POLYACRYLAMIDE AMENDMENT FOR EROSION AND RUNOFF CONTROL ON SOILS OF DIFFERING CHARACTERISTICS

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by

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POLYACRYLAMIDE AMENDMENT FOR EROSION AND RUNOFF CONTROL ON SOILS OF DIFFERING CHARACTERISTICS

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ABSTRACT

The use of anionic polyacrylamide (PAM) as a soil amendment is an emerging conservation practice. However, guidelines have not been developed with considerations of soil properties and topographic characteristics. The objectives of these studies were to evaluate the effects of PAM, gypsum, or their combination for four dependent variables of time to initial runoff (TRO), cumulative runoff (RO), and cumulative sediment loss (SL) on different soil materials with selected slopes. Each soil material was packed to a bulk density of 1.3 Mg m^{-3} (81 lb ft^{-3}) in soil test beds subjected to a 61-mm h^{-1} (2.4-in hr^{-1}) simulated rainfall with a kinetic energy (KE) of 1.5 kJ m^{-2} h^{-1} (103 ft lb ft^{-2} hr^{-1}) for 62 min. Differences in TRO, RO, and SL for soils, amendments, and slopes were all significant, as were their two-way interactions ($p<0.01$). Tested soil amendments had varied responses on TRO, RO, and SL within soils. For reducing SL, a high level of PAM had better performance at a steep slope compared to a low level of PAM or ≤40% slope. Generally, the applications of PAM amendment were not effective in reducing RO, but increased TRO. Differing amendment performance for different soils and slopes make it necessary to continue to understand the soil-PAM bonding mechanisms.

CHAPTER 1.
LITERATURE REVIEW

Rationale of Studies

The environmental cost of soil erosion by water and wind processes for on- and off-sites is about $62 billion per year in the US (in 2009 US dollars; Pimentel et al. 1995). The use of anionic polyacrylamide (PAM) as a soil amendment is an emerging conservation practice for upland erosion control. Development of guidelines for use of PAM is necessary for the management tool to effectively reduce soil erosion and surface runoff. Improved guidelines are needed to insure effective and economical conservation for soils of differing physical and chemical properties. Much of the research literature has identified many factors that have been shown to influence its effectiveness for reducing soil erosion and runoff (Agassi et al. 1990; Kinnell 2000; Flanagan et al. 2002a, 2002b; Sojka et al. 2007). Currently, some US State Departments of Transportation (USDOT) and Natural Resources, and the US Environmental Protection Agency (USEPA) have published PAM guidelines for erosion control (USEPA 1992; WDNR 2001; WSDOT 2008). However, these guidelines do not explain (1) how differences in soil properties including texture, pH, and organic matter (OM) may influence the effectiveness of PAM, gypsum, or their combination and (2) how different amounts of PAM work with different slopes.

Given the unique geography within Missouri, erosion control on other lands including forested riparian areas near streams and rivers, and areas undergoing prairie restoration should be of interest to the Missouri Department of Conservation (MDC), Missouri Department of Natural Resources (MDNR), the US Forest Service (USFS), the US Fish and Wildlife Service (USFWS), and the US Department of Transportation (USDOT). Furthermore, individual users can apply the most effective and economical PAM application as a function of local soil and slope. Research on these topics will contribute to improve soil conservation by reducing soil erosion.

Limitation of Conventional Practices

Several conservation practices are recommended to help erosion control for disturbed sites including roads, urban construction sites, landfills, and reclaimed mining sites. Successful vegetation establishment, especially on steep slopes, requires soil protection from direct rainfall or soil particle detachment. The use of mulches, erosion control blankets, tackifiers, and hydroseeding may be employed before vegetation establishment. Mulches may be effective, but are prone to sloughing under intense rainfall and runoff conditions. Erosion control blankets are also effective, but can be costly (\$13,000-\$290,000 ha^{-1} or \$5,206-\$117,992 ac^{-1}; Caltrans 2008). Tackifiers are useful, but require some types of mulch cover to be effective. Polyacrylamide as a soil amendment has been found beneficial in reducing sediment transport and soil erosion, and increasing infiltration, but its effectiveness can be diminished with increasing slope, concentrated water flow, and intensive rainfall. The combination of PAM application with other methods or effective PAM application may promise to enhance the environmental benefits for improved conservation.

The Definition of Soil Erosion

Erosion is a phenomenon of removal or transportation of sediment, soil particles, and rock particles caused by water, wind, or gravity (Brady and Weil 2007). The term of erosion is from “erosion” which means “eating away”, derived from Middle French erosion, from L. erosionem (nom. erosio), from erodere “gnaw away”, or from ex- “away” + rodere “gnaw” (Etymology dictionary 2009). The first known occurrence of the term “erosion” was used in 1541 from the Guy de Chauliac’s medical text “The Questyonary of Cyrurygens” which translated by Robert Copland (Guy de Chauliac 1542). He used “erosion” to describe how ulcers developed in the mouth. The term of “erosion” was first used outside medical subjects by Oliver Goldsmith in his book “Natural History” (Goldsmith 1774). His textbook sought to draw together virtually all that was known about the planet earth, its plants and animals, and even its human inhabitants described from a biological perspective.

Currently, soil erosion has been gradually increased by human land use such as deforestation, overgrazing, unmanaged construction activity, and road-building across the world. Soil erosion is one form of degradation phenomena such as compaction, salinization (accumulation of salts), nutrient depletion, and contamination (Brady and Weil 2007). Soil erosion is distinguished from the physical or chemical weathering of minerals. Soil erosion on cropland in the US was estimated to be $1.8*10^9$ tons ($4.0*10^{12}$ lbs) in 2003 (USDA NRCS 2007).

Detrimental Effects of Erosion

Soil Erosion

Soil erosion causes severe economic losses as well as environmental problems in the US. Approximately, $4*10^9$ tons ($8.8*10^{12}$ lbs) of soil and $1.3*10^{11}$ tons ($2.9*10^{14}$ lbs) of water are lost every year from the US cropland of $1.6*10^8$ ha ($4.0*10^8$ ac; Pimentel et al. 1995). These types of losses translate into an on-site economic loss of more than $38 billion every year, of which are $28 billion for replacement of nutrients and $10 billion for lost water and soil depth (in 2009 US dollars; Troeh et al. 1991; Lal 1994; Pimentel et al. 1995). Soil particles entering streams and rivers are a major cause of off-site erosion and about $8.8*10^8$ tons ($2.0*10^{12}$ lbs) of soil is deposited in the US each year. The total cost of all off-site impacts caused by erosion in the US is about $24 billion per year (Pimentel et al. 1995). They further state during the last 40 years, nearly one-third of the world's arable land has been lost by erosion and the total on- and off-site cost of erosion damages by wind and water is $62 billion each year in the US (in 2009 dollars).

Crop Productivity

Soil erosion causes problems such as reduction of crop production potential, and degradation of the quality of soil and water resources for agricultural purposes. Soil erosion reduces soil productivity by reducing plant nutrient, soil-water holding capacity, and infiltration rate, and also increases runoff and sediment loss (Buntley and Bell 1976; Schertz et al. 1989; Thompson et al. 1991; Troeh et al. 2004). Moreover, loss of productive topsoil reduces soil productivity (Gantzer et al. 1990; Troeh et al. 2004). Approximately $7.5*10^{11}$ tons ($1.7*10^{15}$ lbs) per year of fertile top soil is lost from world agricultural systems, and the US occupied about 9% of whole fertile soil loss in the world (Myers 1993; Pimentel 2006). About 80% of productive land has been moderately or severely eroded, and about $1*10^6$ ha ($2.5*10^6$ ac) of the world cropland is abandoned each year due to reduced productivity (Faeth and Crosson 1994; Lal 1994; Pimentel 2006).

Nonpoint Source (NPS) Pollution

Soil erosion causes hazardous nonpoint source (NPS) pollution when rates become excessive. Nonpoint source pollution occurs when rain induces runoff across fields or pavement. Runoff from human habitations, industrial sites, or bare soils during development contains toxic or harmful contaminants, and thus acts as a source of NPS pollution (CWAC 2009). Nonpoint source pollution increases the potential for siltation and flooding, disrupts aquatic habitats, and degrades the quality of water due to transported agricultural nutrients and chemicals (Clark 1985; Clark et al. 1985; Myers 1993; USEPA 2004; Pimentel 2006). In the US, approximately 60% of the NPS sediment is deposited in rivers, streams, lakes, ponds, and reservoirs, and about $2.4*10^{10}$ tons ($5.3*10^{13}$ lbs) of soil are eroded from the land and end up in streams each year (USDA 1989). Approximately 44% of rivers and streams, 64% of lakes and reservoirs, and 30% of bays and estuary areas are impaired. In total, NPS pollution in- and off-stream water sources costs approximately $11 billion per year in the US (in 2009 US dollars; Pimentel et al. 1995; USEPA 2004).

Factors influencing Soil Erosion

Rainfall

Rainfall is one of the most important factors that induce soil erosion, especially on bare soils. Raindrop induces the breakdown, detachment, transport, and redistribution of soil particles (Hudson 1995; USDA NRCS 2007). Soil particles are also splashed, rolled, or carried in suspension along the soil surface by runoff (Mohammed and Kohl 1987; Agassi et al. 1994; Hudson 1995). These processes of soil erosion by rainfall impacts involve breakdown of soil aggregates, detaching particles, plugging interpedal pores, decreasing porosity, and inducing the surface seal formation in the upper few mm (McIntyre 1958a; Farres 1978; Boiffin 1986; Baumhardt et al. 1990). During a rainfall event, soil erodibility is affected by many physical and chemical factors including clay type and amount, availability of $CaCO_3$, amount of organic matter (OM), salinity, wetting rates, and initial conditions (Meyer and Harmon 1984; Lado et al. 2005).

Kinetic Energy (KE) of Raindrops

The kinetic energy (*KE*) of raindrop is potential ability of rain to detach soil particle and has an important characteristic involving increases in surface seal, runoff, and erosion. The rainfall's impact on a bare soil has been extensively studied (Mohammed and Kohl 1987; Agassi et al. 1994; Hudson 1995). The *KE* of raindrop induces severe breakdown and compaction of soil aggregation on a bare soil (Morin et al. 1981). The magnitude of the *KE* of raindrops has been estimated to be about 260 times greater than the *KE* of surface flow (Hudson 1995). As the *KE* of raindrop increases, the amount of rain before ponding, final infiltration rate, and cumulative infiltration decreased with an equal infiltration rate (Levy et al. 1991). The compaction or consolidation by the *KE* of raindrops may decrease soil erosion as the soil particle cohesion increases (Miller 1987). However, soil erosion or runoff is generally increased by the *KE* of raindrop due to the formation of surface seals. Soil loss during an intensive rainfall is also greater than soil loss during rainfall with a mild intensity (Mermut et al. 1997). A high intensity of rainfall increases an amount of splash-detached materials (Römkens et al. 1986).

A number of equations have been developed to estimate the *KE* of raindrops (Hudson 1995). General form of *KE* expressed by Eq. [1]:

$$KE = f \text{ (logarithm of intensity)} \qquad \text{Eq. [1]}$$

In addition, the universal soil loss equation (USLE) is widely used to estimate erosion from agricultural fields in the US (Wischmeier and Smith 1978). The rainfall factor, *R*, in the USLE is calculated from the *KE* (Laws and Parsons 1943). For intensities of ≤76 mm h^{-1} (≤3 in hr^{-1}), the *KE* can be estimated by Eq. [2]:

$$KE = 0.119 + 0.0873(I) \qquad \text{Eq. [2]}$$

where

KE is the kinetic energy (MJ ha^{-1} mm^{-1}) and

I is the rainfall intensity (mm h^{-1}).

Soil Surface Sealing

The natural process of rainfall in terms of seal formation is a complex phenomenon. Seal formation and erosion occur simultaneously and establish a dynamic equilibrium (Baumhardt et al. 1990). These processes are influenced by many factors such as rainfall properties, runoff rate, soil type and properties, ground cover, and topographic characteristics (Tackett and Pearson 1965). One of the main properties degraded by surface sealing is relates to soil hydrology. Generally, water infiltration into a bare soil is greatly reduced by complex processes of surface seal related to soil properties such as soil density, porosity, pore-continuity, and pore-size (Duley 1939; Ellison and Slater 1945; McIntyre 1958a, 1958b; Ahuja 1974; Morin and Benyaminy 1977; Moore 1981; Ahuja 1983; Eigel and Moore 1983).

McIntyre (1958a) found that a surface seal consists of two distinguishable parts: (1) an upper “skin” seal of about 0.1 mm (0.004 in) attributed to compaction by raindrop energy, and (2) a “washed-in” zone about 1.5 mm (0.06 in) of decreased porosity, attributed to the accumulation of particles. The difference in water permeability between the “skin” and “washed-in” zones was from 200 to 2000 times, compared to an underlying unsealed soil. In addition, there are two complementary mechanisms of a structural seal formation involved (Agassi et al. 1981): (1) a physical breakdown of soil aggregates caused by wetting and raindrop energy, and (2) physico-chemical dispersion of clay particles that move into the soil with the infiltrating water and that clog pores to form a “washed-in” layer of low permeability. As a result, a great reduction in hydraulic conductivity from the surface seals increases an amount of soil erosion and surface runoff (Römkens et al. 1986; Abu-Sharar et al. 1987).

Soil Texture

The aggregate stability is mainly affected by soil texture (Wakindiki and Ben-Hur 2002). The fine-textured soil-materials readily move into large pores, attach to other soil particles, fill pore-space, thereby reducing macroporosity and water permeability. The water permeability on a coarse textured soil is usually greater than on a clay soil as a result of greater macroporosity (Bouma 1979; McKeague et al. 1982).

The aggregate slaking is a main reason for infiltration reduction on clay soils (Lado et al. 2005). For intermediate clay content ranging from 22.5% to 40.2%, the soil may be more susceptible to seal formation (Mamedov et al. 2001). Abu-Sharar et al. (1987) reported that the cause of reduced saturated hydraulic conductivity (K_s) is often loss of macropores from aggregate slaking (Lebron et al. 2002; Levy and Mamedov 2002). For clay content of >40%, aggregate stability is generally established (Mamedov et al. 2001; Tang et al 2006). For the soils with clay contents ranging from 63% to 80%, aggregate stability often is increased because of relatively high clay content (Lado et al. 2004b). Both of the wetting rate and soil water content also determine the magnitude of slaking forces. The slaking forces increase as a wetting rate increases and soil water content decreases (Lado et al. 2004b).

Slope Factor

Steep slopes, such as highway embankments and landfills, suffer from serious erosion (WDNR 2001; VDCR 2002; WSDOT 2008). Slope is an important factor in determining the erosion rate, which is 84% higher for slopes of 5%-30% than for areas with a flatter slope (Kinnell 2000). Runoff and runoff potential for sediment transport also increase with increasing slope because of the lower ability of water to pond in these areas, which thereby intensifies soil erosion (Huang 1995; Bradford et al. 1996; Fox et al. 1997; Fox and Bryan 1999). Fox et al. (1997) found that infiltration rates are decreased by increasing slope because of the greater ponding depths in areas with high slopes. The proportion of rain intercepted on the ground varied with slope and aspect, or with both factors (Sharon et al. 1988; Agassi et al. 1990). Conversely, a decrease in runoff was often reported with increasing slope, which was related to rill erosion on thin surface crusts by raindrops (Poesen 1984). Results of different studies have supported the idea that rilling on soil surfaces increases the infiltration rate of these soils (Bryan and Poesen 1989; Slattery and Bryan 1992). Furthermore, no significant change in runoff was reported with changes in slope (Lal 1976; Mah et al. 1992).

Contradictory findings may result from differences between experiments (Fox et al. 1997). Soil erosion and runoff are affected by many factors including slope angle and range, aspect, runoff velocity, rainfall intensity, plot size, and soil type (Agassi et al. 1990; Gerits 1990; Gerits and De Lima 1990; Kinnell and Cummings 1993; Fox et al. 1997; Chaplot and Le Bissonnais 2000; Kinnell 2000). Agassi et al. (1990) studied the effects of slope and aspect (windward vs. leeward) on erosion and runoff under natural rainfall. They found that runoff was not affected by slope on the windward aspect and decreased on the leeward aspect with increasing slope. Sediment concentration was three times higher for a 10-m^2 (108 ft^2) test plot with increasing slope than for a plot of the same size with no slope whereas runoff increased by up to 90% for test plots of 1 m^2 (10.8 ft^2) and 10 m^2 (108 ft^2) with increasing slope and rainfall intensity (Chaplot and Le Bissonnais 2000). Kinnell and Cummings (1993), and Kinnell (2002) researched the effects of slope gradient and length, aggregate stability, and soil erodibility on sediment concentration for the four different soils subjected to a 60-min simulated rainfall with an initial intensity of 71 mm h^{-1} (2.8 in hr^{-1}). They found that sediment concentration with a slope length of 600 mm (24 in) was 37% higher at a slope of 5% and 54% higher at a slope of 30% over the four different soils compared with the concentration at a slope length of 150 mm (6 in). Aggregate stability and soil erodibility were also altered by slope gradient and length.

Polyacrylamide (PAM)

Background

Research on Polyacrylamide (PAM) as a soil amendment began in the 1950s, and was applied to furrow irrigation in the Pacific Northwest since the early 1990s (Sojka et al. 2007). Polyacrylamide is the generic name for "a group of very high molecular weight macromolecules produced by free radical polymerization of acrylamide. It is an anionically charged comonomer, mainly the sodium salt of acrylic acid, sodium acrylate" (Horticultural Alliance, Inc. 2006).

Actions of Polyacrylamide (PAM)

Polyacrylamide is a chemical material made of repeating monomer chains of acrylamides and acrylates (Agassi et al. 1981; Seybold 1994; Sojka et al. 2007). Anionic polyacrylamide is reported to be nontoxic and is used for control of furrow irrigation induced erosion (Sojka and Surapaneni 2000; Green and Stott 2001; Sojka et al. 2007). Polyacrylamide with a high molecular weight and moderate negative charge density stabilizes the soil aggregates by enhancing clay flocculation, thereby increasing water infiltration and decreasing soil-particle detachment (Zhang and Miller 1996; Ross et al. 2003; Sojka et al. 2007). When PAM is used with water having sufficient electrolytes, coulombic and van der Waals forces attract cations to soil particles attracting anionic PAM (Orts et al. 1999). Solution Ca^{++} shrinks the diffuse double layer near soil particles, thereby creating "cation bridges" between soil and PAM molecule (Wallace and Wallace 1986). Polyacrylamide only stabilizes soil; however, it does not improve soil with poor structure (Cook and Nelson 1986).

The principle use of PAM is to reduce soil erodibility. Erodibility depends on many factors including soil texture, clay type and amount, OM amount and quality, soil structure, availability of Ca^{++} ions, salinity, soil initial conditions, and cation exchange capacity (Meyer and Harmon 1984; Lado et al. 2005). Gypsum (source of Ca^{++}) is often used with PAM for increasing base saturation and reducing the ratio of exchangeable sodium (Wallace and Wallace 1996). Cations and sufficient electrolytes increase clay flocculation (Keren and Shainberg 1981). In soils with low base saturation, a mixture of PAM with gypsum has been found to improve PAM benefits (Jian et al. 2003).

Clay with Polyacrylamide (PAM)

The adsorption of anionic PAM on clay surfaces depends on clay mineralogy, solution pH, and their cation bridging. The charge neutralization is the primary bonding mechanism between cationic PAM and clay-mineral surfaces; however, the interaction between anionic PAM and clay-mineral surfaces is not well known (Theng 1979; Aly and Letey 1988; Ben-Hur et al. 1992). Polyacrylamide adsorption to solution pH results from (1) the flocculation and dispersion of PAM and (2) the pH dependant charges of soil-PAM bonding. With anionic PAM, the acrylamate negatively charged at high pH by acid dissociation reaction ($-COOH \rightarrow -COO^{-} + H^{+}$), thereby decreasing the adsorption of anionic PAM with increasing solution pH (Lu et al. 2002; Deng et al. 2006).

Laird (1997) also suggested that cation bridging is a major bonding mechanism between anionic PAM and clay surfaces. He found that anionic PAM is effective for flocculation of kaolinite and illite with Ca^{++}, but is not effective with Na^{+}. Anionic polyacrylamide is not also effective with quartz. Lu et al (2002) found that PAM sorption with divalent cations Ca^{++} and Mg^{++} increased by 280 times compared to monovalent cations Na^{+} and K^{+}, mainly due to the stronger charge in Ca^{++} and Mg^{++}. They also suggested that PAM sorption varied with soil texture and was greater in fine soils compared to sandy soils. Bhardwaj and McLaughlin (2007) studied the interactions between clay mineralogy and PAM for turbidity and flocculation control in discharged waters from construction sites. They found that turbidity was affected by both clay mineralogy and exchangeable cations, and smectitic and illitic clays are more dispersive than kaolinitic clays. Therefore, the smectitic and illitic clays produce higher turbidities. Recently, the soils with predominantly smectitic, illitic or kaolinitic clay mineralogy having loam or clay texture, were studied (Mamedov et al. 2008). Mamedov et al. also reported that aggregate stability is increased with high clay content, PAM, and followed the order of clay mineralogy of smectitic < illitic < kaolinitic. Results suggested that the least stable soil benefited the most from PAM with increased stability.

Environmental Considerations of Polyacrylamide (PAM)

Environmental considerations of PAM have been reviewed and reported (Barvenik 1994; Seybold 1994; Bologna et al. 1999). Anionic polyacrylamide is specified by the USDA NRCS for controlling irrigation-induced erosion. Anionic polyacrylamide is used for water treatment purposes and other uses in the US. No significant negative impacts of anionic PAM have been documented for aquatic macrofauna, soil microorganisms, or crops when PAM was used for erosion control at recommended concentrations and rates (Kay-Shoemake et al. 1998a, 1998b). The effects of PAM on biota are buffered due to adsorption and deactivation associated with suspended sediments, humic acids, or other impurities (Goodrich et al. 1991). One important environmental consideration for the use of PAM is that it contains <0.05% acrylamide monomer. Since the acrylamide monomer is known as a neurotoxin and a potential carcinogen, acrylamide could have negative effects on the environment. However, PAM degrades at rates of ~10% y^{-1} as a result of physical, chemical, biological, and photochemical reactions in soils (Wallace and Wallace 1986; Tolstikh et al. 1992; USEPA 1992; Physical and Theoretical Chemistry Laboratory 2009). Moreover, the acrylamide monomer is biodegraded in nature (an apparent half life of 10-20 h) therefore the harness of acrylamide on the environment could be negligible (Shanker et al. 1990).

Use of Polyacrylamide (PAM) for Erosion Control

The use of PAM for upland erosion control from disturbed areas is an emerging conservation practice, which can complement existing practices. Traditional conservation practices for controlling erosion from disturbed areas include the use of mulching, diversions, filter strips, hydroseeding, silt fences, etc. (ASWCC 2003; USDA NRCS 2006). The cost of using PAM for erosion control has been reported to be 50% to 70% of the cost of traditional erosion control measures (VDCR 2002; Broz et al. 2003).

Since use of PAM may reduce erosion and runoff from upland areas, many current studies have focused on the effects of PAM for erosion (Bjorneberg and Aase 2000; Lentz and Sojka 2000; Roa et al. 2000; Thompson et al. 2001; Flanagan et al. 2002a, 2002b; Bjorneberg et al. 2003). Polyacrylamide increases the final infiltration rates by 10%-100% with various rates of PAM (Wallace and Wallace 1986; Shainberg et al. 1990; Levy et al. 1991; Levy et al. 1992). Previous studies have found that a minimum of 5-kg ha^{-1} (4.5-lb ac^{-1}) PAM application on soils can increase aggregate stability (Shainberg et al. 1990; Lentz et al. 1992; Sojka et al. 1998a). The use of 20-kg ha^{-1} PAM (18-lb ac^{-1}) has been suggested as an effective and economical application rate (Smith et al. 1990). The application of PAM at 20 kg ha^{-1} (18 lb ac^{-1}) has reduced erosion and runoff under simulated rainfall (Shainberg et al. 1990; Smith et al. 1990; Levin et al. 1991; Shainberg et al. 1992). The use of 20-kg ha^{-1} (18-lb ac^{-1}) PAM on a coarse-textured tropical Alfisol reduced soil erosion by 90% and runoff by 35% (Cochrane et al. 2005). Polyacrylamide also has been found to reduce turbidity of runoff water (McLaughlin and Bartholomew 2007). Suspended sediment can plug soil pores creating soil surface seals. Lee et al. (2008) measured the difference in cumulative porosity in the 0-2 mm (0-0.079 in) layer of PAM-treated vs. untreated silt loam soil after 60 min of simulated rainfall at 55-mm h^{-1} (2.2-in hr^{-1}) intensity. They found that 82% of porosity remained in PAM stabilized soil compared to just 2% porosity in the untreated soil, illustrating the benefit of PAM for reducing seal formation.

Current Guidelines of Polyacrylamide (PAM)

Some states and federal institutions such as the US Department of Transportation (USDOT), the USDA Natural Resources Conservation Service (USDA NRCS), and the

US Environmental Protection Agency (USEPA) have developed the guidelines for PAM use for erosion and runoff control (USEPA 1992; WDNR 2001; ASWCC 2003; CASQA 2003; USDA NRCS 2006; WSDOT 2008). They generally recommended that PAM may be effective on bare soils which have 40% slopes or flatter without seed or mulch (WDNR 2001). However, these guidelines do not explain how differences in soil properties may influence PAM effectiveness for erosion and runoff control and how PAM works at different slopes.

Measurements of Soil Erosion

Sediment Continuity Equation

The basic relationship for fundamental erosion processes is based on the continuity of mass. For surface runoff, the continuity equation (Foster 1982) is:

$$\frac{\partial q_s}{\partial x} + \rho_s \frac{\partial (cy)}{\partial t} = D_r + D_i$$

where

q_s is sediment load (kg h^{-1} mm^{-1}),

x is distance downslope (mm)

ρ_s is mass density of sediment particles (kg mm^{-3}),

c is sediment concentration (kg kg^{-1}),

y is flow depth (mm),

t is time (h),

D_r is rill erosion or deposition rate (kg h^{-1} mm^{-2}), and

D_i is sediment delivered to the rill from interrill areas (kg h^{-1} mm^{-2}).

Erosion parameters of q_s, D_r, and D_i are measured per unit width of the field. The term of $\frac{\partial q_s}{\partial x}$ represents the change in sediment flow rate with the distance downslope, x, and $\frac{\rho_s \partial (cy)}{\partial t}$ represents the change in sediment storage with time, t.

Furthermore, the term of storage, $\frac{\rho_s \partial (cy)}{\partial t}$, may be neglected when the flow is shallow and gradually varied. Therefore, the basic continuity relationship is simplified to the steady-steady continuity equation:

$$\frac{dq_s}{dx} = D_r + D_i$$

Soil Erosion Prediction Models

Erosion is a complex process resulted from multiple factors such as rainfall, soil properties and topography, vegetation, and management practices. These factors are directly measured under natural or simulated rainfall. These factors are applicable to predict soil erosion in erosion prediction models (Renard et al. 1997). The importance of estimating erosion has been widely emphasized by many researchers who attempted to develop the erosion prediction models since the 1940s (Zingg 1940; Smith 1941; Browning et al. 1947; Musgrave 1947). The most widely known Universal Soil Loss Equation (USLE) was released in 1965 and further developed in 1978 (Wischmeier and Smith 1965, 1978). Recently, the USLE was revised into the model of Revised Universal Soil Loss Equation (RUSLE) including improved empirical data and relationships (Renard et al. 1991, 1997). The USLE and RUSLE are empirical index-based models to predict soil erosion on a long-term annual basis considered for specified rainfall patterns, soil types and topography, cropping systems, and conservation practices. The USLE is given by:

$$A = R \cdot K \cdot L \cdot S \cdot C \cdot P$$

where

A is the computed spatial average soil loss and temporal average soil loss per unit area, expressed in the units selected for K and for the period selected for R (t ha^{-1} y^{-1}),

R is the rainfall-runoff erosivity factor; the rainfall erosion index plus a factor for any significant runoff from snowmelt,

K is the soil erodibility factor; the soil-loss rate per erosion index unit for a specified soil as measured on a standard plot, which is defined as a 22.1-m (72.6-ft) length of uniform 9% slope in continuous clean-tilled fallow,

L is the slope length factor; the ratio of soil loss from the field slope length to soil loss from a 22.1-m (72.6-ft) length under identical conditions,

S is the slope steepness factor; the ratio of soil loss from the field slope gradient to soil loss from a 9% slope under otherwise identical conditions,

C is the cover-management factor; the ratio of soil loss from an area with specified cover and management to soil loss from an identical area in tilled continuous fallow, and

P is the support-practice factor; the ratio of soil loss with a support practice like contouring, strip cropping, or terracing to soil loss with straight-row farming up and down the slope.

However, these prediction models are only valid with many assumptions of cover-management and management-practice, and limited places where the equation's individual factors are available (Wischmeier 1972; Renard et al. 1997).

In the process-based model, the Water Erosion Prediction Project (WEPP) was released in 1989 and developed with a database of soil and climate in 1997 (Laflen et al. 1997). The WEPP model is a simulation model that computes on a daily basis for spatial and temporal variability of hydrology, plant growth, soil physics, and erosion mechanics on hillslopes (Lane and Nearing 1989). Theoretically, this model can predict exactly how rainfall will interact with the soil on a site. Raindrop impact, splash erosion, interrill flow, rill formation, channelized flow, gully formation, and sediment deposition both on- and off-site can be predicted.

Saturated Hydraulic Conductivity (K_s)

Saturated hydraulic conductivity is a quantitative measure used to estimate a rate of water movement through the soil surface sealing by raindrops (Marshall et al. 1996; Hillel 1998). The seal formation blocks a large fraction of pores and water pathways for water entry into the soil surface, thereby reducing infiltration rate (Agassi et al. 1994; Hudson 1995). The *KE* of raindrops is a major factor that can degrade soil structure, thereby reducing K_s (Arend and Horton 1942; Betrand and Sor 1961; Levy et al. 1991; Betzalel et al. 1995). Saturated hydraulic conductivity is also related to soil structure (Geeves et al. 1998), porosity (Arya et al. 1999), pore characteristics (Fuentes et al. 2004), soil texture (Lado et al. 2004b), OM (Lado et al. 2004a), electrolyte concentration (Agassi et al. 1981; Kazman et al. 1983; Shainberg and Letey 1984; Levy et al. 1994), and biological activity (Czarnes et al. 2000).

Knowledge in K_s is essential to understand soil water movement through seals. Saturated hydraulic conductivity is used as a quantitative measure of soil's ability for water transmission in soil and it is a required input for modeling water movement in soils (Mallants et al. 1997). The theory was developed by Darcy in 1859 (Hillel 1998):

$$q = \frac{K_s \Delta H}{L}$$

where

q is volumetric flow rate through the sample cross section called the specific discharge (mm h^{-1}),

ΔH is hydraulic gradient (mm), and

L is sample length (mm).

Measurements of K_s in the laboratory are based on the direct application of Darcy's Law. A hydraulic head difference is imposed on the soil column and the effluent flux of water is measured. Laboratory determination of K_s measured with the constant head method as described by the procedure of Klute et al. (1986). Saturated hydraulic conductivity (mm h^{-1}) is given by:

$$K_s = \frac{QL}{\Delta HAT}$$

where

Q is volume of water that flows through the sample (mm^3),

L is length of the sample (mm),

ΔH is hydraulic head difference imposed across the sample (mm),

A is cross-sectional area of the sample (mm^2), and

T is time of water flows through the sample (h).

Hypotheses of Studies

(1) The use of PAM will reduce erosion and runoff when used alone or in combination with gypsum.

(2) The effectiveness of PAM application at 20 kg ha^{-1} (18 lb ac^{-1}) is significantly less than at 40 kg ha^{-1} (36 lb ac^{-1}). When concentration of electrolytes in the soil solution exceeds the flocculation value of clay, the cementing action of PAM polymers is more effective. However, the application rates of PAM that are too frequent or too concentrated may clog pores and decrease infiltration thereby increasing runoff.

(3) The effectiveness of PAM+gypsum, 20-kg ha^{-1} (18-lb ac^{-1}) PAM + 5-Mg ha^{-1} (1.9-ton ac^{-1}) gypsum, for acid soils is significantly greater than that of PAM without gypsum. High electrolyte concentration from gypsum (a source of Ca^{++}) is thought to flocculate the clay particles, alter the structure of PAM chains, enhance aggregation, and decrease seal formation. With anionic PAM, the acrylamate negatively charged at high pH by acid dissociation reaction ($-COOH \rightarrow -COO^- + H^+$), thereby decreasing the adsorption of anionic PAM with increasing solution pH.

(4) The effectiveness of PAM with gypsum, 20-kg ha^{-1} (18-lb ac^{-1}) PAM + 5-Mg ha^{-1} (1.9-ton ac^{-1}), for fine textured soils is significantly greater than that for medium

textured soils. Cation enhancement of solute is thought to be more effective in fine textured than medium textured soils.

(5) Soil erosion and runoff are significantly increased as slope increases. With increasing slope, runoff and runoff potential for sediment transport increase and sediment loss intensifies. For the untreated bare soil, soil sediment loss doubles as slope increases from 5% to 30%.

(6) Soil erosion and runoff are significantly decreased with PAM amendments of 20 kg ha^{-1} (18 lb ac^{-1}) and 40 kg ha^{-1} (36 lb ac^{-1}) for slopes of 10%, 20%, and 40%; however, the effectiveness of PAM amendment may vary by slope. Sediment loss and surface runoff are typically reduced with a proper amount of PAM.

(7) The effectiveness of PAM application at 20 kg ha^{-1} (18 lb ac^{-1}) is significantly less than at 40 kg ha^{-1} (36 lb ac^{-1}) for slopes of 10%, 20%, and 40%. When the concentration of electrolytes in the soil solution exceeds the flocculation value of clay, the cementing action of PAM polymers is more effective.

(8) Surface seals created from a rainfall would significantly decrease saturated hydraulic conductivity (K_s) and total macro-porosity (Φ_m) compared to soils with no rainfall.

(9) The use of a high-resolution-computed-tomography (HRCT) scanner allows accurate analysis of macro- and meso-pore characteristics, thereby quantifying K_s and Φ_m, or their relationship.

Objectives of Studies

(1) To evaluate the benefits of use of PAM, gypsum, and their combination for increasing time to initial runoff, reducing cumulative runoff, and reducing cumulative sediment loss from four Missouri soil-materials of differing physical and chemical properties,

(2) To determine if amendments of PAM, gypsum, and their combination produce a similar response with two dissimilar Missouri soils with differing soil properties including texture, pH, and soil OM with the amendment performances of PAM, gypsum, and their combination, and

(3) To evaluate the effectiveness of different levels of PAM with increasing slope for increasing time to initial runoff, and reducing erosion and runoff when compared to the unamended or flat sloping soil.

(4) To evaluate K_s in seals of different thicknesses determined using a HRCT scanner.

(5) To investigate relationships between K_s and Φ_m of soil having an equivalent diameter ≥0.015 mm (≥0.0006 in) of pore in the seals.

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CHAPTER 2.

POLYACRYLAMIDE AND GYPSUM AMENDMENTS FOR EROSION AND RUNOFF CONTROL ON TWO DISSIMILAR SOILS

Abstract

Application of polyacrylamide (PAM), gypsum, or their combination generally decreases erosion and runoff. However, their benefits are uncertain for soils with varying properties. The objectives of this study were to evaluate the effects of 5-Mg ha^{-1} (1.9-ton ac^{-1}) gypsum (5G), 20-kg ha^{-1} (18-lb ac^{-1}) PAM (20P), 40-kg ha^{-1} (36-lb ac^{-1}) PAM (40P), and 20-kg ha^{-1} (18-lb ac^{-1}) PAM with 5-Mg ha^{-1} (1.9-ton ac^{-1}) gypsum (20P+5G) for increasing time to initial runoff (TRO), decreasing cumulative runoff (RO), and decreasing cumulative sediment loss (SL) after 62 min of a simulated rainfall on soil materials from two dissimilar soil series (Hoberg and Brussels). Soils were packed to a bulk density of 1.3 Mg m^{-3} (81 lb ft^{-3}) in test beds 0.3 m x 0.3 m x 0.15 m (12 in x 12 in x 6 in) set to a slope of 20% and subjected to a 61-mm h^{-1} (2.4-in hr^{-1}) simulated rainfall with a kinetic energy (KE) of 1.5 kJ m^{-2} h^{-1} (103 ft lb ft^{-2} hr^{-1}). Differences in TRO, RO, and SL for four soil materials (two materials per soil series) and four amendments plus an unamended check (CK) were all significantly different ($p<0.01$). Amendments had varied effects on TRO, RO, and SL. Amendments of 20P, 40P, and 20P+5G increased TRO for soil materials with ≤0.5% OM. The 5G amendment increased TRO for an acid soil material (pH 4.1) with low OM (0.2%). The 20P+5G amendment produced an average 25% reduction in RO. Other amendments reduced RO by an average of 9%-10%. The 40P amendment did not reduce RO, except for a Brussels silt loam surface soil that showed a 41% decrease. The 20P+5G amendment reduced SL by an average of 47% for soil materials except for a high OM (3.7%) soil-material where OM likely interfered with soil-PAM bonding. The order of the amendment effectiveness for increasing TRO, and reducing RO and SL was 20P+5G > 40P > 20P > 5G. Generally, the 20P+5G amendment was the best irrespective of soil Ca^{++} content. On average this amendment increased TRO by 69%, decreased RO by 25%, and decreased SL by 36%. When this amendment was used on an acid soil material with a low OM (0.2%) and low cation exchange capacity (CEC; 9.2 $cmol_c\ kg^{-1}$), it increased TRO by 71% and reduced RO and SL by 45% and 74%. The amendment effectiveness was influenced by soil properties including texture, clay mineralogy, CEC, and OM.

Keywords. PAM—soil erosion—soil organic matter—soil pH—soil texture.

Introduction

Soil erosion is a natural process, but it causes nonpoint source (NPS) water pollution when rates become excessive. In the US, about 60% of NPS sediment is deposited in rivers, streams, lakes, ponds, and reservoirs (USEPA 2004). Nonpoint source sediments damage aquatic organisms, impair water-based recreation, reduce water-storage capacity of reservoirs, and impair navigation. Additionally, NPS sediments increase the frequency and depth of flooding, reduce the capacity of drainage ditches, and increase the cost of municipal water treatment (Clark 1985; Clark et al. 1985). In-stream soil erosion causes damage to aquatic ecosystems and recreational resources, decreases water-storage capacity, and impairs navigation. Off-stream soil erosion causes damage associated with flooding and impaired water-conveyance, and increases cost of water-treatment. In the US, the cost of in-stream and off-stream soil erosion is about $11 billion per year (in 2009 US dollars; Pimentel et al. 1995).

Polyacrylamide is a material made of repeating monomer chains of acrylamides and acrylates (Agassi et al. 1981; Seybold 1994; Sojka et al. 2007). Anionic polyacrylamide is reported to be nontoxic when used according to recommendations and is commonly used to control furrow irrigation induced erosion (Sojka and Surapaneni 2000; Green and Stott 2001; Sojka et al. 2007). When PAM is combined with water having sufficient electrolytes, coulombic and van der Waals forces attract cations to soil particles that in turn attract anionic PAM thereby creating “cation bridges” between soil and PAM (Wallace and Wallace 1996; Orts et al. 1999). By enhancing flocculation, PAM stabilizes soil aggregates and thus decreases soil detachment (Zhang and Miller 1996; Sojka et al. 1998; Ross et al. 2003; Sojka et al. 2007). However, PAM only stabilizes soil and does not improve soil with poor structure (Cook and Nelson 1986).

Use of PAM for upland erosion control is an emerging conservation practice which may reduce erosion and runoff from upland areas (Bjorneberg and Aase 2000; Lentz and Sojka 2000; Roa et al. 2000; Thompson et al. 2001; Flanagan et al. 2002a, 2002b; Bjorneberg et al. 2003). Studies have found that as little as 5-kg ha^{-1} (4.5-lb ac^{-1}) PAM application on soil can increase aggregate stability (Shainberg et al. 1990; Lentz et al. 1992; Sojka et al. 1998). The use of 20-kg ha^{-1} PAM (18-lb ac^{-1}) has been suggested as an effective, economical application rate (Smith et al. 1990). The application of PAM at 20 kg ha^{-1} (18 lb ac^{-1}) has reduced erosion and runoff under a simulated rainfall

(Shainberg et al. 1990; Smith et al. 1990; Shainberg et al. 1992). The use of 20-kg ha^{-1} (18-lb ac^{-1}) PAM on a coarse-textured tropical Alfisol reduced soil erosion by 90% and runoff by 35% (Cochrane et al. 2005). Furthermore, PAM has been found to reduce turbidity of runoff water (McLaughlin and Bartholomew 2007). Suspended sediment can plug soil pores creating soil surface seals. Lee et al. (2008) measured the difference in cumulative porosity in the 0-2 mm (0-0.079 in) layer of PAM-treated vs. untreated silt loam soil after 60 min of a simulated rainfall at 55-mm h^{-1} (2.2-in hr^{-1}) intensity. They found that 82% of porosity remained in PAM stabilized soil compared to just 2% porosity in the unamended soil, illustrating the benefit of PAM for reducing seal formation and runoff.

Some US State Departments of Transportation and Natural Resources and USEPA have published PAM guidelines for use in erosion control (USEPA 1992; WDNR 2001; WSDOT 2008). However, these guidelines do not explain how differences in soil properties may influence soil-PAM effectiveness for control of erosion and runoff. This is important because Lu et al. (2002) found that cation enhancement on PAM sorption varied with soil texture and was greater in fine soils. They also found that OM had a negative effect on PAM sorption with soil. Moreover, Peng and Di (1994) found that sorption of different cations for acid, neutral, and basic pH values had strong interactions with PAM. Thus, the objectives of this study were to evaluate the benefit of PAM, gypsum, or their combination on runoff and sediment loss from Hoberg and Brussels soil-materials when compared to the unamended soils, to determine if they had similar responses, and to explore the relationships of soil properties such as texture, pH, and OM with the amendment performances.

Materials and Methods

The study was conducted using a factorial design with the dissimilar Hoberg and Brussels soil-materials representing factor A, and five soil amendments including a no-amendment control representing factor B. Three replicate samples for each soil material by amendment produced 60 experimental units.

Soils – Factor A

Materials from Hoberg and Brussels soils were collected from field sites. These soil materials were selected to explore the amendment effects for reducing soil erosion and runoff on differing soil materials for the Missouri Department of Transportation. The Hoberg and Brussels soil-materials were collected from the depths of 0-300 mm (0-12 in) and 300-600 mm (12-24 in) producing a total of four soil materials for testing. These soil materials will hereafter be referred to Hoberg 300 and Brussels 300 corresponding to the 0-300 mm (0-12 in) depths, and Hoberg 600 and Brussels 600 corresponding to the 300-600 mm (12-24 in) depths.

The Hoberg soil is a member of the fine-loamy, siliceous, active, mesic Oxyaquic Fragiudalfs. It was collected from a site located at 37°36’36” N lat., 93°06’46” W long., in Dallas County, MO. The site was a cut-slope created during road construction. Soil was excavated until undisturbed soil was exposed and then collected.

The Brussels soil is a member of the clayey-skeletal, mixed, superactive, mesic Typic Hapludolls. It was collected from a site located at 39°55’06” N lat., 94°58’36” W long., along a roadside in Andrew County, MO. The site was used as a soil “borrow” site for clean soil fill and was located about 30 m (100 ft) from the road. Soil was collected from a freshly exposed, undisturbed soil profile by removing about 0.3 m (1 ft) of the exposed face.

The dissimilar Hoberg and Brussels soil-materials ranged in soil and physical properties (table 2.1). Laboratory results of soil characteristics for these soil materials were slightly different from data published in the County Soil Surveys (USDA SCS 1990; USDA SCS 1991). The Hoberg soil had slightly lower clay content and pH, and slightly higher OM for the 0-300 mm (0-12 in) depth. The Hoberg soil had much lower OM for the 300-600 mm (12-24 in) depth. On the other hand, the Brussels soil had much lower OM for both depths.

Soil Amendments – Factor B

Five amendments were studied: 5-Mg ha^{-1} (1.9-ton ac^{-1}) gypsum dry application (5G), 20-kg ha^{-1} (18-lb ac^{-1}) PAM solution application (20P), 40-kg ha^{-1} (36-lb ac^{-1}) PAM solution application (40P), 20-kg ha^{-1} (18-lb ac^{-1}) PAM solution application with 5-Mg ha^{-1} (1.9-ton ac^{-1}) gypsum (20P+5G), and an untreated check (CK). Anionic polyacrylamide suspension (Cytec A110, Superfloc, 80% a.i., 18% charge density, 15 Mg $mole^{-1}$ molecular weight) was mixed in a flask with 600-ml (203-oz) tap water having an electrical conductivity of 0.3 dS m^{-1} and a pH of 6.9 using a magnetic stirrer for 24 h at 21 °C (70 °F). Granular gypsum was applied on soil surface before spraying PAM solution when the 20P+5G amendment applied. Polyacrylamide solution with a concentration of 600 mg L^{-1} was sprayed on the soil using a pressurized hand sprayer, 24 h before each experimental run.

Experimental Procedures

Soils were air-dried and passed through a 10-mm (0.4-in) sieve. Soil characterization was conducted to determine soil properties such as texture, pH, OM, and cation status (table 2.1). Soil texture was determined by pipette (USDA NRCS 2004a), soil water pH by glass electrode (McLean 1982), OM by combustion (USDA NRCS 2004b), CEC by ammonium acetate (Rhoades 1982), and exchangeable cations by ammonium acetate (Thomas 1982) methods.

Soils were packed in test beds 0.3-m wide x 0.3-m long x 0.15-m deep (12-in wide x 12-in long x 6-in deep) for testing in the laboratory (figure 2.1). Two 10-mm (0.4-in) drain tubes were placed at the bottom of each test bed to provide water drainage. Drainage tubes were covered with a fine cloth fabric and overlain with a 0.05-m (2-in) layer of coarse sand on top of which a 0.1-m (4-in) layer of soil was packed. Soil beds were consolidated to a bulk density of 1.30±0.01 Mg m^{-3} (81 lb ft^{-3}; Grossman and Reinsch 2002) using a vibrating shaker to consolidate soil (Series 5 PM2 paint conditioner shaker; Union, New Jersey: Red Devil, Inc.). To reduce aggregate segregation during consolidation, a weighted steel-cover was placed on the soil surface during packing. To reduce water flow along the soil-bed interface during testing, bentonite was mixed with water in a ratio of 1:8 and injected into the interface around the test-bed perimeter to a depth of 50 mm (2 in). Additionally, a 2-mm (0.08-in) sieved soil was placed on the soil surface along the soil-bed interface and compacted.

Simulated rainfall was used to provide rainfall erosivity. A drop-former-type rainfall-simulator was used as described by Regmi and Thompson (2000). Simulated rainfall was applied at an intensity of 60.6±0.5 mm h^{-1} (2.39±0.02 in hr^{-1}). This intensity was chosen because this rainfall rate represents an intense rainstorm for the Midwest having a 10-year, 1-hour return frequency across mid-Missouri (Hershfield 1961). Reverse osmosis water was used with a final water quality of 99.4% pure H_2O. Drop formers were 305-mm (12-in) lengths of 0.76-mm (0.03-in) i.d. plastic tubing spaced 38 mm (1.5 in) apart in an equilateral triangular grid. A stainless steel drop distribution screen was suspended 0.45 m (1.5 ft) below drop formers to rework drops into a broader drop-size distribution closer to natural rainfall. Drop fall height was 13.8 m (45 ft), allowing for drops 4.3 mm (0.17 in) and smaller to reach 95% of terminal velocity. Rainfall kinetic energy (KE) was 1.5 kJ m^{-2} h^{-1} (103 ft lb ft^{-2} hr^{-1}).

Test beds were adjusted to a slope of 20%. Test beds were placed on a frame 0.15 m (6 in) above the floor atop an energy absorbing fabric to minimize raindrop splash. The rainfall simulator was calibrated for 6 min before and after every run. Runoff was collected through the V-trough (figure 2.1). A Plexiglas cover was attached above the V-trough to eliminate rainfall from this area. Teflon spray was applied to the inside of the soil bed and to the V-trough to minimize sediment adhering to these surfaces. Runoff was collected for 2 min every 5 min and then dried for 48 h at 105 °C (221 °F) to facilitate gravimetric runoff and sediment loss measurements.

Statistics

Data were analyzed using a factorial design to study the relationships among the three dependent variables of time to initial runoff (TRO), cumulative runoff (RO), and cumulative sediment loss (SL) among soil materials vs. soil amendments. The statistical analysis was done using the Statistical Analysis System with the General Linear Models procedure Proc GLM (SAS, Release 9.1.3. 2005; Cary, North Carolina: SAS Institute, Inc.). The statistical model used was $X_{ijk} = \mu + A_i + B_j + AB_{ij} + \varepsilon_{ijk}$; where μ is the overall mean; A_i is the i^{th} soil material; B_j is the j^{th} soil amendment; and ε_{ijk} is random error, assuming data were normally distributed with mean = 0 and variance = σ^2. Normality of the residuals was tested by the Shapiro–Wilk test; the distributions were not different from a normal distribution. Differences in amendment means within each soil material were tested using the Tukey's Studentized Range Test (HSD) at a 0.05 probability level.

Results and Discussion

Analysis of variance (ANOVA) tests were conducted on TRO, RO, and SL (table 2.2). All soil amendments, soil materials, and their interactions significantly influenced the response variables (all were $p<0.01$). Therefore, comparison of least square means was used to evaluate differences among soil materials by amendments. Coefficients of determination from the models explained >0.98 of the variation in TRO, RO, and SL. To help explain relationships among soil properties, Pearson correlation coefficients among silt, clay, soil pH, and OM for the dissimilar Hoberg and Brussels untreated-check-soil-materials were analyzed (table 2.3). Time to initial runoff from the unamended CK was positively correlated to silt ($r = 0.84$) and OM ($r = 0.86$), and negatively correlated with clay ($r = -0.99$; all were $p<0.01$). Cumulative sediment loss for the CK was negatively correlated with silt ($r = -0.89$; $p<0.01$) and OM ($r = -0.66$; $p<0.05$), and positively correlated with clay ($r = 0.84$; $p<0.01$). These results concur with the expectation that silt loam soils have a higher infiltration rate compared to heavier-textured, lower OM soils.

Characteristics of the Hoberg soil from the 0-300 mm (0-12 in; Hoberg 300) depth had clay content of 114 g kg^{-1} and highest OM of 37.4 g kg^{-1}, and Hoberg soil from the 300-600 mm (12-24 in; Hoberg 600) depth had clay content of 265 g kg^{-1} and the lowest CEC. Characteristics of the Brussels soil from the 0-300 mm (0-12 in; Brussels 300) depth had clay content of 196 g kg^{-1}, and the Brussels soil from the 300-600 mm (12-24 in; Brussels 600) depth had the highest clay content of 300 g kg^{-1} among the soils tested.

Time to Initial Runoff (TRO)

The TRO-soil amendment effect varied among soil materials; two soil materials (Hoberg 600 and Brussels 300) had significantly increased TRO, and two soil materials (Hoberg 300 and Brussels 600) had only slightly increased TRO with the addition of PAM alone or PAM with gypsum, compared to the same-soil-CK (SS-CK; figure 2.2). Time to initial runoff for the Hoberg 300 soil-material was not improved by soil amendments except for the 20P+5G amendment, which increased TRO 21% compared to the SS-CK ($p<0.05$). The amended Hoberg 600 soil-material had the greatest increase in TRO among soil materials ($p<0.05$). Time to initial runoff for the Hoberg 600 soil-material increased by 29%, 46%, 81%, and 71% for the amendments of 5G, 20P, 40P, and 20P+5G, compared to the SS-CK. Time to initial runoff for the Brussels 300 soil-material was increased by all amendments ($p<0.05$) except for the 5G. Time to initial runoff for the Brussels 300 soil-material increased by 30%, 85%, and 118% with the amendments of 20P, 40P, and 20P+5G, compared to the SS-CK. Time to initial runoff for the Brussels 600 soil-material was also increased by all amendments ($p<0.05$) except for the 5G. Time to initial runoff for the Brussels 600 soil-material increased by 7%, 42%, and 69% for the amendments of 20P, 40P, and 20P+5G, compared to the SS-CK.

We found that the amendments of PAM alone and PAM mixed with gypsum increased TRO on soil materials with low OM, while only the gypsum (5G) increased TRO for soil materials with the lowest CEC (9.2 $cmol_c\ kg^{-1}$) compared to the SS-CK. The 5G amendment was effective on one acid Hoberg 600 soil-material with low OM, but was not effective for the two neutral Brussels 300 and Brussels 600 soil-materials. Our findings suggest that the application of gypsum as a source of electrolytes (Ca^{++}) was not effective for increasing TRO on soils having high OM and ≥27.7-$cmol_c\ kg^{-1}$ Ca^{++}. The magnitude of increase in TRO amendment effect varied by soil material, but the amendments had consistent rankings within soil materials. For all soil materials, the amendments of 20P+5G and 40P consistently increased TRO most for the soil materials with ≤5.1-g kg^{-1} OM. The 20P+5G amendment produced the greatest increase (118% vs. SS-CK) in TRO. This amendment was even effective on the Hoberg 300 soil-material, the least responsive soil material. Time to initial runoff for soil materials with the 40P amendment increased on average 42% compared to the 20P amendment for all soil materials, except for the Hoberg 300 soil-material that had high OM**.** Time to initial runoff for the 20P amendment increased moderately compared to the CK for all soil materials except for the Hoberg 300 soil-material. The 5G amendment only increased TRO for the Hoberg 600 soil-material which had low CEC (p<0.05). Levin et al. (1991) reported that a 20-kg ha^{-1} (18-lb ac^{-1}) PAM amendment mixed with a 5-Mg ha^{-1} (1.9-ton ac^{-1}) gypsum applied to a loam, sandy loam, and clay and subjected to a 33-mm h^{-1} (1.3-in hr^{-1}) simulated rainfall kept high infiltration rates and delayed time to ponding (aka TRO), and reduced surface seal formation for all soil materials compared to a 20-kg ha^{-1}

(18-lb ac^{-1}) PAM amendment or the unamended soil. Acid soils may be improved by adding gypsum to flocculate clay and to maintain soil aggregation (Yu et al. 2003; Tang et al. 2006). However, sorption of PAM decreases with high soil OM, which reduces the soil-PAM accessible sorption sites. Decreased sorption increases electrostatic repulsion between PAM and soil reducing the PAM benefit (Lu et al. 2002). Our results suggested that the amendments of 40P and 20P+5G increased TRO for all soil materials except for the acid Hoberg 300 soil-material which had high OM; the gypsum alone was effective for increasing TRO only for the acid Hoberg 600 soil-material which had low OM and low CEC.

Cumulative Runoff (RO)

The soil amendments had a varied effect on RO among soil materials; all soil materials had slightly reduced RO with the 5G amendment ($p<0.05$; figure 2.3). Other amendments had mixed effects on RO. Cumulative runoff for the Hoberg 300 soil-material was reduced by all amendments except for 40P ($p<0.05$). Cumulative runoff for the Hoberg 300 soil-material was significantly reduced by 9%, 4%, and 7% for the amendments of 5G, 20P, and 20P+5G, compared to the SS-CK. Results for the two silt loam soil-materials (Hoberg 300 vs. Brussels 300) showed a greater average RO reduction of 33% for the amended Brussels 300 soil-material (compared to an average 5% reduction for the amended Hoberg 300 soil-material). This was probably because of high OM in the Hoberg 300 soil-material that interfered with amendment action (Lu et al. 2002). Cumulative runoff for the Hoberg 600 soil-material also was reduced by all except the 40P amendment ($p<0.05$). Cumulative runoff for the Hoberg 600 soil-material was significantly reduced by 18%, 8%, and 45% for the amendments of 5G, 20P, and 20P+5G, compared to the SS-CK. Comparing the RO for the Hoberg 600 soil-material with Hoberg 300 soil-material which had similar acid pH, we believe that the greater reduction occurring on the Hoberg 600 soil-material was caused by relatively higher clay and lower OM contents. Cumulative runoff for the Brussels 300 soil-material was also reduced by all amendments (p<0.05). Cumulative runoff for the Brussels 300 soil-material was significantly reduced by 9%, 33%, 41%, and 50% for the amendments of 5G, 20P, 40P, and 20P+5G, compared to the SS-CK. Our findings agree with results showing that the applications of PAM, gypsum, or their combination increase infiltration rate on silt loam soils by improving soil aggregate stability (Sojka et al. 2007).

The magnitude of decrease in RO produced by amendments varied by soil material, but the amendments had consistent rankings within soil materials. This is similar to findings by Sirjacobs et al. (2000) who found that PAM-produced decreases in infiltration rates varied by soil. For all soil materials, the 20P+5G amendment consistently decreased RO the most, significantly reducing RO for all soil materials except the Brussels 600 soil-material. The average reduction for these three soil materials was 34% compared to their SS-CK. Results agree with studies that have shown application of PAM+gypsum or gypsum alone to be effective for reducing runoff on acid silt loam soils because the increased Ca^{++} concentration promotes clay flocculation, thus helps to maintain infiltration rate (Kazman et al. 1983; Gal et al. 1984; Smith et al. 1990; Sojka et al. 2007). On average, the 5G amendment significantly reduced RO by 10% for all soil materials (p<0.05), with the greatest reduction (18%) for the Hoberg 600 soil-material, which had an acid pH with relatively high clay content. The 20P amendment reduced RO by 10% when averaged across all soil materials. The 40P amendment caused no significant reduction in RO for any soil material except the Brussels 300 soil-material which was reduced 41% compared to the SS-CK. Results showed that the 40P amendment significantly increased RO an average of 4% for all soil materials except the Brussels 300, compared to the 20P amendment. The ineffectiveness of 40P may be related to changes in soil structure, where application of concentrated PAM (concentrations of >1% of 15 Mg mole^{-1} PAM molecular weight) may plug pores thereby increasing runoff (Jian et al. 2003; Sojka et al. 2007). Our findings agree with results of Lentz (2003) who suggested clogging from viscous PAM in his study for PAM concentrations from 250 mg L^{-1} to 1,000 mg L^{-1}. Their saturated hydraulic conductivities for a silt loam and clay loam with 1,000-mg L^{-1} PAM solutions were reduced by 60% and >90%. He found that PAM solution with a concentration of ≥500 mg L^{-1} inhibited infiltration rate on silt loam soils. Yu et al. (2003) found that the use of a mixture of PAM plus gypsum on silt loam and sandy clay soils significantly reduced runoff by 38% compared to the unamended soils; however, the application of PAM alone did not reduce runoff. Our results show that the amendments of 5G and 20P+5G decreased RO; however, the 40P amendment was not effective in reducing RO.

Cumulative Sediment Loss (SL)

The effectiveness of soil amendments for reducing SL varied among soil materials; two soil materials (Hoberg 600, Brussels 300) had significantly reduced SL with all amendments and two soil materials (Hoberg 300, Brussels 600) had varied responses (figure 2.4). Generally, soil materials had SL values reduced up to 74% when the amendment of PAM, gypsum, or their combination was applied compared to the SS-CK. All amendments used on the acid Hoberg 600 soil-material with relatively high clay content and low CEC demonstrated anticipated significant reductions in SL (p<0.05). Cumulative sediment loss for the Hoberg 600 soil-material for the amendments of 5G, 20P, 40P, and 20P+5G reduced SL by 8%, 32%, 68%, and 74% compared to the SS-CK. The 40P amendment was more effective in reducing SL than the 20P for two acid soil materials (Hoberg 300, Hoberg 600). For the Hoberg 600 soil-material, the 20P+5G amendment was the most effective in reducing SL and was also better than the 5G amendment. Amendments of PAM alone (20P, 40P) used on the Hoberg 300 soil-material also significantly reduced SL (p<0.05). As with the Hoberg 600 soil-material, the 40P amendment was more effective than the 20P amendment in reducing SL for the Hoberg 300 soil-material (40% SL reduction vs. 14% SL reduction, compared to the SS-CK). However, no reduction in SL was found with the additions of gypsum (5G, 20P+5G) for the Hoberg 300 soil-material. Cumulative sediment loss for the Brussels 300 soil-material was reduced by all amendments (p<0.05). Use of the gypsum amendments (5G, 20P+5G) reduced SL the most, on average 37%, and the SL with PAM alone (20P, 40P) was only slightly reduced for the Brussels 300 soil-material, compared to the SS-CK. However, no benefit was found for using the 40P amendment compared to 20P for this soil material. Cumulative sediment loss for the Brussels 600 soil-material was also reduced by an average of 23% with the 5G and 20P+5G amendments compared to the SS-CK (p<0.05). Surprisingly, no benefit was found for using amendments of PAM alone (20P, 40P). These results may be related to relatively low clay content and high soil pH for the Brussels soils (Brussels 300, Brussels 600). Our findings agree with Tang et al. (2006)

who studied the effects of PAM+gypsum vs. PAM alone on 4-mm (0.16-in) sieved sodic soils of different clay contents using a simulated rainfall with an intensity of 36 mm h^{-1} (1.4 in hr^{-1}). They found that the effectiveness of PAM alone on stabilizing micro-aggregates may be limited with insufficient clay content (<400 g kg^{-1}) on sodic soils, and the clay flocculation is the predominant mechanism to determine erosion rate. Our soil materials had a relatively low range of clay content from 114 g kg^{-1} to 300 g kg^{-1} compared to their study. Our results partially agree with their study and found that the effectiveness of soil amendments was also affected by soil pH or CEC as well as clay content and sufficient electrolytes.

Cumulative sediment loss with the 20P+5G amendment was significantly reduced by an average of 47% for the soil materials of Hoberg 600, Brussels 300, and Brussels 600, and caused the greatest SL reduction (74% reduction for the Hoberg 600 soil-material compared to the SS-CK). The surprising fact that no SL reduction occurred with the 20P+5G amendment for the Hoberg 300 soil-material likely resulted from interference from higher OM. Findings from the Hoberg 300 soil-material are in concurrence with results from Nadler and Letey (1989) and Lu et al. (2002) who reported that the PAM sorption decreases with high soil OM. Studies have supported this idea that high OM increases aggregate stability, thus reduces the soil-PAM accessible sorption sites in soils (Auerswald 1995; Mbagwu and Auerswald 1999). However, the change in sediment loss has not been previously measured for PAM-amended soils with high soil OM, related to interfering soil-PAM bonding in soil aggregates.

Previous studies have found that the 20P+5G amendment typically was better for reducing SL compared to PAM or gypsum alone (Levin et al. 1991; Jian et al. 2003; Yu et al. 2003; Tang et al. 2006). Gypsum is often used as a source of electrolytes (Ca^{++}) with PAM for flocculating clay and thus reduces SL on dispersive soils that have a low base saturation (Keren and Shainberg 1981; Ben-Hur et al. 1992). Yu et al. (2003) found that PAM+gypsum reduced soil erosion by 30% compared to the unamended soils. Tang et al. (2006) also suggested that PAM+gypsum significantly reduced soil loss vs. PAM alone. We agree with studies that show the PAM+gypsum amendment significantly reduces SL with soils which had a low base saturation compared to PAM or gypsum alone. However, we found that while the 20P+5G amendment is effective for reducing SL for most soil, it may not be effective for soils that have higher soil OM.

Summary and Conclusions

The study objectives were (1) to evaluate the benefit of PAM, gypsum, and their combination for increasing TRO, and reducing RO and SL from the dissimilar Hoberg and Brussels soils when compared to unamended soil, (2) to determine if these amendments produced a similar response among soil materials tested, and (3) to explore the relationships of soil properties including; texture, pH, and OM with PAM and gypsum amendment performance for increasing TRO, and reducing RO and SL. The effectiveness of soil amendments varied with soil material. Generally, the amendments reduced SL, sometimes by as much as 74%, but had moderate effect on TRO, and the least effect on RO (some amendments had no significant effect on RO). The TRO-amendment effects varied among soil material. The TRO-values for the unamended soils were significantly correlated with silt ($r = 0.84$), clay ($r = -0.99$), and OM ($r = 0.86$), documenting that silt loam soils have a higher infiltration rate compared to heavier-textured, lower OM soil. The RO-values for the unamended soils were only correlated with OM (r = 0.70). Cumulative sediment loss also varied for each soil material and correlated with silt (r = -0.89), clay (r = 0.84), and OM (r = -0.66). These results show that with high OM, soil was less erodible and had a higher infiltration rate. The coefficients of determination for the ANOVA explained >98% of the variation in the response variables of TRO, RO, and SL, based on the soil and amendment factors, indicating a good model fit.

The order of the amendment effectiveness for increasing TRO, and reducing RO and SL was 20-kg ha^{-1} (18-lb ac^{-1}) PAM with 5-Mg ha^{-1} (1.9-ton ac^{-1}) gypsum > 40-kg ha^{-1} (36-lb ac^{-1}) PAM > 20-kg ha^{-1} (18-lb ac^{-1}) PAM > 5-Mg ha^{-1} (1.9-ton ac^{-1}) gypsum applications. The PAM+gypsum amendment was the best irrespective of soil Ca^{++} content. This amendment increased TRO by an average of 69%, and decreased RO and SL by averages of 25% and 36%, respectively. The PAM+gypsum amendment reduced SL by an average of 47% for the three soil materials except for a high OM (3.7%) soil-material that likely interfered with soil-PAM bonding. When PAM+gypsum amendment was applied to an acid soil material (Hoberg 600) which had low OM (0.2%) and low CEC (9.2 $cmol_c$ kg^{-1}), this amendment increased TRO by 71%, and decreased RO and SL by 45% and 74%. After saturation, the amendments of gypsum alone and PAM+gypsum reduced RO the most. Sufficient electrolytes in the water, with or without PAM, help flocculate clay and thus reduce RO. On average the amendment of 40-kg ha^{-1} (36-lb ac^{-1}) PAM increased TRO by 50% and decreased SL by 32% whereas that of 20-kg ha^{-1} (18-lb ac^{-1}) PAM only increased TRO by 18% and decreased SL by 17%. The amendment of gypsum alone increased TRO and decreased SL by averages of 2% and 16%. No difference in RO was found with all amendments except for gypsum alone and PAM+gypsum, and these RO values were 9%-10% less compared to the SS-CK. In addition, although the 40-kg ha^{-1} (36-lb ac^{-1}) PAM amendment effectively reduced TRO, it did not reduce RO, except for a Brussels silt loam surface soil that showed a 41% decrease compared to the SS-CK. This application may cause pore plugging, and thus increase RO in some cases.

Results suggest that the best amendment for increasing TRO, and reducing RO and SL in the soil materials tested was PAM+gypsum for all soil materials except for a high OM soil. Amendments of PAM alone significantly increased TRO for all soil materials except for a high OM soil, but were less effective than PAM+gypsum. Moreover, amendments of PAM alone also significantly reduced SL for all soil materials except for a neutral silty clay loam soil-material. The PAM+gypsum amendment better reduced SL for all soils compared to PAM alone amendments. Amendments of gypsum with or without PAM reduced RO the most, but PAM alone amendments were not effective for reducing RO. Future work relating PAM and gypsum amendments over a wider range of soils differing in properties will produce data that will allow development of better application recommendations over a range of soils.

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Table 2.1. Physical and chemical properties of the Hoberg soil from 0-300 mm (0-12 in; Hoberg 300) and from 300-600 mm (12-24 in; Hoberg 600), and Brussels soil from 0-300 mm (0-12 in; Brussels 300) and from 300-600 mm (12-24 in; Brussels 600).

Soils	**Texture**	**Sand**	**Silt**	**Clay**	**Organic Matter**	**pH**	**Cation Exchange Capacity**	**Exchangeable Cations** Ca	Mg	K	Na
		------------- *g kg*$^{-1}$			--------------		--------------- *cmol*$_c$ *kg*$^{-1}$				---------------
Hoberg 300	Silt Loam	156	730	114	37.4	5.0	13.1	7.2	1.2	0.3	0.0
Hoberg 600	Loam	434	301	265	1.7	4.1	9.2	2.4	2.0	0.2	0.2
Brussels 300	Silt Loam	137	667	196	3.4	7.5	16.3	27.7	5.3	0.2	0.2
Brussels 600	Silty Clay Loam	196	504	300	5.1	7.6	15.9	58.7	3.2	0.3	0.0

Table 2.2. ANOVA table for time to initial runoff (TRO), cumulative runoff (RO), and cumulative sediment loss (SL) for the Hoberg soil-materials from 0-300 mm (0-12 in; Hoberg 300) and 300-600 mm (12-24 in; Hoberg 600), and the Brussels soil-materials from 0-300 mm (0-12 in; Brussels 300) and 300-600 mm (12-24 in; Brussels 600) amended with the 5-Mg ha^{-1} (1.9-ton ac^{-1}) gypsum (5G), 20-kg ha^{-1} (18-lb ac^{-1}) PAM (20P), 40-kg ha^{-1} (36-lb ac^{-1}) PAM (40P), and 20-kg ha^{-1} (18-lb ac^{-1}) PAM mixed with 5-Mg ha^{-1} (1.9-ton ac^{-1}) gypsum (20P+5G), and unamended soil (CK), subjected to a 62-min simulated rainfall having an intensity of 61 mm h^{-1} (2.4 in hr^{-1}; KE = 1.5 kJ m^{-2} h^{-1} or 103 ft lb ft^{-2} hr^{-1}).

Source	***df***	**TRO†**	**RO‡**	**SL§**
		----------------------	*F*	----------------------
Soil	3	14,250.00	1,494.64	118.69
Amendment	4	2,964.27	126.57	172.91
Soil * Amendment	12	464.90	62.93	72.93
Error	40			
Total	59			
Error *MS*		0.03	1.44	15,558.95
R^2		0.999	0.993	0.980

† Time to initial runoff
‡ Cumulative runoff for 62 min
§ Cumulative sediment loss for 62 min

Table 2.3. Correlation coefficients for silt, clay, soil pH, and soil organic matter (OM) for the unamended Hoberg soil-materials from 0-300 mm (0-12 in; Hoberg 300) and 300-600 mm (12-24 in; Hoberg 600), and Brussels soil-materials from 0-300 mm (0-12 in; Brussels 300) and 300-600 mm (12-24 in; Brussels 600; n = 12).

Variables	**TRO**	**RO**	**SL**
	---------------------------- *r* ----------------------------		
TRO	1.000		
RO	0.248	1.000	
SL	-0.863 **	-0.017	1.000
Silt	0.842 **	0.039	-0.887 **
Clay	-0.987 **	-0.219	0.839 **
pH	-0.158	-0.467	-0.152
OM	0.855 **	0.699 *	-0.657 *

* Significant at the 0.05 probability level.

** Significant at the 0.01 probability level.

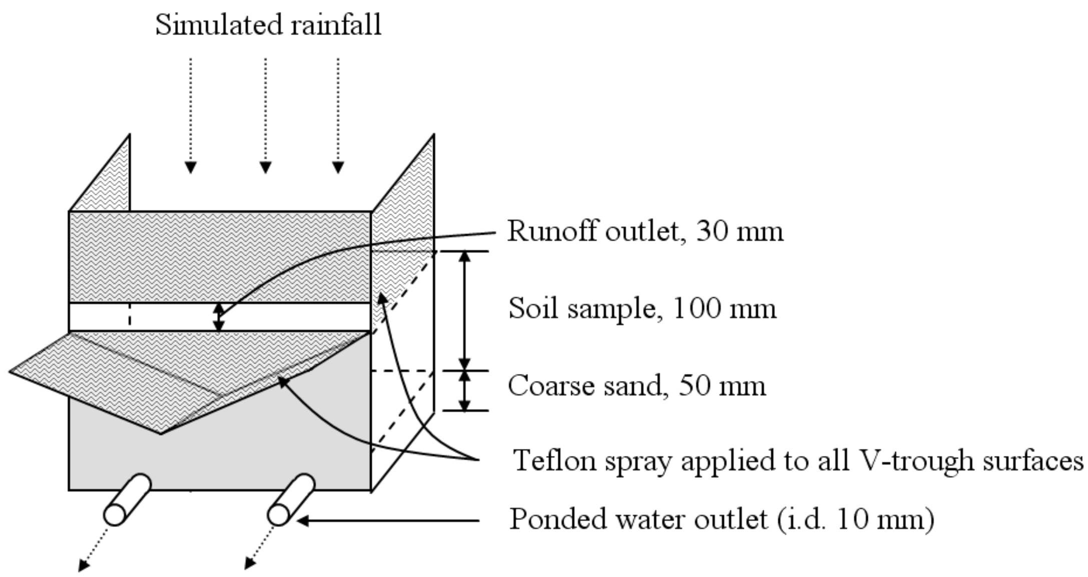

Figure 2.1. Soil test bed used for runoff and detachment collection (0.3-m wide x 0.3-m long x 0.15-m deep; 12-in wide x 12-in long x 6-in deep).

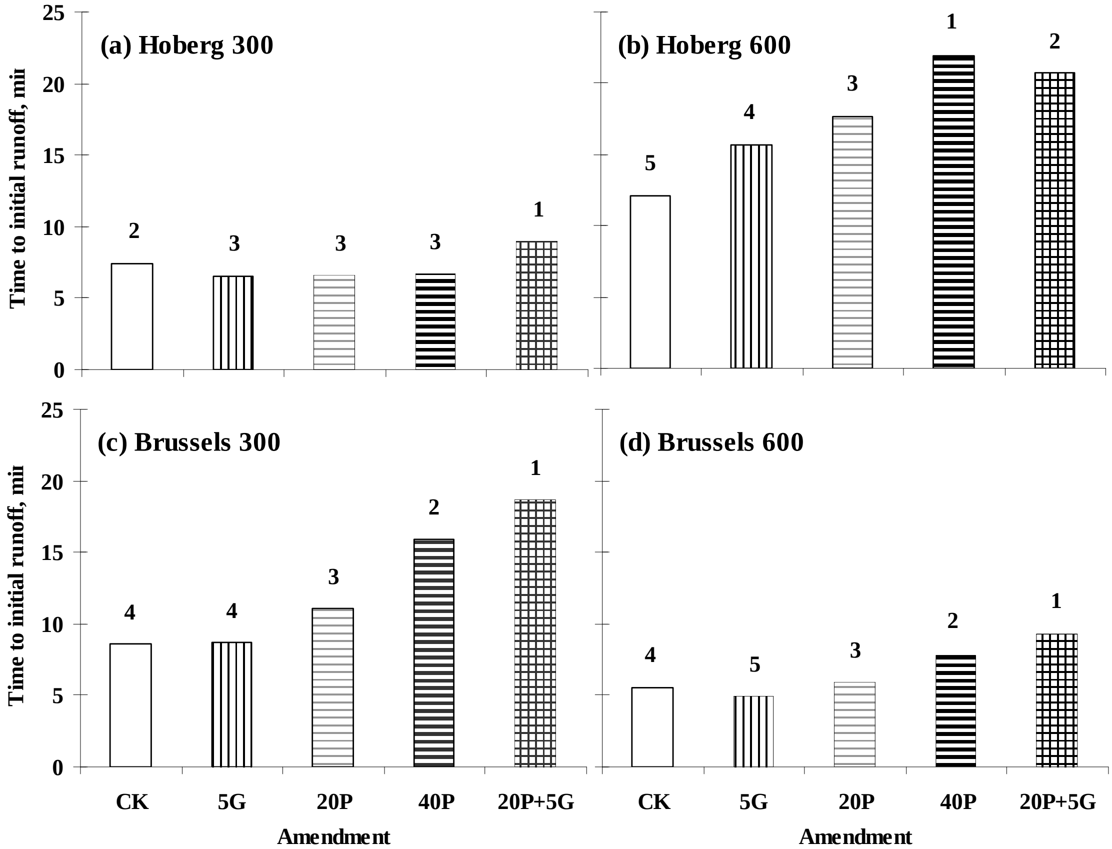

Figure 2.2. Time to initial runoff for (a) Hoberg soil-material from 0-300 mm (0-12 in; Hoberg 300), (b) Hoberg soil-material from 300-600 mm (12-24 in; Hoberg 600), (c) Brussels soil-material from 0-300 mm (0-12 in; Brussels 300), and (d) Brussels soil-material from 300-600 mm (12-24 in; Brussels 600) having the amendments of 5-Mg ha^{-1} (1.9-ton ac^{-1}) gypsum (5G; ▥), 20-kg ha^{-1} (18-lb ac^{-1}) PAM (20P; ▤), 40-kg ha^{-1} (36-lb ac^{-1}) PAM (40P; ▤), 20-kg ha^{-1} (18-lb ac^{-1}) PAM mixed with 5-Mg ha^{-1} (1.9-ton ac^{-1}) gypsum (20P+5G; ▦), and unamended soil (CK; □). The same numbers above mean bars within soil materials indicate values are not significantly different as determined by the Tukey's HSD test (p<0.05; SE $\overline{X}$ =0.018; n = 3).

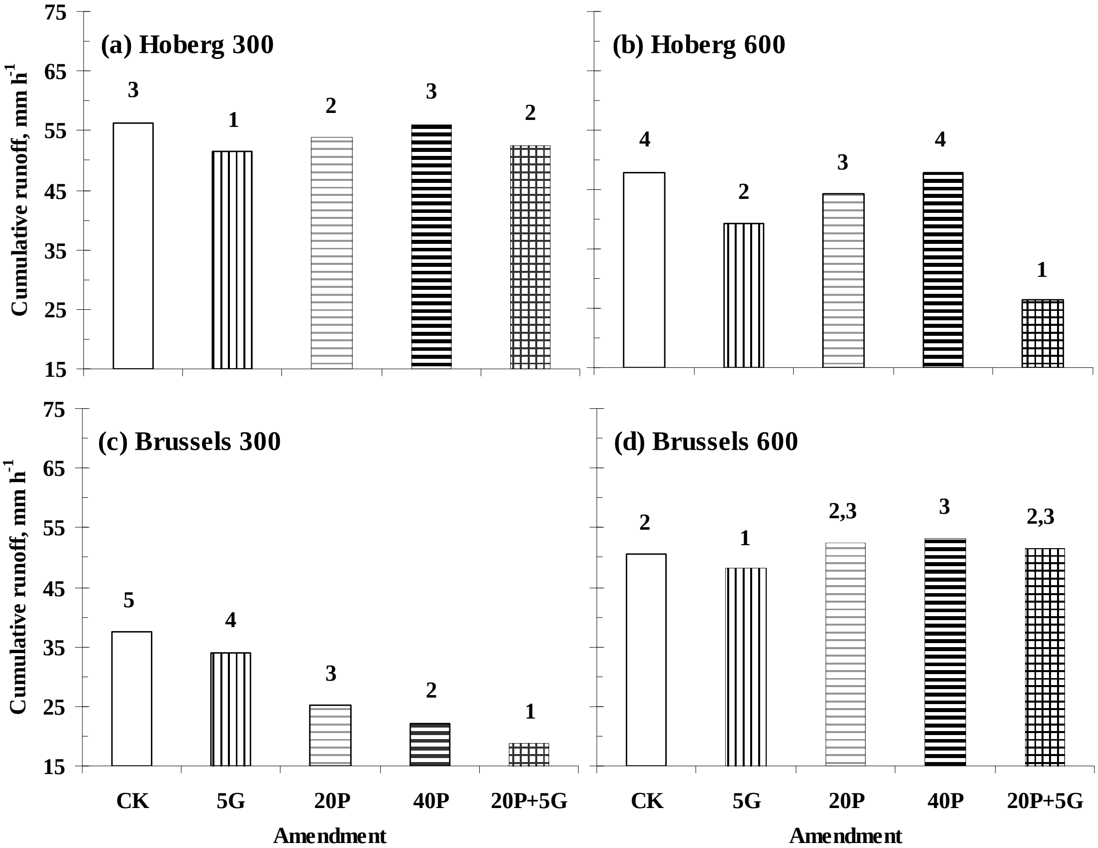

Figure 2.3. Cumulative runoff for (a) Hoberg soil-material from 0-300 mm (0-12 in; Hoberg 300), (b) Hoberg soil-material from 300-600 mm (12-24 in; Hoberg 600), (c) Brussels soil-material from 0-300 mm (0-12 in; Brussels 300), and (d) Brussels soil-material from 300-600 mm (12-24 in; Brussels 600) having the amendments of 5-Mg ha^{-1} (1.9-ton ac^{-1}) gypsum (5G; ▥), 20-kg ha^{-1} (18-lb ac^{-1}) PAM (20P; ▤), 40-kg ha^{-1} (36-lb ac^{-1}) PAM (40P; ▤), 20-kg ha^{-1} (18-lb ac^{-1}) PAM mixed with 5-Mg ha^{-1} (1.9-ton ac^{-1}) gypsum (20P+5G; ▦), and unamended soil (CK; □). The same numbers above mean bars within soil materials indicate values are not significantly different as determined by the Tukey's HSD test (p<0.05; SE $\overline{X}$ =0.128; n = 3).

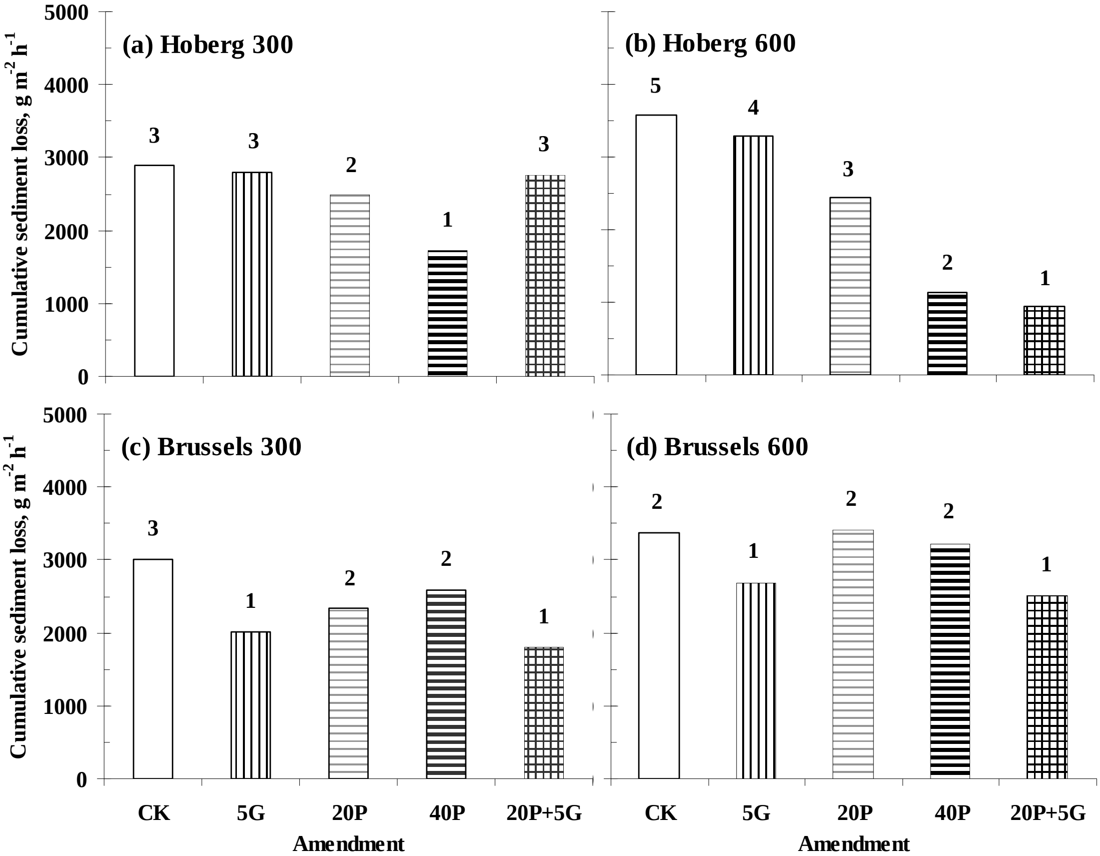

Figure 2.4. Cumulative sediment loss for (a) Hoberg soil-material from 0-300 mm (0-12 in; Hoberg 300), (b) Hoberg soil-material from 300-600 mm (12-24 in; Hoberg 600), (c) Brussels soil-material from 0-300 mm (0-12 in; Brussels 300), and (d) Brussels soil-material from 300-600 mm (12-24 in; Brussels 600) having the amendments of 5-Mg ha^{-1} (1.9-ton ac^{-1}) gypsum (5G; ▥), 20-kg ha^{-1} (18-lb ac^{-1}) PAM (20P; ▤), 40-kg ha^{-1} (36-lb ac^{-1}) PAM (40P; ▤), 20-kg ha^{-1} (18-lb ac^{-1}) PAM mixed with 5-Mg ha^{-1} (1.9-ton ac^{-1}) gypsum (20P+5G; ▦), and unamended soil (CK; □). The same numbers above mean bars within soil materials indicate values are not significantly different as determined by the Tukey's HSD test (p<0.05; SE $\overline{X}$ =13.259; n = 3).

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CHAPTER 3.

SLOPE STEEPNESS AND THE PERFORMANCE OF POLYACRYLAMIDE TO REDUCE SOIL EROSION AND RUNOFF

Abstract

When used effectively, anionic polyacrylamide (PAM) can reduce soil erosion. Slope is an important factor determining erosion rate; however, PAM guidelines have not been developed for different slopes. The objective of this study was to evaluate of the extent to which 20-kg ha^{-1} (18-lb ac^{-1}) PAM (20P) and 40-kg ha^{-1} (36-lb ac^{-1}) PAM (40P) increase the time to initial runoff (TRO), decrease runoff (RO), and decrease sediment loss (SL) on Mexico silt loam soils adjusted to slopes of 10%, 20%, and 40%. Soils were packed to a bulk density of 1.3 Mg m^{-3} (81 lb ft^{-3}) in test beds 0.3 m x 0.3 m x 0.15 m (12 in x 12 in x 6 in) and were subjected to a 61-mm h^{-1} (2.4-in hr^{-1}) simulated rainfall with a kinetic energy (KE) of 1.5 kJ m^{-2} h^{-1} (103 ft lb ft^{-2} hr^{-1}) for 62 min. Differences in TRO, RO, and SL for all slopes and PAM amendments were all highly significant, as were all two-way interactions (p<0.01). Time to initial runoff for an unamended soil (0P) decreased linearly with increasing slope, whereas the TRO values with 20P and 40P were higher at ≥20% slopes compared to 0P. At a 40% slope, the 40P treatment for increasing TRO was more effective compared to 20P. These results showed that a high level of PAM results in a larger increase in TRO values on steep slopes. Slope was not a significant factor reducing RO. Polyacrylamide treatments (20P, 40P) increased RO for all slopes compared to 0P. Application of PAM may tend to promote plugged pores. Generally, the SL for all treatments increased with increasing slopes. Applications of 20P and 40P

reduced SL by up to 72% across all slopes compared to values observed for 0P. A higher level of PAM reduced SL by a greater amount than a lower level of PAM at ≥20% slopes. Findings suggest that PAM treatments (20P, 40P) increase TRO at ≥20% slopes. However, no treatment was effective for reducing RO at all slopes. Polyacrylamide was effective for reducing SL for all slopes; however, a high level of PAM was better at ≥20% slopes. Slope steepness is a critical factor in determining appropriate level of PAM treatment for reducing soil erosion. Future work relating to PAM applications for differing slopes, rainfall intensities, and plot sizes would be beneficial in developing guidelines for PAM use.

Keywords. PAM—rainfall—runoff—slope—soil erosion—time to initial runoff.

Introduction

Soil erosion produces nonpoint source (NPS) pollution. Nonpoint source pollution increases the potential for siltation and flooding, disrupts aquatic habitats, and degrades water quality (Myers 1993; USEPA 2004; Pimentel 2006). In the US, approximately $2.4*10^{10}$ tons ($5.3*10^{13}$ lbs) of soil are eroded from the land and end up in streams each year (USDA 1989). In total, NPS pollution from in- and off-stream sources costs approximately $11 billion per year in the US (in 2009 US dollars; Pimentel et al. 1995; USEPA 2004).

The use of anionic PAM is an emerging means of reducing soil erosion and runoff. Anionic polyacrylamide is a non-toxic chemical material that flocculates soil particles

(Agassi et al. 1981; Seybold 1994; Sojka et al. 2007). Polyacrylamide has a high molecular weight and a moderate negative charge density that stabilizes soil aggregates by flocculating clay (Helalia and Letey 1988; Zhang and Miller 1996; Ross et al. 2003; Sojka et al. 2007). The effect of stabilized soil aggregates can reduce soil erodibility and help maintain water infiltration, and thus reduce runoff.

The use of PAM has been shown to reduce erosion and runoff from upland areas (Bjorneberg and Aase 2000; Lentz and Sojka 2000; Roa et al. 2000; Thompson et al. 2001; Flanagan et al. 2002a, 2002b; Bjorneberg et al. 2003). An application of 20-kg ha^{-1} (18-lb ac^{-1}) PAM has been suggested as an effective, economical application amount (Smith et al. 1990; Shainberg et al. 1992). Guidelines for the use of PAM by state and federal institutions such as the US Department of Transportation (USDOT), the USDA Natural Resources Conservation Service (USDA NRCS), and the US Environmental Protection Agency (USEPA) have been published for erosion and runoff control (USEPA 1992; WDNR 2001; ASWCC 2003; CASQA 2003; WSDOT 2008). These guidelines recommended that PAM should be used on slopes of 40% or less for bare soils without seed or mulch. However, the benefits of applying PAM for control of erosion and runoff are not well known for varying slope steepnesses.

Soil erosion increases with slope steepness, and thus is an important factor determining erosion rate (Renard et al. 1997; Fox and Bryan 1999; Chaplot and Le Bissonnais 2000; Kinnell 2000; Zhu et al. 2001). Interrill and rill erosion increase with increasing slope partly because of increasing runoff and flow velocity (Fox and Bryan 1999). These researchers studied interrill erosion rate with slope steepness and its relationship with runoff velocity with simulated rainfall. They found that soil loss was correlated (r = 0.81) with runoff velocity. Kinnell (2000) studied the effects of slope steepness on sediment concentration for the four soils subjected to a 62-min simulated rainfall with an intensity of 71 mm h^{-1} (2.8 in hr^{-1}). He found that sediment concentration from a plot length of 600 mm (24 in) was 37% higher at 5% slope, and was 54% higher at 30% slope compared to the concentration at a 150-mm (6-in) slope length. This work shows that interrill erosion is strongly influenced by slope steepness.

Runoff has also been found to increase with slope steepness because of increased surface drainage, thus intensify soil erosion (Huang 1995; Bradford et al. 1996; Fox et al. 1997; Fox and Bryan 1999). Fox et al. (1997) found that runoff increases with increasing slope steepness because of the smaller ponding depth and reduced surface storage. No significant change in runoff had also been reported with changes in slope for longer duration rainfall (Lal 1976; Mah et al. 1992). Lal (1976) studied that the effects of slope on runoff using field runoff plots on slopes of 1%, 5%, and 15% on an Alfisol. He found that slope steepness was not significant factor in determining total runoff; however, total runoff from the mulched and no-till plots was less when compared to total runoff from the plowed or bare-fallow plots. Mah et al. (1992) also found that total runoff varied with soils, but it did not change with slope, during a 60-min simulated rainfall at 50 mm h^{-1} (2.0 in hr^{-1}).

Given the documented relationships between slope steepness and soil erosion, and slope steepness and runoff, the question of how well PAM reduces erosion and runoff develops deserves study and should be answered. The objectives of this study were to evaluate the benefits of PAM amendments of 20 kg ha^{-1} (18 lb ac^{-1}) and 40 kg ha^{-1} (36 lb ac^{-1}) for controlling erosion and runoff on 10%, 20%, and 40% slopes compared to unamended Mexico silt loam soil.

Materials and Methods

This study measured the response of a Mexico silt loam soil for two levels of PAM amendment and an unamended check (Factor A), and three slope steepnesses (Factor B) subjected to one hour of simulated rainfall. Three amendments with three replicates produced 27 experimental units. The Mexico silt loam soil is a member of the fine, smectitic, mesic Aeric Vertic Epiaqualfs. Its surface soil is highly erodible with an erodibility K-factor of 0.43 in the Revised Universal Soil Loss Equation (RUSLE).

Soil Amendments - Factor A

Two levels of an aqueous PAM amendment (20P, 40P) were used along with an unamended control (0P). Anionic polyacrylamide (Cytec A110, Superfloc, 80% a.i. 18% charge density, 15-Mg mole^{-1} molecular weight) was mixed with 600-ml (203-oz) tap water having an electrical conductivity of 0.3 dS m^{-1} and a pH of 6.9, using a magnetic stirrer for 24 h at 21 °C (70 °F). The 600-mg L^{-1} PAM solution was sprayed on the soil using a pressurized hand sprayer 24 h before testing.

Soil Slopes - Factor B

Slopes of 10%, 20%, and 40% were used.

Experimental Procedure

Mexico soil was collected from a site at 38°53’27” N lat., 92°12’19” W long. Soil was sampled at depths of 0-300 mm (0-12 in) after removing vegetation from the soil surface. Soil was air-dried and passed through a 10-mm (0.4-in) sieve. General soil characterization is presented in table 3.1. Soil texture was determined by pipette (USDA NRCS 2004a), soil water pH by glass electrode (McLean 1982), organic matter (OM) by combustion (USDA NRCS 2004b), cation exchange capacity (CEC) by ammonium acetate (Rhoades 1982), and exchangeable cations by ammonium acetate (Thomas 1982) methods.

Soils were packed in test beds 0.3 m x 0.3 m x 0.15-m deep (12 in x 12 in x 6-in deep; figure 3.1). Two 10-mm (0.4-in) drain tubes were placed in the bottom of the test beds to provide drainage. The bottom of the test beds was covered with a fine woven cotton fabric, and then with a 50-mm (2-in) layer of coarse sand. Soil was packed in a 100-mm (4-in) layer. Soil was consolidated to a bulk density of 1.30±0.01 Mg m^{-3} (81 lb ft^{-3}; Grossman and Reinsch 2002) using a vibrational shaker (Series 5 PM2 shaker, Union, Red Devil, Inc. NJ). A 4.5-kg (9.9-lb) weighted-metal-cover was placed on the soil during consolidation to reduce aggregate segregation. To reduce water flow along the boundary of the test beds during rainfall, bentonite slurry was injected into the interface to a depth of 50 mm (2 in). Additionally, 2-mm (0.08-in) sieved soil sample was placed on the soil surface along the soil-bed interface and was firmly compacted manually using a 10-mm wide lab spatula.

Simulated rainfall was produced with a drop-former type of rainfall simulator (Regmi and Thompson 2000). Drop-formers consisted of 305-mm (12-in) lengths of 0.76-mm (0.03-in) i.d. plastic tubing spaced 38 mm (1.5 in) apart in an equilateral triangular grid. A stainless steel droplet distribution screen was suspended 0.45 m (1.5 ft) below the drop-former tank to rework drops into a broader drop-size distribution closer to natural rainfall. The height of drop fall was 13.8 m (45 ft), allowing drops 4.3 mm (0.17 in) and smaller to reach 95% of terminal velocity.

Rainfall was applied at 60.6±0.5 mm h^{-1} (2.39±0.02 in hr^{-1}) for 62 min. This intensity represents an intense rainstorm with a 10-year, 1-hour return frequency across mid-Missouri (Hershfield 1961), having a KE of 1.5 kJ m^{-2} h^{-1} (103 ft lb ft^{-2} hr^{-1}). Reverse osmosis water used to achieve a water quality of 99.4% pure water (AQUA-CLEER, Series B water treatment system, Culligan Systems, Rosemont, IL).

Test beds were placed 0.15 m (6 in) above the floor. The floor was covered with nonwoven geotextile fabric to absorb and minimize raindrop splash. The rainfall simulator was measured 6 minutes before and after every run. No significant differences in intensity were observed during testing. Runoff was collected at the end of the test bed using a V-trough (figure 3.1). A Plexiglas cover was placed above the V-trough to eliminate rainfall from outside test bed. Teflon spray was applied to the inside test bed wall and to the V-trough to minimize sediment adhesion to these surfaces. Runoff was collected for 2 minutes every 5 minutes and then dried for 48 h at 105 °C (221 °F) to collect runoff and sediment loss. These values were summed, and the one-hour cumulative values were used for analysis.

Statistics

Data were analyzed with factorial designs to study TRO, RO, and SL. Statistical analysis was conducted using the General Linear Models procedure (SAS 2005). The statistical model used for analysis of variance (ANOVA) was $X_{ijk} = \mu + A_i + B_j + AB_{ij} + \varepsilon_{ijk}$ where μ is the overall mean; A_i is the i^{th} amendment; B_j is the j^{th} slope; and ε_{ijk} is random error with is assumed to be normally distributed with mean = 0 and variance = σ^2. Normalities of residuals from the three ANOVAs were tested with the Shapiro–Wilk test, and were not different from a normal distribution. Differences in amendment and slope means were tested using the Tukey's Studentized Range Test (HSD) at a 5% probability level.

Results and Discussion

Analysis of variance for the dependant variables of TRO, RO, and SL were determined (table 3.2). All amendments, slopes, and their interactions for these variables were significant ($p<0.01$). Therefore, least square means comparison was used to evaluate differences among amendments, slopes and their interaction. Coefficients of determination from the models explained >0.97 of the variation in all variables.

Time to Initial Runoff (TRO)

Time to initial runoff for 0P was characterized by a decrease with increase in slope, indicating that steeper slopes increase runoff ($p<0.05$; figure 3.2). This behavior has been well documented by past research. The 20P and 40P amendments decreased TRO for the 10% slope by an average of 5% ($p<0.04$; $p<0.001$) compared to 0P, indicating a disadvantage in using PAM. In contrast, the 20P and 40P amendments increased TRO for the 20% slope by on average of 12% (both were $p<0.001$) compared to 0P, indicating a benefit in using PAM at steeper slopes. No difference in the TRO values were found for PAM amended soil on slopes between 10% and 20% ($p<0.16$). For the 40% slope, the 20P and 40P amendments increased TRO by 19% and 27% (both

p<0.001) compared to 0P, and the TRO for 40P was significantly greater than for the 20P (p<0.001). The TRO results for slopes >10% suggest a benefit in using PAM. Results show that PAM amendments (20P, 40P) increased TRO compared to unamended soil at slopes of ≥20% (p<0.001).

Cumulative Runoff (RO)

Runoff was not significantly influenced by slope steepness across slopes of 10%, 20%, and 40% for the same level of PAM (figure 3.3; p>0.97). However, runoff was 11% greater for the 40P application vs. the 20P application (p<0.001). The finding that slope is not a significant determinate of RO agrees with results of Bradford and Foster (1996) who measured runoff under a 90-min simulated rainfall at an intensity of 72 mm h^{-1} (2.8 in hr^{-1}) at slopes of 9% and 20%. They found that the runoff was not influenced by slope steepness. Agassi et al. (1990) also found that runoff was not influenced by slope steepness.

Averaged across slopes, runoff for 20P and 40P increased by 11% and 21% compared to 0P (p values <0.001). This increase with increasing amounts of PAM may be a result of using a 600-mg L^{-1} PAM solution concentration**.** Results have been found showing that a PAM solution with a concentration >500-mg L^{-1} may clog soil macro pores (Flanagan et al. 1997; Lentz 2003). Lentz (2003), working with furrow irrigation, found PAM solutions with concentrations of ≥500 mg L^{-1} inhibited infiltration into a silt loam and clay loam soil, reducing the saturated hydraulic conductivity by 60% and >99%, respectively, when a 1,000-mg L^{-1} PAM solution was used. However, results have been found that do not show an increase in RO with increasing amounts of PAM (Mattingly et al. 2010, *in review*). This work found decreased RO for a silt loam soil at 4% slope, when PAM at both 20- and 40-kg ha^{-1} levels having a 750-mg L^{-1} concentration. It is likely that differences in RO were altered by the small slope steepness. Runoff increases with increasing slope steepness, because of smaller ponding depth and surface storage (Fox et al. 1997). In addition, Mattingly et al. used a soil of a lower bulk density that would have produced greater macro porosity compared to result of our study. Their larger soil macro porosity may have reduced possible pore clogging negating the increases in RO with PAM we found (Lentz 2003).

Cumulative Sediment Loss (SL)

Sediment loss increased with increasing slope (p<0.001; figure 3.4). These results agree those of Kinnell (1994) who suggested that sediment transport in shallow rain-impacted flows increases as slope increases. Results also agree with Singer and Blackard (1982) measured soil loss from small plots under a 76-mm h^{-1} (3-in hr^{-1}) simulated rainfall on two soils adjusted to slopes from 3% to 50%. They found that the soil loss rapidly increased up to 40% slope.

Sediment loss for 0P increased by 25% and 52% at slopes of 20% and 40%, respectively, compared to a 10% slope (p<0.001). At a 10% slope, no difference in SL was found between the 20P and 40P levels (p<0.34). Average SL for these levels was 71% less than for 0P (p<0.001). At a 20% slope, a significant difference (p<0.001) was found in SL between the 20P and 40P that was characterized by a 40% and 53% lower SL than for the 0P (p<0.001). At a 40% slope, a significant difference (p<0.001) was also found in SL between the 20P and 40P and SL for these was 20% and 54% less than the 0P

(p<0.001). Increasing amounts of PAM decreased sediment loss. The 20P and 40P amendments reduced SL by up to 72% (p<0.001) across all slopes compared to 0P. We found that PAM (20P, 40P) decreased SL for all slopes, and the 40P reduced SL more than 20P at ≥20%. We could not find any current research on the effect of PAM at different levels of PAM or different slopes.

Our findings show that the 40P treatment was more effective at greater slopes compared to 20P. Our results agree with those of Hayes et al. (2003) who studied the benefit of PAM at levels from 5.6- to 10.5-kg ha^{-1} (5.0- to 9.3-lb ac^{-1}) for reducing sediment loss. They found tat a 10.5-kg ha^{-1} (9.3-lb ac^{-1}) level of PAM on a bare sandy soil at 20% slope decreased sediment loss up to 29% more than a 5.6-kg ha^{-1} (5.0-lb ac^{-1}) level.

Summary and Conclusions

This study evaluated the effects of two levels of PAM amendments (20P, 40P) on a Mexico silt loam soil subjected to three slopes (10%, 20%, and 40%) in comparison to an unamended control (0P). Three dependant variables (TRO, RO, and SL) were conducted using a 61-mm h^{-1} (2.4-in hr^{-1}) simulated rainfall with a KE of 1.5 kJ m^{-2} h^{-1} (103 ft lb ft^{-2} hr^{-1}) for 62 min. All soil amendments, slopes, and soil amendments by slope interactions were statistically significant using (p<0.05).

Time to initial runoff for the 0P decreased with increasing slope, indicating that steeper slopes increase runoff. Polyacrylamide amendments (20P, 40P) decreased TRO for the 10% slope, indicating a disadvantage in using PAM. However, PAM increased

TRO for the 20% and 40% slopes compared to 0P, indicating a benefit in using PAM at steeper slopes. No difference in TRO was found for PAM amended soil on slopes from 10% and 20%. Polyacrylamide amendments increased TRO compared to unamended soil at slopes of ≥20%. Slope was not a significant factor determining RO. Polyacrylamide amendments significantly increased RO for all slopes, and the RO with a higher level of PAM was greater across all slopes than with a lower level of PAM. Application of a high level of PAM may tend to promote plugged pores, thereby increasing RO. Sediment loss increased with increasing slope. Application of PAM amendments reduced SL by up to 72% across all slopes compared to 0P. No difference in SL was found between the 20P and 40P amendment at the 10% slope. A higher level of PAM was more effective for reducing SL than a lower level of PAM at ≥20% slopes.

Slope steepness is a critical factor in determining appropriate level of PAM amendment for reducing soil erosion. Generally, a higher level of PAM was more effective for reducing SL than a lower level of PAM at steep slopes more than 20%. Future work relating to PAM applications for differing slopes, rainfall intensities, and plot sizes would be beneficial in developing guidelines for PAM use.

Acknowledgements

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Table 3.1. Physical and chemical properties of the Mexico silt loam soil from a depth of 0-300 mm (0-12 in).

Soil	**Depth**	**Texture**	**Sand**	**Silt**	**Clay**	**Organic Matter**	**pH**	**Cation Exchange Capacity**	**Exchangeable Cations**			
									Ca	**Mg**	**Na**	**K**
	mm		---------- *g kg*$^{-1}$ ----------					------------ *cmol*$_c$ *kg*$^{-1}$ ------------				
Mexico	0-300	Silt loam	55	723	222	28.9	7.4	23.1	16.6	2.4	1.0	0.3

Table 3.2. ANOVA table for time to initial runoff (TRO), runoff (RO), and sediment loss (SL) for the Mexico silt loam amended with 20-kg ha^{-1} (18-lb ac^{-1}) PAM (20P) and 40-kg ha^{-1} (36-lb ac^{-1}) PAM (40P) along with an unamended control (0P), subjected to a 61-mm h^{-1} (2.4-in hr^{-1}) simulated rainfall with a KE of 1.5 kJ m^{-2} h^{-1} (103 ft lb ft^{-2} hr^{-1}) for 62 min.

		TRO†	**RO††**	**SL§**
Source	***df***	--------------------------	*F*	--------------------------
Slope	2	209.48 **	0.07	2,271.87 **
PAM	2	51.28 **	387.27 **	1,511.51 **
Slope * PAM	4	41.35 **	4.62 **	104.07 **
Error	18			
Total	26			
Error MS		0.05	0.69	3801.68
R^2		0.974	0.978	0.998

† Time to initial runoff
†† Cumulative runoff for 62 min
§ Cumulative sediment loss for 62 min
** Significant at the 0.01 probability level

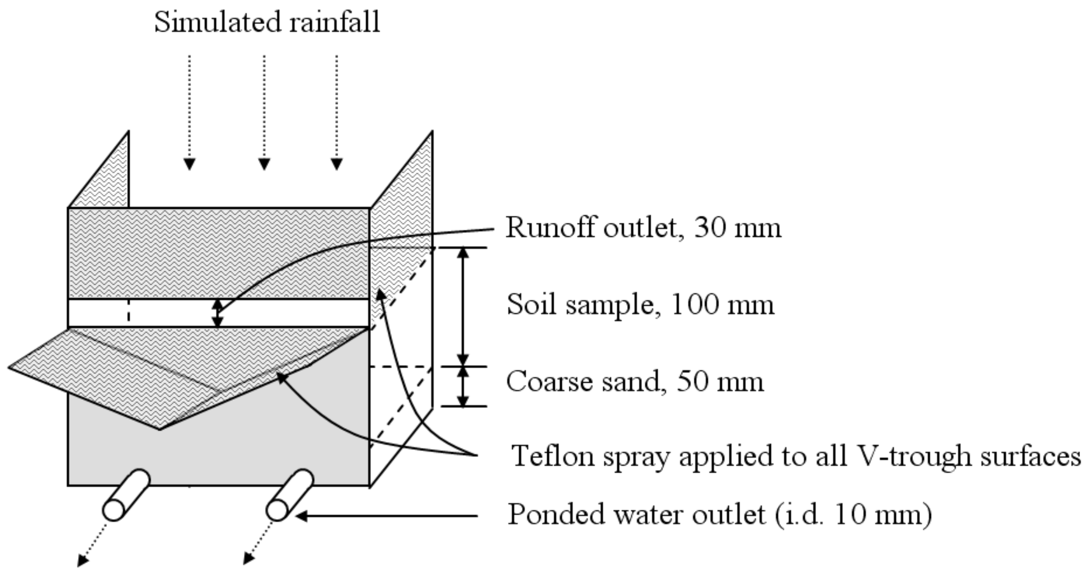

Figure 3.1. Soil test bed with the V-trough for runoff and detachment collection (0.3-m width x 0.3-m long x 0.15-m deep or 12-in width x 12-in long x 6-in deep).

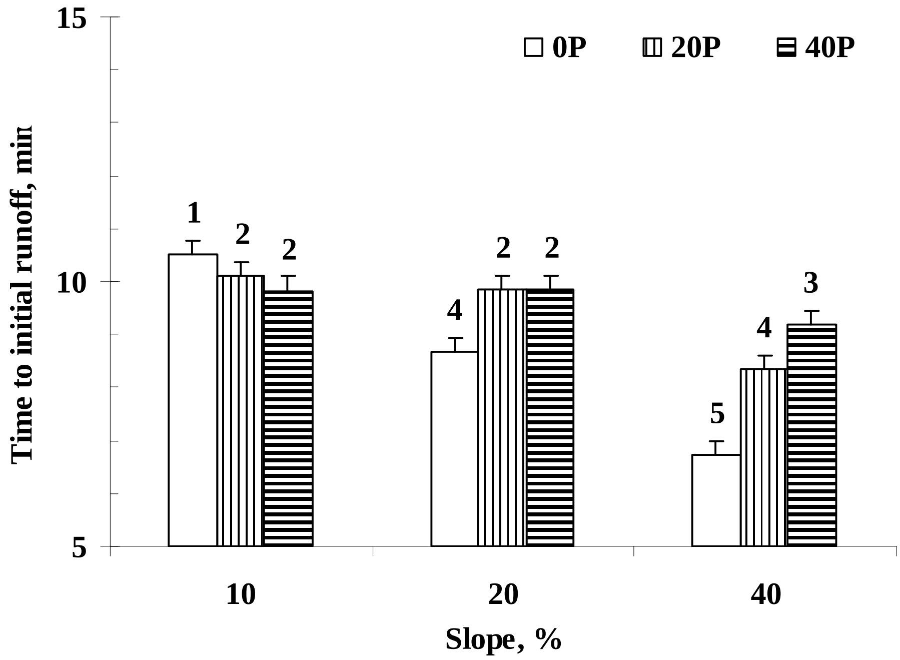

Figure 3.2. Time to initial runoff for a Mexico silt loam soil subjected to two PAM treatments at 20 kg ha^{-1} (18 lb ac^{-1}; 20P) and 40 kg ha^{-1} (36 lb ac^{-1}; 40P) shown alongside an unamended control (0P) after a 61-mm h^{-1} (2.4-in hr^{-1}) simulated rainfall with a KE of 1.5 kJ m^{-2} h^{-1} (103 ft lb ft^{-2} hr^{-1}) for 62 min. Vertical error bars are 95% confidence intervals of the mean; and numbers above error bars indicate significantly differences determined by the Tukey's HSD test (p<0.05; SE$\overline{X}$=0.035; n=3).

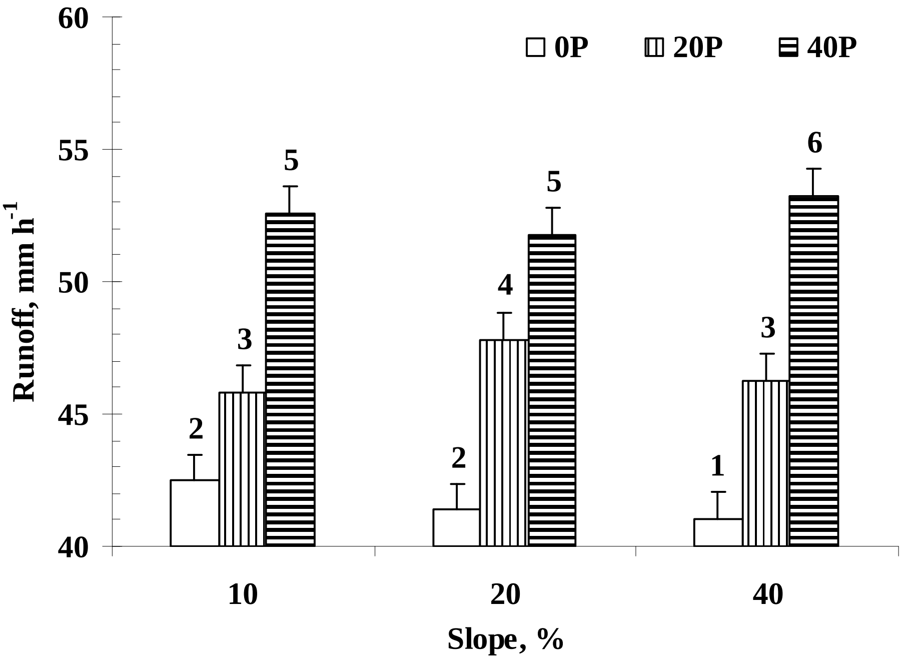

Figure 3.3. Runoff from a Mexico silt loam soil subjected to two PAM treatments at 20 kg ha^{-1} (18 lb ac^{-1}; 20P) and 40 kg ha^{-1} (36 lb ac^{-1}; 40P) shown alongside an unamended control (0P) after a 61-mm h^{-1} (2.4-in hr^{-1}) simulated rainfall with a KE of 1.5 kJ m^{-2} h^{-1} (103 ft lb ft^{-2} hr^{-1}) for 62 min. Vertical error bars are 95% confidence intervals of the mean; and numbers above error bars indicate significantly differences determined by the Tukey's HSD test (p<0.05; SE$\overline{X}$=0.133; n=3).

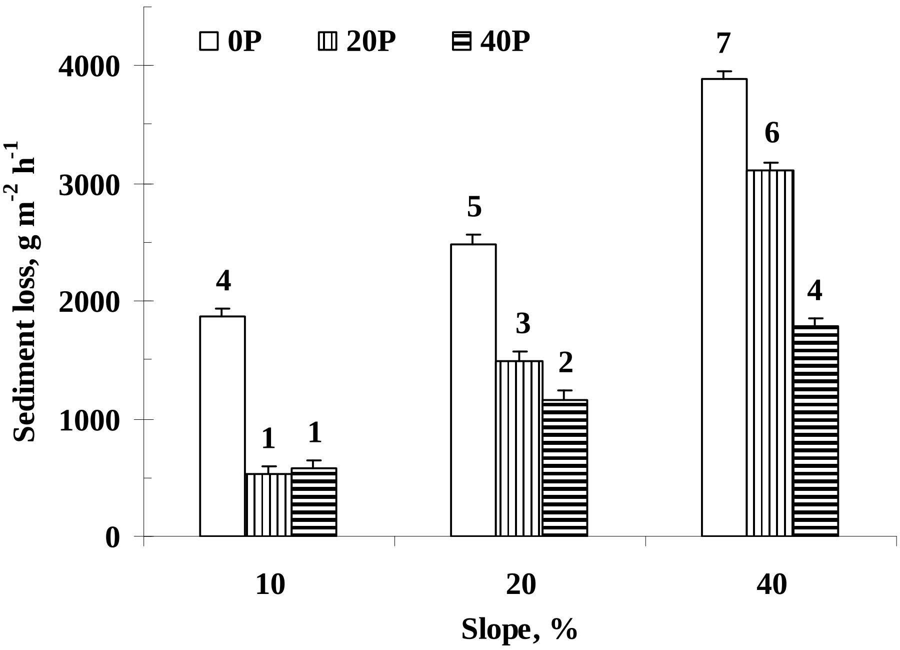

Figure 3.4. Sediment loss from a Mexico silt loam soil subjected to two PAM treatments at 20 kg ha^{-1} (18 lb ac^{-1}; 20P) and 40 kg ha^{-1} (36 lb ac^{-1}; 40P) shown alongside an unamended control (0P) after a 61-mm h^{-1} (2.4-in hr^{-1}) simulated rainfall with a KE of 1.5 kJ m^{-2} h^{-1} (103 ft lb ft^{-2} hr^{-1}) for 62 min. Vertical error bars are 95% confidence intervals of the mean; and numbers above error bars indicate significantly differences determined by the Tukey's HSD test (p<0.05; SE $\overline{X}$ =9.873; n=3).

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CHAPTER 4.

SATURATED HYDRAULIC CONDUCTIVITY OF SURFACE SEALS ESTIMATED FROM COMPUTED-TOMOGRAPHY-MEASURED POROSITY

Abstract

Relationships between saturated hydraulic conductivity (K_s) and porosity (Φ) have been developed with prior research. However, assessment of relationships between K_s and Φ are often limited because of difficulties estimating Φ distributions in seals. In addition, theoretical approaches for estimating K_s using numerical methods or empirical data produce significant variability in K_s within surface seal layers. The objectives of this study were to evaluate K_s in seals of different thickness determined using a High-Resolution-Computed-Tomography (HRCT) scanner and to investigate relationships between K_s and total macro-porosity (Φ_m) of soil having an equivalent diameter (e.d.) $\geq$ 15 µm (≥0.0006 in) within developing seals. A Mexico silt loam soil was packed to a bulk density (ρ_b) of 1.1 Mg m^{-3} (69 lb ft^{-3}) in cylinders 160-mm i.d. by 160-mm high (6.3-in i.d. x 6.3-in high) and subjected to 61-mm h^{-1} (2.4-in hr^{-1}) simulated rainfall for 0-, 7.5-, 15-, 30-, and 60-min to create a range in seal formation. Different thicknesses of the seal layers were determined using analysis of HRCT images. The K_s values in and below the seals were estimated using a measured effective saturated hydraulic conductivity (K_{s-eff}). The K_s relationship with Φ_m was described by the "Kozeny and Carmen" equation $K_s = B\Phi_m^n$ where B and n are empirical constants. Seal layers were characterized with

“Kozeny and Carmen” n values of 33 for the seal layers, and 24 for 0-120 mm (0-4.7 in) soil below the seals. This approach successfully characterized the spatial distribution of K_s with Φ_m in and below the seals (r^2 values were 0.96 for seal layers and 0.69 for soil below the seals).

Keywords. computed tomography—image analysis—Kozeny-Carmen equation—macro-porosity.

Introduction

Saturated hydraulic conductivity of a soil is a quantitative measure of the soil’s ability to transmit water when submitted to a hydraulic gradient. Many studies have been attempted to estimate K_s related to water permeability and Φ of soils. The equations of water permeability have been proposed using soil particle diameter and were extended using empirical data (table 4.1; Hazen 1892; Krumbein and Monk 1943; Puckett et al. 1985; Rawls and Brakensiek 1989; Shepherd 1989; Dane and Puckett 1992; Jabro 1992; Alyamani and Sen 1993; Sperry and Peirce 1995; Wösten et al. 1999; Cronican 2004). Kozeny (1953) and Marshall (1958) developed the K_s equations based on Φ, specific surface, and pore radius. Puckett et al. (1985) used a regression model to estimate K_s using soils from the lower coastal plain of Alabama, which contained sand contents of 34.6% to 88.5% and clay contents of 1.4% to 42.1% (R^2 = 0.77). Dane and Puckett (1992) extended their study using additional data (R^2 = 0.45). They also found that a ρ_b and Φ were not correlated with a change in K_s for sandy soils. However, many studies even used these parameters and suggested many other parameters from soil properties and its physical conditions as the input variables in estimating K_s (Ahuja et al. 1989; Jabro 1992; Wösten et al. 2001; Park and Smucker 2005).

Relationships between K_s and Φ have been proposed (Kozeny 1953; Carman1956; Ahuja et al. 1989; Rawls and Brakensiek 1989; Franzmeier 1991; Park and Smucker 2005). Based on the concept that Φ is related to hydraulic radius of the pore, the Kozeny (1953) proposed a permeability theory from the geometric properties of porous media. This permeability theory was then modified by Carman (1956). The Kozeny-Carman equation was often applied to studies estimating K_s using Φ that may be written as (Kozeny 1953; Carman 1956; Ahuja et al. 1989; Franzmeier 1991):

$$K_s = B\Phi_m^n \qquad \text{Eq. [1]}$$

where K_s is the saturated hydraulic conductivity, B and n are the constants and Φ_m is the macro-porosity. Ahuja et al. (1989) evaluated the spatial distribution of K_s using the effective Φ (Φ_e) from eight soils (Renfrow, Cecil, Lakeland, Norfolk, Wagram, and three types of Hawaii) and proposed a power law equation with exponent of 3.355 ($R^2 = 0.84$; $n = 297$). Franzmeier (1991) also suggested the K_s equation using Alfisols and Mollisols of Indiana ($R^2 = 0.86$; $n = 15$), and Park and Smucker (2005) found power low relationships between K_s and Φ_m for no tillage and native forest soils. Rawls and Brakensiek (1989) suggested a simplified graphical method to determine K_s in soils which had 1.5% OM using an exponential regression including parameters of Φ, and percentages of clay and sand contents from 1323 soils across the US.

Raindrops induce soil surface seals on bare soils decrease K_s (Agassi et al. 1994; Hudson 1995; Marshall et al. 1996; Hillel 1998). When raindrops break soil aggregates, the seal is formed through complex physical processes of detaching particles and plugging of pores (McIntyre 1958; Segeren and Trout 1991; Ruan et al. 2001). The kinetic energy (*KE*) of raindrops is a major cause of soil-aggregate disintegration on the soil surface (Arend and Horton 1942; Betrand and Sor 1961; Betzalel et al. 1995). Seal formation from the impact of *KE*, resulting in (1) physical disintegration and compaction of soil aggregates and (2) physicochemical clay dispersion and detachment in the soil surface layer (McIntyre 1958; Agassi et al. 1981). Studies on surface seals found that the seals increase ρ_b, shear strength, runoff, and soil loss, thereby decreasing infiltration, Φ, and K_s (Bradford et al. 1987; Baumhardt et al. 1990; Arya et al. 1999). For steady-state condition, the values of K_s in seals were estimated by (Sharma et al. 1981; Hillel 1998):

$$K_{sc} = \frac{q_c z_c}{\psi_u} \qquad \text{Eq. [2]}$$

where K_{sc} is the saturated hydraulic conductivity of the seal, q_c is the flux through a seal, z_c is the vertical thickness of the seal, and ψ_u is the suction head through the seal. Baumhardt et al. (1990) alternatively presented this equation with a function of the hydraulic impedance resulting from relationship between infiltration rate and pressure measurements (Eq. [3]):

$$K_{sc} = d / R_s \qquad \text{Eq. [3]}$$

where K_{sc} is the saturated hydraulic conductivity of the seal, *d* is the seal thickness of 5 mm (0.2 in), and R_s is the measured hydraulic impedance.

Determinations of K_s and Φ in developing seals have been researched as based on its thickness (Tackett and Pearson 1965; Hillel and Gardner 1970; Morin et al. 1981; Šimůnek et al. 1998; Perez et al. 1999). They found similar results where the saturated seal layer within a 5-mm (0.2-in) thickness had low permeability; however, the measured K_s values in the seals had a wide variability up to 2,000 times compared to the measured K_s values in the unsealed soils. In addition, a determination of seal thickness is not clearly defined in developing seals. Studies have been attempted to measure the thickness of seal layer using various approaches, however, the established seal thicknesses were not consistent and had a wide range of 0.1 mm to >10 mm (Tackett and Pearson 1965; Morin et al. 1981; Bresson and Boiffin 1990; Roth 1997; Fohrer et al. 1999; Wakindiki and Ben-Hur 2002).

The use of computed tomography (CT) scanners is an alternative and has become widely accessible for characterizing the pore geometry in soils (Hopkins et al. 1981; Anderson and Hopmans 1994; Gantzer and Anderson 2002). Studies of intact soil samples at different resolutions of picture element size ≥70 μm have been published (Anderson et al. 1988; Bresson et al. 2004). However, analysis of CT images for characterizing pore geometry has been limited because of a low resolution (Bui et al. 1989; Udawatta et al. 2008). The use of an HRCT scanner allows for 2-dimensional or 3-dimensional analysis of macro- and meso-pore characteristics and will promise a certain result for hydraulic measurements in soils (Ketcham and Carlson 2001; Ketcham 2005, 2006; Gantzer et al. 2006). The objectives of study were to evaluate K_s in seals of different thicknesses determined using an HRCT scanner and to investigate relationships between K_s and Φ_m of soil having an e.d. ≥0.015 mm (≥0.0006 in) of pore in the seals.

Materials and Methods

Experimental Procedure

Mexico silt loam soil (fine, smectitic, mesic Aeric Vertic Epiaqualf) was air-dried and then passed through a 4-mm (0.16-in) sieve. Soil characterization was conducted to determine soil properties such as texture, pH, OM, and cation status (table 4.2). Soil texture was determined by pipette (USDA NRCS 2004a), soil water pH by glass electrode (McLean 1982), OM by combustion (USDA NRCS 2004b), CEC by ammonium acetate (Rhoades 1982), and exchangeable cations by ammonium acetate (Thomas 1982) methods.

Soil was packed in test cylinders 160-mm i.d. by 160-mm high (6.3-in i.d. x 6.3-in high; figure 4.1). To reduce soil loss, a layer of fine mesh-nylon-organdy was attached over the cylinder bottom. Soil samples were packed in four stages. The first stage used a quarter of the air-dried soil packed using 10 drops of a 2-kg (4.4-lb) packing hammer from a height of 250 mm (9.8 in), having 4.9 kg m s^{-2} (3.6 ft lb) per drop. This process was continued for the other three sample stages. After packing each stage, the soil surface was scarified with a fork to reduce any layering. The ρ_b of the repacked test cylinders was 1.11±0.01 Mg m^{-3} (69 lb ft^{-3}; Grossman and Reinsch 2002). The complete packed sample had a length of 120 mm (4.7 in) leaving 40 mm (1.6 in) of empty cylinder as a boundary on top. To reduce interfacial flow along the soil-core interface, bentonite slurry was used along the interface around test cylinders with a depth of 50 mm (2 in). Soil sample cylinders were allowed to slowly wet from the bottom with de-aerated tap water over 24 h.

Simulated rainfall was used to create different thicknesses of surface seal. A drop-former-type rainfall-simulator was used as described by Regmi and Thompson (2000). Simulated rainfall was applied at an intensity of 60.6±0.5 mm h^{-1} (2.39±0.02 in hr^{-1}). This intensity was chosen because this rainfall rate represents an intense rainstorm for the Midwest having a 10-year, 1-hour return frequency across mid-Missouri (Hershfield 1961). Reverse osmosis water was used with a final water quality of 99.4% pure water. Drop formers were 305-mm (12-in) lengths of 0.76-mm (0.03-in) i.d. plastic tubing spaced 38 mm (1.5 in) apart in an equilateral triangular grid. A stainless steel drop distribution screen was suspended 0.45 m (1.5 ft) below drop formers to rework drops into a broader drop-size distribution closer to natural rainfall. Drop fall height was 13.8 m (45 ft), allowing for drops 4.3 mm (0.17 in) and smaller to reach 95% of terminal velocity. Rainfall kinetic energy was 1.5 kJ m^{-2} h^{-1} (103 ft lb ft^{-2} hr^{-1}). As rainfall proceeded, ponded water in the cylinder head space was vacuum aspirated through 10-mm (0.4-in) diam. Tygon vacuum-tubing placed on the soil surface and positioned around the inside cylinder diameter to avoid ponding.

Laboratory determination of $K_{s\text{-}eff}$ was done using the constant head method as described by the procedure of Klute et al. (1986). A high-flow-filter-paper disc was placed on the soil surface to reduce erosion during testing. Water was siphoned slowly onto a high-flow-filter-paper disc until the water level reached 10 mm (0.4 in) above the soil surface. After about 30 min or until the hydraulic head stabilized, the effluent was collected during three 10-min periods. The effluent water was measured by collecting the water and weighing it.

Computed-Tomography Scanning

A double-cylinder core-sampler 13.5-mm (0.5-in) i.d. by 16.0-mm (0.6-in) long was used to collect seal samples using nylon cylinders 11.5-mm (0.5-in) i.d. by 10-mm (0.4-in) long in 0.5-mm (0.02-in) thick after rainfall. This sampler was pressed into soil surface after rainfall and excavated. Excavated seal sample dried for 24 h at 25°C (77 °F). After drying samples, silica flour was used to fill-in the upper and lower ends of the cylinder used to contain the sample. The sample was confined and sealed with a tight fitting end cap fastened with plastic electrical tape to ensure seal samples would not more inside the cylinders container. Samples were placed inside a small box lined with foam designed to cushion samples from any shock, and the box was hand carried to the HRCT facility until scanned.

Scanning was done at the High-Resolution X-ray Computed Tomography Facility of the University of Texas at Austin, Dep. of Geological Sciences in 2005. The setting was 180 kV and 0.088 mA with a focal spot size of ~0.02 mm (~0.0008 in). A series of 27 slices was acquired with each turntable rotation, in which 1600 angular projection were obtained over 214 s. The inter-slice spacing was 0.0148 mm (0.0006 in), and each 1024 by 1024 slice image had a field of view of 13.8 mm (0.54 in), resulting in a pixel spacing of 0.0135 mm (0.0005 in). The raw detector data were corrected for X-ray spikes, ring artifacts, and rotational inconsistencies, and reconstructed as 8- and 16-bit TIFF images to facilitate analysis. A total of 600-700 images were acquired for each sample.

Image Analysis of High-Resolution Computed-Tomography

To avoid cracking artifacts when created during drying, HRCT-images were divided into 7 subvolumes from 0- to 4.5-mm (0- to 0.18-in) image-thickness (figure 4.2). Subvolumes were inspected to ensure they contained no crack artifacts; five subvolumes without artifacts were used. These subvolumes were analyzed to determine Φ_m with an e.d. ≥0.015 mm (≥0.0006 in) for each sample. Soil profiles were conducted using *ImageJ* image-processing software (Rasband 1997-2007).

Data collected from HRCT images were used to separate a layer into the seal and below. The values of Φ_m were produced from 2-dimensional HRCT-images having a thickness of 0 to 4.5 mm (0- to 0.18-in), starting from the surface (107 slices per no-rainfall-sample by 0.042-mm [0.0017-in] thickness and 310 slices per sample by 0.0148-mm [0.0006-in] thickness). Voxel segmentation was done by converting grayscale images into binary images using the threshold feature of *ImageJ*. The values of HRCT-gray-scale were measured from relatively large identified air-filled areas, including boundary regions. These areas had a lower limit of 20-51 (mean = 42.8). The upper limit was used as the threshold value to differentiate voids from solids: values lower than 51 were classified as voids and values greater than 51 were classified as solids (mean = 90.6). Threshold segmentation of HRCT images is necessary to separate voxels containing solids or voids. Equivalent diameter was calculated using an Eq. [4], as presented by Gantzer and Anderson (2002):

$$D_e = 2\sqrt{s/\pi} \qquad \text{Eq. [4]}$$

where D_e is the equivalent diameter in mm and s is the macropore area in mm^2. The "*3D-objects-counter plug-in*" counts the number of pores and determines a pore volume for each image stack (Cordelieres and Jackson 2005).

Effective Saturated Hydraulic Conductivity

The initial porosity from no-rainfall-samples (n = 15) was calculated using a measured ρ_b of actual soil-sample-cylinder with an assumption of particle density 2.65 Mg m^{-3} (165 lb ft^{-3}). The initial porosity was assumed to be a constant Φ for soil below seals. Using HRCT-images, different thicknesses of the seal layers (L_1) were determined by a linear regression of the measured Φ_m (figure 4.3). The thicknesses of soil below seal layers (L_2) were achieved using differences between total length of sample (L_T) and estimated thickness of the seal layers (L_1), shown in table 4.3. The value of K_s for soil below seals (K_2) was measured using a no-rainfall-sample in laboratory and the values of $K_{s\text{-}eff}$ for each sample were also measured after different seal formations, creating using different rainfall durations. Therefore, the K_s (K_1) values for the seal layers can be estimated using a given Eq. [5], as presented by Jury et al. (2004):

$$K_{eff} = \frac{L_T}{L_1 / K_1 + L_2 / K_2} \qquad \text{Eq. [5]}$$

where L_T is a total length of soil sample in mm, L_1 is a thickness of seals in mm, L_2 is a thickness of soil below seals in mm, K_1 is a K_s for the seals in mm h^{-1}, and K_2 is a K_s for soil below seals in mm h^{-1}. The values of measured $K_{s\text{-}eff}$ were decreased with increasing rainfall duration and were 88% less with a rainfall of 60 min, compared to no rainfall.

Results and Discussion

Time to Initial Runoff (TRO)

After a rainfall, the values of Φ_m were significantly increased with increasing seal thickness ($p<0.001$) and decreasing rainfall duration ($p=0.002$; figure 4.4). Two independent parameters, seal thickness and rainfall duration, influenced a change in Φ_m from seal thicknesses of 0-4 mm (0-0.16 in) and rainfall durations of ≤60 min. A power regression of Φ_m was also performed with two independent parameters of seal thickness and rainfall duration. This model used a constant ρ_b value of 1.11 Mg m^{-3} (69 lb ft^{-3}) and the same soil properties (Eq. [6]).

$$\Phi_m = (0.0152 \times D + 0.557) \times R^{-0.0012 \times D - 0.029} \qquad \text{Eq. [6]}$$

where Φ_m is a total macro-porosity, D is a seal thickness of ≤4.5 mm (≤0.18 in), and R is a rainfall duration of ≤60 min. The coefficient of multiple determination was significant and explained >0.91. Results agreed with studies on the seal formation by raindrops. The surface seal or "skin" indicating that it is likely a result of deposition of fine particles in suspension is denser and has a lower porosity and lower hydraulic conductivity than that of soil below the "washed-in" zone (Arend and Horton 1942; Tackett and Pearson 1965; Betrand and Sor 1961; Pagliai et al. 1983; Betzalel et al. 1995). Baumhardt et al. (1990) investigated seal conductance using a rainfall with an intensity of 20 to 90 mm h^{-1} (0.8 to 2.4 in) and developed using the Kozeny-Carman equation related to Φ in the seals (Eq. [7]):

$$K_{sc} = \frac{\Phi_{sc}^3}{\alpha(1 - \Phi_{sc})^2} \qquad \text{Eq. [7]}$$

where K_{sc} is the saturated hydraulic conductivity of the seals, α is the effects of the pore specific surface and shape, and Φ_{sc} is the seal porosity. They found that the final conductance of 10-mm seals was varied with different rainfall intensity and it was increased by up to 82% with a 90-mm h^{-1} (3.5-in hr^{-1}) rainfall, compared to a 20-mm h^{-1}

(0.8-in hr^{-1}) rainfall.

Relationship between Saturated Hydraulic Conductivity and Total Macro-porosity

The significant differences in relationship between K_s and Φ_m were found for two layers of the seals (K_1) and 0-120 mm (0-4.7 in) soil below the seals ($K_{s\text{-}eff}$), shown in figure 4.5 and 4.6. Findings showed power law relationships between K_s and Φ_m for all layers. Seal layers were characterized with the Kozeny and Carmen equation *n* values of 34.0 for seal layer, and 23.5 for 0-120 mm (0-4.7 in) soil below the seals. This approach successfully characterized the spatial distribution of K_s with Φ_m in and below the seals (r^2 values were 0.96 for seal layers and 0.69 for soil below the seals). The power regression equations for the seals (Eq. [8]) and 0-120 mm (0-4.7 in) soil below the seals (Eq. [9]) were estimated:

$$K_s = 9 \times 10^8 \Phi_m^{32.96} \qquad (r^2 = 0.96) \qquad \text{Eq. [8]}$$

$$K_s = 2 \times 10^7 \Phi_m^{23.57} \qquad (r^2 = 0.69) \qquad \text{Eq. [9]}$$

where K_s is the saturated hydraulic conductivity in mm h^{-1} and Φ_m is the total macro-porosity in mm^3 mm^{-3}. The values of K_s for the seals were more dependent on Φ_m changes than that for 0-120 mm (0-4.7 in) soil below the seals.

These results agree with study of Ahuja et al. (1989) who studied relationship between K_s and Φ_e using experimental data for 8 different soils (n = 297). They used the Kozeny-Carmen with the exponents ranged from 4 to 5, which is given by Eq. [10]:

$$K_s = 1058.4 \Phi_e^{3.36} \quad (r^2 = 0.71) \qquad \text{Eq. [10]}$$

where K_s is the saturated hydraulic conductivity in cm h^{-1} and Φ_e is the effective porosity. Park and Smucker (2005) also found power law relationships between K_s and Φ_m with the exponents of 7.83 for no tillage and 11.53 for native forest, which are given by Eq. [11] and Eq. [12]:

$$K_s = 374.4\Phi_m^{7.8342} \qquad (r^2 = 0.45) \qquad \text{Eq. [11]}$$

$$K_s = 41587\Phi_m^{11.525} \qquad (r^2 = 0.84) \qquad \text{Eq. [12]}$$

where K_s is the saturated hydraulic conductivity in mm h^{-1} and Φ_m is the total macro-porosity in mm^3 mm^{-3}. Relationships between K_s and effective or total porosity were developed with a power regression with a relatively high degree of success. Rawls and Brakensiek (1989) developed an empirical equation for estimating K_s using field data from 1323 soils across the US, shown in figure 4.7. They developed a regression equation related to Φ and percentages of sand and clay contents (Eq. [13]):

$$K_s = 10 \times \exp\begin{pmatrix} 19.52348n - 8.96847 - 0.028212C + 0.00018107S^2 \\ -0.0094125C^2 - 8.395215n^2 + 0.077718Sn \\ -0.00298S^2n^2 - 0.019492C^2n^2 + 0.0000173S^2C \\ +0.02733C^2n + 0.001434S^2n - 0.0000035C^2S \end{pmatrix} \qquad \text{Eq. [13]}$$

where K_s is the saturated hydraulic conductivity in mm h^{-1}, n is the porosity, and S and C are the percentages of sand and clay contents. Their estimated K_s were not well-fit with 0-120 mm (0-4.7 in) soil below the seals, and native forest soils from Park and Smucker (2005), possibly because of a wide variation of ρ_b and Φ. However, their estimated K_s was better fit with sealed or no tilled soils which had higher ρ_b and lower Φ. With a consideration of ρ_b, Jabro (1992) estimated K_s using published data from 350 soil samples (Eq. [14]):

$$\log(K_s) = 10 \times [9.56 - 0.81\log(Si) - 1.09\log(C) - 4.46(\rho_b)] \quad (R^2 = 0.68) \quad \text{Eq. [14]}$$

where K_s is the saturated hydraulic conductivity in mm h^{-1}, Si and C are the percentages of silt and clay contents, and ρ_b is the bulk density in Mg m^{-3}. However, this equation is not valid for this study which used the same soil and packing ρ_b.

Summary and Conclusions

The study objectives were to evaluate K_s in and below the seals subjected to 61-mm h^{-1} (2.4-in hr^{-1}) simulated rainfall for 0-, 7.5-, 15-, 30-, and 60-min to create a range in seal formation, and to determine relationships between K_s and Φ_m of soil having an equivalent diameter (e.d.) ≥0.015 mm (≥0.0006 in) within developing seals.

Data collected from an HRCT scanner were appropriate for defining the seal thickness and characterizing macropore in the seals. After a rainfall, the values of Φ_m were significantly increased with increasing seal thickness (p<0.001) and decreasing rainfall duration (p=0.002). A power regression of Φ_m was performed with seal thicknesses and rainfall durations (R^2>0.91). Results show significant differences in relationship between K_s and Φ_m for the seals and soil below the seals. Findings show that the K_s relationship with Φ_m was described by the "Kozeny and Carmen" equation $K_s = B\Phi_m^n$. Seal layers were characterized with "Kozeny and Carmen" n value of 32.96 for the seal layers (r^2 = 0.96), and 23.57 for 0-120 mm (0-4.7 in) soil below the seals (r^2 = 0.69). The exponent value for the seal layers was 28% higher than that for the effective saturated hydraulic conductivity ($K_{s\text{-}eff}$). The values of K_s for the seals were more dependent on Φ_m changes than that for 0-120 mm (0-4.7 in) soil below the seals. In comparison with published data, exponent values from the Kozeny-Carman equation are varied with Φ_m and bulk density (ρ_b) of soils and these values were generally increased with higher ρ_b and lower Φ_m. Results show that relationships between K_s and Φ_m in the seals can be estimated with the Kozeny-Carman equation using HRCT scanner image data, and this method is valuable for quantitative analysis or measurement of soil surface seals.

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Table 4.1. Studies of measuring or estimating saturated hydraulic conductivity (K_s) from sealed or unsealed soils using parameters of published empirical data used different soil and water properties.

Study	**Parameters**	**Data size**	R^2
Tackett and Pearson (1965)[1]	bulk density	-	-
Puckett et al. (1985)[2]	%clay	42	0.77
Rawls and Brakensiek (1989)[3]	%clay, %sand, total porosity	1323	-
Baumhardt et al. (1990)[4]	seal porosity, pore specific surface	-	-
Dane and Puckett (1992)[5]	%clay	1196	0.44
Jabro (1992)[6]	%clay, %silt, bulk density	350	0.68
Ahuja et al. (1989)[7]	effective porosity	297	0.84
Alyamani and Sen (1993)[8]	grain-size distribution curve	32	0.94
Wösten et al. (1999)[9]	%clay, %organic matter, bulk density	5521	0.18
Cronican (2004)[10]	%clay, %sand	136	0.65
Park and Smucker (2005)[11]	total porosity	31	>0.45

[1]Sealed layers from upper 25 mm surface soil.

[2]Soils with 34.6%-88.5% sand contents and 1.4%-42.1% clay contents.

[3]Soils with 1.5% organic matter, 5%-70% sand contents, and 5%-60% clay contents.

[4]Seal thickness of 0-5 mm.

[5]Soils from the lower coastal plain of Alabama.

[6]Soils with a silt loam texture.

[7]Soils from Cecil, Lakeland, Norfolk, Renfrow, Wagram, and Hawaii (n =8).

[8]Soils with a sandy texture.

[9]Soils from 14 European countries.

[10]Soils with >70% sand content.

[11]Total porosities of macroaggregates ranging from 2 mm to 9.5 mm.

Table 4.2. Physical and chemical properties of the Mexico silt loam soil for a depth of 0-300 mm (0-12 in).

Soil	Depth	Texture	Sand	Silt	Clay	Organic Matter	pH	Cation Exchange Capacity	Exchangeable Cations			
									Ca	Mg	Na	K
	mm		---------- $g\ kg^{-1}$ ----------					------------ $cmol_c\ kg^{-1}$ ------------				
Mexico	0-300	Silt loam	55	723	222	28.9	7.4	23.1	16.6	2.4	1.0	0.3

Table 4.3. Saturated hydraulic conductivity for seal layers (K_1) from the measured effective saturated hydraulic conductivity ($K_{s\text{-}eff}$) on a Mexico silt loam soil, subjected to 7.5-, 15-, 30-, and 60-min simulated rainfalls with an intensity of 61 mm h^{-1} (2.4 in hr^{-1}) having a kinetic energy (*KE*) of 1.5 kJ m^{-2} h^{-1} (103 ft lb ft^{-2} hr^{-1}).

Rainfall	**Seal layer**			**Below seal layer**			**Total length of sample**		
	Φ_m†	L_1‡	K_1§	Φ_m	L_2¶	K_2#	Φ_m	L_T††	$K_{s\text{-}eff}$‡‡
	mm^3 mm^{-3}	mm	mm h^{-1}	mm^3 mm^{-3}	mm	mm h^{-1}	mm^3 mm^{-3}	mm	mm h^{-1}
7.5 min	0.52	0.98	0.41	0.56	119.0	72.90	0.56	120.0	30.00 ±2.3
	0.54	1.90	1.24	0.56	118.1	72.90	0.56	120.0	38.09 ±2.7
15 min	0.53	3.40	0.87	0.56	116.6	72.90	0.56	120.0	21.78 ±0.8
	0.53	2.35	1.06	0.56	117.7	72.90	0.56	120.0	31.32 ±1.6
30 min	0.53	3.82	0.53	0.56	116.2	72.90	0.56	120.0	13.70 ±0.9
	0.54	4.35	1.13	0.56	115.7	72.90	0.56	120.0	22.06 ±1.0
60 min	0.51	3.63	0.30	0.53	116.4	72.90	0.53	120.0	8.75 ±1.8

† Total macro-porosity from high-resolution-computed-tomography (HRCT) images.
‡ CT-measured seal thickness.
§ Estimated saturated hydraulic conductivity from measured effective saturated hydraulic conductivity.
¶ Measured total tickness minus CT-measured seal thickness.
# Measured saturated hydraulic conductivity from no-rainfall-sample.
†† Measured total lengh of soil samples.
‡‡ Measured effective saturated hydraulic conductivity conducted by the constant head method (Klute et al. 1986)

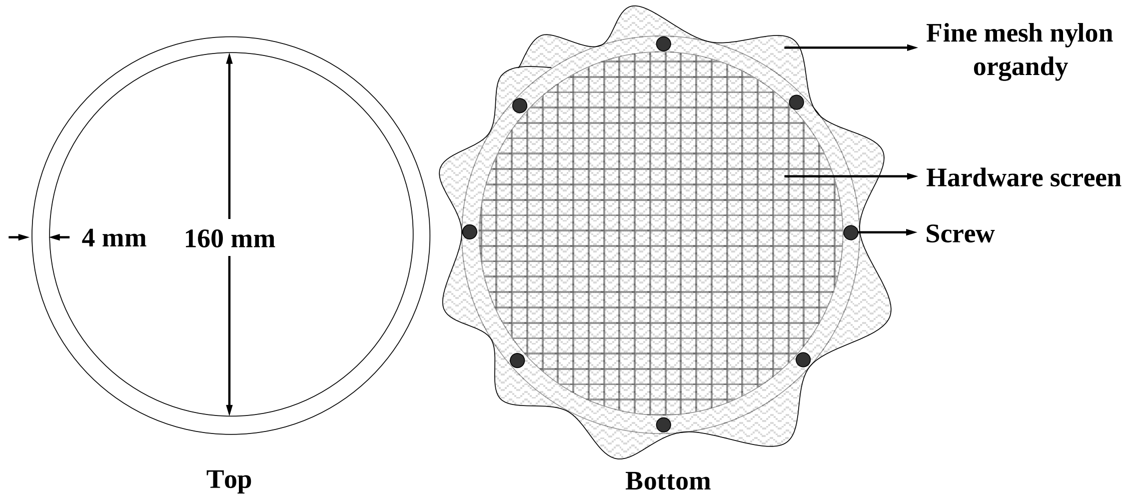

Figure 4.1. Test cylinder 160-mm i.d. x 160-mm high (6.3-in i.d. x 6.3-in high) used for a measurement of effective saturated hydraulic conductivity ($K_{s\text{-}eff}$).

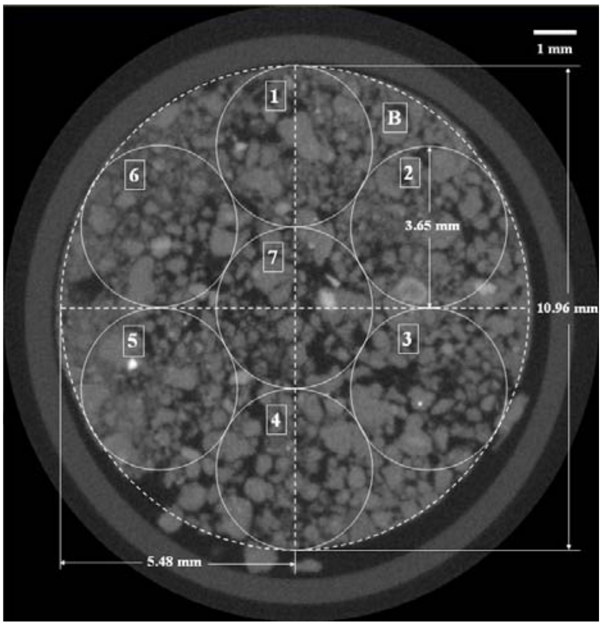

Figure 4.2. An example of high-resolution-computed-tomography (HRCT) image-division into 7 subvolumes for *ImageJ* processing.

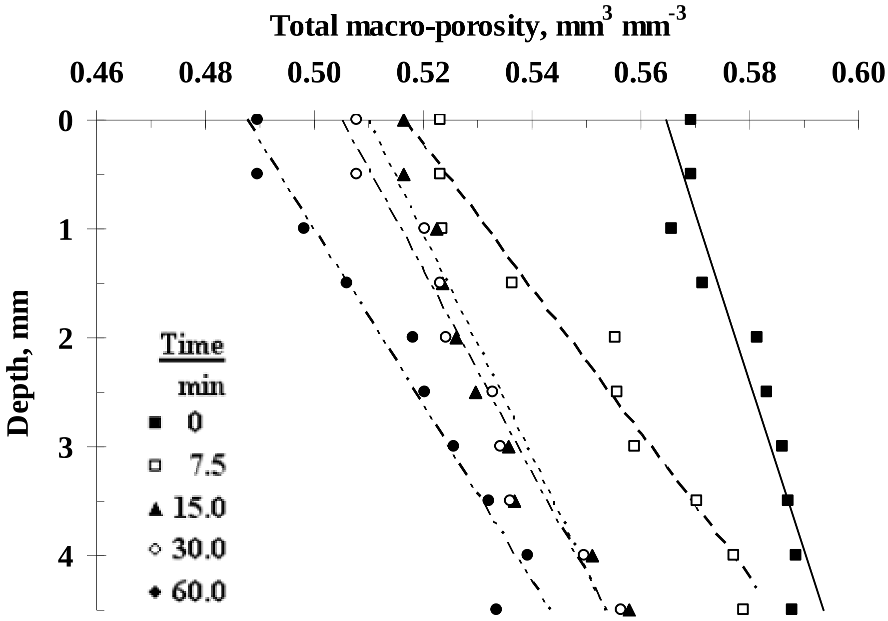

Figure 4.3. Total macro-porosity (Φ_m ; >15µm e.d.) using a high-resolution-computed-tomography (HRCT) images for a thickness of 0-4.5 mm (0-0.18 in) with an interval of 0.5 mm (0.02 in) of Mexico silt loam soils, subjected to 0-, 7.5-, 15-, 30-, and 60-min simulated rainfalls with an intensity of 61 mm h^{-1} (2.4 in hr^{-1}) having a kinetic energy (*KE*) of 1.5 kJ m^{-2} h^{-1} (103 ft lb ft^{-2} hr^{-1}). Symbols represent least-square mean values (n = 9).

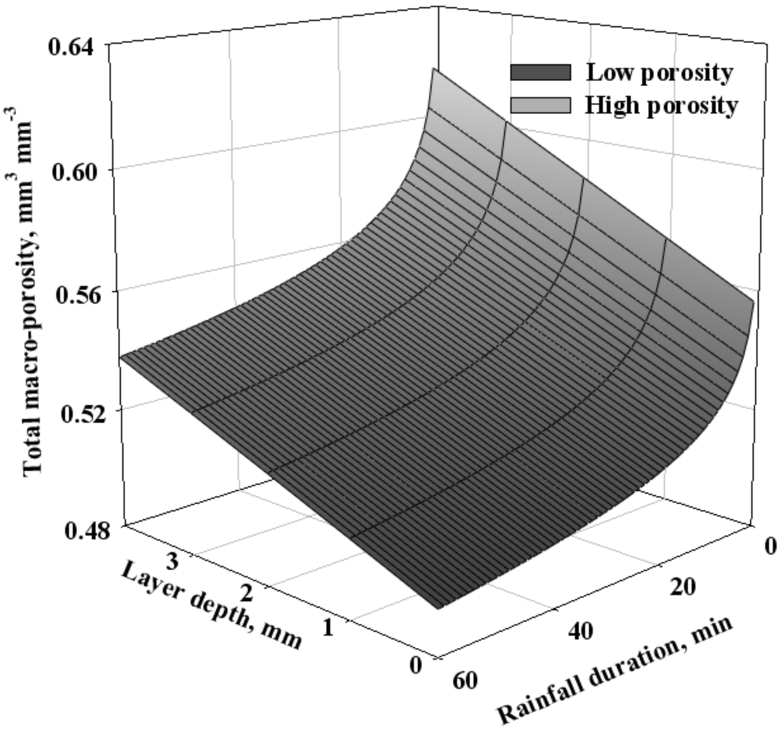

Figure 4.4. Relationship among the total macro-porosity (Φ_m), thickness of seal layer, and rainfall duration having an intensity of 61 mm h^{-1} (2.4 in hr^{-1}) for a Mexico silt loam soil.

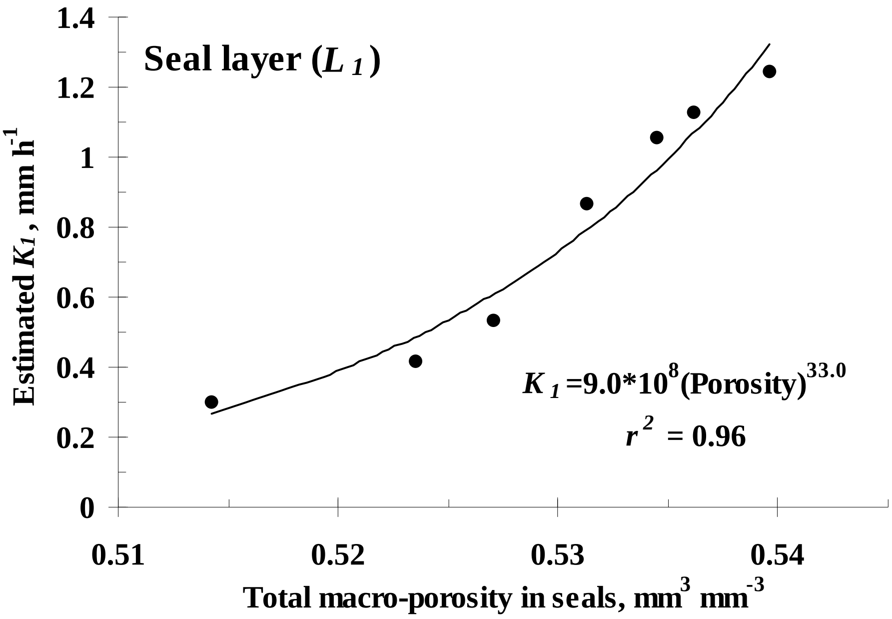

Figure 4.5. Power-law relationship between the saturated hydraulic conductivity (K_s) and total macro-porosity (Φ_m) for the seal layer (L_1) on a Mexico silt loam soil.

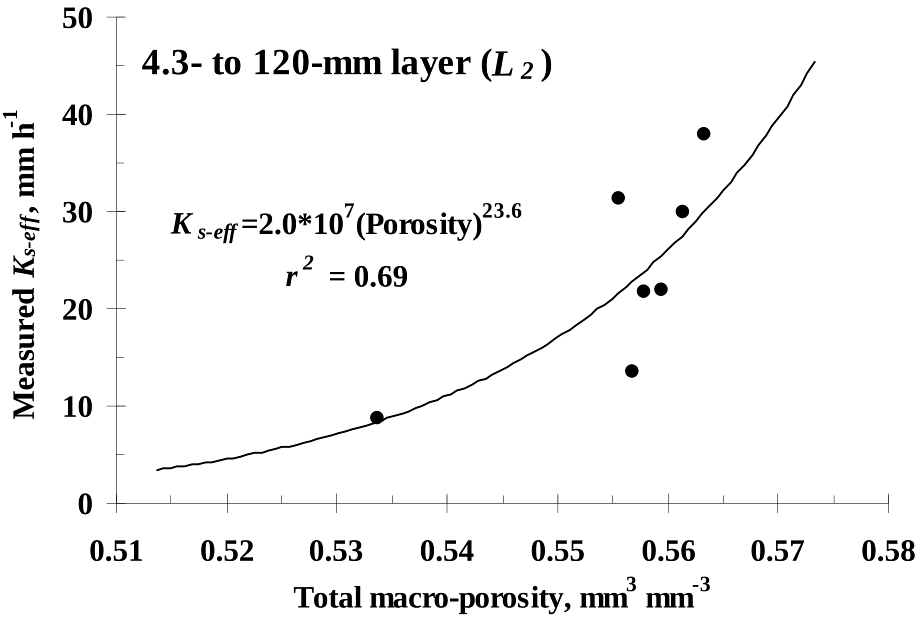

Figure 4.6. Power-law relationship between the saturated hydraulic conductivity (K_s) and total macro-porosity (Φ_m) for 4.3-120 mm (0-4.7 in) soil below the seals (L_2) on a Mexico silt loam soil.

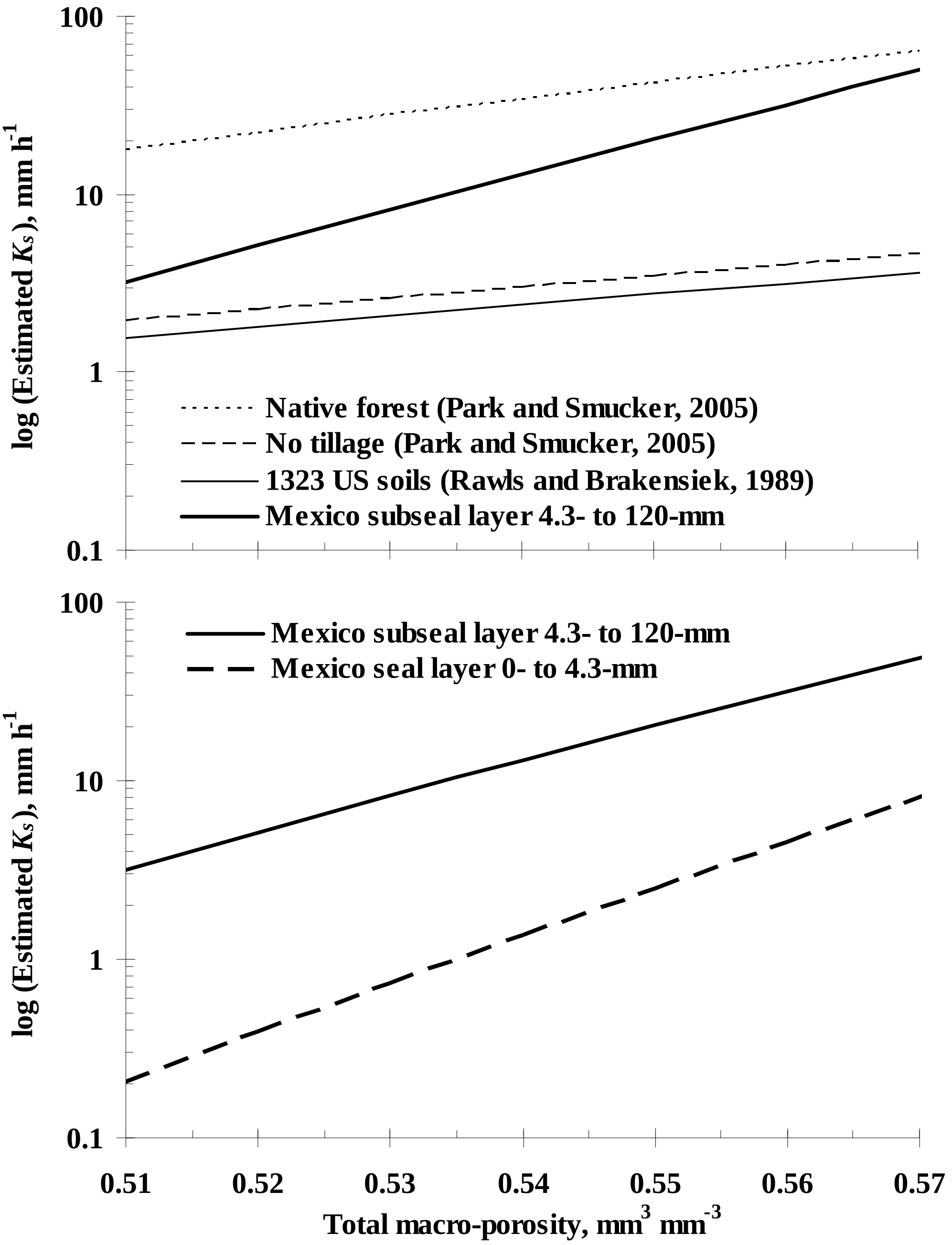

Figure 4.7. Power-law relationships between estimated saturated hydraulic conductivity (K_s) and total macro-porosity (Φ_m) for two layers of the subseal and seal on Mexico silt loam soils compared to studies of Park and Smucker (2005) and Rawls and Brakensiek (1989).

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CHAPTER 5.

SUMMARY & CONCLUSIONS

The use of anionic polyacrylamide (PAM) as a soil amendment is an emerging conservation practice. Application of PAM, gypsum, or their combination generally decreases erosion and runoff. Literature on PAM studies identified many factors that have been shown to influence its effectiveness for reducing erosion and runoff. When effectively used with considerations of soil properties including texture, pH, and organic matter (OM), PAM greatly reduces erosion and runoff. Slope is also an important factor determining erosion rate.

Current reports from the US State Departments of Transportation (USDOT), the US Departments of Agriculture Natural Resources Conservation Service (USDA NRCS), and the US Environmental Protection Agency (USEPA) have published the beneficial use of PAM for erosion and runoff control on disturbed sites including road, urban construction sites, landfills, and reclaimed mining sites. However, established PAM guidelines do not explain (1) how differences in soil properties influence the effectiveness of PAM, gypsum, or their combination and (2) how different amounts of PAM work at different slopes. The objective of these studies was to evaluate the amendment effects of PAM, gypsum, or their combination for increasing time to initial runoff (TRO), and decreasing cumulative runoff (RO) and cumulative sediment loss (SL) on soils of differing properties or slopes using a 61-mm h^{-1} (2.4-in hr^{-1}) simulated rainfall with a kinetic energy (KE) of 1.5 kJ m^{-2} h^{-1} (103 ft lb ft^{-2} hr^{-1}) for 62 min.

The use of computed tomography (CT) scanners is an alternative and has become widely accessible for characterizing the pore geometry in soils. Studies of intact soil samples at different resolutions of picture element size ≥70 μm have been published. However, analysis of CT images for characterizing pore geometry has been limited because of a low resolution. The use of a High-Resolution-Computed-Tomography (HRCT) scanner allows for 2-dimensional or 3-dimensional analysis of macro- and meso-pore characteristics and will promise a certain result for hydraulic measurements in soils. The objectives of study were to evaluate saturated hydraulic conductivity (K_s) in seals of different thicknesses determined using an HRCT scanner and to investigate relationships between K_s and total macro-porosity (Φ_m) of soil having an e.d. ≥0.015 mm (≥0.0006 in) of pore in the seals.

The following conclusions are drawn from these studies:

(1) Differences in TRO, RO, and SL for three soils (Hoberg, Brussels, and Mexico) and soil amendments of PAM, gypsum, or their combination amendments (5-Mg ha^{-1} (1.9-ton ac^{-1}) gypsum dry application (5G), 20-kg ha^{-1} (18-lb ac^{-1}) PAM solution application (20P), 40-kg ha^{-1} (36-lb ac^{-1}) PAM solution application (40P), 20-kg ha^{-1} (18-lb ac^{-1}) PAM solution application with 5-Mg ha^{-1} (1.9-ton ac^{-1}) gypsum (20P+5G), and an untreated check (CK)), and slopes (10%, 20%, and 40%) were all significant, as were their two-way interactions in these studies ($p<0.01$), and the coefficients of determination for the ANOVA explained >0.98 of the variation in the response these variables based on the soil and amendment factors, indicating a good model fit.

(2) The amendment effectiveness of 5G, 20P, 40P, and 20P+5G for increasing TRO,

decreasing RO, and decreasing SL varied with soil materials from two dissimilar soil series (Hoberg and Brussels) which had different soil properties including texture, pH, and OM.

(3) All amendments reduced SL, sometimes by as much as 74%, but had moderate effect on TRO, and the least effect on RO (some amendments had no significant effect on RO). Generally, the order of the effectiveness for increasing TRO, and reducing RO and SL was 20P+5G > 40P > 20P > 5G amendment applications.

(4) The amendment of PAM+gypsum was the best irrespective of soil Ca^{++} content. This amendment increased TRO by an average of 69%, and decreased RO and SL by averages of 25% and 36%. The 20P+5G amendment reduced SL by an average of 47% for the soils with a high OM that likely interfered with soil-PAM bonding. When PAM+gypsum amendment was applied to an acid soil which had low OM (0.2%) and low CEC (9.2 $cmol_c$ kg^{-1}), this amendment increased TRO by 71%, and decreased RO and SL by 45% and 74%.

(5) No difference in RO was found with all amendments except for the 20P+5G amendment. After the soil is saturated with water, the amendments of 5G or 20P+5G reduced RO the most. Sufficient electrolytes in the water, with or without PAM help flocculate clay, thereby reducing RO.

(6) The 40P amendment was more effective for reducing SL compared to 20P. On average the 40P amendment increased TRO by 50% and decreased SL by 32% whereas the 20P amendment increased TRO by 18% and decreased SL by 17%.

(7) Slope was a significant factor determining the TRO. The TRO for the unamended soil had a nearly linear decrease with increasing slope ($p<0.05$). The TRO for

20P- and 40P-amended soils significantly increased TRO at slopes of ≥20%. No difference in TRO was found between the 20P and 40P amendments at slopes of 10% and 20%. However, the 40P amendment was more effective for increasing TRO at a slope of 40% compared to 20P.

(8) Slope was not a significant factor determining the RO. However, PAM amendments (20P, 40P) significantly increased RO for all slopes compared to no amendment. Moreover, the RO with a higher level of PAM was greater across all slopes than with a lower level of PAM.

(9) Slope was a significant factor determining the SL. The SL for either PAM (20P, 40P) amended soils or the unamended soil increased with increasing slopes ($p<0.05$). Two levels of PAM amendment reduced SL by up to 72% across all slopes compared to the unamended soil. No difference in SL was found between these PAM amendments at a slope of 10%. However, averaged SL of PAM (20P, 40P) amended soils was 71% less than for the unamended soil at a slope of 10%. A higher level of PAM was more effective for reducing SL than a lower level of PAM at slopes of ≥20%.

(10) Cumulative sediment loss for the unamended soils had a nearly linear increase with increasing slope whereas the SL for the 20P- and 40P-amended soils had nearly logarithmic increases. The increase in SL slowed down with increasing PAM levels across slopes. A high level of PAM is more effective for reducing SL with a steep slope compared to a low level of PAM.

(11) After a rainfall, the values of Φ_m were significantly increased with increasing seal thickness ($p<0.001$) and decreasing rainfall duration ($p=0.002$). A power-law

regression of Φ_m was also performed with seal thicknesses and rainfall durations (R^2>0.91).

(12) The significant differences in relationship between K_s and Φ_m for two layers of the seals and soil below the seals.

(13) Seal layers were characterized with "Kozeny and Carmen" *n* value of 32.963 for the seal layers (r^2 = 0.96), and 23.567 for 0-120 mm (0-4.7 in) soil below the seals (r^2 = 0.69).

(14) In comparison with published data, exponent values from the Kozeny-Carman equation are varied with Φ_m and bulk density (ρ_b) of soils and these values were generally increased with higher ρ_b and lower Φ_m.

(15) Relationships between K_s and Φ_m in the seals can be estimated using the Kozeny-Carman equation and an HRCT scanner is valuable for quantitative analysis or measurement of surface seals.

Future work relating PAM and gypsum amendments over a wider range of soils differing in their properties, slopes, rainfall intensities, and plot sizes will allow determination of the amendment effectiveness, and produce data that will allow development of better application recommendations. Research on this topic will contribute to improved conservation, and result in better control of erosion and runoff. In addition, future work relating improved relationships between K_s and Φ_m with additional data of ρ_b and OM should allow better estimation of distributed K_s.

CHAPTER 6.

FUTURE RESEARCH

Development of Polyacrylamide and Biopolymer for Erosion Control

Departments and institutes such as the U.S. State Departments of Transportation and Natural Resources and U.S. Environmental Protection Agency, and international research institutes have published guidelines for use of anionic polyacrylamide (PAM) in erosion control. However, these guidelines did not consider many aspects of soil property, topography, and specific local condition. In addition, the effective methodology of PAM application needs to be developed and other biopolymers should be explored to effectively reduce soil erosion with current environmental issues and considerations.

I plan to join the environmental research team named Eco-STAR at the Kangwon National University to produce data and develop better guidelines for adapting PAM or new polymers with other best management practices to the Grand Korean Waterway Project. The Grand Korean Waterway, officially known as the Pan Korea Grand Waterway is a proposed long canal connecting Seoul and Busan, two of South Korea's largest cities. The Grand Korean Waterway Project would spend $17.1 billion to build a network of waterways linking South Korea's major northern and southern rivers, eventually to branch up to major North Korean cities. The current president of South Korea, Mr. Lee, consistently promoted that the 3,100-km-long waterways would roll back the country's logistics costs by a third, stimulate the slow regional economies, create thousands of jobs and boost tourism. By taking the heavy transports off the roads onto the waterways, Lee highlights that companies will enjoy a logistics cost cut, residents along the canal will see an economic boost, shipbuilders will reap business benefits, all the while carbon emissions and energy consumption are reduced.

Their PAM research team consisted of researchers who have advanced knowledge of physical and chemical soil sciences and environmental engineering from many universities and institutes including the University of Bayreuth in Germany and Research Institute of Kangwon, Yonsei University, Korea University, Seoul National University, Kangwon National University, and Rural Development Administration in South Korea. Research funds are being provided by the Complex TERRain and ECOlogical Heterogeneity (TERRECO; http://www.bayceer.uni-bayreuth.de/terreco/) from Germany and the Eco-STAR Project (http://www.me.go.kr/kor/index.jsp) from the Ministry of Environment of Korea Government. They will investigate the effects of PAM and biopolymers for reducing soil erosion and develop these materials as a part of climate change work related to carbon sequestration.

Grand Korean Waterway Project

South Korea's four waterways are the Han, Kum, Naktong, and Somjin Rivers. These follow a gradual descent to the west and south. The Han River flows westward from the foothills of the Taebaek Divide for nearly 514 km before reaching the Yellow Sea. The Kum River meanders nearly 401 km as it drains the southwestern peninsula, first flowing north from the low country of southern Korea, then turning west and finally south to the Yellow Sea. The Naktong River winds for 521 km from the southern end of the Taebaek mountains and empties into the East Sea at the southeastern corner of the peninsula. The gradual descent of Korea's major rivers and streams makes for wider waterways and slower currents, permitting inland river navigation for long distances, which is very important for internal commerce.

Because of its environmental and economic advantages, the waterway project was the first public pledge of the President of South Korea before he was elected to President in 2007. The Korea government with President Mr. Lee plans to build a network of waterways linking South Korea's major northern and southern rivers, eventually to branch up to major North Korean cities. They consistently promoted that the 3,100-km-long waterways would roll back the country's logistics costs by a third, stimulate the slow regional economies, create thousands of jobs and boost tourism. South Korea is currently making cross-country transports via three main expressways. The Kyongin Highway connects Seoul and Incheon, Kyungbu Highway connects Seoul and Busan, while the Honam Highway flows through the southwestern cities. By taking the heavy transports off the roads onto the waterways, they highlights that companies will enjoy a logistics cost cut, residents along the canal will see an economic boost, shipbuilders will reap business benefits, all the while carbon emissions and energy consumption are reduced. As the President of South Korea, Mr. Lee, and his transition team already admitted, the widespread public and expert opinion is that the pan-watery initiative should only move forth with more solid proof of benefits. Now they are trying to attract public input because of its huge construction cost, and now the four rivers projects are in review for environmental and economic justification.

Development of Environmental Assessment Tools

Due to the geographical location of South Korea in the Asian monsoon belt, more than half of annual precipitation occurs during the summer season through May to September. This causes significant amounts of soil loss from cropland, which is directly linked to the deterioration of surface water quality. Therefore, accurate and real-time estimation of soil erosion has been a great need in South Korea. Development of soil erosion models such as the empirical Revised Universal Soil Loss Equation (RUSLE) and the physically based model of the Water Erosion Prediction Project (WEPP) for South Korea would be a valuable study. These studies will use a scenario of cultivation to assess environmental effects more accurate by using climate, soil, slope, and cropping management inputs.

In Korea, the databases are not well-developed and need to be improved. Current information from the Meteorological Information Web Service System in Disaster Prevention of Meteorological Administration (MIWSS-DPMA), the Agricultural Soil Information System (ASIS), and Crop Information Center of Rural Development Administration (CIC-RDA) in Korea are not sufficient. My possible future research will be to implement the WEPP model and RUSLE to better predict erosion for a range of conditions. My study will focus on developing an environmental assessment program to conserve agricultural environments in a few countries.

APPENDICES

Appendix 1-1. Official soil description: Hoberg series for chapter 2.

HOBERG SERIES

The Hoberg series consists of very deep, moderately well drained soils that have a fragipan. They formed in a thin mantle of loess and the underlying residuum from cherty limestone. Slopes range from 2 to 8 percent. Permeability is moderate above the fragipan, slow in the fragipan and moderate below the fragipan. Mean annual temperature is 56 degrees F, and mean annual precipitation is 41 inches.

TAXONOMIC CLASS: Fine-loamy, siliceous, active, mesic Oxyaquic Fragiudalfs

TYPICAL PEDON: Hoberg silt loam - on a 3 percent northeast facing convex slope in grass at an elevation of 1,225 feet. (Colors are for moist conditions unless otherwise noted.)

Ap--0 to 7 inches; dark brown (7.5YR 3/2) silt loam, brown (7.5YR 5/2) dry; moderate very fine and fine granular structure; very friable; many fine roots; common worm channels and casts; 5 percent chert gravel; slightly acid; clear smooth boundary. (5 to 12 inches thick)

Bt1--7 to 13 inches; brown (7.5YR 4/4) silty clay loam; moderate very fine subangular blocky structure; friable; many fine roots; common worm channels and casts; few faint clay films on faces of peds; 5 percent chert gravel; slightly acid; clear smooth boundary.

Bt2--13 to 22 inches; reddish brown (5YR 4/4) silty clay loam; moderate fine and very fine subangular blocky structure; friable; common fine roots; common faint clay films on faces of peds; common worm channels and casts; 10 percent chert gravel; moderately acid; clear wavy boundary. (Combined thickness of the Bt horizon is 10 to 28 inches.)

2Btx--22 to 47 inches; mottled reddish brown (5YR 4/4), light brown (7.5YR 6/4), pinkish gray (5YR 6/2) and pinkish gray (7.5YR 6/2) extremely gravelly silty clay loam; moderate very coarse prismatic structure; very firm; 60 percent brittle: few very fine roots in top few inches; common distinct clay films on vertical faces of prisms; 75 percent chert gravel; extremely acid; gradual wavy boundary. (11 to 35 inches thick)

3Bt--47 to 72 inches; dark red (2.5YR 3/6) and dark reddish brown (2.5YR 3/4) extremely gravelly clay; moderate fine angular blocky structure; very firm; many distinct clay films on faces of peds; 70 percent chert gravel; few fine distinct light brown (7.5YR 6/4) masses of iron accumulation; few fine iron-manganese concretions (Fe and Mn oxides); strongly acid.

TYPE LOCATION: Lawrence County, Missouri; about 5 miles west of Mt. Vernon; 1,500 feet north and 1,170 feet west of the SE corner of Sec. 31, T. 28 N., R. 27 W.; USGS Stotts City, Missouri topographic quadrangle.

Appendix 1-2. Official soil description: Knox series for chapter 2.

KNOX SERIES

The Knox series consists of very deep, well drained, moderately permeable soils that formed in thick loess. These soils are on strongly dissected hills and bluffs bordering the Missouri River Valley and its tributaries. Slopes range from 2 to 35 percent. Mean annual temperature is 55 degrees F, and mean annual precipitation is 36 inches.

TAXONOMIC CLASS: Fine-silty, mixed, superactive, mesic Mollic Hapludalfs

TYPICAL PEDON: Knox silt loam - on a 7 percent convex slope. (Colors are for moist soil unless otherwise stated.)

A--0 to 7 inches; very dark grayish brown (10YR 3/2) silt loam, grayish brown (10YR 5/2) dry; weak very fine granular structure; friable; many roots; few wormholes and worm casts; moderately acid; clear smooth boundary. (6 to 9 inches thick)

E--7 to 12 inches; brown (10YR 4/3) silt loam; weak very fine granular structure; friable; many roots; few wormholes and wormcasts; moderately acid; clear smooth boundary. (0 to 8 inches thick)

Bt1--12 to 23 inches; dark yellowish brown (10YR 4/4) silty clay loam; moderate very fine subangular blocky structure; firm; few roots; many faint clay films on faces of peds; grayish brown silt coatings on faces of some peds: moderately acid; clear smooth boundary.

Bt2--23 to 35 inches; dark yellowish brown (10YR 4/4) silty clay loam; moderate medium subangular blocky structure; firm; few roots; common faint clay films on faces of some peds and old root channels; moderately acid; gradual smooth boundary.

Bt3--35 to 61 inches; dark yellowish brown (10YR 4/4) silty clay loam; moderate coarse subangular blocky structure; friable; commom faint clay films on the faces of some peds; moderately acid; gradual smooth boundary. (Combined thickness of the Bt horizon is 32 to 54 inches.)

BC--61 to 70 inches; dark yellowish brown (10YR 4/4) silt loam; weak coarse prismatic structure; friable; few faint clay flows along vertical cleavages; neutral.

TYPE LOCATION: Jackson County, Missouri; about 3 miles north of Buckner; 330 feet north and 260 feet west of the southeast corner of sec. 34, T. 51 N., R. 30 W.

Appendix 1-3. Official soil description: Mexico series for chapter 3 and 4.

MEXICO SERIES

The Mexico series consists of very deep, poorly drained soils formed in loess over loamy sediments derived from till. These soils are on ridge and hillsides of the Central Claypan Till Plains and have slopes of 0 to 4 percent. Mean annual temperature is about 12 degrees C (53 degrees F), and mean annual precipitation is 991 millimeters (39 inches).

TAXONOMIC CLASS: Fine, smectitic, mesic Vertic Epiaqualfs

TYPICAL PEDON: Mexico silt loam - on a 1 percent slope on an interfluve in a cultivated field at an elevation of 243 meters (798 feet). (Colors are for moist soil unless otherwise stated.)

Ap--0 to 23 centimeters (0 to 9 inches); very dark grayish brown (10YR 3/2) silt loam, grayish brown (10YR 5/2) dry; moderate medium and thin platy structure; friable; few fine roots; common fine tubular pores; few fine prominent yellowish brown (10YR 5/6) masses of oxidized iron; few fine faint black (10YR 2/1) iron-manganese concretions; slightly acid; abrupt smooth boundary. [13 to 23 centimeters (5 to 9 inches) thick]

Btg1--23 to 38 centimeters (9 to 14 inches); 70 percent dark grayish brown (10YR 4/2) and 30 percent grayish brown (10YR 5/2) silt loam; weak fine subangular blocky structure; friable; few fine roots; common fine and medium tubular pores; very few faint dark grayish brown (10YR 4/2) clay films on faces of peds; few distinct gray (10YR 6/1) silt coats on faces of peds; common fine prominent strong brown (7.5YR 5/6) and yellowish brown (10YR 5/8) masses of oxidized iron; few fine distinct black (10YR 2/1) iron-manganese concretions; friable; strongly acid; abrupt smooth boundary. [Thickness of the upper Btg horizon(s) is 0 to 23 centimeters (0 to 9 inches).]

Btg2--38 to 53 centimeters (14 to 21 inches); 70 percent dark grayish brown (10YR 4/2) and 30 percent gray (10YR 5/1) clay; moderate fine subangular blocky structure; friable; few very fine roots; few fine tubular pores; many distinct dark gray (10YR 4/1) clay films on faces of peds; few distinct very dark grayish brown (10YR 3/2) organoargillans on faces of peds; few distinct gray (10YR 6/1) silt coats on faces of peds; common fine prominent red (2.5YR 4/6) and strong brown (7.5YR 5/6) masses of oxidized iron; few fine faint black (10YR 2/1) iron-manganese concretions; very strongly acid; clear smooth boundary.

Btg3--53 to 69 centimeters (21 to 27 inches); grayish brown (10YR 5/2) silty clay; moderate fine subangular blocky structure; firm; few very fine roots; few fine tubular pores; 60 percent distinct grayish brown (10YR 5/2) clay films on faces of peds; common distinct very dark grayish brown (10YR 3/2) organoargillans on faces of peds and along surfaces of pores; many fine prominent yellowish brown (10YR 5/6) and few fine prominent yellowish red (5YR 4/6) masses of oxidized iron; few fine prominent black (10YR 2/1) iron-manganese concretions; very strongly acid; abrupt smooth boundary.

Btg4--69 to 86 centimeters (27 to 34 inches); grayish brown (10YR 5/2) silty clay; weak medium

(continued)

prismatic structure parting to weak fine subangular blocky; firm; few very fine roots; common fine tubular pores; common distinct dark grayish brown (10YR 4/2) clay films on faces of peds; common coarse prominent brown (7.5YR 4/4) and common fine prominent red (2.5YR 4/6) masses of oxidized iron; few fine prominent black (10YR 2/1) iron-manganese concretions; few fine prominent black (10YR 2/1) masses of manganese; strongly acid; abrupt smooth boundary. [Thickness of the middle Btg horizon(s) is 25 to 66 centimeters (10 to 26 inches).]

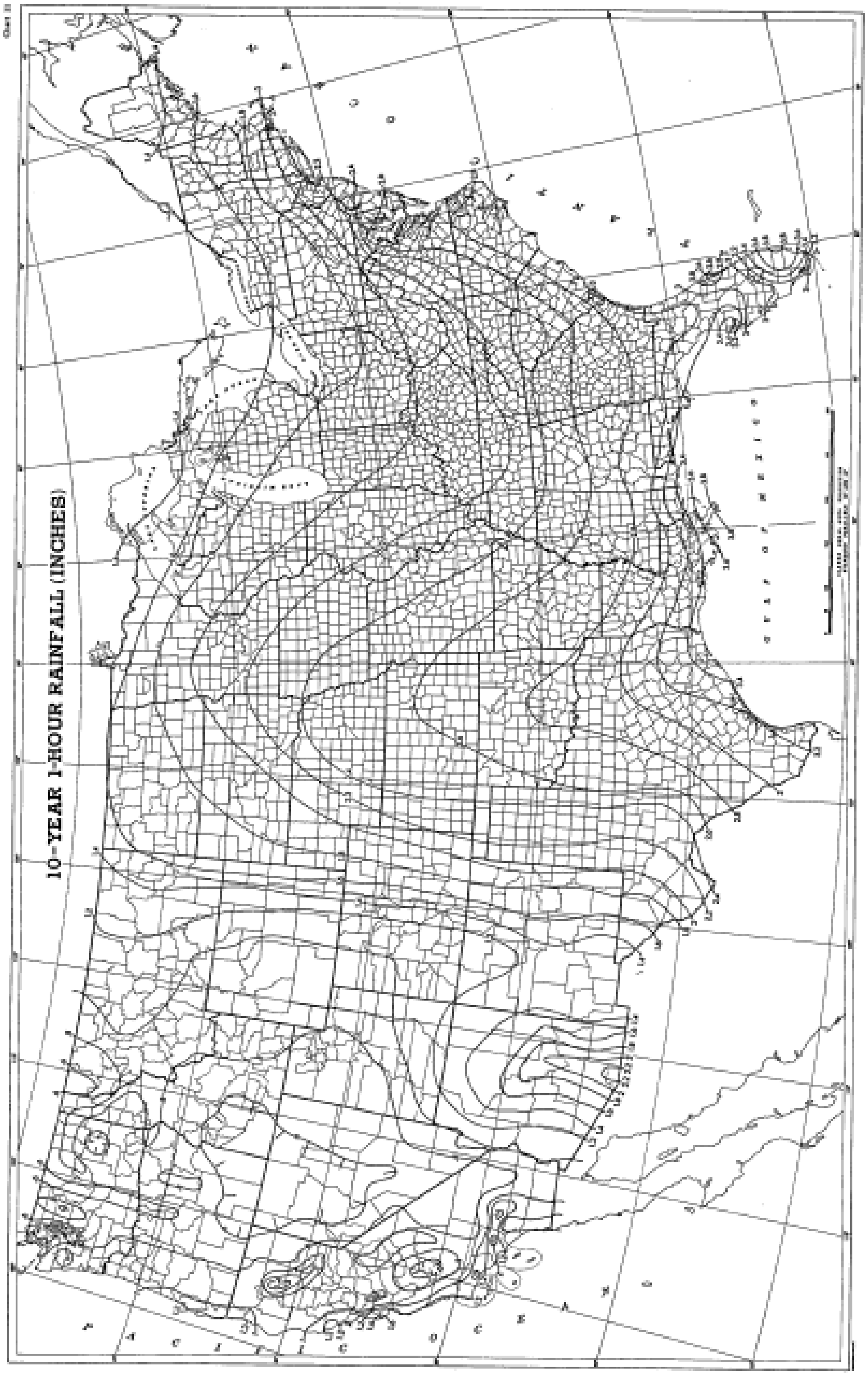
Btg5--86 to 107 centimeters (34 to 42 inches); light brownish gray (10YR 6/2) silty clay loam; moderate medium prismatic structure; firm; few very fine roots; common fine tubular pores; few faint gray (2.5Y 6/1) clay films on surfaces along pores; few coarse prominent strong brown (7.5YR 4/6) and few fine prominent dark yellowish brown (10YR 4/6) and reddish brown (5YR 4/4) masses of oxidized iron; few fine prominent black (10YR 2/1) masses of manganese on vertical faces of peds; few fine prominent black (10YR 2/1) iron-manganese concretions; strongly acid; gradual smooth boundary. [Thickness of the lower Btg horizon(s) is 13 to 50 centimeters (5 to 20 inches).]

2Btg6--107 to 135 centimeters (42 to 53 inches); gray (10YR 5/1) silty clay loam; moderate medium prismatic structure; firm; few very fine roots; few fine tubular pores; common faint gray (10YR 6/1) clay films on faces of peds; few medium prominent strong brown (7.5YR 4/6) and few fine prominent yellowish brown (10YR 5/6) masses of oxidized iron; few fine distinct black (10YR 2/1) masses of manganese; moderately acid; clear smooth boundary.

2Btg7--135 to 203 centimeters (53 to 80 inches); gray (10YR 5/1) silty clay loam; weak coarse prismatic structure parting to weak medium subangular blocky; firm; few fine tubular pores; many faint gray (2.5Y 5/1) clay films on faces of peds; common medium prominent dark yellowish brown (10YR 4/6) and brown (7.5YR 4/4) masses of oxidized iron; slightly acid.

TYPE LOCATION: Montgomery County, Missouri; about 3 miles east of Montgomery City; 341 meters (1,119 feet) east and 149 meters (489 feet) north from the southwest corner of sec. 23, T. 49 N., R. 5 W; New Florence USGS quadrangle, latitude 38 degrees 59 minutes 45 seconds N. and longitude 91 degrees 26 minutes 44 seconds W; UTM, Zone 15, 634616 easting, 4317461 northing, NAD 83.

Appendix 2. An intense rainstorm with a 10-year, 1-hour return frequency across mid-Missouri (Hershfield 1961).



Appendix 3-1. Data for runoff and sediment loss with no amendment (CK) subjected to a 62-min simulated rainfall with an intensity of 61 mm h^{-1} (2.4 in hr^{-1}) for chapter 2.

Soil	**Time**	**Runoff**			**Sediment loss**		
	min	-------------- mm --------------			-------------- g m^{-2} --------------		
Hoberg AP		Rep. 1	Rep. 2	Rep. 3	Rep. 1	Rep. 2	Rep. 3
	0	0	0	0	0	0	0
	5	0.313	0.353	0.324	28.22	26.56	15.89
	10	1.778	1.744	1.805	170.11	178.89	170.67
	15	2.020	1.977	1.969	148.44	157.78	151.56
	20	2.067	2.097	1.960	123.33	123.78	119.56
	25	2.094	2.043	2.048	114.11	115.44	103.11
	30	2.052	1.972	2.043	101.33	97.11	91.33
	35	2.068	2.046	2.049	91.89	87.67	84.44
	40	2.077	2.056	2.051	86.78	82.44	79.56
	45	2.026	2.029	2.083	85.33	75.89	68.33
	50	2.032	2.082	2.105	82.44	79.89	71.22
	55	1.988	2.070	2.075	79.00	77.11	72.33
	60	2.019	2.046	1.993	80.44	70.11	71.00
SUM		22.533	22.516	22.504	1191.44	1172.67	1099.00
Hoberg B1		Rep. 1	Rep. 2	Rep. 3	Rep. 1	Rep. 2	Rep. 3
	0	0	0	0	0	0	0
	5	0.120	0.216	0.127	22.00	26.22	37.44
	10	1.492	1.592	1.615	133.78	146.33	147.33
	15	1.624	1.684	1.657	152.22	154.78	154.67
	20	1.671	1.737	1.775	149.00	152.11	153.78
	25	1.706	1.725	1.791	137.67	145.11	146.00
	30	1.713	1.756	1.739	131.22	126.67	140.56
	35	1.701	1.755	1.742	114.67	124.11	126.33
	40	1.712	1.783	1.728	127.11	128.56	126.00
	45	1.743	1.783	1.751	114.11	123.67	117.44
	50	1.767	1.758	1.825	112.56	113.00	110.33
	55	1.763	1.807	1.773	100.00	105.56	97.78
	60	1.757	1.809	1.700	93.78	111.00	92.67
SUM		18.770	19.405	19.222	1388.11	1457.11	1450.33

(continued)

Soil	Time	Runoff			Sediment loss		
	min	--------------- mm ---------------			--------------- g m^{-2} ---------------		
Knox A1		Rep. 1	Rep. 2	Rep. 3	Rep. 1	Rep. 2	Rep. 3
	0	0	0	0	0	0	0
	5	0.181	0.030	0.023	12.00	4.00	17.56
	10	1.187	1.091	1.053	190.78	189.67	188.11
	15	1.361	1.266	1.310	161.56	167.89	174.56
	20	1.326	1.347	1.389	144.67	157.22	153.44
	25	1.368	1.262	1.346	121.11	129.78	132.33
	30	1.538	1.347	1.434	103.33	121.78	99.89
	35	1.492	1.239	1.457	99.44	87.22	86.67
	40	1.489	1.326	1.416	86.22	90.22	78.00
	45	1.401	1.287	1.404	70.56	84.44	75.33
	50	1.482	1.321	1.407	74.89	70.00	65.11
	55	1.555	1.229	1.398	73.00	68.56	55.67
	60	1.465	1.271	1.406	65.67	61.33	49.44
SUM		15.846	14.014	15.043	1203.22	1232.11	1176.11
Knox Bt		Rep. 1	Rep. 2	Rep. 3	Rep. 1	Rep. 2	Rep. 3
	0	0	0	0	0	0	0
	5	0.410	0.354	0.342	63.22	46.78	21.67
	10	1.695	1.742	1.749	162.22	169.44	173.11
	15	1.746	1.720	1.673	148.44	135.22	162.11
	20	1.804	1.854	1.737	139.67	137.78	142.44
	25	1.781	1.797	1.832	128.44	115.00	134.22
	30	1.876	1.767	1.841	127.22	114.33	120.78
	35	1.791	1.754	1.832	118.44	109.00	115.89
	40	1.847	1.772	1.896	111.44	100.56	116.67
	45	1.764	1.691	1.875	94.44	87.67	106.89
	50	1.863	1.782	1.889	95.78	87.67	103.56
	55	1.823	1.808	1.929	92.67	84.22	107.89
	60	1.888	1.784	1.918	91.56	84.89	97.56
SUM		20.289	19.824	20.513	1373.56	1272.56	1402.78

Appendix 3-2. Data for runoff and sediment loss with 5-Mg ha^{-1} (1.9-ton ac^{-1}) gypsum amendment (5G) subjected to a 62-min simulated rainfall with an intensity of 61 mm h^{-1} (2.4 in hr^{-1}) for chapter 2.

Soil	**Time**	**Runoff**			**Sediment loss**		
	min	--------------- mm ---------------			--------------- g m^{-2} ---------------		
Hoberg AP		Rep. 1	Rep. 2	Rep. 3	Rep. 1	Rep. 2	Rep. 3
	0	0	0	0	0	0	0
	5	0.283	0.210	0.305	49.22	44.78	45.33
	10	1.510	1.461	1.422	177.33	175.78	185.67
	15	1.660	1.675	1.647	165.89	152.44	167.56
	20	1.805	1.769	1.885	132.78	116.56	132.22
	25	1.887	1.857	1.848	94.33	93.11	109.33
	30	1.898	1.820	1.960	92.33	86.67	80.78
	35	1.918	1.912	1.964	80.67	72.44	88.78
	40	1.976	1.909	1.879	78.89	70.11	84.11
	45	1.957	1.852	1.994	73.78	66.67	77.22
	50	1.964	1.843	1.940	68.11	67.11	52.33
	55	1.961	1.942	1.979	66.67	60.56	56.22
	60	1.970	1.942	1.936	62.11	59.78	66.11
SUM		20.790	20.191	20.759	1142.11	1066.00	1145.67
Hoberg B1		Rep. 1	Rep. 2	Rep. 3	Rep. 1	Rep. 2	Rep. 3
	0	0	0	0	0	0	0
	5	0.094	0.099	0.035	10.44	24.00	8.44
	10	0.844	1.053	0.921	126.56	133.33	120.44
	15	1.490	1.504	1.485	160.56	153.33	141.44
	20	1.502	1.405	1.520	155.22	150.11	144.56
	25	1.488	1.436	1.541	154.78	155.67	153.67
	30	1.444	1.395	1.473	153.67	161.00	156.33
	35	1.446	1.396	1.491	157.22	139.56	144.44
	40	1.449	1.360	1.449	149.78	144.89	135.22
	45	1.487	1.424	1.471	132.44	134.78	129.78
	50	1.579	1.374	1.496	112.22	127.56	108.89
	55	1.544	1.402	1.504	108.11	108.11	104.78
	60	1.565	1.436	1.515	107.67	102.78	108.78
SUM		15.932	15.283	15.901	1528.67	1535.11	1456.78

(continued)

Soil	Time	Runoff			Sediment loss		
	min	--------------- mm ---------------			--------------- g m^{-2} ---------------		
Knox A1		Rep. 1	Rep. 2	Rep. 3	Rep. 1	Rep. 2	Rep. 3
	0	0	0	0	0	0	0
	5	0.113	0.067	0.075	25.11	18.89	13.78
	10	0.441	0.380	0.353	48.78	44.89	47.22
	15	0.887	0.697	0.750	66.89	51.11	57.11
	20	1.079	0.980	1.055	74.78	61.89	63.78
	25	1.189	1.108	1.141	80.22	64.33	72.00
	30	1.347	1.195	1.239	86.56	62.44	74.22
	35	1.426	1.267	1.282	85.67	62.33	74.00
	40	1.469	1.385	1.403	85.44	67.44	73.56
	45	1.570	1.420	1.436	84.44	66.33	77.33
	50	1.556	1.482	1.471	84.44	66.11	77.89
	55	1.571	1.508	1.495	85.67	67.56	83.44
	60	1.663	1.588	1.584	95.56	76.78	74.44
SUM		14.312	13.077	13.283	903.56	710.11	788.78
Knox Bt		Rep. 1	Rep. 2	Rep. 3	Rep. 1	Rep. 2	Rep. 3
	0	0	0	0	0	0	0
	5	0.172	0.199	0.146	22.78	43.67	38.56
	10	1.569	1.730	1.575	147.78	157.67	148.11
	15	1.625	1.667	1.670	137.89	151.78	143.00
	20	1.664	1.795	1.715	126.56	137.11	136.22
	25	1.602	1.761	1.687	100.22	113.22	103.89
	30	1.721	1.773	1.731	96.11	103.22	90.11
	35	1.775	1.855	1.757	80.56	97.22	89.22
	40	1.706	1.734	1.760	68.22	77.89	80.44
	45	1.750	1.837	1.729	69.22	67.89	74.56
	50	1.732	1.871	1.755	64.22	51.67	62.56
	55	1.871	1.807	1.749	67.33	54.67	56.56
	60	1.808	1.817	1.732	57.00	58.00	53.44
SUM		18.996	19.846	19.005	1037.89	1114.00	1076.67

Appendix 3-3. Data for runoff and sediment loss with 20-kg ha^{-1} (18-lb ac^{-1}) PAM amendment (20P) subjected to a 62-min simulated rainfall with an intensity of 61 mm h^{-1} (2.4 in hr^{-1}) for chapter 2.

Soil	**Time**	**Runoff**			**Sediment loss**		
	min	--------------- mm ---------------			--------------- g m^{-2} ---------------		
Hoberg AP		Rep. 1	Rep. 2	Rep. 3	Rep. 1	Rep. 2	Rep. 3
	0	0	0	0	0	0	0
	5	0.632	0.507	0.587	47.89	33.56	9.44
	10	1.776	1.732	1.736	145.00	160.00	152.44
	15	1.843	1.841	1.816	134.00	144.22	130.33
	20	1.880	1.921	1.882	103.11	106.67	112.89
	25	1.957	1.907	1.937	80.78	101.33	94.11
	30	1.941	1.878	1.960	72.22	84.67	83.56
	35	1.984	1.873	1.967	65.44	81.89	75.67
	40	1.956	1.858	1.953	71.78	78.56	68.89
	45	1.996	1.895	1.965	62.22	73.56	69.11
	50	1.925	1.921	1.938	54.00	70.44	61.44
	55	1.934	1.907	1.956	51.33	69.44	55.89
	60	1.975	1.918	1.956	46.89	71.11	57.22
SUM		21.799	21.158	21.653	934.67	1075.44	971.00
Hoberg B1		Rep. 1	Rep. 2	Rep. 3	Rep. 1	Rep. 2	Rep. 3
	0	0	0	0	0	0	0
	5	0.088	0.054	0.139	8.78	10.89	6.33
	10	0.549	0.616	0.621	60.78	54.67	54.00
	15	1.393	1.124	1.475	87.78	84.56	81.00
	20	1.739	1.627	1.780	114.33	102.44	101.33
	25	1.752	1.713	1.785	106.44	97.78	101.22
	30	1.798	1.687	1.808	103.78	88.89	97.89
	35	1.798	1.644	1.794	97.11	89.22	98.56
	40	1.789	1.659	1.758	101.22	83.67	99.00
	45	1.737	1.687	1.777	97.89	80.00	87.89
	50	1.727	1.680	1.749	92.00	76.78	92.56
	55	1.769	1.715	1.747	92.56	68.00	82.33
	60	1.773	1.745	1.749	77.44	65.78	82.78
SUM		17.912	16.950	18.180	1040.11	902.67	984.89

(continued)

Soil	Time	Runoff			Sediment loss		
	min	--------------- mm ---------------			--------------- g m^{-2} ---------------		
Knox A1		Rep. 1	Rep. 2	Rep. 3	Rep. 1	Rep. 2	Rep. 3
	0	0	0	0	0	0	0
	5	0.082	0.074	0.056	14.44	16.89	20.78
	10	0.177	0.163	0.213	27.22	26.78	26.67
	15	0.533	0.402	0.471	109.44	91.22	96.78
	20	1.011	0.935	0.993	110.22	105.67	99.00
	25	1.036	0.920	1.030	90.67	90.00	96.33
	30	1.038	0.938	1.037	84.11	89.56	94.67
	35	1.059	0.962	1.063	84.44	90.67	89.00
	40	1.028	1.005	1.053	84.67	83.44	88.56
	45	1.033	1.076	1.066	85.11	86.56	86.56
	50	1.057	1.112	1.093	86.11	88.67	86.89
	55	1.072	1.070	1.104	78.11	81.33	79.56
	60	1.087	1.141	1.097	79.89	75.56	76.78
SUM		10.213	9.795	10.277	934.44	926.33	941.56
Knox Bt		Rep. 1	Rep. 2	Rep. 3	Rep. 1	Rep. 2	Rep. 3
	0	0	0	0	0	0	0
	5	0.214	0.063	0.076	27.67	18.33	16.00
	10	1.811	1.838	1.780	181.56	175.78	164.78
	15	1.866	1.929	1.844	161.44	166.33	164.33
	20	1.822	1.854	1.783	141.89	142.11	148.22
	25	1.878	1.868	1.806	128.11	134.11	123.89
	30	1.859	1.948	1.875	122.56	132.56	124.89
	35	1.903	1.972	1.874	115.22	126.78	126.78
	40	1.909	1.998	1.918	110.00	120.22	110.89
	45	1.895	1.942	1.931	99.78	108.00	93.78
	50	1.922	2.008	1.942	91.11	102.67	95.56
	55	1.910	1.966	1.897	85.22	96.33	97.22
	60	1.873	1.999	1.897	82.44	82.89	76.78
SUM		20.862	21.385	20.622	1347.00	1406.11	1343.11

Appendix 3-4. Data for runoff and sediment loss with 40-kg ha^{-1} (36-lb ac^{-1}) PAM amendment (40P) subjected to a 62-min simulated rainfall with an intensity of 61 mm h^{-1} (2.4 in hr^{-1}) for chapter 2.

Soil	**Time**	**Runoff**			**Sediment loss**		
	min	--------------- mm ---------------			--------------- g m^{-2} ---------------		
Hoberg AP		Rep. 1	Rep. 2	Rep. 3	Rep. 1	Rep. 2	Rep. 3
	0	0	0	0	0	0	0
	5	0.895	0.726	0.808	46.67	50.67	44.33
	10	1.892	1.738	1.941	123.11	115.11	111.56
	15	1.959	1.973	1.895	96.22	103.11	91.11
	20	1.940	1.986	1.868	75.78	74.00	72.11
	25	2.007	2.065	1.938	62.11	49.22	53.11
	30	1.998	2.022	1.979	61.11	47.44	45.11
	35	1.989	1.955	1.938	44.33	47.22	43.00
	40	1.913	1.927	1.901	39.67	39.33	43.11
	45	2.045	2.013	2.000	45.00	36.33	41.89
	50	2.055	1.916	2.036	41.00	47.78	38.11
	55	1.930	1.884	1.991	39.00	46.22	37.78
	60	2.063	1.954	2.004	39.78	32.67	43.11
SUM		22.684	22.160	22.299	713.78	689.11	664.33
Hoberg B1		Rep. 1	Rep. 2	Rep. 3	Rep. 1	Rep. 2	Rep. 3
	0	0	0	0	0	0	0
	5	0.106	0.097	0.151	11.00	8.67	15.00
	10	0.139	0.313	0.226	9.44	16.00	15.67
	15	1.151	1.355	1.234	40.67	38.89	29.44
	20	1.622	1.767	1.710	40.78	38.56	39.56
	25	1.828	1.971	1.893	34.78	41.56	42.22
	30	1.926	1.984	1.987	41.44	38.56	43.44
	35	1.943	1.996	2.014	40.56	39.33	37.11
	40	1.973	1.959	2.012	45.78	46.33	37.78
	45	1.944	2.101	2.046	50.11	51.67	45.67
	50	1.897	2.076	1.993	45.00	49.44	46.00
	55	2.042	2.068	2.011	49.56	48.22	47.56
	60	2.008	1.957	2.042	48.78	45.78	44.78
SUM		18.580	19.643	19.319	457.89	463.00	444.22

(continued)

Soil	Time	Runoff			Sediment loss		
	min	--------------- mm ---------------			--------------- g m^{-2} ---------------		
Knox A1		Rep. 1	Rep. 2	Rep. 3	Rep. 1	Rep. 2	Rep. 3
	0	0	0	0	0	0	0
	5	0.083	0.096	0.075	17.22	20.78	17.22
	10	0.169	0.244	0.222	26.78	30.44	26.22
	15	0.247	0.277	0.346	30.22	34.11	27.89
	20	0.389	0.539	0.499	45.00	56.44	54.11
	25	0.687	0.777	0.715	115.56	131.00	127.33
	30	0.985	1.071	0.879	135.67	122.56	118.22
	35	1.026	1.105	0.959	119.78	118.56	108.78
	40	0.953	1.084	0.932	113.56	112.22	105.11
	45	0.964	1.070	0.916	115.00	116.56	102.44
	50	0.967	1.086	0.946	118.89	119.22	92.78
	55	1.016	1.120	0.963	111.67	114.67	84.44
	60	1.069	1.119	0.984	109.11	112.67	81.67
SUM		8.555	9.587	8.436	1058.44	1089.22	946.22
Knox Bt		Rep. 1	Rep. 2	Rep. 3	Rep. 1	Rep. 2	Rep. 3
	0	0	0	0	0	0	0
	5	0.065	0.059	0.088	10.56	8.78	14.22
	10	1.775	1.652	1.758	140.22	131.56	141.89
	15	1.849	1.859	1.832	143.67	138.00	139.00
	20	1.920	1.969	1.916	140.44	138.33	132.89
	25	1.903	1.951	1.924	130.33	123.89	119.00
	30	1.876	1.869	1.979	123.67	127.11	130.33
	35	1.921	1.956	1.938	123.11	118.11	128.11
	40	1.933	2.005	1.854	114.22	105.22	113.00
	45	1.954	2.032	1.950	112.89	104.00	99.67
	50	1.986	1.973	2.011	90.33	97.11	92.11
	55	2.005	1.940	2.055	91.33	93.33	98.44
	60	1.948	2.018	1.996	76.44	90.56	85.11
SUM		21.133	21.285	21.301	1297.22	1276.00	1293.78

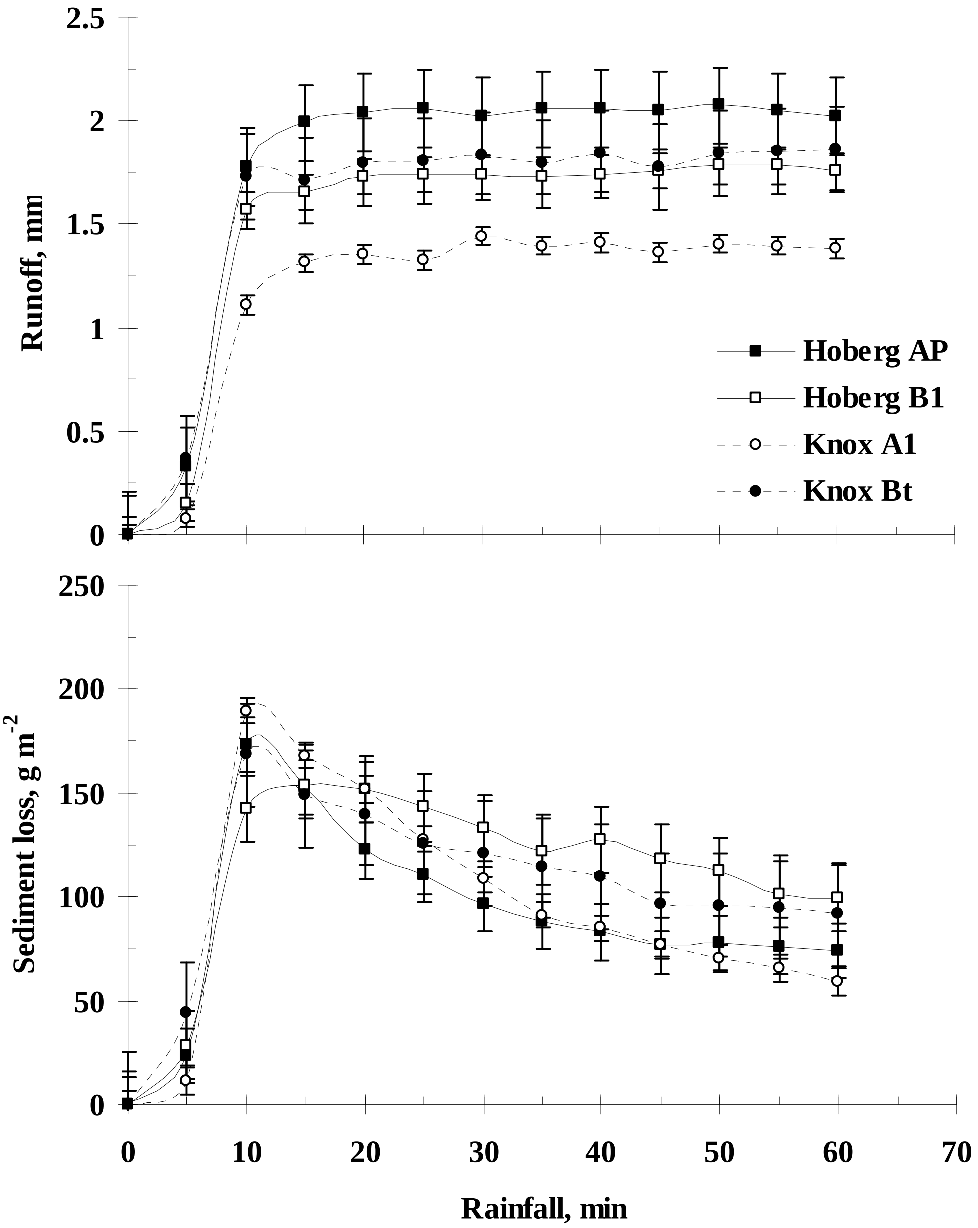
Appendix 3-5. Data for runoff and sediment loss with 20-kg ha^{-1} (18-lb ac^{-1}) PAM mixed with 5-Mg ha^{-1} (1.9-ton ac^{-1}) gypsum amendment (20P+5G) subjected to a 62-min simulated rainfall with an intensity of 61 mm h^{-1} (2.4 in hr^{-1}) for chapter 2.

Soil	Time	Runoff			Sediment loss		
	min	-------------- mm --------------			-------------- g m^{-2} --------------		
Hoberg AP		Rep. 1	Rep. 2	Rep. 3	Rep. 1	Rep. 2	Rep. 3
	0	0	0	0	0	0	0
	5	0.371	0.381	0.389	64.00	54.56	32.44
	10	1.558	1.581	1.603	182.67	188.11	192.67
	15	1.870	1.821	1.885	121.78	127.56	107.56
	20	1.896	1.848	1.897	87.11	99.33	91.33
	25	1.882	1.854	1.918	87.67	86.78	83.44
	30	1.957	1.815	1.936	82.67	88.67	77.44
	35	2.074	1.796	1.928	80.78	82.78	77.89
	40	1.986	1.910	1.980	82.22	83.00	82.33
	45	1.937	1.880	1.946	85.22	75.56	78.22
	50	1.923	1.845	1.966	85.89	80.56	71.00
	55	1.899	1.847	1.964	83.56	83.56	69.33
	60	1.970	1.827	1.947	84.00	86.89	75.22
SUM		21.323	20.404	21.358	1127.56	1137.33	1038.89
Hoberg B1		Rep. 1	Rep. 2	Rep. 3	Rep. 1	Rep. 2	Rep. 3
	0	0	0	0	0	0	0
	5	0.056	0.085	0.050	8.89	11.89	11.78
	10	0.084	0.140	0.112	8.56	11.22	14.89
	15	0.257	0.242	0.299	17.56	17.44	14.44
	20	1.138	0.847	1.060	41.44	41.33	36.44
	25	1.407	1.321	1.334	52.67	54.89	55.11
	30	1.304	1.306	1.292	49.11	45.22	45.11
	35	1.245	1.302	1.285	38.22	36.00	28.67
	40	1.134	1.193	1.117	35.67	35.89	26.11
	45	0.990	1.117	1.066	36.33	34.89	26.11
	50	0.927	1.044	0.979	38.67	31.44	26.22
	55	0.922	1.068	0.902	33.33	29.56	24.89
	60	0.923	0.991	0.976	45.11	30.56	24.11
SUM		10.387	10.656	10.471	405.56	380.33	333.89

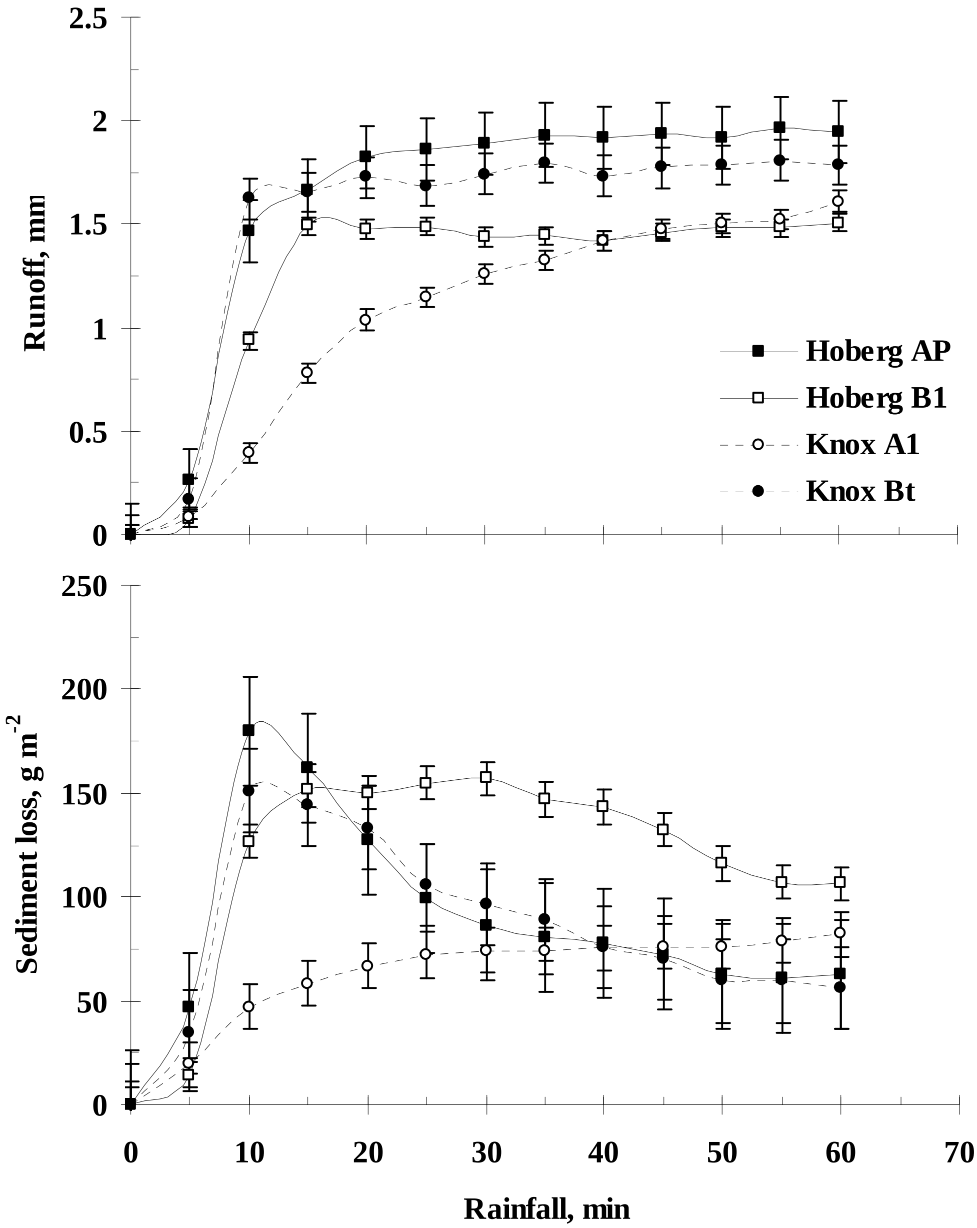
(continued)

Soil	Time	Runoff			Sediment loss		
	min	--------------- mm ---------------			--------------- g m^{-2} ---------------		
Knox A1		Rep. 1	Rep. 2	Rep. 3	Rep. 1	Rep. 2	Rep. 3
	0	0	0	0	0	0	0
	5	0.146	0.126	0.077	20.89	24.89	21.78
	10	0.229	0.237	0.202	41.33	37.44	42.56
	15	0.350	0.323	0.302	53.44	48.67	51.22
	20	0.491	0.472	0.453	65.33	55.78	57.67
	25	0.697	0.630	0.535	71.44	60.67	62.22
	30	0.635	0.648	0.565	63.56	66.78	65.89
	35	0.761	0.652	0.672	63.22	59.67	69.22
	40	0.787	0.678	0.725	69.44	65.89	67.78
	45	0.894	0.710	0.780	75.00	64.44	71.44
	50	0.967	0.769	0.853	70.33	65.44	70.89
	55	1.005	0.968	0.967	67.67	68.89	72.56
	60	1.108	1.116	0.996	84.44	72.11	72.89
SUM		8.070	7.329	7.126	746.11	690.67	726.11
Knox Bt		Rep. 1	Rep. 2	Rep. 3	Rep. 1	Rep. 2	Rep. 3
	0	0	0	0	0	0	0
	5	0.116	0.054	0.029	31.11	11.44	38.56
	10	1.671	1.453	1.536	129.56	129.33	126.22
	15	1.808	1.784	1.945	119.22	115.33	109.67
	20	1.866	1.775	1.941	90.78	84.78	91.11
	25	1.927	1.752	1.908	75.78	75.33	80.56
	30	1.996	1.761	1.877	81.22	73.67	77.33
	35	1.882	1.796	1.859	85.11	75.89	77.11
	40	1.984	1.845	1.856	81.00	84.33	74.00
	45	2.014	1.921	1.894	83.33	89.67	75.67
	50	2.056	1.855	1.911	89.67	77.44	78.78
	55	1.989	1.961	1.945	94.00	75.22	77.00
	60	2.024	1.937	1.936	95.00	78.89	77.78
SUM		21.333	19.894	20.637	1055.78	971.33	983.78

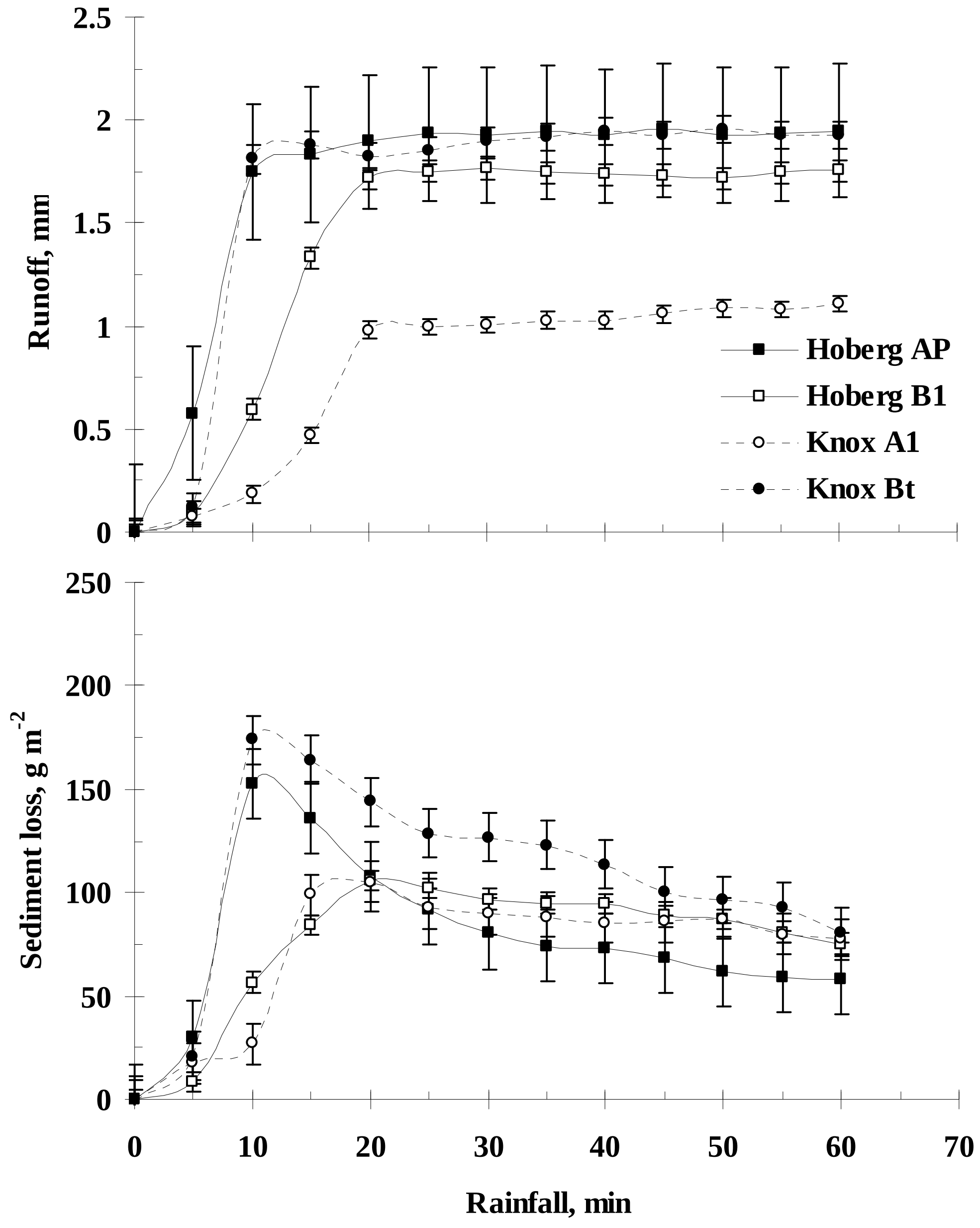
Appendix 4-1. Figures for runoff and sediment loss with no amendment (CK) subjected to a 62-min simulated rainfall with an intensity of 61 mm h^{-1} (2.4 in hr^{-1}) for chapter 2.



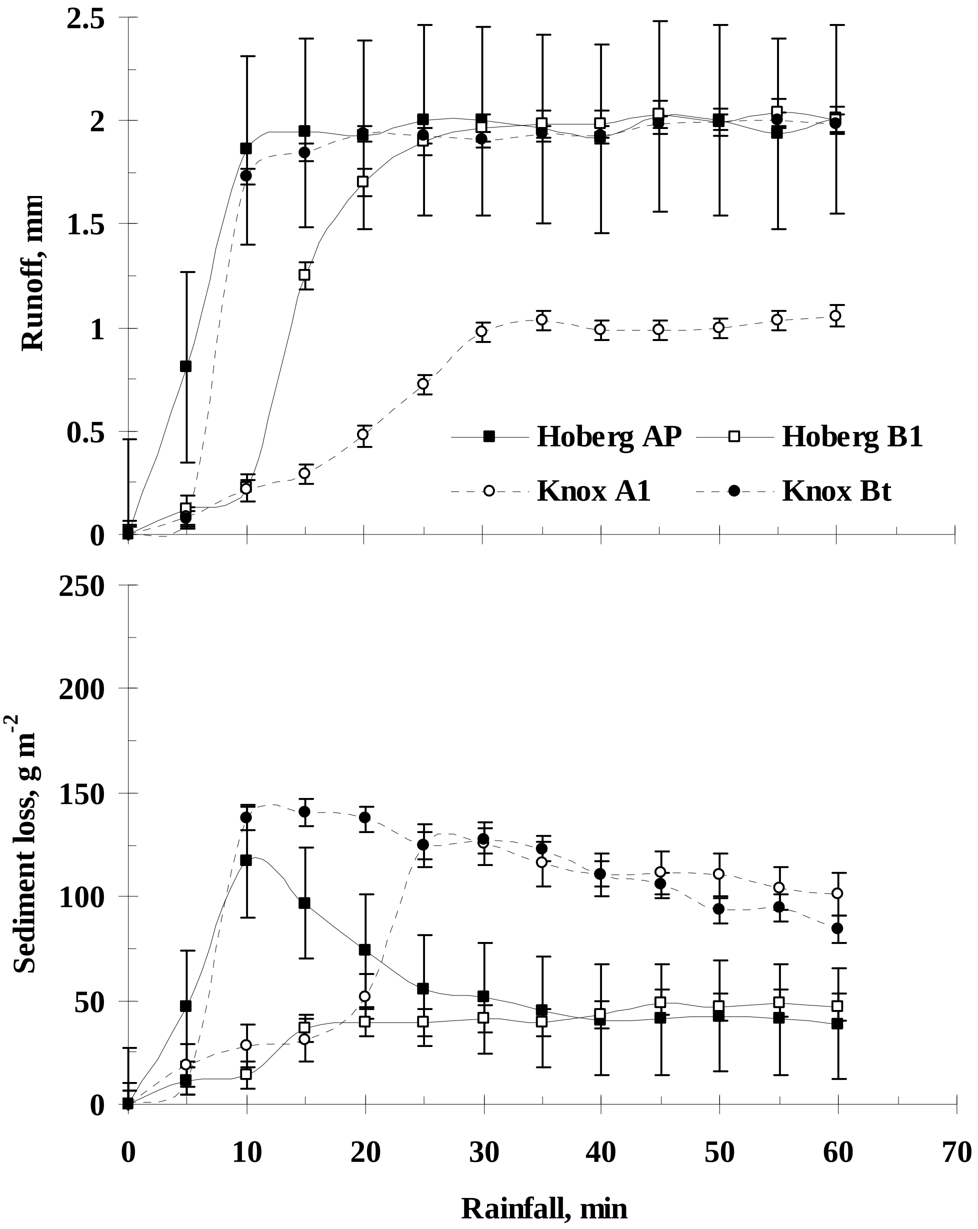
Appendix 4-2. Figures for runoff and sediment loss with 5-Mg ha^{-1} (1.9-ton ac^{-1}) gypsum amendment (5G) subjected to a 62-min simulated rainfall with an intensity of 61 mm h^{-1} (2.4 in hr^{-1}) for chapter 2.



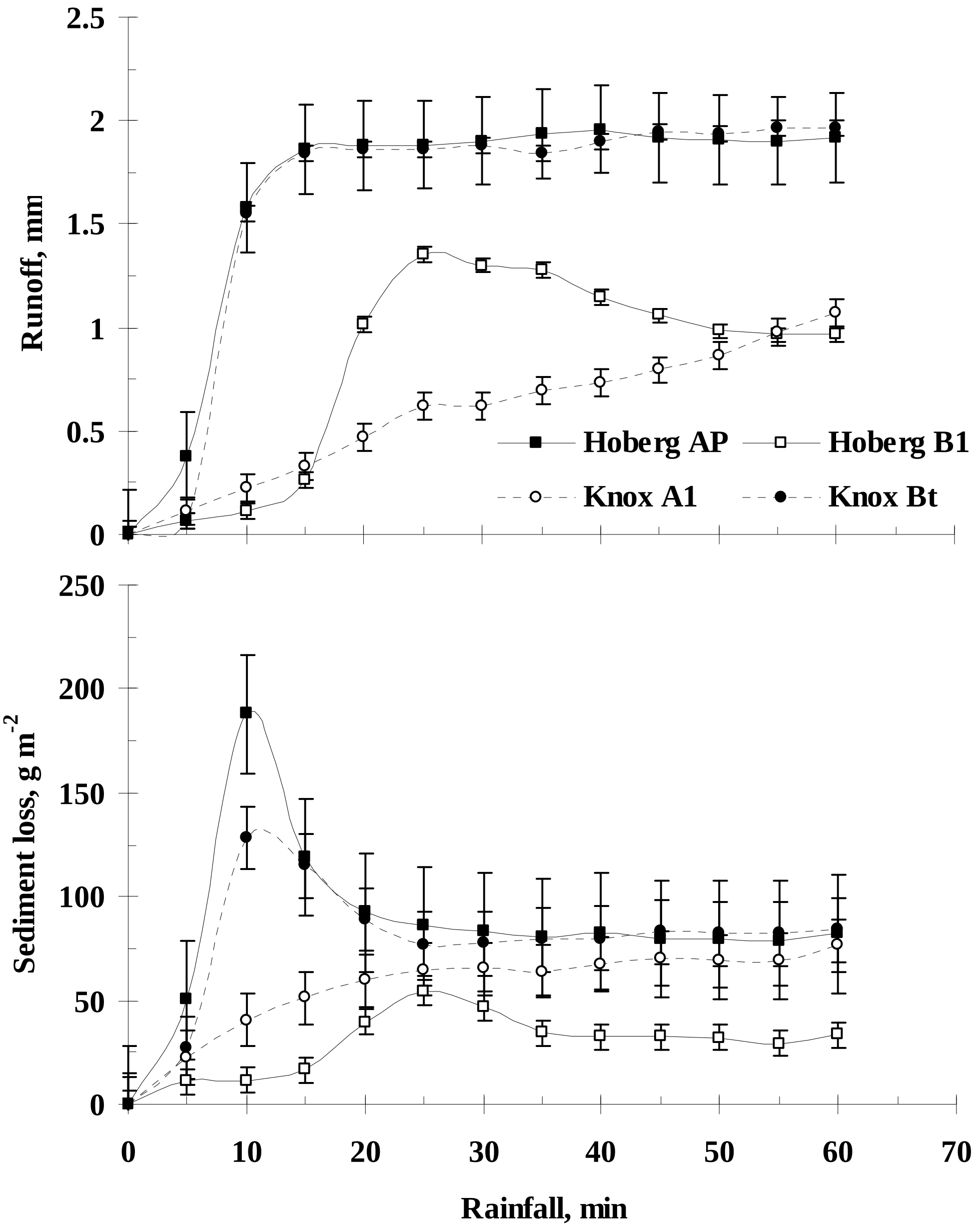
Appendix 4-3. Figures for runoff and sediment loss with 20-kg ha^{-1} (18-lb ac^{-1}) PAM amendment (20P) subjected to a 62-min simulated rainfall with an intensity of 61 mm h^{-1} (2.4 in hr^{-1}) for chapter 2.



Appendix 4-4. Figures for runoff and sediment loss with 40-kg ha^{-1} (36-lb ac^{-1}) PAM amendment (40P) subjected to a 62-min simulated rainfall with an intensity of 61 mm h^{-1} (2.4 in hr^{-1}) for chapter 2.



Appendix 4-5. Figures for runoff and sediment loss with 20-kg ha^{-1} (18-lb ac^{-1}) PAM mixed with 5-Mg ha^{-1} (1.9-ton ac^{-1}) gypsum amendment (20P+5G) subjected to a 62-min simulated rainfall with an intensity of 61 mm h^{-1} (2.4 in hr^{-1}) for chapter 2.



Appendix 5-1. SAS output for the time to initial runoff (TRO) using the SAS system (Release 9.1.3. in 2005) for chapter 2.

MODOT Study
The GLM Procedure

Class Level Information

Class	Levels	Values
Trt	5	20P 20P+5G 40P 5G CK

Number of Observations Read 20
Number of Observations Used 20

Dependent Variable: pTimeRO

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	7	503.5981693	71.9425956	16.78	<.0001
Error	12	51.4491118	4.2874260		
Corrected Total	19	555.0472811			

R-Square	Coeff Var	Root MSE	pTimeRO Mean
0.907307	18.74704	2.070610	11.04500

Source	DF	Type I SS	Mean Square	F Value	Pr > F
Trt	4	109.3486671	27.3371668	6.38	0.0055
pH	1	94.9303228	94.9303228	22.14	0.0005
Clay	1	59.0588955	59.0588955	13.77	0.0030
Silt	1	240.2602839	240.2602839	56.04	<.0001

Source	DF	Type III SS	Mean Square	F Value	Pr > F
Trt	4	109.3486671	27.3371668	6.38	0.0055
pH	1	153.3449238	153.3449238	35.77	<.0001
Clay	1	197.9539493	197.9539493	46.17	<.0001
Silt	1	240.2602839	240.2602839	56.04	<.0001

Parameter		Estimate	Standard Error	t Value	Pr > |t|
Intercept		100.7924016 B	11.90873503	8.46	<.0001
Trt	20P	1.9083333 B	1.46414241	1.30	0.2169
Trt	20P+5G	6.0000000 B	1.46414241	4.10	0.0015
Trt	40P	4.6833333 B	1.46414241	3.20	0.0077
Trt	5G	0.5500000 B	1.46414241	0.38	0.7137
Trt	CK	0.0000000 B	.	.	.
pH		7.9424597	1.32806287	5.98	<.0001
Clay		-2.8595463	0.42083646	-6.79	<.0001
Silt		-1.4146238	0.18897236	-7.49	<.0001

Least Squares Means

Trt	pTimeRO LSMEAN	Standard Error	Pr > |t|	LSMEAN Number
20P	10.3250000	1.0353050	<.0001	1
20P+5G	14.4166667	1.0353050	<.0001	2
40P	13.1000000	1.0353050	<.0001	3
5G	8.9666667	1.0353050	<.0001	4
CK	8.4166667	1.0353050	<.0001	5

(continued)

Least Squares Means for effect Trt
Pr > |t| for H0: LSMean(i)=LSMean(j)

Dependent Variable: pTimeRO

i/j	1	2	3	4	5
1		0.0162	0.0824	0.3718	0.2169
2	0.0162		0.3862	0.0029	0.0015
3	0.0824	0.3862		0.0154	0.0077
4	0.3718	0.0029	0.0154		0.7137
5	0.2169	0.0015	0.0077	0.7137	

NOTE: To ensure overall protection level, only probabilities associated with pre-planned comparisons should be used.

Obs	_NAME_	Trt	LSMEAN	STDERR	NUMBER	COV1	COV2	COV3	COV4	COV5
1	pTimeRO	20P	10.3250	1.03531	1	1.07186	0.00000	0.00000	0.00000	0.00000
2	pTimeRO	20P+5G	14.4167	1.03531	2	0.00000	1.07186	0.00000	0.00000	0.00000
3	pTimeRO	40P	13.1000	1.03531	3	0.00000	0.00000	1.07186	0.00000	0.00000
4	pTimeRO	5G	8.9667	1.03531	4	0.00000	0.00000	0.00000	1.07186	0.00000
5	pTimeRO	CK	8.4167	1.03531	5	0.00000	0.00000	0.00000	0.00000	1.07186

Appendix 5-2. SAS output for the cumulative runoff (RO) using the SAS system (Release 9.1.3. in 2005) for chapter 2.

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                              MODOT Study
                        Class Level Information

                 Class        Levels   Values
                 Soil              4   HoAp HoBt KxAp KxBt
                 Trt               5   20P 20P+5G 40P 5G CK

                   Number of Observations Read        60
                   Number of Observations Used        60

Dependent Variable: RO
                                     Sum of
     Source                DF       Squares     Mean Square    F Value    Pr > F
     Model                 19   8286.469958      436.129998     302.39    <.0001
     Error                 40     57.691667        1.442292
     Corrected Total       59   8344.161625

                R-Square    Coeff Var     Root MSE     RO Mean
                0.993086     2.764469     1.200954    43.44250

     Source                DF     Type I SS     Mean Square    F Value    Pr > F
     Soil                   3   6467.140708     2155.713569    1494.64    <.0001
     Trt                    4    730.192458      182.548115     126.57    <.0001
     Soil*Trt              12   1089.136792       90.761399      62.93    <.0001

     Source                DF   Type III SS     Mean Square    F Value    Pr > F
     Soil                   3   6467.140708     2155.713569    1494.64    <.0001
     Trt                    4    730.192458      182.548115     126.57    <.0001
     Soil*Trt              12   1089.136792       90.761399      62.93    <.0001

                  Tukey's Studentized Range (HSD) Test for RO

          NOTE: This test controls the Type I experimentwise error rate.

                  Alpha                                  0.05
                  Error Degrees of Freedom                 40
                  Error Mean Square                  1.442292
                  Critical Value of Studentized Range 3.79069
                  Minimum Significant Difference       1.1754

          Comparisons significant at the 0.05 level are indicated by ***.

                          Difference
                 Soil       Between     Simultaneous 95%
               Comparison     Means    Confidence Limits

               HoAp - KxBt     2.8667     1.6912   4.0421  ***
               HoAp - HoBt    12.9183    11.7429  14.0938  ***
               HoAp - KxAp    26.5250    25.3496  27.7004  ***
               KxBt - HoAp    -2.8667    -4.0421  -1.6912  ***
               KxBt - HoBt    10.0517     8.8762  11.2271  ***
               KxBt - KxAp    23.6583    22.4829  24.8338  ***
               HoBt - HoAp   -12.9183   -14.0938 -11.7429  ***
               HoBt - KxBt   -10.0517   -11.2271  -8.8762  ***
               HoBt - KxAp    13.6067    12.4312  14.7821  ***
               KxAp - HoAp   -26.5250   -27.7004 -25.3496  ***
               KxAp - KxBt   -23.6583   -24.8338 -22.4829  ***
               KxAp - HoBt   -13.6067   -14.7821 -12.4312  ***

NOTE: This test controls the Type I experimentwise error rate, but it generally has a
higher Type II error rate than REGWQ.
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(continued)

Alpha	0.05
Error Degrees of Freedom	40
Error Mean Square	1.442292
Critical Value of Studentized Range	3.79069
Minimum Significant Difference	1.1754

Means with the same letter are not significantly different.

Tukey Grouping	Mean	N	Soil
A	54.0200	15	HoAp
B	51.1533	15	KxBt
C	41.1017	15	HoBt
D	27.4950	15	KxAp

NOTE: This test controls the Type I experimentwise error rate.

Alpha	0.05
Error Degrees of Freedom	40
Error Mean Square	1.442292
Critical Value of Studentized Range	4.03913
Minimum Significant Difference	1.4003

Comparisons significant at the 0.05 level are indicated by ***.

Trt Comparison	Difference Between Means	Simultaneous 95% Confidence Limits		
CK - 40P	3.2292	1.8289	4.6295	***
CK - 20P	4.0958	2.6955	5.4961	***
CK - 5G	4.8104	3.4101	6.2107	***
CK - 20P+5G	10.7250	9.3247	12.1253	***
40P - CK	-3.2292	-4.6295	-1.8289	***
40P - 20P	0.8667	-0.5336	2.2670	
40P - 5G	1.5813	0.1809	2.9816	***
40P - 20P+5G	7.4958	6.0955	8.8961	***
20P - CK	-4.0958	-5.4961	-2.6955	***
20P - 40P	-0.8667	-2.2670	0.5336	
20P - 5G	0.7146	-0.6857	2.1149	
20P - 20P+5G	6.6292	5.2289	8.0295	***
5G - CK	-4.8104	-6.2107	-3.4101	***
5G - 40P	-1.5813	-2.9816	-0.1809	***
5G - 20P	-0.7146	-2.1149	0.6857	
5G - 20P+5G	5.9146	4.5143	7.3149	***
20P+5G - CK	-10.7250	-12.1253	-9.3247	***
20P+5G - 40P	-7.4958	-8.8961	-6.0955	***
20P+5G - 20P	-6.6292	-8.0295	-5.2289	***
20P+5G - 5G	-5.9146	-7.3149	-4.5143	***

NOTE: This test controls the Type I experimentwise error rate, but it generally has a higher Type II error rate than REGWQ.

Alpha	0.05
Error Degrees of Freedom	40
Error Mean Square	1.442292
Critical Value of Studentized Range	4.03913
Minimum Significant Difference	1.4003

(continued)

Means with the same letter are not significantly different.

Tukey Grouping		Mean	N	Trt
	A	48.0146	12	CK
	B	44.7854	12	40P
C	B	43.9188	12	20P
C		43.2042	12	5G
	D	37.2896	12	20P+5G

Level of Soil	Level of Trt	N	RO Mean	RO Std Dev
HoAp	20P	3	53.8416667	0.83678452
HoAp	20P+5G	3	52.5666667	1.35769412
HoAp	40P	3	55.9500000	0.67268120
HoAp	5G	3	51.4500000	0.84520708
HoAp	CK	3	56.2916667	0.03818813
HoBt	20P	3	44.2000000	1.61612964
HoBt	20P+5G	3	26.2666667	0.34671073
HoBt	40P	3	47.9500000	1.35922772
HoBt	5G	3	39.2583333	0.91731038
HoBt	CK	3	47.8333333	0.82171061
KxAp	20P	3	25.2416667	0.64823478
KxAp	20P+5G	3	18.7750000	1.23794184
KxAp	40P	3	22.1500000	1.58646620
KxAp	5G	3	33.8916667	1.65006313
KxAp	CK	3	37.4166667	2.30547356
KxBt	20P	3	52.3916667	0.98499154
KxBt	20P+5G	3	51.5500000	1.80052076
KxBt	40P	3	53.0916667	0.23228933
KxBt	5G	3	48.2166667	1.21971650
KxBt	CK	3	50.5166667	0.88116873

Least Squares Means

Soil	RO LSMEAN	LSMEAN Number
HoAp	54.0200000	1
HoBt	41.1016667	2
KxAp	27.4950000	3
KxBt	51.1533333	4

i/j	1	2	3	4
1		<.0001	<.0001	<.0001
2	<.0001		<.0001	<.0001
3	<.0001	<.0001		<.0001
4	<.0001	<.0001	<.0001	

Trt	RO LSMEAN	LSMEAN Number
20P	43.9187500	1
20P+5G	37.2895833	2
40P	44.7854167	3
5G	43.2041667	4
CK	48.0145833	5

Least Squares Means for effect Trt
Pr > |t| for H0: LSMean(i)=LSMean(j)

i/j	1	2	3	4	5
1		<.0001	0.0847	0.1528	<.0001
2	<.0001		<.0001	<.0001	<.0001
3	0.0847	<.0001		0.0025	<.0001
4	0.1528	<.0001	0.0025		<.0001
5	<.0001	<.0001	<.0001	<.0001	

Appendix 5-3. SAS output for the cumulative sediment loss (SL) using the SAS system (Release 9.1.3. in 2005) for chapter 2.

```
                              MODOT Study
                          The GLM Procedure

                       Class Level Information
                 Class        Levels    Values
                 Soil              4    HoAp HoBt KxAp KxBt
                 Trt               5    20P 20P+5G 40P 5G CK

                   Number of Observations Read        60
                   Number of Observations Used        60

Dependent Variable: Sed
                                   Sum of
      Source                DF        Squares     Mean Square    F Value    Pr > F
      Model                 19    29918474.14      1574656.53     101.21    <.0001
      Error                 40      622358.00        15558.95
      Corrected Total        59    30540832.14

                R-Square     Coeff Var      Root MSE     Sed Mean
                0.979622      4.904226      124.7355     2543.429

      Source                DF      Type I SS     Mean Square    F Value    Pr > F
      Soil                   3     5540126.11      1846708.70     118.69    <.0001
      Trt                    4    10761135.96      2690283.99     172.91    <.0001
      Soil*Trt              12    13617212.06      1134767.67      72.93    <.0001

      Source                DF    Type III SS     Mean Square    F Value    Pr > F
      Soil                   3     5540126.11      1846708.70     118.69    <.0001
      Trt                    4    10761135.96      2690283.99     172.91    <.0001
      Soil*Trt              12    13617212.06      1134767.67      72.93    <.0001

                  Tukey's Studentized Range (HSD) Test for Sed

          NOTE: This test controls the Type I experimentwise error rate.

                  Alpha                                 0.05
                  Error Degrees of Freedom                40
                  Error Mean Square                 15558.95
                  Critical Value of Studentized Range  3.79069
                  Minimum Significant Difference       122.09

         Comparisons significant at the 0.05 level are indicated by ***.

                           Difference
                  Soil        Between    Simultaneous 95%
               Comparison       Means    Confidence Limits

               KxBt - HoAp      513.78     391.70   635.87  ***
               KxBt - KxAp      696.47     574.38   818.55  ***
               KxBt - HoBt      783.83     661.75   905.92  ***
               HoAp - KxBt     -513.78    -635.87  -391.70  ***
               HoAp - KxAp      182.68      60.60   304.77  ***
               HoAp - HoBt      270.05     147.96   392.14  ***
               KxAp - KxBt     -696.47    -818.55  -574.38  ***
               KxAp - HoAp     -182.68    -304.77   -60.60  ***
               KxAp - HoBt       87.37     -34.72   209.45
               HoBt - KxBt     -783.83    -905.92  -661.75  ***
               HoBt - HoAp     -270.05    -392.14  -147.96  ***
               HoBt - KxAp      -87.37    -209.45    34.72
```

(continued)

Tukey's Studentized Range (HSD) Test for Sed

NOTE: This test controls the Type I experimentwise error rate, but it generally has a higher Type II error rate than REGWQ.

Alpha	0.05
Error Degrees of Freedom	40
Error Mean Square	15558.95
Critical Value of Studentized Range	3.79069
Minimum Significant Difference	122.09

Means with the same letter are not significantly different.

Tukey Grouping	Mean	N	Soil
A	3041.95	15	KxBt
B	2528.17	15	HoAp
C	2345.48	15	KxAp
C	2258.12	15	HoBt

NOTE: This test controls the Type I experimentwise error rate.

Alpha	0.05
Error Degrees of Freedom	40
Error Mean Square	15558.95
Critical Value of Studentized Range	4.03913
Minimum Significant Difference	145.44

Comparisons significant at the 0.05 level are indicated by ***.

Trt Comparison	Difference Between Means	Simultaneous 95% Confidence Limits		
CK - 5G	498.65	353.20	644.09	***
CK - 20P	523.27	377.83	668.71	***
CK - 40P	1026.23	880.79	1171.67	***
CK - 20P+5G	1192.00	1046.56	1337.44	***
5G - CK	-498.65	-644.09	-353.20	***
5G - 20P	24.63	-120.82	170.07	
5G - 40P	527.58	382.14	673.02	***
5G - 20P+5G	693.35	547.91	838.80	***
20P - CK	-523.27	-668.71	-377.83	***
20P - 5G	-24.63	-170.07	120.82	
20P - 40P	502.96	357.52	648.40	***
20P - 20P+5G	668.73	523.29	814.17	***
40P - CK	-1026.23	-1171.67	-880.79	***
40P - 5G	-527.58	-673.02	-382.14	***
40P - 20P	-502.96	-648.40	-357.52	***
40P - 20P+5G	165.77	20.33	311.21	***
20P+5G - CK	-1192.00	-1337.44	-1046.56	***
20P+5G - 5G	-693.35	-838.80	-547.91	***
20P+5G - 20P	-668.73	-814.17	-523.29	***
20P+5G - 40P	-165.77	-311.21	-20.33	***

NOTE: This test controls the Type I experimentwise error rate, but it generally has a higher Type II error rate than REGWQ.

Alpha	0.05
Error Degrees of Freedom	40
Error Mean Square	15558.95
Critical Value of Studentized Range	4.03913
Minimum Significant Difference	145.44

(continued)

Means with the same letter are not significantly different.

Tukey Grouping	Mean	N	Trt
A	3191.46	12	CK
B	2692.81	12	5G
B	2668.19	12	20P
C	2165.23	12	40P
D	1999.46	12	20P+5G

Level of Soil	Level of Trt	N	Sed Mean	Sed Std Dev
HoAp	20P	3	2484.25000	182.612808
HoAp	20P+5G	3	2753.16667	135.571091
HoAp	40P	3	1722.66667	61.875042
HoAp	5G	3	2794.83333	112.528978
HoAp	CK	3	2885.91667	122.130139
HoBt	20P	3	2439.75000	172.851815
HoBt	20P+5G	3	933.16667	90.909410
HoBt	40P	3	1137.58333	24.305778
HoBt	5G	3	3283.83333	79.931351
HoBt	CK	3	3496.25000	135.385561
KxAp	20P	3	2335.25000	19.136026
KxAp	20P+5G	3	1802.41667	70.136177
KxAp	40P	3	2578.16667	188.155742
KxAp	5G	3	2002.08333	243.274065
KxAp	CK	3	3009.50000	70.012053
KxBt	20P	3	3413.50000	88.252833
KxBt	20P+5G	3	2509.08333	114.019826
KxBt	40P	3	3222.50000	28.464891
KxBt	5G	3	2690.50000	95.131159
KxBt	CK	3	3374.16667	170.799834

Least Squares Means

Soil	Sed LSMEAN	LSMEAN Number
HoAp	2528.16667	1
HoBt	2258.11667	2
KxAp	2345.48333	3
KxBt	3041.95000	4

i/j	1	2	3	4
1		<.0001	0.0003	<.0001
2	<.0001		0.0622	<.0001
3	0.0003	0.0622		<.0001
4	<.0001	<.0001	<.0001	

Trt	Sed LSMEAN	LSMEAN Number
20P	2668.18750	1
20P+5G	1999.45833	2
40P	2165.22917	3
5G	2692.81250	4
CK	3191.45833	5

i/j	1	2	3	4	5
1		<.0001	<.0001	0.6313	<.0001
2	<.0001		0.0023	<.0001	<.0001
3	<.0001	0.0023		<.0001	<.0001
4	0.6313	<.0001	<.0001		<.0001
5	<.0001	<.0001	<.0001	<.0001	

Appendix 6-1. Data for runoff and sediment loss with no amendment (CK) subjected to a 62-min simulated rainfall with an intensity of 61 mm h^{-1} (2.4 in hr^{-1}) for chapter 3.

Slope	Time	Runoff			Sediment loss		
	min	--------------- mm ---------------			--------------- g m^{-2} ---------------		
		Rep. 1	Rep. 2	Rep. 3	Rep. 1	Rep. 2	Rep. 3
10%	0	0	0	0	0	0	0
	5	0.054	0.136	0.080	10.22	9.00	11.33
	10	1.039	0.973	1.029	62.56	57.22	59.89
	15	1.459	1.388	1.464	86.11	83.44	79.44
	20	1.597	1.500	1.457	88.89	87.67	85.78
	25	1.580	1.518	1.471	76.33	78.56	73.00
	30	1.679	1.603	1.511	68.78	64.22	68.67
	35	1.637	1.613	1.566	70.67	67.33	64.89
	40	1.718	1.627	1.585	66.56	63.89	58.67
	45	1.648	1.599	1.604	62.44	54.33	53.56
	50	1.723	1.606	1.607	62.11	58.67	58.67
	55	1.668	1.622	1.608	65.78	57.00	53.89
	60	1.674	1.663	1.657	58.33	56.78	52.78
SUM		22.533	22.516	22.504	1191.44	1172.67	1099.00
20%	0	0	0	0	0	0	0
	5	0.067	0.136	0.139	20.86	21.76	17.83
	10	0.906	1.086	1.091	79.39	85.67	80.18
	15	1.278	1.403	1.410	101.04	106.31	99.47
	20	1.396	1.517	1.518	103.39	105.07	104.18
	25	1.554	1.500	1.504	99.24	96.10	91.95
	30	1.525	1.591	1.589	92.96	88.70	90.61
	35	1.552	1.549	1.550	86.46	90.16	89.15
	40	1.535	1.594	1.591	83.66	81.64	85.11
	45	1.604	1.610	1.610	80.52	79.84	80.29
	50	1.577	1.606	1.613	83.21	86.91	79.39
	55	1.517	1.549	1.548	80.18	80.29	81.75
	60	1.614	1.608	1.606	84.44	79.84	81.75
SUM		18.770	19.405	19.222	1388.11	1457.11	1450.33
40%	0	0	0	0	0	0	0
	5	0.309	0.282	0.261	65.32	65.32	54.62
	10	1.062	1.095	0.976	118.31	117.15	112.74
	15	1.259	1.267	1.325	140.75	149.58	153.07
	20	1.392	1.384	1.428	140.63	148.07	152.02
	25	1.452	1.520	1.483	141.44	139.58	144.23
	30	1.485	1.518	1.551	139.35	137.96	142.26
	35	1.474	1.612	1.525	142.37	137.61	146.79
	40	1.496	1.584	1.540	134.00	133.89	140.98
	45	1.500	1.595	1.522	131.68	132.03	135.75
	50	1.503	1.614	1.558	133.66	126.68	139.82
	55	1.530	1.671	1.595	125.99	129.24	134.93
	60	1.536	1.733	1.602	124.36	123.66	125.52
SUM		20.790	20.191	20.759	1142.11	1066.00	1145.67

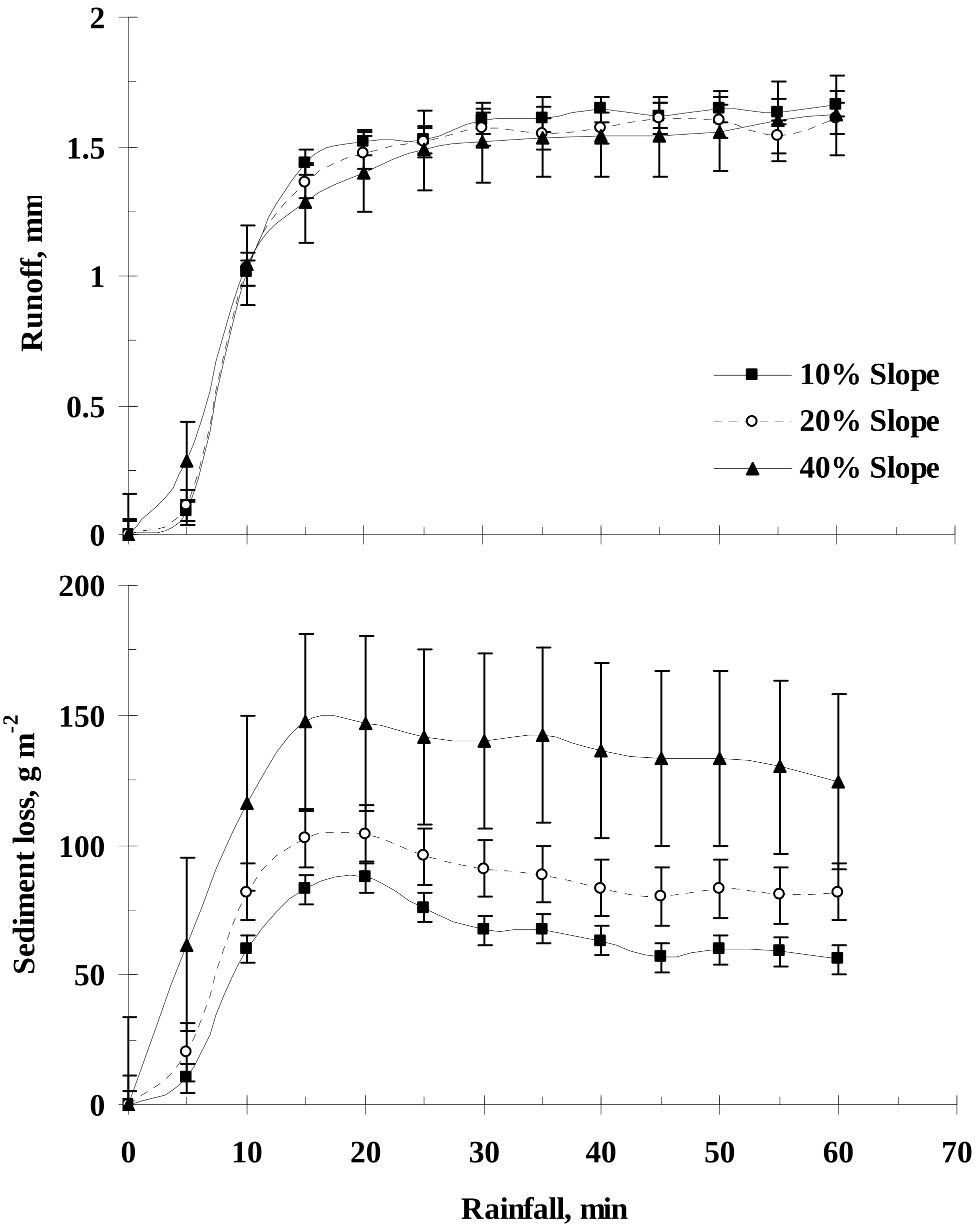
Appendix 6-2. Data for runoff and sediment loss with 20-kg ha^{-1} (18-lb ac^{-1}) PAM subjected to a 62-min rainfall with a 61-mm h^{-1} (2.4-in hr^{-1}) intensity for chapter 3.

Slope	Time	Runoff			Sediment loss		
	min	---------------- mm ----------------			---------------- g m^{-2} ----------------		
		Rep. 1	Rep. 2	Rep. 3	Rep. 1	Rep. 2	Rep. 3
10%	0	0	0	0	0	0	0
	5	0.097	0.141	0.057	11.78	12.11	6.11
	10	1.444	1.477	1.533	36.11	33.89	32.56
	15	1.612	1.701	1.618	25.78	21.33	32.67
	20	1.665	1.712	1.659	25.33	23.56	23.78
	25	1.648	1.683	1.705	19.78	19.33	16.44
	30	1.736	1.700	1.731	22.00	17.67	12.33
	35	1.650	1.683	1.700	20.44	22.44	16.00
	40	1.634	1.671	1.680	15.44	12.67	17.00
	45	1.665	1.702	1.706	14.11	11.00	11.11
	50	1.662	1.614	1.706	14.22	7.22	9.00
	55	1.617	1.625	1.736	12.89	7.22	7.33
	60	1.673	1.648	1.700	14.11	11.78	10.67
SUM		22.533	22.516	22.504	1191.44	1172.67	1099.00
20%	0	0	0	0	0	0	0
	5	0.140	0.170	0.177	27.25	27.47	25.57
	10	1.499	1.577	1.538	72.22	68.07	76.70
	15	1.689	1.681	1.660	58.87	55.85	62.80
	20	1.672	1.722	1.674	55.17	59.66	57.08
	25	1.739	1.760	1.704	54.16	59.99	52.59
	30	1.805	1.772	1.752	56.07	60.22	54.50
	35	1.811	1.815	1.754	50.46	54.61	46.20
	40	1.766	1.803	1.767	48.22	46.43	44.41
	45	1.778	1.801	1.762	51.36	43.62	45.53
	50	1.680	1.796	1.761	43.40	41.60	42.95
	55	1.653	1.756	1.753	40.26	39.47	42.39
	60	1.705	1.736	1.719	37.57	45.08	45.19
SUM		18.770	19.405	19.222	1388.11	1457.11	1450.33
40%	0	0	0	0	0	0	0
	5	0.393	0.375	0.450	61.48	68.46	70.43
	10	1.529	1.627	1.637	125.40	118.08	115.18
	15	1.662	1.728	1.680	147.49	143.07	145.74
	20	1.687	1.684	1.665	130.05	136.10	136.33
	25	1.729	1.714	1.694	116.22	116.34	113.55
	30	1.682	1.711	1.691	106.69	104.48	100.53
	35	1.689	1.689	1.721	98.21	101.69	94.95
	40	1.650	1.643	1.682	100.53	98.91	97.98
	45	1.577	1.607	1.691	98.44	100.07	92.05
	50	1.579	1.636	1.701	93.79	89.61	85.89
	55	1.520	1.531	1.601	89.38	95.65	81.70
	60	1.512	1.501	1.635	82.87	87.63	83.22
SUM		20.790	20.191	20.759	1142.11	1066.00	1145.67

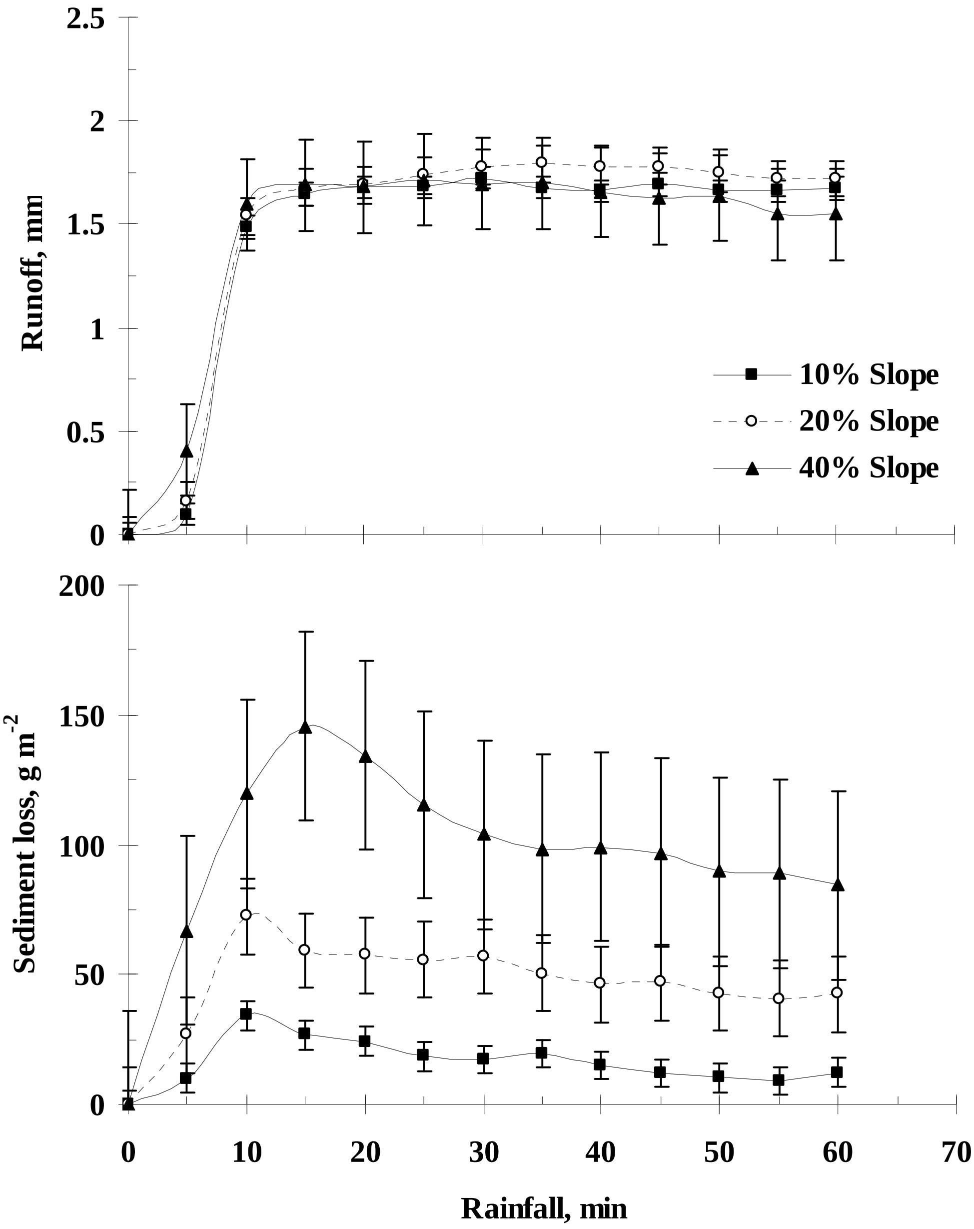
Appendix 6-3. Data for runoff and sediment loss with 40-kg ha^{-1} (36-lb ac^{-1}) PAM subjected to a 62-min rainfall with a 61-mm h^{-1} (2.4-in hr^{-1}) intensity for chapter 3.

Slope	Time	Runoff			Sediment loss		
	min	---------- mm ----------			---------- g m^{-2} ----------		
		Rep. 1	Rep. 2	Rep. 3	Rep. 1	Rep. 2	Rep. 3
10%	0	0	0	0	0	0	0
	5	0.286	0.357	0.255	17.33	19.56	12.56
	10	1.791	1.823	1.762	42.00	37.56	33.56
	15	1.871	1.858	1.808	31.11	26.44	26.00
	20	1.862	1.874	1.835	26.33	20.33	22.00
	25	1.865	1.870	1.866	19.22	16.00	13.00
	30	1.831	1.876	1.908	21.67	15.56	15.89
	35	1.860	1.890	1.927	23.56	19.56	16.44
	40	1.939	1.873	1.907	21.67	15.44	16.11
	45	1.970	1.913	1.954	21.00	16.44	17.56
	50	1.957	1.924	1.915	14.56	10.11	11.67
	55	1.866	1.935	1.935	13.33	6.89	11.00
	60	1.894	1.899	1.925	13.56	10.67	10.78
SUM		22.533	22.516	22.504	1191.44	1172.67	1099.00
20%	0	0	0	0	0	0	0
	5	0.362	0.429	0.343	39.14	36.11	35.66
	10	1.864	1.895	1.807	76.48	69.08	65.83
	15	1.831	1.893	1.804	59.66	54.72	54.16
	20	1.826	1.905	1.843	54.16	45.53	49.23
	25	1.780	1.905	1.853	43.17	39.14	32.74
	30	1.895	1.894	1.861	43.40	37.12	35.55
	35	1.848	1.889	1.833	39.92	34.31	32.63
	40	1.806	1.872	1.822	34.54	31.85	34.54
	45	1.859	1.895	1.792	35.21	30.95	29.94
	50	1.798	1.910	1.857	28.03	24.67	25.12
	55	1.850	1.889	1.828	28.37	22.99	24.67
	60	1.765	1.854	1.799	25.57	19.74	17.83
SUM		18.770	19.405	19.222	1388.11	1457.11	1450.33
40%	0	0	0	0	0	0	0
	5	0.268	0.268	0.327	68.22	72.76	66.94
	10	1.783	1.783	1.846	91.00	94.49	95.88
	15	1.930	1.926	1.970	89.26	101.35	95.65
	20	1.982	1.947	1.979	86.93	88.68	78.33
	25	1.941	1.929	1.888	66.48	71.01	72.99
	30	1.894	1.957	1.933	58.81	57.41	58.00
	35	1.869	1.865	1.970	50.32	48.46	45.68
	40	1.923	1.847	1.923	50.21	49.63	43.23
	45	1.924	1.848	1.912	42.89	44.63	44.51
	50	1.839	1.897	1.927	30.10	40.10	38.47
	55	1.954	1.909	1.956	34.05	41.72	34.52
	60	1.933	1.883	1.954	30.80	28.24	29.87
SUM		20.790	20.191	20.759	1142.11	1066.00	1145.67

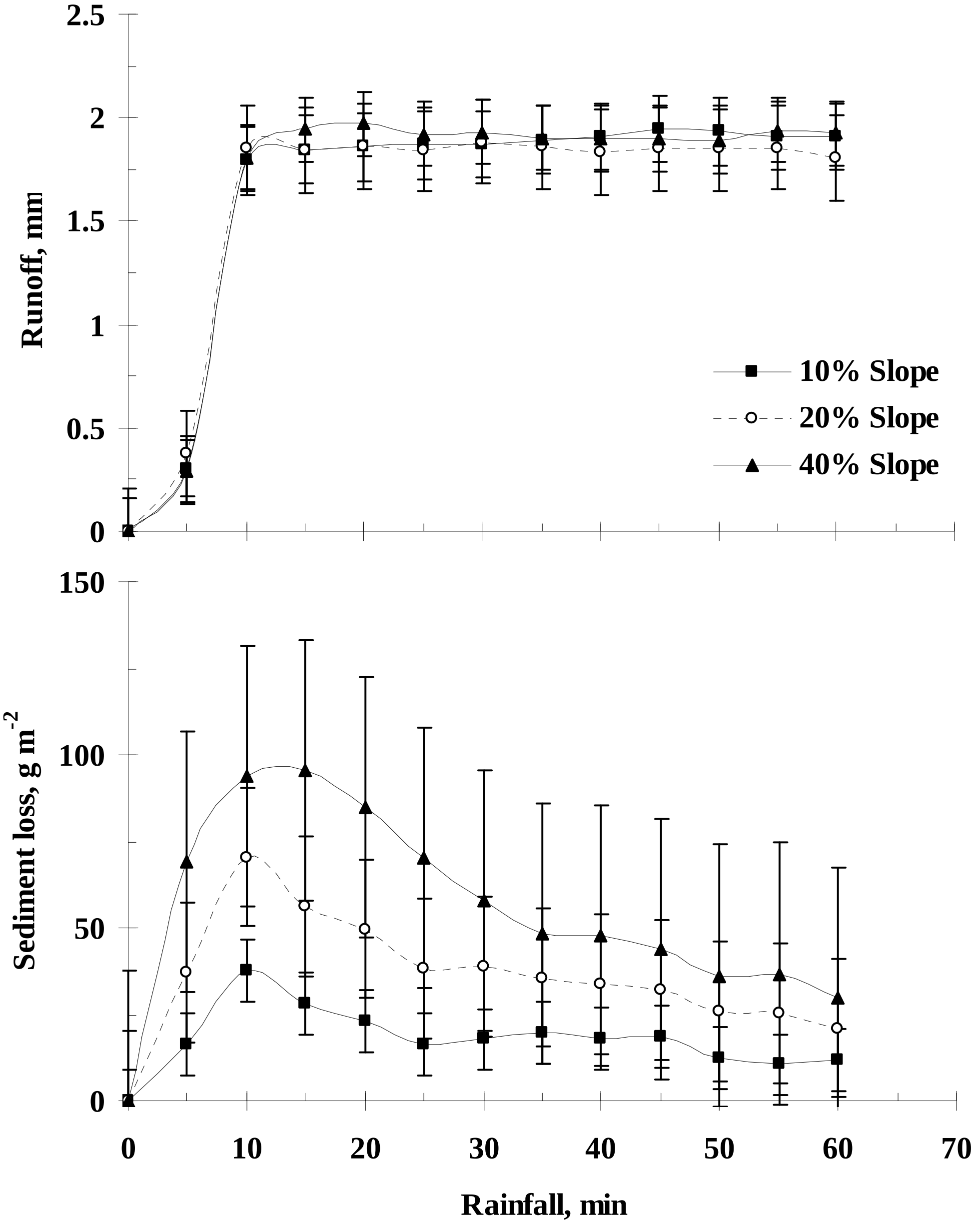
Appendix 7-1. Figures for runoff and sediment loss with no amendment (CK) subjected to selected slopes and a 62-min simulated rainfall with an intensity of 61 mm h^{-1} (2.4 in hr^{-1}) for chapter 3.



Appendix 7-2. Figures for runoff and sediment loss with 20-kg ha^{-1} (18-lb ac^{-1}) PAM amendment (20P) subjected to selected slopes and a 62-min simulated rainfall with an intensity of 61 mm h^{-1} (2.4 in hr^{-1}) for chapter 3.



Appendix 7-3. Figures for runoff and sediment loss with 40-kg ha^{-1} (36-lb ac^{-1}) PAM amendment (40P) subjected to selected slopes and a 62-min simulated rainfall with an intensity of 61 mm h^{-1} (2.4 in hr^{-1}) for chapter 3.



Appendix 8-1. SAS output for the time to initial runoff (TRO) using the SAS system (Release 9.1.3. in 2005) for chapter 3.

Slope Study
The GLM Procedure
Class Level Information

Class	Levels	Values
Slope	3	10 2.5 5
Trt	3	20P 40P CK

Number of Observations Read	27
Number of Observations Used	27

Dependent Variable: ROt

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	8	32.34902963	4.04362870	85.87	<.0001
Error	18	0.84766667	0.04709259		
Corrected Total	26	33.19669630			

R-Square	Coeff Var	Root MSE	ROt Mean
0.974465	2.351213	0.217008	9.229630

Source	DF	Type I SS	Mean Square	F Value	Pr > F
Slope	2	19.73031852	9.86515926	209.48	<.0001
Trt	2	4.83022963	2.41511481	51.28	<.0001
Slope*Trt	4	7.78848148	1.94712037	41.35	<.0001

Source	DF	Type III SS	Mean Square	F Value	Pr > F
Slope	2	19.73031852	9.86515926	209.48	<.0001
Trt	2	4.83022963	2.41511481	51.28	<.0001
Slope*Trt	4	7.78848148	1.94712037	41.35	<.0001

Tukey's Studentized Range (HSD) Test for ROt

NOTE: This test controls the Type I experimentwise error rate.

Alpha	0.05
Error Degrees of Freedom	18
Error Mean Square	0.047093
Critical Value of Studentized Range	3.60930
Minimum Significant Difference	0.2611

Comparisons significant at the 0.05 level are indicated by ***.

Slope Comparison	Difference Between Means	Simultaneous 95% Confidence Limits		
10 - 5	0.6878	0.4267	0.9489	***
10 - 2.5	2.0567	1.7956	2.3177	***
5 - 10	-0.6878	-0.9489	-0.4267	***
5 - 2.5	1.3689	1.1078	1.6300	***
2.5 - 10	-2.0567	-2.3177	-1.7956	***
2.5 - 5	-1.3689	-1.6300	-1.1078	***

NOTE: This test controls the Type I experimentwise error rate, but it generally has a higher Type II error rate than REGWQ.

(continued)

Alpha	0.05
Error Degrees of Freedom	18
Error Mean Square	0.047093
Critical Value of Studentized Range	3.60930
Minimum Significant Difference	0.2611

Means with the same letter are not significantly different.

Tukey Grouping	Mean	N	Slope
A	10.1444	9	10
B	9.4567	9	5
C	8.0878	9	2.5

NOTE: This test controls the Type I experimentwise error rate.

Alpha	0.05
Error Degrees of Freedom	18
Error Mean Square	0.047093
Critical Value of Studentized Range	3.60930
Minimum Significant Difference	0.2611

Comparisons significant at the 0.05 level are indicated by ***.

Trt Comparison	Difference Between Means	Simultaneous 95% Confidence Limits		
40P - 20P	0.1956	-0.0655	0.4566	
40P - CK	0.9789	0.7178	1.2400	***
20P - 40P	-0.1956	-0.4566	0.0655	
20P - CK	0.7833	0.5223	1.0444	***
CK - 40P	-0.9789	-1.2400	-0.7178	***
CK - 20P	-0.7833	-1.0444	-0.5223	***

NOTE: This test controls the Type I experimentwise error rate, but it generally has a higher Type
II error rate than REGWQ.

Alpha	0.05
Error Degrees of Freedom	18
Error Mean Square	0.047093
Critical Value of Studentized Range	3.60930
Minimum Significant Difference	0.2611

Means with the same letter are not significantly different.

Tukey Grouping	Mean	N	Trt
A	9.6211	9	40P
A	9.4256	9	20P
B	8.6422	9	CK

Level of Slope	Level of Trt	N	-------------ROt------------- Mean	Std Dev
10	20P	3	10.1000000	0.26457513
10	40P	3	9.8333333	0.15275252
10	CK	3	10.5000000	0.10000000
2.5	20P	3	8.3333333	0.19857828
2.5	40P	3	9.1900000	0.19697716
2.5	CK	3	6.7400000	0.23643181
5	20P	3	9.8433333	0.15275252
5	40P	3	9.8400000	0.34597688
5	CK	3	8.6866667	0.20816660

(continued)

Least Squares Means

Slope	ROt LSMEAN	LSMEAN Number
10	10.1444444	1
2.5	8.0877778	2
5	9.4566667	3

Least Squares Means for effect Slope
Pr > |t| for H0: LSMean(i)=LSMean(j)

Dependent Variable: ROt

i/j	1	2	3
1		<.0001	<.0001
2	<.0001		<.0001
3	<.0001	<.0001	

Slope	ROt LSMEAN	95% Confidence Limits	
10	10.144444	9.992472	10.296417
2.5	8.087778	7.935805	8.239750
5	9.456667	9.304694	9.608639

Least Squares Means for Effect Slope

i	j	Difference Between Means	95% Confidence Limits for LSMean(i)-LSMean(j)	
1	2	2.056667	1.841745	2.271588
1	3	0.687778	0.472856	0.902699
2	3	-1.368889	-1.583810	-1.153967

NOTE: To ensure overall protection level, only probabilities associated with pre-planned comparisons should be used.

Trt	ROt LSMEAN	LSMEAN Number
20P	9.42555556	1
40P	9.62111111	2
CK	8.64222222	3

Least Squares Means for effect Trt
Pr > |t| for H0: LSMean(i)=LSMean(j)

Dependent Variable: ROt

i/j	1	2	3
1		0.0720	<.0001
2	0.0720		<.0001
3	<.0001	<.0001	

Trt	ROt LSMEAN	95% Confidence Limits	
20P	9.425556	9.273583	9.577528
40P	9.621111	9.469139	9.773084
CK	8.642222	8.490250	8.794195

(continued)

Least Squares Means for Effect Trt

i	j	Difference Between Means	95% Confidence Limits for LSMean(i)-LSMean(j)	
1	2	-0.195556	-0.410477	0.019366
1	3	0.783333	0.568412	0.998255
2	3	0.978889	0.763967	1.193810

NOTE: To ensure overall protection level, only probabilities associated with pre-planned comparisons should be used.

Slope	Trt	ROt LSMEAN	LSMEAN Number
10	20P	10.1000000	1
10	40P	9.8333333	2
10	CK	10.5000000	3
2.5	20P	8.3333333	4
2.5	40P	9.1900000	5
2.5	CK	6.7400000	6
5	20P	9.8433333	7
5	40P	9.8400000	8
5	CK	8.6866667	9

Least Squares Means for effect Slope*Trt
Pr > |t| for H0: LSMean(i)=LSMean(j)

Dependent Variable: ROt

i/j	1	2	3	4	5	6	7	8	9
1		0.1497	0.0366	<.0001	<.0001	<.0001	0.1647	0.1595	<.0001
2	0.1497		0.0014	<.0001	0.0019	<.0001	0.9556	0.9704	<.0001
3	0.0366	0.0014		<.0001	<.0001	<.0001	0.0016	0.0016	<.0001
4	<.0001	<.0001	<.0001		0.0001	<.0001	<.0001	<.0001	0.0615
5	<.0001	0.0019	<.0001	0.0001		<.0001	0.0017	0.0018	0.0108
6	<.0001	<.0001	<.0001	<.0001	<.0001		<.0001	<.0001	<.0001
7	0.1647	0.9556	0.0016	<.0001	0.0017	<.0001		0.9852	<.0001
8	0.1595	0.9704	0.0016	<.0001	0.0018	<.0001	0.9852		<.0001
9	<.0001	<.0001	<.0001	0.0615	0.0108	<.0001	<.0001	<.0001	

Slope	Trt	ROt LSMEAN	95% Confidence Limits	
10	20P	10.100000	9.836776	10.363224
10	40P	9.833333	9.570109	10.096557
10	CK	10.500000	10.236776	10.763224
2.5	20P	8.333333	8.070109	8.596557
2.5	40P	9.190000	8.926776	9.453224
2.5	CK	6.740000	6.476776	7.003224
5	20P	9.843333	9.580109	10.106557
5	40P	9.840000	9.576776	10.103224
5	CK	8.686667	8.423443	8.949891

(continued)

Least Squares Means for Effect Slope*Trt

i	j	Difference Between Means	95% Confidence Limits for LSMean(i)-LSMean(j)	
1	2	0.266667	-0.105588	0.638922
1	3	-0.400000	-0.772255	-0.027745
1	4	1.766667	1.394412	2.138922
1	5	0.910000	0.537745	1.282255
1	6	3.360000	2.987745	3.732255
1	7	0.256667	-0.115588	0.628922
1	8	0.260000	-0.112255	0.632255
1	9	1.413333	1.041078	1.785588
2	3	-0.666667	-1.038922	-0.294412
2	4	1.500000	1.127745	1.872255
2	5	0.643333	0.271078	1.015588
2	6	3.093333	2.721078	3.465588
2	7	-0.010000	-0.382255	0.362255
2	8	-0.006667	-0.378922	0.365588
2	9	1.146667	0.774412	1.518922
3	4	2.166667	1.794412	2.538922
3	5	1.310000	0.937745	1.682255
3	6	3.760000	3.387745	4.132255
3	7	0.656667	0.284412	1.028922
3	8	0.660000	0.287745	1.032255
3	9	1.813333	1.441078	2.185588
4	5	-0.856667	-1.228922	-0.484412
4	6	1.593333	1.221078	1.965588
4	7	-1.510000	-1.882255	-1.137745
4	8	-1.506667	-1.878922	-1.134412
4	9	-0.353333	-0.725588	0.018922
5	6	2.450000	2.077745	2.822255
5	7	-0.653333	-1.025588	-0.281078
5	8	-0.650000	-1.022255	-0.277745
5	9	0.503333	0.131078	0.875588
6	7	-3.103333	-3.475588	-2.731078
6	8	-3.100000	-3.472255	-2.727745
6	9	-1.946667	-2.318922	-1.574412
7	8	0.003333	-0.368922	0.375588
7	9	1.156667	0.784412	1.528922
8	9	1.153333	0.781078	1.525588

NOTE: To ensure overall protection level, only probabilities associated with pre-planned comparisons should be used.

(continued)

```
                        Plot of ROt*TrtSlope.  Symbol used is '.'.
                        Plot of p*TrtSlope.    Symbol used is 'P'.

    ROt |
        |
     11 +
        |
        |
        |                                                    .
        |                                                    .
        |  .
        |  .                                         .
     10 +                   .       .
        |  .                .       .                .
        |                   .       .
        |                                            .
        |
        |                                  .
        |                                  P
      9 +                                  .
        |                                                                    .
        |                                                                    P
        |                                                                    .
        |         .
        |         P
        |         .
      8 +
        |
        |
        |
        |
        |
        |
      7 +                                                            .
        |
        |                                                            .
        |
        |                                                            .
        |
        |
      6 +
        |
        ---+---------+---------+---------+---------+---------+---------+---------+---------+--------
        20P_10   20P_2.5   20P_5    40P_10   40P_2.5   40P_5     CK_10   CK_2.5    CK_5

                                        TrtSlope

NOTE: 28 obs hidden.
```

(continued)

```
                    Plot of r*TrtSlope.  Symbol is value of Rep.

   r |
     |
 0.4 +
     |
     |                                           2
     |
     |
 0.3 +
     |
     |
     |                                                                    3
     |                                                            3
 0.2 + 2
     |
     |         2        2       3        1
     |
     |
 0.1 + 3                                                  2
     |
     |         1                         2
     |                                                            2
     |
 0.0 +--------------------------------------------------------------1------------------
     |                                           3
     |                  1       1
     |                                                                    2
     |
-0.1 +                                                    3
     |
     |                  3       2
     |                                                                    1
     |
-0.2 +
     |         3                         3
     |                                                            1
     |
     |
-0.3 + 1
     |                                           1
     |
     |
     |
-0.4 +
     |
    ---+---------+---------+---------+---------+---------+---------+---------+--------
    20P_10   20P_2.5   20P_5    40P_10   40P_2.5    40P_5    CK_10   CK_2.5     CK_5

                                    TrtSlope
```

(continued)

```
                    The UNIVARIATE Procedure
                         Variable:  r

                            Moments

N                      27    Sum Weights               27
Mean                    0    Sum Observations           0
Std Deviation      0.1805618    Variance          0.03260256
Skewness          -0.0943387    Kurtosis          -0.7830501
Uncorrected SS     0.84766667    Corrected SS      0.84766667
Coeff Variation            .    Std Error Mean    0.03474913

                  Basic Statistical Measures

        Location                    Variability

    Mean     0.00000     Std Deviation           0.18056
    Median   0.00000     Variance                0.03260
    Mode    -0.13333     Range                   0.69000
                         Interquartile Range     0.29333

                 Tests for Location: Mu0=0

      Test           -Statistic-    -----p Value------

      Student's t    t         0    Pr > |t|    1.0000
      Sign           M       0.5    Pr >= |M|   1.0000
      Signed Rank    S       1.5    Pr >= |S|   0.9721

                   Tests for Normality

   Test                  --Statistic---    -----p Value------

   Shapiro-Wilk          W     0.975503    Pr < W      0.7499
   Kolmogorov-Smirnov    D     0.103507    Pr > D     >0.1500
   Cramer-von Mises      W-Sq   0.03549    Pr > W-Sq  >0.2500
   Anderson-Darling      A-Sq  0.242422    Pr > A-Sq  >0.2500

                  Quantiles (Definition 5)

                  Quantile      Estimate

                  100% Max      0.360000
                  99%           0.360000
                  95%           0.233333
                  90%           0.220000
                  75% Q3        0.160000
                  50% Median    0.000000
                  25% Q1       -0.133333
                  10%          -0.250000
                  5%           -0.300000
                  1%           -0.330000
                  0% Min       -0.330000

                   Extreme Observations

          ------Lowest------       ------Highest-----

             Value      Obs           Value      Obs

          -0.330000      22        0.166667       6
          -0.300000       1        0.200000       2
          -0.250000      16        0.220000      18
          -0.223333      12        0.233333      27
          -0.220000      15        0.360000      23
```

(continued)

```
                   Stem Leaf                     #             Boxplot
                      3 6                        1                |
                      2 023                      3                |
                      1 006677                   6             +-----+
                      0 0367                     4             *--+--*
                     -0 7333                     4             |     |
                     -1 7330                     4             +-----+
                     -2 522                      3                |
                     -3 30                       2                |
                        ----+----+----+----+

                    Multiply Stem.Leaf by 10**-1


                              Normal Probability Plot
                 0.35+                                              +++*++
                     |                                         *+*++*
                     |                                   *****+*+
                     |                              ****++
                     |                          *****
                     |                     +++**+
                     |                 *++*+**
                -0.35+             ++*+++
                      +----+----+----+----+----+----+----+----+----+----+
                          -2        -1         0        +1        +2
```

Obs	Rep	Slope	Trt	ROt	p	r	student	l95m	u95m
1	1	10	20P	9.80	10.1000	-0.30000	-1.69313	9.8368	10.3632
2	2	10	20P	10.30	10.1000	0.20000	1.12875	9.8368	10.3632
3	3	10	20P	10.20	10.1000	0.10000	0.56438	9.8368	10.3632
4	1	10	40P	9.80	9.8333	-0.03333	-0.18813	9.5701	10.0966
5	2	10	40P	9.70	9.8333	-0.13333	-0.75250	9.5701	10.0966
6	3	10	40P	10.00	9.8333	0.16667	0.94063	9.5701	10.0966
7	1	10	CK	10.50	10.5000	0.00000	0.00000	10.2368	10.7632
8	2	10	CK	10.60	10.5000	0.10000	0.56438	10.2368	10.7632
9	3	10	CK	10.40	10.5000	-0.10000	-0.56438	10.2368	10.7632
10	1	2.5	20P	8.40	8.3333	0.06667	0.37625	8.0701	8.5966
11	2	2.5	20P	8.49	8.3333	0.15667	0.88419	8.0701	8.5966
12	3	2.5	20P	8.11	8.3333	-0.22333	-1.26044	8.0701	8.5966
13	1	2.5	40P	9.35	9.1900	0.16000	0.90300	8.9268	9.4532
14	2	2.5	40P	9.25	9.1900	0.06000	0.33863	8.9268	9.4532
15	3	2.5	40P	8.97	9.1900	-0.22000	-1.24163	8.9268	9.4532
16	1	2.5	CK	6.49	6.7400	-0.25000	-1.41094	6.4768	7.0032
17	2	2.5	CK	6.77	6.7400	0.03000	0.16931	6.4768	7.0032
18	3	2.5	CK	6.96	6.7400	0.22000	1.24163	6.4768	7.0032
19	1	5	20P	9.81	9.8433	-0.03333	-0.18813	9.5801	10.1066
20	2	5	20P	10.01	9.8433	0.16667	0.94063	9.5801	10.1066
21	3	5	20P	9.71	9.8433	-0.13333	-0.75250	9.5801	10.1066
22	1	5	40P	9.51	9.8400	-0.33000	-1.86244	9.5768	10.1032
23	2	5	40P	10.20	9.8400	0.36000	2.03176	9.5768	10.1032
24	3	5	40P	9.81	9.8400	-0.03000	-0.16931	9.5768	10.1032
25	1	5	CK	8.52	8.6867	-0.16667	-0.94063	8.4234	8.9499
26	2	5	CK	8.62	8.6867	-0.06667	-0.37625	8.4234	8.9499
27	3	5	CK	8.92	8.6867	0.23333	1.31688	8.4234	8.9499

Appendix 8-2. SAS output for the cumulative runoff (RO) using the SAS system (Release 9.1.3. in 2005) for chapter 3.

```
                          Slope Study
                       The GLM Procedure
                    Class Level Information

              Class       Levels    Values

              Slope            3    10 2.5 5
              Trt              3    20P 40P CK

             Number of Observations Read        27
             Number of Observations Used        27
```

Dependent Variable: ROc

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	8	549.6849533	68.7106192	99.20	<.0001
Error	18	12.4680353	0.6926686		
Corrected Total	26	562.1529887			

R-Square	Coeff Var	Root MSE	ROc Mean
0.977821	1.773565	0.832267	46.92622

Source	DF	Type I SS	Mean Square	F Value	Pr > F
Slope	2	0.1001162	0.0500581	0.07	0.9305
Trt	2	536.7786180	268.3893090	387.47	<.0001
Slope*Trt	4	12.8062191	3.2015548	4.62	0.0096

Source	DF	Type III SS	Mean Square	F Value	Pr > F
Slope	2	0.1001162	0.0500581	0.07	0.9305
Trt	2	536.7786180	268.3893090	387.47	<.0001
Slope*Trt	4	12.8062191	3.2015548	4.62	0.0096

```
             Tukey's Studentized Range (HSD) Test for ROc

      NOTE: This test controls the Type I experimentwise error rate.

             Alpha                              0.05
             Error Degrees of Freedom             18
             Error Mean Square              0.692669
             Critical Value of Studentized Range  3.60930
             Minimum Significant Difference       1.0013

      Comparisons significant at the 0.05 level are indicated by ***.

                        Difference
             Slope        Between     Simultaneous 95%
           Comparison       Means    Confidence Limits

            5   - 10        0.0311    -0.9702  1.0324
            5   - 2.5       0.1419    -0.8594  1.1432
            10  - 5        -0.0311    -1.0324  0.9702
            10  - 2.5       0.1108    -0.8905  1.1121
            2.5 - 5        -0.1419    -1.1432  0.8594
            2.5 - 10       -0.1108    -1.1121  0.8905

NOTE: This test controls the Type I experimentwise error rate, but it generally has a
higher Type II error rate than REGWQ.
```

(continued)

```
       Alpha                            0.05
       Error Degrees of Freedom              18
       Error Mean Square              0.692669
       Critical Value of Studentized Range  3.60930
       Minimum Significant Difference      1.0013

 Means with the same letter are not significantly different.

  Tukey Grouping        Mean     N   Slope

        A      46.9839     9   5
        A      46.9528     9   10                          A
        A      46.8420     9   2.5

NOTE: This test controls the Type I experimentwise error rate.

       Alpha                                 0.05
       Error Degrees of Freedom                18
       Error Mean Square                 0.692669
       Critical Value of Studentized Range  3.60930
       Minimum Significant Difference       1.0013

Comparisons significant at the 0.05 level are indicated by ***.

                Difference
       Trt         Between    Simultaneous 95%
     Comparison       Means   Confidence Limits

    40P - 20P       5.9110      4.9097   6.9123  ***
    40P - CK       10.9090      9.9077  11.9103  ***
    20P - 40P      -5.9110     -6.9123  -4.9097  ***
    20P - CK        4.9980      3.9967   5.9993  ***
    CK  - 40P     -10.9090    -11.9103  -9.9077  ***
    CK  - 20P      -4.9980     -5.9993  -3.9967  ***

NOTE: This test controls the Type I experimentwise error rate, but it generally has a
higher Type
                    II error rate than REGWQ.

       Alpha                                 0.05
       Error Degrees of Freedom                18
       Error Mean Square                 0.692669
       Critical Value of Studentized Range  3.60930
       Minimum Significant Difference       1.0013

 Means with the same letter are not significantly different.

   Tukey Grouping        Mean     N   Trt

         A      52.5329     9   40P
         B      46.6219     9   20P
         C      41.6239     9   CK

Level of    Level of         -------------ROc-------------
Slope       Trt        N          Mean        Std Dev

10         20P       3      45.8226667      0.53558971
10         40P       3      52.5663333      0.14096217
10         CK        3      42.4693333      1.09055322
2.5        20P       3      46.2550000      0.80814665
2.5        40P       3      53.2370000      0.66910313
2.5        CK        3      41.0340000      1.10033677
5          20P       3      47.7880000      0.59836109
5          40P       3      51.7953333      1.10872284
5          CK        3      41.3683333      0.91604658
```

(continued)

Least Squares Means

Slope	ROc LSMEAN	LSMEAN Number
10	46.9527778	1
2.5	46.8420000	2
5	46.9838889	3

Least Squares Means for effect Slope
Pr > |t| for H0: LSMean(i)=LSMean(j)

Dependent Variable: ROc

i/j	1	2	3
1		0.7809	0.9377
2	0.7809		0.7218
3	0.9377	0.7218	

Slope	ROc LSMEAN	95% Confidence Limits	
10	46.952778	46.369935	47.535621
2.5	46.842000	46.259157	47.424843
5	46.983889	46.401046	47.566732

Least Squares Means for Effect Slope

i	j	Difference Between Means	95% Confidence Limits for LSMean(i)-LSMean(j)	
1	2	0.110778	-0.713486	0.935042
1	3	-0.031111	-0.855375	0.793153
2	3	-0.141889	-0.966153	0.682375

NOTE: To ensure overall protection level, only probabilities associated with pre-planned comparisons should be used.

Trt	ROc LSMEAN	LSMEAN Number
20P	46.6218889	1
40P	52.5328889	2
CK	41.6238889	3

Least Squares Means for effect Trt
Pr > |t| for H0: LSMean(i)=LSMean(j)

Dependent Variable: ROc

1		<.0001	<.0001
2	<.0001		<.0001
3	<.0001	<.0001	

Trt	ROc LSMEAN	95% Confidence Limits	
20P	46.621889	46.039046	47.204732
40P	52.532889	51.950046	53.115732
CK	41.623889	41.041046	42.206732

(continued)

Least Squares Means for Effect Trt

i	j	Difference Between Means	95% Confidence Limits for LSMean(i)-LSMean(j)	
1	2	-5.911000	-6.735264	-5.086736
1	3	4.998000	4.173736	5.822264
2	3	10.909000	10.084736	11.733264

NOTE: To ensure overall protection level, only probabilities associated with pre-planned comparisons should be used.

Slope	Trt	ROc LSMEAN	LSMEAN Number
10	20P	45.8226667	1
10	40P	52.5663333	2
10	CK	42.4693333	3
2.5	20P	46.2550000	4
2.5	40P	53.2370000	5
2.5	CK	41.0340000	6
5	20P	47.7880000	7
5	40P	51.7953333	8
5	CK	41.3683333	9

Least Squares Means for effect Slope*Trt
Pr > |t| for H0: LSMean(i)=LSMean(j)

Dependent Variable: ROc

i/j	1	2	3	4	5	6	7	8	9
1		<.0001	0.0001	0.5326	<.0001	<.0001	0.0097	<.0001	<.0001
2	<.0001		<.0001	<.0001	0.3368	<.0001	<.0001	0.2714	<.0001
3	0.0001	<.0001		<.0001	<.0001	0.0489	<.0001	<.0001	0.1226
4	0.5326	<.0001	<.0001		<.0001	<.0001	0.0368	<.0001	<.0001
5	<.0001	0.3368	<.0001	<.0001		<.0001	<.0001	0.0480	<.0001
6	<.0001	<.0001	0.0489	<.0001	<.0001		<.0001	<.0001	0.6287
7	0.0097	<.0001	<.0001	0.0368	<.0001	<.0001		<.0001	<.0001
8	<.0001	0.2714	<.0001	<.0001	0.0480	<.0001	<.0001		<.0001
9	<.0001	<.0001	0.1226	<.0001	<.0001	0.6287	<.0001	<.0001	

Slope	Trt	ROc LSMEAN	95% Confidence Limits	
10	20P	45.822667	44.813153	46.832180
10	40P	52.566333	51.556820	53.575847
10	CK	42.469333	41.459820	43.478847
2.5	20P	46.255000	45.245487	47.264513
2.5	40P	53.237000	52.227487	54.246513
2.5	CK	41.034000	40.024487	42.043513
5	20P	47.788000	46.778487	48.797513
5	40P	51.795333	50.785820	52.804847
5	CK	41.368333	40.358820	42.377847

(continued)

Least Squares Means for Effect Slope*Trt

i	j	Difference Between Means	95% Confidence Limits for LSMean(i)-LSMean(j)	
1	2	-6.743667	-8.171334	-5.315999
1	3	3.353333	1.925666	4.781001
1	4	-0.432333	-1.860001	0.995334
1	5	-7.414333	-8.842001	-5.986666
1	6	4.788667	3.360999	6.216334
1	7	-1.965333	-3.393001	-0.537666
1	8	-5.972667	-7.400334	-4.544999
1	9	4.454333	3.026666	5.882001
2	3	10.097000	8.669333	11.524667
2	4	6.311333	4.883666	7.739001
2	5	-0.670667	-2.098334	0.757001
2	6	11.532333	10.104666	12.960001
2	7	4.778333	3.350666	6.206001
2	8	0.771000	-0.656667	2.198667
2	9	11.198000	9.770333	12.625667
3	4	-3.785667	-5.213334	-2.357999
3	5	-10.767667	-12.195334	-9.339999
3	6	1.435333	0.007666	2.863001
3	7	-5.318667	-6.746334	-3.890999
3	8	-9.326000	-10.753667	-7.898333
3	9	1.101000	-0.326667	2.528667
4	5	-6.982000	-8.409667	-5.554333
4	6	5.221000	3.793333	6.648667
4	7	-1.533000	-2.960667	-0.105333
4	8	-5.540333	-6.968001	-4.112666
4	9	4.886667	3.458999	6.314334
5	6	12.203000	10.775333	13.630667
5	7	5.449000	4.021333	6.876667
5	8	1.441667	0.013999	2.869334
5	9	11.868667	10.440999	13.296334
6	7	-6.754000	-8.181667	-5.326333
6	8	-10.761333	-12.189001	-9.333666
6	9	-0.334333	-1.762001	1.093334
7	8	-4.007333	-5.435001	-2.579666
7	9	6.419667	4.991999	7.847334
8	9	10.427000	8.999333	11.854667

NOTE: To ensure overall protection level, only probabilities associated with pre-planned comparisons should be used.

(continued)

```
                        Plot of ROc*TrtSlope.  Symbol used is '.'.
                        Plot of p*TrtSlope.    Symbol used is 'P'.

    ROc |
     54 +                                   .
        |
        |                                   P
        |                                   .       .
        |                           .       .
        |                           .
     52 +
        |                                           P
        |                                           .
        |                                           .
        |
        |
     50 +
        |
        |
        |
        |
        |                  .
     48 +
        |                  .
        |                  .
        |          .
        |
        |  .       P
     46 +  .       .
        |  P       .
        |  .
        |
        |
        |
     44 +
        |                                                   .
        |
        |
        |
        |                                                   P        .
     42 +                                                   .                .
        |                                                   .
        |                                                                    P
        |                                                            .
        |
        |                                                                    .
     40 +                                                            .
        ---+---------+---------+---------+---------+---------+---------+---------+---------+--------
-+--
       20P_10    20P_2.5   20P_5    40P_10   40P_2.5    40P_5    CK_10   CK_2.5    CK_5

NOTE: 23 obs hidden.
```

(continued)

```
                       Plot of r*TrtSlope.  Symbol is value of Rep.

      r |
    1.5 +
        |
        |
        |                                           2
        |                                                    1
        |                                                            2
        |
    1.0 +
        |
        |          3
        |
        |                  2                3
        |
        |                                                                    3
    0.5 +  3                                                                  2
        |
        |
        |
        |
        |                           2
        |  2
    0.0 +---------------------------------------------------------------------------------
-----
        |                           1
        |          2                        1                        3
        |                  3
        |
        |                                                    2
        |                  1
   -0.5 +
        |  1                                2       1
        |
        |          1                                3
        |
        |                                                    3
        |
   -1.0 +
        |                                                            1       1
        |
        |
        |
        |
        |
   -1.5 +
        |
        ---+---------+---------+---------+---------+---------+---------+---------+--------
-+--
        20P_10   20P_2.5   20P_5   40P_10   40P_2.5   40P_5    CK_10    CK_2.5    CK_5

                                        TrtSlope
```

(continued)

```
                 The UNIVARIATE Procedure
                      Variable:  r

                        Moments

N                      27    Sum Weights              27
Mean                    0    Sum Observations          0
Std Deviation     0.69248814    Variance          0.47953982
Skewness         0.35304335    Kurtosis          -0.8791672
Uncorrected SS    12.4680353    Corrected SS      12.4680353
Coeff Variation           .    Std Error Mean     0.1332694

               Basic Statistical Measures
       Location                    Variability
    Mean     0.00000    Std Deviation          0.69249
    Median  -0.11900    Variance               0.47954
    Mode      .         Range                  2.33600
                        Interquartile Range    1.13900

               Tests for Location: Mu0=0

      Test          -Statistic-    -----p Value------
      Student's t    t        0    Pr > |t|    1.0000
      Sign           M     -2.5    Pr >= |M|   0.4421
      Signed Rank    S      -10    Pr >= |S|   0.8153

                  Tests for Normality
  Test                --Statistic---    -----p Value------
  Shapiro-Wilk         W     0.95111    Pr < W     0.2281
  Kolmogorov-Smirnov   D    0.136479    Pr > D    >0.1500
  Cramer-von Mises     W-Sq 0.068451    Pr > W-Sq >0.2500
  Anderson-Darling     A-Sq 0.416881    Pr > A-Sq >0.2500

                Quantiles (Definition 5)
                Quantile      Estimate
                100% Max      1.278667
                99%           1.278667
                95%           1.222667
                90%           1.155000
                75% Q3        0.554667
                50% Median   -0.119000
                25% Q1       -0.584333
                10%          -0.872333
                5%           -1.036000
                1%           -1.057333
                0% Min       -1.057333


                  Extreme Observations

       ------Lowest------       -----Highest-----

          Value     Obs          Value     Obs

       -1.057333     25        0.72700     15
       -1.036000     16        0.86900     12
       -0.872333      9        1.15500     17
       -0.729000     10        1.22267      7
       -0.278000     24        0.512000     23
```

(continued)

```
 Stem Leaf                    #           Boxplot
   12 28                      2              |
   10 6                       1              |
    8 7                       1              |
    6 83                      2              |
    4 005                     3           +-----+
    2                                     |     |
    0 76                      2           |  +  |
   -0 44298                   5           *-----*
   -2 53                      2           |     |
   -4 9875                    4           +-----+
   -6 39                      2              |
   -8 7                       1              |
  -10 64                      2              |
       ----+----+----+----+
  Multiply Stem.Leaf by 10**-1

                      Normal Probability Plot
 1.3+                                          * ++*
    |                                       * +++
    |                                     *+++
    |                                  *+*+
    |                               ***+
    |                             +++
 0.1+                           +++**
    |                         *****
    |                      +**
    |                   ****
    |                **+
    |             +*+
-1.1+     *  +*+
     +----+----+----+----+----+----+----+----+----+----+
         -2       -1        0       +1       +2
```

Obs	Rep	Slope	Trt	ROc	p	r	student	l95m	u95m
1	1	10	20P	45.257	45.8227	-0.56567	-0.83242	44.8132	46.8322
2	2	10	20P	45.889	45.8227	0.06633	0.09761	44.8132	46.8322
3	3	10	20P	46.322	45.8227	0.49933	0.73481	44.8132	46.8322
4	1	10	40P	52.480	52.5663	-0.08633	-0.12705	51.5568	53.5758
5	2	10	40P	52.729	52.5663	0.16267	0.23938	51.5568	53.5758
6	3	10	40P	52.490	52.5663	-0.07633	-0.11233	51.5568	53.5758
7	1	10	CK	43.692	42.4693	1.22267	1.79925	41.4598	43.4788
8	2	10	CK	42.119	42.4693	-0.35033	-0.51554	41.4598	43.4788
9	3	10	CK	41.597	42.4693	-0.87233	-1.28371	41.4598	43.4788
10	1	2.5	20P	45.526	46.2550	-0.72900	-1.07278	45.2455	47.2645
11	2	2.5	20P	46.115	46.2550	-0.14000	-0.20602	45.2455	47.2645
12	3	2.5	20P	47.124	46.2550	0.86900	1.27880	45.2455	47.2645
13	1	2.5	40P	53.100	53.2370	-0.13700	-0.20161	52.2275	54.2465
14	2	2.5	40P	52.647	53.2370	-0.59000	-0.86823	52.2275	54.2465
15	3	2.5	40P	53.964	53.2370	0.72700	1.06984	52.2275	54.2465
16	1	2.5	CK	39.998	41.0340	-1.03600	-1.52455	40.0245	42.0435
17	2	2.5	CK	42.189	41.0340	1.15500	1.69967	40.0245	42.0435
18	3	2.5	CK	40.915	41.0340	-0.11900	-0.17512	40.0245	42.0435
19	1	5	20P	47.342	47.7880	-0.44600	-0.65632	46.7785	48.7975
20	2	5	20P	48.468	47.7880	0.68000	1.00067	46.7785	48.7975
21	3	5	20P	47.554	47.7880	-0.23400	-0.34435	46.7785	48.7975
22	1	5	40P	51.211	51.7953	-0.58433	-0.85989	50.7858	52.8048
23	2	5	40P	53.074	51.7953	1.27867	1.88166	50.7858	52.8048
24	3	5	40P	51.101	51.7953	-0.69433	-1.02176	50.7858	52.8048
25	1	5	CK	40.311	41.3683	-1.05733	-1.55595	40.3588	42.3778
26	2	5	CK	41.871	41.3683	0.50267	0.73971	40.3588	42.3778
27	3	5	CK	16.769	16.5473	0.22167	0.81530	16.1434	16.9512

Appendix 8-3. SAS output for the cumulative sediment loss (SL) using the SAS system (Release 9.1.3. in 2005) for chapter 3.

```
                          Slope Study
                        The GLM Procedure
                     Class Level Information

                 Class       Levels   Values
                 Slope            3   10 2.5 5
                 Trt              3   20P 40P CK

                Number of Observations Read        27
                Number of Observations Used        27

Dependent Variable: SLc
                                   Sum of
      Source                DF       Squares    Mean Square   F Value   Pr > F
      Model                  8   30347758.11     3793469.76    997.84   <.0001
      Error                 18      68430.31        3801.68
      Corrected Total       26   30416188.43

              R-Square    Coeff Var     Root MSE     SLc Mean
              0.997750     3.289006     61.65780     1874.663

      Source                DF      Type I SS    Mean Square   F Value   Pr > F
      Slope                  2   17273127.93     8636563.97   2271.77   <.0001
      Trt                    2   11492130.69     5746065.34   1511.45   <.0001
      Slope*Trt              4    1582499.49      395624.87    104.07   <.0001

      Source                DF    Type III SS    Mean Square   F Value   Pr > F
      Slope                  2   17273127.93     8636563.97   2271.77   <.0001
      Trt                    2   11492130.69     5746065.34   1511.45   <.0001
      Slope*Trt              4    1582499.49      395624.87    104.07   <.0001

               Tukey's Studentized Range (HSD) Test for SLc

        NOTE: This test controls the Type I experimentwise error rate.

               Alpha                                 0.05
               Error Degrees of Freedom                18
               Error Mean Square                 3801.684
               Critical Value of Studentized Range  3.60930
               Minimum Significant Difference       74.181

        Comparisons significant at the 0.05 level are indicated by ***.

                         Difference
              Slope        Between     Simultaneous 95%
            Comparison       Means    Confidence Limits

            2.5 - 5        1213.07     1138.89   1287.25  ***
            2.5 - 10       1938.90     1864.72   2013.08  ***
            5   - 2.5     -1213.07    -1287.25  -1138.89  ***
            5   - 10        725.83      651.65    800.01  ***
            10  - 2.5     -1938.90    -2013.08  -1864.72  ***
            10  - 5        -725.83     -800.01   -651.65  ***

NOTE: This test controls the Type I experimentwise error rate, but it generally has a
higher Type II error rate than REGWQ.
```

(continued)

Alpha	0.05
Error Degrees of Freedom	18
Error Mean Square	3801.684
Critical Value of Studentized Range	3.60930
Minimum Significant Difference	74.181

Means with the same letter are not significantly different.

Tukey Grouping	Mean	N	Slope
A	2925.32	9	2.5
B	1712.25	9	5
C	986.42	9	10

Tukey's Studentized Range (HSD) Test for SLc

NOTE: This test controls the Type I experimentwise error rate.

Alpha	0.05
Error Degrees of Freedom	18
Error Mean Square	3801.684
Critical Value of Studentized Range	3.60930
Minimum Significant Difference	74.181

Comparisons significant at the 0.05 level are indicated by ***.

Trt Comparison	Difference Between Means	Simultaneous 95% Confidence Limits		
CK - 20P	1036.03	961.84	1110.21	***
CK - 40P	1571.74	1497.56	1645.92	***
20P - CK	-1036.03	-1110.21	-961.84	***
20P - 40P	535.72	461.53	609.90	***
40P - CK	-1571.74	-1645.92	-1497.56	***
40P - 20P	-535.72	-609.90	-461.53	***

NOTE: This test controls the Type I experimentwise error rate, but it generally has a higher Type II error rate than REGWQ.

Alpha	0.05
Error Degrees of Freedom	18
Error Mean Square	3801.684
Critical Value of Studentized Range	3.60930
Minimum Significant Difference	74.181

Means with the same letter are not significantly different.

Tukey Grouping	Mean	N	Trt
A	2743.92	9	CK
B	1707.89	9	20P
C	1172.18	9	40P

Level of Slope	Level of Trt	N	-------------SLc------------- Mean	Std Dev
10	20P	3	522.68667	50.0625063
10	40P	3	572.03667	79.6922489
10	CK	3	1864.53667	74.6613356
2.5	20P	3	3106.82333	55.8049257
2.5	40P	3	1784.69333	53.6225702
2.5	CK	3	3884.44667	62.7648830
5	20P	3	1494.17000	9.6182795
5	40P	3	1159.80333	95.2550294
5	CK	3	2482.77333	26.2430969

(continued)

Least Squares Means

Slope	SLc LSMEAN	LSMEAN Number
10	986.42000	1
2.5	2925.32111	2
5	1712.24889	3

Least Squares Means for effect Slope
Pr > |t| for H0: LSMean(i)=LSMean(j)

Dependent Variable: SLc

i/j	1	2	3
1		<.0001	<.0001
2	<.0001		<.0001
3	<.0001	<.0001	

Slope	SLc LSMEAN	95% Confidence Limits	
10	986.420000	943.240591	1029.599409
2.5	2925.321111	2882.141702	2968.500520
5	1712.248889	1669.069480	1755.428298

Least Squares Means for Effect Slope

i	j	Difference Between Means	95% Confidence Limits for LSMean(i)-LSMean(j)	
1	2	-1938.901111	-1999.966017	-1877.836205
1	3	-725.828889	-786.893795	-664.763983
2	3	1213.072222	1152.007317	1274.137128

NOTE: To ensure overall protection level, only probabilities associated with pre-planned comparisons should be used.

Trt	SLc LSMEAN	LSMEAN Number
20P	1707.89333	1
40P	1172.17778	2
CK	2743.91889	3

(continued)

Least Squares Means for Effect Trt

i	j	Difference Between Means	95% Confidence Limits for LSMean(i)-LSMean(j)	
1	2	535.715556	474.650650	596.780461
1	3	-1036.025556	-1097.090461	-974.960650
2	3	-1571.741111	-1632.806017	-1510.676205

NOTE: To ensure overall protection level, only probabilities associated with pre-planned comparisons should be used.

Slope	Trt	SLc LSMEAN	LSMEAN Number
10	20P	522.68667	1
10	40P	572.03667	2
10	CK	1864.53667	3
2.5	20P	3106.82333	4
2.5	40P	1784.69333	5
2.5	CK	3884.44667	6
5	20P	1494.17000	7
5	40P	1159.80333	8
5	CK	2482.77333	9

Least Squares Means for effect Slope*Trt
Pr > |t| for H0: LSMean(i)=LSMean(j)

Dependent Variable: SLc

i/j	1	2	3	4	5	6	7	8	9
1		0.3399	<.0001	<.0001	<.0001	<.0001	<.0001	<.0001	<.0001
2	0.3399		<.0001	<.0001	<.0001	<.0001	<.0001	<.0001	<.0001
3	<.0001	<.0001		<.0001	0.1302	<.0001	<.0001	<.0001	<.0001
4	<.0001	<.0001	<.0001		<.0001	<.0001	<.0001	<.0001	<.0001
5	<.0001	<.0001	0.1302	<.0001		<.0001	<.0001	<.0001	<.0001
6	<.0001	<.0001	<.0001	<.0001	<.0001		<.0001	<.0001	<.0001
7	<.0001	<.0001	<.0001	<.0001	<.0001	<.0001		<.0001	<.0001
8	<.0001	<.0001	<.0001	<.0001	<.0001	<.0001	<.0001		<.0001
9	<.0001	<.0001	<.0001	<.0001	<.0001	<.0001	<.0001	<.0001	

Slope	Trt	SLc LSMEAN	95% Confidence Limits	
10	20P	522.686667	447.897737	597.475597
10	40P	572.036667	497.247737	646.825597
10	CK	1864.536667	1789.747737	1939.325597
2.5	20P	3106.823333	3032.034403	3181.612263
2.5	40P	1784.693333	1709.904403	1859.482263
2.5	CK	3884.446667	3809.657737	3959.235597
5	20P	1494.170000	1419.381070	1568.958930
5	40P	1159.803333	1085.014403	1234.592263
5	CK	2482.773333	2407.984403	2557.562263

(continued)

Least Squares Means for Effect Slope*Trt

i	j	Difference Between Means	95% Confidence Limits for LSMean(i)-LSMean(j)	
1	2	-49.350000	-155.117519	56.417519
1	3	-1341.850000	-1447.617519	-1236.082481
1	4	-2584.136667	-2689.904186	-2478.369147
1	5	-1262.006667	-1367.774186	-1156.239147
1	6	-3361.760000	-3467.527519	-3255.992481
1	7	-971.483333	-1077.250853	-865.715814
1	8	-637.116667	-742.884186	-531.349147
1	9	-1960.086667	-2065.854186	-1854.319147
2	3	-1292.500000	-1398.267519	-1186.732481
2	4	-2534.786667	-2640.554186	-2429.019147
2	5	-1212.656667	-1318.424186	-1106.889147
2	6	-3312.410000	-3418.177519	-3206.642481
2	7	-922.133333	-1027.900853	-816.365814
2	8	-587.766667	-693.534186	-481.999147
2	9	-1910.736667	-2016.504186	-1804.969147
3	4	-1242.286667	-1348.054186	-1136.519147
3	5	79.843333	-25.924186	185.610853
3	6	-2019.910000	-2125.677519	-1914.142481
3	7	370.366667	264.599147	476.134186
3	8	704.733333	598.965814	810.500853
3	9	-618.236667	-724.004186	-512.469147
4	5	1322.130000	1216.362481	1427.897519
4	6	-777.623333	-883.390853	-671.855814
4	7	1612.653333	1506.885814	1718.420853
4	8	1947.020000	1841.252481	2052.787519
4	9	624.050000	518.282481	729.817519
5	6	-2099.753333	-2205.520853	-1993.985814
5	7	290.523333	184.755814	396.290853
5	8	624.890000	519.122481	730.657519
5	9	-698.080000	-803.847519	-592.312481
6	7	2390.276667	2284.509147	2496.044186
6	8	2724.643333	2618.875814	2830.410853
6	9	1401.673333	1295.905814	1507.440853
7	8	334.366667	228.599147	440.134186
7	9	-988.603333	-1094.370853	-882.835814
8	9	-1322.970000	-1428.737519	-1217.202481

NOTE: To ensure overall protection level, only probabilities associated with pre-planned comparisons should be used.

(continued)

```
                        Plot of SLc*TrtSlope.  Symbol used is '.'.
                        Plot of p*TrtSlope.    Symbol used is 'P'.

    SLc |
   4000 +
        |                                                            .
        |                                                            .
        |
        |
        |
   3500 +
        |
        |
        |
        |          .
        |          .
   3000 +
        |
        |
        |
        |
        |
   2500 +                                                                      .
        |                                                                     .
        |
        |
        |
        |
   2000 +
        |                                                    .
        |                                   .                .
        |                                   .
        |
        |
   1500 +                   .
        |
        |
        |                                           .
        |                                           P
        |                                           .
   1000 +
        |
        |
        |
        |                           .
        |  .                        P
    500 +  .                         .
        ---+---------+---------+---------+---------+---------+---------+---------+--------
-+--
       20P_10   20P_2.5   20P_5   40P_10   40P_2.5   40P_5    CK_10   CK_2.5    CK_5

                                        TrtSlope

NOTE: 35 obs hidden.
```

(continued)

```
                       Plot of r*TrtSlope.  Symbol is value of Rep.

      r |
        |
    125 +
        |
        |
        |                                            1
        |
    100 +
        |
        |                           1
        |
        |                                                    1
     75 +
        |                                                            3
        |
        |                                   2
        |  1
     50 +
        |          2
        |
        |
        |
     25 +                                                                     2
        |          1
        |
        |                  2
        |                                                                     1
      0 +----------------------------------------------------------------------------------
----
        |                  1
        |
        |
        |  2                                                 2
    -25 +                                    3
        |                                                                     3
        |  3                        2        1                        2
        |                                                            1
        |                                            2
    -50 +
        |                           3
        |
        |          3                                 3       3
        |
    -75 +
        |
        ---+---------+---------+---------+---------+---------+---------+---------+--------
-+--
        20P_10   20P_2.5   20P_5    40P_10   40P_2.5   40P_5     CK_10   CK_2.5    CK_5

                                        TrtSlope

NOTE: 1 obs hidden.
```

(continued)

```
                 The UNIVARIATE Procedure
                      Variable:  r

                        Moments
N                      27    Sum Weights             27
Mean                    0    Sum Observations         0
Std Deviation      51.302389    Variance          2631.93511
Skewness          0.67703619    Kurtosis          -0.6657888
Uncorrected SS    68430.3129    Corrected SS      68430.3129
Coeff Variation            .    Std Error Mean    9.87314936

               Basic Statistical Measures
       Location                   Variability
    Mean      0.0000     Std Deviation          51.30239
    Median  -19.2567     Variance                   2632
    Mode       .         Range                 174.38000
                         Interquartile Range    80.38000

               Tests for Location: Mu0=0

      Test         -Statistic-    -----p Value------

      Student's t   t        0    Pr > |t|    1.0000
      Sign         M      -2.5    Pr >= |M|   0.4421
      Signed Rank   S      -12    Pr >= |S|   0.7792

                  Tests for Normality
  Test                --Statistic---    -----p Value------
  Shapiro-Wilk         W    0.918442    Pr < W     0.0362
  Kolmogorov-Smirnov   D    0.164821    Pr > D     0.0587
  Cramer-von Mises     W-Sq  0.134188   Pr > W-Sq   0.0379
  Anderson-Darling     A-Sq  0.787247   Pr > A-Sq   0.0377

                Quantiles (Definition 5)
                Quantile      Estimate
                100% Max      109.3367
                99%           109.3367
                95%            91.2933
                90%            82.4033
                75% Q3         43.3867
                50% Median    -19.2567
                25% Q1        -36.9933
                10%           -62.9533
                5%            -63.1467
                1%            -65.0433
                0% Min        -65.0433

                  Extreme Observations

        ------Lowest-----       ------Highest-----

          Value     Obs           Value     Obs

        -65.0433     24         61.4967     14
        -63.1467      9         72.3533     18
        -62.9533     12         82.4033      7
        -55.6467      6         91.2933      4
        -44.2933     23        109.3367     22
```

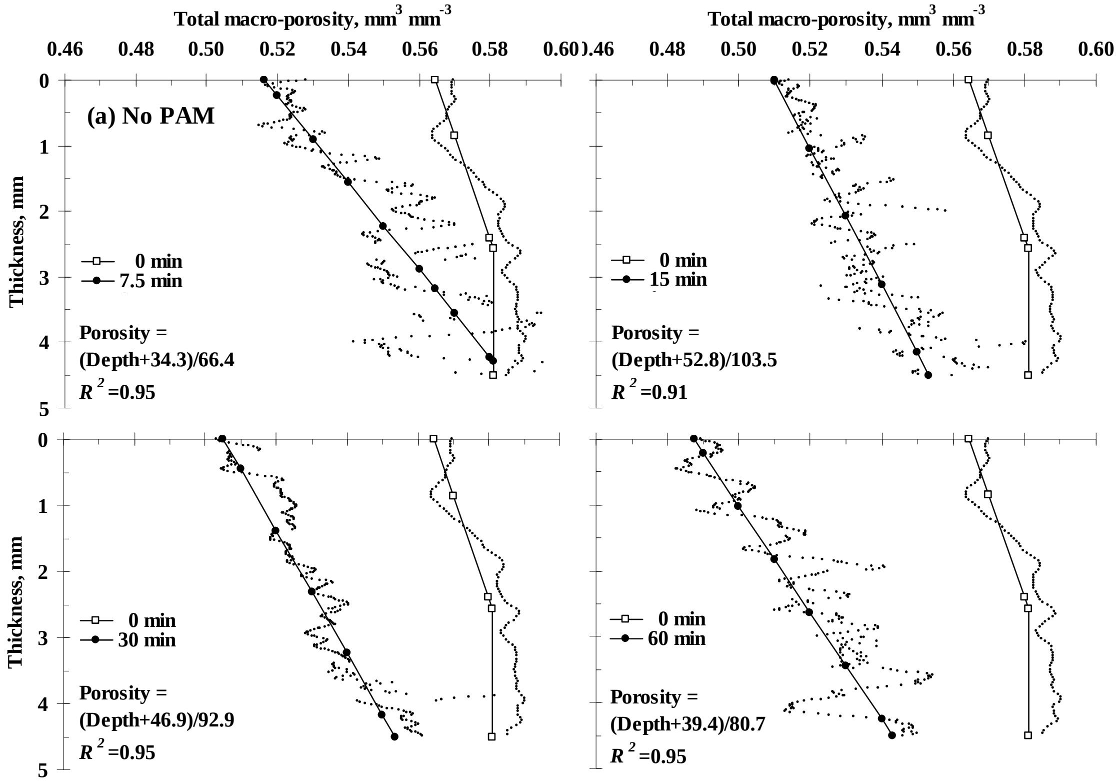
(continued)

```
Stem Leaf                  #           Boxplot
  10 9                     1              |
   8 21                    2              |
   6 12                    2              |
   4 37                    2           +-----+
   2 03                    2           |     |
   0 61                    2           |  +  |
  -0 974                   3           *-----*
  -2 7653952               7           +-----+
  -4 640                   3              |
  -6 533                   3              |
     ----+----+----+----+
 Multiply Stem.Leaf by 10**+1
```

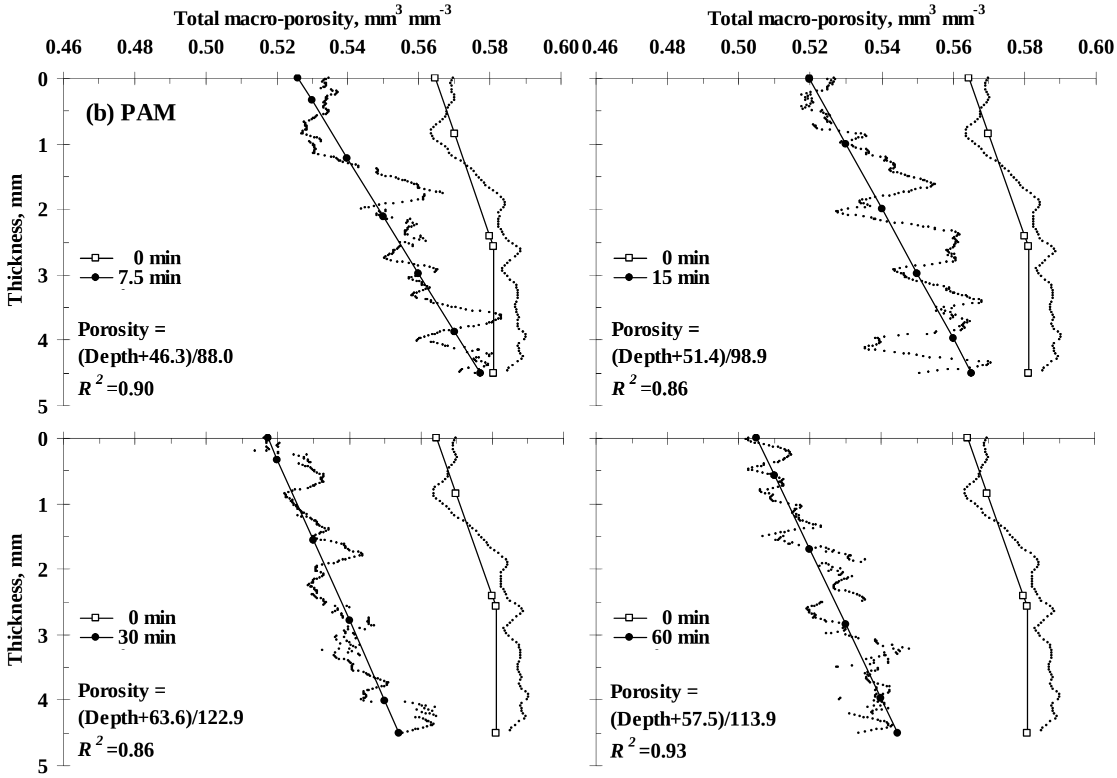
```
                The UNIVARIATE Procedure
                     Variable:  r

                     Normal Probability Plot
110+                                               *+++
   |                                        *  *+++
   |                                     **++++
 50+                                  **+++
   |                              ++*+
   |                          +++***
-10+                        +++***
   |                   ********
   |                **++
-70+    *   *++*+
    +----+----+----+----+----+----+----+----+----+----+
        -2        -1         0        +1        +2
```

Obs	Rep	Slope	Trt	SLc	p	r	student	l95m	u95m
1	1	10	20P	580.00	522.69	57.313	1.13845	447.90	597.48
2	2	10	20P	500.56	522.69	-22.127	-0.43951	447.90	597.48
3	3	10	20P	487.50	522.69	-35.187	-0.69893	447.90	597.48
4	1	10	40P	663.33	572.04	91.293	1.81341	497.25	646.83
5	2	10	40P	536.39	572.04	-35.647	-0.70807	497.25	646.83
6	3	10	40P	516.39	572.04	-55.647	-1.10534	497.25	646.83
7	1	10	CK	1946.94	1864.54	82.403	1.63683	1789.75	1939.33
8	2	10	CK	1845.28	1864.54	-19.257	-0.38251	1789.75	1939.33
9	3	10	CK	1801.39	1864.54	-63.147	-1.25432	1789.75	1939.33
10	1	2.5	20P	3126.39	3106.82	19.567	0.38866	3032.03	3181.61
11	2	2.5	20P	3150.21	3106.82	43.387	0.86181	3032.03	3181.61
12	3	2.5	20P	3043.87	3106.82	-62.953	-1.25048	3032.03	3181.61
13	1	2.5	40P	1747.70	1784.69	-36.993	-0.73482	1709.90	1859.48
14	2	2.5	40P	1846.19	1784.69	61.497	1.22154	1709.90	1859.48
15	3	2.5	40P	1760.19	1784.69	-24.503	-0.48672	1709.90	1859.48
16	1	2.5	CK	3844.64	3884.45	-39.807	-0.79070	3809.66	3959.24
17	2	2.5	CK	3851.90	3884.45	-32.547	-0.64649	3809.66	3959.24
18	3	2.5	CK	3956.80	3884.45	72.353	1.43720	3809.66	3959.24
19	1	5	20P	1487.53	1494.17	-6.640	-0.13189	1419.38	1568.96
20	2	5	20P	1505.20	1494.17	11.030	0.21910	1419.38	1568.96
21	3	5	20P	1489.78	1494.17	-4.390	-0.08720	1419.38	1568.96
22	1	5	40P	1269.14	1159.80	109.337	2.17182	1085.01	1234.59
23	2	5	40P	1115.51	1159.80	-44.293	-0.87982	1085.01	1234.59
24	3	5	40P	1094.76	1159.80	-65.043	-1.29199	1085.01	1234.59
25	1	5	CK	2488.38	2482.77	5.607	0.11137	2407.98	2557.56
26	2	5	CK	2505.76	2482.77	22.987	0.45660	2407.98	2557.56
27	3	5	CK	2454.18	2482.77	-28.593	-0.56797	2407.98	2557.56

Appendix 9-1. Total macro-porosities from high-resolution-computed-tomography images on unamended Mexico silt loam soils subjected to 7.5-, 15-, 30-, and 60-min simulated rainfall durations with an intensity of 61 mm h^{-1} for chapter 4.



Appendix 9-2. Total macro-porosities measured from high-resolution-computed-tomography images on PAM-amended Mexico silt loam soils subjected to 7.5-, 15-, 30-, and 60-min simulated rainfall durations with an intensity of 61 mm h^{-1} for chapter 4.



VITA

Sang Soo Lee was born 10 August in 1978, and grew up in Pyeongtaek-si, South Korea. He received a B.S. degree in the Department of Natural Resources and Technologies, Yonsei University in 2003 and a M.S. degree in the Department of Soil, Environmental and Atmospheric Sciences, University of Missouri in 2006. He also obtained his Ph.D. degree in the Department of Soil, Environmental and Atmospheric Sciences, University of Missouri, Columbia in 2009. His M.S. study evaluated the soil physical properties or soil surface seals on anionic polyacrylamide (PAM) amended soils subjected to various simulated rainfall and the effectiveness of high resolution X-ray computed tomography to determine the benefits of PAM on soil surface seals. His Ph.D. study was to investigate the amendment effectiveness of PAM and gypsum on soils of differing characteristics. Finally, he wishes to contribute and help find solutions to problems of hunger, loss of soil productivity, and environmental contaminations in the world. Currently, he will join to the Kangwon National University, South Korea, as a postdoctoral research associate. He will expand and develop his PAM study and wishes to contribute finding solutions of hunger, loss of soil productivity, and environmental contaminations in the future.