February 1996 rain-on-snow flood: looking to the west-northwest across the Nisqually River delta from I-5. Pat Pringle photo.

Lawrence, Massachusetts, lies partially submerged during flooding in October 1996.

Big Thompson Canyon, east of Estes Park, Colorado; bouldery deposits of July 1976 flood that killed hundreds of people.

The drainage basin of a river includes all of slopes that drain water downslope to feed the river.

Above, Chehalis R. near Porter; right, flood deposits in Cowlitz R. floodplain near Randle. 13 big floods since 1479 AD

MSH ash 1479 AD

When flood peaks meet high tides!
Orting subdivision during ROS flood of February 1996

Forestry landslide hazard zonation takes rain-on-snow zones into account. Map by Pat Pringle

Generalized cross sections of a stream channel at various flows.

A flood scour hole eroded next to the downstream end of one of the Alaska Highway bridge support piers in the Johnson River.

Q = VA; (cubic ft/sec)
Discharge = velocity x cross sectional area

Measuring current via ADCP, Acoustic Doppler current profiler

Flash flood magn. map for USA. Higher numbers (orange) are most susceptible to flash floods. Higher values are for more extreme floods.
~velocity needed to pick up and transport sediment particles of various sizes.

Table 11-1 Characteristics of Floods with Increasing Proportion of Sediment in Water

<table>
<thead>
<tr>
<th>Flood Type</th>
<th>Water Floods</th>
<th>Hyperconcentrated Flows</th>
<th>Debris Flows</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sediment concentration (g/cm³)</td>
<td>0.4–2.0</td>
<td>20–47</td>
<td>47–77</td>
</tr>
<tr>
<td>Rock density (g/cm³)</td>
<td>1.65–1.73</td>
<td>1.33–1.80</td>
<td>1.08–1.35</td>
</tr>
<tr>
<td>Depositions, bedforms, and channel shapes</td>
<td>Sandbars, low mounded bars</td>
<td>Similar to floods</td>
<td>Coarse-grained alluvial fans, terminal fans, response to braided channels</td>
</tr>
<tr>
<td>Sedimentary structures</td>
<td>Horizontal stratification</td>
<td>Marine mud streaks, wave induced sorting, normal or reverse grading</td>
<td>Poor sorting, clast-supported, cobble-boulder sand</td>
</tr>
<tr>
<td>Sediment texture</td>
<td>Well-sorted, poorly sorted, rounded pebbles</td>
<td>Poor sorting, clast-supported, cobble-boulder sand</td>
<td>Poor sorting, matrix-supported, 0-1 cm granules, 0-1 cm clasts</td>
</tr>
</tbody>
</table>

Meanders erode the outsides of bends and can migrate until one meander bend spills over to one farther downstream, leaving an abandoned oxbow lake.

Meanders in the Smith River south of Great Falls, Montana, nicely illustrate the eroding cut bank on the outside of a meander and the depositional gravelly point bar on the inside of the meander. Flow is toward the lower left.

Cross sections of typical meandering stream channel.

meandering river on the Arctic Coastal Plain.
House built 10 meters back but on the outside of a big meander bend of the Clark Fork River near Plains, Montana.

Overland flow erodes gullies and carries sediment down onto depositional fans.

This cross section shows the main channel, natural levees, and floodplain of a river.

Flood hazard zones vary on alluvial fans. All of the flow from a canyon concentrates at the apex of the fan, then spreads out.

This bedrock channel of the Middle Fork of the Smith River is north of Crescent City, California.

braided river channel of the Wairou River is southwest of Blenheim, New Zealand.
Pebbles swirling in whirlpools drilled these cylindrical potholes in McDonald Creek, Glacier National Park, Montana.

An ice jam built up at a river constriction threatens a bridge at Gorham, New Hampshire.

Ice jams fill the channel of the Red River below Grand Forks, North Dakota, caused this flood in April 1997.

In this aerial view of the Red River flood in North Dakota, April 27, 1997, thin white lines around some “islands” are sandbags. The view is near Harwood, north of Fargo.

The Red River flows north along the border of North Dakota and Minnesota, through southern Manitoba, and into Lake Winnipeg.

Downtown Grand Forks was mostly submerged during the 1997 flood.
This flooded subdivision lay near a river meander south of Fargo, North Dakota.

Several different approaches were taken to hold back the Red River flood in Fargo in April 1997.

(a) Water level in Canyon Lake on the Guadalupe River rose about 40 feet (12 meters) in four days during the flood in early July 2002 (blue line).

(b) The flood crested at 7 feet (2.1 meters) above the spillway.
Fig. 11-29, p.283

Stream order: First-order streams have no tributaries but join to form a second-order stream and so on.

Fig. 11-34, p.287

Fig. 11-38, p.287

Groundwater flow directions depend on climate.

This hydrograph shows the flood level for the Red River at Fargo, North Dakota, March 24 to June 30, 1997.

hydrograph is a plot of stream discharge versus time for a similar eighteen-hour rainfall event for the same area before and after urbanization.
Storm rainfall entering the stream precedes the flood crest that it causes. The flood hydrograph nearest the rainfall area is highest and narrowest. Farther downstream at B, the flood hydrograph crests at a lower level but lasts longer.

**Fig. 11-38, p.287**

Hydrograph of December 2007 flood at Doty.
Chehalis Basin

“Most of the precipitation falls between October and May. The driest months are July and August.”

http://www.crcwater.org/newsltr/news9810.html#75

Length: 115 mi (185 km) [1]
Watershed: 2,660 mi² (6,889 km²) [2]
Discharge at near Satsop, WA:
- average 6,425 ft³/s (182 m³/s) [3]
- maximum 47,000 ft³/s (1,331 m³/s)
- minimum 440 ft³/s (12 m³/s)
Discharge elsewhere:
- mouth (Grays Harbor) 11,208 ft³/s (317 m³/s) [2]

The Chehalis River floods large areas of Chehalis, and also submerges several sections of Interstate 5. The river was almost 10 feet over flood stage. (Steve Bloom/The Olympian)

A Centralia neighborhood is submerged. Flood damage to a segment of the interstate in this Chehalis area will keep the highway closed until Friday at the earliest, a transportation department official said. STEVE RINGMAN / THE SEATTLE TIMES

Private airplanes find safe haven Tuesday from the rising Chehalis River at the Lewis County Airport. (Steve Bloom/The Olympian)

Airplanes were moved to high ground at Chehalis Airport. Officials said it’s the worst flooding in years in and around Chehalis and Centralia including Interstate 5. STEVE RINGMAN / THE SEATTLE TIMES
Flood waters from the Chehalis River inundate a neighborhood in Centralia. STEVE RINGMAN / THE SEATTLE TIMES

The barrier on Interstate 5 between the northbound and southbound lanes is swept away in places as the highway passes through Centralia. STEVE RINGMAN / THE SEATTLE TIMES

Looking south, semi trucks sit stranded on high ground above the flooded Interstate 5 at Exit 77 in Chehalis. STEVE RINGMAN / THE SEATTLE TIMES

A Centralia neighborhood is submerged. STEVE RINGMAN / THE SEATTLE TIMES

The freeway overpass in Chehalis was underwater, including Wal-Mart on the right. I-5, which runs below, was completely submerged. STEVE RINGMAN / THE SEATTLE TIMES

Wal-Mart store in Chehalis. SkyKING photos
You can't actually see Interstate 5 in this photo, it's under the flood water. Notice the exit sign on the bottom of the photo, just a little left of center, and the freeway overpass in the middle of the photo. Dec. 4, 2007. WA DOT

Mud up to 3 feet thick sits in fields, around homes and on roads in and around Curtis — and it's starting to dry up. Occupants of this Ceres Hill Road home are burning their furniture and belongings destroyed by the flood. STEVE RINGMAN / THE SEATTLE TIMES

Bridge over Chehalis. SkyKING photos

Two men examine the flow of the Chehalis River that ripped down the Chandler Road Bridge, on the way from Highway 6 to the town of Doty. STEVE RINGMAN / THE SEATTLE TIMES

SR 6 under a massive mud slide near Pe Ell

Did development, logging set the stage for disaster?

• By Lynda V. Mapes
  Seattle Times staff reporter
• Sunday, December 09, 2007
Flooded Chehalis A new automobile dealership, at bottom of photo, is being built just off Interstate 5 on an island of fill in the Chehalis River floodplain. Some nearby stores, including a Home Depot and Wal-Mart, were hard hit by last week’s high waters.

STEVE RINGMAN / THE SEATTLE TIMES

Clear-cuts and mudslides Tons of earth and vegetation washed away from clear-cut hillsides last week and slammed into Stillman Creek, a tributary of the south fork of the Chehalis River.

STEVE RINGMAN / THE SEATTLE TIMES

Acres of timber and debris backed up behind this bridge in the Boisfort Valley, which was inundated by the flooding of the south fork of the Chehalis River.

STEVE RINGMAN / THE SEATTLE TIMES

Despite being built on a plateau of fill, this Walgreens pharmacy near the Chehalis River sustained water damage during last week’s flooding. STEVE RINGMAN / THE SEATTLE TIMES

Ranch House BBQ co-owner Melanie Tapia gets a hug from Ginny Wallace, a friend and DOT worker who stopped by to check on them Monday, Dec. 3, 2007 after a wall of mud from nearby Kennedy Creek destroyed the popular Highway 8 restaurant near Olympia, Wash.

http://www.dnr.wa.gov/ABOUTDNR/MANAGEDLANDS/Pages/amp_na_chehalis.aspx
The flood frequency plot for Squaw Creek, a tributary of the Mississippi River at Ames, Iowa, is plotted for before and after the largest flood of historic record in 1993. The recurrence interval or inverse of exceedence probability is also shown.

Table 11-2 Chance of a Flood of a Given Size in a Certain Period of Time

<table>
<thead>
<tr>
<th>Flood (Recurrence Interval)</th>
<th>Occurrence (%) in Any 10 Years 25 Years 100 Years</th>
</tr>
</thead>
<tbody>
<tr>
<td>50-year</td>
<td>2 40 86</td>
</tr>
<tr>
<td>100-year</td>
<td>1 22 63</td>
</tr>
<tr>
<td>1,000-year</td>
<td>1 9.5</td>
</tr>
<tr>
<td>10,000-year</td>
<td>1</td>
</tr>
</tbody>
</table>

The 100-year flood for Mercer Creek, Washington, near Seattle, went up fast following rapid urbanization from 1977 to 1994.

In this aerial view of the Kentucky River flood at Hazard, Kentucky, in 1963, the floodplain is underwater.

FEMA’s definitions for flood insurance purposes. Line AB is flood elevation before encroachment. Line CD is the flood elevation after encroachment. Surcharge is the rise in flood water level near the channel as a result of artificial narrowing of the floodplain. The surcharge is not to exceed 1.0 foot (FIA requirement) or lesser amount if specified by a particular state.
This example of a National Flood Insurance flood hazard map is for part of East Lansing, Michigan.

**Sidebar 11-3**

The velocity times the channel roughness is proportional to the average water depth of the channel times the square root of its slope:

\[ Vn = 1.49R^{0.6} s^{1/2} \]

where

- \( R \) = hydraulic radius is proportional to average water depth
- \( n \) = Manning roughness coefficient.

For straight, small streams or grassy floodplains with no pebbles, \( n \) is roughly 0.03.

For sinuous small streams with bouldery bottoms or floodplains with scattered brush, \( n \) is roughly 0.05.

For brushy flood zones or floodplains with trees, \( n \) can be between 0.10 and 0.15.

\( s \) = slope of the channel.

**Sidebar 11-4**

Carrying capacity is proportional to discharge:

\[ L \propto Q^n \]

where

- \( L \) = suspended load transport rate (e.g., cm^3/sec.)
- \( Q \) = discharge (e.g., cm^3/sec.)
- \( n \) = an exponent generally between 2.2 and 2.5

**Sidebar 11-2**

Drag or total friction on the stream bottom is proportional to velocity squared:

\[ \tau_f \propto v^2 \]

where

- \( \tau_f \) = friction
- \( v \) = velocity

**Sidebar 11-5**

Induced Transport Mechanisms for Different Flow Types

- Larger, may not stick of all or stick to stream only one dead at head of river
- Finer, lasts longer in suspension
- For trees, they stick to stream of suspended particles, with water and substrate moving together as the current velocity. Trees may be caught at the surface of the river and moved along by the river.
- For trees, they stick to stream of suspended particles, with water and substrate moving together as the current velocity. Trees may be caught at the surface of the river and moved along by the river.

All of these flow types are diagrammatic. Different flows are more distinct due to their higher velocities and the larger objects they carry. These are usually higher velocities that move large objects, and these greater waves can be seen by large and average objects.
Sidebar 11-6  Stream Power

\[ P = S_s \times V \]

where
\[ P = \text{stream power in watts per m}^2 \]
\[ S_s = \text{boundary shear stress: } w \times R \times s \]
\[ w = 1 \text{ g/cm}^3 \text{ for pure water with no sediment} \]
\[ R = \text{hydraulic radius (i.e., average depth) = wetted cross-sectional area / wetted perimeter} \]
\[ s = \text{energy slope of the channel (often first approximated as the water surface slope)} \]
\[ V = \text{velocity in m/sec}. \]

Sidebar 11-7

\[ \text{recurrence interval } (T) = 1/P = (n + 1)/m \]
\[ \text{exceedance probability } = P = m/(n + 1) \]

where
\[ m = \text{rank} \]
\[ n = \text{number of years of record}. \]

Sidebar 11-8  How a Recurrence Interval Can Change

The importance of having a long enough record can be emphasized with data from Susan Creek in the Amor, Iowa, drainage. In 1922, the largest flood in thirty years of record had a recurrence interval of:
\[ T = \frac{n+1}{m} = \frac{37}{35} \text{ or } 1.05 \text{ years} \]

Following the new record flood in 1953, that same previous record flood (now the second largest in thirty-eight years of record) had a recurrence interval of:
\[ T = \frac{n+1}{m} = \frac{38}{35} = 1.11 \text{ years} \]

Note that it does not matter for this analysis, how much larger the 1953 flood was, just that it was larger. In the first case, the recurrence interval problem can be seen from Figure 11-42, where a recurrence interval of 40 years would have a projected 40 year recurrence interval. Following the new record flood in 1953, that same 10,000 cubic foot per second flood flow would now be calculated as only a 50 year recurrence interval! Similarly, we can consider the expected volume of the 100-year flood: in 1992, the New River flood in 1992, has a projection of 50,000 cubic feet per second. After the 1992 flood, the expected volume of the 100-year recurrence flood would be 55,000 cubic feet per second, not per year. After the 1992 flood, the expected volume of the 100-year recurrence flood would be 55,000 cubic feet per second, not per year.