RETENTION OF SEDIMENT AND PHOSPHORUS IN FORESTED STREAMSIDE MANAGEMENT ZONES OF THE GEORGIA PIEDMONT UNDER SIMULATED OVERLAND FLOW CONDITIONS

by

WILLIAM JAMES WHITE

(Under the Direction of Lawrence A. Morris)

ABSTRACT

To protect stream water quality, foresters have implemented Best Management Practices (BMPs) which include streamside management zones (SMZs) within which harvesting and site disturbance are limited. Significant stream protection may be achieved by filtering of sediment and phosphorus in forest litter layers and organic matter rich surface horizons. This project investigated the retention of sediment and phosphorus in 5m (wide) x 10m (deep) plots to which simulated overland flow was applied from a tank and dispenser system. Plots were located on five slopes ranging from 2%-20% and either had an undisturbed forest floor or had the forest floor removed. Surface water samples were collected at 0, 2, 4, 6, and 10 meters within the SMZ during a 1-hour overland flow simulation.

INDEX WORDS: sediment, phosphorus, water quality, SMZ, BMP

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DEDICATION

I dedicate this work to the advancement of science and the hope of a better world for the future.

ACKNOWLEDGEMENTS

I thank my professors Dr. Larry Morris and Dr. C. Rhett Jackson for their continued guidance, support, and patience and for the knowledge that they passed on to me. I appreciate Dr. Larry West's help in the formative stages of this study as well as in the final writing and revising of this document. I would like to thank the entire hydrology lab group who assisted in fieldwork as well as Lee Ogden, Doug Marshall, Amy Parker, Martha Campbell, Jay Brown and Alexandra de Pinho. Without them, this research would never have been completed. Finally, I would like to thank my wife Angela for her patience and support.

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CHAPTER 1

INTRODUCTION AND LITERATURE REVIEW

Background

Non-point source pollution from silvicultural activities has come under increased scrutiny due to the Federally mandated Total Maximum Daily Load (TMDL) program. The Clean Water Act of 1972 mandates that all states must develop a TMDL program to protect the nation's water as drinkable, fishable, and swimmable. Each state has to identify surface waters within its boundaries that do not meet water quality guidelines and give them a priority ranking. This ranking is based on the severity of the pollution as well as the types of uses that would be made of these waters. The state then must develop a water quality improvement plan for these impacted streams and implement the plan within a certain time frame agreed upon by the state and the Environmental Protection Agency (EPA). These plans must address both point and non point source pollutants. Typically, non-point source pollutants are addressed through the implementation of Best Management Practices (BMPs). Because commercial forests cover a large portion of the Southeast, the effectiveness of forestry BMPs is a major concern.

Among the non-point source pollutants of concern from silvicultural activities are sediment, nutrients, increased stormflows, increased water temperatures, herbicides, and insecticides. One way to decrease pollutants reaching stream channels is to leave a protected strip of forested land on each side of a stream. A Streamside Management Zones (SMZ) is a strip of forested land running parallel to either side of a stream that is intended to work as a filter for removing pollutants from surface waters flowing through it. SMZs are accepted as a pollution control practice by the USDA-Natural Resources Conservation Service when most of the pollutant movement is in shallow groundwater and diffuse overland flow (Lowrance 1998). SMZs are an important component of forestry BMPs. This project investigated and quantified SMZ effectiveness in retaining sediment and phosphorus carried with dispersed overland flow moving through SMZs. Experiments were conducted to evaluate the effect of SMZ slope and forest floor O horizon condition on the removal of sediment and phosphorus in overland flow. Results from this study provide insight into the mechanisms of pollutant removal by SMZs and the adequacy of current BMP guidelines.

Literature review

The overall chemical quality of water draining from forests is generally high. Some forest practices, however, may alter concentrations of certain chemicals, thus affecting water quality. Forest harvesting and site preparation, especially fertilization, can affect concentrations of important plant and aquatic ecosystem nutrients (Binkley and Brown 1993).

Sites that have been recently clearcut or prepared for planting often have large areas of bare soils that can produce overland flow during rainfall. Overland flow causes surface erosion and moves sediment, along with nutrients and fertilizers, downslope and potentially discharges these materials into streams. One benefit of forested SMZs is that their organic soil cover (litter layer), overstory trees, and understory vegetation aid in filtering sediment and re-infiltrating surface flow coming from the hillslopes (NCASI 1992). The filtering efficiency of SMZs is dependent on many factors including width, stem density, slope of the SMZ, slope of the contributing hillslope, length and area of the contributing hillslope, treatment of the harvest or site preparation areas, bare soil coverage, and soil types (Swank 1990, Magette et al. 1989, Rivenbark and Jackson in review). More information is needed regarding all of these variables.

Soils of the Piedmont are Ultisols characterized by Bt horizons with high clay content. Phosphorus is strongly bound by iron-oxide coatings on soil particles and is not particularly mobile in the soil environment (Sharpley et al. 1993). Phosphorus tends to move into SMZ's and their associated streams when erosion from upland areas carries sediment downslope (Sharpley et al. 1993). Movement of phosphorus through SMZs is predicted to be closely associated with the movement of particles. Because of the high surface area for adsorption, colloidal-sized clay easily binds phosphorus and is an important factor in phosphorus transport. McDowell and Sharpley (2003) found that clay platelets and organic matter flocculate into particles of about 1 - 4 μm in size and represent over 90% of the total volume of sediment transported in suspension. These flocculated particles dominate phosphorus transportation in particulate form. McDowell and Sharpley found that up to 43% of total phosphorus was removed from manure enriched water as it flowed over 10 m strips of soil.

It is well established that riparian forests are effective in trapping sediments produced in agricultural practices (Cooper et al. 1987, Lowrance et al. 1986, Peterjohn and Correll 1984). Cooper et al. (1987) and Lowrance et al. (1987) investigated sediment deposition within forested SMZs ranging in width from 6 m to 20 m and located in agricultural watersheds. They found that a large amount of coarse sediment deposited within the first few meters of the forest-field boundary and that finer sediments deposited further into the SMZ. Peterjohn and Correll (1984) also saw decreases in coarse sediment, but observed an increase of fine particles in solution within 20 m of the edge of the SMZ. However, they observed up to 400% reduction of sediment concentration in surface runoff that passed through a 50 m forested buffer. When large buffers are left around streams, the chance of water and associated pollutants reaching streams is greatly reduced.

Many studies have been conducted on grass filter strips or vegetated filter strips (VFSs) that are part of a three-zone buffer system developed by the USDAFS, USDA Agricultural Research Service, and USDA Soil Conservation Service, and Stroud Water Research Center in Stroud, PA (Welsch 1991). This system includes an unmolested forested zone directly adjacent to the stream, another shrub or forested zone that can be managed for timber or other uses, and then a grassed strip for a total buffer width of about 50 m. VFSs are most desirable and maintainable in agricultural practices where erosion is a major concern and large quantities of fertilizer are applied every year. The strip can be mown frequently for easy removal of nitrogen and phosphorus taken up by the grass growing in that zone, while the other two zones provide more filtering capacity and all of the benefits of a forested SMZ. The term VFS has taken on a broader meaning incorporating the entire stram buffer and is often used synonymously with SMZ.

Early studies of SMZs were mainly concerned with the removal of sediments from overland flow. Phosphorus removal studies have become more abundant because of the concern of eutrophication of surface waters from chronic inputs of phosphorus. Phosphorus can be removed from overland flow by sedimentation of particulates, adsorption onto mineral soil or organic matter, plant uptake, and use by aquatic biota. While some results have been contradictory, SMZs have ultimately proven effective at retaining sediment and phosphorus. Total phosphorus removal is closely related to sediment removal. Dillaha et al. found that on 9.1-m-long plots when 70 to 98% of total suspended solids were removed, 65 to 93% of total phosphorus was removed. It is important to mention that in this study 90% of total phosphorus was bound to sediment. When more phosphorus is in the soluble form, then less is expected to be retained. Hayes (1979 and 1984), Patty et al. (1997), Overcash et al. (1981), and others have found that the primary mode of soluble phosphorus retention was infiltration of water into the soil profile.

Two recently completed studies, conducted on forest land, evaluated the effectiveness of SMZs in the Georgia Piedmont. Rivenbark and Jackson (in review) surveyed harvested and site-prepared areas in Georgia. These investigations found that locations of concentrated flow with evidence of sediment movement through an SMZ occurred with a spatial frequency of one breakthrough per 20 acres of harvested site. In a subsequent study, Ward and Jackson (in review) found that SMZs removed over 70% of coarse sediment from concentrated flow. Only one study that I have found evaluated filtration of clays within SMZ' s. Loch et al. (1999) found that on plots with slopes ranging from 6% to 29%, there was less than a 5% difference in the concentration of clay-sized particles entering and exiting the plot. Plot lengths varied from 2 to 30 meters.

In the southeastern United States, about 350,000 ha of pine plantations were fertilized in 1996, mainly with nitrogen (N) and phosphorus (P) (NCSFNC 1997). Since many aquatic ecosystems are limited by low concentrations of N or P, addition of fertilizers to streams typically increases primary productivity and may increase the growth rate of fish (Perrin et al. 1987). While forestry activities generally impose short-term effects (Lynch et al.1985), high and chronic doses of these elements can cause stream and lake eutrophication (Reddy et al. 1996,Cuker and Hudson 1992). With the current intensification of fertilizer use in southeastern forests and increasing concern over non-point source pollutants, the impacts of fertilizer use need to be re-evaluated.

Fertilizer applications in managed forests may alter stream chemistry, but the extent of the alteration is affected by the type of fertilizer used (i.e. urea or ammonium nitrate), the method of application (i.e. aerial or ground), and the presence or absence of buffer strips (Binkley and Allen 1999). Tabbara (2003) conducted a rainfall simulation study where fertilizer and manure were either broadcast or mechanically incorporated into the soil. He found that losses of phosphorus were greater on all plots when inorganic fertilizer was applied and that incorporation increased total suspended solids, but decreased dissolved as well as total phosphorus in runoff. Soluble phosphorus losses increase in relation to total phosphorus as application rates increase (McDowell and Sharpley 2003, Kleinman and Sharpley 2003).

Different elements and their various molecular forms respond differently. For example, buffer strips currently appear to be more effective for retaining N than P (Comerford et al. 1992) and are more effective on NH_4 forms of N than on NO_3 forms (Perrin et al. 1984). Current water quality standards have focused on NO_3 for human health concerns, while total P has been the focus of eutrophication concerns.

Filtering of sediment and pollutants is only one benefit of SMZs. In a review of the effectiveness of SMZs in the primarily agricultural Little River watershed near Tifton, Georgia, and other locations in the Coastal Plain, Lowrance (1998) showed that not only were sediment, nitrogen, and phosphorus concentrations in the streams reduced, but large woody debris input was significantly higher than in areas where there were buffers, and shading and temperature mediation from decreased light penetration was apparent in buffered zones. These studies were conducted in low slope areas (2-7%) where either row crop agriculture or pasture land dominated the uplands.

There has been limited research on sediment removal in SMZs on managed forest lands and no studies that evaluate the removal of phosphorus. Most research on sediment and P retention within SMZs has been done in agricultural settings. Typically, evaluations have been made for SMZs with low gradients, such as could be associated with plowed fields. In contrast, forest activities can be conducted on steep slopes. Consequently, the range of slope conditions associated with forested SMZs is greater than for agricultural SMZs. McDowell and Sharpley (2003) also found that soils from agricultural areas have higher pH than soils fro forested areas, and therefore, more soluble phosphorous present in overland flow and less phosphorus that is bound in the sediment fraction. This suggests that the movement of sediment and phosphorus in managed forest systems is not entirely comparable to agricultural findings and that more research needs to be completed in this area to ensure the most beneficial recommendations for environmental guidelines in each discipline.

Project objectives

This project evaluates the effectiveness of forested SMZs characteristic of the hilly Piedmont in retaining overland flow and its constituents, including colloidal and aggregated clay and associated adsorbed phosphorus as well as soluble phosphorus. Specific objectives were to:

(1) quantify the retention of water, in the form of overland flow, within forested SMZs,

(2) quantify retention of dispersed and aggregated clay within forested SMZs,

(3) quantify retention of phosphorus within SMZs,

(4) relate retention of pollutants to characteristics of forested SMZs.

We hypothesized that retention would be less on steep slopes and greater on shallow slopes because higher flow velocities would decrease the chance for sediment to settle and also decrease contact time for phosphorus to adsorb in the SMZ. We also hypothesized that retention would increase with litter depth because greater depths would break up flow, slowing the velocity, aiding in the settling of particles out of solution, promoting dispersed sheet flow, and allowing for increased contact time with the organic litter layer as well as the mineral soil. We also believed that retention would be related to antecedent moisture conditions because higher moisture contents would decrease the amount of water that could be retained in the soil and therefore less clay and phosphorus in solution would infiltrate the soil profile. Retention was also hypothesized to be related to distance traveled through the SMZ. The further the solution travels there would be more time for settling and adsorption as well as infiltration.

These objectives were approached using experimental plotscale studies. Artificial overland flow was dispersed across the top of 5-m wide by 10-m deep plots for a range of slopes and forest floor conditions.

CHAPTER 2

MATERIALS AND METHODS

Sites selection and plot establishment

To evaluate and quantify the potential for SMZs to filter colloidal-sized clay sediments, and adsorbed and soluble phosphorus, movement of these pollutants through forested SMZs was measured under controlled conditions. Five sites, along a gradient of slope classes, 0-2%, 5-7%, 10-12%, 15-17%, and 20-22%,were selected in recently established or designated SMZs in the Piedmont of northeastern Georgia. On each site, a 5-m wide plot was established beginning at the edge of the undisturbed SMZ and extending 10 m toward the stream. In order to evaluate the influence of ground (O horizon) disturbance in SMZs, a second plot was established on sites with intermediate slopes (5-7%, 10-12%and 15-17%). On these plots, the forest floor was removed by raking the plot with flexible tine rakes to remove the O horizon and leave bare mineral soil exposed with a minimal amount of disturbance to the soil as possible.

Plot characterization

Prior to the first simulation run, surface cover type was classified as leaf litter, branch litter <4 cm diameter, coarse wood >4 cm diameter, or bare soil using a diagonal transect across each plot, with measurements at 10 cm intervals. These data are included in Appendix A. Where an O horizon was present, the depth to mineral soil was recorded to 0.1 cm and the A horizon thickness and texture was recorded for each plot (Table 2.1). Additionally, overstory and understory basal area was measured and recorded by species, and age of two dominant trees on or immediatly adjacent to the experimental plots were determined by increment coring.

Runoff simulation

Before running the experiment with kaolin and phosphorus added, a water only experiment was run to evaluate background concentrations of sediment and phosphorus.. Each plot had water applied to it in the manner described below with no sediment or chemicals added. Samples were analyzed as described below. Also in order to evaluate residual effects of the first chemical experiment, another water-only run was conducted between the first and second experimental run on two plots. The results of these water only runs are reported in Table 2.2. Phosphorus concentrations were low and did not change significantly across the 10 m plot. We were apprehensive that after an experimental run the plots would become loaded with sediment and phosphorus and we might have a problem with hysteresis. But, phosphorus concentrations were actually lower during the second water run than in pretreatment water runs. Sediment concentrations were low and did not change significantly between pre and post treatment. Overall, comparison of pre-chemical and post chemical indicated that the first chemical experiment would not significantly impact the outcome of further chemical experiments. Initial conditions for each chemical overland flow experiment is reported in Table 2.3.

Runoff was simulated by applying a suspension of unwashed kaolinite clay and phosphorus to the upslope edge of the 5-m (wide) by 10-m (deep) plots using a 5-m wide dispersing system similar to one described by McCutcheon et al. (2000) (Figure 2.1). The Soil Conservation Curve Number Method was used to calculate the total runoff volume (around 13000 L) produced in a clear-cut area of 0.16 ha, with a high intensity rainfall event of 50 mm hr^{-1} and a return period of 1 year. These values were based, in part, on results of Rivenbark and Jackson's (in review) survey of upslope conditions leading to SMZ concentration areas and breakthrough occurrence on commercially harvested and regenerated sites in the Georgia Piedmont.

Runoff solution concentrations were formulated on the basis of expected concentrations and content of runoff associated with a rainfall event with a return frequency of one year occurring immediately after fertilizer application. Target phosphorus concentrations were around 1.0 ppm. In addition, commercially mined kaolin was added to the mixture so that the final concentration in applied runoff was 5.0 g L^{-1}. The kaolin was not chemically pre-treated and, consequently, had surface coating of iron oxides that provided some surface adsorption. The kaolin was not dispersed prior to addition and the resulting suspension contained both colloidal sized clay and small aggregates.

To prepare the suspensions, concentrated mixes were prepared in 20 L buckets the day before (approximately 20 hours) each run. Three 1140 L tanks were used to mix the prepared concentrated mixtures with clean water pumped from local wells and delivered to the site in a tanker truck. The concentrated mix and water was mixed in the tanks approximately 10 minutes before being applied to the site. A near constant runoff volume was simulated by sequentially emptying the mixing tanks and using a hand adjusted flow valve to adjust flow rates so that each mixing tank emptied over a 5.5 minute interval. In practice, flow rates were greater when a new tank was started because of greater hydraulic head. During experimental runs approximately 13,680 L were applied to the 10 m long experimental plot. In practice, the volume varied because of the difficulty of precisely leveling mixing tanks in the field, but the volume difference was not large. Simulations were completed in about 70 minutes.

Simulations were conducted at two different times of the year, separated by at least one month, to include variation in antecedent soil moisture. Soil moisture was measured by Time Domain Reflectometry (TDR) (Topp et al. 1980) so that for each plot there was one experiment conducted with a higher antecedent moisture condition. In practice, the difference in soil moisture was small and not significantly different.

Instrumentation and sampling

Four surface runoff and sediment samplers as described by Franklin et al. (2001) were installed on each plot at 2.0, 4.0, 6.0, and 10.0 m from the upslope edge of the SMZ (Figure 1.1). To install samplers, 5 cm holes were bored with a bucket auger, 0.62 cm diameter steel threaded rods set in the holes and the holes filled with cement and capped with soil. Surface collectors were placed on the rods and adjusted to level using standard nuts. Sample collectors were placed immediately behind each surface collector by excavating a hole with a post hole digger and placing two 20 cm diameter capped PVC pipes in the hole. Holes were cut through these pipes to provide access to a 15 cm diameter x 45 cm long sample collector, also constructed of PVC, which was placed within each retaining pipe. These samplers were connected to the appropriate 1/10 or 1/100 sample split outlet port of the surface collectors with PVC pipe. During each simulated runoff event, samples were collected from these PVC collectors as they filled. Samples were also collected from water exiting the flow spreader in order to establish initial concentrations entering the SMZ. Samples were collected in the field and returned to the laboratory for analysis.

Flow pathways and plot water budgets

The degree to which phosphorus, sediment and other materials are retained in SMZs depends on a variety of factors. One of the most important among these is the flow path of water through the SMZ. Dispersed sheet flow will tend to have lower velocities and greater contact with surfaces. This slower movement allows larger particles to settle out and increases contact time with the O horizon and mineral soil which aids in adsorption of soluble contaminants. It is interesting to note that silt and sand sized sediment filtration has been observed to be significant even with concentrated flows moving through SMZs (Ward 2001). Decreased velocities also increase the ability for water to infiltrate into the soil. Velocity measurements were made by attaching a 1 m long string to metal rods that were driven into the ground with one rod being downslope from the other in the active flow path. This allowed for easy mobile measurement of a 1 meter segment of flow path. Then, Formulabs® FTW Red Liquid 50 dye was applied to the flowpath directly uphill of the specified 1 m flow segment so the flow was easily visible even with the forest floor intact. A stopwatch was used to measure the time it took the water to travel the 1 m distance. This was done at 4 locations in the plot (at 1-2 m, 4-5 m, 6-7 m and 9-10 m) when flow was present.

Runoff that was evenly distributed across the upper edge of the experimental plots tended to concentrate as it moved through the SMZ as a result of microtopographic variation even though care was taken to select experimental plots that were uniform in appearance. Width of flowpaths were measured at 0, 2, 4, 6, and 10 meters by stretching a measuring tape across the plot and visually inspecting where flow occured. A summary of flow paths for each slope class is presented in Table 3.2. Flow tended to concentrate as it moved through the plot with a average of only 47% of the plot having surface flow at the lower edge. Since surface flow samplers were installed systematically within experimental plot, some samplers collected little or no runoff and others, that happened to be in a concentrated flow path, collected runoff that represented more than the actual width of the plot they sampled. As a consequence of this, and the limited number of runoff collectors, estimates total runoff volume at each distance obtained using runoff collectors were not accurate.

Initially, two sets of TDR rods were placed within the plot at 0 m, 5 m, and 10 m from the application pipe to measure antecedent moisture conditions. The 0.31 cm diameter stainless steel welding rods were cut to a length of 30 cm and driven into the soil in parallel at a 20 degree angle so that the actual depth to which soil moisture content was measured was 10 cm. (Topp et al. 1980.) Soil moisture measurements were taken just prior to the start of a run, and again at one hour into the run. After the first set of experimental runs were completed, and it became apparent that the surface flow collectors were not adequate for measuring the actual amount of runoff volume at each distance, additional TDR rods were installed so storage data could be used to estimate the amount of runoff exiting the lower edge of the experimental plot.

Each plot was instrumented with additional TDR rods both on and off-side (at a distance of 1 m for all plots and 1 m and 4 m for the 2% slope plot), and downslope from the plots (at 12 m and 14 m), enabling us to measure the moisture increase in a larger volume of soil, and therefore, to develop a better estimate of the quantity of water retained within the SMZ. These additional rods were cut to 30 and 60 cm lengths, and installed vertically to depths of 30 and 60 cm. The final arrangement of TDR rods is shown on Figure 2.1. For estimates of water storage, time-zero moisture content was subtracted from the time-1 hr moisture content at each of the slope locations, then the average of the soil moisture increases were used to calculate a volumetric water increase for the 10 cm deep by 5 m wide by 10 m long soil volume. Water was not believed to infiltrate significantly below a depth of 60 cm in 1 hour, however, this assumption was not specifically tested. Macropore flow which could be significant could have been contributed to flow below 60 cm during the simulation run. Thus our estimates of infiltrated water should be considered low biased.

Application of the Topps equation (Topp et al. 1980) converted TDR readings into volumetric moisture content. The difference between initial soil moisture content and moisture content 1 hour later was then calculated similar to the 10 cm depth calculations. To estimate the amount of water that exited the lower edge of the experimental plot, the water stored in the soil was subtracted from the total amount of water applied. To estimate the minimum amount of water that infiltrated during the runs that only had data for 10 cm depth, an envelope curve was constructed by plotting the relationship between the water retained in the top 10 cm of soil and the volume retained in 30 cm and 60 cm and drawing a line that represents the lower limit of the data (Figures 2.2 and 2.3). The equation of this line was then used to extrapolate the volumes retained in the top 30 and 60 cm of soil. These volumes are a low estimate because all of the actual data points are located either on or above the envelope curve. It is also important to note that the relationship between the 30 cm and 60 cm volumes (Figure 2.4) is significantly ($R^2 = 0.95$) positive. This means that there is a significant additional volume of water being stored between 30 cm and 60 cm. We do not know how much water, if any, is stored below a depth of 60 cm, but the relationship between volumes for 30 cm and 60 cm suggest that some water infiltrated below 60 cm.

Sample analysis

During each sampling event water from collectors and the flow spreader was sampled during the first third, middle third and last third of each run and sub-sampled to a volume of 500 mL. In addition, lab replicates were taken on 10% of the samples as a quality control measure.

Colloidal concentrations were determined using Stokes' Law settling equations for particles in solution by a method developed by Kilmer and Alexander (1949). Water samples were agitated and allowed to settle at 18°C. A pipette was then used to draw off a 5.56 mL sample of water and sediment at a depth of 5 cm after 2 minutes passed and then again after 3 hours and 18 minutes passed. This produced a sample containing particles of 20µm and less and a sample containing particles of 2 µm and less in size for each water sample. These samples were pipetted into small ceramic crucibles that were then dried and weighed to determine the weight of the sample and calculate concentration (g L^{-1}).

Water samples were analyzed for total phosphorus in the soluble fraction and soluble orthophosphates. Orthophosphate phosphorus was measured in samples that were passed through a 0.22 µm Millipore® filter and analyzed on an ALPKEM EnviroFlow 3000™ (Doc. A001976 Rev. D, ALPKEM Div. of O. I. Analytical). This is a colorimetric method that reacts molybdenum and antimony with orthophosphate and reads the absorbance at 880 nm^{-1}. This method is explained in detail in Standard Method for the Examination of Water and Wastewater (Clesceri et al. 1998). Total phosphorus in the soluble fraction was determined using the same analytical methods, but prior to analysis, the phosphorus in samples was hydrolyzed into orthophosphate by a Kjeldahl digestion process.

We attempted to measure total phosphorus on soils so that total P retention could be evaluated. Each filter that was used to obtain dissolved P samples was weighed before filtering and retained after filtering and placed in a drying oven at 60^{E} Celsius and then re-weighed to determine the weight of the soil on the filter. These filters with soil were then digested and analyzed for total phosphorus by methods described in Methods of Soil Analysis: Part 3 Chemical Methods (Sparks et al. 1996). Unfortunately the amount of soil that was attached to the filter was so low (0.02 to 0.4 g) that the amount of phosphorus present could not be measured accurately.

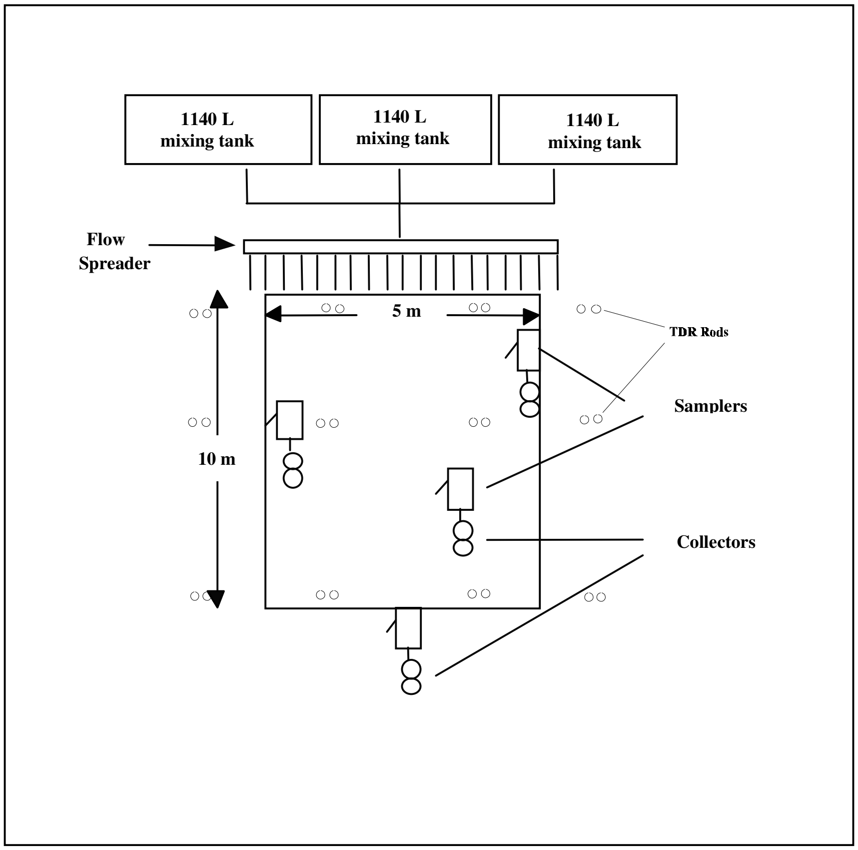

Figure 2.1 Schematic representation of experimental plot for study of SMZ filtering of colloidal clay, and phosphorus.

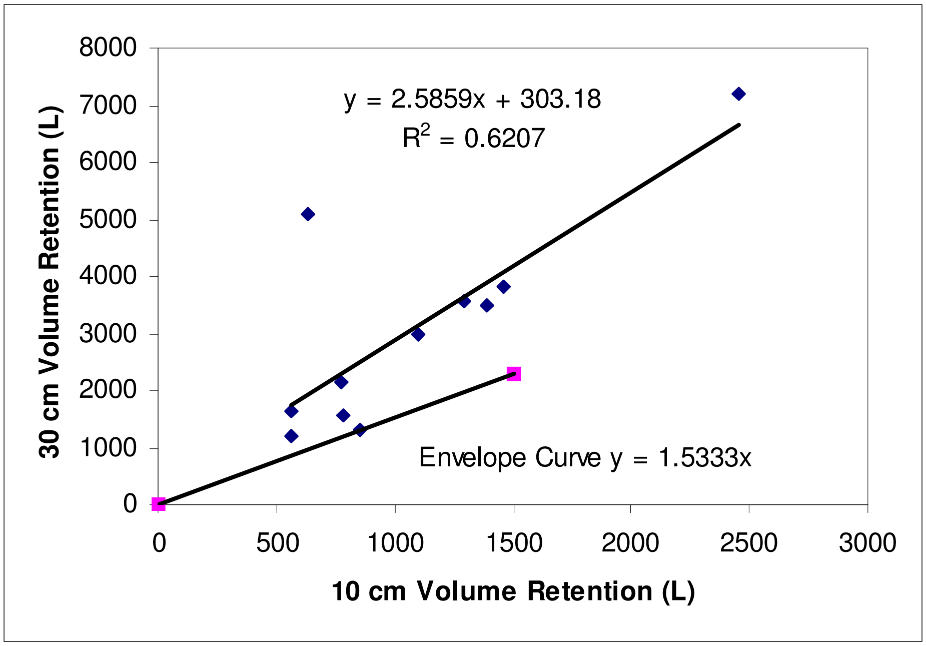

Figure 2.2 Graphical presentation of the relationship between the volume of water retained in the top 10 cm and top 30 cm of soil and a constructed envelope curve showing the lower limit of the relationship.

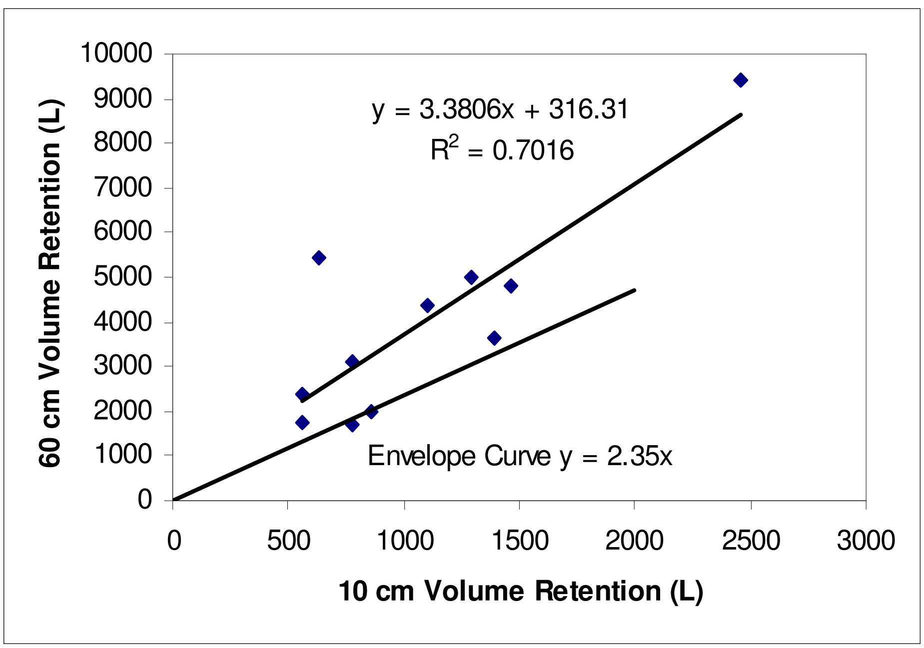

Figure 2.3 Graphical presentation of the relationship between the volume of water retained in the top 10 cm and top 60 cm of soil and a constructed envelope curve showing the lower limit of the relationship.

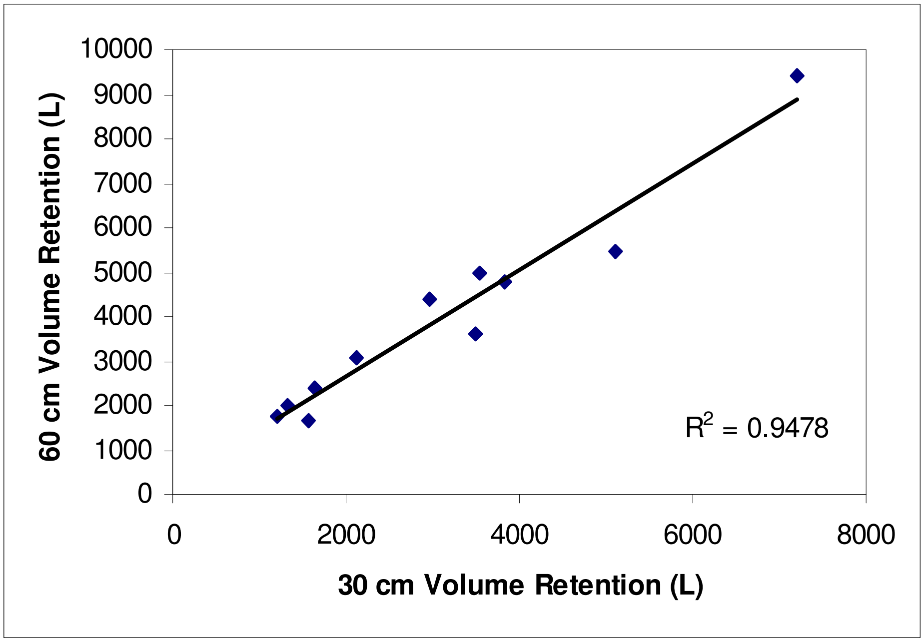

Figure 2.4 Graphical representation of the relationship between the volume of water retained in the top 30 cm of soil and the top 60 cm of soil.

Table 2.1 Slope and vegetative characteristics of SMZs from which intact O horizons samples were collected.

					O Horizon	A Horizon[1]	
Site	Location	Slope Class ---%---	Dominant Overstory Species	Age of Dominant Trees ----yrs----	Average Thickness ----cm----	Texture	Thickness ----cm----
1	Jasper	1-2	Sycamore (*Plantanus occidentalis)* Sweetgum (*Liquidambar styraciflua*) Winged Elm (*Ulmus alata*)	45	1.3 ± 1.5	Silt Loam	15
2	Putnam	5-7	Northern red oak (*Quercus rubra*) Southern red oak (*Quercus falcata*) Mockernut hickory (*Carya tomentosa)* Pignut hickory (*Carya glabra*) Sweetgum (*Liquidambar styraciflua*)	75	2.2 ± 1.2	Sandy Loam	12
3	Clarke	10-12	Southern red oak (*Quercus falcata*) Sweetgum (*Liquidambar styraciflua*)	55	2.7 ± 1.9	Sandy Loam	10
4	Putnam	15-17	Northern red oak (*Quercus rubra*) Southern red oak (*Quercus falcata*) Mockernut hickory (*Carya tomentosa)* Pignut hickory (*Carya glabra*) Sweetgum (*Liquidambar styraciflua*)	90	8.3 ± 2.9	Sandy Loam	10
5	Putnam	20-22	Northern red oak (*Quercus rubra*) Southern red oak (*Quercus falcata*) Mockernut hickory (*Carya tomentosa)* Pignut hickory (*Carya glabra*) Sweetgum (*Liquidambar styraciflua*)	60	6.5 ± 2.3	Sandy Loam	8

[1] Complete soil profile descriptions are found in appendix D.

Table 2.2 Results for control runs showing the amount of water retained on each plot along with initial pollutant concentrations at the application pipe and final concentrations at 10 meters.

				Total Phosphorus*		< 20 µm Size Particle*		< 2 µm Size Particle*	
Location	Slope Class	Date	Water Retained	Input	10 m	Input	10 m	Input	10 m
			----%----	-----µg L^{-1}------		---------g L^{-1}---------			
Jasper	1-2%	02/07/02	18	0.1	.19	0.2	0.16	0.07	0.1
Putnam	5-7%	12/11/01	32	0.14	.18	0.08	0.11	0.04	0.08
Clarke	10-12%	11/14/01	ND	0.14	0.15	0.09	0.17	0.14	0.19
Clarke	10-12%	02/28/02	37[1]	ND	ND	0.14[1]	0.09[1]	0.04[1]	0.06[1]
Jasper	15-17%	12/05/01	39	0.18	0.05	0.26	0.15	0.05	0.14
Jasper	20-22%	01/17/02	23	0.18	0.19	0.12	0.08	0.06	0.06
Jasper	20-22%	05/01/02	35[1]	0.07[1]	0.06[1]	0.14[1]	0.11[1]	0.7[1]	0.1[1]

ND No data

[1] indicates water only run that occurred after a chemical run

* no significant difference between initial and final concentrations

Table 2.3 Initial conditions of individual runoff simulation runs

Location	Slope class	Conditions	Date	Initial soil moisture	Mean application rate	Initial P conc	Initial kaolin conc
				%	L min^{-1}	mg L^{-1}	g L^{-1}
Jasper	2%	undisturbed wet	02/14/02	29.0 ± 5.6	144	1.01	2.11
Jasper	2 %	undisturbed dry	06/04/02	16.2 ± 6.9	151	1.32	1.52
Putnam	5 %	undisturbed wet	12/13/01	20.4 ± 4.1	160	0.95	1.94
Putnam	5 %	undisturbed dry	05/24/02	20.4 ± 8.2	173	0.89	2.31
Putnam	5 %	disturbed wet	12/19/01	24.2 ± 2.8	196	1.21	2.3
Putnam	5 %	disturbed dry	05/30/02	18.2 ± 1.0	197	1.26	1.98
Clarke	10 %	undisturbed wet	03/14/02	32.2 ± 3.1	200	1.22	2.6
Clarke	10 %	undisturbed dry	09/21/01	20.9 ± 5.7	156	0.54	2.6
Clarke	10 %	disturbed wet	10/11/01	22.6 ± 0.0	188	0.99	2.35
Clarke	10 %	disturbed dry	05/03/02	30.7 ± 2.7	206	0.67	2.35
Putnam	15 %	undisturbed wet	12/06/01	17.7 ± 1.6	167	0.17	ND
Putnam	15 %	undisturbed dry	05/17/02	21.5 ± 2.5	181	0.89	2.23
Putnam	15 %	disturbed wet	01/10/02	29.6 ± 1.8	167	1.47	2.63
Putnam	15 %	disturbed dry	05/21/02	26.4 ± 5.2	176	0.75	2.33
Putnam	20 %	undisturbed wet	01/24/02	25.9 ± 0.0	196	1.03	2.93
Putnam	20 %	undisturbed dry	05/15/02	22.6 ± 1.7	203	1.06	1.71

CHAPTER 3

RESULTS AND DISCUSSION

Water dynamics

The most important pathways for phosphorus retention in SMZs are settling of sediment with phosphorus adsorbed to it, adsorption of dissolved phosphorus to either forest floor O horizon or mineral soil, and physical infiltration of water into the soil profile. Sediment may either infiltrate or settle out of solution onto the forest floor. Infiltration of water is important because, independent of the concentration, all of the mass of the solutes in the solution that infiltrates are retained in the soil profile unless it reaches groundwater and/or streams either through deep micropore and mesopore percolation or macropore flow. It is therefore necessary to quantify the amount of water retained within the SMZ and retention through this infiltration is related to antecedent moisture conditions.

Table 3.1 summarizes the antecedent moisture conditions and percent moisture increase for each run incrementally to a soil depth of 60 cm and the percent of water retained in the SMZ associated with each depth. Total water retention varied from 18% to 69% with an average of 31% of total water applied being retained within 10 meters of the SMZ (down to 60 cm). In other words, on average, 31% of pollutant attenuation is associated with infiltration alone.

Infiltration is controlled in part by the travel time of water as it flows through the SMZ. Travel time should decrease with slope and increase with O horizon thickness due to higher flow resistance. Travel times on the undisturbed plots ranged from 47 sec m^{-1} on the 2% slope to 11 sec m^{-1} on the 20% slope (Figure 3.1). A lower slope class should result in slower flow travel time because of a smaller difference in head over the same distance traveled as steeper slopes. The 15% undisturbed plot does not conform to this assumption. The travel time was long at 46 sec m^{-1} and this may be explained by the fact that this slope class had the thickest forest floor O horizon.

Removing the O horizon has a major effect on overland flow travel time. Comparison of the 15% undisturbed plot with its corresponding disturbed plot results in a travel time that is much shorter at 4 sec m^{-1}. The phenomenon is similar, though not as great, when the 5% paired plots are compared. There is a 12 sec m^{-1} difference between undisturbed and disturbed conditions. This was not true on the 10% slope class because there was channelization on the 10% undisturbed plot which lead to high velocities. Channelization affected every slope class to some degree where visible surface flow was reduced from 100% at the application pipe to 90% at the 2 m transect and surface flow occurred across only 47% of the plot at the lower edge of the 10 m long plot. A summary of flow paths for each slope class is presented in Table 3.2. This concentration of flow increased flow velocity by increasing depth, thus reducing potential infiltration and pollutant retention within the SMZ.

Sediment retention

Observed reductions in concentrations and mass within the 10-m SMZ for each run are reported in Table 3.3. A significant reduction in sediment concentrations was observed over all slope classes and ranged from 42 - 94 % with an average of 62% reduction of total sediment in suspension. Mass reductions are reported (Table 3.3) based on volume of water retained to a depth of 60 cm. Total sediment mass was reduced between 53 - 96 % and averaged 72 % reduction of total mass across all slope conditions. The primary particle size fraction retained was greater than 20 µm. Particles this size were present because of aggregates of clay remaining after the kaolin was prepared in the mixtures for application. Smaller particles were also retained on plots where velocity was slow enough to allow settling. Retention of the larger sized particles in our study corresponds to an earlier study by Ward and Jackson (in press) that showed that over 70% of coarse sediment was retained from concentrated flows through SMZs in the Georgia Piedmont. It is interesting to note that the highest reductions were in the 15-17% and 20-22% slope classes. This is believed to be because of the thickness of the O horizon on these plots. Average thickness of the O horizon is presented in Table 2.2. The thickness of the forest floor O horizon in this study has shown to be important in slowing flow velocity and increasing retention. Figure 3.2 shows that the percentage of total sediment retained increases as litter thickness increases, though there is an average of approximately 70% retention on slopes where the forest floor O horizon was completely removed. The majority of retention is related to silt size and larger aggregates that readily fall out of solution. Figure 3.3a showsa large amount of sediment is removed in the first 2 meters of the SMZ and that only 2-3% of sediment is removed each meter beyond 2 meters. Sixty-nine percent of total sediment, on average, is retained in the first 2 meters. Rate of reduction decreases after 2 meters because of the lack of retention of colloidal sized particles (2 µm).This idea is reinforced by Figure 3.3b that show the concentration being drastically reduced within the first 2 meters concentrations appear to level off after 4 meters. There is always less retention where the O horizon has been removed, even though most of the sediment also drops out in the first 2 meters in these plots.

A lack of knowledge of dynamics of small particle movement through SMZs in overland flow was the stimulus for investigating < 20 µm size particle and < 2 µm size particle movement through our study plots. Figure 3.4a shows less retention of < 20 μm sized particles than total sediment and more of a correlation with distance. This can be explained by the fact that this size class contains silt sized particles that settle out more slowly than larger particles so that settling would occur more slowly across a longer distance. Figure 3.4b shows that the concentration of <20 μm particles is reduced over 10 meters for undisturbed plots, but it is not reduced for disturbed plots. Mass retention was still significant with an average of 65% retention of < 20 μm sized particles applied on undisturbed plots and 42% retention on disturbed plots. Retention on disturbed plots was primarily due to infiltration of water.

There is no significant retention of colloidal particles within the 10 m SMZ. Any pollutants bound to these particles are not retained. Figure 3.5a represents the retention of < 2 μm size particles, or the true colloidal clay fraction of total sediment, across the 10 m plot. There is no correlation between distance traveled and retention of colloidal particles or the reduction of concentration of these particles in solution (Figure 3.5b). The results are highly variable with an range of 177% increase to 45% decrease on the undisturbed plot with an average of a 51% increase at 10 meters and a standard deviation of 70%. On the disturbed plot there was a range of 30% increase to 39% decrease with an average of 6% decrease in colloidal materials at 10 meters and a standard deviation of 30%.

Phosphorus retention

Phosphorus bound to sediment is retained to the extent sediment is retained. This would normally be a significant portion of the total amount of phosphorus. Peterjohn and Correll (1984) and Lowrance et al. (1984) found that 83% to 95% of the total amount of phosphorus contained in samples was bound to sediments. In this study, the amount of phosphorus bound to soils was low. The kaolin that was used had little iron oxides present and therefore few sites of possible adsorption. This was confirmed by our results. The amount of diammonium phosphate added to our slurry would result in a 1 μgL^{-1} concentration of total phosphorus present including that bound to soil, and initial readings at zero meters during experimental runs gave total soluble phosphorus levels near 1 μgL^{-1}. Therefore, most of the phosphorus added was not bound, but stayed in solution. Because of the lack of adsorption of phosphorus to sediments, the ability of SMZs to retain phosphorus is underestimated in this study. However, if concentrations of adsorbed phosphorus reported by Lowrance et al. (1984) were applied to the mass of sediment reported in this study 60 - 70% of total phosphorus could be retained by the settling of particles alone.

Observed reductions in concentrations and mass of total soluble phosphorus within the 10-m SMZ for each experimental run are reported in Table 3.3. Reduction in total soluble phosphorus concentrations varied from a 3% increase to a 85% decrease with an average of 43% of total soluble phosphorous concentration being reduced within the 10-M SMZ. Even though there was an increase in concentrations in one case and low decreases in other cases, there were significant reductions in mass of total soluble phosphorus observed for all slope classes with a range of 35% to 86% reduction, and an average of 59% reduction in concentration within the experimental plot area.

Figure 3.6 shows that there is a weak positive relationship between slope and total soluble phosphorus retained. This seems counterintuitive, but as was the case with sediment, higher retention is related to O horizon thickness (Figure 3.7) and the slopes with the thickest O horizon are the 15-17% and the 20-22% slopes. There is actually very little change in phosphorus retention from one slope class to another. All slopes were effective in removing phosphorus.

Since most of the sediment was retained in the first 2 meters of the plot, then the phosphorus bound to that sediment also dropped out in the first 2 meters. As silt sized particles settled, phosphorus associated with those particles was retained slowly across the plot in the same manner. All other phosphorus bound to the colloidal clay sized particles was not retained predictably. Since sediment retention was not as great in the disturbed plots, phosphorus bound to soil particles passed through those plots in greater quantities.

Another important pathway for retention is through the adsorption of phosphorus out of solution onto the forest floor O horizon and mineral soil. Phosphorus in solution occurs in two broad categories, organic and inorganic. Dissolved organic phosphorus is usually the majority of total phosphorus in the soluble fraction found in naturally occurring surface waters (Horne and Goldman 1994). This fraction is made up of various types of nucleic acids such as RNA and DNA as well as humic and fulvic acids. These forms are largely unreactive though some are hydrolyzed into orthophosphate that is more reactive. Inorganic phosphorus occurs in the form of orthophosphate and is in general a small portion of total phosphorus in the soluble fraction because of the ability for biota to rapidly consume it and convert it into organic forms. Dissolved inorganic orthophosphate has been found to be a good representation of biologically available phosphorus (BAP) (Wilson and Walker 1989) thus, its importance in considering impacts of runoff on surface waters.

There is an absence of literature concerning the dynamics of phosphorus in overland flow generated during rainstorms. However, the role of biological processes in removing dissolved inorganic phosphorus from overland flow is not likely to be important. Adsorption to organic materials and mineral soil is expected to dominate the process of retention.

Figure 3.8a shows total phosphorus in the soluble fraction retention as it traveled across the 10-m SMZ. There is a weak positive relationship. The largest range of values occurs at 2 meters. This is probably because little of the reactive orthophosphate has adsorbed out of solution and there is a release of humic and fulvic acids from organic material that contain phosphorus. Humic and fulvic acids are readily dissolvable in water (Sumner 2000). In practice, when filtering samples for analysis, there was always brownish discoloration in samples taken during the first third of the run from every collector. This would explain the phenomenon at 2 meters as well as the fact that percentage of total phosphorus in the soluble fraction retained (59%) was less than that of orthophosphate (66%) (Figure 3.9a). While orthophosphate was adsorbed out of solution, organic acids were being added into solution and the effect was a counter-action resulting in lower total phosphorus in the soluble fraction retention. Figure 3.8b and 3.9b show the concentration changes of total phosphorus in the soluble fraction and orthophosphate respectively. Orthophosphate made up about 80% of initial total phosphorus, but was only 63% of the total after traveling 10 m. It is apparent that orthophosphate was more readily retained which reinforces the probability that sorption occurred slowly across the plot and that organic acid release kept total phosphorus concentration up.

Figure 3.9 represents adsorption of orthophosphate out of solution across the 10-m SMZ. There is a significant positive relationship between distance traveled through the SMZ and retention of soluble orthophosphate. As the orthophosphate in solution passes through the SMZ it comes in contact with adsorption sites and is slowly taken out of solution and bound to the organic materials or mineral soil.

The amount of phosphorus that can be bound is a function of the amount of adsorption sites available and the amount of contact time with the possible adsorption sites. Therefore, a thick O horizon has a double effect on adsorption. It provides many sites for adsorption to organic surfaces in addition to the mineral soil and slows the velocity of the flow to increase contact time with possible adsorption sites. As shown in Table 2.2 the slopes with the thickest organic layer are also the steepest slopes. Figure 3.8 shows that the highest retention of total phosphorus in the soluble fraction occurs where the O horizon was the thickest, although, there was an average of 50% retention on the slopes even where the O horizon was removed.

It is important not to overlook the importance of the mineral soil in binding phosphorus out of solution. Meyer (1979) showed that adsorption of inorganic and organic phosphorus compound by sediments occurs rapidly, particularly in fine grained sediments, and may regulate streamwater concentrations of dissolved phosphorus. Since the depth of overland flow is so shallow there is significant contact between water and soil and adsorption of phosphorus out of solution onto the mineral soil may be more important than adsorption onto organic materials. Even so, litter thickness does play an important role in lowering the velocity of overland flow and provides the benefits of low velocity that have already been discussed.

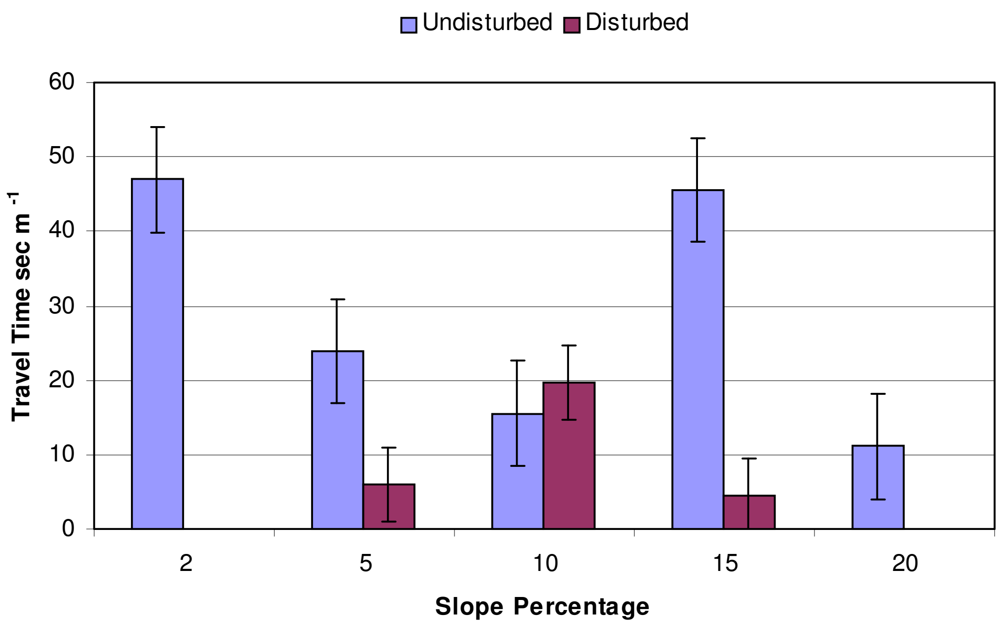

Figure 3.1 Average travel time of simulated overland flow for each slope class comparing undisturbed and disturbed plots

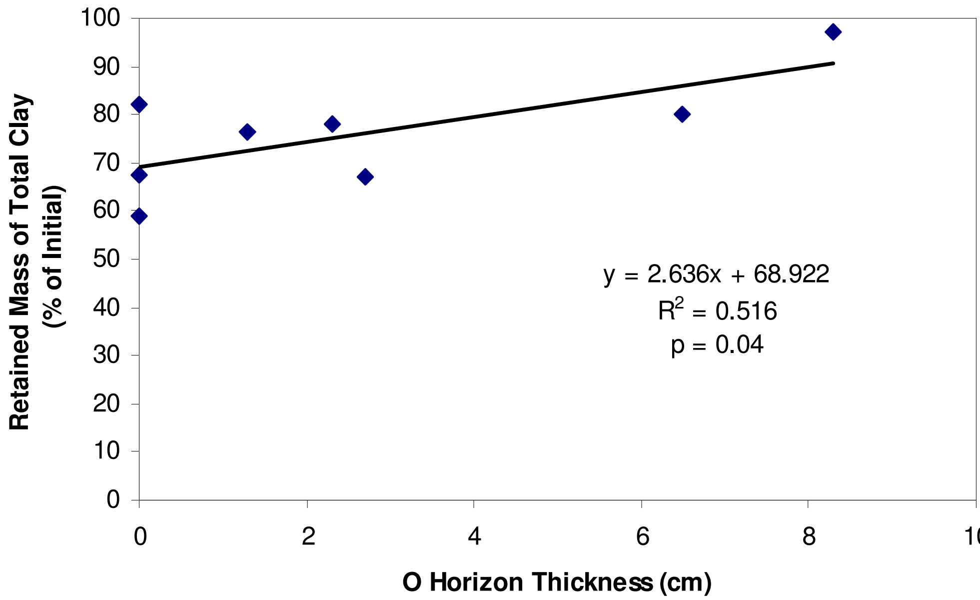

Figure 3.2 Mass of total sediment retained within a 10-m SMZ as related to thickness of forest floor O horizon.

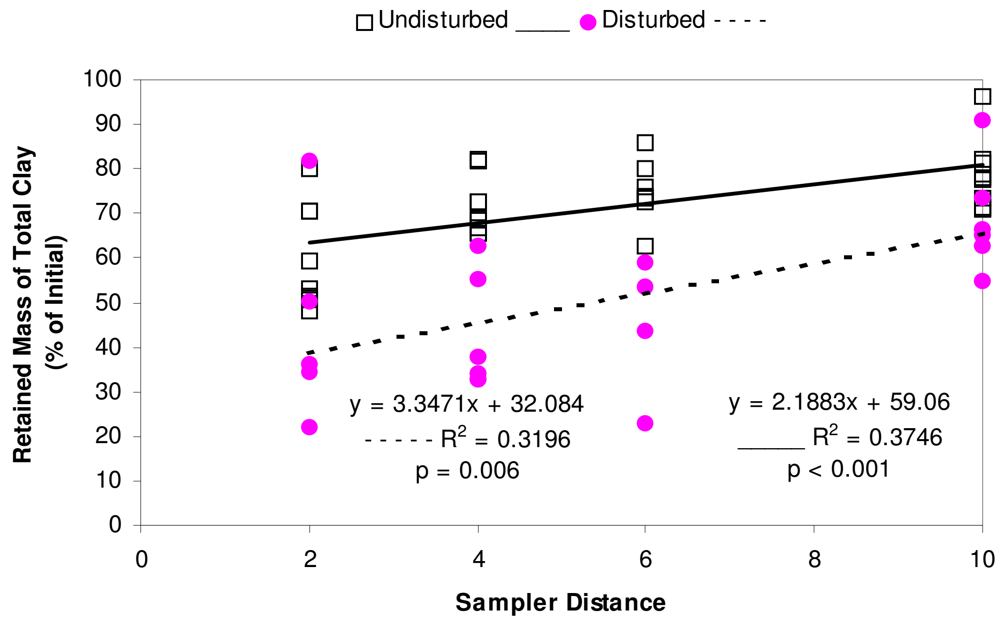

Figure 3.3a Mass of total sediment retained within a 10 - m SMZ related to distance traveled. Undisturbed plots are compared with plots with forest floor removed.

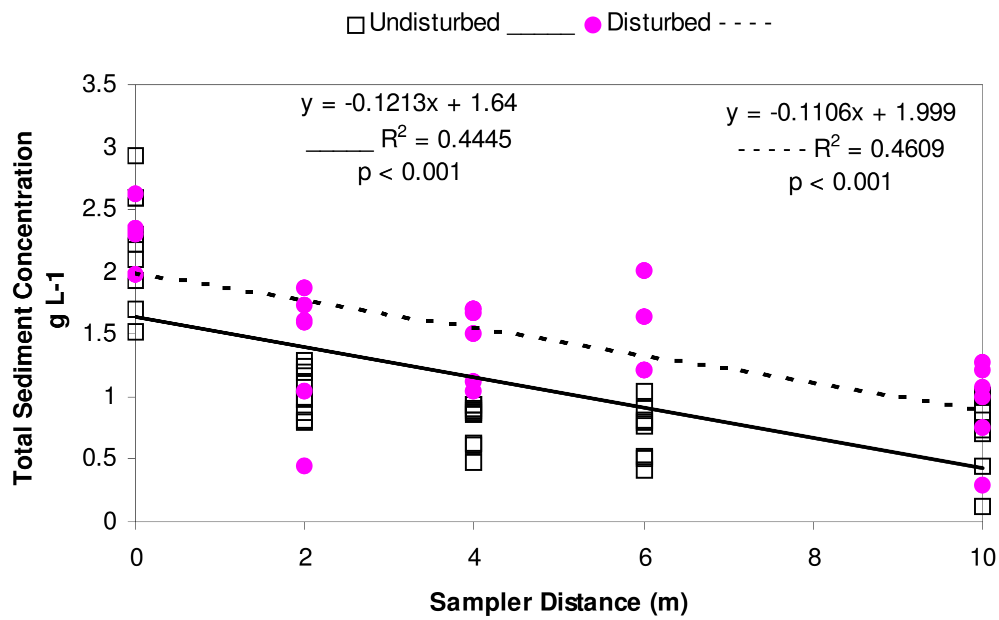

Figure 3.3b Concentration change of total sediment within a 10 - m SMZ related to distance traveled. Undisturbed plots are compared with plots with forest floor removed.

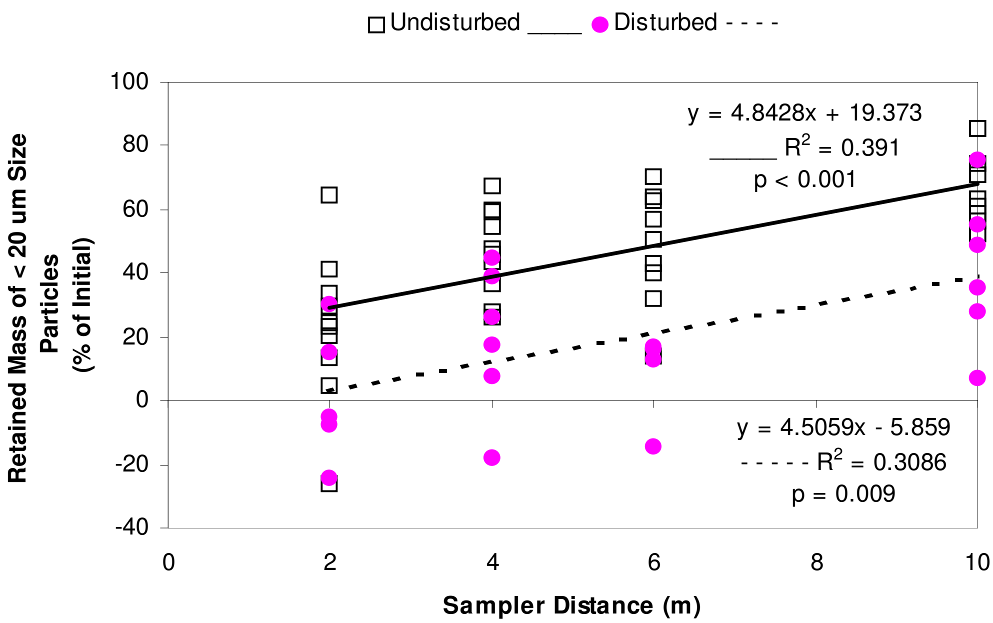

Figure 3.4a Mass of < 20 µm particles retained within a 10-m SMZ as related to distance traveled.

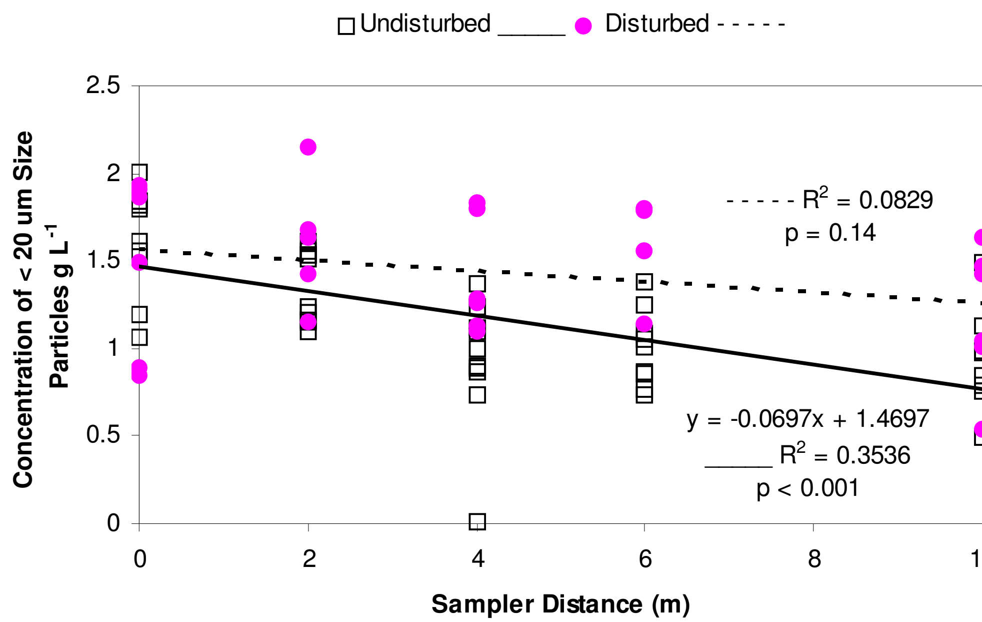

Figure 3.4b Concentration change of < 20 µm particles within a 10-m SMZ as related to distance traveled.

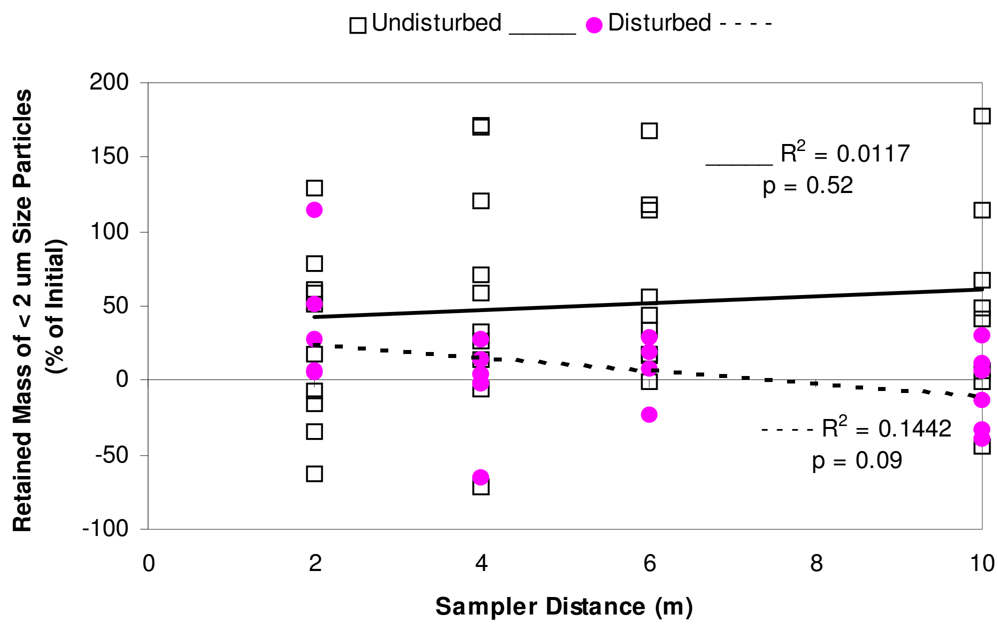

Figure 3.5a Mass of < 2 µm particles retained within a 10-m SMZ as related to distance traveled.

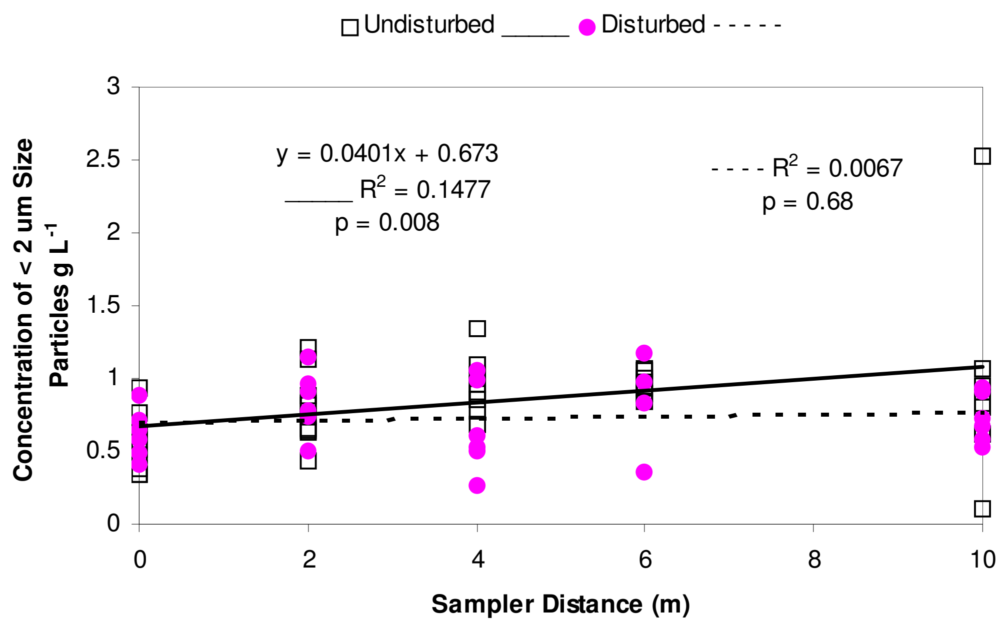

Figure 3.5b Concentration change of < 2 µm particles within a 10-m SMZ as related to distance traveled.

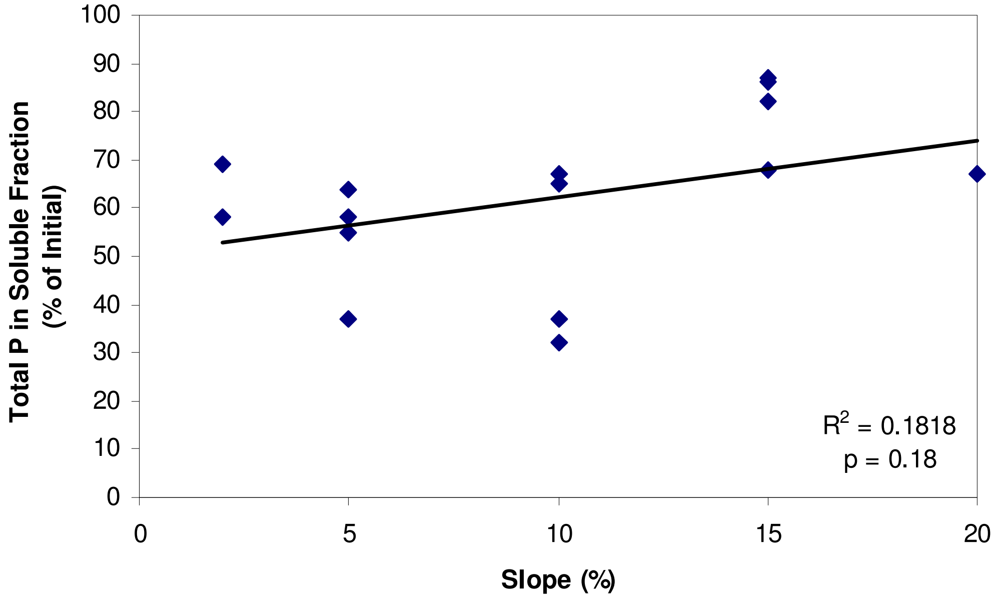

Figure 3.6 Mass of total phosphorus in the soluble fraction retained within a 10-m SMZ as related to slope percentage.

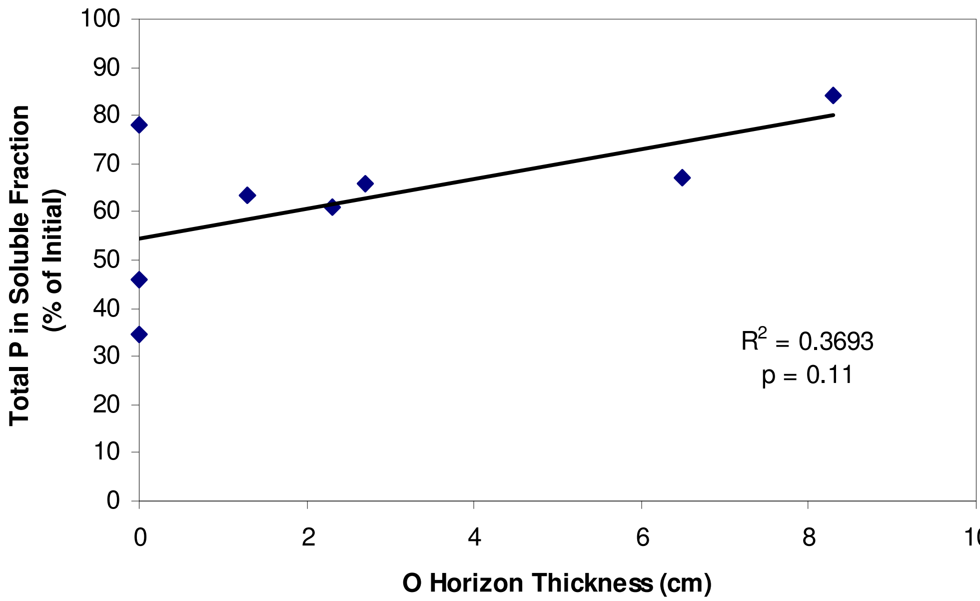

Figure 3.7 Mass of total phosphorus in the soluble fraction retained within a 10-m SMZ as related to thickness of the O horizon.

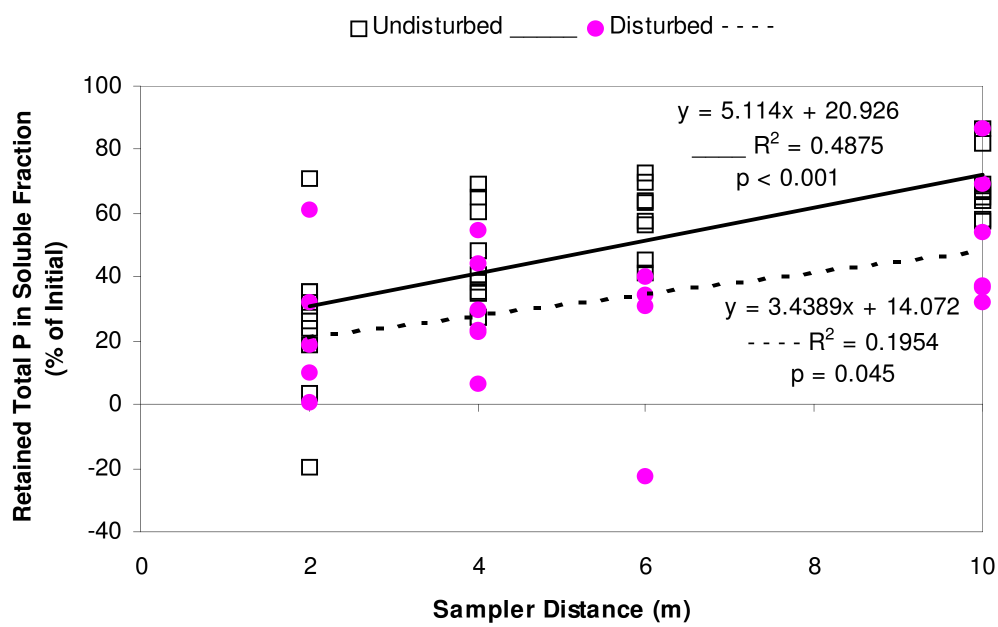

Figure 3.8a Mass of total phosphorus in the soluble fraction retained in a 10-m SMZ as related to distance traveled. Undisturbed plot are compared with plots with the forest floor removed.

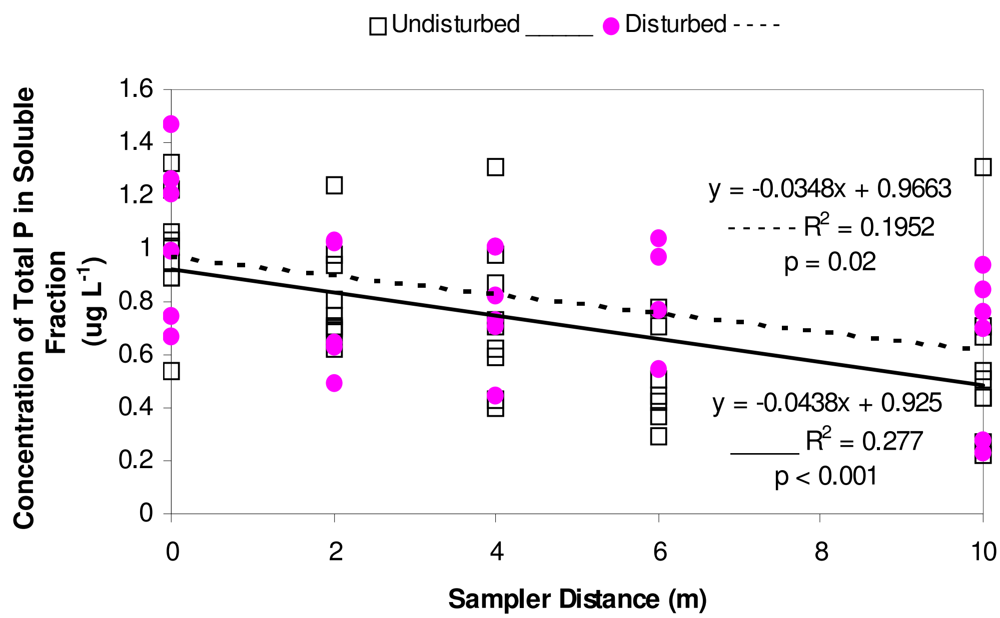

Figure 3.8b Concentration change of total phosphorus in the soluble fraction in a 10-m SMZ as related to distance traveled. Undisturbed plot are compared with plots with the forest floor removed.

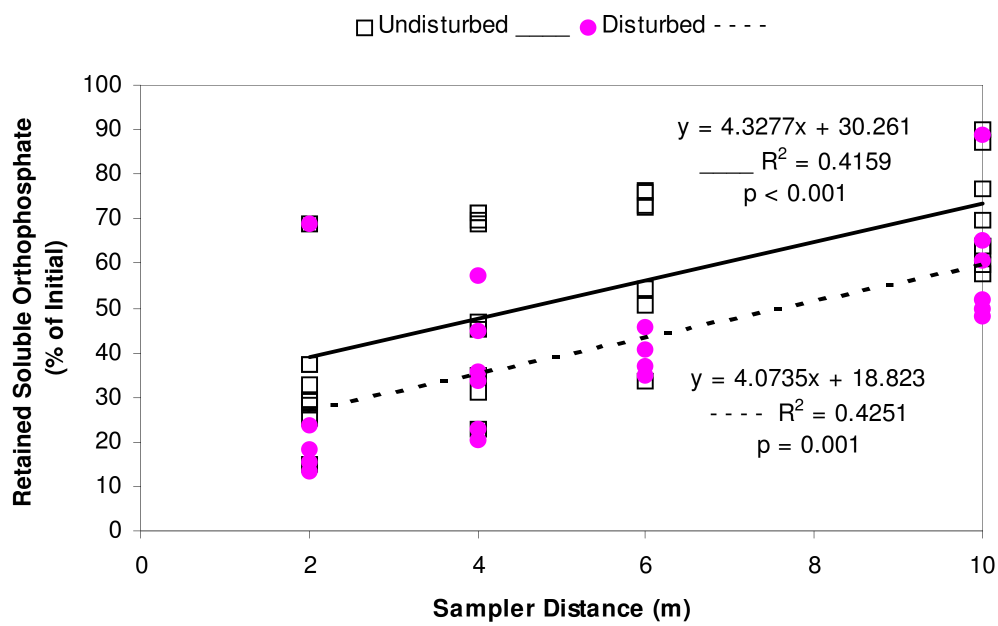

Figure 3.9a Mass of soluble orthophosphate retained in a 10-m SMZ as related to distance traveled. Undisturbed plot are compared with plots with the forest floor removed.

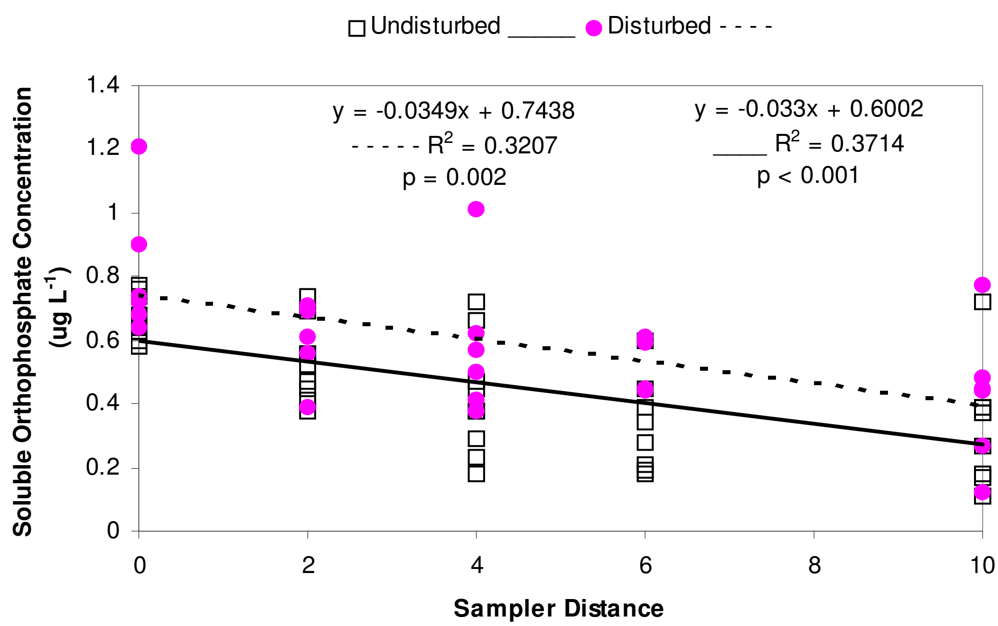

Figure 3.9b Concentration change of soluble orthophosphate in a 10-m SMZ as related to distance traveled. Undisturbed plot are compared with plots with the forest floor removed.

Table 3.1 Initial moisture conditions, percent moisture increase, and percent of total water retained in 10 m deep SMZ for all runoff events.

Location	Slope Class	Conditions	Date	Depth --cm--	Initial Moisture Conditions ----%----	Moisture Increase ----%----	Volume Retained ---%---
Jasper	1-2 %	water only	02/07/02	10	38	8	8
				30	—	—	12*
				60	—	—	18*
Jasper	1-2 %	undisturbed wet	02/14/02	10	29	4.9	5
				30	31.3	13.1	37
				60	32.6	7	40
Jasper	1-2 %	undisturbed dry	06/04/02	10	16.2	18.9	18
				30	19.1	18.5	53
				60	24.2	12.1	69
Putnam	5-7 %	water only	12/11/01	10	22.6	27	14
				30	—	—	21*
				60	—	—	32*
Putnam	5-7 %	undisturbed wet	12/13/01	10	20.4	33.6	17
				30	—	—	26*
				60	—	—	40*
Putnam	5-7 %	undisturbed dry	05/24/02	10	20.4	27.8	14
				30	19.1	23.3	36
				60	28.7	12.1	37
Putnam	5-7 %	disturbed wet	12/19/01	10	24.2	15.3	8
				30	—	—	12*
				60	—	—	18*
Putnam	5-7 %	disturbed dry	05/30/02	10	18.4	15.5	8
				30	24	14.2	22
				60	29.9	10.3	32

Location	Slope Class	Conditions	Date	Depth --cm--	Initial Moisture Conditions ----%----	Moisture Increase ----%----	Volume Retained ---%---
Clarke	10-12 %	water only	02/28/02	10	25.8	18.5	9
				30	26.5	16.9	26
				60	28.8	11.9	37
Clarke	10-12 %	undisturbed wet	03/14/02	10	32.2	11.2	6
				30	32.8	11	17
				60	32.9	8	25
Clarke	10-12 %	undisturbed dry	09/21/01	10	21	25.5	13
				30	—	—	20*
				60	—	—	31*
Clarke	10-12 %	disturbed wet	05/03/02	10	30.6	11.2	6
				30	35.1	8.1	12
				60	34.4	5.9	18
Clarke	10-12 %	disturbed dry	10/11/01	10	22.6	29	15
				30	—	—	24*
				60	—	—	35*
Putnam	15-17 %	water only	12/5/01	10	14.9	30.5	16
				30	—	—	26*
				60	—	—	39*
Putnam	15-17 %	undisturbed wet	05/17/02	10	21.5	22	11
				30	22	18.8	29
				60	26.8	14.6	45
Putnam	15-17 %	undisturbed dry	12/06/01	10	17.7	32.5	16
				30	—	—	25*
				60	—	—	39*
Putnam	15-17 %	disturbed wet	01/10/02	10	29.6	13.1	7
				30	—	—	10*
				60	—	—	16*

Location	Slope Class	Conditions	Date	Depth --cm--	Initial Moisture Conditions ----%----	Moisture Increase ----%----	Volume Retained ---%---
Putnam	15-17 %	disturbed dry	05/21/02	10	26.3	15.6	8
				30	32.4	10.4	16
				60	36.3	5.6	17
Putnam	20-22 %	water only	01/17/02	10	18.2	28.1	14
				30	—	—	22*
				60	—	—	34*
Putnam	20-22 %	water only	05/01/02	10	16.6	20.9	11
				30	19.1	18.2	28
				60	28.7	11.4	35
Putnam	20-22 %	undisturbed wet	01/24/02	10	25.9	19.4	14
				30	—	—	15*
				60	—	—	23*
Putnam	20-22 %	undisturbed dry	05/15/02	10	22.6	17.1	9
				30	28.4	8.8	14
				60	32.2	6.6	20

* extrapolated data

Table 3.2 Concentration of surface flow within 10 m long runoff simulation plots within SMZ's of various slopes.

Distance	Slope Class				
	1-2 %	5-7%	10-12%	15-17%	20-22%
m	----------------------- % of Initial Width -----------------------				
0	100	100	100	100	100
2	88	97	85	99	80
4	86	90	79	81	62
6	66	93	40	73	76
10	29	38	50	58	58

Table 3.3 Concentration and mass reduction expressed as a percentage of total clay and total phosphorus for each experimental plot with varying antecedent moisture conditions.

				Concentration Reduction		Mass Reduction	
Location	Slope class	Conditions	Date	Total Phosphorus	Total Sediment	Total Phosphorus	Total Sediment
				------- % -------			
Jasper	1-2 %	undisturbed wet	02/14/02	29	50	53	68
Jasper	1-2 %	undisturbed dry	06/04/02	1	42	58	76
Putnam	5-7 %	undisturbed wet	12/13/01	30	62	53*	75*
Putnam	5-7 %	undisturbed dry	05/24/02	42	62	60	76
Putnam	5-7 %	disturbed wet	12/19/01	22	45	34*	53*
Putnam	5-7 %	disturbed dry	05/30/02	33	46	50	62
Clarke	10-12 %	undisturbed wet	03/14/02	59	62	65	59
Clarke	10-12 %	undisturbed dry	09/21/01	49	62	53*	71*

				Concentration Reduction		Mass Reduction	
Location	Slope class	Conditions	Date	Total Phosphorus	Total Sediment	Total Phosphorus	Total Sediment
Clarke	10-12 %	disturbed wet	05/03/02	-3	48	35	67
Clarke	10-12 %	disturbed dry	10/11/01	23	48	26*	63*
Putnam	15-17 %	undisturbed wet	05/17/02	76	94	85	96
Putnam	15-17 %	undisturbed dry	12/06/01	70	ND	80*	ND
Putnam	15-17 %	disturbed wet	01/10/02	85	89	86*	90*
Putnam	15-17 %	disturbed dry	05/21/02	63	67	68	72
Putnam	20-22 %	undisturbed wet	01/24/02	57	76	66*	80*
Putnam	20-22 %	undisturbed dry	05/15/02	58	74	66	78

* extrapolated data

CHAPTER 4

CONCLUSIONS

Water entering SMZs as dispersed sheet-flow does not remain evenly distributed across the forest floor. Channelization and microtopography dictate flowpaths. However, a 10-m SMZ is still effective in filtering sediment and phosphorus from overland flow. Infiltration of water is an important pathway for retention of pollutants. An average of 31% of retention of phosphorus and sediment was due to infiltration alone.

Coarse sediment was readily retained in the first 2 meters of the SMZ. Smaller particles are not retained as well. The < 20 μm size class of particles was somewhat retained in plots where the forest floor O horizon was not disturbed, but retention in disturbed plots retention was low and primarily due to infiltration. The < 2 μm sized particles were not retained significantly in either disturbed or undisturbed plots.

Total phosphorus in the soluble fraction was retained significantly in both disturbed and undisturbed plots with more being retained on undisturbed plots. Orthophosphate was also retained significantly during both disturbed and undisturbed conditions. A higher percentage of orthophosphate than total phosphorus in the soluble fraction. It is belive that this was due to an influx of readily soluble organic acids.

Slope class was hypothesized to be an important factor in pollutant retention with steeper slopes being less effective, but pollutant retention was significant in every slope class. O horizon thickness is important in aiding retention by slowing flow velocity allowing settling of particles and increased contact for adsorption of phosphorus out of solution. Ten meter SMZs are wide enough to retain large amounts of pollutants from overland flow.

Further research that needs to be conducted is an evaluation of how frequently dispersed sheet-flow enters SMZs. It is not known if this phenomenon occurs frequently or if most overland flow enters SMZs as already channelized flow. It is also not known how much of the water that infiltrates the soil goes through macropores, straight to streams or ground water. More replicates of experiments need to be done with varying slopes and O horizon thicknesses to be able to say more confidently which characteristics are the most important in filtering pollutants from overland flow.

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APPENDIX A

Surface conditions of 5 sites used for evaluating pollutant retention in the Streamside Management Zones (SMZs) adjacent to managed forests in the Georgia Piedmont of the Southern United States. Information provided for undisturbed plots and plots from which the O horizon was removed by hand raking.

Slope Class and Condition	Leaf Litter (O horizon)	Sticks (< 4 mm)	Branches (>4 mm or Exposed Roots	Mineral Surface (A horizon)
	--------------------------Exposed Surface %--------------------------			
0-2%				
Undisturbed	92	6	0	2
5-7%				
Undisturbed	92	7	1	0
Disturbed	17	5	3	75
10-12%				
Undisturbed	65	19	3	13
Disturbed	ND[1]	ND[1]	ND[1]	ND[1]
15-17%				
Undisturbed	86	10	3	1
Disturbed	36	0	0	64
20 %				
Undisturbed	93	2	3	2

[1] No Data

APPENDIX B

Sediment concentration changes for the < 20 µm and < 2 µm size particles within 10-m SMZs. Each experimental run is represented showing both wet and dry experiments and disturbed vs. undisturbed plots.

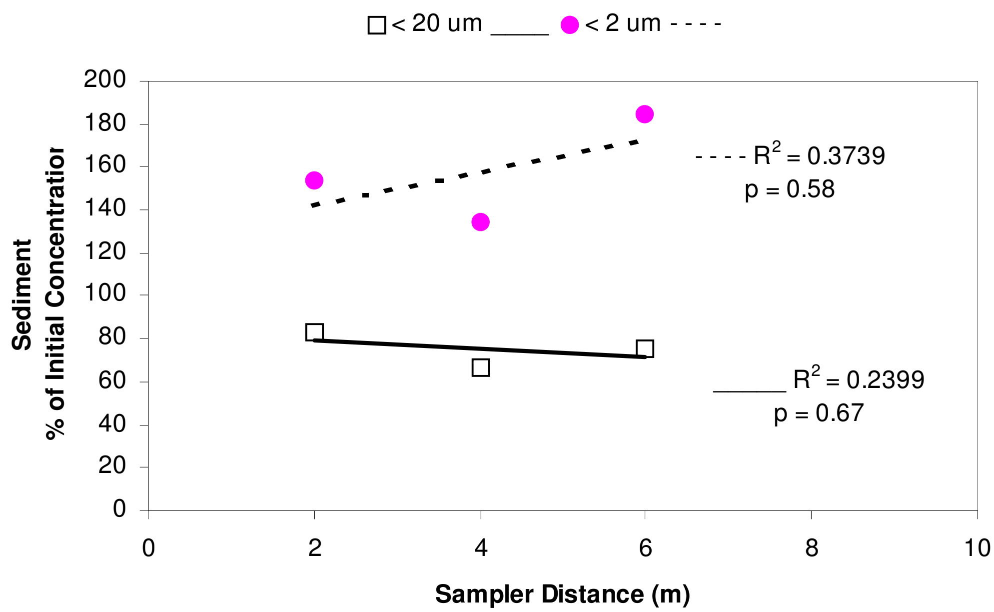

Figure B.1 Two percent slope with wet antecedent moisture conditions

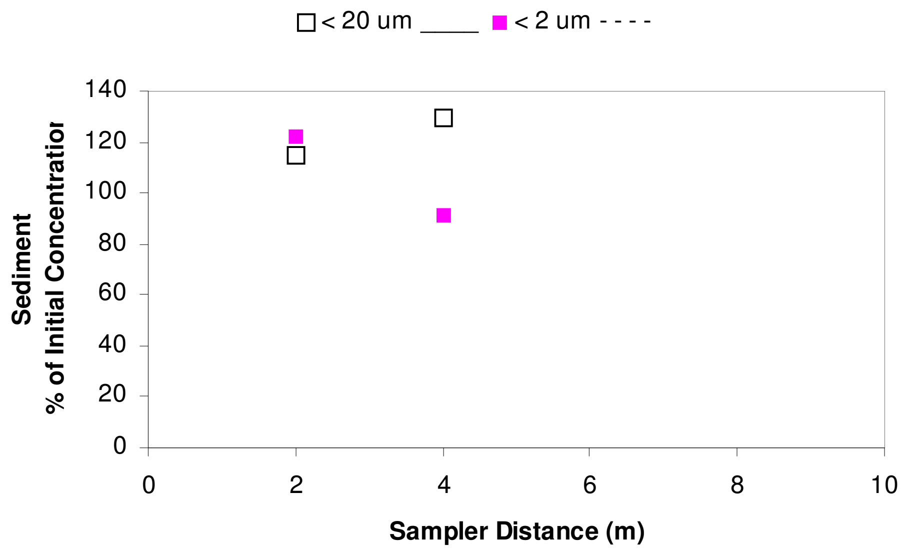

Figure B.2 Two percent slope with dry antecedent moisture conditions

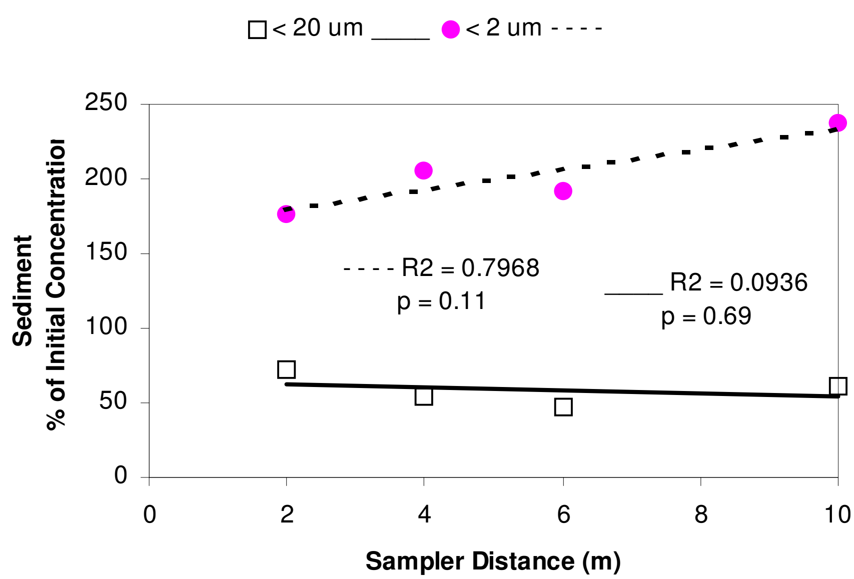

Figure B.3 Five percent slope undisturbed plot with wet antecedent moisture conditions

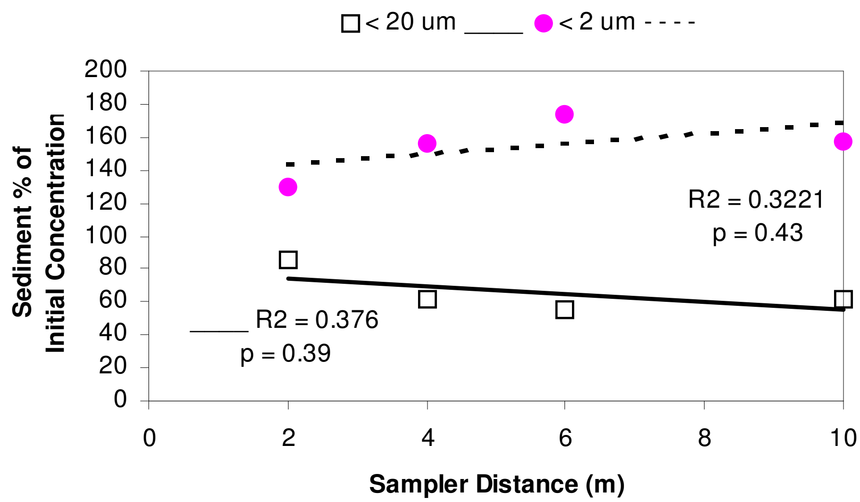

Figure B.4 Five percent slope undisturbed plot with dry antecedent moisture conditions

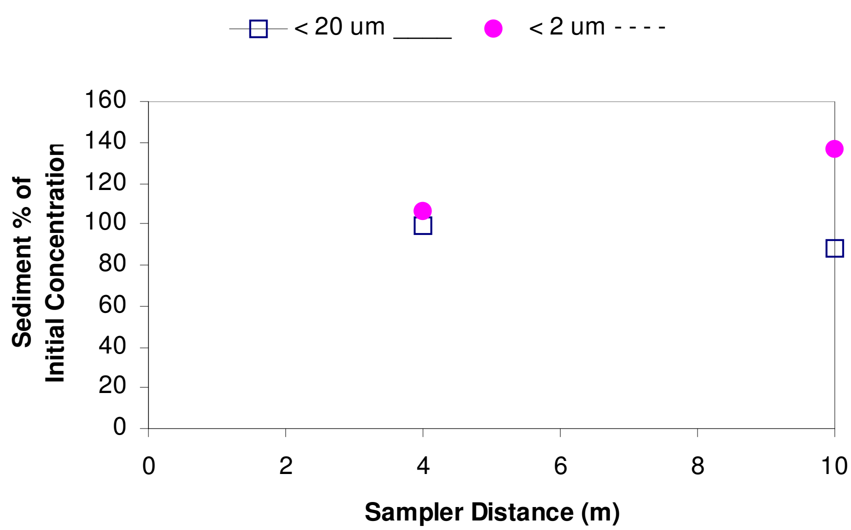

Figure B.5 Five percent slope disturbed plot with wet antecedent moisture conditions

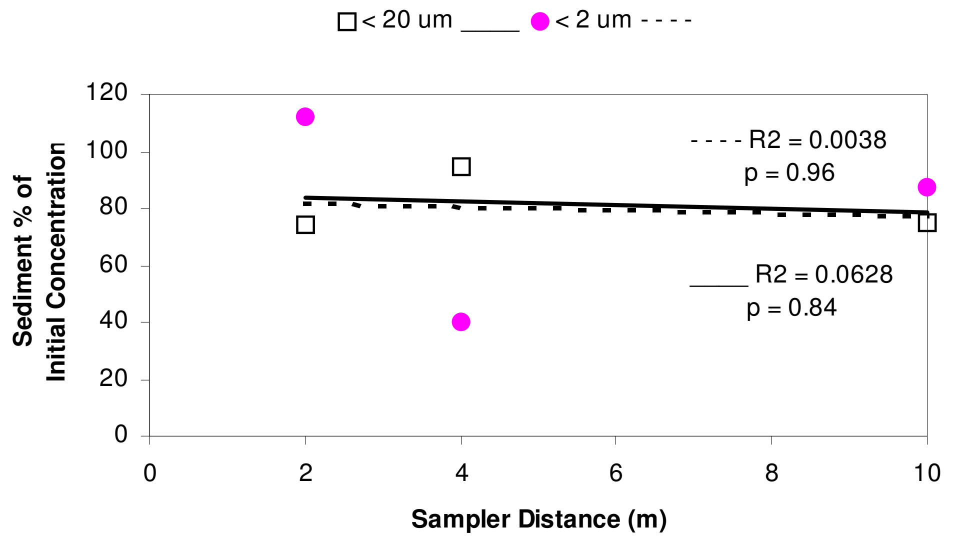

Figure B.6 Five percent slope disturbed plot with wet antecedent moisture conditions

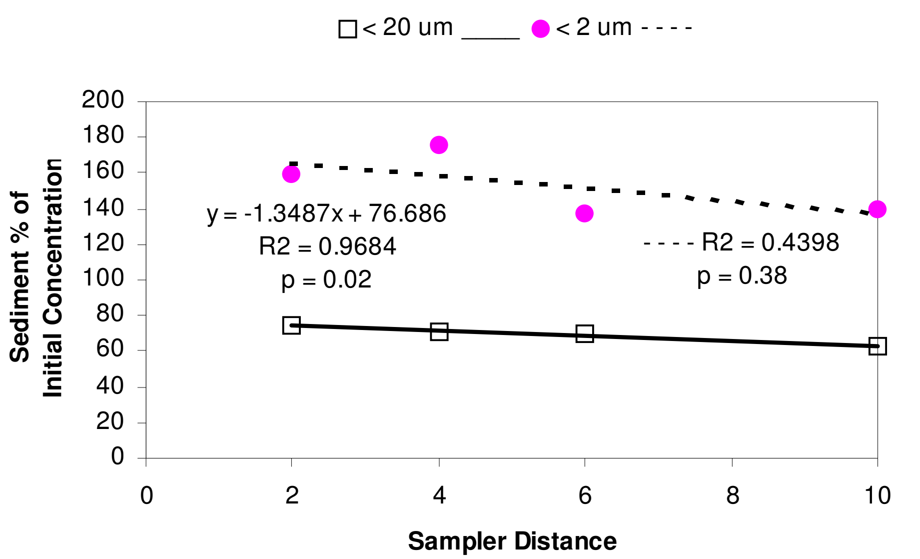

Figure B.7 Ten percent slope undisturbed plot with wet antecedent moisture conditions

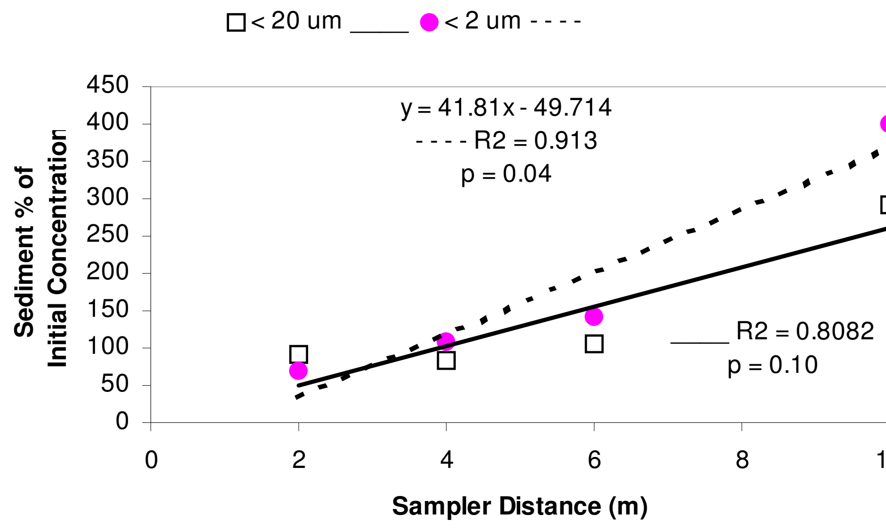

Figure B.8 Ten percent slope undisturbed plot with dry antecedent moisture conditions

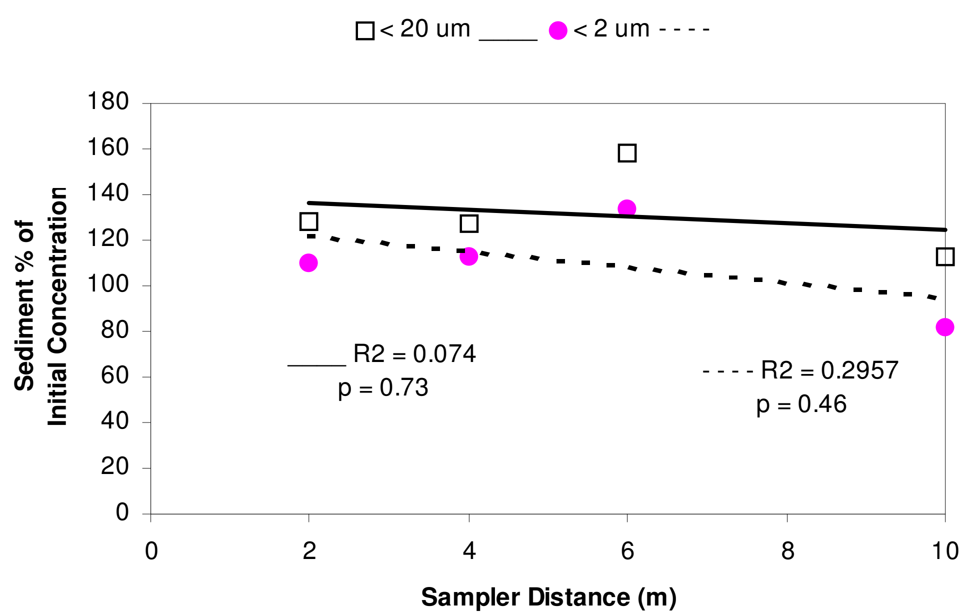

Figure B.9 Ten percent slope disturbed plot with wet antecedent moisture conditions

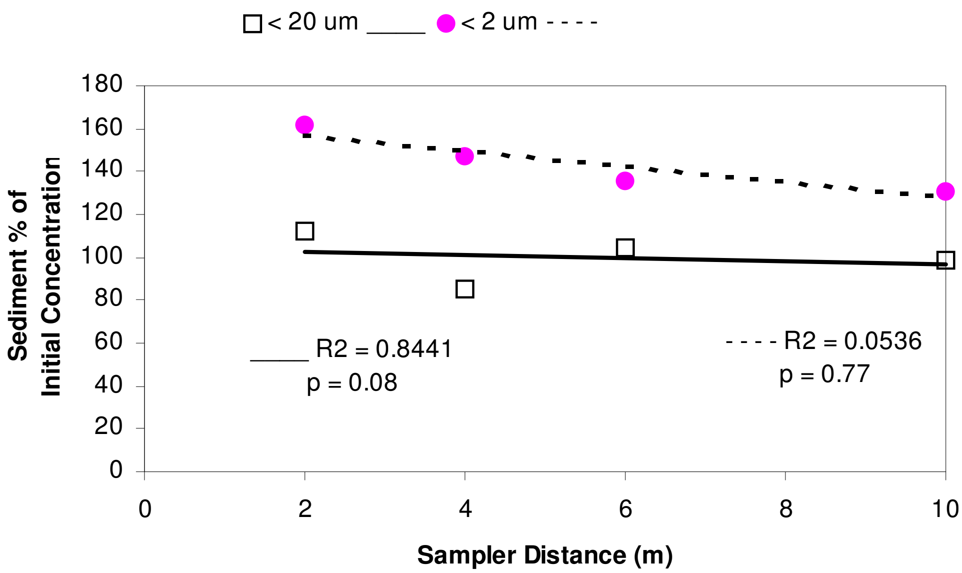

Figure B.10 Ten percent slope disturbed plot with dry antecedent moisture conditions

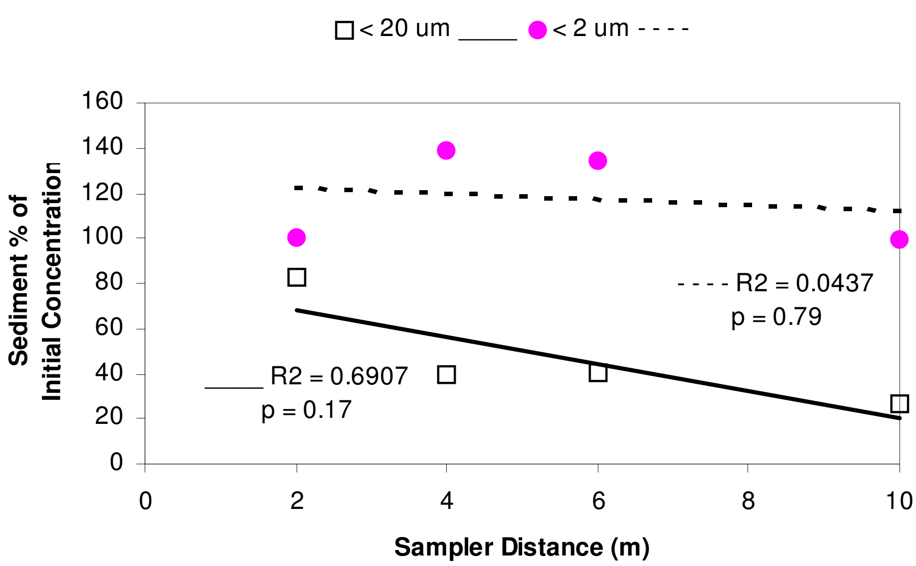

Figure B.11 Fifteen percent slope undisturbed plot with wet antecedent moisture conditions

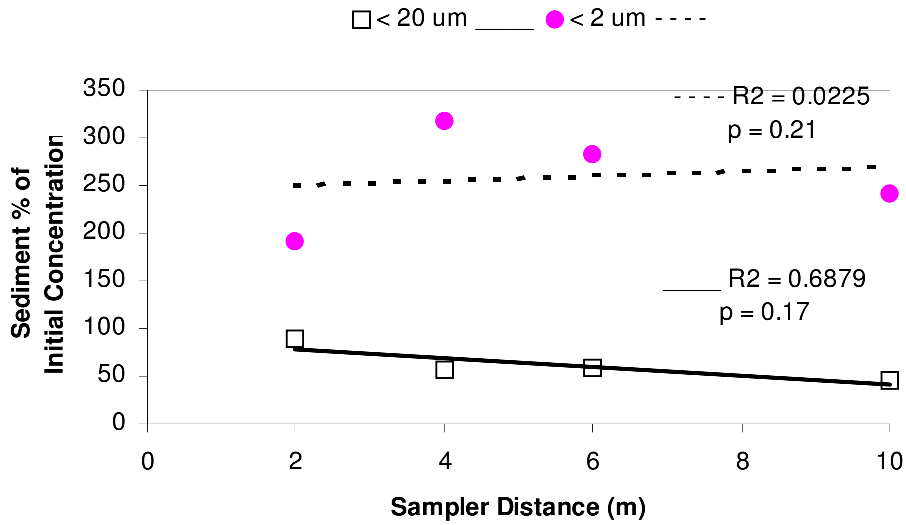

Figure B.12 Fifteen percent slope undisturbed plot with dry antecedent moisture conditions

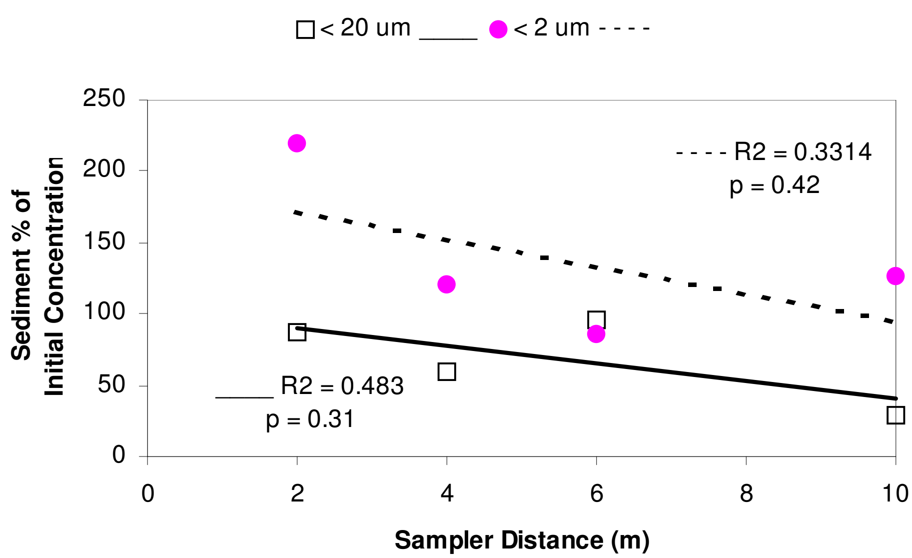

Figure B.13 Fifteen percent slope disturbed plot with wet antecedent moisture conditions

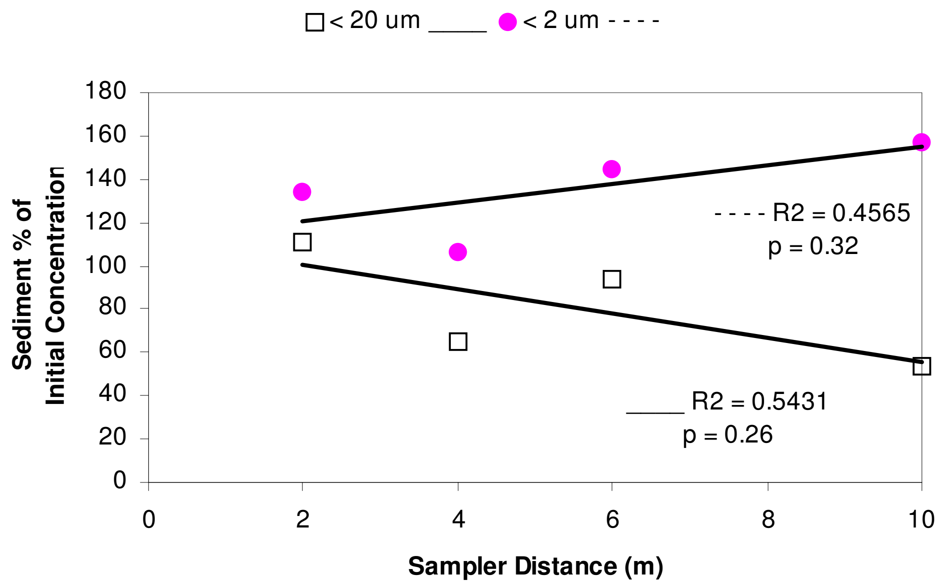

Figure B.14 Fifteen percent slope disturbed plot with dry antecedent moisture conditions

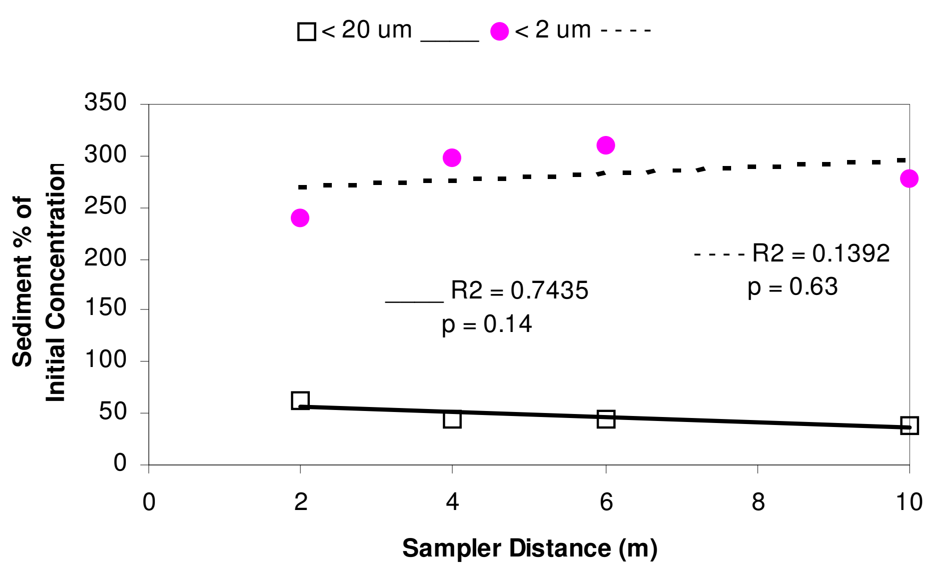

Figure B.15 Twenty percent slope with wet antecedent moisture conditions

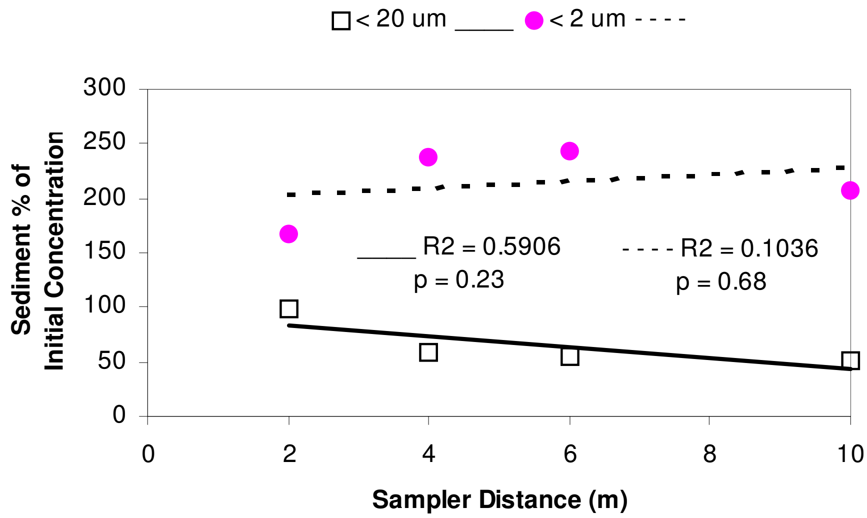

Figure B.16 Twenty percent slope with dry antecedent moisture conditions

APPENDIX C

Concentration reduction of total phosphorus in the soluble fraction and orthophosphate presented as the percentage of initially applied concentration left in solution after traveling through the SMZ. Each experimental run is represented showing both wet and dry experiments and disturbed vs. undisturbed plots.

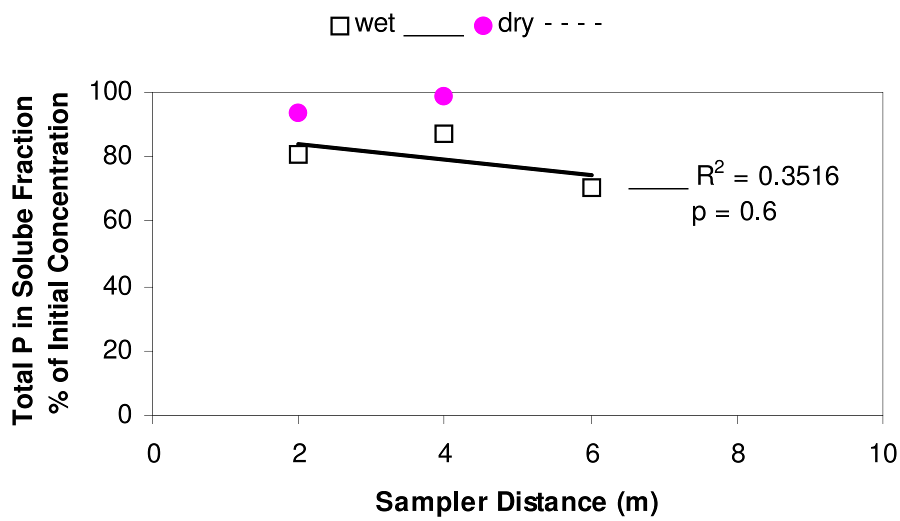

Figure C.1 Total phosphorus in the soluble fraction concentration reduction during wet and dry conditions on the two percent slope plot

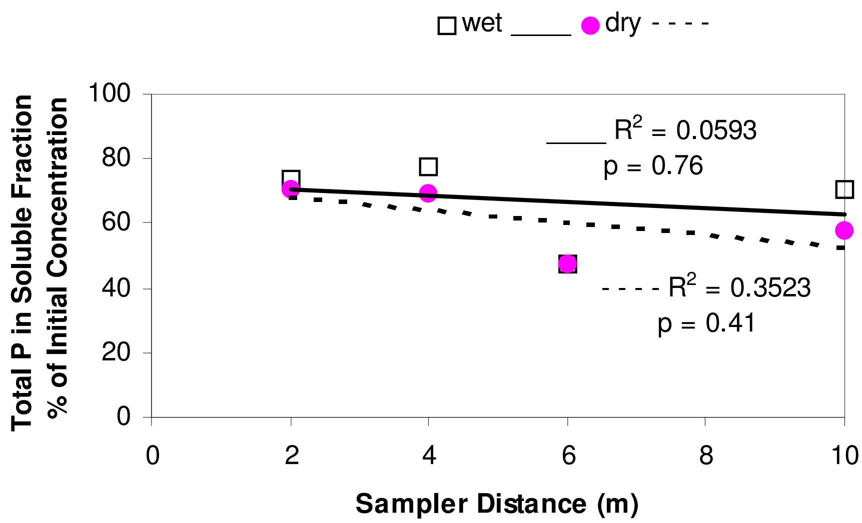

Figure C.3 Total phosphorus in the soluble fraction concentration reduction during wet and dry conditions on the five percent slope undisturbed plot

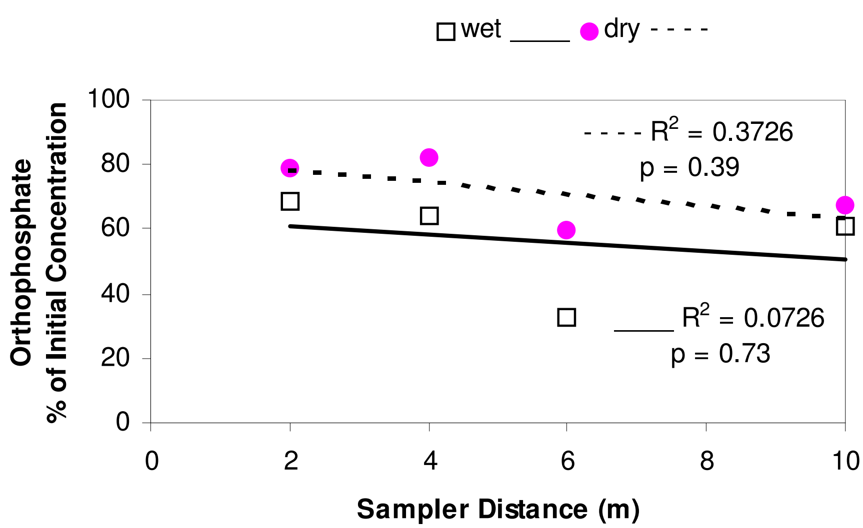

Figure C.4 Orthophosphate concentration reduction during wet and dry conditions on the five percent slope undisturbed plot

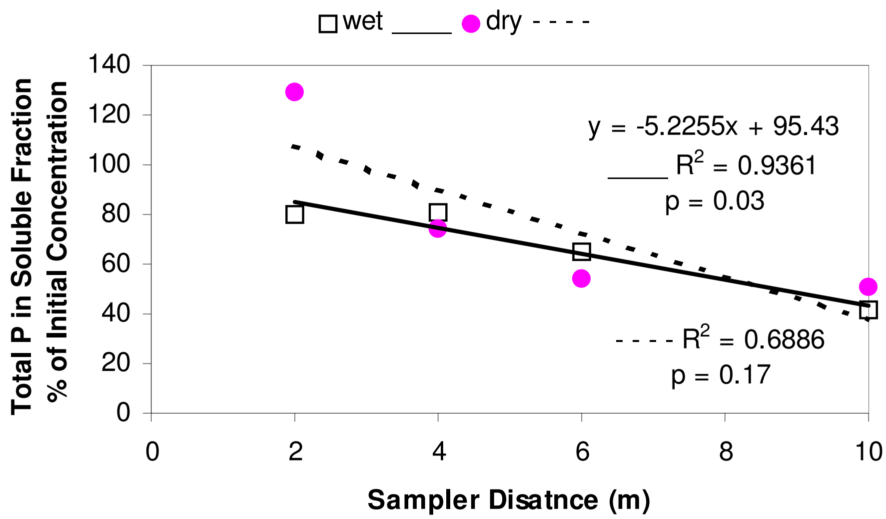

Figure C.5 Total phosphorus in the soluble fraction concentration reduction during wet and dry conditions on the five percent slope disturbed plot

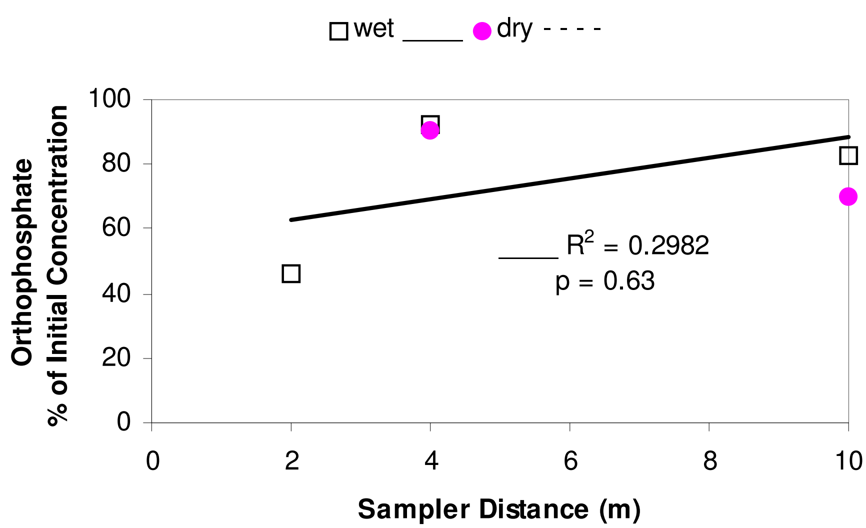

Figure C.6 Orthophosphate concentration reduction during wet and dry conditions on the five percent slope disturbed plot

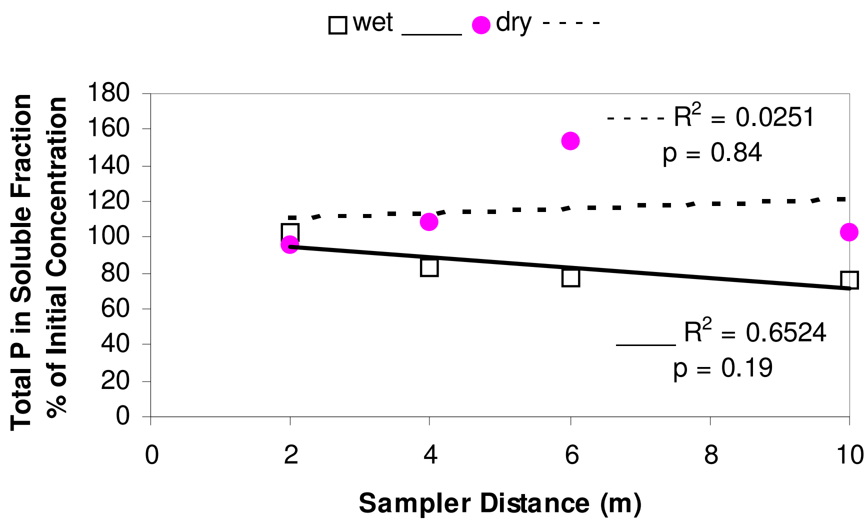

Figure C.7 Total phosphorus in the soluble fraction concentration reduction during wet and dry conditions on the ten percent slope undisturbed plot

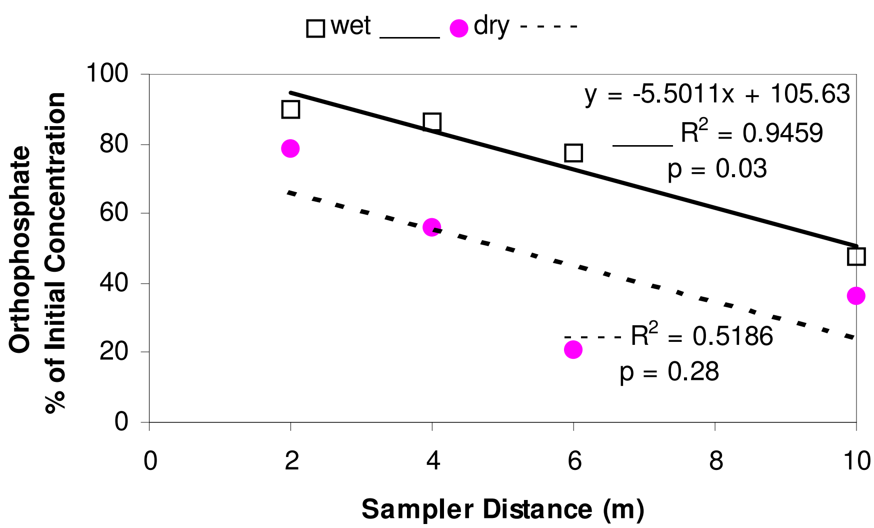

Figure C.8 Orthophosphate concentration reduction during wet and dry conditions on the ten percent slope undisturbed plot

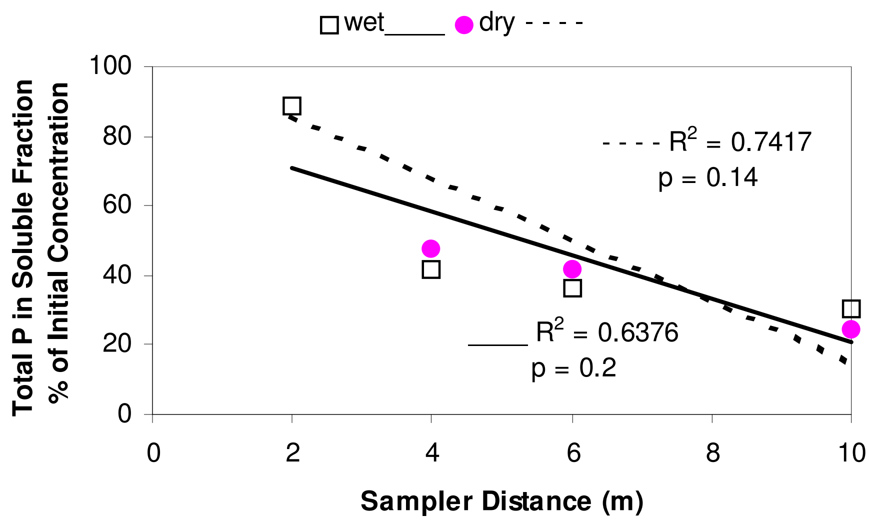

Figure C.9 Total phosphorus in the soluble fraction concentration reduction during wet and dry conditions on the ten percent slope disturbed plot

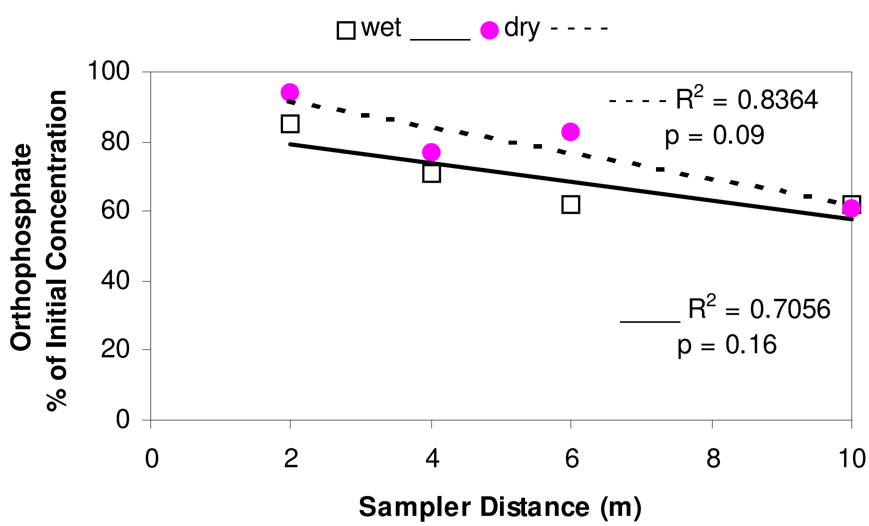

Figure C.10 Orthophosphate concentration reduction during wet and dry conditions on the ten percent slope disturbed plot

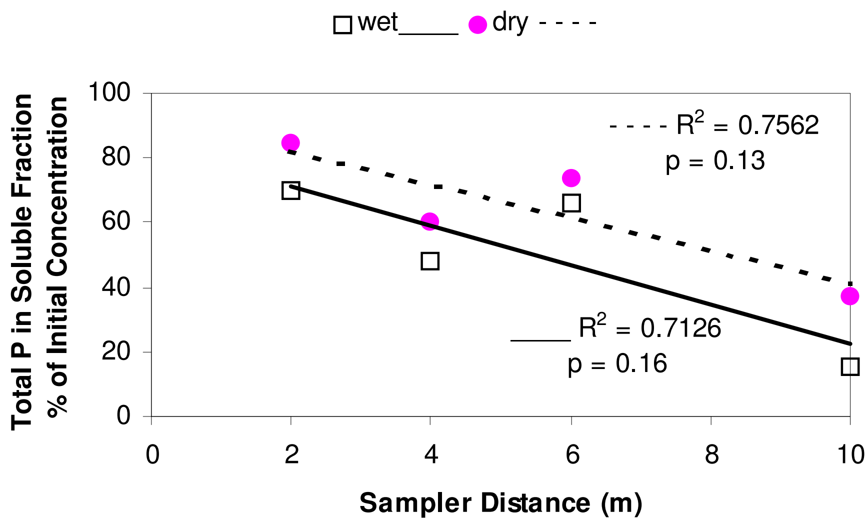

Figure C.11 Total phosphorus in the soluble fraction concentration reduction during wet and dry conditions on the fifteen percent slope undisturbed plot

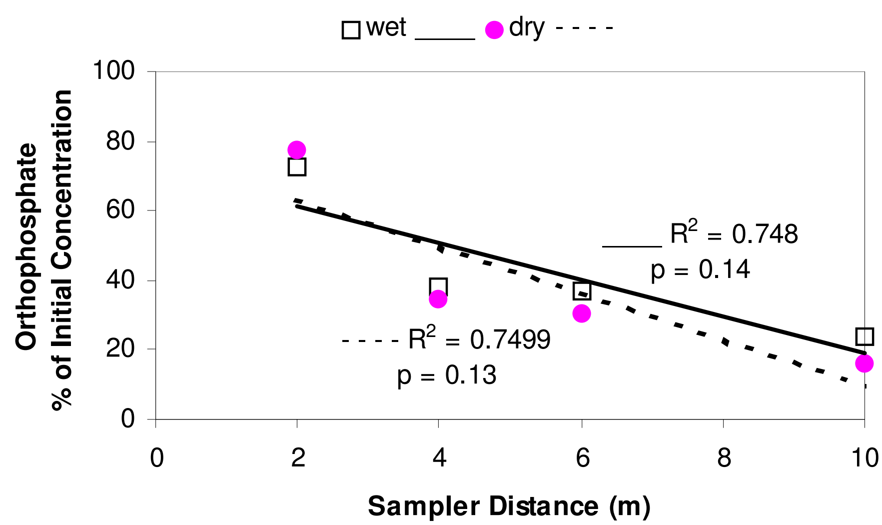

Figure C.12 Orthophosphate concentration reduction during wet and dry conditions on the fifteen percent slope undisturbed plot

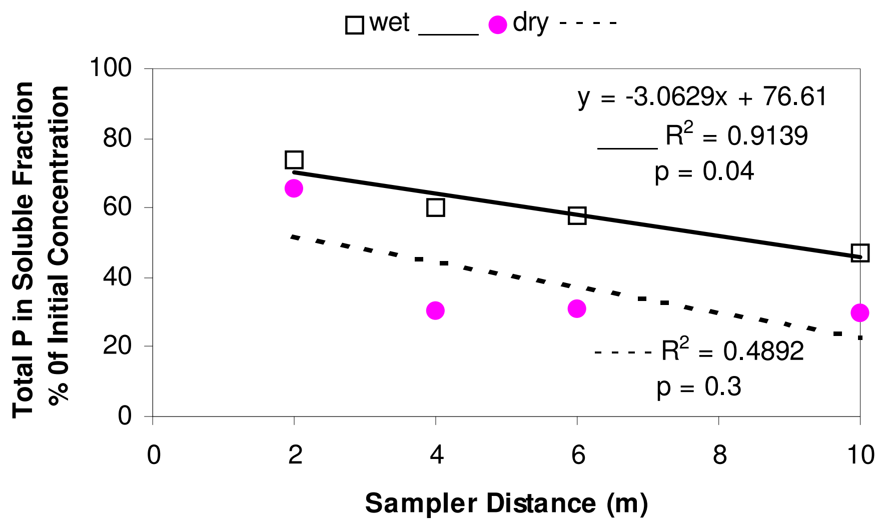

Figure C.13 Total phosphorus in the soluble fraction concentration reduction during wet and dry conditions on the fifteen percent slope disturbed plot

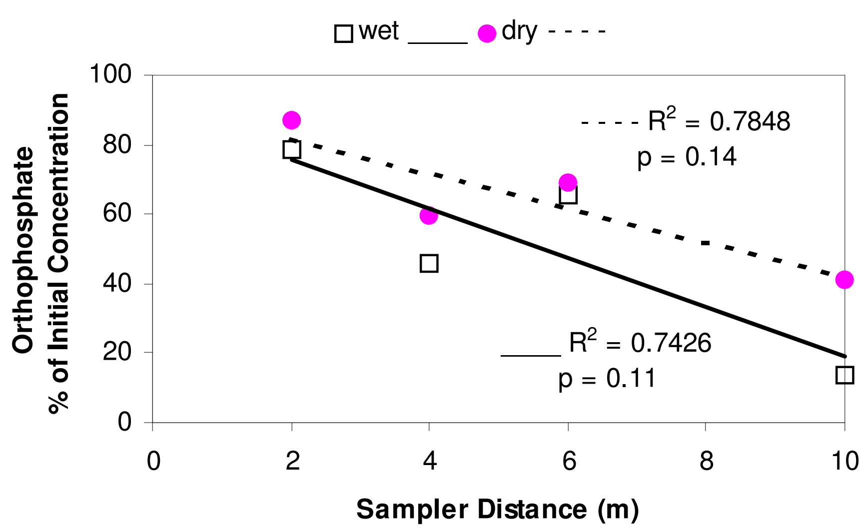

Figure C.14 Orthophosphate concentration reduction during wet and dry conditions on the fifteen percent slope disturbed plot

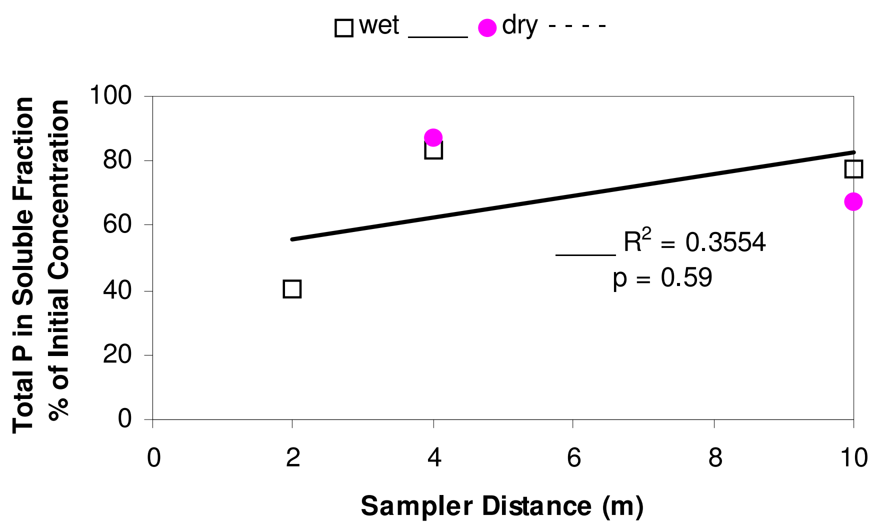

Figure C.15 Total phosphorus in the soluble fraction concentration reduction during wet and dry conditions on the twenty percent slope plot

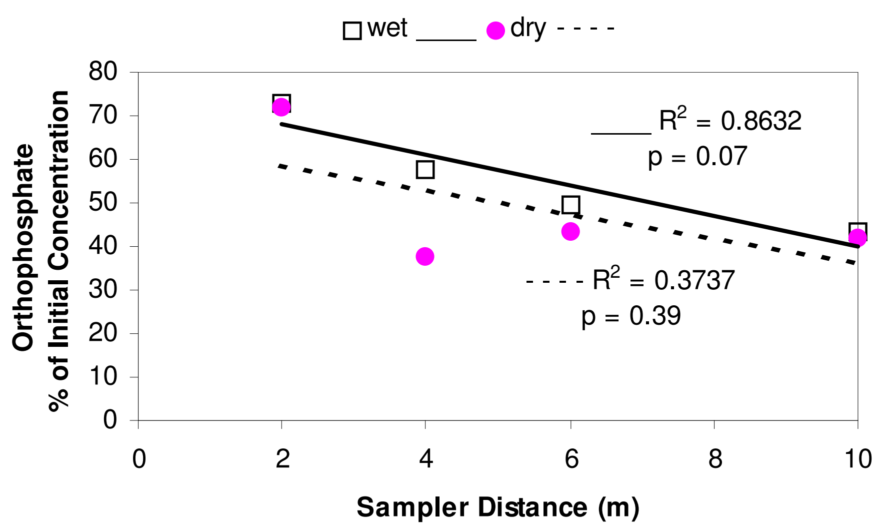

Figure C.16 Orthophosphate concentration reduction during wet and dry conditions on the twenty percent slope plot

APPENDIX D

Profile descriptions for the soil series at experimental plot sites constructed from notes made in the field.

Cecil Series - Taxonomic class: Fine, kaolinitic, thermic Typic Kanhapludults
Found at our 5-7%, 15-17%, and 20-22% slope sites. This description is a conglomerate of the three soils that I described in the field.

Ap - 0 to 12 cm, reddish-brown (5YR 5/4) sandy loam; weak, fine granular structure; very friable; many fine roots; few coarse sand grains and small pebbles; abrupt boundary

BC - 12 to 30 cm, yellowish red (5YR 5/6) sandy clay loam; weak, meduim and fine, granularstructure; friable; many fine roots; many coarse sand grains and pebbles; gradual boundary

Bt1 - 30 to 40 cm, red (2.5YR 4/8) clay loam, moderate, fine and medium subangular blocky structure; friable, clay films on peds,; gradual boundary

Bt2 - 40 to 140 cm, red (10R 4/8) clay, moderate, fine and medium subangular blocky structure; friable, clay films on peds,; gradual boundary

Bt3 - 140 to 150 cm, red (10R 4/6) clay loam, moderate, medium subangular blocky structure; friable, clay films on peds,; gradual boundary

C - 150+ cm, red (2.5YR 4/8) sapprolite that chrushes to sandy clay loam

Chewacla Series - Taxonomic Class: Fluvaqentic Dystrochrept

Found at our 0-2% slope site

Ap - 0 to 15 cm, reddish brown (5YR 4/4) silt loam; weak, fine, granular structure; friable; many fine roots; abrupt boundary.

Bw1 - 15 to 40 cm, brown (10YR 4/3) clay loam; common, fine, distinct mottles of light yellowish brown (10YR 6/4); weak, medium, subangular blocky structure, friable; clear boundary

Bw2 - 40 to 100 cm, dark brown (10YR 3/3) silty clay loam; common, fine, distinct mottles of light brownish grey (10YR 6/2); weak, medium, subangular blocky structure, friable; clear boundary

Bg - 100 to 130+ cm, light brownish grey (10YR 6/2) silty clay loam; common, fine, distinct mottles of yellowish brown (10YR 5/8); weak, medium, subangular blocky structure, friable

Madison Series - Taxonomic class: Fine, kaolinitic, thermic Typic Kanhapludults

Found on our 10% slope site.

Ap - 0 to 10 cm, yellowish red (5YR 5/6) sandy loam; weak, fine granular structure; very friable many fine roots; clear abrupt boundary

BAt - 10 to 18 cm, red (2.5YR 4/8) sandy clay loam; weak, medium, subangular blocky structure, friable, common fine roots; diffuse boundary

Bt1 - 18 to 50 cm, red (2.5YR 4/8) clay; medium, subangular blocky structure, friable; few roots; diffuse boundary

Bt2 - 50 to 120 cm, red (2.5YR 4/8) clay loam; medium, subangular blocky structure, friable; diffuse boundary

C - 120+ cm, mottled black and dark grey sapprolite