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Managing nonperennial headwater streams in temperate forests of the United States

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ABSTRACT

Forest management guidelines are designed to protect water quality from unintended effects of land use changes such as timber harvest, mining, or forest road construction. Although streams that periodically cease to flow (nonperennial) drain the majority of forested areas, these streams are not consistently included in forest management guidelines. This paper reviews management guidelines for nonperennial (intermittent and ephemeral) streams draining temperate forests in the continental U.S., evaluates potential impacts of land use activities on ecosystem services provided by these streams, and identifies information needed to incorporate nonperennial streams into water quality protection practices. For federally administered lands, national management guidance is deliberately nonprescriptive, deferring to regional and forest-level recommendations for both perennial and nonperennial streams. Most state guidelines recommend riparian management zone (RMZ) protection for perennial streams (48/50 states) and intermittent streams (45/50 states), but only Alaska and West Virginia require RMZs around ephemeral streams. Based on the National Hydrography Dataset, an average of 58% of forested land area in the U.S. drains to nonperennial headwater streams, making these stream types the most common connectors between forested lands and the aquatic system. Land uses that modify flow regimes in these streams can affect sediment and organic matter transport and distribution, stream temperature dynamics, and biogeochemical processing. Nonperennial streams also provide material subsidies to downstream waters and serve as temporary habitats for some aquatic species. However, limited research has examined how forest land uses affect ecosystem services and biota in these streams. Therefore we highlight a set of key questions about nonperennial streams in forests, not the least of which is simply understanding where headwater stream channels are located and associated patterns of flow duration. Although many questions remain, we also note where recent advances in data collection, modeling and process-level research provide opportunities to resolve uncertainties around nonperennial streams in forested landscapes of the continental U.S.

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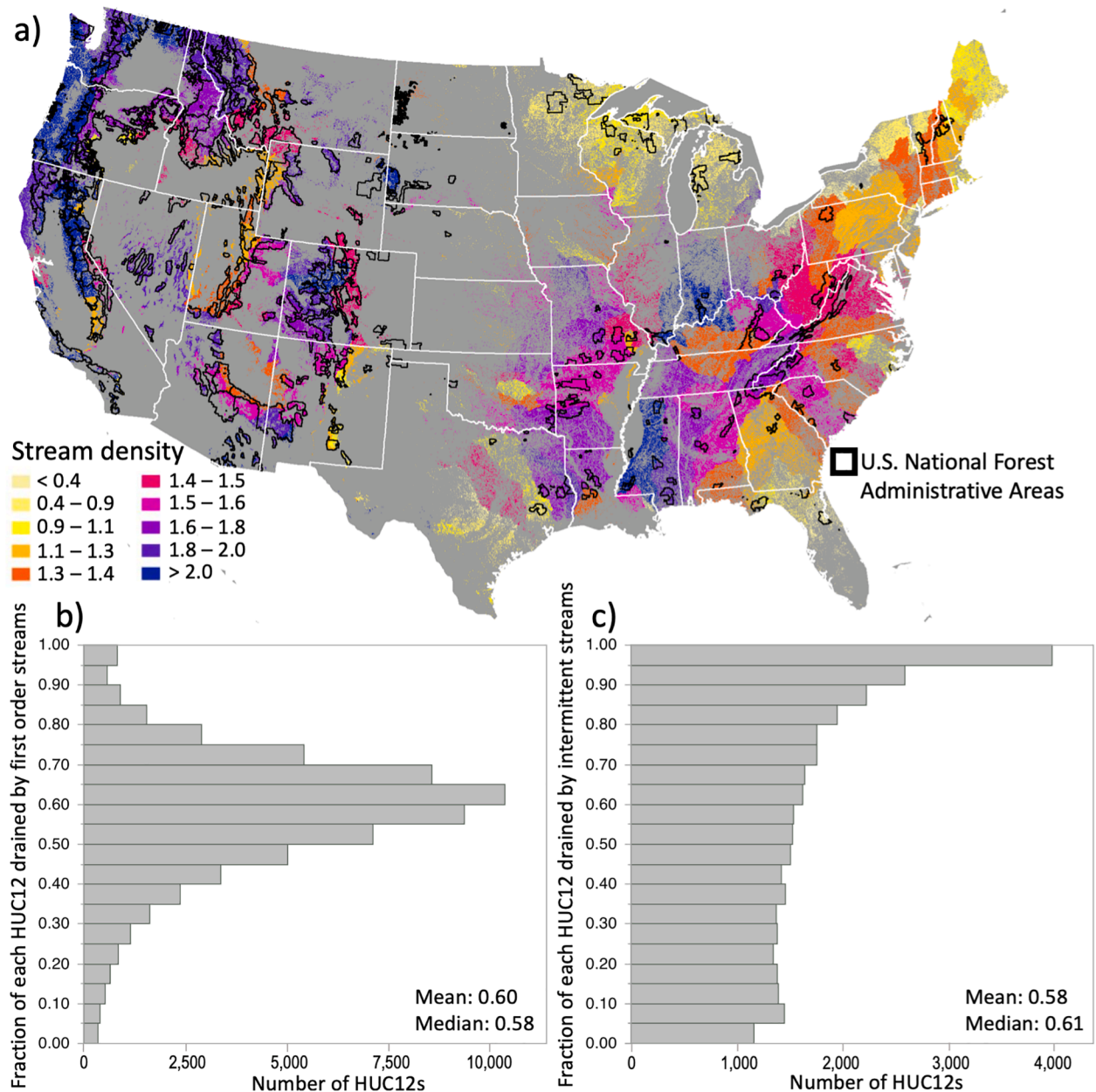


Fig. 1. Stream networks for forested watersheds of the continental U.S. showing (a) stream density (km km^{-2}), (b) fraction of forested watershed land area drained by first order headwater streams, and (c) fraction of first order streams in forested watersheds that are classified as nonperennial (intermittent or ephemeral); note that these classifications are uncertain, as described in the manuscript. Stream data from National Hydrography Dataset High Resolution (NHDHR) flowlines (USGS, 2020a) using only stream and river (Streamriver class) segments. Colored areas in (a) are forested pixels from the National Land Cover Dataset (NLCD, Yang et al., 2018), with stream densities calculated for USGS Hydrologic Unit Code (HUC) 12 watershed subdivisions aggregated to HUC4 scale for visualization. Only HUC12s with forested area > 50% are shown in (b) and (c). Black lines in (a) are boundaries of U.S. National Forest Administrative Areas. Calculations in (b) and (c) are for the same forested watersheds shown in (a), but subdivided into smaller HUC12 watershed sub-units.

1. Introduction

Forested watersheds are widely recognized as important water supply sources in temperate zones. In the United States (U.S.), streams draining land administered by the USDA Forest Service (USFS, Fig. 1a) provide more than half of the nation's water supply (Furniss et al., 2010; Brown et al., 2008). Natural resources on forested lands are managed for multiple uses such as timber harvest, grazing, mining, and recreation. Active vegetation management includes prescribed burning, pre-commercial thinning, wildfire suppression, and pesticide application. Changes in forest land uses can affect streamflow, sediment, organic matter, and thermal regimes (Wohl et al., 2015; Steel et al., 2017; Wohl

et al., 2019; Segura et al., 2020), potentially disrupt aquatic and riparian ecosystems (Anderson et al., 1976; Nisbet, 2001), and ultimately degrade water quality of managed watersheds (Binkley and Brown, 1993). Accordingly, management guidelines are developed with the intent to reduce or mitigate potential impacts of land use on aquatic and riparian habitat and downstream water quality (e.g., Aust and Blinn, 2004; Ice et al., 2004; Shepard, 2006; Croke and Hairsine, 2006; Anderson and Lockaby, 2011; Cristan et al., 2016).

A major challenge for effective stream management on forested lands is lack of knowledge regarding the full extent of stream networks (Richardson and Danehy, 2007; Bishop et al., 2008). This information is critical for determining whether forest management activities will affect

Table 1

Summary of state riparian management zone (RMZ) guidelines for perennial, intermittent, and ephemeral streams, presented as number of states within each region. The states included in the four regions are shown in Fig. 3.

RMZ Details	Perennial Streams				Intermittent Streams				Ephemeral Streams			
	West Coast (n = 5)	Interior West (n = 8)	Northern (n = 24)	Southern (n = 13)	West Coast (n = 5)	Interior West (n = 8)	Northern (n = 24)	Southern (n = 13)	West Coast (n = 5)	Interior West (n = 8)	Northern (n = 24)	Southern (n = 13)
Recommended	5	7	23	13	4	7	21	13	1	1	1	1
Required by state law or statute	4	3	6	1	3	3	4	1	1	0	1	0
Adjust for adjacent slopes	3	3	12	8	3	3	13	7	1	0	0	0
Adjust for stream width	3	0	8	2	2	0	8	1	1	0	0	0
Adjust for fish	2	1	1	1	2	0	1	1	1	0	0	0
Adjust for municipal use	2	3	3	3	2	2	3	3	0	0	0	0
Allows operations within RMZ	1	5	22	13	3	5	23	13	4	8	24	13

surface water sources and downstream water quality. Locations of smaller headwater streams are often not well documented (Meyer et al., 2007; Colson et al., 2008) even though they drain the majority of land area in forests (Fig. 1b). Most current stream inventories are based on topographic maps that have limited spatial accuracy and may not correctly classify streams into perennial, intermittent, or ephemeral categories (Fritz et al., 2013; Villines et al., 2015; Hafen et al., 2020). For the purposes of this paper, we broadly define perennial streams as flowing year-round; intermittent as flowing only part of the year, with sustained groundwater contributions allowing prolonged flow, and ephemeral as flowing primarily in direct response to precipitation with variable or no inputs from shallow groundwater sources (Costigan et al., 2016; Busch et al., 2020). Collectively the intermittent and ephemeral types are nonperennial, meaning flow is not continuous in space and time (Whiting and Godsey, 2016; Jaeger et al., 2007). Current estimates indicate that these nonperennial streams make up the majority of headwater stream length in forested lands (Fig. 1c). Flow regimes in headwater streams are sensitive to changing climate (Dhungel et al., 2016), meaning that a static flow class (perennial, intermittent, ephemeral) may not capture the range of flow conditions in past, present, and future climates.

Land management decisions are based on the widely accepted premise that ecosystem services provided by streams are important, societally relevant, and worth protecting (Martin-Ortega et al., 2015; Penaluna et al., 2017). However, most of the scientific understanding of streams and their ecosystem services is based on studies of large, perennial streams (Kovach et al., 2019). Far fewer studies have focused on how land uses impact ecosystem processes in nonperennial headwater streams (e.g., Chiu et al., 2017), with fewer still attempting to relate processes in these streams to their influence on downstream perennial waters (e.g., Warrick et al., 2005). In this review we examine: (1) how current forest management guidelines apply to nonperennial streams; (2) potential impacts of forest land uses on selected processes in nonperennial streams, with a primary focus on timber harvest impacts; and (3) information needed to incorporate nonperennial streams into water quality protection practices. We focus geographically on forested headwater watersheds of the continental U.S. (CONUS) (Fig. 1a), though parts of this review may be relevant for forested watersheds across the globe.

2. Forest management guidelines for nonperennial streams

Guidelines for contemporary forest management in the U.S. are often referred to as “best” management practices (BMPs), which focus on water quality protection from nonpoint source pollution to ensure compliance with the Clean Water Act (33 U.S.C §§ 1251; Binkley and Brown, 1993; Ellefson et al., 2001). In watersheds that support rare

species, guidelines also address aquatic and terrestrial habitat protection to comply with the Endangered Species Act.

A primary focus of forest management guidelines is establishing a management zone along stream segments in areas proposed for treatments to reduce chemical contamination, prevent increases in water temperature, and limit inputs of sediment, logging slash, and other large organic materials produced by forestry activities. Throughout this paper, we call these areas riparian management zones (RMZs), although many different naming conventions are used in management guidelines. On federal lands administered by the USFS, the National Core BMPs (USDA-FS, 2012) refer to streamside areas as aquatic management zones, and in regional guidance documents these areas have been termed riparian conservation areas, water influence zones, streamside management units, stream environment zones, and riparian reserves. We distinguish an RMZ from a “buffer”, as some forest harvest is allowed in most RMZs, whereas “buffer” typically indicates a band of vegetation left in its pre-harvest / pre-treatment condition. The term “buffer” makes no assumptions about the composition, structure, height, or density of the vegetation left adjacent to the stream other than that it is left undisturbed by direct human activities.

On National Forests, the National Core BMPs (USDA-FS, 2012) provide general guidance for designating RMZ width and managing RMZs to protect water quality and maintain stream, aquatic, and riparian function and processes. Determining stream channel type (perennial, intermittent, ephemeral) is a key component of National Core BMP recommendations, but the guidelines are deliberately nonprescriptive, allowing managers to adapt them to local conditions. For a given region or National Forest, project-specific management plans are developed depending on local features such as presence of valued aquatic biota (e.g., species listed under the Endangered Species Act), steepness of terrain, and compliance with state, tribal, and national water quality goals. RMZ designation and BMP implementation are more prescriptively directed in forest-level management plans, with recently revised plans tending to have more specific guidance than older plans. Notable exceptions to individual forest-level or project-specific plans are the Pacific Anadromous Fish Strategy (PACFISH; U.S. Forest Service and U.S. Bureau of Land Management, 1994) and the Inland Fish Strategy (INFISH; U.S. Forest Service, 1995), which are multi-agency mandates for watershed management across vast expanses of federal lands along the Pacific Coast and in the Upper Columbia River Basin, USA. PACFISH and INFISH were developed in response to regulatory proceedings of the Endangered Species Act to protect aquatic and riparian habitat for threatened and endangered salmonid fishes. These strategies amended forest plans of 20 National Forests and 10 Bureau of Land Management Field Offices, increasing protection of intermittent streams on federal lands in the Pacific Northwest and western regions of the U.S. (Henderson et al., 2005).

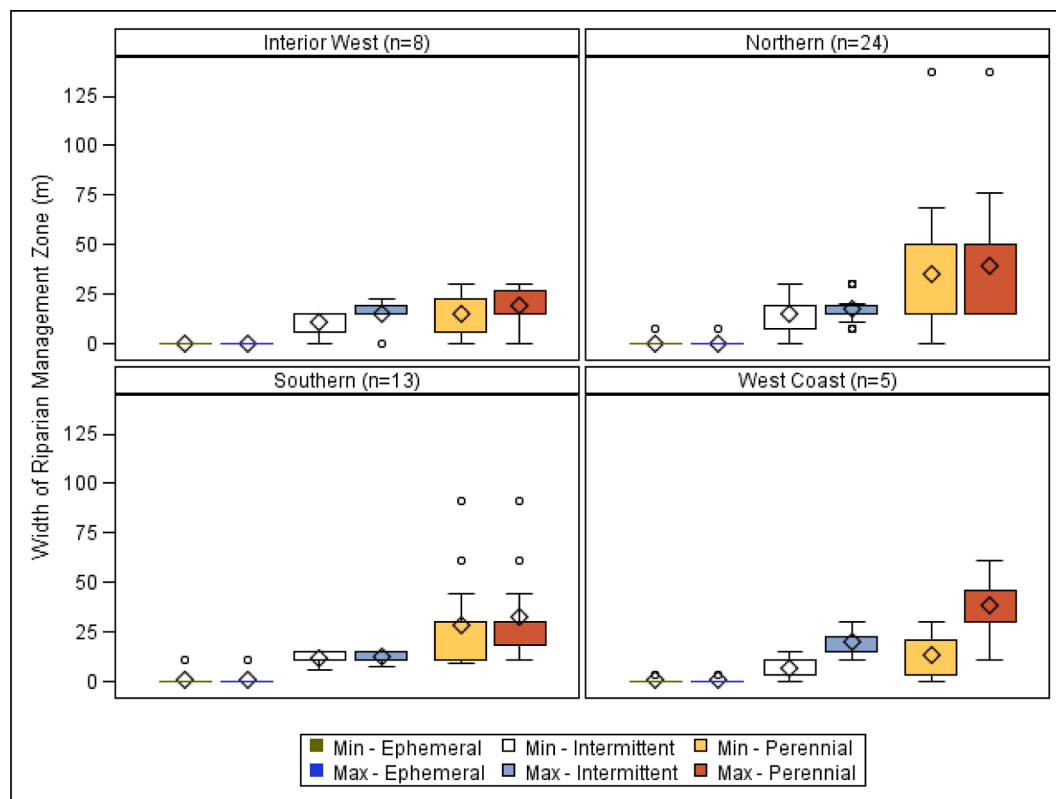


Fig. 2. Means ($\diamond$) of minimum and maximum riparian management zone (RMZ) widths surrounding ephemeral, intermittent, and perennial streams in four regions as defined by U.S. Forest Service Forest Inventory analysis (FIA, <https://www.fia.fs.fed.us/regional-offices/>, Fig. 3). Boxes represent the range in minimum and maximum RMZ widths among individual states in each region between the 25th and 75th percentile (the interquartile range, IQR); whiskers represent the spread of data that fall within 1.5 times the IQR, and outliers ($\circ$) are datapoints beyond 1.5 times the IQR.

Most state guidelines are more specific and prescriptive than the USFS National Core BMPs. We reviewed forest management guidelines by state and found that in most states, perennial ($n = 49$ states) and intermittent ($n = 46$ states) streams are explicitly or implicitly recognized as needing RMZ designation (Table 1). This is an increase in the number of states including intermittent streams in RMZ recommendations over the 40 that had these recommendations in 2001 (Blinn and Kilgore, 2001). Nearly all states provide forest practice guidebooks that tier to general requirements under the Clean Water Act (33 U.S.C §§ 1251), and approximately a quarter of states now have laws or statutes explicitly requiring RMZs for perennial and intermittent streams (Table 1). While 82% of states have updated guidelines over the past 20 years, only two states (Alaska, West Virginia) have revised guidelines to require RMZs for ephemeral streams; two additional states (Alabama, Montana) recommend RMZs for ephemeral streams. The minimum RMZ recommendations for intermittent streams have only changed modestly in the last two decades (Table 1).

Although we compare state guidelines using the perennial, intermittent, and ephemeral terminology (Table 1), these terms are not present in all state guidelines. For example, Washington's regulations refer to intermittent streams as "seasonal" streams. Similarly, California's guidelines include streams "capable of sediment transport", whether or not they continuously flow (California Department of Forestry and Fire Protection, 2020). Montana's streamside management zone law considers average duration of flow, with the RMZ requirements dependent on whether the streams flow fewer than six months per year (Rogers, 2006).

In most state guidelines, RMZ widths and allowable practices within RMZs are less protective for ephemeral and intermittent streams than perennial streams (Fig. 2). Recommended widths vary across regions and states depending on terrain steepness, stream size, fish occupancy,

and contribution to municipal water supply (Table 1). Some state recommendations for RMZs are based on the use of the stream water (e.g., Washington, Oregon, California, Idaho, Montana), with highest level of protection for fish-bearing streams and/or streams that are used for domestic drinking water (Washington Forest Practices Board, 2001; Oregon Department of Forestry, 2018; California Department of Forestry and Fire Protection, 2020; Barkley et al., 2015; Rogers, 2006). Where intermittent streams support fish or other species included in state guidelines, the RMZ requirements match those for perennial streams. For intermittent streams without fish, state RMZ recommendations range from including no RMZ requirement, to narrower RMZs, and in some cases RMZ widths similar to perennial streams. RMZ protections in Idaho depend on whether streamflow is present at the time of treatment operations, with reduced protection when intermittent stream channels are dry (Barkley et al., 2015). Guidelines for RMZs in Michigan vary with stream order, steepness of adjacent land, and public versus private ownership (Michigan Department of Natural Resources, 2018).

Most states allow limited harvest operations within RMZs of intermittent streams, with exceptions that prohibit some operations (Delaware, Idaho, California) or all operations (Utah, Nevada, Wisconsin, Washington, Oregon, Alaska). The requirements for retaining overstory trees can differ between intermittent and perennial streams (EMNRD, 2008; Wyoming State Forestry Division; South Carolina Forestry Commission; Stringer et al., 2018; Georgia Forestry Commission; Brogan et al., 2006; Tennessee Department of Agriculture, 2003; West Virginia Division of Forestry, 2018; Colorado State Forest Service, 2010). For ephemeral streams, some state guidelines (e.g. South Carolina, Kentucky, North Carolina, Tennessee, Michigan) recommend that disturbances be avoided within and near stream channels, but usually there are no RMZ requirements. The exception is West Virginia, which requires a reduced width RMZ for ephemeral streams as compared to

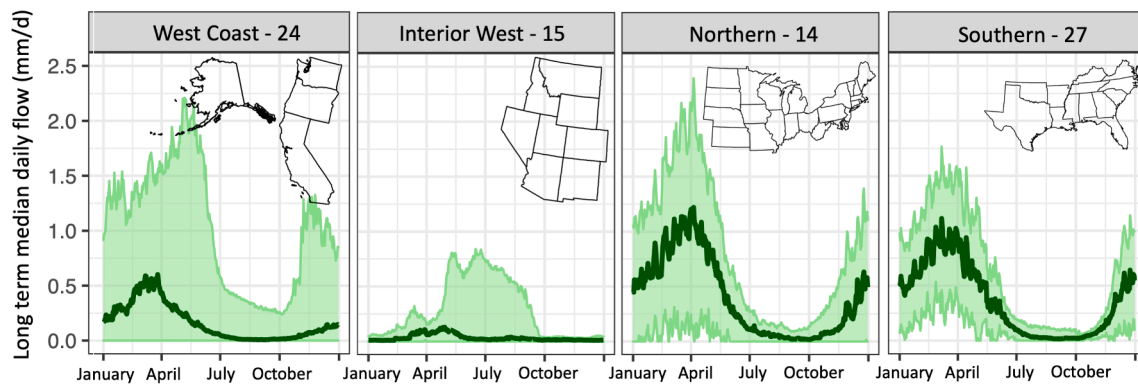


Fig. 3. Median daily flow (drainage area-normalized) for USGS reference stream gages with nonperennial flow for water years 1980–2018 (USGS, 2020b; Hammond et al., 2021). In each plot the dark line indicates the median flow for each day of year across all years of record and all nonperennial stream gages in the region, with the number above each panel indicating the number of gages used. The light green area indicates one standard deviation above and below the median. Regional subdivisions are those used by the U.S. Forest Service Forest Inventory analysis (FIA, <https://www.fia.fs.fed.us/regional-offices/>). Note, although Alaska and Hawaii are included in the West Coast region for Table 1 and Fig. 2, they are not part of the daily flow dataset (Hammond et al., 2021).

perennial and intermittent (West Virginia Division of Forestry, 2018). Finally, some states apply guidelines or requirements only to perennial streams (e.g., Vermont; Wilcox et al., 2019), do not specify the types of streams to consider (e.g., Nevada; Nevada State Conservation Commission, 1994; Nevada Code, 2010), or have no management guidelines at all (e.g., Arizona; Ice et al., 2004).

These varying guidelines and their level of detail regarding stream types pose contrasting management challenges. Where guidelines are explicit about the types of streams addressed in management plans, accurate information is needed on stream location, flow duration, and aquatic species present. Where guidelines are broader or more ambiguous, the decision to include a stream in a management plan is largely made at the discretion of the land manager. Management guidelines for RMZs included in state or federal forest management plans can vary in the degree to which guidelines are followed, as certain practices are considered voluntary and/or at the discretion of land managers. In other countries, examination of actual buffers used during timber harvest has shown region-wide patterns of poorly applied protections and infrequent adherence to minimum buffer guidelines for small streams when their application is voluntary or unmonitored (Kuglerová et al., 2020). Such lack of information about nonperennial stream location and use by biota could default to limited or no protection. Although BMP monitoring on federal, state, and private forest lands largely indicates the effectiveness of RMZs for perennial streams (Cristan et al., 2016), implementation and monitoring of BMPs has likely been biased toward perennial streams, given the general lack of BMP evaluation studies that focus on or even mention nonperennial streams. The variability in guidelines between states exemplifies how much management practices can vary between political jurisdictions, even though stream systems connect across political boundaries.

3. Impacts of land use and management on nonperennial forest streams

Land uses in uplands can affect streams if they change the inputs of water, sediment, and other materials to the stream network. The majority of upland area in forests drains into headwater nonperennial streams (Fig. 1b,c) rather than into higher order perennial streams, meaning that headwater nonperennial streams are often the first point of connection between uplands and stream networks. In spite of this, direct studies on the effects of land management on nonperennial streams are rare, with van Meerveld et al. (2020) recently calling nonperennial streams “Aqua temporaria incognita” to emphasize how little is known about them. In this section, we introduce how land use activities may alter streamflow regimes, sediment export, organic matter dynamics,

stream temperature, and biotic ecosystems of nonperennial streams.

3.1. Streamflow regimes

3.1.1. Temporal and spatial patterns

Intermittent streamflow timing is largely driven by seasonal variability in water inputs (snowmelt, rainfall) and outputs (evapotranspiration; ET). For most streams in temperate forests of the U.S., drying is most likely during the summer and fall, when potential ET is highest (Fig. 3). In west coast forests with Mediterranean climates, the summer is commonly a time of precipitation deficit, so streams sustain flow through the summer only if they are supplied by persistent groundwater sources. Many forest streams of the drier interior West are fed by snowmelt, so highest flow is most likely during spring and summer, with driest conditions in fall and winter.

Streamflow can also be spatially intermittent, typically with reduced active (flowing) stream network extent in dry times of year. In many environments, flowing channels expand and contract seasonally, with the greatest headward extent of channels during wet times of year and (or) when ET is low (Barefoot et al., 2019; Jensen et al., 2017). Other stream networks have more stable flow locations, especially where bedrock exerts a strong control on water flow paths (Shaw, 2016; Whiting and Godsey, 2016; Lovill et al., 2018). Watersheds with varying bedrock geology may have a combination of both stable and migrating flow heads (Jaeger et al., 2007; Martin et al., 2021). Downstream of flow heads, water may move to the subsurface in stream segments with highly permeable substrates such as karst or coarse sediment deposits (Ward et al., 2018; Durigetto et al., 2020). Flow can also re-emerge downstream due to changes in channel slope, topographic convergence or valley confinement (Baxter and Hauer, 2000; Jensen et al., 2017).

3.1.2. Land use impacts

Land use activities can modify nonperennial streamflow regimes if they change the timing and/or quantity of water delivery. The timing of water delivery relates to the pathways of water from uplands to streams. In most mesic temperate forests, water reaches streams through subsurface pathways (e.g., Hewlett and Hibbert, 1967), and infiltration excess overland flow is rare. Water traveling slowly through subsurface pathways sustains flow in channels after rainfall has stopped. Land uses that reduce surface infiltration capacity can change flow paths by increasing the likelihood of infiltration excess overland flow (Wondzell and King, 2003; Larsen et al., 2009), particularly where severe ground disturbance is combined with intense rainfall (Megahan et al., 1995; Meyer and Wells, 1997; Orem and Pelletier, 2016). The ground disturbances that cause this effect may be limited to unpaved roads, skid trails



Fig. 4. Examples of nonperennial forest streams showing: (a) forest road with flowing surface water; (b) channel reach filled with recent sediment deposits, where surface flow infiltrates into the coarse sediments; (c) jam of large wood changing sediment storage and flow paths in a stream reach; (d) example of organic matter (OM) sources to stream after wildfire, including ash, litter, and eventually, burned wood when trees fall into the stream channel.

(Dickerson, 1976), or other areas where heavy equipment is operated. Cable yarding, which is commonly used for timber harvest in steep terrain, keeps heavy machinery off of slopes, and yields only small areas of compaction where logs drag. After forest harvest, a range of practices has been used historically to remove logging slash and competitive brush to prepare harvest sites for replanting, including activities like broadcast slash burning and drum chopping. Such practices can reduce infiltration and increase overland flow, at least temporarily (e.g. Hewlett and Doss, 1984; Harr et al., 1975). Post-harvest restoration activities, such as ripping or mulching skid trails and other areas disturbed by heavy equipment are now routinely used to restore infiltration capacity and reduce overland flow from disturbed patches.

Forest roads may be more permanent locations with reduced infiltration and therefore greater infiltration excess overland flow. Roads can also modify flow paths by capturing subsurface flow where roads are cut into steep slopes. Flow intercepted along cutslopes can be converted to overland flow before it would have naturally reached the stream (Wemple and Jones, 2003; Burroughs et al., 1972; Megahan, 1972; Moore and Wondzell, 2005). Depending on topography, soils, and climate, some roads capture more flow than others (Wemple and Jones, 2003; Luce, 2002). If roads capture substantial flows that are re-routed directly into streams, then the presence of roads, in effect, extends the length of the channel network, especially the nonperennial portion (Wemple et al., 1996; Croke and Mockler, 2001, Fig. 4a). By conveying overland flow rapidly to streams, roads can lead to more rapid stream-flow response to rainfall.

Forest land uses can also modify the quantity of water reaching streams via changes in evapotranspiration. Trees are generally able to transpire more water than the herbaceous vegetation that grows soon after forest removal because of deeper root systems and larger leaf areas, although transpiration responses to disturbance can be highly variable

(Amiro et al., 2006). The effects of changes in vegetation on streamflow have long been examined through paired catchment studies (see reviews by Bosch and Hewlett, 1982; Brown et al., 2005), which have shown that forest clear cutting over entire mesic headwater catchments leads to increases in total annual streamflow in the years immediately following forest harvest. Increases in late summer discharge have also been observed immediately after forest harvest (Perry and Jones, 2017; Robinson and Dupeyrat, 2005; Li et al., 2018) or wildfire (Kinoshita and Hogue, 2015). These types of flow changes would likely be associated with increases in flowing channel extent, with flow persisting longer in intermittent reaches.

Forest land use changes are not always detectable in streamflow, in part based on the size of the land change relative to drainage area. Prior studies have indicated that at least 20% of a catchment would need to be impacted by vegetation change before the effect would be detectable in streamflow (Bosch and Hewlett, 1982). Headwater streamflow in locations affected by vegetation change may be more sensitive than flow in larger perennial streams, for which land use changes affect a smaller portion of total drainage area. The ability to detect and quantify hydrologic effects of disturbance also depends on the magnitude of the disturbance effect relative to variability in streamflow caused by climate, and the rate and nature of vegetation recovery (Brown et al., 2005; Adams et al., 2012). Due to the heterogeneity of forest disturbances, climates, and hydrologic processes, many types and time scales of flow regime changes are possible. For example, conversion of old-growth forest to younger aged forest can cause decreased late-summer discharge in the later decades of long-running paired watershed studies because young trees may transpire more water than old-growth trees (Kuczera, 1987; Moore et al., 2004; Delzon and Loustau, 2005). Thus as forests recover from disturbance, baseflows may decline, and even be lower than the pre-disturbance condition (Perry and Jones,

2017; Segura et al., 2020; Safeeq et al., 2020; Coble et al., 2020). Natural disturbances that cause substantial forest dieoff may lead to increases, no change, or even decreases in streamflow (Adams et al., 2012; Goeking and Tarboton, 2020). Thus the effects of forest land uses on non-perennial streamflow regimes are likely to be highly variable and site-specific.

Some forested lands include areas of active or past mining, which can dramatically change the topography and alter the contributing areas to downstream rivers (Ross et al., 2016; Jaeger and Ross, 2021). Underground mining can cause land subsidence, which affects both the water reaching streams and the topographic gradients between uplands and streams (Sidle et al., 2000). In some cases, streams may be diverted below ground (Slaughter et al., 1995), while elsewhere streams may gain flow due to connections with groundwater that did not exist prior to mining (Morrison et al., 2018). The legacy effects of mining (surface and underground) and reclamation activities on streamflow patterns are highly variable and can persist for decades following mining and reclamation activities (Dickens et al., 1989; Bonta et al., 1997; Miller and Zégre, 2014). Recent modeling of reclaimed watersheds that had been surface mined indicate that changes in flow paths caused by mining would reduce streamflow during low flow periods under future climate scenarios, although this response can be mitigated by implementing different forestry reclamation approaches (Williamson and Barton, 2020).

While most forest disturbances are followed by vegetation regrowth, not all disturbances are transient. For example, although forest harvest patches are usually replanted rapidly, the road network used to access cutting units is often maintained, in which case the effects of roads on watershed hydrology persist over longer time periods. Other forest land uses such as campgrounds, day use areas, parking areas, field stations, and ski areas also have more persistent changes in forest cover. These more permanent land use conversions represent a small (<1%) portion of forested land area, but they can have localized effects on headwater streamflow regimes. For example, ski areas have been associated with sustained changes in streamflow (Wemple et al., 2007), channel network extent, and adjustments of channel morphology (David et al., 2009).

3.2. Sediment regimes

Sediment and streamflow regimes are highly inter-connected. Sediment can reach streams via erosion during overland flow, mass movements, or bank erosion (MacDonald and Coe, 2007). In undisturbed landscapes, nonperennial streams may store a large fraction of sediments produced during major storms and release these sediments gradually to downstream reaches (Dieterich and Anderson, 1998; Dewey et al., 2020), potentially limiting or moderating erosion and habitat degradation downstream. In contrast, erosion from overland flow can lead to rill and gully formation, expansion of the channel network, and more downstream sediment export (Istanbulluoglu et al., 2002; 2003; Bastola et al., 2018; Wilson et al., 2021). Although RMZs around streams are often effective at intercepting sediment from upland diffuse overland flow, concentrated flow in gullies and rills can breach RMZs (Rashin et al., 2006; Lakel et al., 2010). Where rills and gullies connect to streams, their sediment inputs can be as high as those found in streams without RMZs (Gomi et al., 2006), creating substantial changes in downstream sediment loads (Fig. 4b). If the excess overland flow that forces rill and gully incision is temporary, and vegetation recovers after disturbance, rills and gullies may disappear in a few years as side walls collapse, and channels refill with sediment (Wohl and Scott, 2017).

Roads are a ready source of chronic fine sediment to streams (Reid and Dunne, 1984; Luce and Black, 1999) and can be associated with altered stream channel morphology (Pechenick et al., 2014). Road decommissioning practices such as ripping can help restore infiltration capacity and reduce overland flow and erosion, although even after decommissioning, roads may still have reduced infiltration and elevated surface erosion compared to undisturbed forests (Luce, 1997; Sosa-Pérez

and MacDonald, 2017).

Reducing surface disturbance in riparian zones is often a focus of forest management guidelines because these zones are adjacent to nearby streams. Movement of skidders or road construction equipment through riparian areas is a well-recognized source of sediment to streams, leading to restrictions on logging equipment use in RMZs (e.g. Keim and Schoenholtz, 1999). Recreational off-road vehicle use in riparian areas and stream crossings can also elevate sediment delivery to streams (e.g. Marion et al., 2014), particularly activities like “mudding” (a recreational activity involving driving off-road vehicles through mud) that disrupt soils and promote erosion of fine sediments.

Mass movements are another cause of changing sediment regimes in stream networks, in some cases leading to the greatest geomorphic changes following vegetation removal in steep uplands (Montgomery et al., 2000; Jackson and Roering, 2009). The frequency of mass movements can increase after logging (Sidle et al., 1985; Brardinoni et al., 2003; Benda et al., 2005) and along forest roads (Wemple et al., 2001; Montgomery, 1994). The sediment evacuated from steep terrain may cause substantial channel reorganization downstream by diverting or blocking channels, forming deposition fans or sediment wedges, and leading to changes in channel form (Hoffman and Gabet, 2007; Benda, 1990; Benda and Dunne, 1997). Mass movements can also lead to establishment of new channel heads by creating zones of groundwater flow convergence (Dieterich and Dunne, 1993; McNamara et al., 2006). While landslides and debris flows can be large sediment sources in many areas with steep topography, they are episodic and infrequent. Chronic, smaller magnitude sediment production is often dominated by bank erosion (Hassan et al., 2005).

Changes in the patterns of deposition and scour along streams may affect patterns of flow intermittency by shifting how water moves between the surface and subsurface. For example, deposition of fine-textured sediment within a stream can reduce hydraulic conductivity of the channel bed and hyporheic exchange with groundwater (Wharton et al., 2017). Locations of large sediment deposits can become zones of water infiltration and reduced flow duration (Ward et al., 2018; Fig. 4b).

3.3. Organic matter

Organic matter (OM) inputs to headwaters may come from wind-thrown trees, litter fall from riparian and upland vegetation, overland flow or mass wasting, leachate from organic matter in the subsurface, and dispersal of soil and canopy fauna into streams (Wipfli et al., 2007). Riparian inputs of OM per unit stream area generally decrease with increasing stream size (Connors and Naiman, 1984), making OM input particularly important in headwater streams. As with sediments, headwater nonperennial streams tend to store large amounts of OM relative to similar sized perennial streams (Dieterich and Anderson, 1998; Acuña et al., 2004). Moreover, OM decomposition rates in nonperennial streams tend to be slower due to low microbial growth rates and little physical breakdown during dry periods, as well as reduced densities of macroinvertebrate shredders (Richardson, 1990; Sabater et al., 2016). However, during flowing conditions, the resulting large standing stocks of accumulated benthic OM become available to downstream perennial reaches either gradually through seasonal flow or episodically during storm events, potentially providing increased stability to the detrital-based food webs in headwater stream networks over annual or decadal time periods (Richardson et al., 2005; Larned et al., 2010).

Coarse organic material in the form of large branches, logs, chunks of wood, and roots, can directly influence channel morphology and sediment characteristics (Fig. 4c). Studies on coarse OM specific to nonperennial streams are extremely sparse (but see Wohl et al., 2018; Galia et al., 2020 for drier climates), though prior research on forested headwater streams may not have distinguished between perennial and nonperennial streams (e.g., May and Gresswell, 2003). Because many nonperennial streams are headwaters with lower flow and smaller channel dimensions, they tend to retain much of the coarse wood that



Fig. 5. Thin RMZ retained around a nonperennial stream in an area of timber harvest.

falls in them, and more of it may initially be suspended over channels. However, episodic flash flood and debris flow events can transport substantial volumes of wood out of these channels to downstream reaches. Given the nature of these processes, we might expect the wood balance of nonperennial streams to be dominated by local inputs and decomposition, but some may occasionally release large pulses of accumulated wood to downstream segments. The changes in channel morphology caused by large wood can alter in-channel biological communities, sediment storage, and the movement and transformation of nutrients and other materials (Blaen et al., 2018; Short et al., 2015; Wipfli et al., 2007).

Smaller forms of organic material, including particulate and dissolved OM, contribute to local and downstream metabolic processes and carbon cycling (Richardson, 2019a; 2019b), with dissolved OM most likely to be transported downstream. Fine particulate and dissolved OM can be derived from direct instream growth or allochthonous inputs from riparian vegetation. Macroinvertebrates are primary consumers of fine particulate OM, and they may subsequently become food for predators. The presence of these invertebrates and therefore the breakdown of OM may be reduced when nonperennial streams are dry (Datry et al., 2011), with heterogeneous decomposition as flow paths become fragmented (Abril et al., 2016). Multiple studies have found that stream wetting and drying patterns also affect dissolved organic carbon dynamics (von Schiller et al., 2015; Hale and Godsey, 2019). Dissolved OM is available to microorganisms and constitutes a demand for oxygen that can limit habitat suitability in some intermittent streams (Larsen and Woelfle-Erskine, 2018).

Land use activities can affect all forms of OM input with subsequent implications for in-channel or downstream OM processes. The primary mechanisms of change are: 1) altering the proximal forest canopy that provides OM inputs to the stream (Fig. 4d); 2) increasing sunlight on the stream allowing greater algal growth, and 3) altering dissolved organic carbon inputs from runoff and shallow groundwater inputs from adjacent forests. Direct removal of vegetation adjacent to stream channels will substantially reduce particulate OM until vegetation regrows (Webster et al., 1992), with an even longer delay for large wood inputs (Bilby and Likens, 1980; Verry et al., 1999). Log jams may become century-scale legacies of past riparian harvest on large OM (Wohl and

Goode, 2008). Roots from streamside trees also influence channel morphology; root loss after forest harvest can lead to bank failure, which can impact sediment storage and surface water expression. Changes in dissolved organic carbon inputs to streams from adjacent forest areas through runoff and leaching have complex responses to harvest, with reports of both increases and decreases depending on initial organic matter loads in the stand, moisture dynamics, changes in temperature, and time following harvest (e.g. Meyer and Tate, 1983; Laudon et al., 2011; Schelker et al., 2013; Lajtha and Jones, 2018).

3.4. Temperature

Perennial streams have been the primary focus of stream temperature research, although their temperature dynamics may be quite different from those of smaller nonperennial headwater streams (Moore et al., 2005). High stream temperatures are a water quality concern because they can limit habitat suitability for aquatic species. High stream temperatures are most likely during warmer seasons with lower flow where incoming solar radiation is a dominant energy source (Webb and Zhang, 1997; Roon et al., 2021). Consequently, loss of riparian canopy from timber harvest, removals of hazard trees, or other activities can lead to increases in warm season stream temperature (e.g. Poole and Berman, 2001).

Concerns over solar radiation and stream heating have been a primary motivation for suggesting or requiring RMZs along perennial streams. However, there have been many questions about the utility of RMZs for nonperennial channels, leading to inconsistent, optional, or ineffective application of RMZs. One example is the “compromise” of using narrower RMZs for harvest around nonperennial channels since there seems to be no “stream” to shade, and offering some nod to other values from riparian forests. Unfortunately, the riparian forest does not exist independently of the surrounding forest stand, and the thin strips prescribed for RMZs around nonperennial streams may be more vulnerable to blowdown (e.g. Jackson et al., 2001 and Fig. 5).

In some forest headwater streams, flow is supplied by shallow groundwater inputs and has relatively little opportunity for heating along the channel; in these locations, stream temperatures may be less sensitive to increased solar energy inputs from harvest or fire (e.g. Story

et al., 2003; Janisch et al., 2012; Kelleher et al., 2011; Mayer, 2012; Luce et al., 2014). Even under low flow conditions in nonperennial channels, surface water heating by solar radiation may be limited if the water is sourced by groundwater and is spatially intermittent. In some cases, subsurface flow maintains longitudinal connectivity along channels even as surface water becomes separated into disconnected pools (e.g. Ward et al., 2018). Because solar heating of subsurface water is relatively minor (e.g. Story et al., 2003), shallow groundwater inflow can cool stream temperatures during summer (Wigington et al., 2006; Larsen and Woelfle-Erskine, 2018). This can allow surface water along spatially intermittent streams and stream junctions with seemingly “dry” channels to provide locally cold habitat (Ebersole et al., 2001; Snyder et al., 2015). Temperatures of shallow subsurface water can also be sensitive to land use change such as loss of canopy to harvest or wildfire; however, the warming of groundwater is generally less than the direct warming of stream water by increased solar radiation, so even the warmed shallow groundwater inputs are still a cooling influence on peak stream temperatures (Guenther et al., 2014).

Because of the importance of groundwater for stream temperature, activities that change surface–subsurface exchanges of water along stream corridors can influence temperature regimes. Compaction of ephemeral channels during harvest (e.g. Burns, 1972), siltation of the streambed reducing down-valley transmissivity, and channel scour removing the hyporheic zone (e.g. Dunham et al., 2007) can each reduce hyporheic zone subsurface flow. This forces more flowing water to be exposed on the surface to solar radiation. Less is known about overland flow influences on stream temperatures during rain storms in forested ecosystems, although this can cause temperature spikes during summer rains in urban systems (e.g. Nelson and Palmer, 2007). Although these examples provide some insight into how disturbance may affect nonperennial stream temperatures, there is neither a formal framework nor substantial focused research on temperature in headwater nonperennial streams and their overall contribution to thermal regimes downstream perennial reaches.

3.5. Biota

Headwaters, including nonperennial streams, are vital components of upland ecosystems, potentially regulating the spatial and temporal distribution of suitable physical environmental conditions and ecosystem processes that influence terrestrial and aquatic biota (Richardson and Danehy, 2007; Studinski et al., 2012). Consequently, human-induced changes to the landscape that alter the amount, predictability, spatial distribution, and connectivity of headwater habitats can affect not only the species that intermittently use or inhabit these periodically dry stream channels, but also the species downstream in the perennial stream network (Datry et al., 2014; Leibowitz et al., 2018). Here we focus on the importance of nonperennial streams for aquatic biodiversity in general and then consider influences downstream specifically for fish, which are often the focus of management guidelines.

At the reach scale, nonperennial streams typically support lower aquatic macroinvertebrate and fish species diversity than perennial reaches due to the effects of drying on habitat availability (Poff and Ward, 1989; Stanley et al., 1997). However, recent evidence suggests that when semi-aquatic and terrestrial flora and fauna are included, biodiversity within and adjacent to nonperennial reaches is often equal to or higher than that observed for comparable perennial reaches, particularly in landscapes where seasonal drying is predictable and extensive (Larned et al., 2010). For instance, in arid landscapes, nonperennial stream valleys are oases that frequently support more productive and diverse vegetative communities than the surrounding uplands, although the processes behind these responses are not entirely clear (Katz et al., 2012). In turn, these communities create more favorable microclimates that provide primary habitat, breeding areas, temporary refuges, and movement and migration corridors for biota. Nonperennial streams can be important habitats for terrestrial

invertebrates, amphibians, reptiles, birds, and mammals (Corti and Datry, 2016; Sánchez-Montoya et al., 2017).

Across river networks, nonperennial stream habitats can have a disproportionately high influence on beta- and regional diversity of both aquatic macroinvertebrate (Valente-Neto et al., 2020) and fish (Rogosh and Olden, 2019) communities. Although not fully understood, the patterns of aquatic community diversity at least partly depend on complex interactions between the length of the drying period, the spatial topology of drying within river drainages, and the predictability of drying over time (Sánchez-Montoya et al., 2018), all of which are vulnerable to changing land use. The distributions of lotic (flowing water), lentic (isolated pools), and terrestrial (dry) habitats shift seasonally thereby increasing habitat heterogeneity. Differences in communities in each phase of wetting and drying increase biodiversity at larger scales over annual cycles (Datry et al., 2014; Stubbington et al., 2017). Where seasonal drying is predictable, it can exert strong selection pressures that favor specialized behavioral, morphological, physiological, or life history adaptations that increase tolerance or resilience to drying (Lytle and Poff, 2004; Walters, 2011), sometimes resulting in higher rates of endemism and regional biodiversity (Meyer et al., 2007).

Despite the importance of nonperennial streams in maintaining biodiversity, management guidelines have focused primarily on the extent to which headwater habitats are used by fish or influence fish downstream. The role of nonperennial streams for fish has not been extensively studied in forested ecosystems (Richardson and Danehy, 2007), although in arid portions of the U.S. fish are strongly dependent on them (Minckley and Deacon, 1991; Perkin et al., 2017). Here we highlight a selected range of examples across forested ecosystems in the U.S. that demonstrate the importance of nonperennial streams for fish.

Although fish are often absent from nonperennial streams during low flow periods, several studies indicate that they do use intermittent streams seasonally. In the northwestern U.S., fish, including salmon and trout, are known to track stream network expansions (Erman and Hawthorne, 1976; Woelfle-Erskine et al., 2017; Wigington et al., 2006). Erman and Hawthorne (1976) reported that 39–47% of nonnative rainbow trout (*O. mykiss*) spawned in a single intermittent tributary to a perennial stream in the eastern Sierra Nevada Mountains. In this study, researchers found that egg incubation, emergence, and emigration of juveniles to perennial streams occurs within the seasonal window when nonperennial streams are flowing. Emigration from these systems has not been studied extensively, but one study of eight native fish species in forested streams of the southeastern U.S. reported that the probability of emigration increased as stream networks contracted, and stream flows became intermittent (Albanese et al., 2004).

Use of nonperennial streams by many fish species in forested systems can pose important tradeoffs. These streams represent a large area of potential habitat, thus supplementing what is available to fish within the perennial network (Schlosser, 1995). In some cases, use of intermittent portions of the network allows species to avoid adverse ecological interactions with members of their own species (e.g. intraspecific competition) or other species more characteristic of the perennial network (Meyer et al., 2007). However, use of intermittent streams by fish entails risks, such as the chance that stream segments will become disconnected, dry, or otherwise unsuitable. For example, Hwan and Carlson (2016) reported that increasing intermittency was associated with declining survival in juvenile trout and salmon in a northern California stream. Thus it is not clear when use of nonperennial streams represents a net benefit to fish (e.g., Battin, 2004; Richardson, 2019a; 2019b). More research is needed to evaluate the costs and benefits of use of nonperennial streams by fish and other biota as well as the role of these streams in providing habitat and supplying cold water or trophic subsidies for different species in the context of the full range of stream types in a channel network (Richardson and Danehy, 2007; Ebersole et al., 2015).

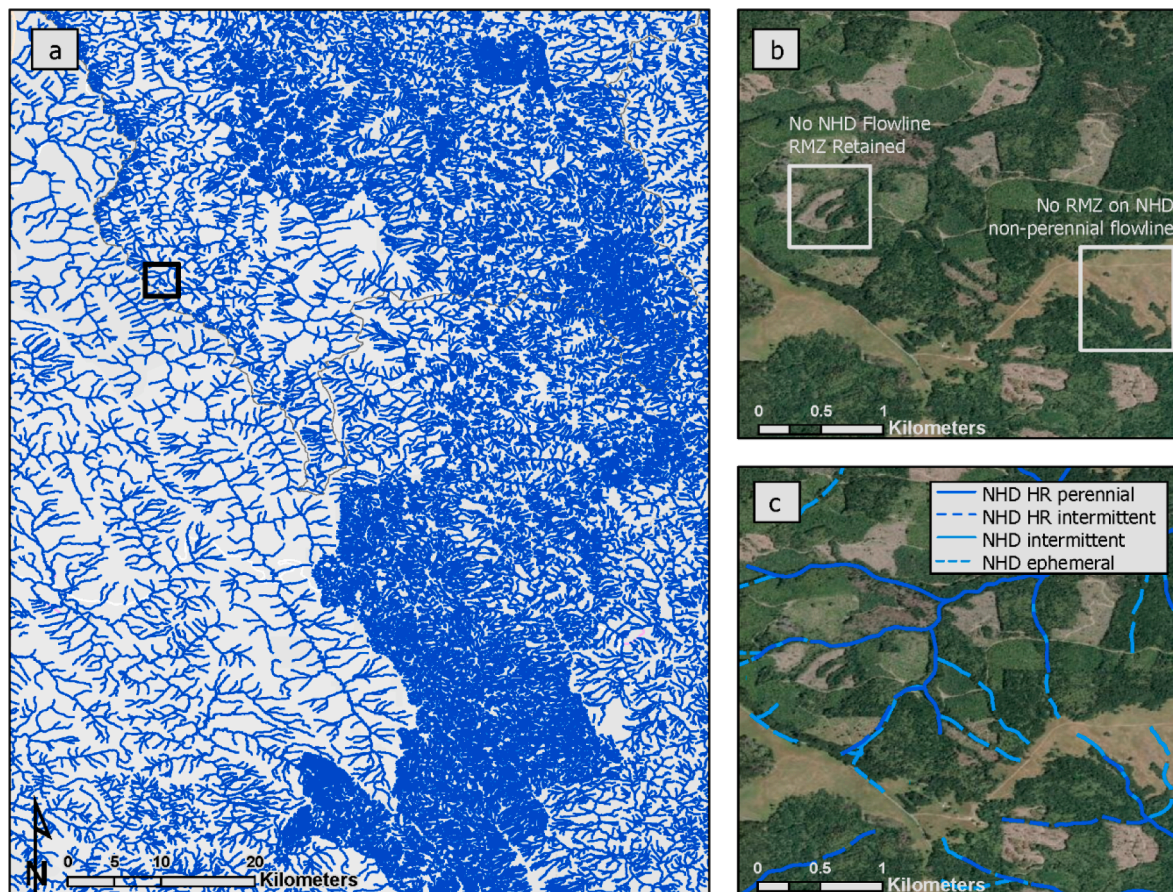


Fig. 6. Example challenges in using geospatial datalayers for management plans: (a) Inconsistencies in mapped stream density within the NHD dataset; (b and c) examples of RMZs compared to NHD HR flowlines. Some flowlines have no evident RMZ, which could be because no stream was evident in the field along these channel segments. Other locations have RMZs even though the NHD does not indicate a flowline.

4. Incorporating nonperennial streams into forest management plans

Our review and others highlight some examples of water, sediment, and organic matter connectivity between stream types and the importance of nonperennial streams for aquatic biota (Fritz et al., 2018; Leibowitz et al., 2018). Because of this connectivity, integration of nonperennial streams into forest management decisions would provide more protection for stream networks. The key aspect of management we have highlighted in this review is RMZs. Determining where to establish RMZs involves: (1) identifying nonperennial stream locations; and (2) determining stream flow duration.

A stream channel is an incised feature with a defined bed and banks (Dietrich and Dunne, 1993) generally with evidence of scour or sediment deposition from recent surface flow (Montgomery and Dietrich, 1988). If flowing water is not present, evidence of recent flow may include fluvially transported sediments, dried algae, or mesic vegetation that is distinct in species composition and/or phenology compared to surrounding areas. In many nonperennial channels, these features are clearly visible; however, determining if a feature is a true channel is more ambiguous in other areas. For example, legacy gullies can persist for decades to centuries on the landscape without active flow; they have defined beds and banks but no recently transported sediments. Transient saturated areas may not have any clear incised channel feature (Rashin et al., 2006), even though they clearly have surface and groundwater connectivity to downstream channels. Thus the interpretation of channel presence/absence might require subjective decisions about the sensitivity of the feature to disturbance and its possible downstream impacts. For example, if a legacy gully is downstream of a heavily

disturbed area that could produce infiltration excess overland flow, then an RMZ might help prevent reactivation of the gully.

Channel locations are frequently obtained from geospatial datasets. In the U.S., stream network maps are available from the National Hydrography Dataset in both Medium Resolution (NHD MR, 30 m) and High Resolution (NHD HR, 10 m) (<https://www.usgs.gov/core-science-systems/ngp/national-hydrography>). Because of the finer resolution of the NHD HR, this dataset generally includes more headwater streams, often considerably more. While NHD datasets are useful for illustrating regional differences in stream types (Fig. 1), they were not created in the same way across the country and can have boundary effects where stream densities vary between adjacent watersheds (Fig. 6). Field evaluations of these flow lines have found that they miss headwater streams in some regions, with prior studies reporting > 200% lower stream lengths in high resolution NHD compared to observations (Fritz et al., 2013; Villines et al., 2015; Fig. 6), while over-representing the stream network extent in others (Martin et al., 2021). There is an active stewardship program specifically aimed at updating stream information (<https://www.usgs.gov/core-science-systems/ngp/national-hydrography/stewardship-and-community>), and managers conducting field visits can therefore update NHD based on more detailed field reconnaissance of streams.

In addition to NHD flowlines, topographic and other geospatial data may be used to estimate stream channel locations. Techniques for mapping channels from topographic data include statistical and terrain morphology methods that search for incised features (Passalacqua et al., 2010; Sofia et al., 2011; Clubb et al., 2014; Hooshyar et al., 2016), flow routing algorithms (e.g., Moore and Grayson, 1991; Costa-Cabral and Burges, 1994; Tarboton, 1997), and topographic wetness indices (e.g.,

Beven and Kirkby, 1979; Barling et al., 1994; Hjerdt et al., 2004). These approaches have been combined with surface water features to estimate depth to groundwater, saturated areas, and potential expansion areas of surface channel networks (de Alwis et al., 2007; Ågren et al., 2015). However, topographic data alone are often insufficient for mapping stream channel networks accurately (e.g., Helmlinger et al., 1993; Orlandini et al., 2011; Hastings and Kampf, 2014) because they can miss the heterogeneity in flowpaths caused by variability in subsurface properties or by storage, infiltration, or barriers along surface flow paths (Bracken and Croke, 2007). Consequently, to design effective management plans, field site visits are usually necessary to identify surface water flow paths and their connectivity to downstream waters.

If project planning stratifies RMZs by stream channel type (perennial, intermittent, ephemeral), correctly identifying stream type poses an additional challenge. The NHD provides channel type classes, which were mainly derived from the cartographer stream type interpretation for USGS 1:24,000 topographic maps. These maps generally used solid lines for perennial streams and dashed lines for intermittent and ephemeral streams (Fishburn and Allord, 2017). Although these classes are often the best available information, classification accuracy is a notable concern because of the potential geographic inconsistencies in methods used to identify intermittent and ephemeral streams (Fig. 6). Stream type determinations are, in many cases, decades old and no longer accurate (Hafen et al., 2020).

Decisions about whether or not to apply RMZs to headwater nonperennial streams face several trade-offs. Where stream networks are dense, meaning a high length of stream per area (Fig. 1a), applying RMZs to all streams may be costly or infeasible; on the other hand, preferentially applying RMZs only to certain types of streams may require more extensive field work to determine stream type during project planning. The subjectivity in determining stream types may partly explain why implementation of RMZs is not always well aligned with management guidelines (Kuglerová et al., 2020; Fritz et al., 2020). Further, in cases of severe disturbance, erosion and mass movements can lead to creation of new channels that would not have been mapped as channels using pre-disturbance field assessments or topographic data. Thus, in addition to identifying pre-disturbance channels, managers could aim to identify locations that could develop flow and sediment connections to downstream waters. This may include topographic hollows likely to saturate during wet conditions or steep convergent slopes susceptible to rilling and gullying. Rather than prescribing fixed RMZ requirements by channel type, management plans could build on holistic watershed assessment and emphasize interventions most likely to minimize stream changes across the full channel network. Because of the heterogeneity and complexity of hydrological processes, it may not be realistic to identify fixed guidelines that apply to all landscapes. This implies the need for managers to be trained in the field, where they can observe flow locations and patterns and develop management guidelines that are most appropriate for each unique landscape.

5. Conclusions

Nonperennial headwater streams are ubiquitous on forested lands, comprising the majority of stream length. While these streams clearly influence physical and biotic processes throughout stream networks, they have proven challenging to address in a management context. Even basic information regarding the locations of nonperennial stream channels and their geomorphic and hydrologic persistence remains difficult to resolve. Accordingly, policies for managing nonperennial streams vary widely. To facilitate the path forward to addressing these issues, we conclude with a list of key questions that emerge from this review:

1. How can we identify locations within forested watersheds that are most likely to develop surface flow connectivity to stream channels after disturbance?

RMZs are most needed in locations that may produce overland flow and surface erosion after land disturbance. We need observations from streams in a variety of landscapes to determine what factors drive upland-stream connectivity and stream network expansion, both in undisturbed conditions and following different types of chronic and episodic disturbances.

2. What are the most effective methods for accurately identifying locations of stream channels and categorizing their flow durations on managed forests?

New developments in remote sensing, ground-based surveys, physically-based models and statistical models offer promising new opportunities to address this most basic question about nonperennial streams (review in Shanafield et al., 2021). Targeted efforts through community sourced field data on headwater streams (Kampf et al., 2018; Njue et al., 2019), including qualitative flow/no flow observations, can be a useful approach to meet data scarcity challenges in this portion of the stream network where streams are abundant, but data are limited. Widespread data collection is needed to improve maps of nonperennial streams across the broad range of physiographic conditions in forests.

3. To what extent do changes in flow, sediment, organic matter, and temperature regimes in nonperennial channels propagate downstream?

Nonperennial stream processes affect the larger perennial streams that are often the focus of management plans. Spatial and temporal dynamics of stream ecosystem components are inter-connected across stream networks. System-level research is needed to explore these dynamic processes in a variety of forest and stream types, both with and without management interventions.

4. To what extent do species of concern rely on nonperennial headwater streams?

Responses of aquatic and semi-aquatic species to nonperennial stream changes are difficult to anticipate, as their dependencies on these streams have not been well-studied. This equates to uncertainty regarding the vulnerability and adaptive capacity of these species to changing climate (e.g., Kovach et al. 2019) and a need for studies examining reliance of species on different stream types.

5. Where recommended, how are best management practices applied in managed forests near nonperennial streams, and how effective are these practices for protecting water quality and ecosystem services?

Relative to perennial streams, evaluations of BMP implementation for nonperennial streams are lacking. Additional monitoring studies are needed to examine RMZ effectiveness across the range of stream types and RMZ sizes. Such studies could inform decisions about which management practices to apply along nonperennial streams.

6. How will changing climate, particularly shifts in temperature and precipitation regimes, impact the spatial and temporal distribution of nonperennial streams, and how will semi-aquatic and aquatic species respond?

Nonperennial streams are sensitive to changes in temperature and precipitation, with shifts towards increased drying more likely in locations with reduced snowpack and/or reduced summer precipitation (e.g. Godsey et al. 2014; Kormos et al. 2016; Wuebbles et al. 2017). In contrast, locations with increasing precipitation / decreasing aridity may experience longer flow durations (Hammond et al., 2021). These climate-induced streamflow changes are not directly within land manager control, but understanding them is essential for developing

management strategies that maintain the resilience of streams to change. Improved understanding of all aspects of climate vulnerability in these systems could help managers craft effective climate adaptation strategies (Crausbay et al. 2020).

These broad questions have yet to be investigated systematically for nonperennial forested stream networks. Addressing them can help inform practical issues related to identifying stream types as well as shape future management guidelines. Although current management practices in the U.S. tend to include more protections for perennial than nonperennial streams, protecting nonperennial source waters may be most beneficial for the channel network as a whole because these streams are often the first point of connection between uplands and the aquatic system. Any stream in a channel network has the potential to impact ecosystem services in downstream reaches, so excluding nonperennial headwater streams from management plans can mean missing a substantial source of potential impairment to receiving waters. Streams are not static features but rather adjust to conditions within the watershed and the episodic disturbances that shape channel form. This means that streamside management in forests requires adaptive approaches that address both current and potential future changes along stream corridors.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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