STREAM EROSION AND BEACH DEPOSITION DURING THE
DECEMBER 2007 STORM, HOOD CANAL, WASHINGTON

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Abstract

A strong winter storm hit western Washington and Oregon in the first week of December 2007. An accumulation of snow was closely followed by high sustained winds with gusts up to 130 kph (80 mph), much warmer temperatures, and about 300 mm of rain, causing record flooding, substantial tree blowdown, and significant damage to roads and property. An example of the geomorphic effects is found in an area along Hood Canal just north of Dewatto Bay where abnormal discharges along high-gradient streams (12°-17°) in small drainage basins (0.073-0.259 km$^2$) resulted in severe erosion and the deposition of large fans (313-4985 m$^3$) onto beaches. Storm waves quickly cut scarps up to 1.5 m high into the alluvial fans; at some fans longshore currents deposited beach ridges at the high tide line. The correlation between drainage basin area and the estimated volume of sediment deposited is inconsistent and therefore best investigated on a case-by-case basis bearing in mind such factors as substrate, vegetation, land use, and road and culvert placement.
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Objectives

This study seeks to quantify the significance of the December 2007 storm, especially with respect to the east shore of Hood Canal in northern Mason County (Figures 1, 7, 8, 9, 10). In this field area six kilometers north of Dewatto Bay I researched five alluvial fans built on the shore, as well as erosional and depositional features upstream of the deposits in the stream valleys. The streams experienced such high discharges that the full length of their channels experienced erosion; effectively simultaneously the streams deposited alluvial fans onto the beach. Through a literature search investigating the widespread effects of the storm I was able to put the event in historical perspective, while the measurements taken at Hood Canal allowed me to observe firsthand the magnitude of the event.
Significance

As of late, weather has become less predictable and less characteristic of documented climate patterns. Whether or not these events are coincidences or part of a changing global climate pattern is yet to be agreed upon, but rain-on-snow events near sea level such as this one are historically unusual in the Puget Lowland. In fact, the December 2007 storm is classified as a 500-year flood event (Reiter 2008). The storm caused millions of dollars in damage (Figure 2) and may have disrupted or destroyed newly rejuvenated salmon runs (Dunagan 2007).

Fig. 2 Image of fallen Weyerhaeuser trees due to the December 2007 storm event. Photo by Greg Gilbert of the Seattle Times, 2007.
Background

As is the way with many Pacific Northwest winter storms, this system originated in the tropical Pacific Ocean and was swept northeastward by the jet stream to collide with the Pacific Northwest. Typically referred to as a Pineapple Express, this type of storm is characteristic of the La Niña weather pattern. In La Niña years, the ocean surface temperatures in the equatorial Pacific Ocean are anomalously cooler by as much as 1° C. These temperatures alter weather patterns around the Pacific; in La Niña years, western Washington and Oregon tend to be up to 0.5° C cooler than average, and precipitation rates in the Pacific Northwest increase by 0.5-1.5 mm per day above the long-term average. In contrast, the southeastern United States typically experiences less precipitation and higher temperatures than normal in La Niña years (NOAA 2008).

![Image of the two-storm series of the December 2007 rain-on-snow event that encountered the Pacific Northwest. Photo from Storm Events Summary, www.weyerhaeuser.com.](image-url)
This rain-on-snow event was caused by a series of two storms in quick succession (Figure 3). The event began on 1 December 2007 with snowfall across the Puget Lowland and in the Olympic and Cascade mountain ranges. Over the course of the first and second of December about 0.3 m of snow fell in local areas of the lowland (Washington State Dept. of Natural Resources 2008) which is more snow than typically accumulates in a single event due to the temperate climate.

The snow accumulation was followed closely by a rapid 10° C increase in temperature (NOAA, NCDC 2007). The abnormally large amounts of snow were rapidly melted by unexpectedly large amounts of rain (approximately 200 mm on 3 December and 60 mm on 4 December) (DNR 2008). The combined snowmelt and rainfall caused extremely high discharges in local rivers. The highest discharge on record for Big Beef Creek, approximately 30 km north of my field area on Hood Canal, was measured on 3 December 2007 (USGS 2011). The estimated discharges of the Hood Canal streams in my field area are listed in Data Collection.

In addition to the flooding many areas experienced gale-force (63-117 km/h) winds with gusts up to hurricane-force (>117 km/h). Along the coast between Newport, Oregon and Hoquiam, Washington, gusts were in excess of 161 km/h (DNR 2008). The saturated ground and high winds combined to topple trees throughout northwestern Oregon and western Washington, especially in northwestern Oregon and on the Olympic Peninsula (DNR 2008). A tree blowdown aerial survey of 600,000 hectares along the Washington coast conducted by Washington State Department of Natural Resources estimates that at least 27000 conifers and 2000 hardwoods were toppled (Figure 2) (DNR 2008).
Since prolonged or high-intensity rainfall is likely to trigger landslides, it is unsurprising that many roads around the region were closed due to mass-wasted debris on the roadway. Once soil is saturated, it is not uncommon for it to detach from consolidated or impermeable bedrock or substrate. The soil—now colluvium—naturally flows and slides downhill. Also on the list of landslide triggers are rain-on-snow events. In rain-on-snow events the ground may be frozen and therefore impermeable as well as covered with snow. A rapid increase in temperature and precipitation melts the snow and generates large amounts of water flowing over the ground. These floods accumulate debris as they flow downhill. The mass-wasting events that built each of the five alluvial fans in question were hyperconcentrated flows—an intermediate stage between a debris flow, which has more debris than water, and flood waters with normal sediment concentrations (Figure 4) (WA DNR 2011). Hyperconcentrated flows form deposits very similar to those generated during water floods, but hyperconcentrated flow deposits tend to be more poorly sorted and show less stratification and imbrication (Costa 1987). The high sediment content of hyperconcentrated flows causes an increase in buoyancy and dispersive forces as support mechanisms (Costa 1987).
Damage caused by the storm extended from northwestern Oregon through all of western Washington, including the Willapa Hills, Olympic Peninsula, and the Puget Lowland. Many counties, including Mason County, were declared federal disaster areas (Martin 2007), sections of Interstate 5 were closed, and five deaths resulted due to the storm.

Near Hood Canal the flood demolished two bridges on the Tahuya River, stranding 150-200 people (Farley 2007). “Mudflows” covered or removed sections of the road intermittently along Dewatto Bay and the Tahuya coast (Farley 2007).
In my field area Capstan Rock Road is located upslope of the shore of Hood Canal; all culverts needed clearing after the storm, as they were at least partially, if not entirely, clogged with sediment and debris washed down the streams during the event. The blocked culverts caused water to wash over the road in many places, gullying as it went. In places, utility wires were exposed and gullies ran for such lengths and depths that entire vehicles could conceivably be contained in them (Figure 5). At least one building on Capstan Rock Road was damaged, and the road washed out in one place in addition to the multiple driveways that needed considerable repair (James Aitken, written communication, 2007). Additionally, the deposited fans buried many small craft pulled above high tide for safekeeping (Robert Carson, oral communication, 2010) (Figure 6).
Fig. 6 Image of buried rowboat and canoe beneath Heusser Creek’s fan. Approximately a meter of sediment was deposited during the event. Photo by Clare Carson, 2008
Local Geography

Fig. 7 Google image of northwestern Washington showing the Olympic Mountains and the Puget Lowland. Southern Hood Canal is highlighted in the white rectangle.

Fig. 8 Google image of southern Hood Canal. The study area is highlighted in the white rectangle.
Fig. 9 Google image of the study area. Roads are evident in clear-cuts but difficult to discern in wooded areas. Width of the image is approximately 2 km.
Fig. 10 Map of the field area on Hood Canal. Five of the eight creeks were studied. Streams are dashed in blue, drainage basins are dashed in red. Capstan Rock Rd. runs along the coastline at about 200’ elevation south of Capstan Rock Creek. Compiled from 7.5-minute topographic maps of the region (Liliwaup, Eldon), contours are in feet.
Immediately to the east of Washington State’s Olympic Mountains lies Hood Canal, a Pleistocene subglacial meltwater channel connected to the greater Puget Sound (Thorson 1980). The Puget Lobe of the Cordilleran Ice Sheet left a network of such channels, which are now filled with marine water, forming Puget Sound (Thorson 1980). According to the geologic map of the area, the substrate consists of (from the top of the stratigraphic section, following down) loose ablation till, compact lodgment till, outwash that is prone to mass wasting, some more undifferentiated till, cemented in areas, and finally, more outwash which is also susceptible to mass wasting (Contreras et al. 2010). Though the sediment is variable on a meter scale, each of the streams runs through basically the same stratigraphic section.

My study takes place along western Washington’s Hood Canal. I investigated five small drainage basins and the alluvial fans that were built where the drainages empty onto the east shore of Hood Canal (Fig. 10).

People with permanent residences or vacation homes and cabins inhabit portions of both sides of the canal. The upper portions of each of the five drainage basins in question have been harvested for lumber within the last ten years, with the exception of the northernmost Camp Poison Ivy Creek. Camp Poison Ivy Creek has had more time to reestablish vegetation.

The climate is generally temperate with cool, wet winters and moderately warm and dry summers. Winter storms typically move from the southwest toward the northeast; the maritime air brings in precipitation from the moist ocean surface. Daily precipitation on Hood Canal in late November and early December averages at
approximately 3 mm per day, so the soil is consistently damp, though slightly less than saturated (NOAA 2008).

Trees in the area are mainly Douglas fir, western red cedar, western hemlock, red alder and big leaf maple. The underbrush includes salal, evergreen huckleberry, salmonberry and devil’s club.

In this temperate rainforest soils are generally young and poorly developed. Slopes are steep due to mass wasting and stream and wave erosion. What soils do exist are developed on thin colluvium over Pleistocene glacial and interglacial (?) deposits.

The dominant winds are from the southwest such that longshore drift is generally to the north down Hood Canal; frequent northwest winds, particularly in summer, cause longshore drift to the south up Hood Canal.

**Study Area**

Many small permanent streams descend from just below the till plain (elevation approximately 150 m; 500 ft) down the steep east side of Hood Canal’s trough. I studied five drainages, which from south to north are Heusser Creek, Aitken Creek, Early Root Creek, Knudsen Creek, and Camp Poison Ivy Creek (Figure 10).

Heusser Creek is just meters north of Hornet Creek, combined they are referred to as Two Creeks. During the event, Hornet Creek’s culvert became clogged with sediment and most of its flow diverted into Heusser Creek. The flood deepened Heusser Creek’s channel, eroding as much as a meter below its initial stable depth. About halfway between the road and the beach, Heusser Creek plunges over a 2-3-m-high waterfall as it runs across lodgment till. Heusser’s is the smallest fan of the five studied. Just north of
Heusser Creek are small pebble beach ridges of sediments winnowed out of the fan over the past three years. Nearby Hornet Creek has a small, steep fan, which I did not measure.

![Photo of Aitken Creek fan looking southwest. Photo by Bob Carson, August 2010](image)

Aitken Creek is the next drainage to the north of Heusser Creek (Figure 11). Its channel was deeply incised in places. A resistant area of lodgment till 45 m downstream of the culvert causes a 1-2 m high waterfall. The fan itself shows considerable longshore drift to the north but its edge is still clearly visible due to buried oyster beds and an obvious break in slope.
Early Root Creek is the narrowest and steepest drainage of the five observed streams. Its fan, like Aitken Creek’s, is clearly discernible based on oyster beds and a steeper slope than that of the equilibrated beach (Figure 12). Early Root Creek’s fan is remarkably semi-circular in comparison to the others.
Knudsen Creek’s channel experienced many landslides and contained at least eight fallen trees with 0.5-1 m diameters. Its fan is well defined to the south but has experienced considerable longshore drift to the north, making the location of its margin difficult to determine. (Figure 13)

![Image of the edge of the Camp Poison Ivy Creek fan looking northwest. Photo by Bob Carson, March 2010.](image)

Camp Poison Ivy Creek is by far the largest drainage with the largest fan. In walking up the creek I did not encounter the upstream limit of deposition before the channel became blocked by fallen trees and woody debris. Several landslides ranging in height from 6-10 m and 20-35 m in length deposited large volumes of sediment into the stream. (Figure 14)

**Data Collection**

I spent 23-25 August 2010 in the field, nearly three years after the rain-on-snow event took place. For each of the five fans, the slope, area and volume estimates are
based on measurements taken in the field with a Brunton compass, clinometer and tape measure (Figure 15). Some fan thicknesses were estimated based on markers such as signs on trees that were originally two meters above the ground and are now only one meter from the current ground surface. At the extreme high tide level each fan has a wave-cut scarp, which likely formed during and soon after the rain-on-snow event (Figures 16, 17).

<table>
<thead>
<tr>
<th>Creek</th>
<th>Drainage area (km²)</th>
<th>Drainage slope</th>
<th>Mean scarp height (m)</th>
<th>Deposition volume (m³)</th>
<th>Erosion volume (m³)</th>
<th>Discharge (m³/s)</th>
<th>Velocity (m/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heusser</td>
<td>0.112</td>
<td>0.287</td>
<td>0.66</td>
<td>705.58</td>
<td>225.151</td>
<td>41.23</td>
<td>8.25</td>
</tr>
<tr>
<td>Hornet</td>
<td>0.144</td>
<td>0.234</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Two Creeks</td>
<td>0.224</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Atikken</td>
<td>0.162</td>
<td>0.276</td>
<td>1.3</td>
<td>1668.65</td>
<td>120</td>
<td>12.6</td>
<td>5.3</td>
</tr>
<tr>
<td>Early Root</td>
<td>0.073</td>
<td>0.308</td>
<td>0.871</td>
<td>1283.512</td>
<td>202.5</td>
<td>39.33</td>
<td>8.74</td>
</tr>
<tr>
<td>Knudsen</td>
<td>0.177</td>
<td>0.274</td>
<td>0.868</td>
<td>1484.34</td>
<td>216</td>
<td>79.89</td>
<td>9.98</td>
</tr>
<tr>
<td>Camp Poison Ivy</td>
<td>0.259</td>
<td>0.219</td>
<td>0.375</td>
<td>2911.575</td>
<td>unknown</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Fig. 15 Measured and calculated data collected from the fans at Hood Canal (see text for details).

Fig. 16 Image of the wave-cut scarp in Heusser Creek fan taken soon after the event. Note the presence of fine sediments in the deposit. Photo by Clare Carson, 2008.
It was the height of this scarp on each fan that I chose to use as the thickness estimate for my calculations. It was not possible to estimate the thicknesses of all the fans based on other markers, so the scarp heights are more consistent and reliable than memory or rough estimates. Estimates of depths of erosion are based on the height of vegetation above the current channel bottom. Drainage basin areas were gathered using a planimeter on a 7.5-minute topographic maps of the region (Liliwaup, Eldon) (Figure 10).

For more than two years, waves have reworked the beach portion of the alluvial fans. The reworked fans overlie oyster beds, seaweed and stones with large barnacles. We measured the areas of the reworked fans on the beaches as well as the portions of the fans above high tide. This involved one person standing at a fixed point near the foot of each fan scarp, holding the end of the tape measure and a Brunton to obtain azimuths.
The other individual walked to the edge of the fan, made evident by its slope or truncated oyster beds (Figure 18). This provided several radii for each fan and made it possible to map each one individually in order to find the surface areas with a planimeter.

![Fig. 18 Image of a truncated oyster bed. To the right of the field notebook clasts are mostly bare of barnacles and oysters are not present. August 2010](image)

Upstream I estimated the depth the streams had eroded below vegetation along their channels. I estimated widths and measured channel lengths between such landmarks as the upstream limit of deposition at the heads of fan mouths and the downstream limit of the erosional channels.

A scarp 0.7-m high exists at the toe of Aitken Creek’s fan; this could be due to the fans’ deposition during very low tide, wave erosion, or other unknown causes. Most of the fan margins merge gradually into the beach slope. Local tide charts tell us the tides ranged between 11.8 ft (3.6 m) at the highest and 0.3 ft (0.1 m) at the lowest during the event. Mean high tide is 10.5 ft (3.2 m) and mean low tide is 0.

In general my measurements could have been improved by punctuality. Had measurements been taken during or immediately after the event I could have more accurately assessed the original dimensions of each fan. It also would have been helpful
to dig into each of the fans to buried oyster beds and barnacles in order to more accurately measure their thicknesses.

**Results**

As a result of the early December rain-on-snow event, stable channels with plant growth suffered severe erosion. Our estimates reflect the erosion that took place downstream of the blocked culverts at the road (except for the Camp Poison Ivy drainage basin, which has no culvert), but it is apparent that more erosion took place upstream for two reasons: the culverts became blocked with sediment, and our erosion estimates are consistently less than our calculated volumes deposited during the event. In the channels just upstream of the beach it is evident that originally erosive streams switched to a depositional nature later in the event (Figure 19).

![Fig. 19 Diagram illustrating the building of alluvial fans. The brown line indicates the original stream morphology. During the event the streambed eroded to the level of the blue line on the right while the fan built up to the level of the blue line at the mouth of the stream. As time went on, the channel eroded down to the level of the green line on the right and the fan built up to the level of the green line on the left. Note the uphill progression of the inflection in slope that indicates the boundary between deposition and erosion.](image-url)
Longshore drift has redistributed much of the alluvium (Figure 20). The fans themselves remain evident because they are higher than the rest of the beach, and in less than three years only small barnacles have colonized the new deposits. Fines have been washed away from the cobbles, and the pebbles are accumulating in beach ridges near the wave-cut scarps (Figure 21).
The measurements taken at Hood Canal were subsequently used in calculations.

To derive discharges I used the Manning equation:

\[ Q = \frac{AR^{2/3} S^{1/2}}{n} \]

where 
- \( Q \) = discharge (m\(^3\)/s)
- \( A \) = cross-sectional area (m\(^2\))
- \( R \) = hydraulic radius (m)
- \( P \) = wetted perimeter = 1.5[(width)+2(depth)]
- \( S \) = slope
- \( n \) = Manning resistance = 0.040 for these streams

In order to backsolve for velocity I used the equation \( Q = wdv \) where \( w \) is stream width, \( d \) is stream depth, and \( v \) is velocity (Figure 15).

In addition to discharges and velocities, I compared fan surface areas, erosion depths, mean scarp heights, and drainage basin areas in order to find any important correlations in the data.
It is difficult to draw a conclusion based on the “fan area vs. mean scarp height” plot (Figure 22). We might expect fans with greater extents to be thicker than those that have small areas. According to the plot that is not the case. This may have something to do with the sediment load of the hyperconcentrated flow itself. A flow with proportionally more sediment and less water may not extend as far onto the beach as a flow with more fast-moving water and less sediment and debris.
The “fan area vs. total depositional area” plot is nicely linear (Figure 23). It allows us to infer that in valleys where there was a large fan there was a proportionally large amount of deposition into the mouth of the valley. This is expected, since the flow had to have gone on long enough to build the fan outward onto the beach while simultaneously filling the valley. As the fans on the beach grew, sediment was deposited in the mouths of the streams (Figure 1, 11, 12, 13, 14, 18).

![Image of Plot](image.png)

**Fig. 24** Plot showing drainage basin area versus total depositional area of the five fans.

It is also difficult to draw conclusions based on the “drainage basin area vs. total depositional area” plot (Figure 24). We might expect a greater depositional area from streams that have a larger drainage basin, but that appears not to be the case. The total depositional area may be dependent, as mentioned above, on the sediment load of the stream during the event. Because the substrate varies slightly from drainage to drainage, the sediment availability may be slightly different for each stream. The presence of more human activity may also make a difference in sediment availability. Drainages where
there has been no recent logging or where there are no artificially oversteepened slopes or roads will be more stable than those with recently altered morphologies.

![Depositional vs. erosional volume plot](image)

**Fig. 25** Plot of depositional versus erosional volume for four of the fans. I never found the end of deposition and start of erosion at Camp Poison Ivy Creek, so the data point is missing.

The “depositional vs. erosional volume” plot shows no apparent trend (Figure 25). My estimates for the volume of sediment eroded are inaccurate, since they do not take the entire drainage basin into account. The sediment volumes from upstream were largely blocked by the culverts that allow the streams to run under Capstan Rock Road. With the exception of Camp Poison Ivy Creek the road crosses through each drainage at an elevation of about 60 m.
Conclusions

In the past many studies have been done on alluvial fans where streams flow into valleys (Giles 2010, Zygmunt 2009, Barrier 2010), but little work has been done on fans built onto beaches. At the Hood Canal field area I found that the base level of the stream raised during the event, building alluvial fans on the beach and in the mouths of the streams. Prochaska and others (2008) found that flow velocities calculated in relation to channel slope and flow depth, as the Manning equation employs, present ranges of reasonable velocity predictions. Stream flow velocities of 10 m/s or less are typical less than 500 m upstream of alluvial fans. My velocity calculations are in accordance with this average; however, their velocities were calculated for streams whereas mine are for hyperconcentrated flows.

Within recent history the largest comparable rain-on-snow event before the December 2007 storm was in the January 1986 (Times Wire Services 1986). During the 1986 storm driveways and roads were gullied to depths of approximately 2 m but stream channels did not undergo significant erosion. The channels appear to have been stable for at least a century prior to the December 2007 event (Robert Carson, oral communication, 2011). Given this context, it is possible that a 500-year storm event is to be expected only once in centuries, or that such large storms will occur more often as a result of a changing climate pattern. It is unclear whether rain-on-snow events will continue to become more frequent at low elevations.
Acknowledgments

Thanks go to my dear friend Eric Nesbit who volunteered his time to help us take measurements in the field, Nick Bader for walking me through GIS in baby steps, and Bob Carson for his exceedingly patient guidance. My gratitude also goes towards my forever-supportive parents, the brothers I’m glad I have for life, and the friends who keep me in line.
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