# Recovery Potential Metrics
# Summary Form

**Indicator Name:** WATERSHED SOIL RESILIENCE

**Type:** Ecological Capacity

**Rationale/Relevance to Recovery Potential:** Soil texture and slope characteristics affect the degree of nitrogen retention, bank stability, overland flow and erosion potential, and soil characteristics can even completely over-ride land cover effects. Higher stream slopes increase soil erosion potential, and thus, Phosphorus transport potential in overland flow. Soil texture has been called the single most important watershed characteristic affecting water quality of the Great Lakes. Stream nutrients can be associated with soil properties, and fine-textured soils with higher runoff potentials appear to limit the transport of leached Nitrogen.

**How Measured:** Measured from mapped soil survey data within a selected corridor width, e.g. 30 meters, 90 meters. Based on selection of specific soil types documented as better for nitrogen processing, stability/erosion resistance, and other factors as appropriate to the study area. Assigning scores to different soil types based on the properties discussed should be done specifically for the area undergoing assessment, as national generalizations are limiting. Another option is to measure % area within the corridor that has soils with high resilience properties.

**Data Source:** Soil survey data varies from State to State in digital availability. States with fully digitized county soil survey-level information can use this metric most effectively. Physical and chemical properties of soils are available for most areas as part of the US General Soils Map through the NRCS Soil Data Mart (See: http://soildatamart.nrcs.usda.gov/ ).

**Indicator Status (check one or more)**
_______ Developmental concept.
___x__ Plausible relationship to recovery.
_______ Single documentation in literature or practice.
___x__ Multiple documentation in literature or practice.
_______ Quantification.

**Comments:** Sound relationship apparent but metrics need to be developed specific to state or sub-state scale soil and climatic properties.

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**Supporting Literature (abbrev. citations and points made):**

- (Paul and Meyer 2001) Soil characteristics also affect the degree of nitrogen retention, of importance when on-site septic systems are prevalent (Hoare 1984, Gerritse et al. 1995) (343).
- (Norton and Fisher 2000) Ritter (1986) demonstrated that stream nutrient export was more highly correlated with hydrologic characteristics than with land use and livestock density in southern Delaware watersheds, some of which were within the Choptank and Chester basins. Sonzogni et al. (1980) stated that soil texture was the single most important watershed characteristic which effected water quality of the Great Lakes.

  We have shown that the soil characteristics can completely over-ride land cover effects. Although the Choptank and Chester watersheds had very similar land cover extent and spatial patterns (Figs. 1 and 2), they differed in their topographic and soil characteristics (Table 7) which undoubtedly influenced the hydrologic flow path of nutrients from cropland to streams (356-358).

- (Paul and Meyer 2001) Sediment texture is also important, and metal concentration in sediments was inversely correlated to sediment particle size in several urban New Jersey streams (Wilber & Hunter 1979). In addition, geomorphic features have been shown to influence metal accumulations. Higher sediment metal concentrations were found in areas of low velocity (stagnant zones, bars, etc.) where fine sediments and organic particles accumulate, whereas areas of intermediate velocities promoted the accumulation of sand-sized metal particles, which can also be common in urban streams (Rhoads & Cahill 1999) (344).
- (Norton and Fisher 2000) Soil hydrologic characteristics contrasted markedly between the two watersheds. The major difference in hydrologic categories between the Chester and Choptank watersheds was the amount of soils with low (A) and moderately low (B) runoff potentials. The Choptank study area contains considerably more (*) soil with low runoff potential compared to that in the Chester, while the Chester has more (*) soil with moderately-low runoff potential compared to that in the Choptank (Table 7). The standard deviation for all hydrologic classes was high, which reflected the high variation found between individual subwatersheds.

  There were significant effects of hydrologic class on stream N and P concentrations. The four hydrologic classes were combined into two categories (A_B and C_D), and were found to explain the most variation in multiple regression analysis for predicting stream nutrient concentrations (Fig. 10). Correlation coefficients determined for soils with low runoff potential and nutrients in the Chester (*r*2_0.40** for TN and NO3_, 0.24* for TP) were much higher compared to those computed for forest (upland forest and NO3_, *r*2_0.27*). The correlation coefficients computed for Choptank soils with low runoff potential and stream N (*r*2_0.63** for TN and 0.58** for NO3_) were lower than those calculated from forest (*r*2_0.75*** for TN and 0.71*** for NO3_ and forest on hydric soil) (355).
- (Norton and Fisher 2000) The coarse textured, low runoff potential soils of the Choptank may have provided a direct pathway between nitrogen inputs (fertilizers) at the soil surface and the riparian forest. The fine textured, high runoff potential soils of the Chester do not provide this link, possibly due to the greater amount of overland flow and evapotranspiration in this basin as a result of these soil properties (Table 3, Fig. 11) (358).
- (Norton and Fisher 2000) However, the ability of these forests to retain nutrients from agricultural uplands requires an efficient delivery of nutrients. When coastal plain watersheds are characterized by sandy soils, there appears to be a strong relationship between riparian forest cover and low stream nutrient export (Peterjohn and Correll, 1984; Jordan et al., 1993; Gilliam, 1994). However, a watershed characterized by fine-textured soil (the Chester) did not appear to efficiently transport nutrients originating from agricultural activities in uplands to riparian forests. In this watershed, we could not demonstrate any association between low N and P and the presence of riparian forest (356).
- (Norton and Fisher 2000) The influence that forest has on stream N and P must be viewed in context of a wide variety of basin characteristics. While stream N and P in the Choptank were strongly linked to land cover, stream nutrients in the Chester were more closely associated with soil properties. Analysis of soil texture and hydrologic properties indicates that the Choptank had coarser-textured surface soils and was better drained compared to soil in the Chester. The fine-textured soils with higher runoff potentials in the Chester appeared to limit the transport of leached N from cropland to riparian forest. In addition to soil properties, higher stream slopes resulted in higher soil erosion potential and thus, P transport potential in overland flow.

  Results of this investigation reinforce the need for integration of hydrological, geological, land cover and soil properties. To understand the anthropogenic effects on water quality, we needed to consider all four properties (359-360).
- (T.M. Wynn et al. 2008) The goal of this research was to determine if streambank soil erodibility and critical shear stress varied throughout the year due to subaerial processes (freeze–thaw cycling, soil desiccation, etc.). Soil erodibility ($k_d$) and critical shear stress

($\tau_c$) were measured using a multiangle submerged jet test device (Hanson and Cook, 2004). Study results showed temporal variations in $k_d$ and $\tau_c$ were highly significant, monthly and seasonally. In contrast, spatial differences in both parameters (i.e., between sites; Fig. 2) were not statistically significant. The streambank soils were most susceptible to fluvial entrainment during the winter (median kd=0.73 $cm^3$/N-s and median $\tau_c$=6.5 Pa) and the summer (median $k_d$=0.35 cm3/N-s and median $\tau_c$=4.8 Pa), as compared to spring and fall (median $k_d$=0.25 cm3/N-s and median $\tau_c$=15.1 Pa). These findings demonstrate quantitatively that soils are more susceptible to erosion during the winter, providing credence to the observations of Wolman (1959), Twidale (1964), Knighton (1973), Hooke (1979), and Thorne and Lewin (1979) that streambank soils appeared to erode more following freeze–thaw cycling. While no significant correlation was found between indicators of soil desiccation (low soil moisture or high soil temperature), these findings also suggest that soil desiccation during the summer may increase $k_d$ and decrease $\tau_c$

- (T.M. Wynn et al. 2008) Regression analysis indicated 80% of the variability in $k_d$ was explained by the number of freeze–thaw cycles occurring during the 10 days prior to jet testing. Additionally, decreases in bulk density were correlated with increases in both soil moisture at the time of testing and the number of freeze–thaw cycles that occurred over the previous 30 days ($R^2$ =0.86). Given the small data set (n=12) and the large spatial variability inherent in many soil properties, such strong correlation between $k_d$ and bulk density and freeze–thaw cycling is surprising. These findings provide quantitative evidence that freeze–thaw cycling can exert a strong influence on the susceptibility of some streambank soils to fluvial entrainment.
- (T.M. Wynn et al. 2008) Studies by Couper and Maddock (2001) and Couper (2003) indicated freeze–thaw cycling contributes to more bank erosion than wetting–drying cycles, while Wood (2001) observed that both freeze–thaw cycling and desiccation equally accelerated the weathering and erosion of cohesive soil blocks in the basal area of actively eroding streambanks along Goodwin Creek, Mississippi.
- (T.M. Wynn et al. 2008) The freezing process causes a migration of soil water toward the freezing front and can lead to the formation of large ice crystals that decrease soil density (Branson et al., 1996). This effect is particularly pronounced in fine-grained soils: the pore sizes in silty soils are small enough to create a gradient in soil suction, but large enough to allow relatively rapid water movement toward the freezing front (Gatto and Ferrick, 2002). Soils with a silt-clay content <20% are considered “frost-susceptible” (Matsuoka, 1996).
- (T.M. Wynn et al. 2008) These research results have potential implications for streambank erosion modeling and stream restoration projects. Current practice assumes soil erodibility remains constant throughout the year. Evaluation of current models and design practices is necessary to determine whether the potential for error based on changes in soil erodibility over time exists. Upon further investigation, consideration of temporal variability in streambank soil erodibility for regions and soils susceptible to degradation from freeze–thaw cycling or desiccation cracking may be necessary. Additionally, restoration designs should consider the implications of changes in soil erodibility during the year in the design process.
- (Wynn and Mostaghimi 2006) The most significant factor determining the soil erosion rate in this study was bulk density (BD). Increases in bulk density resulted in decreases in soil erodibility and increases in the critical shear stress for the overall dataset as well as for Group 1 and Group 3 soils. Bulk density explained 33 percent and 52 percent of the variance in $K_d$ and 36 percent and 46 percent of the variance in $\tau_c$ for the overall and Group 3 soils, respectively. Previous researchers have reported that soil erosion rates decreased with increasing bulk density (Hanson and Robinson, 1993; Allen *et al.,* 1999).
- (Wynn and Mostaghimi 2006) Study results provided evidence that the interaction of stream and soil chemistry significantly influenced streambank erosion. Increases in the ratio of the soil pH to the stream pH resulted in decreases in $\tau_c$ for the overall dataset and increases in $K_d$ for the Group 3 soils. Previous research showed that both soil and stream

pH influence soil erosion (Grissinger, 1982). Soils become more dispersive with increases in pH due to increases in pH-dependent cation exchange capacity (CEC). Increases in CEC with pH increase surface charge on the soil colloids, leading to greater repulsion between soil particles (McBride, 1994). This increase in CEC with pH is particularly important for soils with significant amounts of pH dependent charge, such as kaolinites and illites, and for soils high in organic matter (Grissinger, 1982; McBride, 1994).

- (Wynn and Mostaghimi 2006) The soil salt concentration, expressed in units of normality (PW) was negatively correlated to soil erodibility. Similar results were reported by Arulanandan *et al.* (1980) for a flume study on the erosion of cohesive soils. As discussed in McBride (1994), the flocculation of suspended particles increases with increasing cation charge and concentration; the solution cations reduce repulsion between the negatively charged soil particles.
- (Wynn and Mostaghimi 2006) Unsurprisingly, soil texture influenced the critical shear stress. The critical shear stress of cohesionless bed sediments is frequently determined by the particle size and specific gravity using Shield's diagram. Factors such as particle shape and sediment standard deviation also influence the drag and lift forces experienced by individual particles (Vanoni, 1975).
- (Wynn and Mostaghimi 2006) For the noncohesive soils in Group 3, the critical shear stress increased with increasing moisture content (MC). This suggests that water films in the soil increased soil cohesion or that the coarser soils were more susceptible to slaking than the fine grained soils. During the course of the study, the authors noted that the streambanks with high sand contents were friable when dry, suggesting that the former explanation – that water films increased soil cohesion – was the more likely explanation of the inverse relationship between $\tau_c$ and MC. This observation was supported by the study results for aggregate stability.
- (Couper 2003) The results indicate that river banks with high silt–clay contents are the most susceptible to erosion by subaerial processes. High susceptibility may influence spatial variations in bank erosion processes and rates, including downstream changes in the effectiveness and significance of subaerial erosion. A 'vertical zoning' of processes on a river bank is recognised, whereby the upper part of the bank is subject to subaerial erosion and the lower part to fluvial erosion. Given that a high silt–clay content tends to indicate increased susceptibility to subaerial erosion but increased resistance to fluvial erosion, this vertical zoning may have implications for bank morphology.
- (Couper 2003) On completion of 30 freeze–thaw cycles, removal of the 'eroded' material from the container revealed that, in the soils with higher silt–clay contents, the base of the sample appeared to have expanded. This was particularly pronounced for the 75% silt–clay content sample, where the edge of the intact soil block had advanced approximately 5 mm across the line representing the original limit of the sample. (Couper 2003) On completion of the 30 freeze–thaw cycles, samples with higher silt –clay contents clearly showed a greater degree of erosion, and production of larger aggregates than samples with lower silt– clay contents. The correlation coefficient between silt–clay content and the mass of eroded material is statistically significant at 0.778 (critical value 0.622, $n = 8$, $p = 0.05$). This increase in severity of erosion, however, occurred primarily between 50% and 55% silt– clay, with considerable difference between these two samples.
- (Couper 2003) Previous research (Thorne and Tovey, 1981; Osman and Thorne, 1988) indicates that banks with a high silt–clay content are the most resistant to retreat driven by fluvial erosion and mass failure. The results described here suggest that these banks will conversely be the most susceptible to subaerial erosion (both summer desiccation and winter freeze–thaw). Subaerial processes could, thus, be expected to account for a larger proportion of the annual erosion rate on river banks with high silt– clay contents. This could be of significance both in the context of comparing erosion rates of different rivers across a region and in accounting for downstreamchanges in erosion rate such as those described by Brierley and Murn (1997), as river banks tend to increase in silt–clay content in a downstream direction (e.g. Lawler et al., 1999). Similarly, a downstream increase in susceptibility to subaerial processes relating to a downstream

increase in soil silt–clay content would hold implications for Lawler's (1992) concept of process dominance, which assumes subaerial activity to be constant throughout the drainagebasin.

- (Biggs, Dunne and Marinelli, 2004) Natural variation in soil texture explains most of the variance in stream nitrate concentrations, while deforestation extent and urban population density explain most of the variance in stream chloride (Cl) and total dissolved nitrogen (TDN) concentrations.
- (Biggs, Dunne and Marinelli, 2004) Terrestrial nutrient dynamics change with soil properties, resulting in regional patterns in nutrient cycling patterns. Nutrient stocks and cycling rates in terrestrial tropical forests increase with soil fertility (Vitousek and Sanford 1986), and nutrient transformation rates in terrestrial systems depend on soil texture (Silver et al. 2000; Vitousek and Matson 1988). In the Rondonia streams, soil properties also correspond to regional patterns in stream nutrient concentrations, suggesting that both terrestrial and aquatic nutrient dynamics are controlled in part by watershed soil properties. Stream P and $NO_3$ are the most affected by soil characteristics; TDN shows a slight but statistically significant effect of soil properties
- (Biggs, Dunne and Marinelli, 2004) Stream nitrate concentrations might be expected to increase or decrease with soil clay content, depending on the relative importance of mobilization and transport. Nitrogen mobilization via mineralization and nitrification typically decreases with soil sand content in tropical soils (Vitousek and Matson 1988; Silver et al. 2000), while nitrate leaching rates typically increase with soil sand content due to decreased rates of nitrate adsorption (Gustafson 1983; Wong et al. 1990) and denitrification (Avnimelech and Raveh 1976) in sandy soils. If mineralization and nitrification in the soil were the principal control on stream nitrate concentrations, we would expect stream nitrate concentrations to decrease with increasing sand content. The fact that we observe the opposite in the Rondonia streams suggests that stream nitrate concentrations in minimally disturbed catchments are controlled more by the leaching characteristics of soils than by rates of mineralization and nitrification in the soil profile.
- (Li, Wang and Tang, 2006) Results showed that the rainfall intensity had a small influence on nutrient concentrations in runoff, but a significant influence on the runoff flow on sloping lands. The slope length influenced the nutrient loss by soil erosion on areas that receive rainfall. The slope gradient influenced the nutrient loss by runoff flux and velocity on sloping land. As the slope gradient decreased, the nutrient loss decreased because of the increase in infiltration. The soil texture, porosity, and water content influenced the motion of soil water and the transfer and form of nutrients in soil, through oxidation and deoxidation. Vegetative coverage influenced the infiltration coefficient of rainwater into subsurface soil, and thus influenced the runoff flow velocity. Therefore, different sloping lands need to be managed in different ways.
- (Lindow, Fox and Evans, 2009) The role of seepage on bank stability has been previously studied at two stream sites in Mississippi, where erosion due to seepage was found to form cavities in stream banks with layered soils of differing conductivity (Fox *et al.*, 2006, 2007; Wilson *et al.*, 2006). Highly permeable soils eroded out from stream banks and caused overhanging soil layers to fail. The stream banks collapsed due to undercutting and cantilever failure of the cohesive layers.
- (Lindow, Fox and Evans, 2009) The major implication of this research is that bank slope stability design based only on fluvial hydraulics analysis may fail due to groundwater instability mechanisms. On layered banks, groundwater seepage processes may be concealed as small-scale failures of underlying less cohesive layers that can lead to larger-scale failures of overlying streambank sediment. These laboratory experiments suggested that the failure mechanism was dependent on bank angle. The results are an important component in furthering bank stability modeling and improving the stream restoration practice.
- (Lindow, Fox and Evans, 2009) Lateral seepage caused bank failure in all stream banks tested, regardless of bank angle. Failure was mainly due to pop-out failures along the toe of the slope and piping by seepage through the underlying sand layer, followed by planar

slope failure of the overlying loam material. However, the mechanisms of failure varied according to initial bank angle. The intermediate sloped bank had the longest time to failure and highest percentage bank saturation. The 90° bank test and 26̃.6° slope test resulted in more rapid failure at lower percentage bank saturation (Table III).

- (Calhoun, Baker and Slater, 2002) Suspended solids concentration in the drainage water was directly related to amount of soil clay. The Paulding watershed yielded the highest concentration of suspended solids. This suggests that nearly level watersheds, especially fine-textured ones, may be important contributors of suspended solids entering the Maumee River.
- (Calhoun, Baker and Slater, 2002) The results from, especially, the Paulding watershed, indicate that low-gradient lake plain watersheds dominated by very poorly drained soils high in clay (>50%) are an important component in export of suspended solids. It is apparent, at the small watershed scale, that soil texture and internal drainage are the controlling factors for median pollutant concentrations. In this particular case soil texture is controlled by parent material and internal drainage can be controlled by man's intervention with tile. Natural internal drainage (very poorly) and slope (nearly level) are controlled by physiography (lake plain).
- (Calhoun, Baker and Slater, 2002) Clayey, lake plain soils that are not tile-drained are greater sources of suspended solids than are the loamy soils found on moraines. Tile-drained soils in the lake plains export more nutrients such as nitrates and phosphates, in solution, than do the better-drained, sloping soils on moraines. Tile-drained soils of the lake plains export substantially less sediment than do the non–tile drained soils. It is obvious that greater attention be given to the lake plains of the Maumee and Sandusky basins both as a pollutant source and as a target for improved agricultural management practices. The assumption that sloping moraine areas are the primary of pollutants should be reexamined based on this review. Careful examination of upstream water quality studies reveals the importance of the soil series in explanation of pollutant export from rural landscapes. Future collection, analysis, and interpretation of water quality data would benefit from a more thorough examination of soils in tributarywatersheds in order to explain pollutant export differences between tributary watersheds.
- (Seely, Lajtha and Salvucci, 1998) In a recent study, Lajtha et al. (1995) found no relationship between stand age and N leaching losses below the rooting zone, but the calculated losses were larger than expected in an aggrading successional forest based on studies in upland forests. They suggested that edaphic factors related to soil texture were the dominant regulators of N retention in these systems. This hypothesis is consistent with the results of Coufteax and Sallih (1994) who found leaching losses of $^{15}N$ applied to cores taken from various forest soils to be positively correlated with particle size.
- (Seely, Lajtha and Salvucci, 1998) The difference in nitrogen leaching loss over the soil texture gradient appears to be related to the retention capacity of DON in the mineral soil. DON concentrations decreased substantially during percolation through the forest floor to ground water in LS and to a lesser extent in FS. No such decrease was observed in CS. Although not directly tested here, the greater surface area presented by the finer mineral soil particles of LS likely facilitated the adsorption of a larger fraction of soil solution DON relative to the more coarsely textured sites during the percolation of soil water through the soil profile. Additionally ,the higher infiltration rates measured in CS and FS may limit the contact time of DON in soil solution with particle surfaces The larger loss of DON observed below the rooting zone in FS may be due to the presence of a much more developed forest floor in FS relative to CS. Thus, in FS there is a larger pool of organic N in the forest floor from which larger quantities of DON may be leached. Additionally, there was a significantly larger microbial biomass present in the 02 horizon of FS relative to CS which may also account for the larger loss of DON in that site by conversion of DIN to DON through microbial processing (Seely & Lajtha 1977).