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Snowmelt and Floods

By: James L. Foster, Code 974, NASA/Goddard Space Flight Center, Greenbelt MD 20771
e-mail: jfoster@glacier.gsfc.nasa.gov

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Audience: Earth Science students in middle school and high school. No math is required beyond simple arithmetic.

Background: The movie "Fargo" won an "Oscar" for Best Original Screen Play at the Academy Awards in the spring of 1997. Fargo and Grand Forks, North Dakota were again in the headlines a few weeks later because of record-setting snowmelt floods.

The winter of 1996 - 97 was the wettest winter on record in the north-central states and one of the snowiest. In many areas of the U.S., snow usually doesn't stick around the entire winter. There's usually a thaw or a warm spell that quickly melts the snow and puts a frown on Frosty's face. In a lot of urban areas snow is a nuisance - it just makes traffic worse, and maybe if the conditions are bad enough, there's a holiday from school. However, in those places where snow accumulates during the winter months, a deep snowpack is often an important source of water for crops and pasture land in the spring. Last year, though, the snowpack was so deep and extensive that major flooding was inevitable in portions of North and South Dakota, Minnesota, Iowa, and Wisconsin. Contributing to the flooding was the extremely flat terrain. Along parts of the Red River, the relief is only about 20 cm (height) per km (length). This means that after a river overflows its banks, the water easily spreads out over a very large area. A relatively small volume of liquid can cover an extensive area. We all experience this anytime we spill a drink on the floor.

A good thing about snow is that it acts like a reservoir. It holds the water (in a frozen state) and, in general, releases it gradually once warmer weather arrives. When snow is falling, the ratio of snowfall in inches accumulated to the depth of water as it melts is about 10 to 1 (10 cm of snow is equivalent to about an 1 cm of water); however, when snow builds up over longer periods, the ratio is more like 3 to 1 or even 4 to 1. Snow crystals or grains become more tightly packed over time due to the weight of the snow itself, which compresses the grains together. In addition, the individual grains are worn down and become rounded, and this permits them to come in closer contact with each other. Thus, because the density is greater, more water is stored in snow that has been around for a while than is stored in the same thickness of snow just after it has fallen.

Exercise: Determine the volume of water stored in the snow in the Red River basin. Also, give some possible reasons for why the flooding of the Red River was greater and occurred later in northern North Dakota than in southern North Dakota? [This is answered in the discussion.]

Needed Information:

For the purposes of this exercise, you may use the following information:

Size of the Red River drainage area above Fargo	17,612 square kilometers
Areal extent of the snow covering the basin when snowmelt began	80% of the Red River basin
Average thickness of the snow when it began to melt	50 cm
Density of the snow at the time of melt	400 kg m^{-3}
Amount of evaporation or sublimation that occurred during melt	To simplify things, we'll say evaporation is negligible

Solution: When snow melts, it's often possible to estimate the extent and the timing of the flooding. During the course of the winter, hydrologists monitor the snowpack by periodically making measurements. The thickness of the snow is measured with a ruler and then a known volume of snow is weighed to get an idea of the density of the snow. This is needed to derive the snow water equivalent (how much water results when the snow melts).

We know that 80% of the basin is covered with 50 cm of snow while the remainder of the basin is snow free. Therefore, 14,089 square km of the basin is covered with 50 cm of snow.

Water has a density of 1,000 kg m^{-3}. Thus, for a snowpack having a density of 100 kg m^{-3}, for every 10 cm of snow there is one cm of water. A density of 400 kg m^{-3} for a 50 cm thick snowpack results in a snow water equivalent of about 20 cm.

So we now know that on every square cm of snow-covered land in the basin, 20 cm of water is stored in the snow. This translates to 2,817,800,000,000,000 (2.8×10^{15}) cubic (cu) cm of water or 2,817,800,000 (2.8×10^{9}) cu m of water for the entire basin.

This is almost 3 cubic km of water. If this water were compressed into an area about 1 km wide over a one hundred km length of the Red River in the vicinity of Fargo, it would be about 28 m deep. Flood stage at Fargo is about 5.2 m.

The above calculation presumes that every drop of melt water would wind up making it to the Red River at about the same time. As mentioned above, we're neglecting evaporation, which would in reality reduce these numbers. Moreover, some of the meltwater would infiltrate into the soil layers. The deep snowpack insulates the soil and keeps it from freezing. If the soil were entirely frozen, most of the meltwater would run off into streams and the infiltration would be minimal. On April 18, 1997 the Red River crested (reached its greatest height) at Fargo at about 12 m, which is about 7 m above the flood stage.

Discussion: In parts of the Great Plains and the upper Mid-West, total precipitation for the year may only be 50 cm, and snow may contribute about 40% of the annual water supply. In the Rocky Mountains, the Sierra Nevada Mountains and the Cascades, the greater snow amounts and deeper snowpacks account for as much as 70% of the yearly water supply. However, in the eastern U.S., Baltimore for example, the contribution of snow to the yearly water supply is less than 10%.

The Red River that defines the North Dakota border with Minnesota flows slowly northward and its water eventually ends up in the Hudson Bay. We tend to think that most rivers flow from north to south or from the top of a map towards the bottom. This is not so. It's true that, in general, the snow is deeper in the northern part of the state than in the southern part, but the amount of area drained is usually much more important in determining how much water will be in the river. The Red River "above" Fargo refers to the elevation of the land, and in this case the land to the south of Fargo has a higher elevation. Consequently, the Red River flows north. If the snow has already melted in the southern part of the basin, but ice is covering the rivers to the north, then the flooding may be especially severe. In essence, the ice creates a dam, causing water to back up and overspread the landscape, forming a large shallow lake.

The rate that the snow melts is crucial in determining how fast water will reach the streams and rivers and thus, how damaging the flooding may be. A number of factors affect snowmelt rate. Of course, the temperature is very important, but the condition of the soil, the level of the water table (was it wet during the autumn?), and if there's rain falling on top of the melting snow, can all have an impact on the rate of snowmelt. Because in the northern Great Plains during the winter of 1996-1997 the snowpack was deep and the soil was saturated by autumn rains, the risk for flooding was known to be very high. This means that the melting snow was less likely to be absorbed by the soil and buffered by grasses and other ground coverings. The result was that meltwater quickly swelled the streams.

Now, remote sensing techniques (measuring the snowpack over larger areas with satellites and aircraft) are used to get a handle on how much water the snow is holding. With satellites, much large areas can be monitored than by making similar measurements on the ground. Additionally, satellites that collect information about the snowpack by sensing in the microwave part of the electromagnetic spectrum are not affected by clouds or by darkness, and furthermore, they are willing to on weekends.