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Inclusion of Freeze–Thaw-Induced Soil and Bank Erosion in CoE Planning, Engineering, O&M, and Model Development

Soil freeze–thaw (FT) processes directly affect soil erodibility and bank-failure susceptibility (Fig. 1) (Gatto et al. 2001, Simon et al. 2000) and thus have substantial impact on shoreline or bank evolution, system-wide sediment management, reservoir infilling, levee stability, and sediment-bound contaminant transport within watersheds. This technical note outlines how FT cycling affects overland soil erosion and bank failure. In so doing, it alerts Corps planners, designers, O&M personnel, and water-resources modelers to the importance of knowing the magnitude of these effects on sediment detachment, failure, and transport in such cold-climate, navigable systems as the Mississippi, Illinois, Ohio, Missouri, Susquehanna, Delaware, Columbia, and Sacramento Rivers, and the Great Lakes and their connecting channels.

Freeze–thaw processes

During freezing, ice crystals form within a soil, tightly binding soil particles and keeping the soil highly resistant to erosion and failure. However, that ice also pushes soil particles apart, reducing interparticle friction so that thawed soils are less cohesive, dense, and strong (Gatto 2000). One FT cycle can reduce soil shear strength by 50% or more (Formanek et al. 1984, Van Klaveren 1987).

Also, the soil–surface geometry of thawed soil is often changed by frost heaving during freezing, unit weight is often increased by the soil water drawn into the freezing soil, and infiltration is reduced because water content is usually high. The magnitude of these effects is variable and depends on soil type, water content, and freezing intensity.

Figure 1. Banks are highly susceptible to failure upon thaw.

Soil FT cycles are generally inferred from surface air temperature records. According to Hershfield (1974), a FT event occurs when the air temperature drops below freezing in a calendar day. The presence of frozen ground, which confirms FT processes, is noted over most of the United States (Fig. 2). The most frost-susceptible soils are cohesive, silty sediments. Silts absorb water rapidly because they have particles small enough to provide comparatively high capillary rise and large enough to furnish voids of adequate size to allow rapid flow of water (Jumikis 1962). These characteristics lead to rapid saturation of the soil voids. Coarser-grained soils do not retain a significant volume of water after wetting, and finer-grained soils do not absorb water rapidly. However, sand may become frost susceptible if it is well compacted (Janson 1963), and needle ice will form in almost any soil type (Chamberlain 1981).

FT effects increase soil erodibility and instability such that overland runoff and floods in the spring often erode significantly more thawed upland and bank soil than at other times of the year (Renard et al. 1997). Research shows that in areas where seasonal frost forms, processes related to soil FT contribute to 40 to 85% of overland soil erosion (Zuzel et al. 1982, McCool 1990) and 30 to 90% of bank failures (Thorne 1978, Sterrett 1980, Gardiner 1983, Reid 1985, Lawler 1993, Chase et al. 2001). When rills (Fig. 3) are present on hillslopes they transport 80% of the sediment eroded from that slope (Mutchler and Young 1975). Thus, rill flows are far more important in hillslope erosion than overland sheet flow.

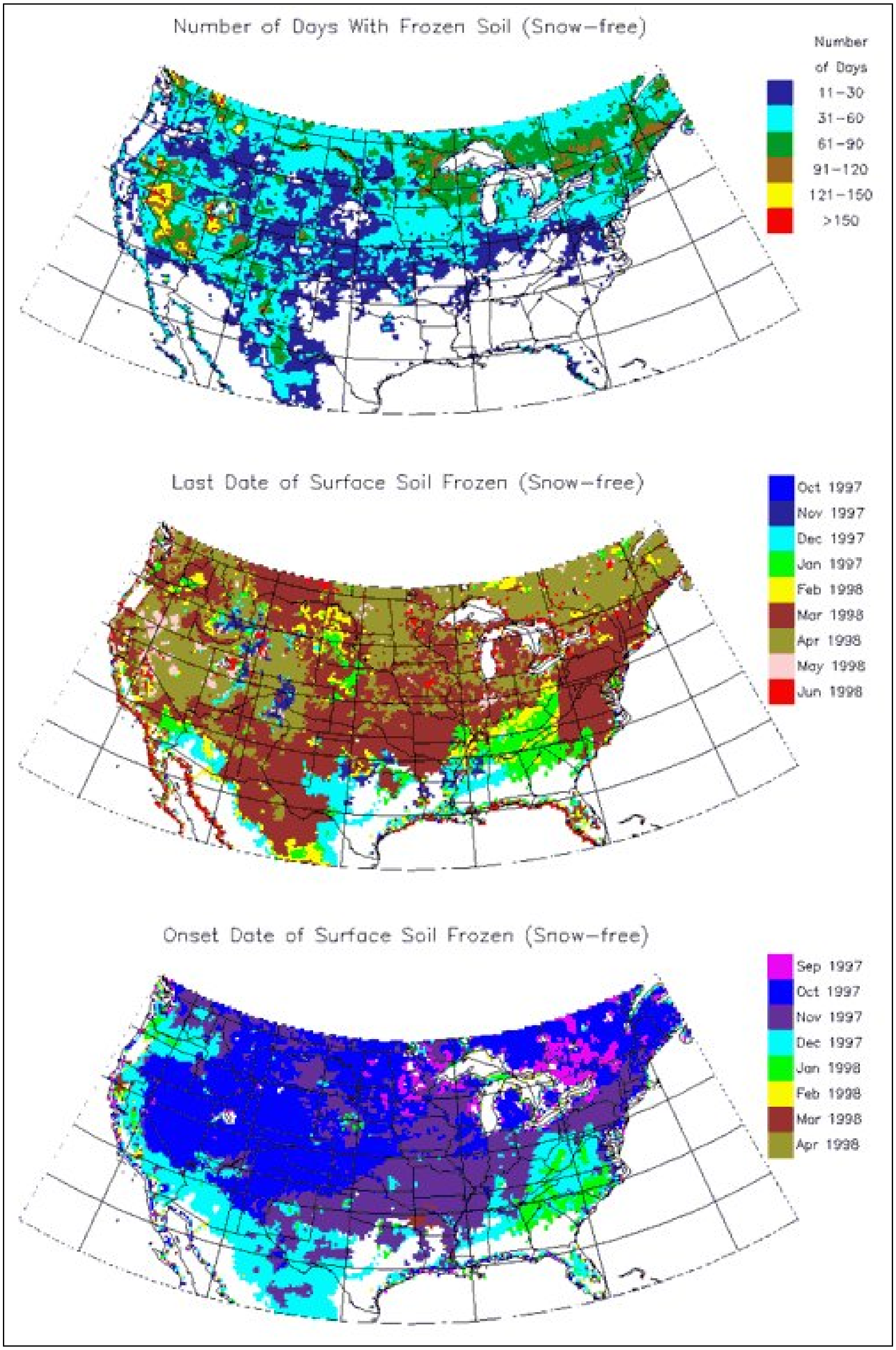

Figure 2. Soil FT detected over snow-free ground using passive microwave. (From Zhang and Armstrong 2001. Used by permission.)

Figure 3. Rill formation is enhanced in frost-susceptible soils as a result of freeze–thaw cycling.

Our research shows that rill development and sediment erosion by channelized flow on a thawed frost-susceptible soil are increased between 1.2 and 4.9 times after just one FT cycle (Ferrick and Gatto in press). The precise magnitude of this increase is directly related to soil moisture. Soil moisture is often high upon thaw and can be equally important in bank failures. Our observations show substantial variations in soil moisture along a silt bank face and between banks with different orientations. Total FT cycles, and freezing intensity and duration, also vary with bank orientation (Gatto and Ferrick in press).

Recommendations

Watersheds that experience ground freezing have greatly enhanced soil erodibility and bank-failure susceptibility following thaw. Much of the sediment load of upland rivers coincides with snowmelt as a result of overland erosion and bank failure during the period of increased soil weakness due to freeze–thaw processes. The sediment load resulting from FT affects most of the major navigable and non-navigable river systems and their tributaries, including the Mississippi, Missouri, Illinois, Ohio, Susquehanna, Delaware, Columbia, and Sacramento, for which the Corps has navigation and flood-control responsibilities. As a result, planning, engineering, and O&M activities that address sediment management should include

1. Confirmation via FT or frozen ground mapping that FT impacts occur in the project area (see, for example, Hershfield 1974);
2. Measurements or estimates of seasonal changes in soil moisture and strength to define FT weakening (one method is proposed in Gatto and Ferrick [in press]);
3. Measurements or estimates of the rate of recovery of soil strength to pre-FT conditions (Gatto and Ferrick in press); and
4. Measurements or estimates of upland sediment eroded by overland flow and bank sediment that failed immediately following spring thaw (Gatto and Ferrick in press).

Future R&D efforts will provide tools that will make these tasks easier by providing geospatially referenced estimates of FT impacts on soil properties. Soil erosion and bank failure models applied in FT-susceptible zones must have the following capabilities:

1. Defines relationships of seasonal changes in soil moisture and strength with the number of FT cycles, the depth of ground frost, and the antecedent soil moisture conditions; and

2. Adjusts seasonal erodibility coefficients compatible with the field data obtained above.

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