands-aquatic system coupling (Gomi et al., 2002; Richardson et al., 2005; Meyer et al., 2007).

Understanding channel-associated processes favoring development of small wetlands benefits both forest management and adaptive-management programs (Morley and Calhoun, 2009). General application of the federal Clean Water Act (1977) to headwater wetlands is of increasing relevance to forest management (Welsch et al., 1995; Nadeau and Rains, 2007). For example, small headwater wetlands (<50 m²) tend toward the lower limit of feasible wetland evaluation and mapping. However, stricter regulation of streams has, over time, extended water quality protections to lower-order channels (Blinn and Kilgore, 2001; Nadeau and Rains, 2007), in part to protect fish (Adams, 2007) from impacts on water budgets and sediment loading in higher-order channels downstream. Further, the forest lands where our study was located are bound by legal trusts that direct these forested public lands to generate revenue for education and other purposes (Omnibus Enabling Act, 1889). A feasible headwaters water-quality policy, protection of threatened species, and generation of revenue from timber production can thus be intertwined—that is, logging may be a primary usage of the often steep terrain where headwater catchments with associated wetlands occur, yet the same forest lands may provide important linkages to downstream habitats of, for example, declining salmonid populations (Wipfli et al., 2007).

Headwater channels that support associated wetlands are not homogeneous, ranging from temporally perennial and spatially continuous, headwall to confluence, to various degrees of temporal and spatial intermittency. Consequently, from differences in headwater catchment hydrology, several types of wetland-like areas might develop, some of which may satisfy robust wetland delineation criteria and others which may not. Thus, one approach to inventorying headwater wetlands in managed forests is to apply a jurisdictional standard, such as the wetland triad (i.e., evaluation of wetland vegetation, soils, and hydrology (US Army Corps of Engineers, 1987)). Adherence to the wetland triad is appealing because the method is rigorous and well established. However, the soil criteria in particular are complex, and strict adherence to all tests may exclude some wetlands of interest, particularly when applied to wetland types not yet well studied. An alternate inventory approach is to set aside the complex soil evaluation criteria and evaluate wetland hydrology and vegetation triad criteria only. This approach has the appeal of more rapid wetland assessment, as well as ease of use by forest managers with no special training beyond vegetation ID—a common knowledge among foresters. Forested seeps often support distinctive vegetative communities (Morley and Calhoun, 2009) that may further facilitate rapid assessment and delineation by forest managers and biologists.

In this initial study, we hypothesized that connected headwater stream–headwater wetland systems consisted of two physically distinct components—(1) broad, very shallow (<3 cm) wetlands and (2) narrow, channelized streamflow—combinations of which may respond differently to disturbances such as logging. Late summer discharge of these small, forested headwater streams was typically <~0.3 L s⁻¹ and thus the surface area of the wetlands could rival that of their associated headwater streams, in effect lengthening the streams, with implications for riparian-zone management.

Here we examine more thoroughly the wetlands associated with 30 headwater catchments. We considered a specific research question: what is the surface area of the wetlands associated with headwater streams? Aside from mapping the wetlands to determine their area to evaluate elsewhere for water quality purposes and biological attributes, our objectives were to: (1) test whether the wetlands satisfied wetland evaluation criteria; (2) explore how relaxing evaluation criteria may influence survey results; and (3) evaluate relationships of headwater wetlands to channel aspect, gradient, and large down wood.

2. Methods

2.1. Study region

Data were collected from the Coast Range of southwest Washington, USA (Fig. 1). Elevation ranges from near sea level to approximately 800 m. Topography is highly dissected (catchments often <3 ha), steep (often >35%), and underlain by a mixture of marine sediments and basalts. Rain is the dominant form of precipitation. Approximately 90% of annual precipitation occurs between October and April (Franklin and Dyrness, 1973). By late summer, many headwater streams of the region become spatially intermittent or dry completely. Forests are coniferous, predominantly ~45–100 years old. Dominant canopy species are Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco), western hemlock (*Tsuga heterophylla* (Raf.) Sarg.), and, nearer the coast, Sitka spruce (*Picea sitchensis* (Bong.) Carr.). Red alder (*Alnus rubra* Bong.) is the dominant hardwood species and often occurs in riparian areas.

As part of broader objectives, including biota interaction with riparian buffer designs (Wilk et al., 2010), we studied two climatically similar areas within the region (Fig. 1). The linear distance between the two areas is approximately 55 km. Area 1 mean annual temperature (1948–2009) and rainfall were, respectively, 9.9 °C and ~128 cm (Olympia, WA (46.967°N, -122.900°W) (WRCC, 2007)). Area 2 mean annual temperature (1980–2009) and rainfall were, respectively, 10 °C and ~212 cm (Raymond, WA (46.650°N, -123.716°W) (WRCC, 2007)). The two areas, however, have contrasting bedrock lithologies, which may affect wetland occurrence (Stein et al., 2004). Crescent Formation basalts underlay Area 1 (McMurphy and Anderson, 1968), whereas marine sandstones predominate at Area 2 (Washington Division of Geology and Earth Resources, 2005).

2.2. Study catchment selection and characteristics

Catchment selection was non-random, drawn from pending timber sales scheduled to be logged within two years and logged only once previously (Wilk et al., 2010). Preference was given to sale units consisting of adjacent catchments where logging could occur in a single operation. Of the 30 catchments studied, twenty-seven were first-order (e.g., Strahler, 1952). Study channels often occupied the entire inner gorge. Typical July–August stream discharges were <0.3 L s⁻¹, estimated from monthly measurements at weirs installed on study channels. The 30 study catchments were nested within eight clusters of 3–5 catchments each (Table 1), with four clusters per study area. Catchment area ranged from 1.1 to 8.1 ha. Channel lengths ranged from 109 to 476 m. The elevation band studied was narrow (~20 to 500 m). Distance between clusters within a region was ~6–16 km (Fig. 1).

Based on year-to-year observation, March–October, catchment streams were of three general types: (a) perennial and spatially continuous; (b) perennial and spatially discontinuous; or (c) seasonal, drying completely by late summer. Mean bankfull width of virtually all study channels was <1.5 m (Table 1). By late sum-

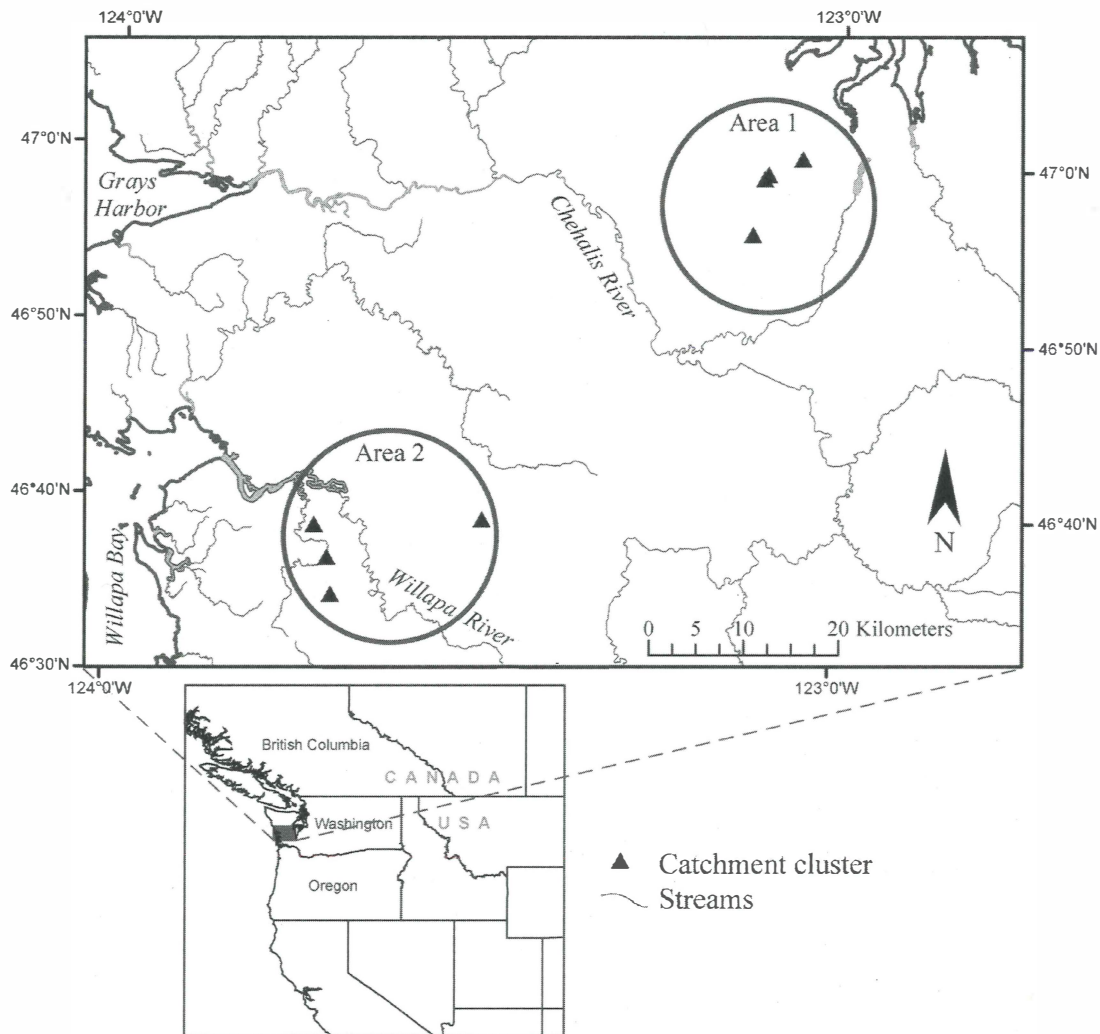


Fig. 1. Locations of headwater study channels evaluated for the presence of headwater wetlands in the Coast Range, Washington, USA. Each black triangle represents a cluster of three to five small headwater catchments.

mer, typical wetted width was 0.2–0.3 m. Typical late-summer depth was 1–3 cm. Areas surrounding the channels surveyed were clearcut then burned ~61–108 years prior to our study (Wilk et al., 2010).

2.3. Candidate wetland identification

Each channel was surveyed for wetlands, confluence to headwall, between mid-June and mid-July of 2004. This is the annual period corresponding to onset of minimum surface discharges and narrowest stream wetted width (July–September) in the region. We searched the bankfull zone of each channel for characteristic regional wetland indicators (Table 2; US Army Corps of Engineers, 1987; USDA, 2003; USDA, undated). The top of the bank or, for entrenched channels, a scour line or adjacent bench, defined bankfull (e.g., Gordon et al., 2004) for these channels, which were often confined.

Each candidate wetland was initially screened in two ways. First, at the time of delineation, there was observed hydraulic connectivity between the wetland and the bankfull zone. Second, we considered only candidate wetlands extending well beyond and

judged to be distinct from the defined channel. Wetland character wholly within the defined and typically flowing stream channel was thus excluded.

2.4. Wetland identification and delineation

Candidate wetlands passing initial screening were then evaluated by one of two methods. At six clusters (21 catchments) we applied a full-triad evaluation method (Table 2). At the remaining two clusters (9 catchments) we relaxed the hydric soil requirement, inventorying all candidate sites by qualifying hydrology and vegetation characteristics alone. Hereafter, we refer to the latter method as the relaxed-triad method. Finally, at the first two of the six clusters surveyed by the full-triad method, candidate wetlands which failed at least one of our definitions (Table 2) were inventoried as for qualifying wetlands. This was done to better understand the types of sites rejected by our method. The wetland verification process thus followed the substantive steps and decision points of the evaluation protocol used by the state of Washington (US Army Corps of Engineers, 1987), but simplified supporting documentation such as describing specialized morphology and physiology of

Table 1

Location and general physical descriptions of 30 forested, predominantly first-order catchments in the Coast Range, Washington, USA. Catchments were arranged in eight clusters (for number of catchments per cluster, see Table 4).

Study area	Cluster	Lat ^a	Long	Geology ^b	Soils ^c	Stream type ^d	Bankfull width (m) ^e
Area 1	I	47.005	–123.057	Basalt flows Flow breccias	Silt loam Very cobbly loam	Step pool/cascade	0.4–1.8
	II	46.985	–123.106	Basalt flows Flow breccias	Gravelly silt loam Very cobbly loam	Step pool/cascade	0.4–0.9
	III	46.931	–123.124	Basalt flows Flow breccias	Silt loam	Pool-riffle	0.4–2.3
	IV	46.992	–123.100	Basalt flows Flow breccias	Gravelly silt loam	Step pool/cascade	–
Area 2	I	46.645	–123.709	Marine sediments Terraced deposits	Silt loam	Pool-riffle	0.5–0.7
	II	46.656	–123.482	Marine sediments	Silt loam	Step pool/cascade	0.2–1.2
	III	46.621	–123.714	Marine sediments Flow breccias	Silt loam	Step pool/cascade	0.6–1.4
	IV	46.580	–123.695	Marine sediments Basic intrusive rock	Silt loam	Step pool/cascade	–

^a Approximate coordinates of reference stream confluence in each cluster, NAD 83.

^b Digital USGS 1:100,000 geology quadrangles.

^c USDA NRCS SURRGO database (USDA, 2005).

^d General stream morphology at each cluster (Montgomery and Buffington, 1998).

^e Averages of multiple channel segments per stream. See methods.

wetland plants. To assess vegetative cover, we identified the three plant species contributing the greatest cover at each wetland. Percent cover of these species was recorded from visual estimation as either <5%, 5–20%, or 21–50%, or >50%.

For our analysis, each wetland was then further described. We collected mid-point coordinates with a multi-channel, WAAS-enabled (± 3 m) Magellan Meridian® GPS receiver. Distance of each wetland from the mainstem was measured to validate its channel-associated, geo-referenced location. Lengths of long and short wetland axes were measured to the nearest 10 cm and recorded with sketches of wetland shape relative to the channel. Percent gradient was determined with a clinometer, and reported as that of the channel segment associated with each wetland (see below). Because aspects of side slope-oriented wetlands could differ from that of the channel by ≥ 90 degrees, we report aspect as that of each wetland-associated channel segment (see below). Aspect was read from a hand-held compass, with any missing values estimated from wetland polygon shapefiles (see below) and topographic layers using ESRI® ArcMap™ v. 9.3 (ESRI, 2009).

Wetland measurements and drawings were then converted to a polygon-GIS layer, geo-referenced and oriented to shapefiles representing the study channel in each headwater catchment (Fig. 2). Mean channel gradient and aspect were calculated by sub-dividing, on site, each channel into adjacent, numbered segments based

on changes in gradient and confinement ratios. Confluence elevations of study channels were extracted from a 10-m digital elevation model. Wetland areas (m²) were calculated from the polygons using automated routines within ESRI® ArcMap™. A sub-set of wetland polygon areas (10%) were verified with direct digitization.

2.5. Channel-associated large down wood

As a possible indicator of wetland development, channel-associated large down wood was inventoried in the year prior to the wetland surveys at 20 of the 30 study catchments. This subset corresponded to those six clusters where the full-triad method was applied (21 total catchments but down wood inventoried in only 20). Channels were surveyed from confluence to headwall, with the bankfull zone treated as a variable-width belt transect. All wood pieces ≥ 10 cm in diameter at the bankfull-zone boundary and ≥ 1 m in length were counted and identified as either suspended or downed. Suspended material was defined as wood which would not modify surface flow in the bankfull state. Orientation of the long axis of each piece of wood inventoried, relative to the channel, was recorded as either (a) $\sim \pm 22$ degrees of exactly parallel to the channel; (b) $\sim \pm 22$ degrees of exactly perpendicular to the channel; or (c) all intermediate orientations, as adapted from Schuett-Hames et al.

Table 2

Wetland triad-indicator criteria applied to determine status of candidate locations as wetlands or non-wetlands. Triad definitions were used to evaluate small wetland features associated with small, headwater channels (bankfull width typically < 1.5 m) in the Coast Range, Washington, USA.

Triad component	Initial test	Secondary test
Hydrology	Surface inundation not related to recent precipitation.	If little or no inundation, ~ 30 cm deep $\times$ 15 cm wide soil pit in representative location strikes water within 30 cm of surface, or partially fills with water in a few minutes.
Soils	Soil pit indicates sandy texture with surface layer of high organic content, or organic streaking of deeper layers. Hydric rating possible for recent stream-side deposits with weak organic development.	If non-sandy, qualifying if thick organic horizon, sulphidic odor, and gley ^a or chroma 1 ^b , or chroma 2 ^b soil matrix with higher chroma mottling.
Vegetation	% cover dominated by obligate or facultative wetland species relative to upland and facultative upland species. Exclude presence of the latter due to heterogeneous micropography (i.e., perched on logs, soil mounds, etc.).	If % wetland and upland cover similar, both soils and hydrology evidence for wetland presence must be strong. May consider revising areal extent to include only portions expressing sufficient wetland character.

^a Munsell, 2000; Gley 1 and Gley 2.

^b Munsell, 2000; 10R, 2.5YR, etc. (i.e., non-gley).

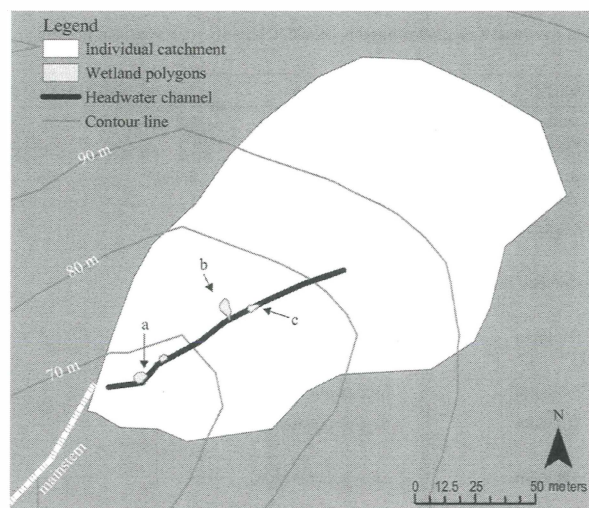


Fig. 2. This is an example of the shape and extent of a typical headwater study catchment and mapped channel, with small channel-associated wetlands, occurring in the Coast Range, Washington, USA, all relative to the same area and length scales. Wetland polygons are geo-referenced to channel length and channel coordinates. Three types of wetland connection to the channel are shown: (a) abutting the channel; (b) sideslope wetland with scour channel; (c) intersected by channel. The dashed line, lower left, is the approximate location of the mainstem (Washington State 1:24,000 hydrologic data layer).

(1999). Hereafter, the latter two orientations combined is referred to as crosswise orientation.

Finally, each piece of wood inventoried was rated using a five-class system of decompositional stage, Class I being least decomposed and Class V being highly decomposed (Sollins, 1982). Species, diameter, and decompositional stage were used to separate the fraction of our sample likely of old-growth origin from that originating from the aggrading stand. Hereafter, we refer to these two fractions of down wood, respectively, as old and new down wood.

2.6. Statistical methods

Summary statistics for wetland areas are reported as group means with associated standard errors. Correlations are reported as Pearson coefficients. All determinations of statistical significance are relative to α of 0.05. For multiple comparisons, P -values are Bonferroni corrected. Data were analyzed with Systat[®] v. 10 (Systat[®] Software, 2000). We report results stratified by lithology where relevant.

3. Results

3.1. Catchments

Except for bedrock lithology, the two study areas were physically similar for the variables considered (Table 3). Overall, 16 catchments were surveyed within Area 1 and 16 were surveyed within Area 2. Total channel length surveyed was 7348 m.

3.2. Wetland occurrence

Overall, 68 headwater wetlands were inventoried during our survey, 38 of which were based on the full-triad method and 30 of which were based on the relaxed-triad method (Fig. 3). Sixty-six percent of total channels surveyed (20 of 30) contained at least one wetland (Table 4). On average, 2.3 wetlands occurred per channel. Wetland polygon distribution within study areas was approxi-

Table 3

Means (SE) of headwater catchment characteristics as observed at two study areas differing in bedrock lithology, Coast Range, Washington, USA.

Catchment characteristic	Sedimentary ($n = 14$)	Basaltic ($n = 16$)
Channel length (m)	235.3 (26.0)	234.2 (21.1)
Catchment area (ha)	4.0 (0.6)	5.3 (0.5)
Channel gradient (%) ^a	21.5 (1.3)	34.9 (2.3)
Confluence elevation (m)	138.4 (21.6)	273.6 (16.2)
Channel aspect, degrees ^a	172.5 (27.2)	156.5 (30.3)
Total qualifying wetland area (m ²)	149.9 (50.9)	217.2 (84.9)

^a Mean of mean per catchment.

mately random (Morans I index = 0.15–0.19). Most wetlands ($n = 45$, 66%) occurred within Area 2; 34% ($n = 23$) occurred within Area 1. Twelve percent of 68 total wetlands were rejected as true wetlands based on insufficient wetland indicators (Table 2; Fig. 3). The predominant reason for rejecting a wetland was inconclusive indication of hydric soils. In these cases soil chroma was >2 . Of the 68 total wetlands observed, $\sim 75\%$ intersected the channel and $\sim 25\%$ abutted the channel. Eighty-one percent of total wetlands were associated with the longitudinal profiles of channels and 19% were associated with channel heads. Seventeen (57%) of 30 total channels surveyed showed little or no wetland development at the channel head. Few occurrences of headwater wetlands attributable exclusively to an obvious, side slope-seep origin were observed. A scour channel associated with a wetland was only noted twice in our total sample. Most transitions between headwater wetlands and upland character were abrupt and could be crossed by a single step.

3.3. Wetland area

Total cumulative wetland area per catchment equaled or exceeded 0.1 ha only once (Table 4). Wetland area as a percentage of catchment area was typically $<0.5\%$ (maximum 2%).

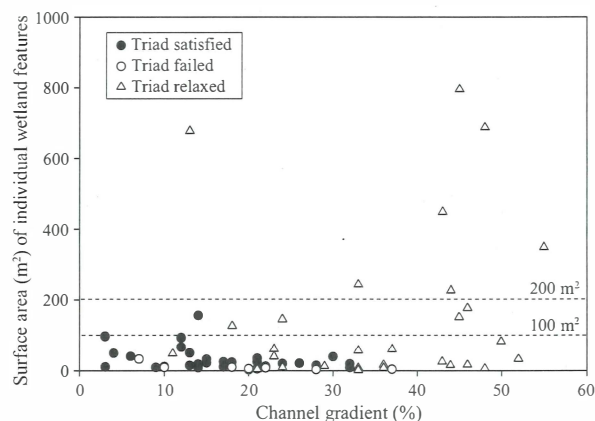


Fig. 3. Classification of wetlands observed in the Coast Range (Washington, USA) as satisfying the wetland triad definition, failing the wetland triad definition, or characterized by an alternate, and less stringent, relaxed-triad definition (see text). Symbols show the outcome of applying the three categories of classification relative to surface area of individual wetlands and channel gradient. Variability in wetland size may increase or some sites may be excluded, depending on the definition applied.

Table 4

Total headwater wetland area by study channel within each area and cluster (i.e., I, II, III, IV (see Table 1). Typical stream surface area (see footnote) was based on mean study channel length and typical July–August mean headwater stream wetted width (0.3 m) for all the streams, Coast Range, Washington, USA.

Area 1	Channel	Wetlands per channel	Total wetland area (m ²)	Area 2	Channel	Wetlands per channel	Total wetland area (m ²)
I	a	0	–	I	a	4	60.9
	b	0	–		b	6	155.3
	c	0	–		c	6	176.5
	d	0	–	II	a	0	–
II	a	2	105.8		b	0	–
	b	0	–		c	1	8.7
	c	0	–		d	1	40.2
	d	0	–	III	a	7	192.1
III	a	0	–		b	3	60.4
	b	2	167.8		c	2	16.1
	c	4	115.8	IV ^a	a	6	386.2
IV ^a	a	3	265.5		b	3	176.0
	b	4	401.7		c	3	692.6
	c	2	814.0		e	3	213.1
	d	5	1155.8				
	e	1	449.1				

Mean study channel length: 234.7 m Typical stream surface area (234.7 m × 0.3 m) = 70.4 m².

^a Surveyed by relaxed-triad method.

Areas of all individual headwater wetlands inventoried were smaller than 0.1 ha (Fig. 3). The largest individual wetland inventoried was 795.2 m² and the smallest was 1.7 m². Of the 68 total wetlands, 82% were smaller than 100 m²; 90% were smaller than 200 m². All individual wetlands of area >200 m² occurred at clusters surveyed by the relaxed triad method.

Mean wetland area differed by survey method. Mean wetland area was largest for the full+relaxed triad combined data set, least for wetlands failing the full triad (Fig. 3). Mean wetland area, full+relaxed triad methods, was 83.1 m² ± 19.4; 1.7–795.2 m² (mean ± SE; range). Mean wetland area, full-triad method only, was 34.0 m² ± 6.1; 3.1–155.6 m². Mean area of candidate wetlands failing our full-triad definition was 10.0 m² ± 3.3; 3.6–32.4 m².

Survey method also influenced results for association between wetland area and bedrock lithology. Overall total wetland area, full+relaxed-triad methods, was 5653.6 m², of which ~61% was associated with basaltic bedrock lithology and ~39% was associated with sedimentary bedrock lithology. Based on data from the full-triad method alone, however, basaltic bedrock lithology was associated with only 38% of total wetland area (389.4 m²) and sedimentary bedrock lithology with 62% (630.2 m²).

3.4. Relationships to gradient and aspect

Overall, wetland frequency was highest along channel segments of low-to-moderate (<35%) gradient, which accounted for 100% of occurrences in the full-triad subset of our data, and 75% of occurrences in the entire data set (Fig. 4). Maximum channel gradient associated with the wetlands inventoried was 55%; minimum associated gradient was 3%. A majority of the wetlands occurring on basaltic bedrock lithology were associated with channel gradients >35%.

Highest total wetland area per catchment was associated with catchments of northerly aspects (Fig. 4). In our non-random sample, total wetland area per catchment was more strongly correlated with a north–south axis (cosine of aspect, $R=0.58$, $P<0.05$) than with an east–west axis (sine of aspect; $R=0.25$, $P=0.61$). Of the 68 headwater wetlands encountered, 48% had northerly (>315° to <45°) aspects.

3.5. Vegetation, soils, and hydrology

Fifteen plant species were inventoried, three of which dominated the wetland-associated flora we observed (Table 5).

Lysichiton americanus Hulten & H. St. John was encountered at 92% of wetlands inventoried by the full-triad method, and *Chrysosplenium glechomifolium* Nutt. was encountered at 76%. Percent cover for these two species often equaled or exceeded 50%.

Gleyed soils were detected at 76% ($n=28$) of wetlands, sulfidic soils at 57% ($n=21$). Soils of matrix chroma ≤2 with high chroma mottling were uncommon (16% of sites evaluated by full triad method ($n=5$)). Typical Munsell® soil color codes were 10Y 3/1 and 5GY 3/1 for qualifying sites, 7.5YR/2 for non-qualifying sites (after allowing for mottling). The most common hydrologic qualifier was soil saturation rather than inundation, the latter occurring at <25% of sites surveyed. Histic epipedons were not generally observed ($n=3$).

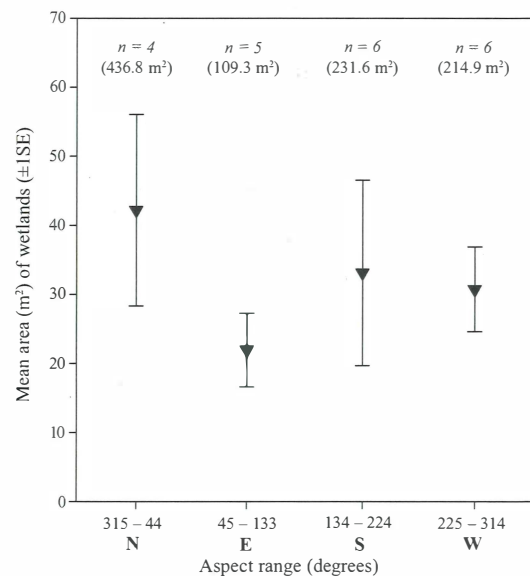


Fig. 4. Mean wetland area in each of four aspect categories. Data are from 21 small, forested headwater catchments in temperate, conifer-dominated timber production lands in the Coast Range, Washington, USA, surveyed by the full-triad method. Total area (m²) of headwater wetlands observed per 90 degree aspect band is in parentheses. Number of catchments (n) are per aspect band.

Table 5

Major plant species occurring on small wetlands (typical extent <50 m²) associated with relatively steep, forested, headwater channels in the Coast Range, Washington, USA. The three wetland plant species highest in percent cover were inventoried, and were common to many wetlands. Data are from the 21 channels surveyed by the full-triad method (see text).

Species	No. of times encountered	% Cover, range
<i>Lysichiton americanus</i> Hulten & H. St. John	35	<5–>50
<i>Chrysosplenium glechomifolium</i> Nutt.	29	<5–50
<i>Mimulus dentatus</i> Nutt. ex Benth.	7	<5
<i>Cardamine angulata</i> Hook.	5	<5–20
<i>Blechnum spicant</i> (L.) Roth	4	<5–20
<i>Mitella</i> spp.	4	5–20
<i>Stachys</i> spp.	4	<5
<i>Tiarella trifoliata</i> L.	4	5–20
<i>Angelica</i> spp.	3	5–20
<i>Equisetum</i> spp.	3	<5
<i>Mitella ovalis</i> Greene	3	<5
<i>Mitella</i> spp.	3	<5–20
<i>Angelica genuflexa</i> Nutt.	2	<5–20
<i>Athyrium filix-femina</i> (L.) Roth	1	<5
<i>Mimulus</i> spp.	1	<5
Simpson's Index (1/D)	5.4	

3.6. Relationship to down wood

A moderate correlation ($R=0.57$, $P<0.05$; $\alpha=0.05$) was observed between total wetland area per channel and total count of all down wood intersecting the channel. The correlation between total wetland area and number of logs only, the wood category accounting for >90% of the inventory, was similar ($R=0.51$, $P<0.05$).

No correlation between total wetland area per catchment and count of wood originating from old growth (~19% of channel wood inventoried) was observed, either for count of down old logs per catchment ($R=0.17$, $P=0.48$), logs oriented crosswise to the channel ($R=0.20$, $P=0.41$), or total number of old wood pieces oriented crosswise to the channel ($R=0.32$, $P=0.17$). Analysis of species, decomposition class, and diameter indicated wood originating from old-growth was predominantly that of ≥ 40 cm diameter and decay class $\geq$ III.

The strongest observed correlation between total wetland area per catchment and down wood was with count of new logs oriented crosswise to the channel ($R=0.72$, $P<0.05$), accounting for approximately 20% of wood inventoried. Correlation with total count of all new channel wood (logs, stumps, suspended logs, etc., of decay class I–III), accounting for approximately 77% of wood inventoried, was slightly lower ($R=0.59$, $P<0.05$).

Mean total count of crosswise-oriented new logs was highest (34.5 ± 2.2) for channels of northerly aspects (≥ 315 to ≤ 44 degrees) and lowest (15.6 ± 4.9) for channels of easterly aspect (45–133 degrees). Means for channels of southerly (134–224 degrees) and westerly (225–314 degrees) aspects were, respectively 19.6 ± 5.4 and 20.3 ± 5.6 .

3.7. Stream surface flow

Observed wetland frequency declined as temporally-perennial and spatially-continuous stream character declined. No wetlands were detected along channels in which surface flow was predominantly seasonal, nor along channels where surface flow occurred only during severe winter storms. Of three clusters where these conditions predominated, accounting for 2610 m of channel length distributed over 16 catchments, only four qualifying wetlands were observed. Two of the three clusters (I, II; Table 4) occurred at Area 1, and were underlain by very cobbly loam (often >10 cm cobble). Headwalls of the third cluster (Area 2, II) abutted a ridge (Table 4).

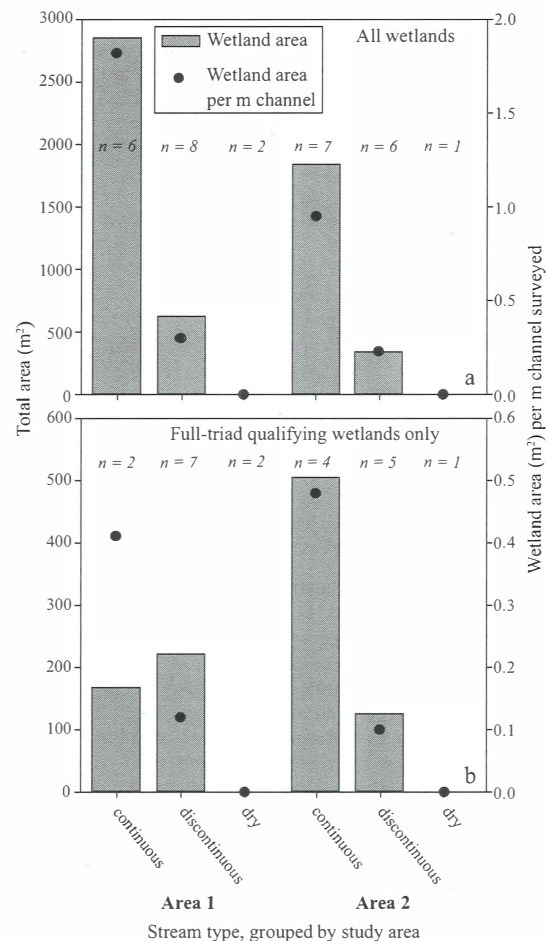


Fig. 5. Surface area of wetlands associated with three categories of headwater streams in the Coast Range, Washington, USA. Data per category are total wetland area per category and total wetland area standardized per meter of channel (i.e., total wetland area per category/total channel length surveyed per category) for (a) a combined survey method (full triad + relaxed triad) of all 30 catchments, and (b) a subset of 21 catchments surveyed by a more restrictive method (full-triad) only. Stream categories are (1) spatially continuous surface flow (headwall to confluence); (2) spatially discontinuous surface flow; and (3) predominantly dry except during winter storms.

Of the remaining sites, wetlands were most strongly associated with temporally-perennial, spatially-continuous streams, both for the full data set and the full-triad method subset (Fig. 5). Standardized to square meters of wetland observed per meter of channel surveyed, wetland area was approximately 4 times higher along streams of predominantly spatially-continuous, temporally-perennial character compared to predominantly discontinuous, seasonal streams, or to dry channels. Even after accounting for total length of channel surveyed, more headwater wetlands were associated with continuously perennial streams in the Area 2 sites.

4. Discussion

Wetlands were common along headwater channels, averaging 2.3 per channel. Of the streams studied, >50% were associated with one or more wetland. Surface area of individual wetlands was typically less than 100 m². However, we likely under-estimated both

frequency and cumulative area of headwater wetlands per catchment because our survey was confined to the bankfull zone. Also, the 30 headwater catchments studied were a small, non-random sample. Were our sample representative, however, every 1000 such catchments would support, on average, ~19 ha of wetlands not typically surveyed. Given that river miles of headwaters greatly exceed that of mainstem rivers, headwater wetland area could, in rugged topography, rival or exceed that of lowlands. Whether wetland area or stream area dominates headwater catchments is thus a key question. Automated detection of small depressional forested (i.e., cryptic) wetlands using LiDAR (light detection and ranging) might be adapted to small forested slope wetlands as a next step in developing hypotheses (Creed et al., 2003).

Occurrences of headwater wetlands were most frequently associated with northerly aspects, the aspect band with the fewest catchments in our sample (Fig. 4). This result seems reasonable given that forested slopes of northerly aspect are likely to be relatively cooler and wetter than corresponding southerly aspects (e.g., Garnier and Ohmura, 1968; Helms, 1980; Perry, 1994). Thus, northerly slopes would be predicted to be a more suitable environment for development of and persistence of small wetlands dependent on stable, perennial water sources. Understanding an association between headwater wetland occurrence and aspect would be of particular interest; given that factors such as air temperature and stream depth may control the thermal sensitivity of small streams (e.g., Adams and Sullivan, 1989; Sullivan et al., 1990; Isaak and Hubert, 2001), such an association could lead to unexpected results, such as rapid heating of small streams of northerly aspects.

Also, notably, >80% of the headwater wetlands inventoried occurred along the longitudinal profiles of channels; 60% of channels surveyed lacked a channel-head wetland. Black (2001) showed the occurrence of small headwater marshes (mean area approximately 120 m²) along the western front of the Olympic Mountains, Washington, was in general frequency and areal range consistent with our results. Perhaps more notable in our study, however, was the apparent strong association of wetlands with continuous, perennial surface flow (Fig. 5). More work is needed to determine if factors inhibiting expression of surface flow in a given, defined channel, except during wet winter months, are related to whether wetland character develops or is sustained. We suspect, due to the seasonally dry climate of the study region, the presence of groundwater may correlate with wetland development, but we did not explore this mechanism. The prolonged summer dry period typical of the study region, however, provides a favorable setting in which to develop hypotheses and test such mechanisms.

Specific to our study, results from the full data set (relaxed-triad method + full-triad method combined) differed relative to results from the full-triad method alone. For example, mean area was ~3 times higher for the full data set. We suspect that the relaxed triad method is recognizing wetland character which would not be inventoried by the more stringent full-triad method, in particular the ribbon-shaped occurrences of wetland plants bordering several channels. Whether some of the largest wetlands inventoried, at least to their observed full extent, would satisfy the full triad's hydric soils definition is also questionable. Headwater wetland inventories based on the relaxed-triad method may thus more accurately capture extents of wetland plant communities associated with headwater channels, whereas the full-triad method is more sensitive to soil character. Still, our relaxed triad method may have underestimated the full extent of headwater-associated wetland plant communities, as vegetation showing strong moisture association can extend well beyond channel heads into zero-order catchments, as well as colonize near-channel lateral slopes (Sheridan and Spies, 2005).

Our down wood results suggest that the headwater wetlands we observed, as they exist now, may be of recent origin rather than an old-growth legacy. This may simply reflect the dominant, existing source of channel-associated wood being the second-growth stand. A case could be made for interaction between small incised channels or narrow, v-shaped catchments vs. tree rooting distance from the channel. However, at the bankfull edge, and for the subset of our data of apparent second-growth origin, we saw little difference between mean diameter of suspended boles (19.6 cm) and that of mean downed boles (19.4 cm), pointing away from the downed group consisting of predominantly tree crowns and a suspended group consisting predominantly of larger, channel-bridging boles. Streamside topographic depressions left by rootballs of toppled trees may also encourage wetland formation, as we observed several rapidly fill with water and fine sediments. However, channel-associated rootballs were not commonly encountered during our inventory, and only 26% of wetlands identified were within the range of rootball size (≤ 10 m²). Thus, other wetland-generating processes may predominate in the catchments studied.

In these headwater areas where forestry is the dominant activity, knowledge of the occurrence, distribution and functionality of small seeps and wetlands for disturbance-sensitive species like amphibians is of special consequence. For example, in the Pacific Northwest, current forest management regulations are essentially inadequate for the protection of headwater amphibians (Olson et al., 2007). Although we did not quantify amphibian abundance relative to the wetlands inventoried, stream- and seep-associated amphibians were among the dominant vertebrate groups observed at the location of our study. Jones et al. (2005) includes coastal tailed frogs (*Ascaphus truei* Stejneger, 1899), two species of giant salamanders, (*Dicamptodon*), the Columbia torrent salamander (*Rhyacotriton kezeri* Good and Wake, 1992), and to a lesser extent, Van Dyke's salamander (*Plethodon vandykei* Van Denburgh, 1906) and Dunn's salamander (*Plethodon dunni* Bishop, 1934) as taxa occurring in our study areas. Of special note, Dunn's and Van Dyke's salamanders, along with Cope's giant salamander (*Dicamptodon copei* Nussbaum, 1970) are on state and federal species of concern lists (ISSSSP, 2010). This designation requires site surveys for presence of these species prior to any ground-disturbing activities such as logging, and if found, can cause alteration of forest management plans to conserve their habitats. Our findings show small wetlands are common along headwater channels. Thus, given the occurrence of headwater streams across landscapes (e.g., Shreve, 1969), the management implications of our findings become increasingly apparent. Concentration of small, forested wetlands within headwater catchments of northerly aspects, as we observed, suggests a testable hypothesis about the larger-scale distribution of forest amphibians.

Finally, we note that one small wetland-like area which failed to qualify as a wetland by our full-triad method in 2004 was re-evaluated in December of 2009 using the same definition, five years after the associated catchment was clearcut. We observed the following: (1) an increase in wetland spatial extent from 3.6 m² to 9.5 m²; (2) increase in vegetation mass and conversion from sparse *L. americanus* to nearly pure, dense bulrush (*Scirpus* spp.); and (3) development of gley soil character with orange mottles. Other post-logging changes in the headwater wetlands studied, observed 2004–2009, suggest small headwater wetlands are in some way highly sensitive to hydrologic disturbance and may 'flicker'—that is, develop or fade—at a time scale of several years. This may reflect short, emergent groundwater paths, so that hydrological effects from disturbances such as timber harvesting of upslope areas occur rapidly in small catchments (Fitzgerald et al., 2003). Particularly relative to annual climate variation, climate change, and associa-

tive effects on species viability, then, dynamics of small headwater wetlands warrant further investigation.

5. Conclusions

If on average every first-order catchment in the study region supported one or more small wetlands, as our sample suggests, then small wetlands carry the potential to influence, on average, every headwater stream. Because of the vast forested area implicated, headwater wetlands warrant evaluation relative to forest management planning to determine their collective impacts. Characteristics of the wetlands observed also suggest a further approach to their study, as well as development of predictive tools, not unlike that of a dichotomous key—i.e., is the catchment of north aspect?, is stream flow perennial and continuous?, etc. It was also noteworthy that survey method—the designation of wetland via full-triad vs. relaxed-triad criteria—influenced results. The latter emphasized all stream-associated, wetland-like habitat, whereas the former captured areas of adequate stability and persistence to develop wetland soil characteristics. The two methods led to differing conclusions about which study areas had greater wetland areas.

Mean areal extent of the wetlands observed was less than 100 m², an order of magnitude below the sensitive-site survey area threshold currently used by Washington for planning timber sales. Headwater wetlands are thus not typically inventoried, and so are not yet well characterized. However, headwater wetlands may be areas of concern for three reasons. First, streamside seeps and wetlands in forested environments provide important habitats for disturbance-sensitive animals like amphibians. Second, the effects of forest management on the short- and long-term presence of these wetlands are largely unknown, and relative to species viability, needs further investigation. Third, the cumulative area of these headwater wetlands can exceed that of the associated stream, of potential significance to water quality. Understanding the frequency, distribution, and extent of headwater wetlands under second-growth and old-growth forest canopies thus addresses gaps in the current science.

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