Muddy Waters: how floods clarify evolving relationships among landscape processes and resource management decision-making in municipal watersheds

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Abstract

Salem, Oregon, a city of 125,000, has long relied on the North Santiam River, flowing out of the Cascade Range into the Willamette Valley, as a municipal source of nearly pristine water. From Feb. 5-9, 1996 northwestern Oregon was inundated by a series of intense storms. These storms, originating in the subtropics, brought a combination of record-breaking rain and warm temperatures. River flood stages the first week of February 1996 were comparable in magnitude to the December 1964 flood, the largest in Oregon since flood control reservoirs were built in the 1940s and 1950s (Taylor 1996, Willis 1997). With the heavy rainfall and flooding, the Army Corps of Engineers flood control reservoirs and the North Santiam River received large amounts of sediment-laden water.

The February 1996 storm produced extremely high turbidity throughout the North Santiam River during and following the storm event. Turbidity readings as high as 140 nephelometric turbidity units (ntu) were measured at the City of Salem's Geren Island water treatment plant intake, which is designed to treat water at less than 10 ntu (Bates et al. 1998). Because the river water is normally of extremely high quality, the city uses a slow-sand filtration system that can treat pathogens and moderate turbidity and has low operating costs relative to conventional filtration systems. High turbidity, however, may damage the slow-sand filters. The turbidity experienced in February 1996 overwhelmed the filtration capability of the city's water-treatment plant, forcing the city to close the plant for 8 days. After initiating unprecedented measures to curtail customers' water use and building emergency pretreatment facilities, the city reengaged the treatment plant before serious water shortages materialized. However, turbidity exceeded drinking water standards set by the U.S. EPA through mid-July, and levels of turbidity remained unusually high for five months thereafter.

The high turbidity triggered diverse economic consequences. Damage from clogging of the filters, plus other short-run costs to the city's water utility totalled $1.1 million. Additional, but undocumented, costs of $20-45,000 occurred as political leaders and staff were diverted from normal activities. Some industrial water customers incurred costs of $2-3 million, primarily lost revenues incurred because they responded to the city's request to curtail operations during the crisis. Workers at the plants experienced a loss of $56,000 in wages during the temporary layoffs. Although the city issued an alert when the treatment plant was closed, asking all residential and commercial customers to limit non-essential uses, the overall impact apparently was no more than an inconvenience, and the alert may have triggered some water hoarding. The city, at a cost of $1.6 million, subsequently increased its ability to cope with future pulses of high turbidity by expanding an early-warning monitoring system, increasing its treatment capacity, securing back-up supplies from other sources, and increasing storage of treated water. Industrial customers also apparently incurred costs of about $80,000 to reduce the risk of future

disruptions by securing back-up supplies and increasing on-site filtration capabilities. Ironically, however, this unprecedented occurrence of high turbidity clarified the value of having a watershed that usually delivers extraordinarily pure water: on average, it allows the city to avoid $2-4 million in annual treatment costs.

In the weeks and months following the February floods, controversy raged over the causes of the water supply problems. Possible contributors included upland forest land management, institutional inadequacies, reservoir management and poor crisis decision-making. In a real sense, the flood's muddy waters revealed the complex and often contradictory web of management objectives among the agencies and parties responsible for water management in the Santiam. It specifically highlighted how management for one narrow set of objectives might exacerbate problems in another sector. For example, decades of logging in the North Santiam basin targeted the most unstable piece of ground, thereby potentially exacerbating production of sediment causing persistent turbidity during storms. The operation of dams for flood control captures and prolongs the release of persistent turbidity downstream, causing problems for municipal water users. Relying on the *normal* behavior of a watershed to produce clean water under all circumstances exposes societal vulnerability to inherent geological hazards and their interactions with land and water use decisions. Trade-offs involved in reducing persistent turbidity turned out to be much more complex in space, in resource management decisions, and in time than was previously assumed.

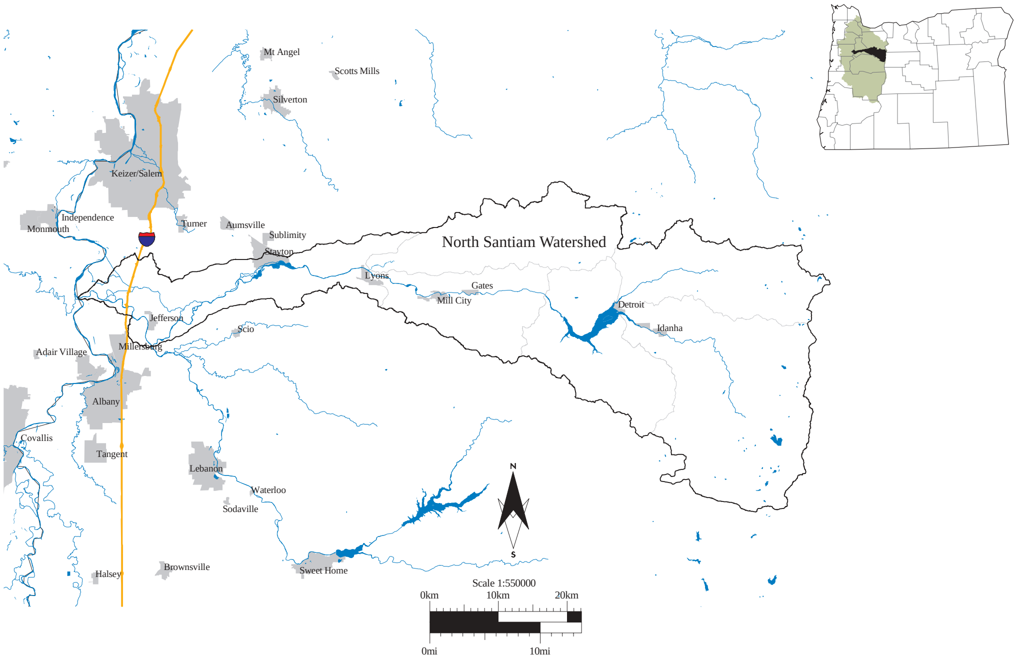
With respect to forest and reservoir management within municipal watersheds, care must be taken to ensure that human activities superimposed on intrinsic geological conditions do not exacerbate existing erosion processes or introduce new ones. Specifically, land and water managers should recognize how watershed processes are coupled in both time and space. In the North Santiam, decades may elapse between flood events capable of producing extreme turbidity; during those decades the combination of land use and geomorphic processes may progressively increase downstream risk. There is a nonuniform spatial distribution of landforms producing turbidity within a watershed, different types of landforms produce different types of turbidity, and landforms and geological processes interact with each other. Consequently, an understanding of the spatial relationships and change over time among sediment production and transport processes is essential to guide land and water use and restoration activities.

More generally, human systems, including institutions, which develop with a narrow sense of time and space become more vulnerable. The lessons of the North Santiam show that cogent watershed planning must recognize time and space scales, tradeoffs, and the imperative that what you do, and when and where you do it matter in land and water management. A proper, more sophisticated accounting of watersheds in space and time gives more options the next time a crisis occurs. Such an accounting will provide for the *correct association* of public concern with those land and water management decisions that have a credible cause/effect relationship on water quality problems. New directions for the watershed that have emerged since the 1996 flood include an early warning monitoring scheme, the prospect of higher resolution spatial planning for the U.S. Forest Service and a broadened multi-agency dialogue regarding water management, as well as a heightened public awareness of the fact that *all* urban residents of the Willamette River Basin live downstream from earthflows, forests and reservoirs.

The 1996 Salem/Santiam flood offers insights into several important watershed-management issues emerging across North America and elsewhere, with special emphasis on three domains of issues: economic, geologic and watershed planning domains. In particular, this case study demonstrates the potential consequences of relying on a watershed to provide high-quality source water for municipal-industrial use, and the economic and institutional adjustments that must be confronted as the demand for high-quality source water rises relative to the demands for timber, flood control, and other goods and services derived from the watershed. This event indicates that the actions of land managers, river managers, and municipal water utilities are interconnected in ways not previously anticipated. Furthermore, the importance of this flood's impacts on turbidity, rather than on more conventional concerns about inundation, highlights the necessity for watershed managers to have a deeper understanding of a watershed's geology, looking beyond topography's impacts on the hydrograph to see how soil composition and geological processes, such as deep earth movements, interact with human activities and infrequent precipitation events to influence water quality. The 1996 Salem/Santiam flood also offers lessons for capitalizing on floods and flood-response planning to shape long-run, watershed management strategies that explicitly recognize these geological characteristics and their impacts on the supply of high-quality source water and other goods and services.

Figure 1: North Santiam Watershed and surrounding area

Note: Context map of Oregon, the Willamette River Basin (green), and the North Santiam watershed (black) within it.



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Introduction

The North Santiam River drains about 766 square miles (1,984 square kilometers) of the western slope of the Cascade Mountains and foothills, joining the South Santiam about 10 miles before the Santiam River flows into the Willamette River (Fig. 1). Elevations in the North Santiam watershed range from 10,500 feet at the top of Mt. Jefferson to 150 feet at the confluence with the South Santiam.

Flows on the lower 60 miles of the North Santiam are regulated by two main structures: Detroit Dam and Big Cliff Dam, built and operated by the U.S. Army Corps of Engineers. The Corps operates Detroit Dam to provide flood control, power production, and recreation. Big Cliff Dam, 3 river miles downriver, smoothes the variations in flow as pulses of water are released from Detroit Reservoir to meet peak demands for hydroelectricity (North Santiam River Cooperative 1997). Detroit Reservoir is filled annually by the runoff from snowmelt and spring storms, kept mostly full during the summer, and then drawn down in the autumn. Combined, the two reservoirs have a storage capacity of 461,000 acre-feet (State of Oregon Water Resources Department 1992).

The city's water intake is located about 30 miles below Big Cliff Dam and 17 miles above Salem, just upstream of the town of Stayton (Fig. 1). Nearly all of the land in the 490,000-acre watershed above the intake is forested, and the area is home to several small towns. More than 70,000 acres of national forest in the watershed have been logged (U.S. Forest Service Detroit District Ranger Station 1998), mostly at elevations below 4000 feet. Higher elevations have been designated wilderness. Skyline logging, with logs hauled to landings by overhead cables, is the primary logging method in the watershed because of the steep terrain, but some helicopter logging also occurs. The volume of timber harvested from the watershed is decreasing, primarily because decades of heavy logging have reduced the number of suitable trees remaining and have triggered tighter environmental restrictions (Shipley 1998). In 1996, for example, 15.6 million board feet of timber were harvested from national forest lands in the watershed, compared to 148 million board feet in 1986 (U.S. Forest Service Detroit Ranger District 1997).

The North Santiam watershed also provides numerous recreational opportunities. Popular recreational pursuits in the subbasin include hiking, fishing, swimming, mountain biking, mountain climbing, driving for pleasure, and sight seeing (North Santiam River Cooperative 1997). The area contains several developed campgrounds and countless undeveloped camping sites. Detroit Lake is a popular recreation spot, with the second highest boating use in Oregon and 735,000 annual recreation visits (State of Oregon Water Resources Department no date). Breitenbush Hot Springs, a private operation, offers hot springs and rustic accommodations year-round.

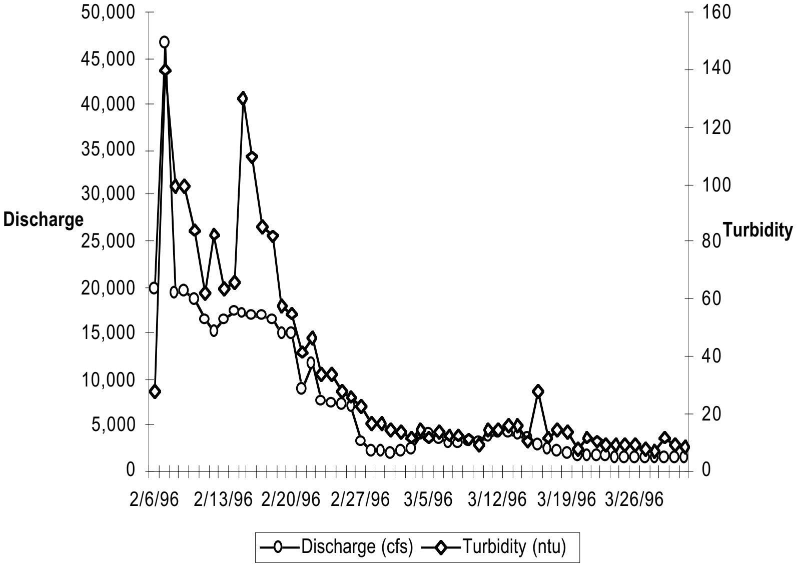
Increases in suspended sediments triggered by the February, 1996 flood and subsequent storms

Unusual weather conditions set the stage for a major flood event in early February 1996. Extremely wet weather during the fall and early winter of 1995-96 saturated soils and filled northwest Oregon streams and reservoirs to high levels. Detroit Dam in the North Santiam watershed, for example, received 68 inches of rain between October 1995 and January 1996, about 148 percent of normal. Unusually high snowfall placed even more moisture in the upper and middle portions of the watershed. By the end of January, the average snowpack in the Willamette Basin was 112 percent of normal.

Then came dramatic temperature changes and record rainfall. During the week of January 29, the northern half of Oregon experienced an intense cold spell for 4-5 days. A moderate storm on February 3 dropped freezing rain throughout the Willamette Valley. On February 6 the weather shifted, with a strong, warm subtropical jet stream bringing record or near-record rainfall to the northern half of the state. Over the ensuing four days, the City of Salem received 8 inches of rain. Above-normal temperatures moved freezing levels to 7,000-8,000 feet, so that rain began falling on snow in the mountains.

The rain and melting snow began streaming off mountainsides at rates unseen for more than 30 years. Streamflows rapidly rose on February 6 and 7, reaching flood-stage levels in many locations. The North Santiam River near Detroit peaked at 24,000 cubic feet per second on February 7, a flow occurring once every fifty years, on average. The rain abated somewhat unexpectedly on February 9. Had the storm continued for another day, some observers (Dyrness et al., 1997) believe peak flows would have been 50 percent higher not just because of additional runoff but also because Detroit Reservoir, which had captured much of the runoff to this point and attenuated downstream flows, was nearly full. With another day's warm rain, the reservoir would have filled and all runoff would have passed over the dam's spillway.

With the heavy rainfall and flooding, the North Santiam quickly muddied. The turbidity sensor automatically closed the headgate to Salem's treatment plant during the night on Monday, February 6. By the next day, the river's turbidity had risen to 140 ntu. Water levels peaked on February 7 but remained unusually high for the remainder of the month as the Corps of Engineers rapidly released flood water from Detroit Dam, first to avoid having floodwaters crest the spillway, and then to create reservoir space for subsequent runoff. In a departure from past experience, turbidity remained high even as water levels began to fall. Figure 2 shows turbidity at the intake and river flows at a nearby gauge through March, 1996. Turbidity at the intake remained above 8 ntu through the end of March, while flows returned to normal levels by the end of February.



Source: ECONorthwest with data from the City of Salem Public Works Department and USGS (1998).

Figure 2: Mean daily discharge and turbidity, February-March 1996

As important as the amount of suspended particles in the water was their composition. The storm triggered the introduction of smectitic clays into the river. Smaller than 0.05 micrometers in diameter, smectite particles do not settle out of still water. Much of the smectite brought into the river by the February storm remained in the reservoir behind Detroit Dam and was delivered downriver throughout the spring and summer until the pool was reduced to its minimum (Bates et al. 1998). Accordingly, turbidity levels at the city's intake remained above 1 ntu through July.

Several storms between November 1996 and January 1997 also caused episodic turbidity exceeding 10 ntu on the North Santiam. Unlike the February storm, however, these turbidity peaks did not remain at extremely high levels for extended periods of time. Following the largest of these storms, on November 18 and 19, turbidity peaked at 91 ntu but quickly returned to normal levels within a short period of time.

Sources of turbidity production in watersheds

Watersheds are physically defined landscape units that naturally funnel all mass (water, sediment, nutrients, wood, etc.) and energy downstream under the influence of gravity to a common outlet. Because of this, watersheds offer a particularly useful delineation for evaluating movement of watershed products, such as sediment that causes turbidity, and consequent effects on downstream users and ecosystems (Montgomery et al., 1995; Omernik and Bailey, 1997). This fact has been recognized in a number of large-scale bioregional conservation efforts, including the Northwest Forest Plan (USDA Forest Service 1994) Salmon recovery (PACFISH 1994), and the Willamette River Basin Restoration Strategy (Willamette Restoration Initiative 2001), that employ a watershed basis for analyzing and managing landscapes. More generally, this capacity of watersheds to produce constituents that can migrate downstream or away from the site of impact is reflected in laws such as the Clean Water Act and NEPA that require management agencies to assess and mitigate the potential cumulative or offsite impacts of land use decisions.

Figure 3: Flood-related headlines from area newspapers

In the days and weeks during and following the flood, it was widely assumed and reported by the media that much of the sediment that caused problems for the Salem water treatment facility was derived from logging activities in the basin's headwaters (Fig. 3). This reflected a widely-held view of a direct causal link between land use (especially forestry) and sediment production and delivery to streams, causing downstream turbidity, such as shown in Figure 4a. Despite the intrinsic appeal of such a simple syllogism, this study confirms decades of research that reveal a more complex relationship among land use activities, sediment production and transport, and turbidity.

Some background on causes of turbidity in water is useful. Turbidity is a measure of the clarity of water in relation to its concentration of light-scattering material. Turbidity in water is typically the result of dissolved and suspended fine organic and inorganic particulates, with the inorganic fraction primarily made up of clays. If turbid water is allowed to stand, most of this material will precipitate out at a rate determined by the size, shape, and density of these constituents and the temperature of the water; as material precipitates the water clarifies. *Persistent turbidity*, on the other hand, is turbidity that does not diminish substantially with time. It results from suspension of extremely fine (<2 microns in diameter) clays that are almost neutrally buoyant in water. After the initial pulse of extremely high turbidity (Fig. 2), which clogged the treatment filters, the primary problem became persistent turbidity which passed through the filtration process and maintained high turbidity readings for several months.

The cause of persistent turbidity can be determined using x-ray diffraction techniques that distinguish between the various clay constituents in a sample of turbid water. In the western Cascade mountains of Oregon, such studies following both the 1996 flood and earlier floods consistently show that water exhibiting persistent turbidity contains high concentrations of a type of clay termed *smectite*, along with lesser amounts of other amorphous clays (Glassman 1997 a,b,c; Youngberg 1971,1975; Pearch 2000, Ambers 2001 a,b; Ulrich in prep.). Smectitic clays are widely but not uniformly distributed throughout the western Cascades. X-ray diffraction techniques can also be used to identify the clay constituents in various landforms and soils, as discussed below. Thus the source of persistent turbidity can be tied, through the clay mineralogy, to particular landforms that have high quantities of smectite. This relationship among landforms, clay mineralogy, and persistent turbidity can be represented as a triangle (Fig. 4b), with each leg defining a causal linkage, as indicated by the arrows, and supported by independent data. In this relationship, land use is not the cause but a contributing factor through its effect on increasing the rate of native erosion processes.

Figure 4a

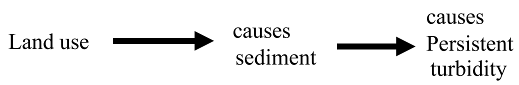


Figure 4b

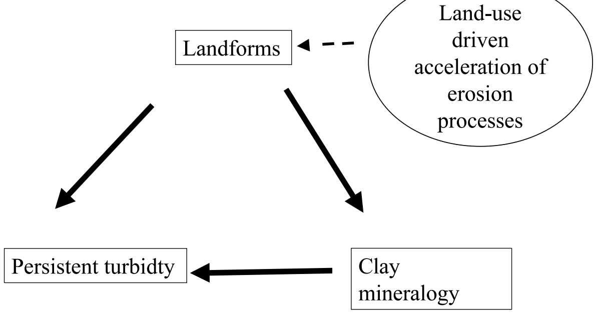


Figure 4: Two conceptual models of the sources of persistent turbidity

The downstream consequence of increased sediment and turbidity is not due solely to the nature of sediment and processes that produce, transport, and deliver it to streams. Another key factor is the ability of the engineered municipal water supply system to filter water and deliver it to consumers. In the next section, we examine how Salem’s water system is configured, how it was operated during and after the 1996 flood, and what the economic consequences were for Salem’s ratepayers.

The City, It’s Response and the Economic Consequences

Salem’s Water System

Drawing water from the North Santiam River allows the city to provide consumers with a reliable, high-quality, and low-cost product. The city’s claim on the river’s water, in the form of water rights, predates statehood and thus, is older than competing claims, and large enough so that the city does not envision a water shortage in the foreseeable future. Equally important, the river’s water is of exceptional quality. It has a low mineral content, making the water suitable, with minimum treatment, for silicon-chip manufacturing, canneries, and other industrial processes. Furthermore, during most of the year river turbidity measures less than 3.0 ntu, close to the current 1 ntu standard for finished (i.e., treated, drinking water) established by the U.S. Environmental Protection Agency. Turbidity standards reflect both aesthetic concerns that arise because most people do not like to drink cloudy water, and health concerns that arise because cloudiness can be associated with the presence of pathogens.

Despite its high quality, the city nonetheless filters all water drawn from the North Santiam. It does so primarily because river water can contain pathogens, such as *Giardia* and *Cryptosporidium* that must be killed or removed to make the water safe to drink. The city also filters the water because turbidity often rises in response to storms. Storms dropping about 1.5 inches of rain in the watershed, which occur frequently, can raise turbidity levels above 6 ntu for a day or so. In addition, there always is some risk that geologic events or human activity above the intake will introduce soil into the river.

Since 1955 the city has relied on a slow-sand filtration system to remove turbidity and pathogens. It consists of several filters, each 5 acres in size, that contain up to three feet of fine sand atop coarse gravel. Raw water is introduced to ponds above the filters and, as gravity draws the water down, the sand removes suspended particles, both organic and inorganic. The filtration is aided by naturally-occurring biological agents that form in the top centimeter or so. After a few weeks, the accumulation of material impedes water flows, and the filter is cleaned by removing the top half-inch of sand. This cycle is repeated until the sand layer becomes too thin. Then, the sand layer is refilled (Salem Public Works 1995; Visscher 1990). In 1996 the system had two 5-acre filters, each with a maximum capacity of about 40 million gallons per day (mgd). The city synchronized their cleaning so that one would be refreshed and brought back on line as the other started clogging.

Slow-sand filtration is less common, especially for large cities, than systems that employ coagulation, flocculation, and sedimentation (CFS) prior to filtration. CFS systems typically are used when the source water has so many suspended particles that they would quickly clog a slow-sand filter. They also are preferred when the quality of source water is highly variable. With CFS, coagulants are mixed into raw water to consolidate suspended particles into larger particles that settle to the bottom of sedimentation tanks and are removed. The water then is filtered, using a coarser-grained medium that allows faster flows than slow-sand filters (Schmit and Boisvert 1997).

Box 1: Advantages & Disadvantages of Slow-Sand Filtration

Advantages

- Low treatment and maintenance costs.
- Simplicity of operation—typically requires 1-2 full-time operators.
- Able to remove disease causing agents such as *Giardia* and *Cryptosporidium*.

Disadvantages

- Vulnerable to turbidity which can clog filters.

Source: American City & County (1997) and Visscher (1990).

With a reliable source of high-quality water, as in the North Santiam, slow-sand filters offer numerous advantages (Box 1). They usually have substantially lower operating and maintenance costs than CFS systems. In their study of municipal water treatment systems in New York, Schmit and Boisvert (1997) found that CFS treatment could increase marginal operating and maintenance costs by 15-30 percent, relative to slow-sand filtration. Slow-sand filters serving a population of 100,000, for example, had annual average per capita operating and maintenance costs of $23-$32, compared to $29-$45 for CFS systems. Salem's slow-sand system is even cheaper, with annual operating and maintenance costs of about $11 per capita. It requires 2-3 full-time operators, versus 8-10 for a comparably sized CFS system and, unless turbidity in the North Santiam stays at high levels for several days, it incurs no costs for coagulants or chemicals other than chlorine.

Another advantage is a slow-sand filter's greater ability to remove potentially harmful organisms, such as *Giardia* and *Cryptosporidium*. Salem's tests show its system consistently removes all cryptosporidium occysts. Furthermore, the system has little susceptibility to operator error.

After filtering the water, Salem disinfects it with chlorine and stores about 100 million gallons in Franzen Reservoir, and 30 million gallons in 14 smaller reservoirs located throughout Salem. From these reservoirs, the water is delivered to about 36,000 residential, 2,800 commercial/industrial, and 35 wholesale accounts (e.g., nearby small utilities).

Daily consumption currently peaks at about 60 mgd, and the city projects that this will increase to 117-130 mgd over the next fifty years (CH2MHill 1994). The city has rights to take 147 million gallons per day (mgd) from the North Santiam, and these rights are senior to virtually all other rights on the river. Hence, even in drought, the city could likely withdraw enough water to meet foreseeable demands.

The numerous advantages of Salem's water system, however, come with risk. Its slow-sand filters require high-quality source water and can be overwhelmed if suspended particles cause turbidity in excess of 10 ntu. To guard against these risks, the city has, among other things, installed an automatic shut-off valve that closes the headgate whenever turbidity exceeds 6 ntu. Brief closures are not uncommon, but the events of 1996 brought additional risks into focus.

Salem's Response

The closure of the headgate to the treatment plant on February 6 left the city with about 130 million gallons of potable water in its reservoirs, roughly a five-day supply at the 28 mgd current usage level. The city quickly began augmenting supplies by pumping about 10 mgd from wells and purchasing a smaller amount from adjacent utilities. By February 13, 7 days after the headgate closed, the city was able to secure supplies of 20 mgd.

Box 2: Salem's Turbidity-Related Water Alerts

Stage Three: Prohibited residents from using water outdoors (i.e., washing vehicles, sidewalks, and parking lots). Prohibited car washes from operating. Large industrial water users asked to conserve water voluntarily. Violations resulted in a $150 fine. In effect February 7-February 22.

Stage Two: Households and businesses asked to cut water use voluntarily by 25 percent and avoid outdoor water use. In effect February 23-March 11.

On February 7, city officials, for the first time ever, declared a Stage Three Alert, prohibiting residents from using water outdoors (e.g., washing sidewalks, parking lots, and vehicles), prohibiting car washes from operating, and enforcing mandatory water conservation (Box 2). Households or business violating the mandatory measures were subject to a fine of $150 and the promise of intense notoriety. Staff also contacted large industrial water users and asked them to conserve water voluntarily and, if possible, to cease operations. A number of businesses, particularly the car washes, either stopped or curtailed operations for as long as 14 days. Several businesses purchased water directly from nearby utilities. Although the response was never quantified, anecdotes indicate that some residents conserved water by reducing shower and bath times, forgoing the washing of clothes, and recycling shower and bath water.

The city also strove to establish some flow of water through the treatment plant. On February 14, the city began diverting water from the river and running it through a makeshift facility where coagulants were added. The water then rested in a settling pond, where some particles dropped out of suspension before the water was applied to slow-sand filter #1. This pretreatment arrangement eliminated most of the suspended particles, but the water going to the filter still had turbidity exceeding 10 ntu. As a result, the filter clogged rapidly and capacity of the filtration system never exceeded 20 mgd, or about 35 percent of the pre-flood capacity.

The filtration of pretreated water plus the acquisition of water from wells and neighboring utilities produced 28-30 mgd, a quantity sufficient to meet average daily use, but continued operation of the filtration system remained somewhat tenuous. After two weeks of mandatory water conservation, the city downgraded to a Stage Two Alert. With the change, the city asked all households and businesses to cut the use of water voluntarily by 25 percent. The Stage Two Alert ended March 11, after turbidity in the North Santiam River clarified to about 10 ntu, a level treatable by the slow-sand filters.

After more than 30 days, the crisis was over, but high turbidity persisted. The source water continued to have high levels of smectite that the filters were unable to remove, so the turbidity of the filtered water exceeded the 1 ntu requirement for finished drinking water through mid-July. To avoid shortages, and after providing reassurance that the smectite causing the problem was not hazardous, the city obtained a waiver from the Oregon Health Division allowing water deliveries.

The bursts of high turbidity between November, 1996, and January, 1997, disrupted, but did not overwhelm the filtration system. An improved emergency pretreatment system enabled the utility to treat about 30 mgd, about one-half the normal capacity. Nonetheless, the city had to purchase water from a nearby utility and pump water from wells. City officials declared a Stage Two Alert only one time during the three-month period, on November 21.

Economic Consequences

The degradation of Salem’s source-water quality had both short- and long-run economic consequences. Initial city loss estimates ranged as high as several million dollars during the first week following the flood. This section of the paper identifies and estimates the value of the damages incurred by the water utility, industrial/commercial water customers, and residential water customers. The estimates of damages are based on interviews with water utility staff and major industrial/commercial customers, and a review of the water utility’s accounting data. Estimation of ecological damages, such as harm to fisheries, the siltation of waterways, and other flood-related damages, may have occurred, but were beyond the scope of this study.

Table 1: Short-Run Damage to the City's Water Utility (1996 Dollars)

Category	Damage
Damage to Filter #1	$1,000,000
Cost of alternative water supplies	$204,467
Installation and operation of emergency pretreatment system	$184,320
Repairs and cleanup	$4,755
Lost revenue associated with forgone sales	$17,000
Diversion of managerial attention	Unquantified
TOTAL	**$1,410,542**

Source: ECONorthwest with information from the City of Salem.

Short-Run Economic Consequences

During and immediately following the February 1996 flood, the water utility, its industrial/commercial customers and their employees, and its residential water users all incurred damages, totaling an estimated $3.4 to $4.4 million (1996 dollars). The short-run costs to the water utility, estimated at $1.1 million, are summarized in Table 1. The accelerated rehabilitation costs to correct the damage to one of the slow-sand filters accounts for the largest share of these costs ($731,601). The utility also had to purchase treated water from neighboring utilities ($204,467), install and operate the emergency pre-treatment system ($184,320), and conduct repairs and cleanup at the treatment plant ($4,755). In addition, interviews with the utility’s major industrial customers indicate that the utility lost an estimated $17,000 in water-sales revenue because these customers curtailed their use of water during the crisis. It was not possible, given the research budget, to survey residential customers and estimate losses in residential revenue. Data from the utility, however, indicate that water use did not drop precipitously during the emergency, perhaps because some residential customers hoarded water to guard against a shortage. Finally, since the city had not recorded data on management and staff attention diverted from tasks on which they would have worked had there not been a crisis, we did not estimate these opportunity costs.

Interviews with water-utility managers and 11 large industrial/commercial customers indicate that the short-run costs to industrial/commercial consumers were between $2.15 and $3.16 million. These costs stemmed primarily from lost revenue ($2-3 million), because the interruption of water use in February 1996 resulted in forgone production and sales, and purchases of alternative water supplies ($129,000). A number of businesses, particularly car washes, either stopped or curtailed operations for as long as 14 days. As in the case of the water utility, we made no assessment of the costs of diverting management and staff attention away from their regular tasks. In addition, several consumers increased the recycling of water at their facilities, but did not record their costs. We found no evidence that the increased turbidity in delivered water damaged the plant or equipment of any industrial/commercial customers.

Although anecdotal evidence suggests that some households conserved water by reducing shower and bath times, forgoing clothes washing, recycling shower and bath water, and purchasing water from other sources, we found no data to estimate the damages to residential consumers. Analyses of averting expenditures and other behavioral changes, such as those by Abdalla (1990), Abdalla and others (1992), Harrington and others (1989), and Laughland and others (1993), were beyond the scope of this study.

A final category of short-run damages is the cost to utility workers of uncompensated overtime and the costs to employees of industrial/commercial customers that were forced to close during the Stage Three Alert. After the crisis had passed, water-utility personnel estimated that they had logged between $20,000 and $45,000 in uncompensated overtime. The failure of municipal workers to record hours of overtime during an emergency is consistent with the findings from other crisis events, such as the Exxon Valdez oil spill (Courant et al., 1993). Managers of the firms that closed during the Stage Three Alert estimated that their workers lost about $56,000 in wages during the emergency.

Long-Run Economic Consequences

Long-run economic consequences, estimated at $1.6 million (1996 dollars), arose as the City of Salem and some of its major industrial/commercial customers made investments to reduce their vulnerability to high sedimentation levels from a similar event in the future. Specifically, the city has invested more than $300,000 through 2001 as part of a larger research effort to identify more precisely the sources of sediment, both human and geologic, and to develop a monitoring system to provide timely information about increases in turbidity. To help with these monitoring efforts, the city has hired an additional water treatment operator, at an annual salary of $58,000. Furthermore, to increase its ability to cope with high turbidity in the future, the city has constructed a permanent pretreatment facility, consisting of a new headgate, a facility for adding coagulants to intake water, and a settling pond, at a cost of $1.2 million.

The city has reassured its major industrial and commercial customers that these steps have reduced the risk of future service interruptions to nearly zero. Nevertheless, at least one industrial customer has drilled a well, at a cost of $80,000, to provide a back-up supply of water, and other firms may have also taken steps to reduce their vulnerability to future interruptions in water service.

<u>Spatial dimensions of sediment and turbidity</u>

Geological sources of persistent turbidity

A more detailed examination of the geography and geology of the Santiam watershed reveals some of the complexity underlying how water and turbidity-causing sediment are produced and delivered downstream (Fig. 6). Although much of western Oregon is underlain by geologic substrates that, when weathered, produce clays, studies in the Salem watershed and elsewhere in the western Cascades have revealed that landforms underlain by smectitic clays are not uniformly distributed but concentrated in particular areas within the watershed (Glassman 1997 a,b,c; Youngberg 1971, 1975; Bates et al. 1998; Pearch 2000; Ambers 2001 a,b; Ulrich in prep.). Moreover, processes capable of delivering this material to streams during storms are also not evenly distributed. The geologic setting and topography of the Santiam watershed are instructive on this point. The watershed is underlain by Tertiary and Quaternary volcanic rocks, primarily andesites and basalts, with some glacial deposits. The basin spans three physiographic provinces with distinctive geologies, landforms, climate, and land use patterns, all of which contribute to the patterns and character of sediment production (Fig. 7). The eastern third of the basin and the headwaters of the North Santiam River are in the High Cascade province, which is a geologically young upland of relatively undissected and unweathered Pleistocene and Holocene volcanics and glacial deposits. Mt. Jefferson, a large Pleistocene volcano, is the highest point in the basin; however most of the High Cascade province has relatively low relief. Since most of the High Cascade region is above 4900 ft. in elevation, winter precipitation is primarily received as snowfall. The combination of low relief, young, hard, and unweathered underlying rocks, and low intensity precipitation result in very limited clay development and few mass movements capable of delivering sediment to channels. Moreover, most of the High Cascade area is managed as Wilderness by the U.S. Forest Service, with only limited timber harvest and road construction along the western margin, further limiting erosion potential.

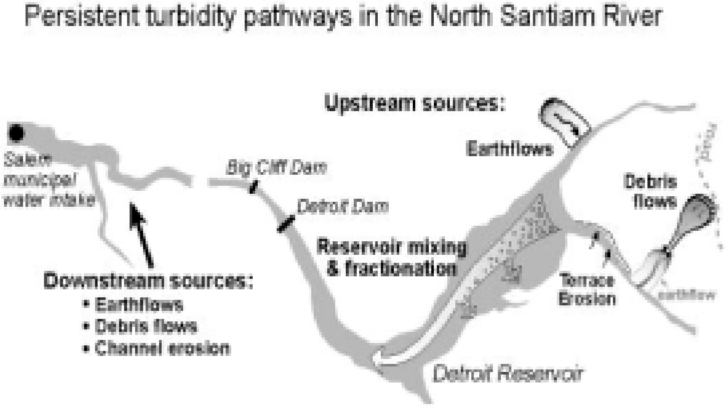
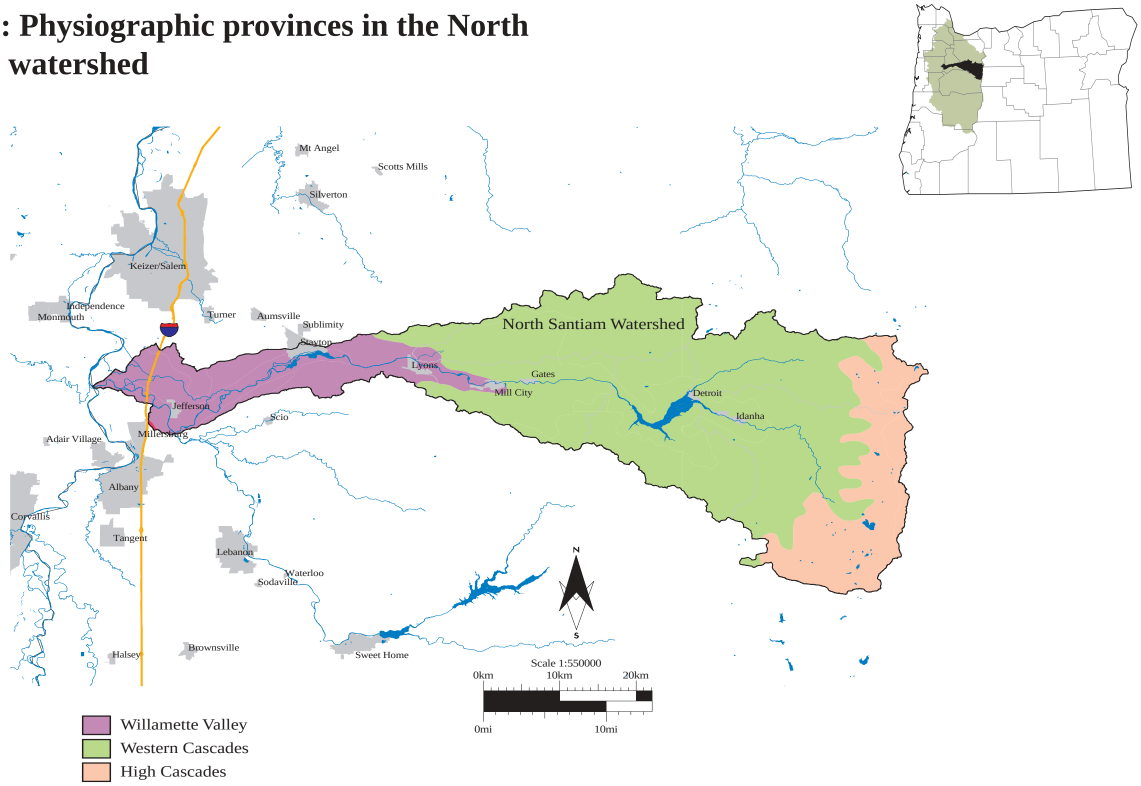


Figure 6: Pathways by which persistent turbidity reaches the North Santiam River

Figure 7: Physiographic provinces in the North Santiam watershed



In contrast, to the west, the middle third of the basin falls within the Western Cascade province, a rugged, steep, and dissected region underlain by a thick, uplifted, and gently warped platform of Tertiary lava, ash, and mudflows. Landforms range from near vertical rock bluffs, to sharp ridges and hillslopes interspersed with rolling uplands of benched or subdued topography. The flatter ground is often associated with earthflows, which are deep-seated, slow-moving mass movements. Earthflows are typically found in areas where small intrusive bodies have cooked and altered the surrounding volcanic pile to clay-producing rock. Much of the clay produced by earthflows is highly smectitic (Glassman a,b,c; Youngberg 1971, 1975; Ulrich in prep.). Landslides and debris flows are common erosional processes in the steeper hillslopes and channels, while glacial outwash terraces are common in valleys and along major stream courses. Winter precipitation falls as rain below 1300 ft. and snow above 4000 ft., but most of the western Cascades lie within the rain-on-snow zone of 1300-4000 ft., where snowpacks may accumulate and melt during warm rainstorms several times each winter, causing high streamflows of the kind witnessed in February 1996 (Harr 1981). Deeply weathered rocks and deposits, large earthflow complexes, high precipitation rates, steep hillslopes, and a variety of mass movement processes result in high sediment production and clay delivery to streams during large storms. Timber harvest on both federal and private lands is the dominant land use, and the entire area is crisscrossed by a dense network of logging roads, further exacerbating the native sediment production potential.

The western third of the basin falls within the Willamette Valley physiographic province, an area of low relief and rolling hills dominated by Pleistocene and Holocene alluvial deposits. Well-developed terrace and floodplain sequences are underlain by gravels, sands, and silts, including an extensive blanket of late Pleistocene lake sediments derived from backwater deposits of the Missoula outwash

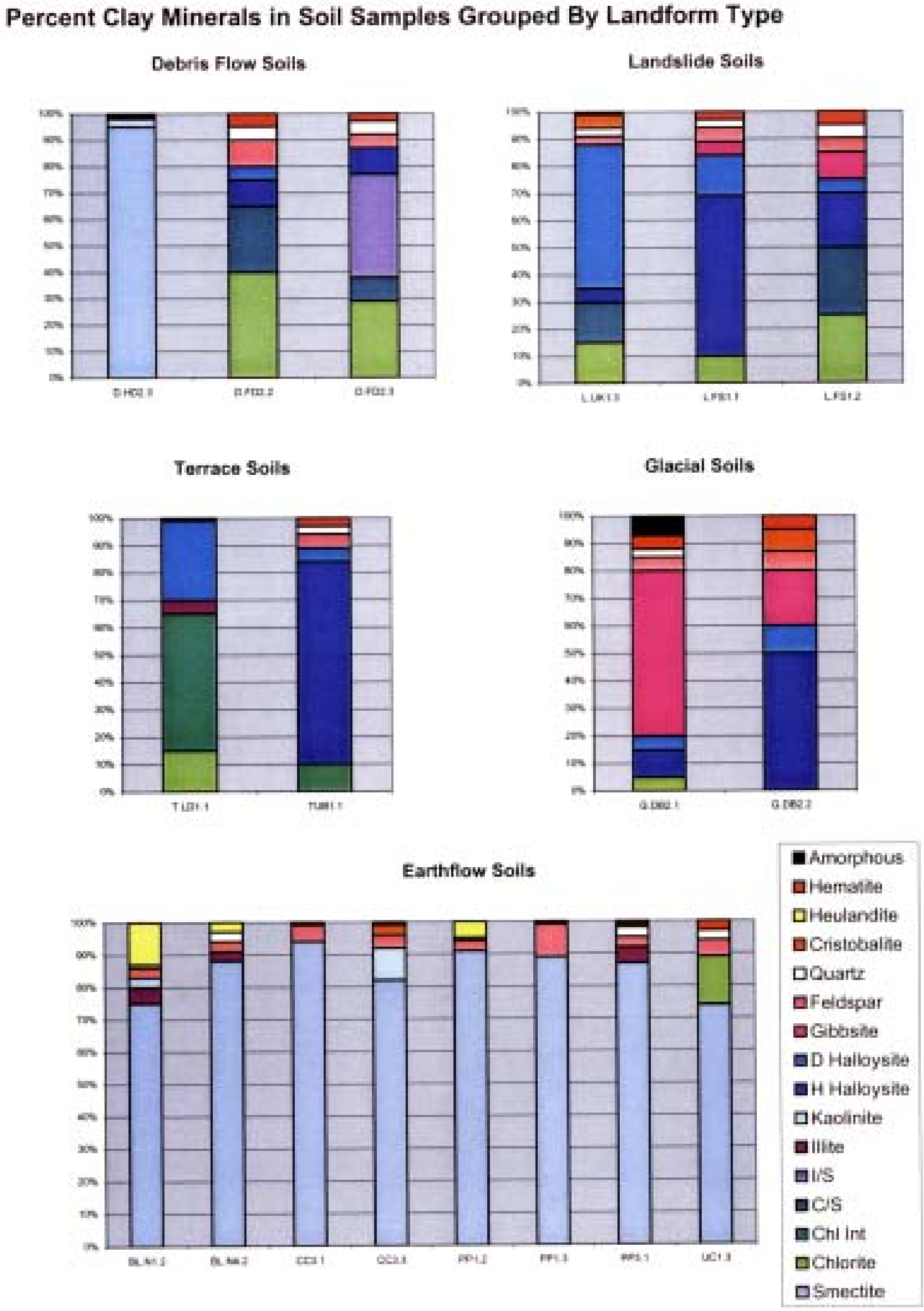


Figure 8: Percent clay minerals in soil samples grouped by landform type. From Ulrich (in prep), samples taken from Divide Creek drainage within the Middle Blowout Creek sub-basin of the North Santiam River watershed. The light blue color represents smectite, which is most commonly present in earthflow soils (all bars in bottom graph) and some debris flow soils (left bar in top left graph).

floods in the Columbia. Although clays are common, most are not composed of the finest, smectitic fractions that result in persistent turbidity. Land use is predominantly agriculture and urban development, resulting in erosion rates several orders of magnitude above undisturbed levels (Anderson, 1954).

A more detailed look at the relationships among landforms, turbidity and clay minerology reveals that earthflows are overwhelmingly the dominant source of smectitic clays producing persistent turbidity in the Santiam basin. Samples from diverse landforms, including stream terraces, landslide deposits, earthflows, and glacial deposits show that smectitc clays comprise between 70 and 90 percent of the clay fraction from earthflows (Fig. 8) (Ulrich in prep.). We found smectite concentrated in only one other landform, soils derived from a debris flow that initiated above an earthflow and traveled through it en route to a stream below. Debris flows traveling through earthflow complexes may incorporate smectitc clays and thereby provide another source of persistent turbidity (Fig. 6). A third potential source for smectite are terraces immediately downstream from earthflow complexes that store smectite-rich sediments derived from the earthflows upstream. Although our limited sampling did not reveal smectite in such terraces and thus did not reveal the extent to which such terraces represent long-term sources of smectite, to be conservative we include them in the subsequent analysis.

Forest land use effects on sources of persistent turbidity

Although our analysis revealed that weathered volcanic landscapes such as the North Santiam watershed naturally produce clays that cause persistent turbidity, we considered how forest land use activities, including logging and road construction, might accelerate or increase natural production rates of smectite and related clays. Our focus was on land use activities that accelerated sediment production or delivery processes in smectite-rich areas of the landscape, i.e., earthflows. Land use activities that we hypothesized might increase sediment production or delivery from earthflows, listed in rough order of decreasing effect, include:

Land use activities

1. forest harvest directly on earthflows themselves, which can accelerate erosion due to compaction, soil disturbance, or changing on-site hydrology resulting in accelerated earthflow movment;
2. harvest in steep unstable areas prone to landsliding upstream from earthflows, where tree harvest can reduce root strength, leading to landslides and debris flows that pass through earthflows;
3. road construction resulting in road-stream crossings upstream of earthflows; such crossings or nodes have a much higher likelihood of failure as slides or debris flows during storms (Wemple et al., 2000); and
4. forest harvest and roads on terraces located immediately downstream of earthflows; soil compaction, disruption, and road failure in these sites might deliver smectite-rich stored sediments into channels.

We conducted a GIS analysis to evaluate the spatial distribution of sites where land use activities might potentially increase sediment production leading to increased persistent turbidity during storms. In this analysis, our primary source of data was the Soil Resource Inventory of the Willamette National Forest, as modified by Doug Shank (Shank 2001). This database consists of a spatially-registered map showing the distribution of field-identified soil/landform units and associated attributes. Soil/landform units of particular interest in this analysis are listed in detail in the appendix of this report. The general types of interest are:

Soil/landform units

1. active earthflows (i.e., areas of currently active earthflow movement as defined by ground deformation, deranged streams, cracks, uprooted, displaced, or tipped trees, and eroding headscarps).
2. dormant earthflows (i.e., areas of past earthflow movement, as defined by hummocky landforms but without active features as defined above);
3. areas mapped as steep and unstable, hence prone to landsliding; and
4. stream terraces below earthflows.

Other data included topography, stream network, and road network for the federally managed forest lands within the North Santiam watershed. These data on soil/landform units were not available for private lands, and thus the following spatial analysis addresses only federally managed public lands in the watershed.

From these data, we first constructed a set of maps identifying locations of active and dormant earthflows that either bordered or were crossed by stream channels, and thus had the potential to deliver sediment directly to the stream network In fact, the high drainage densities within the Cascades meant that almost all of the mapped earthflows were in contact with streams. We then delineated all streams upstream draining to or through mapped earthflows. Road-stream crossings upstream of earthflows and unstable units within upstream areas that drained to earthflows were also identified and mapped. These were interpreted to be potential "trigger sites" for debris flows that might pass through active earthflows, entraining smectitic clays. For these sites we distinguished between those within 1 km upstream of the earthflow and those further away; the former were presumed to pose greater risk than the latter. Finally, we identified stream terraces located within 1 km downstream of earthflows as potential sites for long-term storage of smectitic sediment derived from earthflows.

The maps reveal several important conclusions about the distribution and potential land use impacts on sources of persistent turbidity within the North Santiam watershed. First, the primary sources of smectitic clays are not uniformly distributed over the basin, but are concentrated in certain areas (Fig. 9). In particular most active earthflows are concentrated in the Blowout Creek sub-watershed, with lesser amounts in the Breitenbush and main North Santiam watershed. No earthflows are found within the upper North Santiam and wilderness areas that make up the eastern third of the basin. The reasons for this highly patchy distribution of earthflows are not fully understood, but likely result from the age, composition, and weathering history of the rocks in the western Cascade volcanic pile. The younger rocks making up the High Cascade region have not had sufficient time to weather to produce the high clay concentrations necessary for earthflow evolution.

The distribution of dormant earthflows follows this same trend, but covers a much larger area – in fact 38% of the Blowout Creek sub-watershed is mapped as dormant earthflow. Dormant earthflows represent areas that have likely moved in the past but are not actively deforming and moving today, although distinctive landforms and smectitic clays persist. We are unable to resolve the relative amounts of smectite found within active versus dormant earthflow complexes, and so both are mapped (Fig. 9). We believe, however, that the more dynamic transport processes occurring within active earthflow complexes, particularly their encroachment on streams (Swanson et al., 1985), makes them much more likely sources of most of the smectite in the rivers during high flow events.

Focusing in on the Blowout Creek watershed reveals relationships among active earthflows, streams, and landslide trigger sites (Fig. 10). Many earthflows are surrounded by steep unstable zones; some of these steeper areas are likely headscarps and bluffs formed as the earthflows flowed downhill, leaving harder rock behind. Instability leading to landslides in these areas occurs as the underlying exposed rock along the headscarp is eroded and sapped. Most of these unstable headscarp areas are not likely to fail as true debris flows, since they typically do not concentrate water.

A more likely source of debris flows that can travel through earthflow complexes entraining smectite are steep unstable headwater areas and road-stream crossings upstream of earthflows (see inset, Figure 10). Not all road crossings are potential failure sites; hillslope position (i.e., upper, middle or lower), size of stream, and type, age, and dimensions of culvert are all factors determining failure potential during storms (Wemple et al., 2000). Further GIS analysis including these and other factors could potentially target the highest risk sites.

On the other hand, a much higher number of road crossings that could be potential trigger sites are present if both active and dormant earthflows are considered (Fig. 11). The large areas in these older complexes coupled with dense road and stream networks mean that many more road crossings are present above old, now dormant, earthflows. A much closer look at the potential for these dormant earthflows to contribute smectite should be a component of any management strategy intended to reduce land use effects on turbidity.

Temporal dimensions of sediment and turbidity

Along with being highly concentrated spatially, delivery of smectitic clays to the stream network is also concentrated in time at several scales (Fig. 12). Almost all major turbidity episodes occur during large winter storms; peak streamflows and saturated soils are necessary to fully galvanize and

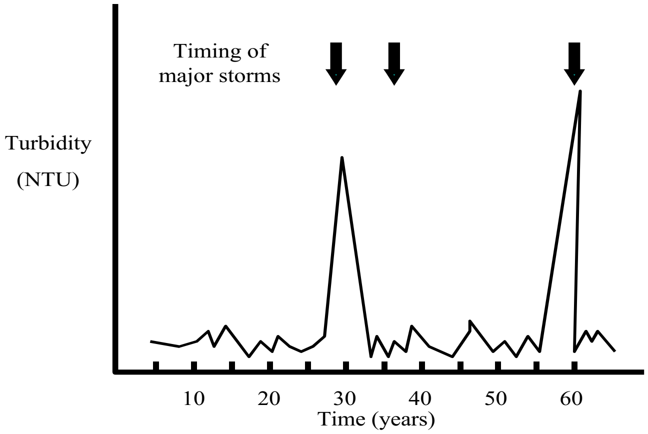


Figure 12: A conceptual model of the relationship in western Oregon of major storm timing and persistent turbidity recharge in landforms proximate to streams

couple the sediment delivery systems. Although data on this are incomplete, we estimate that streamflows on the order of 25-50 year recurrence intervals are required. But not all events of this magnitude have the same impact on turbidity. The floods in 1996 are particularly revealing on this point. In the November following the February 1996 storm, another storm produced peak streamflows that were almost as high as the ones in the preceeding February. Persistent turbidity from this second event was surprisingly low however, suggesting that insufficient time had elapsed since the previous event for the sediment transport system to “reload”. This is not just a metaphor, as a major mechanism promoting sediment input is earthflow encroachment on streams. The earlier storm removed most of the toeslope earthflow material that had been delivered since the last big flood event in 1964, and time periods on the order of a few decades or more are likely necessary for earthflows to move into streams sufficiently to place enough smectitic clays in position where they can be entrained during floods (Swanson et al. 1985).

Discussion

The 1996 flood offers insights into several important watershed-management issues emerging across North America and elsewhere. In particular, this case study demonstrates the potential consequences of relying on a watershed to provide high-quality source water for municipal-industrial use, and the economic and institutional adjustments that must be confronted as the demand for high-quality source water rises relative to the demands for timber, flood control, and other goods and services derived from the watershed. This event indicates that the actions of land managers, river managers, and municipal water utilities are interconnected in ways not previously anticipated. Furthermore, the importance of this flood’s impacts on turbidity, rather than on more conventional concerns about inundation, highlights the necessity for watershed managers to have a deeper understanding of a watershed’s geology, looking beyond topography’s impacts on the hydrograph to see how soil composition and the spatial distribution of geological processes, such as deep earth movements, interact with human activities and infrequent precipitation events to influence water quality. The 1996 Salem/Santiam flood also offers lessons for capitalizing on floods and flood-response planning to shape long-run, watershed management strategies that explicitly recognize these geological characteristics and their impacts on the supply of high-quality source water and other goods and services.

The Salem/Santiam case study facilitates examination of these issues in part because it offers a comprehensible view of the institutions, interests, and transitions associated with the increasing importance of managing a watershed to provide high-quality source water. There are three primary players who, for decades, have operated largely independent of each other and with each focused on an institutionally-specific set of goals. These institutions and their counterparts in other watersheds are operating in a rapidly changing resource-management environment that places greater emphasis on preventing the degradation of water quality. Water increasingly is recognized as a major output from forests and forest managers are being asked to curtail their adverse water-quality impacts. The U.S. Forest Service, which has dramatically reduced logging in this region over the past decade, has estimated that the national forests are the largest single source of water in the U.S. (Sedell et. al., 2000). If the Salem/Santiam experience influences resource-management policies on these lands throughout the contiguous U.S. they could affect the quality of 14 percent of the total surface runoff, and the influence would be larger still if extended to private forests and non-forest public lands. Forest manager’s concern about turbidity generally is focused on trying to limit activities that introduce sediment to streams, but the Salem/Santiam experience demonstrates that the scrutiny afforded their land-management decisions also is effected by the geological characteristics of their lands as well as by actions outside their control, including the operations of downstream dams, the evolution of downstream economies, and the policies of downstream water-utility managers.

The Corps and other river managers find themselves in a similar situation. Prompted by recognition that conventional efforts to achieve flood-control objectives might require modification to meet the objectives of the federal Clean Water Act, Endangered Species Act, and other legislation they have initiated widespread reevaluations of their operations (Stahkiv 1996). Although much of the focus has centered on how the operation of dams affect water temperature and downstream flow patterns, the Salem/Santiam flood reveals that dam operators must also address turbidity issues. To do so, the river managers must look beyond dam operations and develop a better understanding of how upland geologic factors and human activities affect the sediment entering a reservoir, and how decisions by downstream water users affect the value placed on downstream turbidity.

Water-utility managers also face change. Growing human populations demand more water and new industries often require large volumes of high quality water, as is the case in the Santiam and elsewhere in western Oregon with the arrival in the 1990s of semi-conductor manufacturing plants. At the same time, human activities are producing more substances that could be harmful if introduced into public water supplies. Removing some of these substances is becoming more difficult, and funding for new treatment capabilities often is hard to obtain (U.S. GAO 1999). Against this backdrop utility managers are recognizing that the best option is to ensure that source water remains as pure as possible, but are confronted with the reality that, the purity of source water depends on the geological characteristics of the watershed and the decisions of those who control the upstream lands and river. Limitations in the supply of pure water also can induce utility managers to see the importance of implementing pricing and other strategies to control demand.

Each agency’s focus on its own objectives has had important, generally unintended consequences for the others’ ability to accomplish theirs, thus creating a three-way, circular interdependence among the three agencies and their constituents. Some of these spillover impacts have been widely recognized. Logging and road building on the national forests increases stream sediment, some of which settles in Detroit Reservoir, while the remainder passes downstream, where it occasionally has caused the City to incur additional filtration costs. Flood protection afforded by Detroit Dam enables the city to locate its water-treatment facility in an island in the river below the dam, while summertime releases of water from the reservoir increase the supply of water passing the facility’s intake. The city’s dependence on the river for high-quality water caused it to pressure the Forest Service to limit logging that potentially could increase sedimentation, and the Corps to tailor dam operations to protect the city’s water-utility investments.

The 1996 flood brought to light additional, previously unseen or underappreciated interdependencies among the three agencies’ use of the basin and clarified the spatial and temporal dimensions of intrinsic sediment production and turbidity and the ways human activities may exacerbate turbidity. Trade-offs involved in reducing persistent turbidity turned out to be much more complex in space, time and resource management decisions of institutions than was previously assumed. This complexity led, in the Santiam, to increased cooperation among the involved agencies to address research and monitoring as well as land and water use decisions. In addition, the hazards presented by muddy waters will require new approaches on the part of each of the agencies involved. We list a few of what we believe to be the most significant of these for each of the three agencies.

Some issues, options and questions relevant to land and water management in the Santiam watershed:

1. Hazard profile of increased sediment from forest lands in the basin increases with time from last major storm event;
2. Earthflows need to be viewed within their geographic context;
    a. Are they downstream of potential debris flow initiation sites?
    b. Do they deliver directly to stream channels?
3. Roads may interact with earthflows to change movement patterns; sound mgmt principle would be to not increase supply of water to earthflows via roads and perhaps reduce water supply via road/culvert re-engineering or removal;
4. If climate changes, hazard profile for persistent sediment delivery downstream may change as well (e.g., snow changing to rain).
5. Dams should be re-engineered to accommodate outflow from different pool elevations out of concern for turbidity and not solely stream temperature.
6. Flood protection equals occasional high turbidity;
7. Influence others upstream whose actions effect water quality;
8. Substitute alternative water supplies;
9. Substitute for watershed services;
10. Manage water demand.

For the Forest Service, the primary task is to refine its understanding of the spatial distribution on its lands of potential sources of turbidity, especially persistent turbidity, and of the geologic, climatological, and anthropogenic processes that can deliver turbidity to the North Santiam. Our findings, drawn from a small number of samples, indicate that deposits of smectitic clays associated with persistent turbidity are concentrated in deep earth flows and in derivative sediment accumulations downstream. Further research is needed to determine how well these findings apply to landforms throughout the watershed and to develop detailed maps of smectitic deposits and their proximity to streams. This argument is also potentially applicable to the nearby privately owned industrial forest lands, but data did not allow us to address these questions in those locations.

Related research is needed to develop a better understanding of the mechanisms that deliver these clays to the water column. The levels of smectite delivered to Detroit Reservoir by the Februrary, 1996 flood event were unexpected because previous events, at least since the 1964 flood, were noticeably less turbid. So too were subsequent flood events. This pattern raises alternative hypotheses. One is that something about the February event triggered earth movements that delivered smectite to streams. If so, then what characteristics of the February event were significant? Another is that earth flows in the years since 1964 brought smectitic deposits closer to streams but not within reach of flows smaller than those of February, 1996. If so, then what does this tell us about how quickly the remaining deposits might become susceptible to future flood events? Under each hypothesis, what are the effects of road-building, logging, and other human activities?

For the Corps, the challenge is to clarify how the operation of its facilities affects the delivery of turbidity downstream and, where appropriate, to weigh operational alternatives. The events of 1996 indicate that, once smectitic clay appeared in Detroit Reservoir, the Corps' management of the reservoir caused much of it to be released slowly, over the summer and into the autumn, prolonging the impacts on the city's treatment plant and on municipal-industrial users. Further research is needed to ascertain the extent to which alternative operational procedures could flush the smectite out of the reservoir and still allow the Corps to accomplish other objectives, such as flood control. Modifications to the facilities, such as an outlet that could draw water from different depths also warrant investigation.

The city's task is broader. Ultimately, it must bear the risk of future turbidity in its North Santiam water supply and, hence, it must encourage the other agencies to take appropriate actions to reduce turbidity in the North Santiam and, whatever those actions, to manage the risks that remain. It already has taken steps to increase its ability to remove sediment from North Santiam water, expand its storage of treated water, and contract with back-up supplies from neighbors. These supply-side actions can be augmented by investigations into alternatives for managing demand so that future episodes of high turbidity would have less of an adverse impact on the utility, its customers, and the local economy. Inducing customers to increase the efficiency of their water use would enable the city's stored water to last longer, if a future crisis should occur. Adjusting prices to reflect not just the cost of service during normal conditions but the full cost of service, including the intermittent costs of potential turbidity-related crises would encourage water users to trim low-value uses. Developing a more refined plan for curtailing water use during a crisis, and for sharing curtailment costs could lower the overall impact on the economy.

Managers in all three organizations must become more aware of how turbidity-related risks might evolve in the future. All else equal, as Salem's population and economy grow, so will the potential economic damage whenever turbidity disrupts the city's water supply. Hence, management issues associated with turbidity should grow in the attention they demand from managers.

Moreover, managers should pay considerable attention to future research into the hypothesis that earthflows are continually moving smectitic deposits closer to streams, that the February, 1996 flood event scoured those deposits that had become exposed since the previous comparable flood in 1964, and that more deposits will become exposed as time passes. To the extent that this hypothesis is confirmed, then managers will face the prospect of being lulled into complacency. As the period free of persistent turbidity lengthens, one should not conclude that the probability it will appear in the future is diminishing and become less prepared. Quite the opposite. The events of 1996 clearly point out the importance in this basin of measuring turbidity-related risks with time scales appropriate for the underlying geologic setting and climatologic regime.

More fundamentally, managers must better appreciate the value of having a watershed capable of reliably delivering high-quality water. This capability is an asset whose value will grow as the supply of such water becomes increasingly scarce in the face of economic and population growth.

In conclusion, we argue that a proper, more sophisticated accounting of watersheds in space and time gives more options the next time a crisis occurs. A recent GAO study (1998) reviewed the 1996 floods in western Oregon and concluded:

> "an analysis of the overall condition of a municipal watershed is essential to 1) guide project planning and decision-making and identify the restoration activities with the greatest likelihood of success; 2) make sound management decisions concerning the type, location, and sequence of appropriate management activities within the watershed; and 3) *dissociate public concern about water quality from dissatisfaction over other land management issues, such as timber harvesting and road construction*." (emphasis added)

Watershed services are of increasing concern nationally. The experience of the 1996 flood was that persistent turbidity was not part of people's general awareness. In contrast to the GAO study, we argue not for "dissociation" of public concern about water quality from dissatisfaction over other land management issues, but instead for the *correct association* of public concern with land and water management having a credible cause/effect relationship on water quality problems.

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Appendix

DSRI Soil Mapping Units and Land Types

Excerpted from: Willamette National Forest Soil Resource Inventory, June 1973, Legard, H.A., L.C. Meyer, Pacific Northwest Region, US. Department of Agriculture Forest Service.

Mapping Unit	is comprised of land type	and land type	and is mapped as
132	13 (60%)	23 (40%)	Dormant earth flow
133	13 (60%)	33 (40%)	Dormant earth flow
134	13 (70%)	44 (30%)	Dormant earth flow
135	13 (50%)	55 (50%)	Dormant earth flow
137	13 (70%)	64 (30%)	Dormant earth flow
161	16 (60%)	61 (40%)	Terrace
162	16 (60%)	32 (40%)	Terrace
163	16 (60%)	33 (40%)	Terrace
164	16 (60%)	44 (40%)	Terrace
165	16 (70%)	25 (30%)	Terrace

(Mapping units cont’d)

Mapping Unit	is comprised of land type	and land type	and is mapped as
166	16 (70%)	35 (30%)	Terrace
167	16 (60%)	64 (40%)	Terrace
168	16 (60%)	21 (40%)	Terrace
169	16 (50%)	56 (50%)	Terrace
225	22(60%)	25 (40%)	Active earth flow
235	23 (60%)	25 (40%)	Active earth flow
251	25 (60%)	21 (40%)	Debris flow
252	25 (60%)	13 (40%)	Active earth flow
253	25 (60%)	23 (40%)	Active earth flow
254	25 (60%)	14 (40%)	Active earth flow
255	25 (60%)	35 (40%)	Active earth flow
256	25 (60%)	16 (40%)	Active earth flow
334	33 (60%)	25 (40%)	Active earth flow
335	33 (60%)	35 (40%)	Active earth flow
353	33 (60%)	35 (40%)	Active earth flow
	Appears to duplicate 335 – manuscript modified		
356	35 (60%)	16 (40%)	Active earth flow

Land type descriptions:

13. Deep to very deep, slightly plastic soil derived from glacial and colluvial materials. Surface soils are thin gravelly loams. Subsoils are thick gravelly loams, slit loams, and silty clay loams.

14. Deep to very deep, slightly plastic to plastic Landtype derived from resiual and colluvial materials. Surface soils are thin shotty loams and silt loams. Subsoils are thick silt loams, silty clay loams, and clay loams.

16. Deep to very deep, non plastic to slightly plastic Landtype derived from colluvium, glacial till, and alluvium. Surface soils are usually thin gravelly loams and sandy loams. Subsoils are usually thick gravelly cobbly loams that locally may change to sandy loams or silt loams.

21. Shallow nonplastic to slightly plastic Landtype derived from residuum and colluvium. Surface soils are thin gravelly loams. Suboils are thin gravelly loams and clay loams.

23. Moderately deep to deep, slightly plastic to plastic Landtype derived from colluvium and residuum. Surface soils are generally thin shotty loams. Subsoils are generally clay loams, silty clay loams, and clays.

25. Deep plastic Landtype derived from residuum and colluvium. Surface soils are thin loams, silty clay loams, and clay loams. Subsoils are clay loams, silty clay loams and clays.

32. Shallow nonplastic to slightly plastic Landtype derived from residuum and colluvium. Surface soils are gravelly to very gravelly loams. Subsoils are thin gravelly to gravelly cobbly loams and clay loams.

33. Moderately deep to locally deep, slightly plastic to plastic landtype derived from colluvium and residuum. Surface soils are thin loams and silt loams. Subsoils are clay loams and gravelly clay loams.

35. A deep to very deep plastic Landtype derived from colluvium and residuum. Surface soils are thin clay loams. Subsoils are thick to very thick clays and clay loams.

44. Moderately deep nonplastic Landtype derived from glacial till and colluvium. Surface soils are thin gravelly or shotty loams. Suboils are thin to moderately think gravelly or cobbly loams and sandy loams.

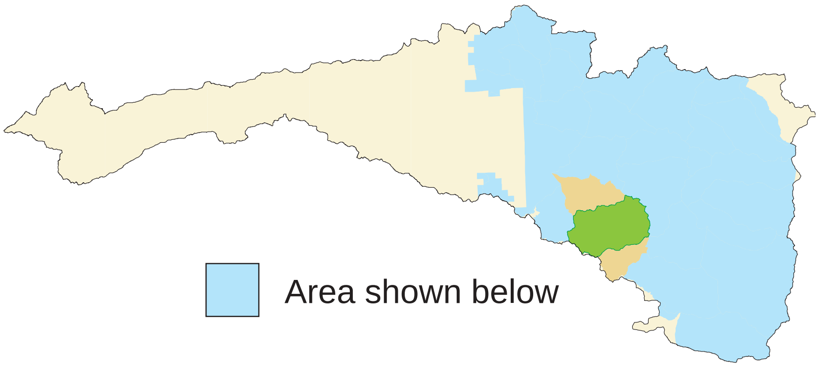
55. Shallow to moderately deep, slightly plastic to plastic, derived from residuum and colluvium. Surface soils consist of gravelly loams and loams. Subsoils consist of gravelly silt loams, silty clay loams, and clay loams.

56. Deep nonplastic Landtype derived from volcanic ejecta and glacial till. Surface soils are thin deposits of pumice. Subsoils are thick gravelly cobbly loams and sandy loams.

61. Shallow nonplastic Landtype derived from residuum and colluvium. Surface soils are thin gravelly to very gravelly loams. Subsoils are thin gravelly or cobbly loams.

64. Moderately deep nonplastic Landtype derived from glacial till and colluvium. Surface soils are thin gravelly sandy loams and loams. Subsoils are thin to moderately thick, gravelly or cobbly sandy loams and loams.

Figure 9


🟦 Area shown below

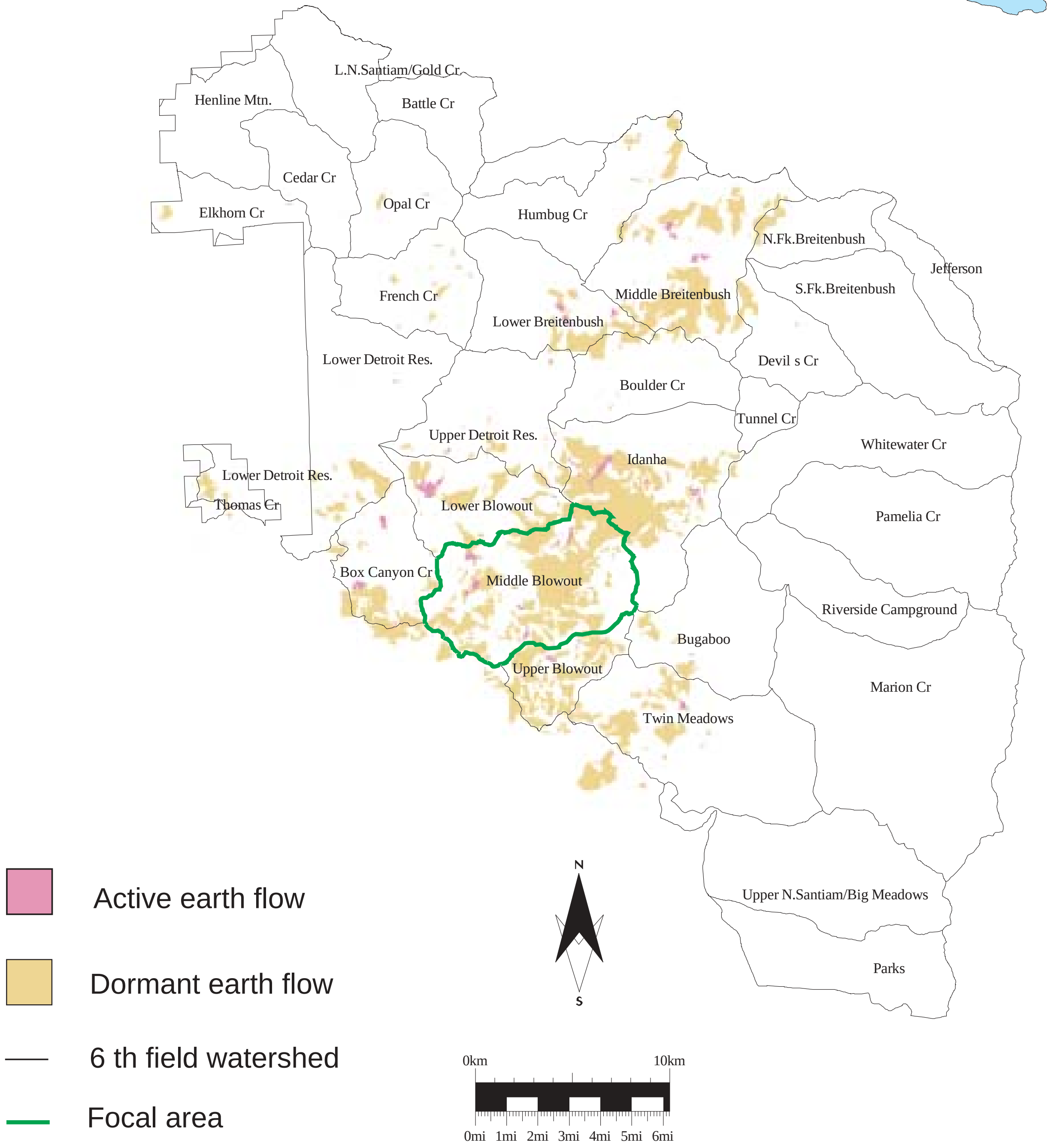

L.N.Santiam/Gold Cr
Henline Mtn.
Battle Cr
Cedar Cr
Opal Cr
Elkhorn Cr
Humbug Cr
N.Fk.Breitenbush
Jefferson
S.Fk.Breitenbush
French Cr
Middle Breitenbush
Lower Breitenbush
Lower Detroit Res.
Devil s Cr
Boulder Cr
Tunnel Cr
Upper Detroit Res.
Whitewater Cr
Idanha
Lower Detroit Res.
Thomas Cr
Lower Blowout
Pamelia Cr
Box Canyon Cr
Middle Blowout
Riverside Campground
Bugaboo
Upper Blowout
Marion Cr
Twin Meadows
Upper N.Santiam/Big Meadows
Parks
N
S
🟪 Active earth flow
🟨 Dormant earth flow
— 6 th field watershed
— Focal area
0km
10km
0mi
1mi
2mi
3mi
4mi
5mi
6mi

Figure 10

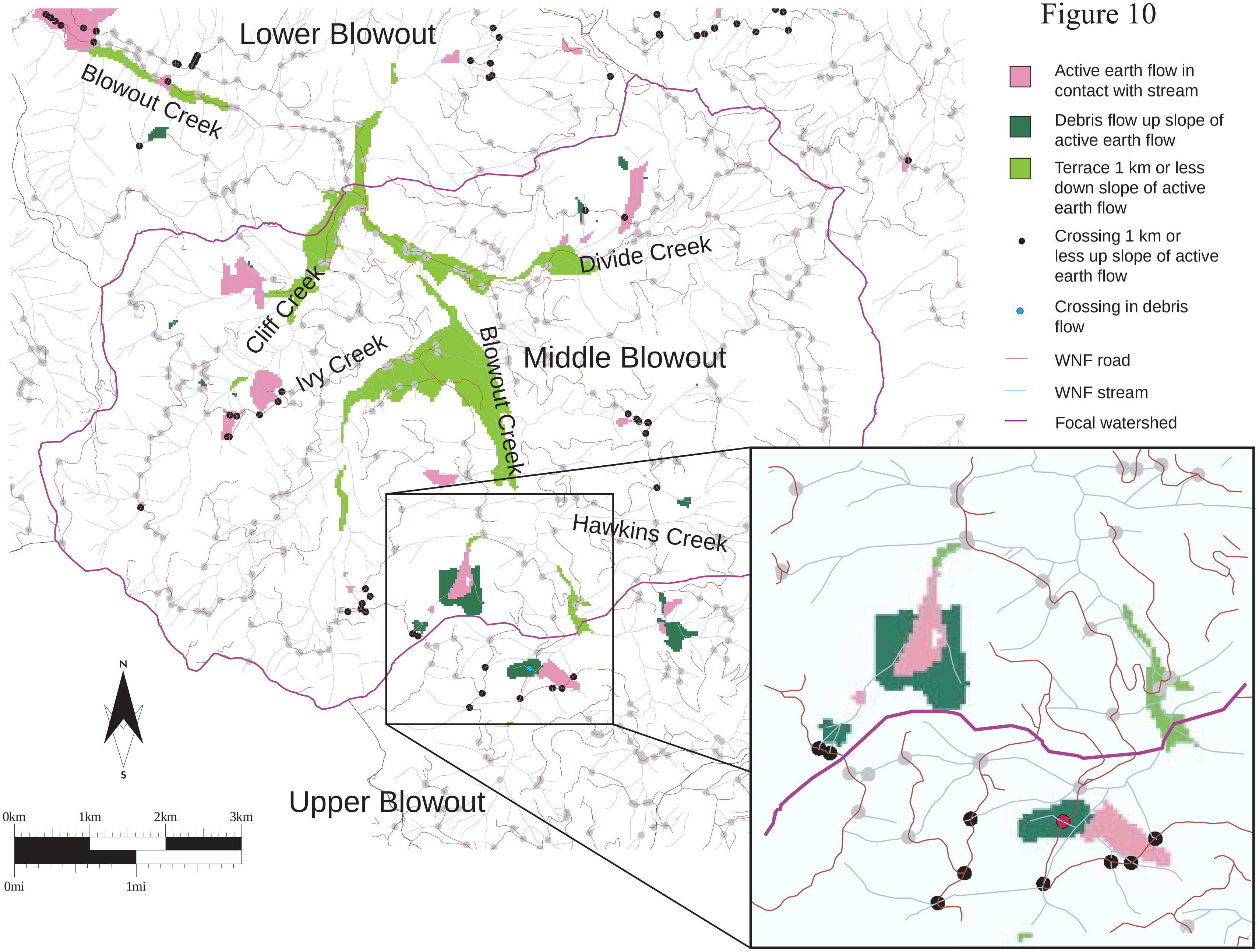
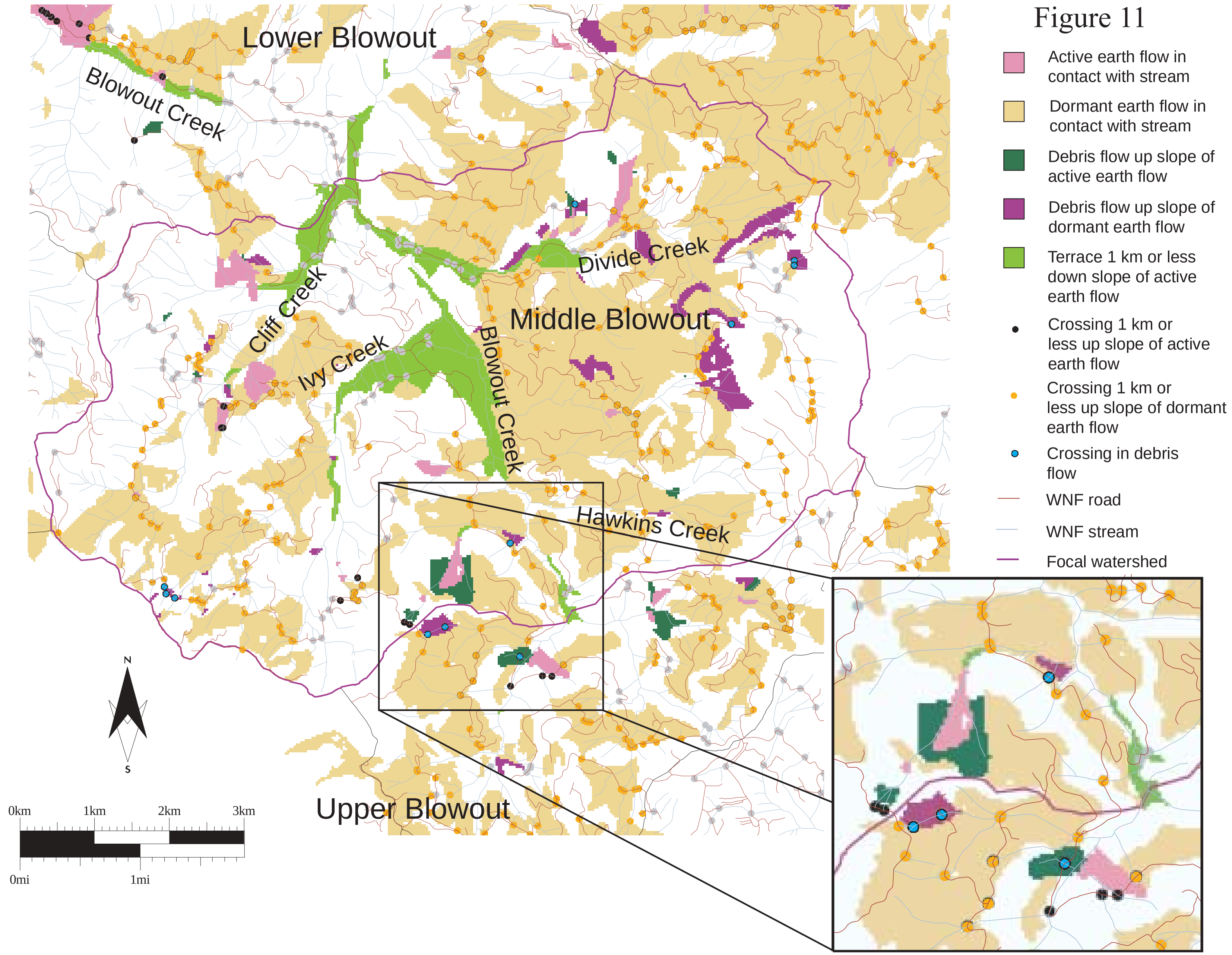

Lower Blowout
Blowout Creek
Cliff Creek
Ivy Creek
Divide Creek
Blowout Creek
Middle Blowout
Hawkins Creek
Upper Blowout
Active earth flow in contact with stream
Debris flow up slope of active earth flow
Terrace 1 km or less down slope of active earth flow
Crossing 1 km or less up slope of active earth flow
Crossing in debris flow
WNF road
WNF stream
Focal watershed
N
S
0km
1km
2km
3km
0mi
1mi

Figure 11


Lower Blowout
Blowout Creek
Cliff Creek
Ivy Creek
Divide Creek
Middle Blowout
Blowout Creek
Hawkins Creek
Upper Blowout
🟪 Active earth flow in contact with stream
🟨 Dormant earth flow in contact with stream
🟩 Debris flow up slope of active earth flow
🟪 Debris flow up slope of dormant earth flow
🟩 Terrace 1 km or less down slope of active earth flow
● Crossing 1 km or less up slope of active earth flow
● Crossing 1 km or less up slope of dormant earth flow
● Crossing in debris flow
WNF road
WNF stream
Focal watershed
N
S
0km
1km
2km
3km
0mi
1mi