Chapter 5

Sediment and Turbidity

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Turbidity measures water clarity by the degree to which light is scattered by suspended solids in the water column. It is often the most variable of all water quality constituents in the drinking water supply (Crittenden et al. 2012). Turbidity is used for process control and regulatory compliance, but also as an indicator of other water quality concerns, such as bacteria, Giardia cysts or Cryptosporidium oocysts (Crittenden et al. 2005). Turbidity does not necessarily indicate increased concentrations of pathogens, but the suspended solids provide refuge sites for pathogens that make raw water more resistant to disinfection. Turbidity is also used as a surrogate for suspended sediment using established site-specific relationships.

Elevated sediment concentrations and the associated turbidity increase treatment costs and make it difficult for water treatment operators to provide safe drinking water

(AWWA 1990; Borok 2014). Suspended sediment, including multiple solutes such as organic matter, can:

- Bind water contaminants and facilitate the transport of nutrients, heavy metals, pesticides and other toxic chemicals (Lick 2008; Bladon et al. 2014; Emelko et al. 2016);
- Facilitate downstream pathogen transport (Dorner et al. 2006; Droppo et al. 2006; Wu et al. 2009);
- Reduce the effectiveness of disinfection treatments (Lechevallier et al. 1981; Emelko et al. 2011; Leziart et al. 2019);
- Contribute to the formation of disinfection byproducts (Krasner et al. 2006; Singer 2006; Krasner 2009); and
- Produce unpleasant taste and odor problems that can dramatically erode public confidence in drinking water safety (McGuire 1995; ODEQ 2010; Kehoe et al. 2015).

While most treatment plants in Oregon have the capacity to remove sediment and other turbidity-causing constituents from source water, effective turbidity reduction is primarily determined by the treatment technology in each plant (USEPA 1999; ODEQ 2010). Conventional treatment plants with advanced filtration systems can treat water with high and variable turbidity levels (more than 50 Nephelometric Turbidity Units, NTUs). However, these systems are typically too expensive for most small communities in Oregon (ODEQ 2010). Consequently, many utilities in Oregon rely on pressurized filtration or slow sand filtration, which can be compromised at relatively low turbidity levels (e.g., less than 10 NTUs). In these cases, some Oregon utilities have installed expensive filtration systems, but these can result in greater use of flocculent and coagulant with increased turbidity, resulting in increased costs to communities (ODEQ 2010; Borok 2014).

5.1. Effects related to access and harvesting

Suspended sediment has important influences on physical, chemical and biological processes in streams (Lisle 1989; Gomi et al. 2005; Withers and Jarvie 2008). From a community water supply perspective, elevated sediment loads and associated turbidity can create challenges for the drinking-water treatment process by reducing the effectiveness of chlorination, increasing the likelihood of taste and odor issues, decreasing the operational life span of reservoirs, and increasing treatment costs (Emelko et al. 2011; Hohner et al. 2016). Increased suspended sediment and turbidity in streams also create many negative effects on aquatic ecosystem health (Newcombe and Macdonald 1991; Goode et al. 2012). As such, turbidity and associated sediment are considered primary pollutants, which are regulated in finished drinking water under the federal Safe Drinking Water Act (USEPA 2004; Borok 2014). In recognition of the importance of maintaining high water quality from source water catchments to help achieve the drinking water standards, turbidity water quality standards have also been developed (OAR 340-41-0036). The turbidity water quality standard indicates that activities within a catchment can result in "no more than a 10% cumulative increase in natural stream turbidities, as measured relative to a control point immediately upstream of the turbidity causing activity" (Borok 2014).

Given the many potential effects associated with too much sediment in water bodies, there has long been concern for increased sediment supply to streams due to forest management activities (Beschta 1978; Harr and Fredriksen 1988; Binkley and Brown

1993). In the Pacific Northwest, where forests and forest harvesting remain important for the economy, understanding the effects of current forest management practices on sediment and turbidity remains a challenge. In part, this relates to the difficulty in determining the background spatial and temporal patterns of suspended sediment and turbidity, as well as the response to disturbances (Fredriksen 1970; Harris and Williams 1971; Beschta 1978; Luce and Black 1999). In general, historical forest management practices, including road building, timber harvesting and site preparation, led to exposure of mineral soils, decreased infiltration capacities of soils, disturbance of stream banks and channels, and increased erosion and fine sediment delivery to stream channels (Brown and Krygier 1971; Beschta 1978; Harr and Fredriksen, 1988; Binkley and Brown 1993). When conducted on steep slopes, these management practices have also been associated with significantly increased occurrence of landslides and mass wasting, which can deliver large quantities of sediment to streams (Montgomery et al. 2000; Schmidt et al. 2001; Swanson and Dyrness 1975).

In response to the association of forest management practices with increased erosion and sediment inputs into streams, timber harvest regulations and best management practices (BMPs) were developed and implemented to reduce these sources of nonpoint source pollution (Ice 2004; Ice et al. 2004). For nonfederal timberlands in Oregon, these BMPs are codified in rules in the Oregon Forest Practices Act. Rules for perennial, fish-bearing streams generally focus on a designated riparian management area along each side of the stream (that varies in width depending on stream size and other factors) where forest management activities are reduced or precluded. Rules for forest roads focus on locating the roads away from water bodies and on routing runoff from the roads away from waterways. Since the 1960s, rules for fish-bearing streams and forest roads have been updated several times. However, non-fish-bearing streams do not have riparian management areas in most of western Oregon, while rules for forest management in steep, landslide-prone areas focus on safety for humans and their structures (Langridge 2011), and do not include provisions for protecting water quality.

Despite improved timber operations and evidence indicating that they are generally effective in reducing erosion and sediment delivery into streams (Cristan et al. 2016), there also continue to be inconsistent and even contradictory results from various studies regarding relationships between forest management, erosion and water quality (Aust and Blinn 2004; Anderson and Lockaby 2011; Cristan et al. 2016). Given that the focus of this review is on downstream community drinking water supplies, it is important to note that much of the uncertainty about the efficacy of current BMPs is partly associated with the many challenges associated with identifying the source of in-stream suspended sediment (Collins et al. 2017). Sources of suspended sediment often respond to complex interactions between numerous factors that influence sediment mobilization and delivery, resulting in high temporal and spatial variability. That variability makes categorical statements about the effects of forest management practices problematic (Grant and Wolff 1991; Collins and Walling 2004).

In general, downstream sediment transport is limited by the conveyance capacity of the upstream channels and floodplains (Trimble 1983). If this conveyance capacity is exceeded by sediment supply, then storage of sediment occurs (Reid and Dunne 2016). However, stored sediment can become remobilized during high-flow events and increase sediment yield in the downstream direction (Bywater-Reyes et al. 2018). Additionally, while larger, heavier particles typically settle out of the water column first, smaller, fine-grained clay particles, which create the greatest challenges for downstream drinking water treatment, tend to remain suspended for longer periods of time and distances, contributing to downstream sediment and turbidity levels often many years after the upstream disturbance (Borok 2014; Emelko et al. 2016). Suspended sediment concentrations and turbidity may change along the course of a stream or river due to many interacting factors. Despite an understanding of these fundamentals, the specific understanding of when and where forest management BMPs are likely to be successful at mitigating sediment delivery to water bodies remains limited (Edwards et al. 2016). This uncertainty is partly because costly and time-consuming field-based studies — necessary to understand interactions between forest management activities and large-scale, long-term sediment transport — have waned in recent decades (Burt and McDonnell 2015; Anderson and Lockaby 2011).

Below, we summarize literature that addresses the effects of forestry activities on suspended sediment and turbidity in water bodies, with a focus on studies published since 2000. Forest BMPs for roads and larger fish-bearing streams have evolved rapidly in the 21st century (Cristan et al. 2016), and questions remain about the effectiveness of these newer practices at mitigating sediment delivery to streams. We focused on recent PNW research conducted in smaller catchments, which is relevant to public water systems that rely on smaller source watersheds and are closer to headwater areas, such as those along the Oregon Coast. There have been few studies on the effects of contemporary forest management practices on sediment and turbidity at a scale relevant to larger drinking water treatment plants in the PNW (MacDonald and Coe 2007). The paucity of large-basin studies can create uncertainty about how research on small catchments relate to drinking water treatment in systems with larger source watersheds.

5.2. Harvesting

Many studies have observed increases in runoff, soil erosion and sediment delivery to streams due to forest management practices (Binkley and Brown 1993; Croke et al. 1999b; Megahan and King 2004; Gomi et al. 2005). The general harvest area (the area of tree harvesting, excluding primary skid trails and haul roads) is the largest area disturbed by ground-based, forest-harvesting activity and equipment (Miller et al. 1996; Ampoorter et al. 2012). Felling trees usually does not significantly disturb soils and expose mineral soils, but movement of logs across the ground to landings often does. Heavy machinery, including harvesters, skidders and forwarders, compact soils, increase bulk density, and decrease air-filled porosity, infiltration capacity, and hydraulic conductivity across the harvest area (Sidle et al. 2006; Mohr et al. 2013). These effects are spatially heterogeneous and difficult to study.

General harvest areas usually have patches of compacted soils interspersed with areas more similar to undisturbed forest floor. Runoff typically builds slowly in harvest areas, even under heavy rainfall, usually starting on the more disturbed patches of the hillslope. But channelized flow tends not to develop in general harvest areas due to the high spatial variability in soil infiltration capacity and the presence of remaining vegetation and loose material on the soil surface. This patchy nature of runoff generation usually limits the ability of runoff in general harvest areas to mobilize large amounts of sediment (Croke and Hairsine 2006). Most available evidence suggests that forest roads, skid trails, log landings and slash burning are usually more likely to produce sediment than harvesting itself (Neary et al. 2009). Assessing nearly 200 harvest units in the Sierra Nevada and California Cascades, Litschert and MacDonald (2009) found that timber harvest alone rarely initiated large amounts of runoff and surface erosion, particularly when BMPs were utilized. Similarly, Megahan and King (2004) found that harvesting often had minor impacts on streams. Stednick and Troendle (2016) maintain that harvesting-related disturbances are usually disconnected from waterways, which reduces their potential for causing increases in sediment inputs. Infiltration rates usually remain high enough in

Pacific Northwest forests, even after harvesting, to minimize infiltration excess, overland flow and associated sediment movement.

However, there are gaps in the evidence base for this general finding. There are exceptions associated with local conditions. Depending on factors that contribute to connectivity across a particular general harvest area, it may be a significant source of sediment. For example, Reid et al. (2010) investigated the role of gullies in sediment production after logging, a rarely studied aspect of forest management. They found that second-cycle logging in Caspar Creek in California resulted in increased streamflow. This increase appeared to coalesce previously disconnected gullies associated with first-cycle logging a century earlier, extending these gullies significantly further upslope. They suggest that higher in-channel erosion associated with these changes compared to control sites is an important source of sediment in the logged sites, and one for which BMPs for riparian areas and roads would not be effective at reducing.

Few studies explicitly quantify the proportional amount of sediment delivered directly to streams from general harvest areas. Significant knowledge gaps remain regarding the relative importance of general harvest areas, skid trails and roads in contributing to overall suspended sediment concentration or turbidity (Croke and Hairsine 2006). In a study from Australia, Croke et al. (1999a, b) found that skid trails generally produce most harvesting-related sediment and that general harvest areas tend to be sediment sinks. However, the study noted challenges in modeling sediment production from general harvest areas and in scaling up plot-level data. The importance of each source depends on site-specific factors, including geology and slope steepness. On steep slopes, concerns over safety and higher logging costs have led to a shift away from cable yarding toward ground-based machinery tethered to an anchor, usually upslope. In response to concerns about soil and water impacts associated with this new technology, Chase et al. (2019) compared soil disturbance and stream-adjacent disturbance of tethered logging and conventional cable harvest methods on steep slopes in Oregon and Washington. They found that tethered systems caused more soil disturbance than cable systems, but that impacts were still below applicable regulatory thresholds. The potential impacts of tethered logging systems on soil compaction, water routing, and associated sediment movement to streams are only beginning to be evaluated.

Anderson and Lockaby (2011) identified uncertainty of sediment sources associated with specific forest management activities as a critical research gap and suggested the use of nuclide or isotopic tracers in existing or future watershed studies to separate the various contributions to streams (Wallbrink and Croke 2002; Walling 2005). Better and more detailed information on the sources of fine sediment is critical for improving understanding of:

- Erosion and sediment delivery processes;
- Sediment-associated nutrient and contaminant fluxes;
- The differential effects of specific sediment sources on aquatic ecosystem health; and
- Whether best management practices aimed at mitigating sediment transport to water bodies are effective (Walling 2013; Sear et al. 2016).

As noted by Gomi et al. (2005), the primary external sources of sediment to streams include streambank erosion, mass movements (landslides and debris flows), roads and trails, and surface erosion on slopes of the general harvest area. The key internal sources of sediment to streams include material stored within the channel system, which may be remobilized during high flow events (Gomi et al. 2005).

Sediment stored within stream channels can originate from natural processes, previous human land uses or from some combination of these. Sediment eroded as a result of human land uses, or "legacy sediment" may be stored in rivers for decades or even centuries (James 2013; Wohl 2015). We found little information on the residence times of sediments in Oregon streams potentially related to forest practices. This gap may be due to the lack of baseline data on natural sediment loads and the difficulty of distinguishing sediment contributed by agriculture, grazing or other land uses. However, research from the Oregon Coast Range (Lancaster et al. 2010; Lancaster and Casebeer 2007) found that a significant portion of sediment from debris flows can remain in the valley bottoms of channels for many decades or centuries. And Koehler et al. (2007) found that the South Fork Noyo River watershed in coastal Northern California contains large volumes of historic sediment that were delivered to channels in response to past logging operations and are presently stored beneath historic terraces and in present-day channels.

Regardless of the original sediment source or sources, increases in water yields and peak flows following forest harvesting can lead to increased suspended sediment and turbidity simply due to remobilization of stored in-channel sediment (Stednick 1996; Brown et al. 2005; Grant et al. 2008; Birkinshaw et al. 2011). Such changes in the hydrologic regime can increase in-channel sources of sediment via stream channel scouring, bedload mobilization and remobilization of previously eroded materials that may be stored in the channel (Anderson and Lockaby 2011; Voli et al. 2013). A key point here is that while modern forest practices have clearly reduced ongoing inputs of sediment to stream channels in many cases, there may be substantial amounts of forestry-related sediments that entered Oregon streams during episodes of historic logging and which remain stored there, available for remobilization, just as Koehler et al. (2007) found in a Northern California watershed. This remobilization could occur due to higher flows associated with current timber harvesting or from infrequent large storms. Streamflow changes after harvesting are discussed in Chapter 4.

A recent study in the Oregon Coast Range used sediment source fingerprinting techniques (Walling 2005; Collins et al. 2010) to quantify the primary sources of suspended sediment in an unharvested, reference catchment and a harvested catchment (Rachels 2018). The primary sources of suspended sediments in the stream draining the harvested watershed were generally from streambank sources (90.2 ± 3.4%), hillslopes (7.1 ± 3.1%) and roads (3.6 ± 3.6%). Similarly, the primary contributions of suspended sediment in the stream draining the reference watershed were streambanks (93.1 ± 1.8%) and hillslopes (6.9 ± 1.8%) (Rachels 2018). These findings were in agreement with previous studies from Georgia, (Fraser et al. 2012), North Carolina (Voli et al. 2013), New Zealand (Basher et al. 2011) and Japan (Hotta et al. 2007). These studies inferred, based on field observations and suspended sediment concentrations, that streambanks could be the primary source of suspended sediment and highlight the importance of forest-harvesting effects on the hydrologic regime. In harvested catchments, streambank contributions are often related to increased streambank destabilization associated with culverts, ditches, riparian vegetation disturbance or stream crossings (Rashin et al. 2006).

Due to limitations in accurately determining sources of sediment in streams, most research investigating forest-harvesting effects on sediment and turbidity have focused on in-stream concentrations and yields. In one study, Reiter et al. (2009) investigated spatial and temporal trends in turbidity using 30 years of water quality data from four locations in the Deschutes River watershed in western Washington (Figure 5.1). The study included catchments at the small headwater scale (2.4 - 3.0 km^2) up to the larger basin scale of the Deschutes River (150 km^2). Overall, Reiter et al. (2009) provided strong

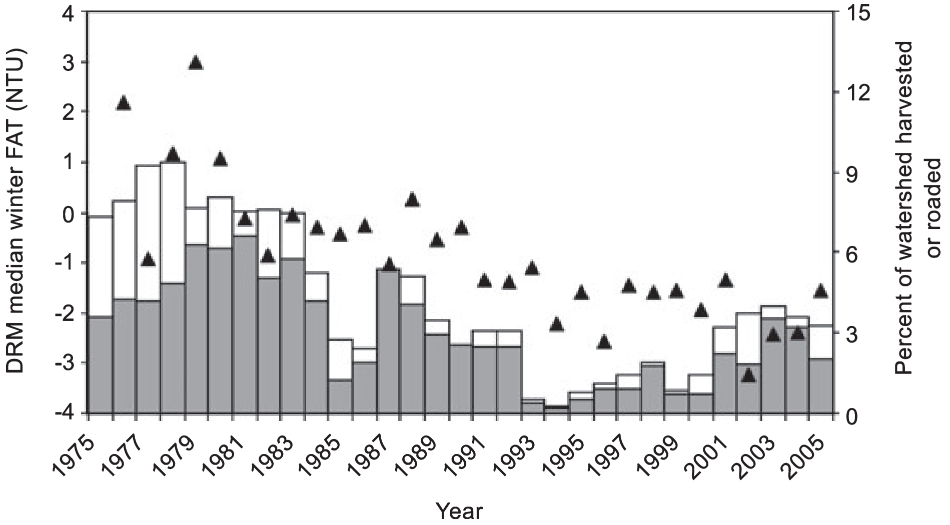

Figure 5.1. Median monthly flow adjusted turbidity (black triangle), percent of catchment harvested (grey bar), and percent of road network constructed (white bar) at the Deschutes River (WA) mainstem site. Note: percent road network constructed in 1988 was unavailable. (Reiter et al. 2009).

evidence for a correlation between annual percent catchment harvested and the median flow adjusted turbidity during winter (p = 0.0002) and spring (p = 0.0281). Similarly, they also provided strong evidence (p = 0.0027) that median flow adjusted turbidity was correlated with the percent of annual road network constructed in the catchments. At the larger basin scale, turbidity, flow-adjusted turbidity and suspended sediment concentrations were all greater than observed at the headwaters scale. However, the authors did not explicitly link upstream to downstream in a manner that would facilitate assessment of the implications to community drinking water. Across all sites, trend analysis provided strong evidence that for similar harvest levels the winter flow-adjusted turbidity had declined in more recent years of the study relative to earlier in the record (p = 0.020). There was not a similar declining trend observed in the record for the spring flow-adjusted turbidity. The authors primarily attributed the significant decreasing trend in the winter flow-adjusted turbidity to improvements in road construction and maintenance practices (Reiter et al. 2009). The authors also indicated the challenges associated with isolating the specific factors contributing to the trends in turbidity due to “complex interactions of land use, landform, and natural disturbance as well as the manner in which the study was designed” (Reiter et al. 2009, p. 803). Reiter et al. (2009) also found winter turbidity values were greater in streams draining catchments dominated by more friable (easily crumbled) geology compared to streams draining catchments consisting of more resistant volcanic geologies (Figure 5.2).

Similarly, Bywater-Reyes et al. (2017) also found that the differences in the suspended sediment yield response to forest harvesting at the Trask River Watershed study in the Coast Range of western Oregon were primarily driven by catchment geology and physiography. Across six years of data from 10 sites, they found the greatest increases in suspended sediment yields after forest harvesting (up to an order of magnitude) occurred in streams draining catchments with more friable lithology (e.g., sedimentary) (Figure 5.3). Comparatively, catchments underlain by more resistant lithology (e.g., intrusives) had lower suspended sediment yields and were more resilient to the effects of forest management activities (Bywater-Reyes et al. 2017). They also observed increases in suspended sediment yields in three of the 10 headwater catchments (26.4 - 37.8 ha), which were harvested with contemporary forest harvesting practices in the first year

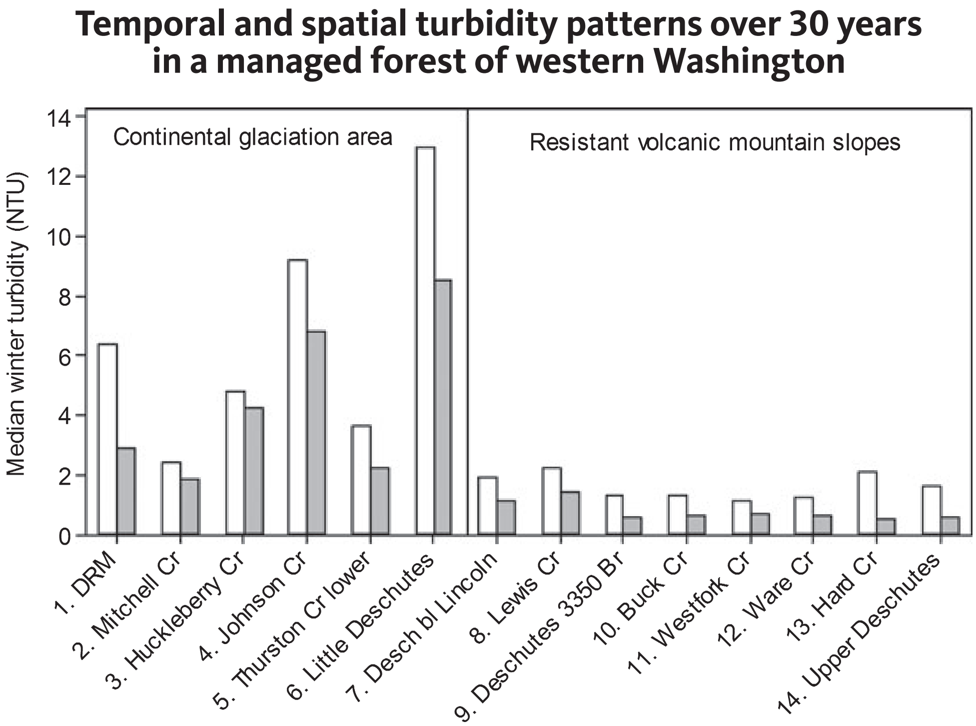

Figure 5.2. Median winter turbidity from grab samples collected during a period of high harvest activity (1982; white bars) and lower harvest activity (1997; gray bars) separated by catchments underlain by more friable lithology (continental glaciation area) and more resistant lithology (resistant volcanic mountain slopes) (Reiter et al. 2009).

after harvesting, with sediment yields increasing annually in one catchment (clearcut without a riparian buffer) for the remaining three years of the study. Consistent with the study by Reiter et al. (2009) in Washington state, Bywater-Reyes et al. (2017) also observed the highest sediment yields at the downstream sites, reflecting an accumulation of sediment from the upstream, headwater catchments (Figure 5.3).

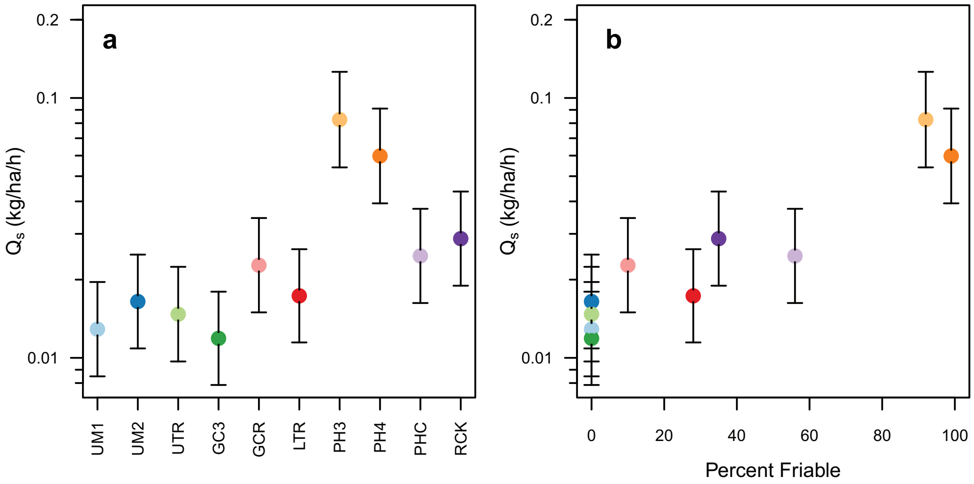

Figure 5.3. Annual suspended sediment yields in each catchment in the Trask Watershed Study as a function of (a) contributing area (catchments ordered from upstream to downstream) and (b) friability of catchment lithology (Bywater-Reyes et al. 2017).

In a follow-up study using about 60 years of data in 10 temperate mountain watersheds (8.5–6,242 ha) in the H.J. Andrews Experimental Watershed in the Pacific Northwest, Bywater-Reyes et al. (2018) investigated the relationship between catchment setting (i.e., lithology and physiography), forest management activities, and suspended sediment yields. Annual suspended sediment yields fluctuated almost four orders of magnitude across the 10 catchments and through time. While the study catchments included a range of lithologies, including hydrothermally altered pyroclastic flows, welded ash-flow tuff, and ridge-capping andesite lava flows, this was a less dominant factor in driving differences in sediment yields across catchments (Bywater-Reyes et al. 2018). Rather, watersheds with greater slope variability (roughness) were more likely to have greater suspended sediment yields and tended to be less resilient to erosion and sediment delivery to streams following both natural and anthropogenic disturbances (Bywater-Reyes et al. 2018).

Richardson et al. (2018), in a unique study investigating downstream sediment transport, cross-dated about 1,500 years of sediment from cores collected from Loon Lake in the Oregon Coast Range. During a time of peak forest harvesting in the region (1939–1978), which coincided with a cool wet phase of the Pacific Decadal Oscillation, sedimentation rates in the lake were about 0.79 g cm^{-2} y^{-1} (0.74–0.92, 95% C.I.). From 1979 to 2012 — a period that coincided with the passing of the Oregon Forest Practices Act regulating harvesting practices in the region — sedimentation rates declined to 0.58 g cm^{-2} y^{-1} (0.48–0.70). The study by Richardson et al. (2018) illustrated how historical forest harvesting activities primed the landscape and lowered the threshold for sediment delivery during the high streamflow events that occurred at the end of the early study period. The study also appeared to provide evidence that forest harvest practices have improved such that sediment delivery to streams in forested headwater regions and subsequent downstream transport have substantially declined. However, strong differences in climate between the historical (wet and cool) and contemporary (warm and dry) periods precluded the authors from definitively disentangling the effects of timber harvesting from climate (Richardson et al. 2018).

The paired watershed approach evaluates forest management while controlling for some climate effects. In another study in the Oregon Coast Range, Hatten et al. (2018) returned to the same watersheds that were harvested in 1966 as part of the Alsea Watershed Study (Stednick 2008) to investigate the effects of contemporary forest harvesting. In the original Alsea Watershed Study, forest harvesting without riparian buffers, road building and slash burning led to about 2.8 times more sediment in the streams draining the harvested catchments compared to the unharvested (reference) catchment (Brown and Krygier 1971; Beschta 1978; Hall 2008) (Figure 5.4). Specifically, sediment yields increased in the post-harvest period by 253% in Needle Branch (no buffers) and 117% in Deer Creek (buffers) compared to the preharvest periods (Beschta and Jackson 2008). However, the recent harvesting practices in Needle Branch differed from the historical harvesting practices in several key ways, including: retention of vegetation as riparian stream buffers, smaller harvest units, no broadcast burning, and retention of woody materials in the stream channel. Road practices also changed. As a result of these shifts in practices, the more recent study illustrated that annual sediment yields in Needle Branch (buffers on small-fish streams, none on nonfish streams) were lower than in Flynn Creek (reference catchment) after contemporary forest harvesting with BMPs (Figure 5.4). In fact, Flynn Creek (reference) often had the highest sediment yields, 55–313 Mg km^{-2} yr^{1}, followed by Deer Creek (no contemporary harvests) at 69–127 Mg km^{-2} yr^{1}, and Needle Branch (buffers on S/F, none on S/N) at 31–102 Mg km^{-2} yr^{1}. The concentrations and yields of suspended sediment observed in Needle Branch after contemporary harvesting were similar to historical pretreatment levels. As

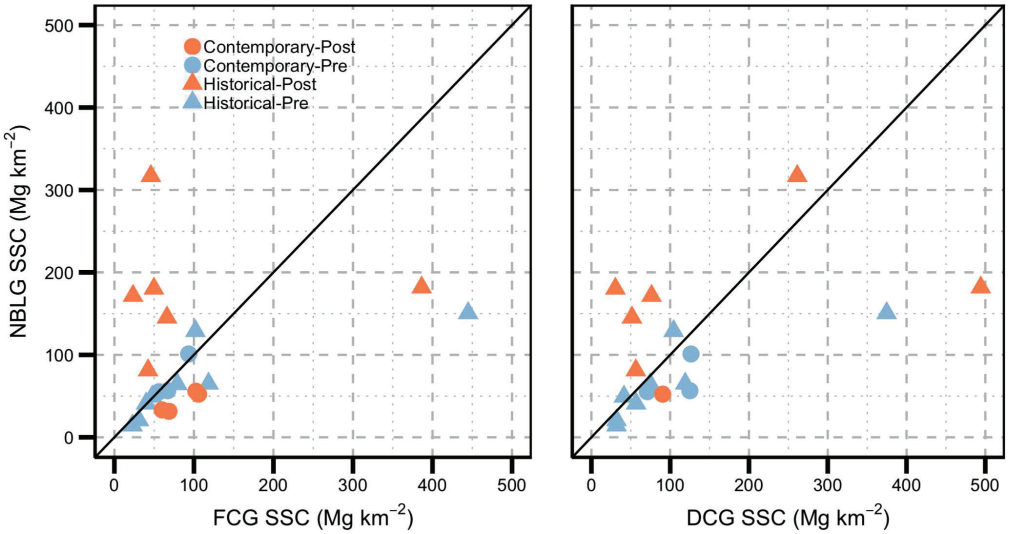

Figure 5.4. Relationships between annual suspended sediment yields in the reference catchments (Flynn Creek, FCG; Deer Creek, DCG) compared to the harvested catchment (Needle Branch, NBLG) during the historical and contemporary pre- and post-harvest periods from the Alsea Watershed Study (Hatten et al. 2018).

such, Hatten et al. (2018) found no evidence that contemporary harvesting techniques affected suspended sediment concentrations or yields.

Our understanding of the magnitude, duration, physical processes and downstream consequences associated with both short- and long-term increases in turbidity and sediment in headwater streams after forest harvesting is incomplete. Improvements in forest harvesting practices, including riparian buffers, smaller harvest units, and less intensive site preparation practices (e.g., broadcast burning), have reduced headwater-scale erosion, suspended sediment and turbidity. But there may be instances where current BMPs are imperfectly implemented. As Rashin et al. (2006) note, forestry BMPs and the erosion and sediment transport processes they are designed to address are highly variable. Moreover, current BMPs do not explicitly address the effects of tree removal on hillslope hydrologic changes, catchment water balance or loss of root strength from decay (Klein et al. 2012; McDonnell et al. 2018). In Oregon, small nonfish streams in general and non-fish-bearing streams in the upper reaches of drinking water source watersheds remain unprotected. Rashin et al. (2006) state that preventing sediment delivery to and physical disturbance of non-fish-bearing streams prevent impacts to water quality downstream. There is also evidence that some catchments are simply more susceptible to increased erosion and sedimentation following forest harvesting (e.g., Bywater-Reyes et al. 2017; 2018).

Fine sediment introduced into streams is more likely to be delivered downstream compared to coarse sediment, woody debris or changes in water temperatures (MacDonald and Coe 2007). But this aspect of sediment mobilization and transport has been rarely quantified. One exception is a study by Jackson et al. (2001) which evaluated particle-size distributions of bed material in 15 first- or second-order Washington Coast Range streams (small streams without salmonid fish) in and nearby commercial timber harvest units prior to and immediately following harvest. Four unharvested basins served as references; five basins had some type of buffer and six basins were clearcut to the channel edge. Buffer widths, averaging from 15 to 21 meters, were dictated by operational considerations with the narrowest 2.3 meters on one side of a stream. In the clearcut streams, slash in the channel trapped fine sediment thereby inhibiting fluvial transport. Fine sediment increased from 12% to 44%, after harvest in five of the six unbuffered streams and were attributed primarily to small bank failures caused by logging operations. Only one of five buffered streams (which received drainage from a logging road and landing) showed increased fines, and unharvested reference streams showed similar or reduced fines.

Current BMPs do not explicitly address the effects of tree removal on hillslope hydrologic changes, catchment water balance or loss of root strength from decay (Klein et al. 2012). As frequently noted in reviews and syntheses of knowledge regarding relationships between forest practices, sediment and water quality (e.g., Anderson and Lockaby 2011), there is a general paucity of research at the larger basin scale, occasionally due to confounding cumulative effects, which creates uncertainty about how to apply research results from the small catchment scale to larger areas. But catchment scale research is relevant to smaller drinking water source watersheds and community water systems that rely on them. Modern BMPs reduce sediment production from forest operations. Sediment is still produced in areas with certain types of erodible soil and rock, in steeply-sloped watersheds and in areas with substantial soil disturbance. In all of these instances, impacts are exacerbated during large storms, especially if they occur immediately after harvesting.

In an unusual study that did generate larger-scale findings, Wheatcroft et al. (2013), using sediment cores and ^{210}Pb geochronology, detected the cumulative effects of timber harvesting at the basin scale in continental shelf sediments of the Pacific Ocean off the Umpqua River, expressed as an increase in sediment accumulation and a shift in sediment grain size toward finer particles. These findings are discussed in more detail below in the section on landsliding.

5.3. Roads (fill failures, chronic sediment, hydrologic connectivity)

Despite many economic and social benefits of forest roads, they also represent a potential hazard to hydrologic, geomorphic and ecologic processes (Jones et al. 2000; Baird et al. 2012). In particular, unpaved forest roads have long been considered one of the primary sources of suspended sediment and elevated turbidity in streams (Brown and Krygier 1971; Beschta 1978; Reid and Dunne 1984; Lane and Sheridan 2002; Gomi et al. 2005). In the western United States, it has been estimated that from 18% to 75% of forest roads are hydrologically connected to the stream network (Coe 2006). Roads are nearly impervious surfaces that often increase overland flow. This increase can cause chronic fine sediment contribution to nearby streams, lakes and reservoirs (Luce 2002). When coupled with forest harvesting or active hauling, sediment delivery to water bodies is often magnified (Bilby et al. 1989; Ziegler et al. 2001).

Impacts of roads range from chronic and long-term contributions of fine sediment into streams to catastrophic mass failures of road cuts and fills during large storms (Beschta 1978; Wemple et al. 2001; Sidle and Ochiai 2006). Many studies have shown an increase in sediment availability and delivery to streams with greater road traffic due to crushing, abrasion and the forcing of fine sediment to the surface (Ziegler et al. 2001; Sheridan et al. 2006; Sosa-Perez and MacDonald 2017a). Additionally, the lateral redistribution of runoff from roads can decrease slope stability and increase peak flows in small streams, leading to more frequent mass movements or elevated in-channel erosion and sediment transport (Brown and Krygier 1971; Beschta 1978; Montgomery 1994; Croke and Mockler 2001). Evidence suggests sediment delivered to water bodies from roads is related to episodic, mass-movement events (Swanson et al. 1987; Mills, 1997;

Fransen et al. 2001). The magnitude and longevity of forest roads' effects on suspended sediment in streams depends on such site-specific factors as traffic, geology, road grade, road connectivity to the stream, and sediment availability for transport (Grant and Wolff 1991; Benda and Dunne 1997; Hassan et al. 2005).

The effects of roads on forest hydrology and causes of their sediment impacts include:

- Low permeability of the road surface to intercepted rainfall and overland flow.
- The susceptibility of road cutbanks and fill-slopes to erosion from rainfall and overland flow.
- Changes in how subsurface water moves downslope (e.g., interception by cutbanks and conversion to faster surface flow).
- Concentration of overland flow, either on the surface or in adjacent ditches, channels or culverts.
- The construction and maintenance of stream crossings.
- Diversion or rerouting of water from natural surface drainage paths.
- Undercutting and overloading of steep slopes which contributes to increased landsliding (Stednick and Troendle 2016; Chang 2012; Wemple and Jones 2003; Guthrie 2002; Gucinski et al. 2001).

Road use and road density are major factors in delivering fine sediment to streams (Bilby et al. 1989; Luce and Black 1999; Dubé et al. 2004). Recently, Araujo et al. (2014) developed a simulation model from time series data of hydrologic variables, suspended sediment and road and terrain characteristics to quantify suspended sediment concentration generated from forest roads in medium-sized coastal watersheds of British Columbia and the broader PNW. Their results illustrated that road traffic was a more important factor than road density in the delivery of fine sediment from roads to streams (Figure 5.5). As an example, their model projected a 12 mg l^{-1} increase in suspended sediment concentration with moderate use of roads and an increase in road density from 15% to 30%. Comparatively, they projected an estimated 55 mg l^{-1} increase in suspended sediment concentration with heavy use of roads with the same increase in road density. Similarly, Miller (2014) observed a 3.3-times increase in sediment yield from forest roads in Hinkle Creek in Oregon if logging trucks drove on the segments during the week prior to a storm. However, there was high variability (95 % CI 1.9 - 4.7-times increase) among road segments and between storm events (Miller 2014). This is consistent with several other studies in the PNW, which have shown two to 130 times more sediment from forest roads with heavy traffic compared to roads with little to no logging truck traffic (Reid and Dunne 1984; Bilby et al. 1989; Luce and Black 1999; Luce and Black 2001; Sugden and Woods 2007).

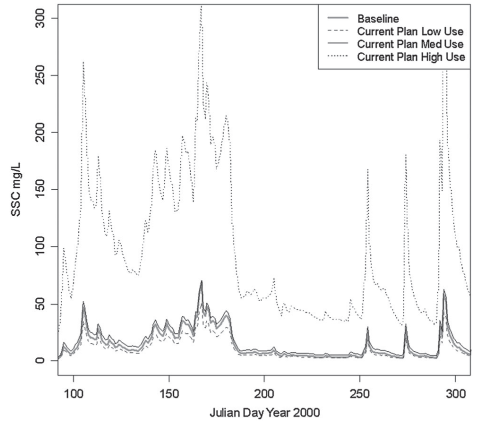

Figure 5.5. Simulation model results illustrating the potential effect of road use on mean daily suspended sediment concentration (Araujo et al. 2014).

Similarly, the frequency of road maintenance operations can be a critical factor influencing the amount of sediment delivered from roads to ditches and streams. Maintenance of the roadbed is critical to prevent rut formation, overland flow, and road erosion (Burroughs Jr. and King 1989; Ziegler et al. 2001). However, this type of maintenance is achieved by periodic grading, which was shown on forest roads in the Oregon Coast Range to result in breaking up of the armor layer, increasing the sediment supply, and temporarily increasing sediment yields from roads to streams (Luce and Black 1999). Such increases in sediment yields are often short-lived. As the armor layer redevelops, sediment yields have been shown to decline as an exponential decay function, with reported declines in sediment yields of 63% to 89 % in the second year and 86% to 99 % in the third year after grading (Megahan and Kidd 1972; Megahan 1974; Luce and Black 2001; Sugden and Woods 2007).

The type and quality of road surfacing material, as well as the erodibility of the underlying parent material (soil and geology), can also affect erosion and sediment yields. For example, Brown et al. (2014) observed 2.6- to 3.5-times higher median suspended sediment concentrations in road surface runoff from unsurfaced (native) roads compared with suspended sediment from roads with low gravel and high gravel surfaces, respectively. Comparatively, Luce and Black (1999) observed nine times greater sediment yields from roads covered with aggregate on a fine textured silty clay loam base compared to roads constructed on a coarser, gravelly loam in the Coast Range of Oregon. This is consistent with most research, which has shown that erosion from roads tends to be highest in regions where soils are silt-dominated, while erosion rates in regions with clay-dominated soils are intermediate, and lowest in gravel-dominated regions (Burroughs Jr. and King 1989; Dubé et al. 2004). In forested, mountainous regions, the majority of road prisms are graded into the subsoil. In these regions, the local geology is often the dominant factor affecting sediment yields from roads. Summarizing results from 15 studies and 10 parent materials in the PNW, Dubé et al. (2004) showed the highest rates of road erosion tended to occur in weathered granite, fine-grained or deeply weathered sedimentary, ash and tuff-dominated geology.

Due to the many potential effects of forest roads on sediment delivery to streams, there have been substantial efforts over the last several decades to modify forest road construction, road maintenance and hauling practices (Gucinski et al. 2001; Wear et al. 2013; van Meerveld et al. 2014). In many regions, runoff from roads is routed into the forest as rapidly and frequently as possible to reduce hydrologic connectivity of roads to streams (Gillies 2007; Baird et al. 2012). Further improvements in forest management practices aimed at reducing sediment delivery to water bodies include:

- Locating roads further away from streams.
- Avoiding impacts to natural drainage patterns.
- Minimizing total area disturbed by roads.
- Avoiding steep slopes (greater than 60%).
- Avoiding wet areas.
- Limiting the number of stream crossings.
- Using less erosive surfacing material.
- Providing more frequent road maintenance (Keller and Sherar 2003; Wear et al. 2013).

Repairing damaged drainage structures or mitigating obvious sediment source points can reduce sediment production, but frequent grading or ditch cleaning may exacerbate it. Additional mitigation efforts include sediment traps in ditches to dissipate energy and reduce sediment transport and the installation of ditch-relief culverts (Reiter et al. 2009). Below, we summarize the findings from current research from the Pacific Northwest investigating the efficacy of current road construction and maintenance practices at mitigating sediment transport to streams.

Reiter et al. (2009) used a water quality dataset collected over 30 years at four locations in the Deschutes River watershed (western Washington) to examine the role of forest management practices on turbidity and suspended sediment transport in streams. Increases in median monthly turbidity and the highest maximum monthly turbidity values tended to coincide with periods of active road construction (Reiter et al. 2009). In all four sub-catchments, road upgrades over the course of the study included:

- Use of less erosive surfacing material;
- Limited wet weather hauling;
- Outsloping of road surfaces, use of water bars or frequent ditch-relief culverts for the rapid diversion of water off roads surfaces, out of ditches and onto the forest floor to facilitate infiltration; and
- Use of sediment traps and energy dissipation at relief culvert outlets (Reiter et al. 2009).

These sediment-control efforts applied to the road system contributed to a consistent decline in suspended sediment and turbidity over the 30-year study. Reiter et al. (2009) also attributed the reduction in sediment and turbidity to a consistent decline in road use over time.

Toman and Skaugset (2011) compared alternative designs of the pavement for unbound aggregate forest roads designed to specifically to minimize turbid runoff caused by subgrade mixing during wet-weather hauling. Alternative designs influenced sediment production but results were not consistent. The treatments produced different results across different research locations and there was no statistically significant treatment effect, suggesting that fine sediment in surface runoff did not originate from the subgrade but rather from the surface aggregate. Toman and Skaugset (2011) suggest that to minimize sediment production from forest roads, managers should be concerned with the unbound aggregate pavement rather than the subgrade. Also, they found that road segments that developed ruts produced considerably more sediment than road segments where ruts did not form, suggesting that managers should design the aggregate pavement to resist rut formation and also consider the availability of fine sediment in the aggregate.

Arismendi et al. (2017) assessed both suspended sediment concentration and turbidity in five non-fish-bearing streams in the Coast Range of Oregon. They quantified suspended sediment concentration and turbidity both above and below road crossings during three successive time-periods, including before road construction/maintenance, after road construction/maintenance, and after forest harvesting and hauling. Many roads existed previously and were reconditioned, improved or surfaced. Counter to their hypothesis, Arismendi et al. (2017) did not find strong statistical evidence that suspended sediment concentration or turbidity increased at the downstream sites relative to the upstream sites after road construction/maintenance, forest harvest or hauling. In another analysis, focused on suspended sediment yields at the subcatchment scale from some of the same sites, Bywater-Reyes et al. (2017) also found no evidence for increases in suspended sediment yields associated with roads. Arismendi et al. (2017) also concluded that the absolute magnitude of change in suspended sediment concentration after road improvements, forest harvest and hauling in the treatment sites was small and likely had minimal biological relevance. The greatest concentrations of suspended sediment and turbidity occurred in their unharvested reference site, which they attributed to an exposed tree root-wad in the stream channel due to windthrow (Arismendi et al. 2017). As a result, they suggested that similar local disturbances in headwater streams, which often occur during discrete spatial and temporal events, could dominate the suspended sediment concentration and turbidity response in headwater streams (Benda and Dunne 1997; Benda et al. 2004; Arismendi et al. 2017). While this study provided evidence that current BMPs associated with forest roads may be effective at mitigating sediment transport to streams, the authors caution against broad generalizations from their findings due to the high spatial and temporal variability in suspended sediment concentrations and turbidity they observed across a small number of study catchments (Arismendi et al. 2017).

Road upgrades and improved BMPs associated with road building have shown promise for decreasing sediment delivery to streams. However, most PNW watersheds contain an interconnected mosaic of older and newer roads designed to different standards, sometimes for different purposes, and crossing terrain of differing sensitivities to erosion and mass wasting. The particular pattern and hydrologic connectivity of this mosaic of road segments has implications for how it will interact with the forest watershed, streams and other downstream water uses (Endicott 2008). Older legacy roads are often the primary source of sediment due to poor water and grade control, as well as road location (Brown et al. 2014). In western Oregon forests, Luce and Black (1999) found high variability in sediment production from road segment to road segment with most segments producing little sediment, and a few key segments producing a great deal. Longer, steeper road segments, cutslopes without vegetation, cleaned ditches and finer-grained soils were all associated with much higher sediment production.

Using the Washington Road Surface Erosion Model (WARSEM), Sugden (2018) modeled changes in sediment delivery to streams in response to systematic BMP upgrades to a 28,000-kilometer legacy forest road network in western Montana and northern Idaho. The roads were on Plum Creek Timber Company lands where BMPs were applied over time in response to BMP legislation, Sustainable Forest Initiative (SFI) requirements and a Native Fish Habitat Conservation Plan (NFHCP) agreement with the U.S. Fish and Wildlife Service. Key BMPs included installing more frequent road drainage features, managing public road access, increasing road surface vegetative cover and installing supplemental filtration near streams. The WARSEM modeling was locally validated based on comprehensive field surveys, which indicated that sediment delivery in these watersheds is dependent on site-specific BMP conditions and that most such delivery occurs at a minority of crossing locations. Results from 10 repeated watersheds (inventoried and modeled before and after BMPs) estimated that sediment delivery (weighted by watershed road length) was reduced by 46% (watershed range: -84% to +57 %) over a 10–15-year period. Delivery rates from these watersheds were similar to an additional 22 watersheds inventoried after BMP upgrades were completed.

Oregon agencies, including departments of environmental quality and forestry, are further distinguishing between *legacy roads* — those built and abandoned before the Oregon Forest Practices Act (and therefore not regulated by it), and *old roads* — those built before current road standards but still in use. Road deactivation, especially of legacy roads, is often suggested as a way to potentially decrease road density, erosion

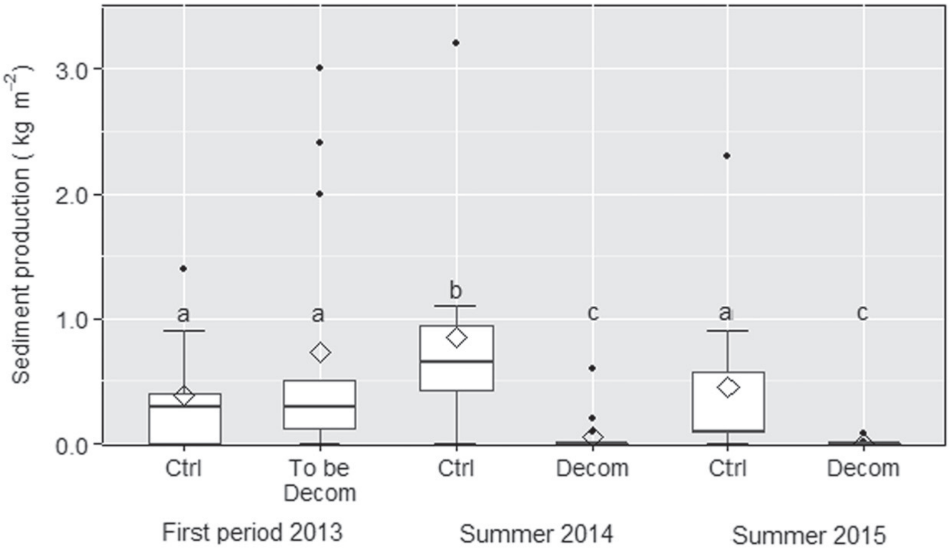

Figure 5.6. Sediment production (kg m-2) during three time periods (before decommissioning, first year after decommissioning, second after decommissioning) from control (Ctrl; n = 10) and decommissioned (Decom; n = 19) road segments. Different letters above the boxplots indicate statistically significant differences (Sosa-Perez and MacDonald, 2017b).

and sediment delivery to streams (Switalski et al. 2004). Deactivation implies an attempt to limit road access but also to reestablish some of the natural hydrogeomorphic characteristics of the site (Allison et al. 2004). Treatments may include gating or permanent traffic barriers, ripping of the roadbed, restoration of stream crossings or full road recontouring (Switalski et al. 2004). A comparison of three erosion-control mulches on decommissioned forest road corridors in the northern Rocky Mountains (Foltz 2012) showed that wood-based alternatives are as effective at reducing sediment production as straw, and that the amount of effective ground cover provided by mulch, plants and litter appeared to be more important than the type of mulch. A recent study in Colorado found that ripping of the roadbed was effective at trapping almost all of the eroded sediment (Figure 5.6) (Sosa-Perez and MacDonald 2017a, b). However, deactivation treatments are not always effective. In a Northern California study, Madej (2001) observed no detectable erosion on 80% of treated road reaches, but observed road fill failures on 20% of road reaches after a 12-year recurrence interval storm event.

Again, there are many research questions on road deactivation and restoration that remain to be addressed, and knowledge regarding mechanisms for the effectiveness of specific BMPs remains limited. There is a pressing need to identify where sediment originates, understand why and how sediment delivery is controlled, and explain exactly how BMPs protect water quality. Understanding these mechanisms and differences between short- and long-term effectiveness will move the science toward the ability to develop the most effective site-specific BMP prescriptions (Edwards et al. 2016). For example, replicated research is needed across various temporal and spatial scales, topographies, soil types and climates to more fully understand the benefits of road decommissioning (Switalski et al. 2004). Additionally, given the associated costs and uncertainty around effectiveness, additional attempts to develop decision trees and other prioritization methods to facilitate decision-making by forest resource managers about which road segments to consider for deactivation or restoration may prove valuable (Thompson et al. 2010). For example, the Geomorphic Road Assessment and Inventory Package (GRAIP) is a process and a set of tools for analyzing the impacts of road systems in forested watersheds in terms of erosion and sediment delivery to streams. The GRAIP is a collaboration between the Forest Service Rocky Mountain Research Station and Utah State University, and can be locally calibrated in a repeatable fashion with minimal effort. It combines a road inventory with a powerful GIS analysis tool set to predict sediment production and delivery, mass wasting risk from gullies and landslides, stream diversion potential, culvert maintenance and fish passage at stream crossings. The road inventory protocol describes how to systematically field inventory a road system using GPS and automated data forms. Quality checked data can then be analyzed in a program implemented in ArcGIS, producing a map of surface erosion, accumulated road sediment in streams, and contributing length by segment, which relates directly to slope stability and gullying risks (Black et al. 2012).

In another example, Takken et al. (2008) present a methodology based on the principle of hydrological connectivity to evaluate the risk of road-derived runoff delivery. Their process allows estimation of runoff volume that may reach a stream through each of three different delivery pathways — stream crossings, gullied pathways and diffuse pathways — during a 1-in-10-year, 30-minute event. The degree of connectivity of a road depends on catchment characteristics, such as topography, road placement, drain spacing and road and drainage density. Risk assessment maps outlining the distribution of different delivery pathways within a catchment are used to assess potential runoff connectivity, highlight hot spots for runoff and sediment delivery, and evaluate different procedures for road rehabilitation or deactivation. Some decision support tools have attempted to include estimates of the potential costs to community drinking water treatment facilities due to increased sediment inputs to the water supply (Allison et al. 2004), and these efforts could continue to be refined.

5.4. Site preparation effects on soils and erosion

The Oregon Forest Practices Act stipulates that after heavy thinnings or clearcuts, industrial timberlands must be replanted to trees within 24 months. Prior to replanting, activities are usually conducted to reduce vegetation that competes with tree seedlings, reduce habitat for animals that damage seedlings, and to create spots for planting (Fitzgerald 2008). To reduce wildfire risk and increase plantable area, site preparation usually includes treatment to reduce the amount of slash (limbs, tops and poor-quality logs) leftover from harvest operations. Site preparation can involve the use of herbicides, mechanized equipment, fire or some combination of these methods.

In the past, site preparation in western Oregon was usually done via broadcast burning. There are longstanding concerns about the impacts of this activity on forest soil protective layers and capacity for infiltration (e.g., Isaac and Hopkins 1937) and its contributions to erosion (e.g., Bennett 1982; Beschta and Jackson 2008). Slash burning often exposes the mineral soil by consuming forest floor material, and severe fires can cause soils to become hydrophobic, increasing the chances of sediment production (Neary et al. 2000). Under current practices, slash is usually piled prior to burning (Fitzgerald 2008), which significantly reduces the areal extent of exposed mineral soil, and slash fires in general are used less extensively than in the past (Swanson et al. 2000). In some cases, some or all of the slash can be distributed onsite. The Forest Practices Act prohibits placing or leaving slash in or near streams.

Mechanical site preparation (e.g. with a rubber-tired skidder or crawler tractor) is used primarily to remove slash or heavy accumulations of nontree understory “brush” vegetation. Disadvantages of mechanical methods include removal of topsoil and soil compaction (Fitzgerald 2008). Tractors and skidders can displace considerable amounts of forest floor organic debris and topsoil into slash piles, and can leave larger areas of bare soil than does harvesting itself, increasing the potential for runoff and erosion. Where soil is compacted over an extended area, mechanical treatments such as disking can improve soil porosity and infiltration rate (Neary et al. 2000). Soil compaction from heavy mechanized equipment can be reduced by conducting treatments when soils are frozen or moisture content is low (Rose and Haase 2006).

Industrial timberlands in western Oregon are typically treated with an herbicide or herbicide blend prior to replanting in order to suppress competing native and invasive species. Neary et al. (2000) maintain that herbicide treatments do not alter the integrity of the forest floor or increase the extent of bare mineral soil left after harvesting and argue that, in general, herbicide use ranks behind both fire and mechanized equipment in severity of impact. But understory plants mitigate erosion by attenuating raindrop energy and reduce soil moisture via transpiration, so the degree to which the soil remains protected following herbicide use is partly a function of slope and how much litter and duff cover remains after the vegetation is killed. For example, Slesak et al. (2015) found that vegetation control with herbicides increased erosion after post-wildfire salvage logging on steeply sloped sites in southern Oregon where there was no forest floor layer. Schmidt et al. (2001) observed reduced root cohesion following herbicide application, consistent with modeling results by Sidle (1992) indicating that suppressing understory vegetation drastically reduces slope stability, which together indicate that herbicide application can act to extend the window of landslide hazard after logging. Chapter 6 discusses forestry pesticides, including herbicides used in site preparation, in greater detail.

Research that distinguishes the effects of site preparation from those of harvesting and roads on water quality appears to be relatively limited. In general, any site preparation activities that contribute to an increase in bare mineral soil, soil compaction or soil mixing have the potential to increase sediment production. As with harvesting activities, if conducted according to current BMPs the potential for site preparation to generate significant additional sediment is probably not large in most cases, especially compared to the effects of roads. But as with all such generalizations, there can be exceptions in specific cases, especially on steeper slopes.

5.5. Increased landslides

In forested headwater catchments, mass wasting processes (e.g., translational slides, debris flows) may be the dominant processes responsible for sediment delivery from hillslopes to the stream network (Dietrich and Dunne 1978; Benda et al. 2005). Many studies have found that unpaved haul roads in steep, unstable terrain can increase the occurrence of mass movements by 25 to 350 times (Gray and Megahan 1981; Amaranthus et al. 1985; Wemple et al. 2001). Landings and skid trails have also been identified as sources of landslides (Keppeler et al. 2003). Across a broad range of conditions, removal of trees has also been shown to reduce the stability of steep slopes and increase the risk of landslides and mass movement (Goetz et al. 2015; Guthrie 2002; Imaizumi and Sidle 2012; Jakob 2000; May 2002; Montgomery et al. 2000; Schmidt et al. 2001); potentially significantly impacting downstream resources (Benda et al. 2005). Numerous investigations have shown that for a period of from about two to 15–20 years after harvesting, the rate of landsliding is about two to 10 times higher than prior to harvest (Sidle and Bogard 2016). The time and duration of increased landslide hazard after harvesting are thought to be primarily functions of the rates of root decay and new root growth, and also species composition and distribution (Chang 2012; Roering et al. 2003; Schmidt et al. 2001). It has been estimated that forest harvesting and forest road construction can increase the densities of landslides impacting streams and the delivery of sediment to stream channels due to mass movement events by about 0.6–138-fold

(Swanson and Dyrness 1975; Beschta 1978; Guthrie 2002; May 2002; Brardinoni et al. 2003; Hassan et al. 2005).

In the Oregon Coast Range, it has been estimated that debris flows can entrain about 2–15 m^3 of sediment per meter of channel length (Benda 1990; May 2002; MacDonald and Coe 2007). However, prediction of the downstream transport rates of this material is challenging due to the typically high flow resistance and roughness in headwater channels (e.g., large woody debris, channel steps, large clasts) (Curran and Wohl, 2003; Benda et al. 2005; Hassan et al. 2005). In fact, large wood in streams can be effective at reducing downstream transport of sediment by decreasing stream velocity and increasing sediment storage (Davidson and Eaton 2013). Estimates in the Pacific Northwest for sediment storage are about 0.5 m^3 of sediment per meter of stream channel (May and Gresswell 2003), although this may be episodically released during mass movements and high-flow events (Benda et al. 2005).

As a result of splash damming and other historic logging practices, many western Oregon streams remain deficient in large wood compared to conditions prior to Euro-American settlement (Montgomery et al. 2003). Landslides that originate in clear-cuts contain less large wood and therefore travel farther and are more likely to enter streams than slides originating in intact forests. Landslides also terminate sooner when they enter areas with forest cover (Guthrie et al. 2010). Large wood and other factors that contribute to flow resistance play a major role in retaining coarser material that forms salmonid spawning gravels but are less effective at inhibiting the transport of very fine-grained material. Historic removal, and current and future supply of large wood in Oregon streams, and the role this key aspect of stream structure plays in sediment storage and release, are fundamental ways in which forest management continues to interact with drinking water source quality.

Increases in occurrence of mass movements following forest harvesting activities have been attributed to changes in hydrologic regimes, rather than due to specific mechanical or construction activities (Sidle and Ochiai 2006; Araujo et al. 2014). After forest harvest, soils become saturated more quickly (Johnson et al. 2007). When soils are saturated, slopes become more susceptible as soil pore pressures rise and cohesion drops, usually during intense rain, snowmelt, or rain-on-snow events. Intact forests on steep slopes contribute to slope stability via both geomechanical and hydrological processes. Tree root systems help to anchor forest soils to the slopes, and the tree overstory attenuates rainfall and soil saturation (Preti 2013). There is considerable evidence showing that increased landsliding after harvesting is strongly linked to the loss of root reinforcement and cohesion in forest soils after the trees are removed and as the roots decompose (Sakals and Sidle 2004; Roering et al. 2003; Guthrie 2002). In a study in the Oregon Coast Range, Schmidt et al. (2001) found that some 100-year old industrial forests had lateral root cohesion and root diameters very similar to 10-year old clearcuts, indicating that harvesting can modify root cohesion for at least a century and that the influence of root cohesion variability on landslide susceptibility cannot be accurately assessed solely on the basis of age class or the presence of one species of vegetation. Root reinforcement also decreases in areas of higher soil moisture because the tensile strength of roots decreases (Hales and Miniat 2017). The amount of reinforcement supplied by roots depends on the tensile strength and distribution of roots in the soil column. Small roots provide proportionally greater cohesive strength than larger roots.

The other primary mechanism by which forests contribute to slope stability is by attenuating rainfall and soil moisture (Preti 2013), which is important because the most common proximate cause of landslides is rainfall and snowmelt (Sidle and Bogard 2016). Mature stands of Douglas-fir and hemlock can reduce the amount of rainfall reaching the ground by 20%–30% or more (Link et al. 2004 and citations therein). Reduction or loss of this canopy interception after harvest increases rainfall intensity and contributes to elevated pore pressure in the soil and reduced slope stability (Baum et al. 2011; Keim and Skaugset 2003). Loss of tree evapotranspiration after harvest also increases soil saturation and reduces shear strength. Sidle and Bogard (2016) argue that in temperate forests, root reinforcement is usually a more important slope-stabilizing agent than transpiration or canopy interception. Increased landslide risk associated with forest harvesting can be reduced by partial cutting of the stand and retention of understory vegetation (e.g. Dhakal and Sidle 2003; Sakals and Sidle 2004; Turner et al. 2010).

Where landscape disturbance (e.g., logging or fires) releases sediment in debris flows, some of this is stored in the steep valley network where it is removed by subsequent debris flows and fluvial entrainment. Sediment storage volumes and transit times determine both the magnitude and duration of downstream effects of the disturbances. Lancaster and Casebeer (2007) argue that as research on debris flows and fluvial sediment transport begins to influence land-use practices, there is a need to understand how much sediment is stored and the characteristics of its release. This study, and Lancaster et al. (2010), used systematic cross sections coupled with ^{14}C dating of random samples from bank, terrace riser, and in-channel materials in coastal Oregon watersheds. They showed that substantial volumes of sediment mobilized by mass wasting after disturbance remains stored for centuries or more, and that recently deposited sediment is more likely to be remobilized than older sediment.

The capacity for storage of sediment delivered to streams by landslides and debris flows, and the rate at which it moves through a stream network, vary with watershed size and topography, land use history, climate events and other factors. Thresholds for sediment movement and mobility vary significantly with grain size and flow volume; fine sediment is much more mobile. Introduction of new sediment and propagation of sediment through a forested watershed are largely episodic and associated with infrequent large storms (MacDonald and Coe 2007; Benda et al. 2005; May and Gresswell 2004). In between debris flow events, fine sediment may be transferred by fluvial flow in pulses during smaller precipitation events (Nistor and Church 2005). Mass wasting processes dominate in many headwaters, giving way to fluvial processes where debris flows form fans at junctions with larger streams.

Sediment production was almost certainly quite high in watersheds where significant historic logging occurred, while sediment storage capacity was reduced in watersheds where splash damming resulted in removal of large wood. Owing to the temporal and spatial complexity of these processes, the amounts and locations of sediment mobilized by historic logging that remains stored in Oregon watersheds are likely highly variable across different stream systems and reaches; studies focused on these questions are limited. However, in light of Oregon's extensive history of industrial logging and known linkages between harvesting in steep coastal watersheds and increases in mass wasting, evidence (e.g. Koehler et al. 2007) suggests that some fraction of the sediment delivered to Oregon waterways under historic practices may remain stored there today. Such "legacy sediment" is deposited when intensified land-use results in sediment deliveries greater than sediment transport capacity and may lead to valley-bottom aggradation, ultimately followed by channel incision when the sediment wave passes and sediment loads decrease. These aggradation–degradation episodes can leave substantial volumes of sediment in storage because vertical channel incision proceeds more quickly than channel widening (Wohl 2015). Modern forest practices appear to significantly reduce sediment production related to timber harvesting. The dynamics of fine-grained and coarse-grained sediment storage, residence times and mobilization differ significantly.

However, even in the absence of additional sediment production, increases in peak flows associated with tree removal can remobilize sediment currently stored in streams but associated with timber harvesting decades ago. The likelihood of this may be compounded by predicted increases in peak flows associated with infrequent large storms and climate change.

The precise ways that root reinforcement and anchoring interact with topography, forest structure, soil depth, geology, changes in water movement and soil moisture after harvest — and the relative influence of these factors on slope stability across different sites — are complex and not fully understood (Hales and Miniat 2017; Moos et al. 2016; Schmidt et al. 2001). Despite the knowledge we have amassed regarding the effects of forest management activities on mass movements and sediment delivery to streams, quantitative evidence of the explicit linkages between upstream inputs and downstream fluxes of sediment relevant to community drinking water supply remains limited (MacDonald and Coe 2007). The linkage between mass movements in headwater streams related to forest harvesting activities and downstream water supply is complicated due to multiple factors. These include: the random and episodic nature of mass movements that makes them difficult to study, cumulative effects from multiple disturbance agents, heterogeneous in-channel storage and release of sediment, and "increasing temporal and spatial variability in the delivery of sediment from hillslopes to headwater streams and from headwater streams to downstream reaches" (MacDonald and Coe 2007, p. 164; Klein et al. 2012). Moreover, existing studies across the PNW do not adequately reflect the broad range of climate, geology, topography and vegetation which drive highly variable hydrologic and mass movement processes across the region.

Much remains to be learned regarding the extent to which forest management activities, which influence mass movements, ultimately impact turbidity and sediment at a scale relevant to most downstream drinking water utilities. There are also information gaps regarding historic and current sediment production from forest practices, sediment storage capacity, and rates of sediment movement through different stream networks in Oregon. However, an interesting study by Wheatcroft et al. (2013) sheds some light on these issues. They quantified sediment accumulation rates over the past 125 years at depths of 70–200 meters on the continental shelf of the Pacific Ocean off the Umpqua River. Wheatcroft et al. (2013), using ^{210}Pb geochronology at a dense array of sampling stations (73), identified a 2- to 4-fold increase in sediment accumulation rates and a shift toward finer sediments that occurred, on average, in 1967 ± 13 years. This period is consistent with the history of industrial logging in the Umpqua basin, which peaked in the two decades after World War II and coincided with a wet phase of the Pacific Decadal Oscillation (1944 - 1978) when average and peak river flows were elevated. Their analysis indicated that hydroclimatic changes alone could not explain the increase in sediment accumulation rates; changes in sediment yield must have occurred, most likely caused by widespread logging in the Umpqua basin uplands.

Wheatcroft et al. (2013) point out that detecting a logging signal on the continental shelf is notable because, despite considerable evidence (e.g., from paired watershed studies) that logging has led to elevated sediment production from disturbed headwaters, it generally remains uncertain whether these effects scale up to encompass entire river basins thousands of square kilometers in area. The authors list some reasons for this uncertainty. First, in any given year, just a small fraction of the basin is disturbed by logging; evidence indicates that only about 1% of the Umpqua basin was logged even in peak harvesting years, far less than typical in paired watershed studies. Another factor is the storage capacity of large basins, whereby sediment mobilized by harvesting activities is deposited before reaching the channel network, or stored in valley bottoms or estuaries. Lastly, intervening processes such as landslides and bank failures may confound or obliterate environmental signals as they propagate through sediment routing systems. All of these potentially contributing factors (and the fact that a significant portion of the watershed had been logged prior to construction of the reservoir) were used by Ambers (2001) to help explain the lack of a logging signal in a flood control reservoir in the western Cascades.

Despite these potentially confounding variables, Wheatcroft et al. (2013) were able to detect the cumulative effects of timber harvesting at the basin scale in Umpqua River continental shelf sediments, expressed as an increase in sediment accumulation and a shift in sediment grain size toward finer particles. The authors also comment on the relatively short time lag between the period of maximal upland disturbance (1945–1955) and estimated age of the sediment accumulation rates increase on the continental shelf (~1967 ± 13 years). They attribute this finding to limits on fine-grained sediment storage capacity in the Umpqua basin and the fact that the fines they found on the shelf are more likely to be readily propagated through the system than coarser material. Noting similar patterns on the Eel River (California) margin, the authors favored the conclusion that timber harvesting results in delivery of more fine-grained sediment to river channels and that this material propagates through the sediment routing system. But they also allowed that timber harvesting, by increasing landslide frequency, could simply lead to an overall increase in sediment export but no change in grain size, and that the fining trend offshore could arise from the inability of post depositional reworking to winnow fines under increased deposition rates.

The study by Wheatcroft et al. (2013) indicates that large volumes of fine-grained sediments mobilized as a result of forestry activities in a coastal Oregon watershed can readily move through the entire stream and river system. Their results focus on a time period when harvesting intensity was higher than today and prior to development of BMPs to mitigate sediment production. Nevertheless, their findings link sediment produced by forestry in an upper watershed to its ultimate fate on the oceanic continental shelf, implying that forestry-related fine sediments can also reach municipal water systems in this and similarly-managed coastal Oregon watersheds. Still, adapting such knowledge to forest management today will require the filling of major information gaps regarding how particular components and aspects of forest operations produce such sediment, and how it propagates through watersheds. MacDonald and Coe (2007) argue that more studies are needed to directly measure the effects of current forest operations on sediment production in headwater areas, explicitly link these sources to the channel network, evaluate sediment routing, and then document whether there is a resulting downstream physical response. This will require explicit consideration of hillslope-channel connectivity (Bracken and Croke 2007) rather than simply using watershed-scale mean or total sediment production.

5.6. Summary and conclusions

Linkages between active forest management and increased sediment loading in streams have been studied extensively and are well-established in broad terms. There is also an expanding body of evidence indicating that modern practices such as improved road-building methods and stream buffers have significantly reduced sediment production from forest management activities, and the chances that this sediment will enter waterways. But these effects and findings are highly variable due to the complexity of interactions among factors such as site-specific ecology, geology and geomorphology; management prescriptions; and land-use histories. The specific sources of mobilized sediment within an actively managed area are also often not clear. Considerable uncertainty remains in predicting precisely how a particular set of forest management actions will affect sediment production in specific cases. Further, there is a paucity of research focused on linkages between sediment inputs related to timber harvesting and associated activities in headwater areas of watersheds and increases in suspended sediment or turbidity in water withdrawn downstream for domestic uses.

A range of potential contributing factors may help explain the lack of research focused on forestry and drinking water linkages. As watershed size and distance from forest management activities increase, it becomes progressively more challenging to isolate and quantify the effects of particular actions (Sidle and Gomi 2017). There are usually cumulative effects resulting from forest management in larger watersheds, partly due to variability in forestry activities (e.g., road building and use, harvesting and site preparation) and timing of their impacts on stream sediment, with some actions having immediate effects and others taking years to become apparent. Timber has been harvested for a century or more in many Oregon watersheds, historically without BMPs in place, with a legacy of sediment production and sediment transfer downstream in many watersheds. Over time, affects accumulate in complex patterns across forestlands managed through multiple harvests and rotations. Distinguishing effects of modern forest practices from those used earlier — and whether increased sediment and turbidity originates primarily from remobilized natural or anthropogenic sediments within streams, streambank erosion, or sources external to the waterway — is difficult and complex. Climate variability, the generally episodic nature of sediment movement, and the outsize influence of stochastic events such as infrequent large storms can introduce additional uncertainty into research findings (e.g., Grant and Wolff 1991). Finally, in larger watersheds, forest management is often not the only land use or potential source of sediments.

For these reasons, it is difficult to make specific, firm conclusions regarding how, where and the extent to which sediment produced by active forest management in a headwater area affects water quality downstream at the drinking water intake. However, an extensive body of evidence accumulated through forestry and sediment-focused research conducted in upper watersheds is highly relevant to drinking water quality (Swanson et al. 2000). Reasoned inferences can be drawn from this evidence base regarding effects on drinking water sources because hillslopes, headwaters and larger downstream waterways are all elements of fundamentally connected and integrated hydrological systems (Bracken and Croke 2007). Headwater streams comprise about 60% to 80% of total stream length in a typical river drainage (Benda et al. 2005) and generate most of the streamflow in downstream areas, and these first- and second-order streams cumulatively contribute to, and can profoundly affect water quality downstream (Nadeau and Rains 2007).

Headwater streamflow is usually routed efficiently downstream, meaning that management-induced changes in streamflow parameters will accumulate downstream (Reiter et al. 2009; Bywater-Reyes et al. 2017; Bywater-Reyes et al. 2018). Because turbidity and fine sediment can be readily transported downstream, changes in headwater inputs of these constituents may be directly linked to downstream conditions. In contrast, linkages between upstream inputs and downstream fluxes for coarse sediment and large woody debris are considerably weaker (MacDonald and Coe 2007). It is also important to note the substantial variation in distances between actively managed forests and drinking water intakes across the range of different municipal water suppliers in Oregon. Findings from studies showing that forest management activities or forest roads can increase sediment production and reduce stream water quality in headwaters can be more reliably extrapolated to indicate that drinking water may also be impacted where intakes are in relatively closer proximity to these management activities and have fewer intervening land uses.

In general, due primarily to the complex interplay of factors outlined above and difficulties in isolating and quantifying the sources and fates of mobilized sediment, we found little direct, quantitative evidence that forestry activities and forest roads impact community drinking water in Oregon. But there is considerable indirect evidence that forestry can have such effects, and likely continues to have effects in certain cases, inferred from the following:

1. Extensive findings regarding linkages between forest harvest activities, forest roads and increases in mass wasting in upper watersheds.
2. Cumulative and legacy effects of harvesting, site preparation and forest roads dating from periods when BMPs were not as robust.
3. Inevitable variability in BMP implementation and effectiveness across different site factors such as land use history, geology, topography (i.e., slope) and also different forest operators, harvesting technologies and climatic conditions.
4. The ability of fine sediment and turbidity to be carried considerable distances, especially during peak flow events.
5. The inherent connectivity of hillslopes, headwaters and larger downstream waterways.
6. The lack of provisions to protect small, non-fish-bearing, ephemeral and intermittent streams during harvesting, and the lack of water quality protection provisions for operations in landslide-prone areas.

5.7. References

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