INVESTIGATING SCALE, RAINFALL-RUNOFF SEQUENCES AND BMP EFFECTS ON PHOSPHORUS, RUNOFF AND SEDIMENT YIELD

By

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NOMENCLATURE

AAWSA	Addis Ababa Water Supply and Sewerage Authority
BMP	Best Management Practice
d	day
DAL	Time after litter application (t, days)
DRP	Dissolved reactive phosphorus in surface runoff (mg/L)
DSSP	Degree of soil saturation with phosphorus (%)
E	Nash-Sutcliffe Efficiency
ET	Evapotranspiration (mm)
h	hour
liter/min	liter per minute
LRW	Legedadi Reservoir Watershed
m	meter
masl	meters above mean sea level
Mg/ha	10^6 grams per hectare
mg/L	milligram per liter
ml	milliliter
mm/hr	millimeter per hour
PCP	Cumulative rainfall prior to the first runoff event (mm)

Nomenclature

PET	Potential evapotranspiration (mm)
r	Pearson correlation coefficient
RFI	Rainfall intensity (mm/hr)
RFS	Rainfall simulation
RPE	Runoff-producing rainfall event
RRS	Rainfall/runoff sequence
RRS1	Runoff event starting from Day 1after poultry litter application
RRS2	Runoff event starting from Day 4 after poultry litter application
RRS3	Runoff event starting from Day 7 after poultry litter application
SAS	Statistical Analysis System
STP	Soil test phosphorus (mg P /kg soil)
SWAT	Soil and Water Assessment Tool
t	Time after litter application (days)
TP	Total phosphorus in surface runoff (mg/L)

CHAPTER 1

INTRODUCTION

1.1. DISSERTATION ORGANIZATION

This dissertation comprises six chapters. Chapter 1 is the introduction which gives an overview of the backgrounds and objectives of the dissertation. A Literature review is given in Chapter 2. Chapters 3, 4, and 5 are the main studies undertaken in this dissertation. Each study has its own abstract, introduction, objective, methodology, results and discussions, summary and conclusions. Chapter 6 gives the summaries, conclusions and recommendations of the findings from this dissertation. Finally, the lists of the references and appendices utilized for the study are given.

Study one (Chapter 3) investigates the effects of rainfall/runoff sequences and poultry litter application on dissolved reactive phosphorus from two soils that differ in soil test phosphorus in a greenhouse experiment using simulated rainfall. In Chapter 4 (Study two), scale effects on hydrology and phosphorus loss in surface runoff from pastures were studied taking into account the variables that affect P movement (soil test P, P application rate, runoff, cultural practices, etc.). In Chapter 5 (Study three), the impacts of a land use change and two Best Management Practice (BMP) scenarios on runoff and sediment yield from the Legedadi Reservoir watershed in central Ethiopia were assessed using the Soil and Water Assessment Tool (SWAT) model.

1.2. BACKGROUND

1.2.1. Phosphorus loss from pasture systems

Phosphorus (P) is an essential nutrient for maintaining crop and animal production. However, P can also impact drinking water quality and aquatic life if excessive amounts are transported to nearby streams and/or water bodies resulting in eutrophication. Eutrophication has been identified as the main cause of impaired surface water quality in the United States (U.S. EPA, 1996; Sims et al., 2000; and Sharpley et al., 2003). Eutrophication restricts water use for fisheries, recreation, industry, and drinking due to the increased growth of undesirable algae and aquatic weeds and to oxygen shortages caused by their death and decomposition. Three primary elements that must exist for P to enter water bodies and cause a problem are: 1) P source (manure, inorganic fertilizer or soil P), 2) transport agent to move P from the source to edge-of-field (soil erosion and runoff), and 3) continual of P transport from edge-of-field to the aquatic system (Campbell and Edwards, 2001). These three elements can be categorized as P source, edge-of-field P transport, and in-stream P transport.

P transport can also be affected by management practices at a given site. BMP alternatives targeted to minimize the offsite transport of P should focus on the following three elements: 1) P transport factors (surface runoff, erosion, and subsurface flow), 2) P source factors (soil, manure, fertilizer), and 3) cultural practices/BMPs, e.g. method and timing of P application, placement, tillage, buffer strip, etc. (USDA-NRCS, 1994). Chapter 3 investigates these factors that influence P loss from pastures. Specifically, P movement factors considered were: surface runoff simulated in a greenhouse (transport), both soil test P and poultry litter application (source), and time interval between litter application and the first runoff event (management).

1.2.2. Scale effects on P loss from pasture systems

Scale refers to the space-time characteristic of a process, observation or model (Sivaplan and Kalma, 1995). The scale at which available data have been collected is typically different from that required by most P models (Bierkens et al., 2000). Studies might be carried out at a much smaller scale, while estimates are needed for larger space-time scales, or vice versa. Spatial scales related to P movement might range from less than a meter to many kilometers. Likewise, the temporal variation can range from minutes to months or a year. Scaling is the transfer of information between different space-time scales: downscaling (from large to small) or upscaling (from small to large).

Research on management practices that aim to reduce P loss in runoff from pastures or crop land has been hampered by the need to study both temporal and spatial effects of scale (Cornish et al., 2002). A wide range of variables such as soil type, rate and type of P applied, BMPs, rainfall and runoff depth, rainfall intensity, vegetation height, topography, etc. influence P loss from pastures. This further complicates the scale effect. Consequently, data collection at different temporal and spatial scales is time-consuming, expensive, and difficult.

A limited number of studies have been conducted on scale effects (e.g., Sharpley and Kleinman, 2003; and Cornish et al., 2002). Sharpley and Kleinman (2003) indicated that flow length has an influence on hydrology, dissolved reactive P (DRP), particulate P (PP), and total P (TP) concentration in runoff from simulated rainfall studies on plots of 2.0 and 32.6 m^2. Cornish et al. (2002) also observed spatial scale (1 m^2 to 140 ha) effect on P concentration in runoff. Similarly, little research has integrated investigation of temporal scale effects on P loss from pastures. As a result, a good strategy to tackle scale related problem would be to assess scale (spatial and temporal) effects on P loss from pastures with the currently available data, and verify the results when additional data are obtained. Hence, Chapter 4 investigates the effects of pasture area (spatial scale) and time after litter application (temporal scale) on hydrology and P loss from pastures that exhibit variability in STP, applied P, BMP, etc.

1.2.3. Watershed models for assessing land use change and BMP effects

Investigating soil erosion and sedimentation, storm runoff and nutrient transport at plot and field levels compared to at a watershed level might be easier since they can easily be compared with controls. However, understanding and accurately quantifying the natural processes involved in soil erosion and sediment yield, and storm runoff at the watershed scale might be challenging due to watershed size, heterogeneity, and resources required. Watershed models are useful tools to utilize by simplifying the complex processes in a given watershed. They help us understand the problems involved, and find solutions through land use changes, best management practice implementation or any other measure that is feasible for the given area (Borah and Bera, 2004). They can even help to assess the cost effectiveness of BMP implementation scenarios to reduce the damaging effect of runoff and sediment on receiving water bodies prior to implementation.

Watershed models can be event based, continuous, or a combination of both (Borah and Bera, 2004). An event model represents a single runoff event occurring over a period of time ranging from an hour to several days. A continuous model operates over an extended period of time (e.g. 100 years), determining flow rates and conditions during both runoff and no runoff periods, thereby keeping a continuous account of the basin moisture condition. After reviewing 17 applications of the SWAT model in referred journals, Borah and Bera (2004) suggested that the Soil and Water Assessment Tool (SWAT) is a promising model for long-term continuous simulation in predominantly agricultural watersheds. The model has been successfully applied for long-term simulations of flow, soil erosion, sediment and nutrient transport in watersheds of different sizes, and having different hydrologic, geologic, and climatic conditions. It was found suitable for predicting yearly flows, sediment and nutrient loads (Borah and Bera, 2004). Its monthly predictions are also good except for months with extreme storm events and hydrologic conditions (Borah and Bera, 2004; Chu and Shirmohammadi, 2004). SWAT also predicts the effects of precipitation variations on monthly water budgets (Van Liew et al., 2003), and BMP implementation on storm runoff and sediment yield (Santhi et al., 2001; and Vache et al., 2002). Chapter 5 of this dissertation investigates the effects of a land use change and two BMP scenarios (conversion of cultivated land to forest, contour strip-cropping and terracing) on runoff and sediment yield from the Legedadi Reservoir watershed in central Ethiopia. The watershed is predominantly agriculture characterized by mixed land uses (crop, pasture and forest).

1.3. OBJECTIVES

The overall objectives of this dissertation were divided into three main parts. Objectives 1, 2, and 3, which are listed below, are the specific focuses of Chapters 3, 4, and 5, respectively.

1. To assess the effects of soil test phosphorus, surface application of poultry litter, rainfall/runoff sequences, and time after litter application on dissolved reactive phosphorus (DRP) in surface runoff from boxes in a controlled greenhouse experiment using simulated rainfall.
2. To investigate the effect of pasture area and days after litter application on hydrology and P loss from pastures.
3. To investigate the impacts of a land use change and two BMP implementation scenarios on watershed runoff and sediment yield from the Legedadi Reservoir watershed using the SWAT model.

CHAPTER 2

LITERATURE REVIEW

2.1. FACTORS THAT AFFECT PHOSPHORUS MOVEMENT FROM PASTURES

In this section review of the literature on P movement considering P source, P transport and P management factors is presented.

2.1.1. Poultry litter rate, application timing, and time interval

Poultry litter is generally applied to meet nitrogen demands of pastures with little considerations given to phosphorus levels in the litter. It contains the major nutrients nitrogen, phosphorus and potassium in unbalanced proportion for pasture requirements. If applied to meet nitrogen requirements poultry litter supplies too much phosphorus (Griffiths, 1998), and repeated application of poultry litter elevates STP (Sharpley et al., 1993). In addition, higher rates of poultry litter application results in increased P loss in runoff (Eghball et al., 2002). Hence, there is a need to carefully manage continual surface application of poultry litter to minimize P impacts on off-site water quality.

Timing of P application relative to the occurrence of intense runoff events is also an important P management factor to limit P loss in runoff. The major portion of annual P loss in runoff generally results from one or two intense storms (Sharpley, 1995). Most of the applied P would be lost if P applications are made during periods of the year when intense storms are likely. As an example, Udawatta et al. (2004) reported that a single year with excessive rainfall and runoff accounted for 30% of total P loss over a period of seven years. This clearly emphasizes the importance of the timing of P application relative to likely intense precipitation or runoff events.

The time interval between litter application and the first runoff event has an influence on DRP, particulate P (PP), and total P (TP) concentration (Eghball et al., 2002). Similarly, Nash et al. (2000) indicated that management of fertilizer application related to timing to the first runoff event appear to be the main method by which P export can be decreased. Westerman and Overcash (1980) observed a 90 percent reduction in P loss as the time interval increased from an hour to 3 days after poultry litter application.

2.1.2. Soil test phosphorus

The effect of surface applied poultry litter manifests itself on the chemical and physical characteristics primarily in the top 5 cm of the soil (Sharpley et al., 1993). A strong correlation was also observed between 0 to 2 cm STP and DRP in surface runoff from tall fescue plots that had previously received different level of manure application (Pote et al., 1996). The relationship between STP and DRP in surface runoff has been assessed by various researchers, and it has been demonstrated that linear relationships do exist between them. These relationships are generally soil specific (Sharpley, 1995; Pote et al., 1996; and Davis, 2002), extraction methods specific (Sharpley, 1995; Daniel et al., 1993; and Pote et al., 1999), site specific due to differences in hydrology, management, etc. (Sharpley et al., 1996 and Pote et al., 1996), and are dependent on whether there were recent manure additions (Andraski and Bundy, 2003).

Pote et al. (1999) studied the relationship between P levels in three ultisols and phosphorus concentrations in runoff and found that several STP methods gave results that were significantly correlated to DRP levels in runoff although distilled water and NH_4-oxalate methods gave the best correlations. Their study showed that the effects of STP levels on DRP concentrations in runoff are not always consistent across soil series, and much of the difference can be attributed to soil infiltration characteristics (hydrology).

This implies the knowledge of soil infiltration characteristics (site hydrology) can improve the usefulness of STP data for estimating DRP concentration in surface runoff. DRP losses in runoff increases with an increase in STP, but slopes found for this relationship vary by an order of magnitude depending on the clay content of the soils (Cox and Hendricks, 2000; Cox, 1994) and/or land use (Sharpley et al., 1996). For this reason, management alternatives based solely on STP may lead to ambiguous conclusions, particularly when different soils are compared (Hooda et al., 2000). Hooda et al. (2000) suggested the degree of soil saturation with P (DSSP) as a better estimate of the potential for P loss to water than soil total P, extractable P, or P sorption capacity. The site and soil-specific relationships generally vary as a function of soil infiltration characteristics (hydrology), runoff amount, land use/management, STP and soil P release characteristics.

2.1.3. Rainfall/runoff depth and duration, and slope

A laboratory scale study showed that loading of runoff constituents (nutrients and sediments) increased with increasing rainfall intensity and rainfall duration while their average concentration decreased linearly with increasing rainfall intensity (Storm et al., 1995). With shorter rainfall duration, slope had the greatest impact on offsite transport of litter constituents including P. According to Storm et al. (1995), a combination of 10 percent slope or less and tall vegetation should represent the best scenario for minimizing losses of litter constituents in surface runoff. Litter DRP losses varied with rainfall volume, and rainfall/runoff duration. Sauer et al. (2000) indicated that variation in runoff depth (volume) has an influence on nutrient transport from grazed pastures that received poultry litter. Edwards and Daniel (1993) also documented the importance of rainfall intensity and runoff volume on the amount of P losses from pastures treated with poultry litter. P concentration decreased with increasing rainfall intensity due to the associated dilution.

Large rainfall/runoff events tend to carry most of the agricultural nonpoint P sources from a given location. As an example, a field-scale study on the effects of precipitation, runoff, and P management on TP loss from cropped watersheds indicated that more TP loss was observed during extreme flow periods (Udawatta et al., 2004). They reported that 30% of the TP loss over a period of seven years took place in a single year that was characterized by high precipitation and flows. Their study indicated that the five largest runoff events out of a total of 66 events contributed up to 27% of TP loss. This clearly emphasizes the importance of large rainfall/runoff events in transporting P besides P source and cultural practices.

2.1.4. Grazing

Soil phosphorus can be removed by plant uptake and crop harvesting, recycled on the soil surface as animal waste from grazing animals, and returned to the soil in plant residues remaining on the surface as decaying root mass. Grazing animals typically return 60 to 99% of the ingested nutrients back to the soil surface in dung and urine (Daniel et al., 2002). Thus, grazing tends to result in the net vertical transport of a more soluble P back to the soil surface extracted from the less soluble soil P by forages from the soil. Nutrients are also transported horizontally from grazed areas to resting, watering, and handling areas whose effect depend on factors such as climate, shade, slope, stocking density and grazing method. The long-term impacts of grazing are restricted to the soil surface and runoff hydrology. Over grazing can increase soil loss by erosion and surface runoff through soil compaction (Daniel et al., 2002). Areas of nutrient accumulation and compaction (e.g. resting areas), relatively small areas, tend to produce much of the offsite nutrient movement.

Livestock exclusion and subsequent riparian vegetation establishment effectively reduced pollutant export from intensively grazed pastures (Frasier et al., 1995). This indicates that the effects of long-term grazing on increasing runoff and nutrient dynamics are temporary processes which can disappear after cattle are excluded (Line et al., 2000).

2.1.5. BMP and P transport factors

Factors that affect the transport of P are forms of P, the processes associated with the forms of P during transport, and the amount of P available for transport (Sharpley and Halvorson, 1994). Runoff from cultivated fields is dominated by PP (75-90%) whereas runoff from pasture fields is generally dominated by the DRP (USDA-SCS, 1994; Sharpley and Halvorson, 1994; and Sharpley and Rekolainen, 1997). The processes that initiate DRP transport are desorption, dissolution, and extraction of DRP from soil and plant material as are soil, stream bank and channel erosion for PP. For P to cause an environmental problem there must be a P source (e.g., soil P, manure or fertilizer application) and a P transport agent to a sensitive location (e.g., leaching, runoff, or erosion). Hence, the concern and emphasis of BMPs should be focused on areas where high potentials of these two conditions intersect.

BMPs can be targeted to the source and transport factors. BMP implementation at the source include manipulation of dietary P intake by animals (addition of enzymes, e.g. phytase, and genetically engineered corn to reduce unavailable phytate-P), composting, alternative use of manure (bioenergy source), manure amendments (e.g., high clay, alum, slaked lime), separation of solid manure from liquid manure, and offsite transport to deficit areas. The transport aspects related to BMPs include efforts to reduce the movement of P from soils to sensitive water bodies through erosion and runoff control. These are conservation tillage, crop residue management, buffer strips, terracing, contour tillage, and impoundments. These practices reduce the impact of rainfall on the soil surface, reduce surface runoff volume and velocity, and increase soil resistance to erosion. Despite these advantages, any one of these measures should not be relied upon as the sole or primary means of reducing P losses in agricultural runoff. These practices generally are more efficient at reducing sediment P than dissolved reactive P.

BMP implementation, such as the use of manure amendment, is a practice that tries to minimize excess P by closely matching litter P availability with litter N availability through reduction of P solubility (Shreve et al., 1995). Poultry litter and/or soil amended with high clays, Al, Fe, and $CaCO_3$ greatly reduces the portion of DRP through adsorption and precipitation processes. Several researchers demonstrated that DRP loss can be reduced by incorporating residues rich in Al and Fe (Shreve et al., 1995; Haustein et al., 2000; Codling et al., 2000; Moore et al., 2000; Bundy et al., 2001; and Smith et al., 2001). As an example, Haustein et al. (2000) carried out a rainfall simulation study on fields of excessively high soil test P treated with aluminum water treatment residual (Al-WTR) and HiClay Alumina (HCA). The treatments were applied at the rates of 0, 2.2, and 18 Mg/ha with time intervals (between treatment application and runoff events) of 1, 30 and 120 days. Both amendments decreased STP levels compared with the controls due to the increased levels of soil Al. In another study, alum addition to poultry litter applied to pastures resulted in a 73% reduction in DRP compared with controls (Moore et al., 2000). Similarly, Smith et al. (2001) observed an 84% reduction in DRP concentration from swine manure treated with high rate of alum and aluminum chloride.

However, heavy metal accumulation, such as Cu and Zn which are used as feed additives, in fields applied with alum treated litter raises new questions about litter management. Generally, alum addition can increase the fertilizer value of poultry litter by increasing the N content while reducing the DRP. This can have a positive impact on the quality of receiving water bodies with regard to P. However, the increased level of nitrogen availability and increased N mineralization exhibited by alum-treated litter may increase the potential contamination of ground and surface waters with NO_3-N. Thus, this has to be considered to use alum as a BMP option as its beneficial use can be offset by the negative impact on ground water quality and potential health hazards (Kohler, 1997).

Brannan et al. (2000) studied the impacts of animal waste BMPs on sediment and nutrient losses in runoff from the Owl Run watershed for ten years, and they indicated that BMPs were effective in reducing both P loads and concentrations in surface runoff with the largest reduction for particulate P (78%) compared to DRP (39%). Overall, BMPs must attempt to bring into balance P inputs and outputs to a pasture system, although this may not be achievable in areas with intensive confined-animal feeding or high poultry industry.

2.2. SCALING ISSUES IN HYDROLOGY AND PHOSPHORUS LOSS

Hydrological processes occur at a multiple of scales. The mathematical descriptions of these processes at different scales are not necessarily identical. Theories of upscaling and downscaling attempt to develop quantitative links among process descriptions at various scales. However, due to the presence of spatial heterogeneity, temporal variability, and the highly non-linear nature of hydrological processes, upscaling or downscaling is not a trivial task (Bierkens et al., 2000).

Previous research on scaling issues have largely focused on theoretical and numerical model application, whereas process-based hydrologic research has mainly been examined at small space-time scales for the purpose of extrapolating results to larger scales (Sivapalan and Kalma, 1995). A number of practical approaches are in use for scaling purposes in hydrological modeling. These are 1) homogeneous assumption, 2) representative elementary area (REA), and 3) hydrological response unit (HRU) (Blöschl et al., 1995). The homogeneous assumption is a straight forward method that assumes each grid is homogeneous. The REA concept was employed for finding a certain preferred time and spatial scale over which the process representations can remain simple and at which distributed catchment behaviors can be represented without the apparently indefinable complexity of local heterogeneity (Wood et al., 1988). The variances and covariance of key variables are invariants above a certain threshold size. It is difficult, however, to determine the threshold size of the REA because it is strongly controlled by environmental characteristics (Blöschl et al., 1995). The HRU is a distributed, homogeneous entity having a common climate, land use, and underlying pedotopological associations controlling hydrological dynamics. The crucial assumption of the HRU is that there should be less variability of hydrological process dynamics within a given HRU than between HRUs.

The literature has a number of research efforts made on scale issues including soil moisture (Western and Blöschl, 1999), depth-duration-frequency curves for storm precipitation (Burlando and Rosso, 1996), rainfall-runoff modeling (Stomph et al., 2002) and distributed models (Blöschl et al., 1995; and Bierkens et al., 2000). However, there is little research on scale effects (e.g. area, time after litter application, etc.) on P loss and hydrology from pastures (Cornish et al., 2002; Sharpley and Kleinman, 2003; and Dougherty et al., 2004). P loss from pastures can impact water quality, and it is imperative to understand the effect of scales in the management of the offsite transport of P. Although data from experimental studies are available, the scale considered usually concentrates on areas with flow length of 2 m or less with a few exceptions that considered areas with flow lengths of 10 m or more. Most of these studies considered a single scale (area and time) at a time (e.g. Storm et al., 1995; Storm et al.,1996a; Storm et al.,1996b; Friend, M., 2003; Edwards et al., 1994). In order to consider the scale effect on P loss and runoff depth (hydrology), it is necessary to combine a number of studies in a common dataset.

2.3. SOIL AND WATER ASSESSMENT TOOL

SWAT is a complex, physically based model with spatially explicit parameterization. It is a long-term continuous model that operates on a daily time step to perform simulations up to 100 years. Precipitation data can be read by the SWAT model on daily or subdaily increments. Daily precipitation data are used when the SCS curve number method is used to simulate surface runoff, while the subdaily precipitation data are required when the Green and Ampt infiltation method is chosen to calculate surface runoff (Neitsch et al., 2002). The model is also GIS interfaced (AVSWAT) to reduce spatial data collection and processing time, and allow the user to modify and assess various alternative management practices efficiently (Diluzio et al., 2002).

The major components of the SWAT model include hydrology, weather, sedimentation, soil temperature, crop growth, nutrients, pesticides, agricultural management, channel routing, and reservoir routing. A complete description of the components of SWAT can be found in Arnold et al. (1998) and Neitsch et al. (2002).

The SWAT model has been successfully used to simulate daily and monthly stream discharge (Spruill et al., 2000), to predict sediment and phosphorus loads (Kirsch et al., 2002), and assess the impact of BMP implementation at the watershed level (Santhi et al., 2001; and Vache et al., 2002). A detailed review of SWAT application is given by Borah and Bera (2004).

CHAPTER 3

RAINFALL SEQUENCE EFFECTS ON PHOSPHORUS LOSS IN RUNOFF FROM PASTURES THAT RECEIVED POULTRY LITTER

3.1. ABSTRACT

Land application of poultry litter to pasture elevates the concentration of phosphorus in surface runoff, and it is becoming an increasing problem to sensitive water bodies. The objectives of this study were to assess the effects of soil test phosphorus (STP), surface application of poultry litter, rainfall/runoff sequences, and time after litter application on dissolved reactive phosphorus (DRP) in surface runoff from pasture in a greenhouse experiment using rainfall simulation. Seventy-two small-scale boxes, which measured 1.0 m long by 0.5 m wide and 0.15 m deep, were filled to a depth of 0.1 m with 75 kg of soils collected from two locations that differ in STP. These two soils (Nixa and Tonti) from the Ozark region were planted to Bermuda, fescue and ryegrass to simulate permanent pasture systems typical of the region. Treatment factors were poultry litter at a rate of 0.0 and 6.7 Mg/ha, low and high STP, and three rainfall/runoff sequences (RRS). The latter refers to runoff-producing rainfall events starting from Day 1, Day 4 and Day 7 after litter application. Composite runoff samples were taken at the end of 30-minutes of continuous runoff for each box. A 2X2X3 factorial arrangement of treatments was employed to assess treatment effects on phosphorus losses in surface runoff using ANOVA procedures. Poultry litter application, RRS and time were found to have a highly significant effect on DRP concentration in surface runoff. Poultry litter had a significant effect on DRP in surface runoff until 18 days after *litter application compared to the controls. Between 18 and 32 days after litter application, the effect on DRP became insignificant for any level of STP or rainfall sequence. DRP loss in the first surface runoff event decreased by more than 50% for consecutive rainfall sequences.*

3.2. INTRODUCTION

The United States is the world's largest producer and exporter of poultry meat and the second-largest egg producer (USDA-ERS, 2004). Historically, the poultry industry is one of the largest and fastest growing livestock production systems in the world, with meat and egg production growing at an annual rate of approximately 5% (Sims and Wolf, 1994). The rapid expansion and intensification of poultry production, which is concentrated in a group of States, is associated with a large amount of litter P production. The beneficial impacts of poultry litter as a nutrient source have been recognized in the production of forages and crops (Huneycutt et al., 1988; Pote et al., 2003). Because the bulky nature of litter limits transportation, generally much of the litter is applied to fields close to the production facility (Bosch and Napit, 1992). Poultry litter that was once considered a resource is increasingly seen as a waste (Sharpley et al., 2000). In other words, there is not enough agricultural land near poultry facilities to use all of the P in litter by poultry producers (Sims et al., 2000). As a result, there is an increasing challenge to balance P inputs as litter P fertilizer and P uptake on pastures in poultry litter producing areas. The imbalance due to the repeated application of poultry litter to pasture leads to elevated P levels in surface runoff. P loss in surface runoff from the Ozark Highlands is believed to be one of the most important contributing factors to eutrophication of nearby water bodies (Edwards and Daniel, 1993).

P is an essential nutrient to maintain crop and animal production. P additions to surface waters from agricultural nonpoint sources, however, are a concern, because the excess P often results in eutrophication of surface waters (Sharpley et al., 2000; Sims et al., 2000; Daniel et al., 1993). Eutrophication may have adverse economic and health effects because of the importance of water-based recreation and degradation of drinking water sources in these poultry producing regions.

The fate of P and P cycling in the environment are important factors in understanding the potential sources for P, impacts of P, and P transport through watersheds (Campbell and Edwards, 2001). P is a naturally occurring element in soils that originates from soil parent materials. The total P content of soil ranges from 0.03 to 0.3% but much of the total P is found in very insoluble primary minerals and precipitated secondary minerals that are not available to plants or soluble in runoff water. Phosphorus transformations affect its solubility and movement. These transformations are complex processes that are influenced by many characteristics of the soil, water, plant, and atmospheric environment.

Soil P exists in both organic and inorganic forms. The organic forms of P derive from animal manure, plant residues, and organic municipal and industrial byproducts, while the inorganic forms mostly derive from inorganic fertilizer additions. Both forms include dissolved P, labile and moderately labile P, and stable P. These are often broadly aggregated as particulate and dissolved reactive P (DRP). In most agricultural soils, 50-75% of the P is in the inorganic form (Sharpley and Rekolainen, 1997), and 75-90% of the P transported in runoff from cultivated land is dominated by surface-bound P or particulate P (PP) (USDA-NRCS, 1994). Surface runoff P from pastures fertilized with poultry litter is dominated by DRP (Edwards and Daniel, 1993). DRP is important to water quality since it is bioavailable to aquatic plants and algae. PP, on the other hand, is bioavailable only when converted to inorganic phosphate, a process acting on 10 to 90% of the total P (USDA-NRCS, 1994).

The offsite transport of P from pastures fertilized with poultry litter to nearby water resources is affected by soil test P, soil properties, rainfall intensity and amount, rainfall frequency, poultry litter rate and time of application, and time interval between litter application and the first runoff event (Sharpley, 1997; Storm et al., 1996; Storm et al., 1995; Edwards et al., 1994b; Sharpley et al., 1994).

3.2.1. Soil test phosphorus

The effect of surface applied poultry litter manifests itself on the chemical, nutrient and physical characteristics primarily in the top 5 cm of the soil (Sharpley et al., 1993). A strong correlation was also observed between 0 to 2 cm STP and DRP in surface runoff from tall fescue plots that had previously received different level of manure application (Pote et al., 1996). The relationship between STP and DRP in surface runoff has been assessed by various researchers, and it has been demonstrated that linear relationships do exist between them. These relationships are generally soil specific (Sharpley, 1995; Pote et al., 1996; and Davis, 2002), extraction methods specific (Sharpley, 1995; Daniel et al., 1993; and Pote et al., 1999), site specific due to differences in hydrology, management, etc. (Sharpley et al., 1996 and Pote et al., 1996), and are dependent on whether there were recent manure additions (Andraski and Bundy, 2003).

Pote et al. (1999) studied the relationship between P levels in three ultisols and phosphorus concentrations in runoff and found that several STP methods gave results that were significantly correlated to DRP levels in runoff although distilled water and NH_4-oxalate methods gave the best correlations. Their study showed that the effects of STP levels on DRP concentrations in runoff are not always consistent across soil series, and much of the difference can be attributed to soil infiltration characteristics (hydrology). This implies the knowledge of soil infiltration characteristics (site hydrology) can improve the usefulness of STP data for estimating DRP concentration in surface runoff. DRP losses in runoff increases with an increase in STP, but slopes found for this relationship vary by an order of magnitude depending on the clay content of the soils (Cox and Hendricks, 2000; Cox, 1994) and/or land use (Sharpley et al., 1996). For this reason, management alternatives based solely on STP may lead to ambiguous conclusions, particularly when different soils are compared (Hooda et al., 2000). Hooda et al. (2000) suggested the degree of soil saturation with P (DSSP) as a better estimate of the potential for P loss to water than soil total P, extractable P, or P sorption capacity. The site and soil-specific relationships generally vary as a function of soil infiltration characteristics (hydrology), runoff amount, land use/management, STP and soil P release characteristics.

3.2.2. Rainfall/runoff sequence vs. time after litter application

DRP in surface runoff is highly sensitive to a non-runoff producing rainfall event combined with the time interval between litter application and the first runoff event (i.e. rainfall/runoff sequence) (Storm et al., 1996b). A number of studies carried out to investigate the factors affecting P export from pastures indicate that the management of fertilizer application related to timing to the first runoff event after litter application appear to be a primary method by which P export can be decreased (Nash et al., 2000; Pierson et al., 2001; Storm et al., 1996b; Storm et al., 1995). Edwards and Daniel (1993) documented the importance of poultry litter application rate, rainfall intensity and the interval between litter application and the first surface runoff event on the amount of nutrients in surface runoff. Of these factors, the least information is available on the effects of non-runoff producing rainfall events, timing of rainfall application relative to first runoff events, and time period after litter application on DRP concentration in surface runoff from pastures. Studies on the effects of surface runoff producing or non-runoff producing rainfall events on P loss will be helpful in developing guidelines and recommendations for the timing of land application of poultry litter in order to minimize the offsite water quality impacts (Storm et al., 1996b).

3.2.3. Transport of P

Sources of dissolved reactive P in surface runoff are desorption, dissolution, and extraction of P from soil, crop residues, and surface applied manure and commercial fertilizer. These processes occur as rainfall interacts with a thin layer of surface soil, before leaving a field in surface runoff (1 to 2.5 cm) (Sharpley et al., 1994). The main factors affecting the transport of P to surface waters are erosion and runoff. Because P is attached to soil materials, erosion largely determines the particulate P (PP) movement from cultivated fields (Sharpley and Rekolainen, 1997). PP includes P sorbed by soil particles and organic matter eroded during flow events. P transport in runoff from pastures is dominated by DRP (Edwards and Daniel, 1993). During the transport of P from the edge of the field to the receiving water body, DRP and PP fractions may change as a result of in-stream processes. This alteration is another factor to be considered while dealing with the offsite transport of P. The amount of P transported is a function of site hydrology, STP, and type and applied P (Sharpley and Rekolainen, 1997).

3.2.4. Objectives of the study

The objectives of this study were to assess the effects of STP, surface application of poultry litter, rainfall/runoff sequences (RRS), and time (days) after litter application on DRP in surface runoff from boxes in a controlled greenhouse experiment using simulated rainfall.

3.3. MATERIALS AND METHODS

3.3.1. Soil collection, box filling and grass establishment

Nixa and Tonti soils were collected from two pastures that have received poultry litter and differ in their STP levels. These soils are silt loam and are typical of pasture soils in the Ozarks region of Oklahoma and Arkansas. The collected soils were transported to Stillwater, Oklahoma for the controlled greenhouse study.

Seventy-two experimental plastic boxes 0.5 m wide, 1 m long and 0.15 m deep were constructed with nineteen 6 mm drain holes drilled in the bottom. The soils were well mixed using a mechanical cement mixer prior to filling the boxes. A permeable weed stopper fabric was placed at the bottom of the boxes to prevent loss of soil through the holes in the bottom of the boxes. The boxes were filled to a depth of 10 cm by adding successive amounts of soil and packing the soil to a typical field bulk density. This resulted in 18 boxes per soil type and STP level. Sets of six boxes were placed on racks at a slope of 5 percent.

In November 2001, a mixture of perennial ryegrass (*Lolium perenne* L.), fescue (*Festuca arundinacea*), and bermudagrass (*Cynodon dactylon*) seed was planted to establish vegetation similar to that of pastures in the Ozark region. The grass was cut to a height of 5 cm starting from January 5, 2002. Surface runoff from the boxes was collected in a 20-liter bucket starting from February 9, 2002.

3.3.2. Surface runoff, irrigation, time interval and rainfall simulator design

In order to approximate the surface runoff and evapotranspiration applicable to the Ozarks highlands, we designed a rainfall and irrigation sequence using the Soil and Water Assessment Tool (SWAT) hydrologic model. SWAT is a physically based basin-scale model that uses readily available data inputs. It was developed to predict the impact of land management practices on water, sediment and agricultural chemical yields in large complex watersheds with varying soils, land use and management conditions over long periods of time (Arnold et al., 1998; and Neitsch et al., 2002). The simulation was carried out for a watershed size of 75 km^2 with a single hydrological response unit under pasture land use and good management practices. The Captina-Nixa-Tonti soil series and a 50-year rainfall record (1 January 1950 to 30 April 2000) from the Kansas station in Delaware County, Oklahoma (http://www.ncdc.noaa.gov for COOPID 344672) were used as input. The soil types are the common type in Arkansas, Missouri and Oklahoma predominantly used for pasture in the Ozarks highlands. The average annual evapotranspiration and surface runoff simulated by SWAT were 936 mm and 220 mm, respectively.

A preliminary rainfall simulation experiment with an intensity of 75 mm/hr was carried out to determine the rainfall amount required to initiate runoff from 24 greenhouse boxes. An average 17 mm of rainfall was required to initiate surface runoff, which translated to approximately 55 mm of rainfall to produce runoff for 30-minute duration. A total of eight runoff events were used for the study. Thus, for eight runoff events, at 55 mm per event, 440 mm rainfall was required. The remaining 496 mm (from the total annual ET of 936 mm) was used to irrigate the greenhouse boxes. Irrigation frequency was carried out once (14.3 mm) or twice (7.6 mm) a week depending on the level of ET in the greenhouse.

DRP in surface runoff from litter applied to pastures decreases rapidly with time following rainfall (Storm et al., 1996b). It was hypothesized that 210 days after litter applications the effect of litter on DRP should become non significant compared to the controls boxes. Using a total of 8 rainfall simulations, a statistical approach using an exponential decay equation (based on study by Storm et al., 1996a and 1996b) was used to determine the time intervals between successive rainfall simulations for a time period of 0 to 210 days. The time intervals between these 8 successive rainfall simulations, starting from the first to the last, were found to be 1, 3, 3, 4, 7, 14, 30 and 148 days, respectively (Figure 3-1). The last rainfall simulation was not carried out since the objective of the study was met at rainfall simulation number 7 on day 62. Litter was applied 24 hours prior to starting the first rainfall simulation at the rate of 6.7 Mg/ha to pre-saturated boxes. After this, the RRS was applied as shown in Table 3-2.

The single nozzle rainfall simulator assembled for this study had a TeeJet spray nozzle with a spray angle of 110 degrees at an operating pressure 103 kPa. It was calibrated to a 94% uniformity coefficient over the rack of six boxes at a rainfall intensity of 75 mm/hr. The nozzle had a capacity of 22.7 liters/min, and was centered at a height of 3 m over the rack. Both rainfall and runoff start times were recorded using stopwatches for each box throughout the study. Runoff rates were recorded manually for each box at two-minute time intervals using a calibrated 20-liter runoff collection bucket.

3.3.3. Experimental treatments, design and statistical analysis

The experimental treatments used for this study were composed of three factors. 1) poultry litter at a rate of 0.0 and 6.7 Mg/ha. Poultry litter was analyzed using the Inductively Coupled Plasma method after digestion with nitric acid. The litter had a total P content of 1.9 % on dry basis (Table 3-1). 2) STP was analyzed using the Mehlich III extraction procedure (Mehlich, 1984). Two STP levels were used: 309 mg P/kg of soil (n = 8 and standard deviation = 39 mg P/kg), and 77 mg P/kg of soil (n = 8 and standard deviation = 5.8 mg P/kg). These two STP levels were referred to as high and low. 3) rainfall/runoff sequence at three levels, i.e. RRS1, RRS2, and RRS3. The RRS treatment refers to whether runoff producing rainfall events started on the first rainfall simulation (Day 1), second rainfall simulation (Day 4) or third rainfall simulation (Day 7) after litter application (Table 3-2). As shown in Table 3-2, the RRS treatment included a rainfall event without runoff for RRS2 and RRS3. Time after litter application is also inherently included which helped to characterize the time trend effect of the above treatments on DRP loss in surface runoff.

There were 24 experimental boxes for each RRS. A non-runoff producing rainfall simulation was achieved by applying rainfall at a rate not to exceed the steady-state infiltration rate determined experimentally for each box using 75 mm/hr rainfall intensity. The non-runoff producing event was made possible by varying the rainfall duration rather than changing the rainfall intensity. Rainfall was applied to the boxes for a total of 15 minutes by turning on the rainfall simulator every other five-minute. As a result, RRS2 and RRS3 boxes received 19 and 38 mm of non-runoff producing rainfall prior to the first runoff event, respectively.

A 2X2X3 factorial arrangement of treatments of poultry litter application rate, STP and RRS with 10 replications for poultry litter treated boxes, and two replications for controls was utilized. Analysis of Variance (ANOVA) procedures using PROC MIXED of PC SAS Version 9.1 (SAS, 2003) was used to assess the effects of RRS, poultry litter application, STP and time after litter application on DRP in surface runoff. Time after litter application was considered as a repeated measure and modeled accordingly with a REPEATED statement and a TYPE option in PROC MIXED. A probability level of 0.05 was considered significant.

3.3.4. DRP analysis

Thirty minutes of surface runoff was collected for each box, and a 60 ml composite sample was taken for analysis. The samples were then filtered (0.45 μm) within 2 h of collection and stored at 4^{o}C until analyzed. The colorimetric molybdenum-blue method of Murphy and Riley (1962) was used to determine DRP on filtered runoff samples. Because more than 90% of P loss from pastures is dominated by DRP

(Edwards and Daniel, 1993; Storm et al. 1995; Storm et al., 1996b), total P was not considered for this study.

3.4. RESULTS AND DISCUSSIONS

3.4.1. Time to runoff start and runoff depth

We define time to runoff start as the time it takes for a given rainfall intensity to initiate runoff. Since rainfall intensity and runoff duration are constant in this study, variation in time to runoff reflects differences in box infiltration (hydrology), which includes initial soil moisture levels. To minimize this effect, the boxes were saturated prior to rainfall simulation with 11.4 mm of water. Rainfall duration was time to runoff plus 30 minutes of runoff which varied from box- to- box depending on box hydrologic characteristics.

Time to runoff start and runoff depth were inversely related (Figure 3-2) for the given 30 minutes runoff duration and rainfall intensity. Time to initiate runoff had a highly significant effect ($P < 0.0001$) on runoff generated from pasture boxes despite the high variability of the data (Figure 3-2). This relationship had also a significant effect on DRP concentrations in surface runoff for rainfall simulations carried out on Days 1, 4 and 7 (Figure 3-3). However, this became non significant for the whole experimental data set (Figure 3-4).

This result suggests the importance of minimizing surface runoff from the first two or three runoff events following manure application. Boxes with high infiltration rate, e.g. longer time to initiate runoff and/or less surface runoff depth, had lower DRP concentrations indicating the importance of box infiltration characteristics. Soil characteristics, specifically infiltration, are important parameters to be considered in P movement. An increase in the infiltration rate minimizes the offsite transport of P to water resources as long as the downward leaching and subsurface movement of P to nearby sensitive water resources is controlled.

3.4.2. Trend of average dissolved reactive P in surface runoff

DRP concentration in surface runoff from litter applied boxes was higher compared to that from controls. The averaged DRP concentration decreased exponentially with increasing time after litter application with successive rainfall (Figure 3-5). DRP concentration in surface runoff from litter applied boxes approached asymptotically to the DRP from the control boxes. Although they were not statistically significant, averaged litter DRP (0.46 mg/L) was higher than control DRP (0.25 mg/L) on Day 62 (Figure 3-5). An exception to this general trend occurred on Day 11 where most boxes (including controls) showed a slight increase in DRP concentration in runoff from their respective DRP values on Day 7 (Table 3-3; Figures 3-5, 3-6, 3-7). Such phenomena have also been observed for field plot studies (e.g., McIsaac et al., 1995). According to McIsaac et al. (1995), the increase in DRP concentration might be due to the effects of antecedent rainfall and/or soil moisture that may cause a high degree of temporal variability in DRP concentrations in runoff.

3.4.3. Effect of STP on dissolved reactive P

STP had a highly significant (P = 0.0002) effect on DRP in runoff from pasture boxes prior to litter application (Table 3-4). There was a slight increase in DRP from Time 1 to 3 (Table 3-4). This could be due to P transformations associated with the pasture establishment and extraction of more soluble P from grass residue (pasture clippings) left in the boxes. Immediately following litter application, STP had no significant effect on DRP concentrations despite the considerable difference of the two soils in STP (Tables 3-3 and 3-5; and Figures 3-5 and 3-7). This is likely the highly soluble P in the litter served as the primary source of P in surface runoff. In other words, recent manure addition masked the STP vs. DRP relationship.

3.4.4. Effect of rainfall/runoff sequence

RRS treatment was added to the experiment to study the time effect of surface runoff events on DRP concentrations in combination with a non-runoff producing rainfall from poultry litter treated pastures. All boxes received rainfall starting from Day 1. However, only RRS1 boxes were subjected to surface runoff producing rainfall events on Day 1 (Table 3-2).

The effect of RRS on the first runoff event DRP concentration is summarized in Table 3-5. RRS1 treated boxes had the highest average DRP concentration (12.1 mg/L) in surface runoff event one day after litter application (Table 3-5; Figures 3-6 and 3-7). For RRS1, DRP concentration ranged from 6.6 to 17.3 mg/L depending on box infiltration and soil characteristics (Figure 3-6). Relative to off-site loss of P from pasture systems, this could be considered as the worst scenario. Immediately after litter application poultry litter is vulnerable to significant interaction with surface runoff water. The average DRP concentration in surface runoff from RRS2 treated pasture boxes at the first runoff event (Day 4) was 4.75 mg/L, and it ranged from 3.37 to 6.77 mg/L (Figure 3-6). Compared to RRS1 treated boxes, the average decrease in DRP concentration in runoff from RRS2 treated boxes was about 60% (7.26 mg/L). Similarly for RRS3 treated boxes, the average concentration of DRP in surface runoff collected at the first runoff event (Day 7) was 2.25 mg/L, which ranged from 1.39 to 3.27 mg/L (Figure 3-6). Compared to RRS2 treated boxes, the average decrease in DRP for the RRS3 treated boxes was about 53% (2.50 mg/L). This would change to 81% or 9.76 mg/L when the comparison is made with RRS1 treated boxes. For all RRS's, the time trend of the DRP indicates less variability and an exponential decrease with increasing time (d) after litter application as shown in Figures 3-6 and 3-7.

RRS had a highly significant effect on DRP from first runoff events (Table 3-5). This emphasizes that rainfall without runoff combined with a longer time interval between litter application and the first runoff event reduces the initial DRP concentration in runoff from litter received pastures. The smallest initial DRP was observed for RRS3 treated boxes which were subjected to a twice non-runoff producing rainfall event and longer time interval between litter application and first runoff event (7 days). This may be due to the onset of the P cycling which changes more soluble P in litter to less soluble forms or the movement of soluble P into the soil. RRS had no significant effect on DRP from control pasture boxes (Table 3-5).

Non-runoff producing rainfall event and timing of litter application to pasture boxes, relative to the first runoff-producing event, influences DRP loss in runoff. The effect of different RRS became significant as the time interval increases (Table 3-5). More DRP loss will be expected in runoff from pastures if litter application is made during periods of the year when intense storms are likely or when there is only a short time interval between application and occurrences of runoff events. The importance of the time interval until the first runoff has been pointed out by various researchers (Pierson et al., 2001; Nash et al., 2000; Sharpley, 1997; Storm et al., 1996b; Edwards and Daniel, 1993) and corroborated by this study along with the importance of the non-runoff producing rainfall event. DRP concentration was extremely sensitive to the time interval between litter application and first surface runoff event with a non-runoff producing rainfall event.

3.4.5. Effect of poultry litter application

Surface application of poultry litter to boxes increased the DRP in surface runoff. The increase in DRP was greatest for RRS1, and least for RRS3 treated boxes. Due to the highly significant litter vs. time interaction ($P < 0.0001$), an analysis of the simple effects of litter versus time was made before drawing any inference. Pearson correlation analysis indicated that DRP in runoff from pasture boxes is highly dependent on time (d) after litter application ($r = -0.65$ with $P < 0.0001$). Table 3-3 shows the statistical summary of the effects of poultry litter, STP and RRS on DRP using the LSD procedure with a DIFF option in LSMEANS statement. Poultry litter had a highly significant effect on DRP in surface runoff from pasture boxes compared to that from control pasture boxes until 18 days after litter application. Its effect became non significant at the 5% significance level after day 18 for any level of STP or RRS in an LSMEANS statement in PC SAS PROC MIXED.

3.4.6. Effect of time after litter application

Time (days after litter application) had a highly significant effect on DRP in surface runoff collected from the boxes ($P < 0.0001$). With increasing time, the DRP is likely to move into the soil with infiltrating water or transform into less soluble forms. Due to these reasons, the effect of the treatments decreased with time. The decrease being highest at the beginning and then decreasing gradually until it approached the DRP concentration in runoff from boxes that didn’t receive litter (controls). The DRP decreased exponentially with time (days) after litter application for both litter treated and control boxes (Figures 3-5 and 3-7). The decline in DRP (litter vs. control) with increasing time after litter application was statistically significant until day 18. Some time between 18 and 32 days after litter application, the effect of poultry litter became insignificant compared with the controls (Figure 3-7).

3.5. SUMMARY AND CONCLUSIONS

P loss in surface runoff from well managed pastures is dominated by dissolved reactive P (Edwards and Daniel, 1993; Storm et al., 1995; Storm et al., 1996b), which may result in eutrophication of receiving water bodies. The main objective of this study was to investigate the effects of soil test phosphorus and surface application of poultry litter (P source), rainfall/runoff sequences and time after litter application (P management) on dissolved reactive P in surface runoff from boxes. The study was carried out using a simulated rainfall in a controlled greenhouse experiment in an effort to establish the pasture land use typical of the Ozark Highlands. Rainfall intensity (75 mm/hr) and runoff duration (0.5 h) were held constant through out the experiment. Time to initiate runoff varied from box to box depending on box hydrology and soil infiltration characteristics. Runoff produced from each box was manually recorded at two-minute intervals, and a composite sample was taken at the end of the 30-minute runoff and analyzed for DRP.

Poultry litter, rainfall runoff sequence (RRS), and time after litter application had a highly significant effect on DRP in surface runoff from pastures. The significant STP effect on DRP loss in runoff prior to litter application was masked following litter application. This indicates that litter P served as the primary source of DRP loss in the surface runoff collected from the boxes.

The effect of poultry litter application on DRP loss was also dependent on the time interval between litter application and the first runoff event, and whether there was a non-runoff producing rainfall event during this interval (RRS). The highest averaged DRP loss was observed in runoff collected from boxes with the shortest time interval between litter application and first surface runoff event. A rainfall without runoff reduced significantly the effect of poultry litter application on DRP loss in the first surface runoff event. A longer time interval (RRS3; 7 days) combined with a two non-runoff producing rainfall events resulted in the highest reduction (80%) in DRP loss in runoff compared with RRS1. RRS1 treated boxes (runoff event on day 1 after litter application) had the highest DRP concentration. For litter received boxes, more than 50 percent reduction in DRP loss was observed in the first runoff events of consecutive RRS treatments, i.e. RRS1 and RRS2, and RRS 2 and RRS3 (Table 3-5). The time trend effects of RRS on DRP indicated that they became less variable and they all approached asymptotically the control DRP from above (Tables 3-5, 3-7).

Time to initiate runoff (i.e. difference of rainfall and runoff duration) was found to have a significant effect on DRP loss in surface runoff from the boxes on days 1, 4, and 7 after litter application. This indicates that any practice that minimizes runoff or increases soil infiltration would minimize the offsite transport of DRP (Figure 3-3). The effect is more significant on DRP from pasture that recently received litter.

An exponential decrease defined the relationship between DRP and time after poultry litter application indicating that poultry litter becomes less available over time for the single application (6.7 Mg/ha). Poultry litter application had a significant effect on DRP loss in surface runoff until 18 days compared to controls. Some time between day 18 and 32 after litter application, the effect of litter was not significant compared with controls although observed litter DRP (0.46 mg/L) was higher than control DRP (0.25 mg/L) at the end of the experiment (Day 62). Time had a highly significant effect on DRP loss in surface runoff from poultry litter received boxes in two ways: time interval between litter application and first runoff event (that ranged from 1 to 7 days) in combination with a rainfall without runoff, and time after litter application (that ranged from 1 to 62 days).

Table 3-1. Poultry litter chemical analysis

Element	% on dry basis	% on "as-is" basis
Total N	3.08	1.97
Total P*	1.94	1.24
Total K	2.82	1.80
Total Ca	2.86	1.82

*Based on inductively coupled plasma analysis after nitric acid digestion at the Agricultural Diagnostic Laboratory of the University of Arkansas, Fayetteville, Arkansas

Table 3-2. Experimental setup for rainfall/runoff sequence and days after litter application.

Rainfall/Runoff Sequence[1]	Time (days)[2]						
	1	4	7	11	18	32	62
RRS1	[3]RO	RO	RO	RO	RO	RO	RO
RRS2	[4]NR	RO	RO	RO	RO	RO	RO
RRS3	NR	NR	RO	RO	RO	RO	RO

[1] RRS1, RRS2, and RRS3 represent runoff-producing rainfall events starting from Day 1, 4 and 7 after litter application, respectively.

[2] Number of days after litter application.

[3] Surface runoff producing rainfall event.

[4] Non-runoff producing rainfall (rainfall without surface runoff) event. It was approximately 19 mm per event.

Table 3-3. Statistical summary of the effects of poultry litter, soil test phosphorus and rainfall/runoff sequence on box averaged dissolved reactive phosphorus.

Poultry Litter Total Phosphorus Rate (kg/ha) [a]	Soil Test P] (mg/kg) [b	Mean Dissolved Reactive Phosphorus (mg/L)						
		Time (Days after litter application)						
		1	4	7	11	18	32	62
		Rainfall/Runoff Sequence 1 [c]						
130	309	11.70^{aA}	3.83^{aB}	2.18^{aC}	2.19^{aC}	1.05^{aD}	0.61^{aD}	0.43^{aD}
	77	12.40^{aA}	3.63^{aB}	1.86^{aC}	2.03^{aC}	1.25^{aCD}	0.78^{aD}	0.48^{aD}
0	309	0.80^{bA}	0.51^{bA}	0.46^{bA}	0.82^{aA}	0.43^{aA}	0.40^{aA}	0.24^{aA}
	77	1.05^{bA}	0.67^{bA}	0.45^{bA}	0.93^{aA}	0.47^{aA}	0.40^{aA}	0.33^{aA}
		Rainfall/Runoff Sequence 2						
130	309	-	4.60^{aA}	2.32^{aB}	2.21^{abB}	0.99^{aC}	0.75^{aC}	0.50^{aC}
	77	-	4.90^{aA}	2.27^{aB}	2.54^{aB}	1.11^{aC}	0.73^{aC}	0.46^{aC}
0	309	-	0.70^{bA}	0.54^{bA}	1.06^{bA}	0.65^{aA}	0.47^{aA}	0.21^{aA}
	77	-	0.60^{bA}	0.51^{bA}	1.23^{abA}	0.59^{aA}	0.38^{aA}	0.28^{aA}
		Rainfall/Runoff Sequence 3						
130	309	-	-	2.30^{aA}	2.68^{aA}	1.23^{aB}	0.93^{aB}	0.48^{aB}
	77	-	-	2.20^{aA}	2.85^{aA}	1.22^{aB}	0.86^{aB}	0.45^{aB}
0	309	-	-	0.50^{bA}	1.27^{bA}	0.56^{aA}	0.50^{aA}	0.20^{aA}
	77	-	-	0.50^{bA}	0.99^{bA}	0.44^{aA}	0.42^{aA}	0.21^{aA}

Least Significant Difference (LSD): small letters indicate comparison along columns and capital letters indicate comparison along rows; values with the same letter are not significantly different at the 0.05 probability level.

[a] Poultry litter application rate was 6.7 Mg/ha for litter received, and 0.0 Mg/ha for control boxes.

[b]Soil test phosphorus was based Mehlich III soil P extraction. Average of eight samples for each level; standard deviations for 309 and 77 mg/kg STP levels were 39 and 5.8 mg/kg, respectively.

[c] Rainfall/Runoff Sequence (1 = Runoff-producing rainfall event (RPE) starting from Day 1, 2 = RPE starting from Day 4, and 3 = RPE starting from Day 7 after litter application).

Table 3-4. Statistical summary of the effect of soil test phosphorus on dissolved reactive phosphorus prior to litter application from pasture boxes.

Soil Test Phosphorus (mg/kg) [1]	Averaged Dissolved Reactive Phosphorus (mg/L)		
	Time [2]		
	1	2	3
309	0.57^{aA}	0.90^{aB}	0.88^{aB}
77	0.33^{bA}	0.66^{bB}	0.90^{aC}

Small letters and capital letters indicate comparisons along column and rows respectively. In both cases values with the same letter are not significantly different at the 0.05 probability level.

[1] High (309 mg/Kg) and Low (77 mg/Kg) using Mehlich III soil P extraction. Soil test was carried out prior to pasture establishment, and there is a considerable time until the first rainfall simulation. However, both STP levels are subjected identical situations even if soil P underwent transformations.

[2] Refers to the three-time repeated rainfall simulations prior to poultry litter application.

Table 3-5. The effect of rainfall/runoff sequence on average first runoff event dissolved reactive P from pasture boxes.

Poultry Litter	Soil Test Phosphorus[a]	Average Dissolved Reactive Phosphorus (mg/L)		
		Rainfall/Runoff Sequence[b]		
		1	2	3
Litter Treated	309	12.40^{aA}	4.90^{aB}	2.20^{aC}
	77	11.70^{aA}	4.60^{aB}	2.30^{aC}
Litter Average		12.05	4.75	2.25
Controls	309	1.10^{bA}	0.60^{bA}	0.50^{bA}
	77	0.80^{bA}	0.70^{bA}	0.50^{bA}
Control Average		0.95	0.65	0.50

Least Significant Difference; small and capital letters indicate comparison along column and rows respectively. Values with the same letter are not significantly different at the 0.05 probability level.

[a] Low (77 mg/kg) and High (309 mg/kg) Mehlich III soil P extraction.

[b] 1 = First runoff-producing rainfall event (RPE) starting from Day 1, 2 = RPE starting from Day 4, and 3 = RPE starting from Day 7 after litter application.

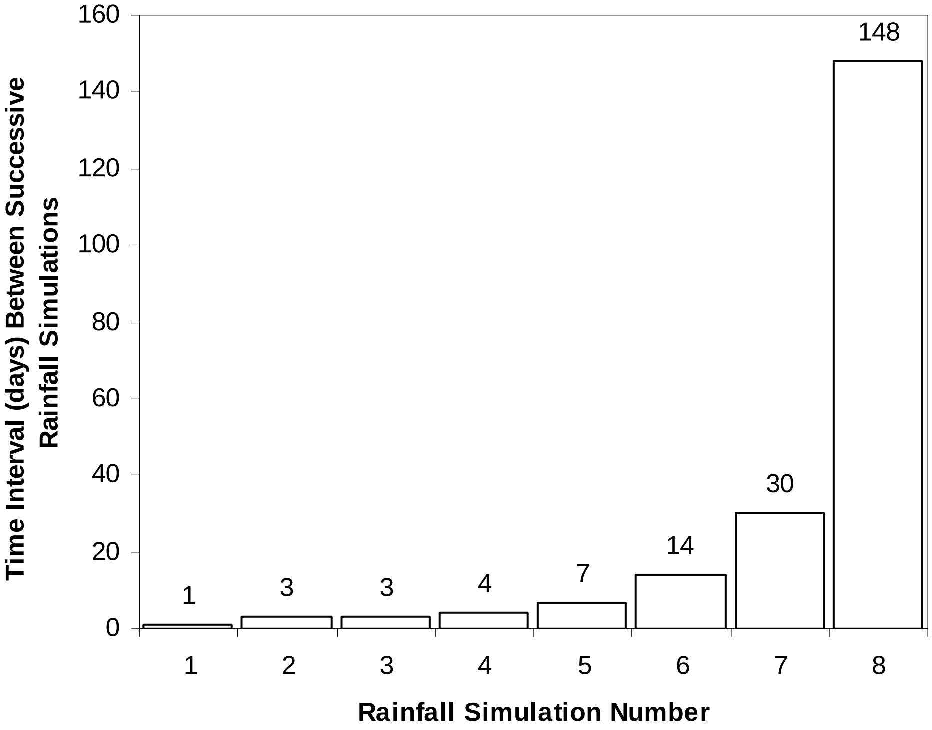


Figure 3-1. Time interval between successive rainfall simulations.

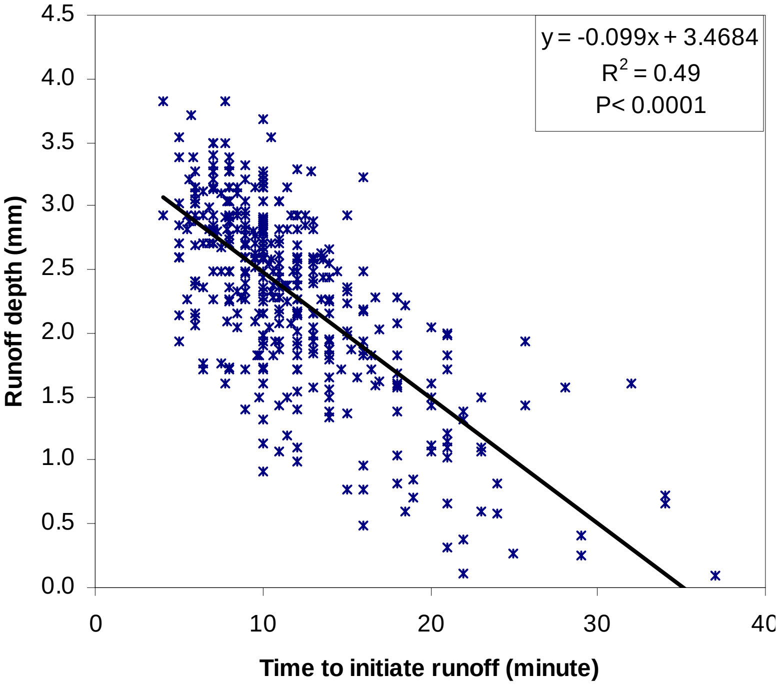


Figure 3-2. The inverse relationship between time to initiate runoff and 30-minute runoff depth.

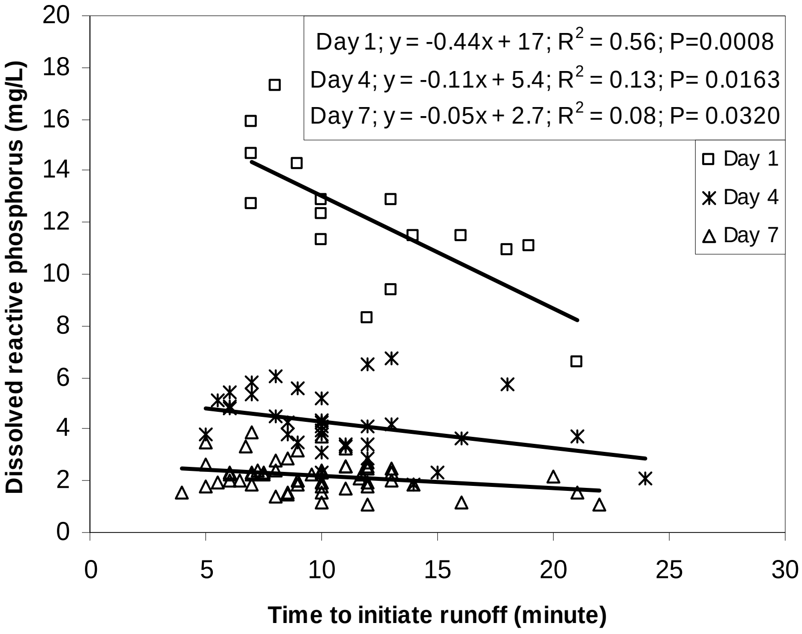


Figure 3-3. Significant effect of time to initiate runoff on dissolved reactive P in surface runoff from litter treated pasture boxes.

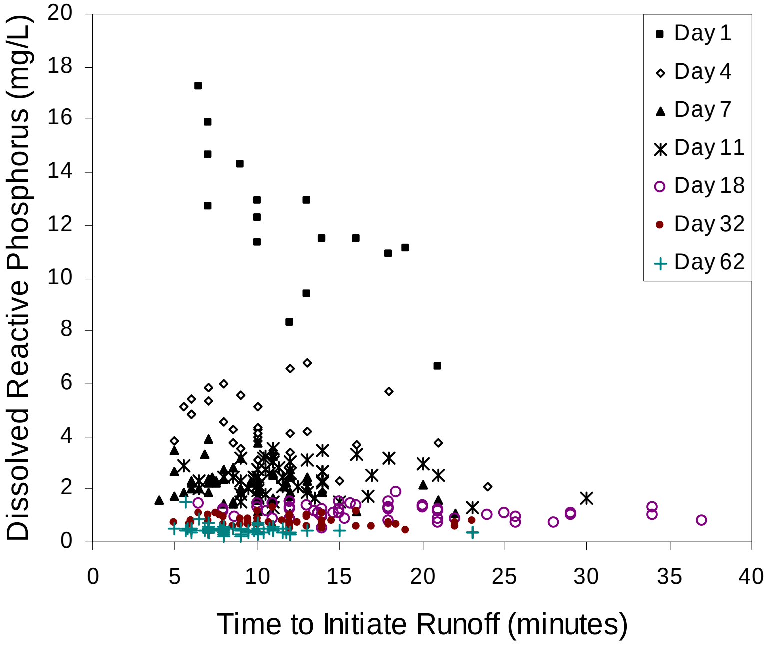


Figure 3-4. A non significant effect of time to initiate runoff on dissolved reactive P for the whole experimental data set.

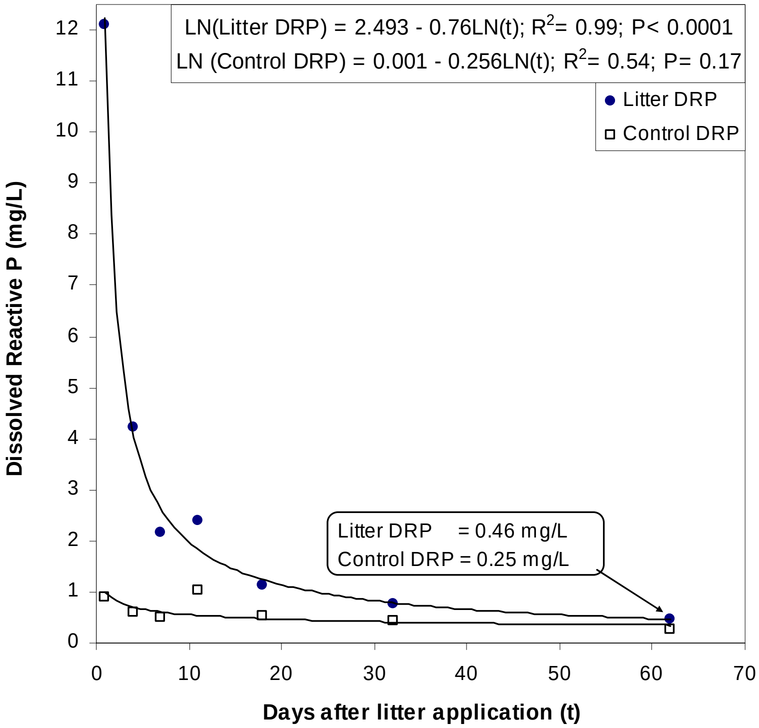


Figure 3-5. Trend of averaged dissolved reactive P in surface runoff from control and litter treated pasture boxes in a controlled greenhouse experiment using a simulated rainfall.

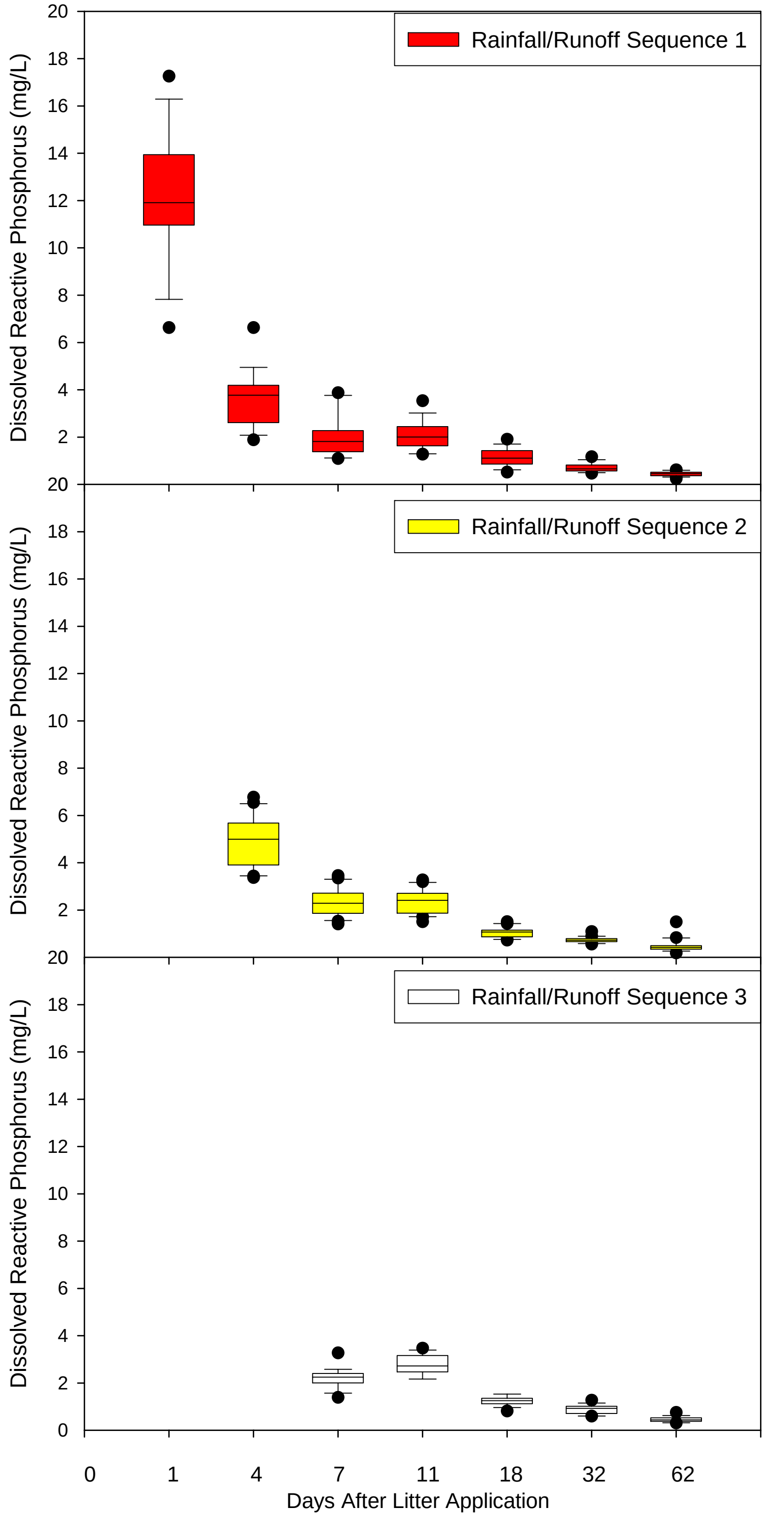


Figure 3-6. The declining effect of rainfall/runoff sequences on dissolved reactive phosphorus with increase in days after litter application from litter treated pasture boxes.

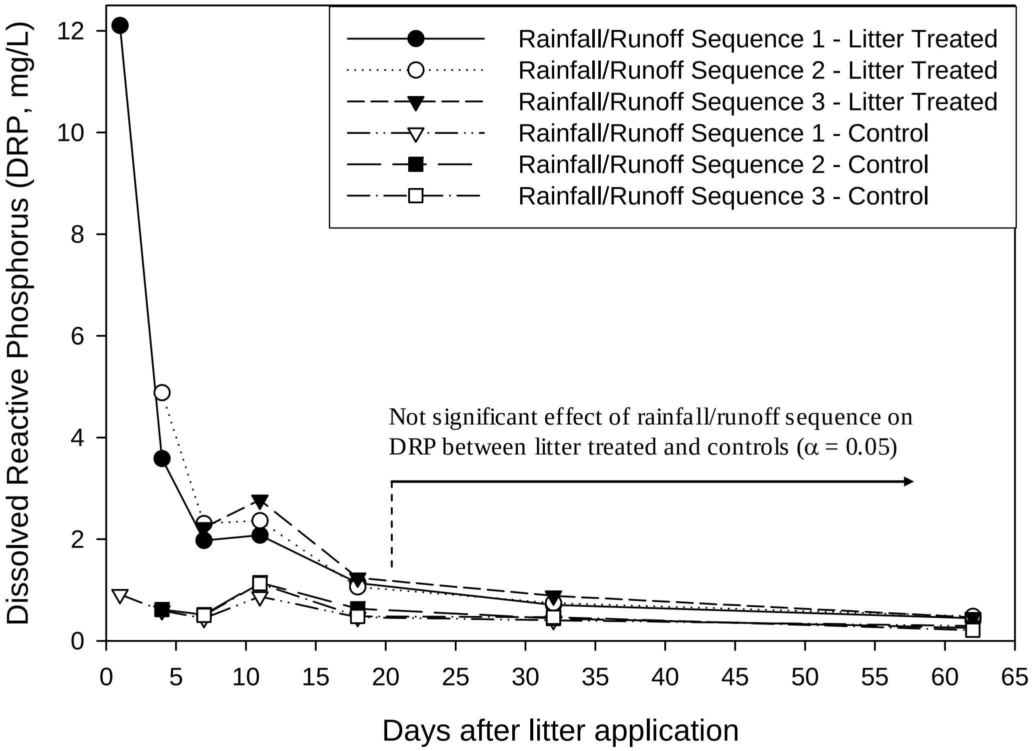


Figure 3-7. The effect of rainfall/runoff sequences vs. days after litter application on averaged dissolved reactive phosphorus in runoff from litter treated and control pasture boxes.

CHAPTER 4

SCALE EFFECTS ON HYDROLOGY AND PHOSPHORUS LOSS FROM PERMANENT PASTURES

4.1. ABSTRACT

Runoff and water quality data from 19 research projects that investigated phosphorus (P) loss from pastures fertilized with poultry litter were summarized in a common dataset. The studies had spatial (area) and temporal (days after litter application, DAL) scale variations that ranged from 0.5 to 80000 m^2*, and 1 to 355 DAL, respectively. The objectives were to investigate overall variable interaction and scale effects on hydrology and P losses in surface runoff from pastures. Variables considered were area, hydraulic conductivity, poultry litter application rate, DAL, slope, soil test phosphorus, alum amendment, grazing rate, pasture height, rainfall intensity, rainfall duration, runoff duration and cumulative precipitation prior to the first runoff event. The summarized dataset was sorted into litter applied and control, and backwards stepwise regression using PROC REG in SAS was performed to analyze variable effects. The final models with significant variables (*$P = 0.1$*) were used to explain the variability in hydrology and P loss from pastures.*

Spatial scale effect existed for hydrology, DRP and TP concentration, DRP and TP load from pastures with the exception of DRP and TP concentration from controls ($P < 0.0001$*). DRP and TP loads increased with increasing areas due in part to increased runoff volume. DRP and TP concentration decreased with increasing area. A temporal scale effect (*$P < 0.0001$*) with an exponential decrease with DAL for DRP and TP*

concentration from both litter received and control pastures was observed. The existence of scale effects for P loss from pastures suggest that a simple averaging procedure based on a homogeneous assumption may not be a suitable method for transferring data from plot- and field-scale to larger scales without considering these effects. Hence, the need to consider scale effects in P management in future studies.

4.2. INTRODUCTION

4.2.1. Scale effects on the hydrology of phosphorus loss

Scale refers to a space-time characteristic of a process, observation or model (Sivaplan and Kalma, 1995). Usually the scale at which available data have been collected is different from that required by P models (Bierkens et al., 2000). As an example, P loss in runoff from pastures can be studied at small scale (a flow length of less than 2 m) but estimates might be needed at larger scales (e.g. flow length of more than 100 m). Research data from small scale studies on P loss from pastures are available. In contrast, there are limited research data from homogeneous land use areas at larger scales. Information on P loss from larger scales (e.g. edge-of-field, watershed), however, may be more important in the management of P. In situations like this, scaling becomes an important issue to obtain data or information for the scale of interest. Scaling is the transfer of information between different space-time scales which can be downscaling (from large to small) or upscaling (from small to large). Scale issues have been identified as a major process not adequately addressed in rainfall/runoff modeling (Wood et al., 1988; NRC 1991; and Sivapalan and Kalma, 1995), and have been identified as an area for continued and sustained research.

Scaling issues are associated with the transfer of information or developing methods to transfer available data at a certain scale to the scale of interest. Some of the reasons for scaling issues are: 1) spatial heterogeneity and temporal variability, and 2) existence of different dominant processes at different scales, e.g. correlations derived at one scale might not be applicable at another (Blöschl et al., 1995).

Investigating P movement at different scales (plot, field or watershed level) is useful to obtain information that will potentially be used in P management (e.g. integration into water quality models). Spatial scales related to P movement might range from less than a meter (laboratory or field plot) to many kilometers (watersheds). Likewise, the temporal variation can range from minutes to months or seasons. Data collection over such a range of scales is difficult and expensive. On the other hand, scaling issues related to P movement are important problems that need adequate attention because of the potential impact of P on water quality. To date, little research has integrated scaling issues and process-based description of P movement across plot or field scales to investigate the effect it would have on larger scale runoff (Cornish et al., 2002; Sharpley and Kleinman, 2003; and Dougherty et al., 2004).

There are a number of studies carried out on P loss and hydrology from pasture systems. However, only few of them considered multiple scales (varying area) at the same time (Edwards et al., 1994; Storm et al., 1996a and 1996b; Vervoort et al., 1998). Even in those projects, which considered multiple pasture areas (spatial scale), scale effect was not the main objective. Investigation of scale effects on P loss and hydrology necessitated combining data from a number of projects in a common dataset.

4.2.2. Objectives of the Study

The objective of this study was the investigation of scale effects (variations in area and days after litter application) on P losses and runoff depth from pastures accounting for variables that affect P movement from pastures.

4.3. MATERIALS AND METHODS

Runoff and water quality data from 19 research projects that investigated phosphorus loss from pastures fertilized with poultry litter were summarized in a common dataset (Table 4-1). The projects consisted of variations in pasture area and days after litter application (DAL) that ranged from 0.5 m^2 to 8 ha (spatial scale), and 1 to 355 days (temporal scale), respectively (Table 4-1, 4-2). The projects were conducted to address varying objectives, and the outcomes of which were published in referred journals or available as reports. Only the first runoff event water quality data following litter application to pasture systems were summarized in the aforementioned research projects. The list of these references along with their spatial scales is given in Table 4-1. Of the 19 research projects, twelve had area less than 18 m^2, which were carried out in Oklahoma with the exception of one in Missouri. The rest were edge-of-field studies (> 0.4 ha) carried out in Arkansas, Georgia and Texas (Table 4-1).

Thirteen independent variables were chosen for this study. However, not all of these variables were considered in each of the summarized research projects. As a result, missing values were observed for some of these variables. Missing data were considerable for edge-of-field studies (e.g. rainfall intensity, rainfall and runoff duration) (Tables 4-3 and 4-4). However, data needed to undertake the study (e.g. rainfall and runoff depth, litter P_2O_5 rate, STP, DRP and TP losses in runoff) were available. The independent (explanatory) variables utilized in this study were: area (m^2), soil hydraulic conductivity (mm/hr), poultry litter P_2O_5 application (kg/ha), days after litter application (DAL, days), average plot/field slope (%), STP (Mehlich III, mg/kg), alum amendment (Mg/ha), grazing rate (animal unit/ha), pasture height (mm), rainfall intensity (mm/hr), rainfall duration (minutes), runoff duration (minutes), and cumulative precipitation prior to the first runoff event (PCP, mm). Runoff depth (hydrology, mm), DRP concentration (mg/L), TP concentration (mg/L), DRP load (g) and TP load (g) were the response variables.

Backwards stepwise regression technique using PROC REG in PC SAS Version 9.1 (SAS, 2003) was performed to analyze variable effects for the summarized dataset. Regression was used to investigate the overall interaction of the explanatory variables and their effects on the response variables: runoff depth, DRP and TP concentration and load from pastures. Each set of explanatory variables was utilized in a multiple regression, and the least significant variable using a type 3 test was sequentially removed until all variables were significant at the probability level of 0.10. The final regression model was then used to assess how the explanatory variables explained the variability in P losses and runoff depth. In addition, Pearson correlation analysis was also employed to investigate whether pasture area (spatial scale) and DAL (temporal scale) have an influence on DRP and TP losses, and runoff depth (hydrology).

4.4. RESULTS AND DISCUSSIONS

4.4.1. Statistical analysis

There was high variability in area, STP, litter P_2O_5 application rate and PCP in the dataset (Tables 4-2, 4-3 and 4-4). This variability should be considered in the investigation of variable effects on runoff depth, DRP and TP losses from pastures. Tables 4-5 and 4-6 give summaries of the backwards stepwise regressional analysis obtained using PROC REG in SAS for litter treated and control pastures, respectively. Stepwise regression analysis is an approach to analyze the effect of each variable on P loss and runoff depth from pastures step by step. The strength of this effect is indicated by the coefficient of determination (R^2). The variable that doesn't contribute significantly to the variance is eliminated from the analysis. However, if there is multicollinearity (codependence or linear dependence) among the independent variables, the contribution of the correlated variables to the variance explained (R^2) depends on the selection order. As an example, if rainfall duration and runoff depth are correlated, they may explain the same process, and little effect on R^2 is observed when one of the two variables is added or removed from the regression model. Ridge analysis was undertaken to counteract this effect. Whenever a given variable is not significant at $P = 0.1$, it means the given variable didn't significantly explain the variance in the presence of the other variables, and hence is removed from the analysis.

Tables 4-5 and 4-6 give the summary of the statistical analysis. They show variables which were significant at $P = 0.1$, the strength of determination (R^2), significance probability for the regression model (P) and number of observations (N).

4.4.2. Scale effects on P loss and runoff depth

The primary objective of this section is to determine whether scale effects (pasture area and days after litter application) are important determinants of P loss and runoff depth from pastures. This objective could have been much more straightforward if the same level of variables had been used across all the projects. The data had a wide range of variation in the level of the variables used (applied litter P_2O_5 rate, STP, PCP, rainfall and runoff depth, rainfall intensity, rainfall and runoff duration, soil infiltration characteristics, DAL, alum amendment, pasture height, grazing rate and slope) as indicated by the PROC REG analysis (Tables 4-5, 4-6). For assessing the scale effects on P losses and runoff depth, analysis and plot diagrams of averaged data by both area and days after litter application (Figures 4-1 to 4-12) and Pearson correlation analysis (Tables 4-7, 4-8) were employed in addition to the PROC REG analysis.

4.4.2.1. Effect of pasture area

Pasture area (spatial scale) had a significant influence on runoff depth (hydrology), DRP and TP concentration and load from litter treated pastures (Tables 4-5, 4-7; Figures 4-9 to 4-12). The existence of a scale effect on runoff depth and P loss from pasture suggests that a simple averaging procedure based on a homogeneous assumption may not be a suitable method to transfer data from one scale to another. Consequently, scaling needs to be addressed to adequately evaluate the offsite transport of P from pasture systems. Spatial scale effects also existed for runoff depth, DRP and TP loads from control pastures (Tables 4-6 and 4-8; and Figures 4-5 and 4-6).

Hydrology (runoff depth)

The PROC REG analysis indicated that pasture area had a significant effect on runoff depth from pastures (Tables 4-5, 4-6). Positive correlations between runoff depth and area were also observed for both control and litter treated pastures, indicating that there may be a scale effect (Tables 4-7 and 4-8). However, the average runoff depth for the complete data set showed a decreasing trend with an increase in area for both control and litter treated pastures. To clarify this, runoff depth was plotted as shown in Figures 4-1 and 4-2 for litter receiving and control pastures, respectively. Both figures indicate that runoff depth tends to increase with area under simulated rainfall (greenhouse and field plot experiments with area < 18 m^2) and decrease thereafter under natural rainfall (edge-of-field studies with area over 0.4 ha). Compared with the edge-of-field studies, the greenhouse and field plot studies were characterized by high rainfall intensity (Table 4-2) and large runoff/rainfall ratios (Figures 4-1, 4-2). Moreover, plots were more homogeneous in greenhouse and field plot studies than under edge-of-field studies. The combined effect of all these might be the reason for the increasing trend of runoff depth with increasing area for the simulated rainfall experiments. Edge-of-field studies are generally characterized by low intense natural rainfall and more heterogeneity. Thus, during an actual rainfall event, there may be portions of the field which contribute runoff and portions which do not. As area increases, flow from the contributing portions concentrate and runoff volume increases. Both flow depth and velocity tend to increase under this situation. However, due to the existence of non-runoff contributing portions, runoff depth tends to decrease with increasing area as shown in Figures 4-1 and 4-2 for the edge-of-field studies.

Each of the summarized research projects differed in soil infiltration, rainfall intensity, runoff duration, cumulative rainfall prior to the first runoff event (PCP), slope, and grazing rate, which influenced runoff depth from pastures (Table 4-3, 4-4, 4-5, 4-6). The variability is very large, which may be masking the true relationship between hydrology and pasture area. In addition, the decreasing trend for the edge-of-field studies may be a direct result of the characteristics of study sites (Texas, Arkansas, and Georgia) used in the analysis. However, for the simulated rainfall experiments an increase in runoff depth with area was observed (Figures 4-1, 4-2). In either case, there appears to be a scale effect on runoff depth from pastures.

Dissolved reactive phosphorus concentration

DRP concentration from litter receiving pastures decreased with increasing area (Figure 4-3). Pearson correlation given in Table 4-7 also indicated this effect ($r = -0.21$ with $P < 0.0001$). Both indicate the existence of a spatial scale effect on DRP concentration. This result agrees with the findings by Sharpley and Kleinman (2004) where DRP concentration was smaller from 32.6 m^2 than 2 m^2 plots. The decrease in DRP concentration with an increase in area may be due to dilution associated with increased runoff volume and P transformations (e.g., sorption/desorption) that would take place during P movement. Based on Manning’s equation, both flow depth and flow velocity increases as flow volume increases. This can reduce not only the amount of runoff water in direct contact with P sources but also the contact time between the soil matrix and runoff water. Moreover, the amount of P in runoff per unit area tends to decline due to the inclusion of non-P contributing areas. However, there was high variability in DRP concentration with increasing area. This could be due to soil infiltration characteristics/site hydrology and the varying level of litter P_2O_5 applied to pastures. The maximum averaged DRP concentration was observed for pastures with an area of 18 m^2 that received the highest litter P_2O_5 application rate among the summarized projects. The converse is true for projects that had received low averaged litter P_2O_5 application rate (Figure 4-4), which had the lowest DRP concentrations. Moreover, there were variations in rainfall intensity, rainfall and runoff duration among the summarized projects. DRP concentration decreases as these variables increase due to the associated dilution. There was no significant area (spatial scale) effect on DRP concentration from control pastures (Figure 4-3). This may be due to 1) the balance of the P adsorption/desorption processes that take place during transport with no net effect on DRP concentration, and 2) the wide variations in the properties of the soils used in this study that might have confounded the STP effect from control pastures, and 3) the difference in P sources, i.e. soil matrix P vs. poultry litter.

Total phosphorus concentration

For litter receiving pastures, TP concentration loss averaged by pasture area decreased with increasing area (Figure 4-4; R^2=0.17; $P < 0.0001$). Pearson's correlation coefficient also gave a similar result ($r = -0.25$; $P < 0.0001$) (Tables 4-7, 4-8). The PROC REG analysis indicated that pasture area had an influence on TP concentration from litter received pastures ($R^2 = 0.65$; $P < 0.0001$). All these analyses indicate that spatial scale (area) had a significant effect on TP concentration from litter received pastures.

Figure 4-4 shows the effect of increasing area on TP concentration. As area increases, flow length and concentrated flow increases. The increased concentrated flow may dilute the P concentration by reducing the interaction with the soil surface and matrix. In addition, P adsorption during transport, soil infiltration, and site hydrology can affect P concentration. If infiltration increased with increasing area then additional P will move into the soil matrix, resulting in reduced P for offsite transport in surface runoff.

Pasture area had little effect on total P concentration from control pastures. In control pastures, unlike litter received pastures, P source is limited. As a result, TP concentration did not show a significant effect of area.

Dissolved reactive P load

There was a spatial (area) scale effect for DRP load averaged by area from both control (R^2 = 0.49; P < 0.0001) and litter receiving (R^2 = 0.85; P < 0.0001) pastures as shown on Figure 4-5. DRP load and pasture area were also strongly correlated for both control (r = 0.47, P< 0.0001) and litter received (r = 0.66, P< 0.0001) pastures (Tables 4-7, 4-8). DRP load increased with increasing pasture area. DRP is immediately available for aquatic biota, and this is a concern in areas of sensitive water bodies located nearby pastures fertilized with poultry litter. This result emphasizes the importance of hydrology, P source, and pasture area in the management of P loss in runoff from pastures. The scale effect on DRP load from both control and litter treated pastures may be due to the increased runoff depth that may be related to increases in concentrated flow. DRP load was higher from litter received pastures because of the difference in P sources (Figure 4-5).

Total P load

A spatial scale effect on total P load was indicated by both backwards stepwise regression technique (R^2 = 0.36; P < 0.0001) and Pearson correlation analysis (r = 0.50;

P< 0.0001). TP load from both litter received and control pastures averaged by area increased with area (Figure 4-6; $R^2 = 0.50$, $P < 0.0001$).

Similar to the DRP load, the increase in TP load is primarily due to the increase in runoff volume, which may be a result of increased concentrated flow. As area increased, TP load increased, and this is a concern for water resources as excess P delivery to aquatic ecosystems results in eutrophication (U.S. EPA, 1996; Sims, 2000; and Sharpley et al., 2003). P management approaches need to integrate scale effects on TP load accounting for variables that influence P movement, e.g. site specific characteristics such as hydrology and P source.

4.4.2.2. Temporal scale effects

Time after litter application (DAL, days) was included in this study to investigate the possible existence of a temporal scale effect on P loss and runoff depth from pastures. As DAL increases, there is an increasing probability a given field will receive precipitation. To account for this, the cumulative precipitation between litter application and first runoff event was considered as a variable. By accounting for this precipitation, the variability that arises due to the uncontrolled rainfall that occurred under field condition was minimized.

Pearson correlation analyses for both litter treated and control dataset indicated that DAL had a highly significant effect on both DRP and TP concentrations (Tables 4-7 and 4-8). As shown in Figure 4-8, the cumulative precipitation between litter application and first runoff event increases as DAL increases, and this in turn resulted in decreased P concentrations in runoff. This further corroborates the greenhouse study (Chapter 3) that found that precipitation prior to the first runoff event reduces P concentration in surface runoff.

There was temporal scale effect for DRP and TP concentration from litter receiving pastures (Figures 4-9 and 4-10). Although the data were highly variable, P concentration generally decreased exponentially with increasing time after litter application. Time after litter application had a significant effect on TP load (Figure 4-12) while it had minor effect on DRP load (Figure 4-11) and hydrology (Figure 4-6) despite the tendency of an exponential decrease.

Immediately following poultry litter application, P concentration in runoff increases, which can be attributed to the direct dissolution of highly soluble litter P (Daughtery et al., 2004). With increasing DAL and rainfall, however, litter P can be transformed, incorporated, or taken up by plants, and hence less P will be available. Thus, the capacity of the soil matrix to supply P may decrease with time. Research findings by various investigators indicated that there is a reduction in P loss (> 50%) as the time between litter application and first runoff event increases (Chapter 3; Eghball et al., 2002; and Nash et al., 2000). This study considered not only the time interval between litter application and first runoff event, but also the amount of precipitation between litter application and the first runoff event. The decrease in P losses in runoff from pastures was not merely a time factor rather a combination of the time interval with cumulative precipitation between litter application and first runoff event. As the cumulative precipitation increased, P losses in runoff decreased with increasing days after litter application. In other words, precipitation prior to runoff event decreases P concentration in runoff.

4.5. SUMMARY AND CONCLUSIONS

This study was carried out to investigate the spatial and temporal scale effects on runoff depth (hydrology) and P loss from pastures. It also included analysis of the overall effects of a number of variables on hydrology, and DRP and TP concentration and load.

Spatial scale effects existed for DRP and TP concentration from litter receiving pastures (Tables 4-8 and 4-9). Both DRP and TP concentrations decreased as area increased ($r < 0$; $P < 0.0001$; Figures 4-3, 4-4). This may be due to dilution associated with an increase in runoff volume (concentrated flow) with increasing area. In addition, P transformations and site characteristics, such as hydrology and P adsorption and desorption processes, may contribute to the decrease. It should be noted that there was no significant spatial scale (area) effect on DRP and TP concentration from the control pastures. This may be due to the difference in P sources, i.e. the soil matrix vs. poultry litter.

Spatial scale effects also existed for DRP and TP load from both litter received and control pastures (Tables 4-7, 4-8; Figures 4-5, 4-6). DRP land TP load increased with increasing pasture area. The increase in P load with area is due to increased runoff volume. Runoff volume increases with area, and this in turn carries large quantities of P provided the P source is not limited. This is a concern in fields with high runoff potential that received poultry litter. A decrease in runoff depth with an increase in area was observed for the complete dataset.

A temporal scale effect was observed for DRP and TP concentration from both control and litter receiving pastures. This is mainly due to transformations and downward movement of P resulting from the combined effect of precipitation prior to the first runoff event and time after litter application. This makes less DRP and TP available to surface runoff. Both DRP and TP concentrations decreased exponentially with time. This corroborates the findings in Chapter 3. Moreover, Good (2002) observed a two-fold to six-fold decrease in water extractable P during the first 14 days of laboratory incubation of poultry litter indicating a temporal scale effect. Temporal scale effect existed for TP load, while it didn't for DRP load and hydrology.

The existence of the scale (spatial and temporal) effect suggested that a simple averaging procedure (i.e. homogeneous assumption) may not be an appropriate method to transfer plot- and field-scale studies to larger scales without considering these effects. This calls for the integration of the scale effect on P loss and hydrology in the management of P movement from pastures.

Table 4-1. List of data sources utilized in the scale effect study.

No.	Area (m^2)	References for the research projects	Location of study	Study scale
1	0.5	Demissie et al., 2004	Stillwater, Oklahoma	Greenhouse (Laboratory)
2	1.0	Storm et al., 1995; Storm et al., 1996a; Storm et al., 1996b	Stillwater, Oklahoma	”
3	2.0	M. Friend, 2003; Basta et. al., 2000	Neosho, Missouri Miami, Oklahoma	Field plot
4	17.6	Huhnke et al., 1993; Storm et al., 1999; and McCowan et al., 2002	Adair, Delaware, Jay & LeFlore Counties, Oklahoma	”
5	4500	Vervoort et al., 1998	Georgia	Edge-of-field
6	5700	Edwards et al., 1994	Arkansas	”
7	7200	Kuykendall et al., 1999	Georgia	”
9	7600	Kuykendall et al., 1999	Georgia	”
10	10600	Edwards et al., 1994	Arkansas	”
11	12000	Harmel et al., 2004	Texas	”
12	12300	Edwards et al., 1994	Arkansas	”
13	14600	Edwards et al., 1994	Arkansas	”
14	23000	Harmel et al., 2004	Texas	”
15	80000	Harmel et al., 2004	Texas	”

Table 4-2. Simple statistics for the variables utilized in the scale effect study.

Variables and their units	**Litter Treated Pastures**					**Control Pastures**				
	N	Mean	Min	Max	STDV	N	Mean	Min	Max	STDV
Pasture area (m^2)	372	2363	0.5	80000	8139	129	3785	0.5	14600	5270
Hydraulic conductivity (mm/hr)	372	36	15	53	8	129	33	15	53	5
Litter P2O5 rate (kg/ha)	372	149	25	960	172	129	0	0	0	0
Days after litter applications	372	23	1	355	63	129	45	1	355	88
Average slope (%)	372	6	3	15	3	129	4	2	14	2
Soil test P (mg/kg)	357	99	11	506	134	129	435	4	2257	570
Alum (Mg/ha)	334	4	0	80	14	90	3	0	51	12
Grazing rate (AU/ha)	372	3	0	45	11	129	2	0	15	5
Pasture height (mm)	372	74	50	175	35	129	56	50	175	18
Rainfall intensity (mm/hr)	305	62	25	75	13	78	69	64	75	6
Rainfall duration (min.)	302	71	26	204	38	77	56	13	83	15
Runoff duration (min.)	240	44	6	72	15	74	39	30	66	11
Cumulative precipitation prior to the first runoff event (mm)	362	64	0	997	155	124	146	0	617	171
Runoff depth (mm)	367	23	0	166	24	125	22	0	225	39
DRP load (g)	340	130	0	4931	481	113	71	0	2259	260
TP load (g)	296	207	0	6327	698	89	110	0	2280	314
DRP concentration (mg/L)	344	10	0	54	10	120	1	0	13	2
TP concentration (mg/L)	292	19	0	167	23.2	88	2	0	12	2

N	Number of observations
Min	Minimum value
Max	Maximum value
STDV	Standard deviation

Table 4-3. Variable averages by area for litter treated pastures.

Variables and their units	Pasture area (m^2)										
	0.5	1	2	18	4500	7200	7600	10600	12300	23000	80000
Hydraulic conductivity (mm/hr)	33	33	33	40	30	40	35	40	33	15	15
Litter P_2O_5 rate (kg/ha)	130	110	130	171	170	141	141	60	147	339	180
Days after litter application	4	1	1	20	18	49	49	59	134	11	11
Average slope (%)	5	10	5	6	3	7	7	4	3	4	3
Soil test P (Mehlich III, mg/kg)	193	15	77	34	.	51	42	387	423	50	30
Alum (Mg/ha)	0	0	0	7	0	0	0	.	.	0	0
Grazing rate (Animal unit/ha)	0	0	0	6	0	1	1	1	1	0	0
Pasture height (mm)	50	109	50	74	100	100	100	50	50	100	100
Rainfall intensity (mm/hr)	75	39	75	64	.	.	.	.	.	.	.
Rainfall duration (min)	41	107	42	71	.	.	.	.	.	.	.
Runoff duration (min.)	30	.	30	50	.	.	.	.	.	.	.
Cumulative rainfall prior to the first runoff event (mm)	20	0	0	35	37	.	.	317	457	0	6
Runoff depth (mm)	2	26	25	28	41	14	6	3	11	.	.
DRP loading (g)	2	0	0	8	847	1016	689	148	387	1340	2738
TP loading (g)	.	0	.	11	1334	2142	1231	194	470	1411	2899
DRP concentration (mg/L)	2	11	7	15	4	8	10	4	3	1	1
TP concentration (mg/L)	.	13	.	24	6	18	20	5	4	.	.

DRP = Dissolved reactive phosphorus; TP = Total phosphorus; g = gram; min = minute; and “.” = missing data value.

Table 4-4. Variable averages by area for control pastures.

Variables and their units	Area (m^2)								
	0.5	2	18	5700	7200	7600	12000	12300	14600
Hydraulic conductivity (mm/hr)	33	33	33	40	40	35	15	33	30
Litter P_2O_5 rate (kg/ha)	0	0	0	0	0	0	0	0	0
Days after the start of the study	4	1	75	69	43	43	11	0	51
Average slope (%)	5	3	6	2	7	7	2	3	4
Soil test P (Mehlich 3)	174	1393	29	472	44	50	12	367	769
Alum (Mg/ha)	0	14	0	.	0	0	0	.	.
Grazing rate (Animal unit/ha)	0	3	4	1	1	1	0	2	0
Pasture height (mm)	50	50	53	50	100	100	100	50	50
Rainfall intensity (mm/hr)	75	75	64	.	.	.	.	.	.
Rainfall duration (min)	41	46	64	.	.	.	.	.	.
Runoff duration (min.)	30	30	46	.	.	.	.	.	.
Cumulative precipitation prior to the first runoff event (mm)	16	0	142	316	0	.	12	212	299
Runoff depth (mm)	2	9	26	2	12	3	.	7	14
DRP loading (g)	1	0	0	25	8	5	529	94	334
TP loading (g)	.	.	1	30	84	37	531	123	433
DRP concentration (mg/L)	1	2	2	2	0	0	0	1	2
TP concentration (mg/L)	.	.	2	2	1	2	.	2	2

DRP = Dissolved reactive phosphorus; TP = Total phosphorus; g = gram; min = minute; and "." = missing data value.

Table 4-5. Summary of the statistical analysis for pastures receiving litter.

Independent variables & their units	N	Runoff Depth (mm)	DRP Conc. (mg/L)	TP Conc. (mg/L)	DRP Load (g)	TP Load (g)
		$R^2 = 0.70$ $P < 0.0001$	$R^2 = 0.55$ $P < 0.0001$	$R^2 = 0.65$ $P < 0.0001$	$R^2 = 0.31$ $P < 0.0001$	$R^2 = 0.36$ $P < 0.0001$
Pasture area (m^2)	372	***	***	*	*	*
Hydraulic conductivity (mm/hr)	372	***	**	**	***	ns
Litter P_2O_5 rate (Kg/ha)	372	*	***	***	**	***
Days after poultry litter application (days)	372	**	***	ns	ns	ns
Average slope (%)	372	*	ns	**	ns	***
Soil test P (mg/kg)	357	ns	ns	ns	ns	**
Alum amendment (Mg/ha)	334	ns	**	ns	ns	ns
Grazing rate (AU/ha)	372	ns	ns	ns	ns	ns
Pasture height (mm)	372	ns	ns	ns	ns	ns
Rainfall prior to the first runoff event (mm)	305	***	***	ns	ns	ns
Rainfall intensity (mm/hr)	302	***	ns	*	ns	*
Rainfall duration (minute)	240	ns	ns	***	ns	ns
Runoff duration (minute)	362	***	*	ns	***	***

Conc.	Concentration
TP	Total phosphorus
DRP	Dissolved reactive phosphorus
N	Number of observations
R^2	Coefficient of determination
P	Significance probability for the regression model (i.e. Ho: all slopes are zero)

Level of significance of each variable input considered in PROC REG analysis

*	$0.05 < P < 0.1$
**	$0.0025 < P \leq 0.05$
***	$P \leq 0.0025$
ns	Not significant at $P = 0.1$

Table 4-6. Summary of the statistical analysis for control pastures.

Independent variables & their units	N	Runoff Depth (mm)	DRP Conc. (mg/L)	TP Conc. (mg/L)	DRP Load (g)	TP Load (g)
		$R^2 = 0.81$ $P < 0.0001$	$R^2 = 0.65$ $P < 0.0001$	$R^2 = 0.52$ $P < 0.0001$	$R^2 = 0.57$ $P < 0.0001$	$R^2 = 0.50$ $P = 0.0003$
Pasture area (m^2)	129	*	ns	*	***	*
Hydraulic conductivity (mm/hr)	129	ns	ns	ns	***	ns
Days after litter applications (days)	129	***	***	**	***	ns
Average slope (%)	129	ns	**	**	ns	**
Soil test P (mg/kg)	129	*	**	ns	ns	*
Alum amendment (Mg/ha)	90	ns	ns	*	ns	*
Grazing rate (AU/ha)	129	***	ns	*	ns	ns
Pasture height (mm)	129	ns	ns	ns	*	ns
Rainfall prior to the first runoff event (mm)	78	***	***	***	***	*
Rainfall intensity (mm/hr)	77	*	***	*	***	*
Rainfall duration (minute)	74	ns	ns	ns	ns	ns
Runoff duration (minute)	124	***	***	ns	***	ns

Conc.	Concentration
TP	Total phosphorus
DRP	Dissolved reactive phosphorus
N	Number of observations
R^2	Coefficient of determination by the significant variables
P	Significance probability for the regression model (i.e. Ho: all slopes are zero)

Level of significance of each variable input considered in PROC REG analysis

*	$0.05 < P < 0.1$
**	$0.0025 < P \leq 0.05$
***	$P \leq 0.0025$
ns	Not significant at $P = 0.1$

Table 4-7. Pearson correlation analysis of the variables from litter treated pastures.

Independent Variables and their units	Response (dependent) variables				
	Runoff Depth (mm)	DRP Load (g)	TP Load (g)	DRP Concentration (mg/L)	TP Concentration (mg/L)
Pasture Area (m^2)	0.16* 0.002** 367***	0.66 <.0001 340	0.50 <.0001 296	-0.21 <.0001 344	-0.25 <.0001 292
Hydraulic conductivity (mm/hr)	0.16 0.0021 367	-0.29 <.0001 340	-0.26 <.0001 296	0.13 0.0151 344	-0.13 0.0259 292
Litter P_2O_5 rate (kg/ha)	-0.05 0.3287 367	0.10 0.0578 340	0.06 0.3228 296	0.40 <.0001 344	0.73 <.0001 292
Days after litter application (days)	-0.05 0.3646 367	0.09 0.1079 340	0.06 0.312 296	-0.26 <.0001 344	-0.25 <.0001 292
Slope (%)	0.18 0.0006 367	-0.20 0.0002 340	-0.19 0.0008 296	0.22 <.0001 344	0.14 0.0164 292
Soil test P (mg/kg)	-0.36 <.0001 352	0.12 0.0303 325	0.15 0.0129 281	-0.37 <.0001 329	-0.26 <.0001 277
Alum amendment (mm)	0.11 0.0426 329	-0.06 0.297 303	-0.08 0.2219 259	-0.01 0.8122 306	-0.12 0.0549 254
Grazing rate (AU/ha)	0.04 0.4018 367	-0.07 0.2173 340	-0.08 0.1719 296	-0.20 0.0002 344	-0.20 0.0005 292
Pasture height (mm)	0.21 <.0001 367	0.09 0.1062 340	0.07 0.2326 296	0.10 0.0568 344	-0.15 0.0098 292
Rainfall Intensity (mm/hr)	-0.12 0.033 300	0.16 0.0084 274	0.32 <.0001 230	-0.12 0.0499 277	0.17 0.0108 231
Rainfall Duration (minutes)	0.48 <.0001 300	0.01 0.9187 273	-0.09 0.1883 230	0.12 0.0489 274	-0.07 0.2852 231
Runoff Duration (minutes)	0.59 <.0001 236	0.51 <.0001 210	0.39 <.0001 166	0.45 <.0001 212	0.23 0.0023 166
Cumulative Precipitation (mm)	-0.14 0.0096 357	0.15 0.0076 330	0.14 0.0194 286	-0.31 <.0001 334	-0.28 <.0001 284

DRP	Dissolved reactive phosphorus
TP	Total phosphorus
*	Pearson correlation coefficient (r)
**	Probability (P) > $\lvert r \rvert$ under $H_o:\rho = 0$
***	Number of observations (N)

Table 4-8. Pearson correlation analysis of the variables from control pastures.

Independent Variables and their units	Response (dependent) variables				
	Runoff Depth (mm)	DRP Load (g)	Total P Load (g)	DRP Concentration (mg/L)	Total P Concentration (mg/L)
Pasture area (m^2)	0.25* 0.0055** 125***	0.47 <.0001 113	0.50 <.0001 89	-0.06 0.531 120	0.04 0.705 88
Hydraulic conductivity (mm/hr)	-0.76 <.0001 125	-0.42 <.0001 113	-0.40 <.0001 89	0.14 0.119 120	0.08 0.436 88
Days after the start of the study (DAL)	-0.03 0.722 125	-0.04 0.6476 113	-0.09 0.4125 89	-0.16 0.0903 120	-0.28 0.007 88
Slope (%)	-0.05 0.568 125	-0.14 0.143 113	-0.18 0.091 89	0.04 0.634 120	0.27 0.012 88
Soil test P (mg/kg)	-0.24 0.0076 125	0.00 0.983 113	0.32 0.002 89	0.18 0.055 120	0.13 0.239 88
Alum Amendment (mm)	-0.09 0.3809 88	-0.05 0.6822 80	. . 56	-0.04 0.697 82	. . 50
Grazing rate (AU/ha)	-0.06 0.4992 125	-0.12 0.2189 113	-0.14 0.1937 89	-0.11 0.239 120	-0.27 0.012 88
Pasture height (mm)	0.46 <.0001 125	0.19 0.042 113	0.16 0.131 89	-0.18 0.054 120	-0.11 0.308 88
Rainfall Intensity (mm/hr)	-0.65 <.0001 76	-0.17 0.172 68	. . 44	-0.02 0.896 70	. . 44
Rainfall Duration (minutes)	0.37 0.001 76	0.25 0.038 68	0.34 0.022 44	0.24 0.046 69	0.43 0.003 44
Runoff Duration (minutes)	0.52 <.0001 73	0.23 0.062 65	0.60 <.0001 41	0.07 0.572 66	0.60 <.0001 41
Cumulative Precipitation (mm)	-0.17 0.066 120	0.08 0.415 108	0.05 0.660 84	-0.12 0.207 115	-0.24 0.032 83

DRP	Dissolved reactive phosphorus
TP	Total phosphorus
*	Pearson correlation coefficient (r)
**	Probability (P) > |r| under $H_o:\rho = 0$
***	Number of observations (N)

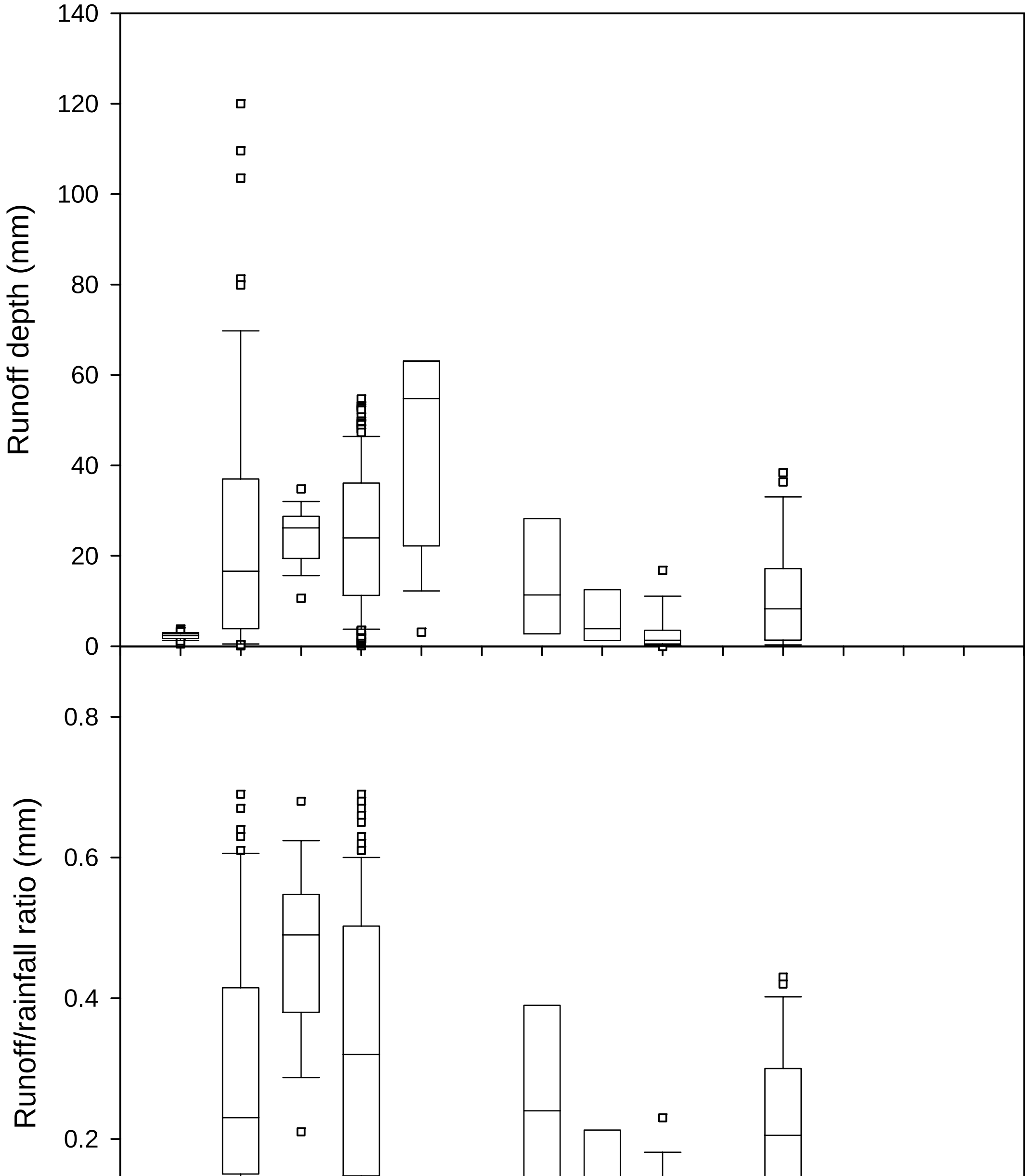


Figure 4-1. Box plot showing variation in runoff depth and runoff/rainfall ratios from pastures that received litter.

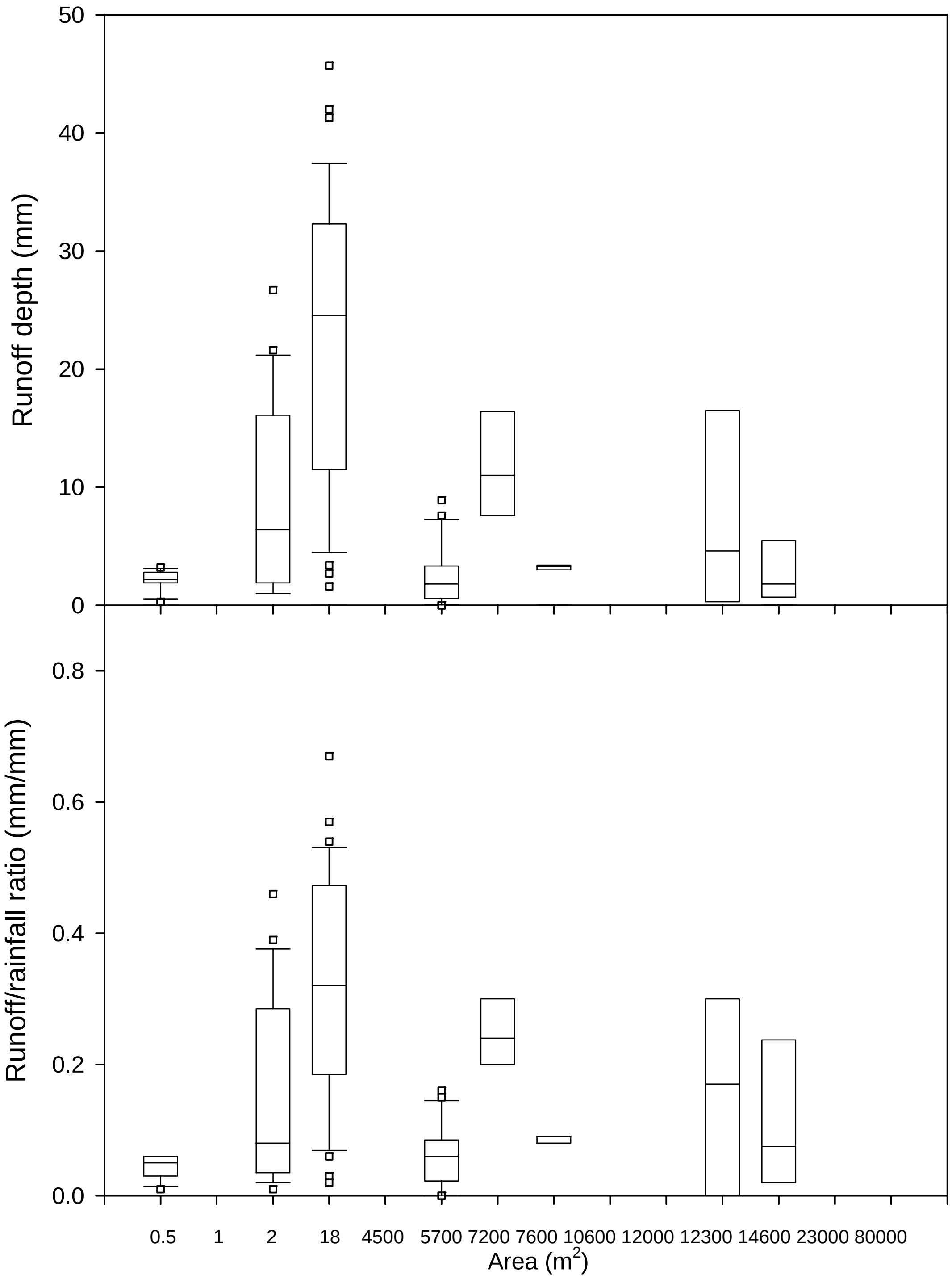


Figure 4-2. Box plot showing variation in surface runoff depth and runoff/rainfall ratios from control pastures.

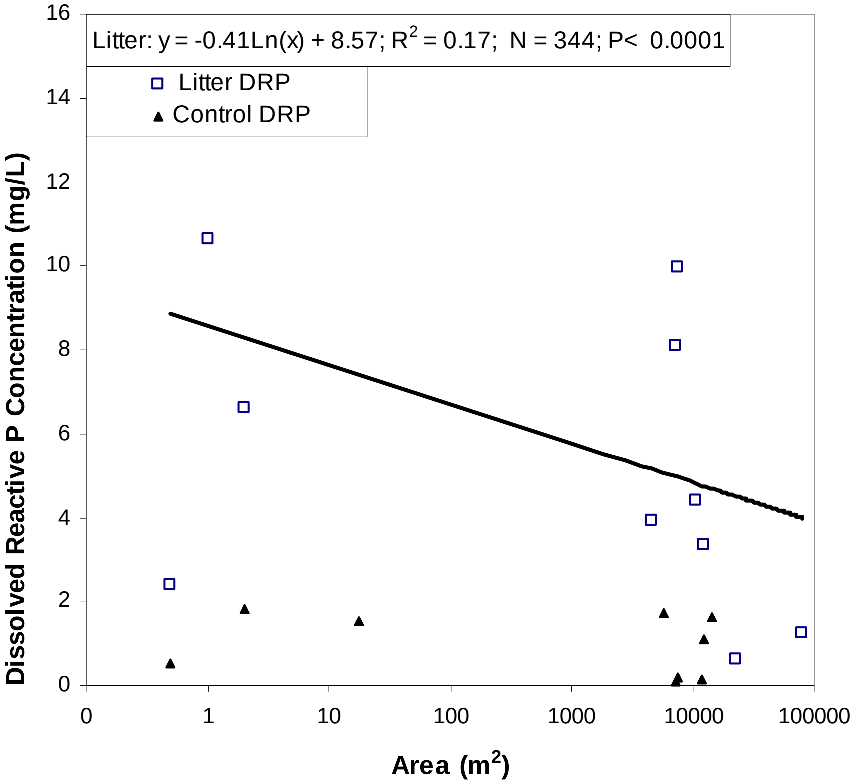


Figure 4-3. The relationship between dissolved reactive P concentration and area from pastures.

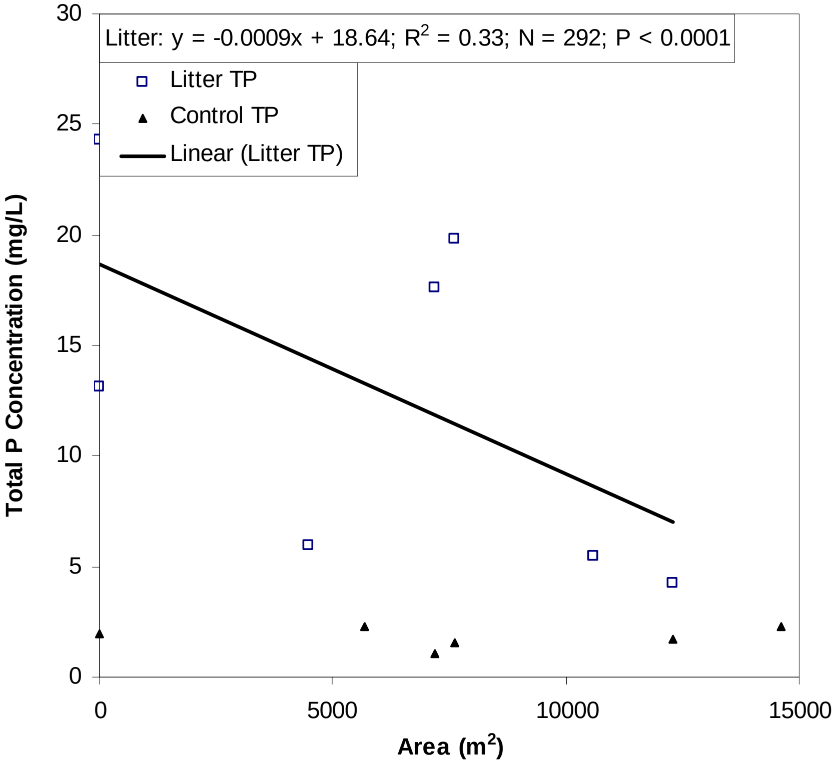


Figure 4-4. The relationship between total P concentration and area from pastures.

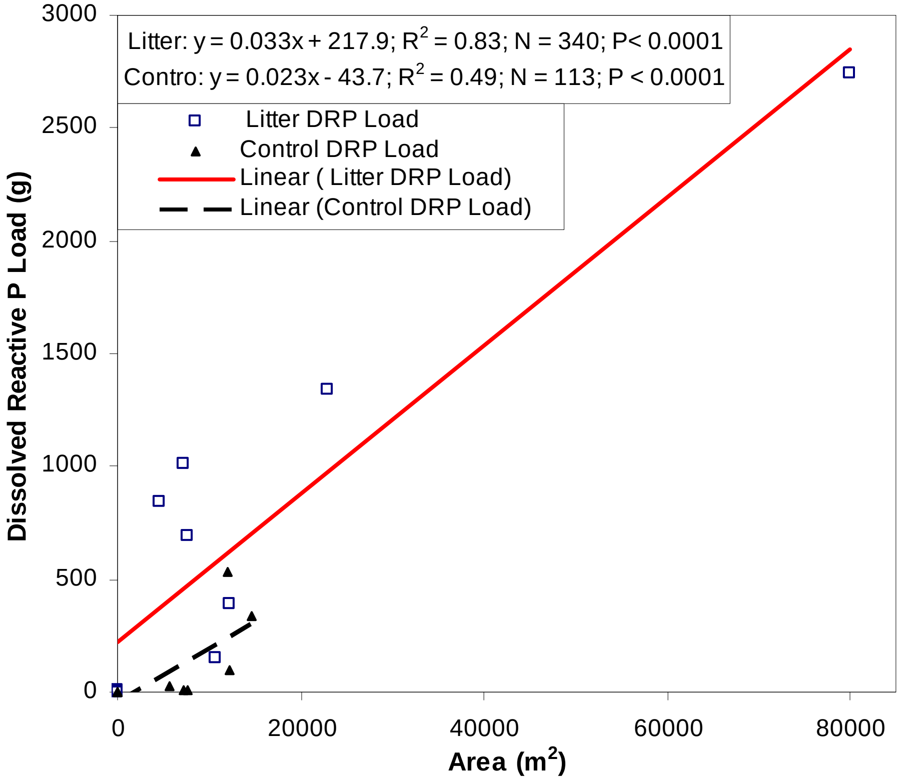


Figure 4-5. Relationship between dissolved reactive P load and area from pastures.

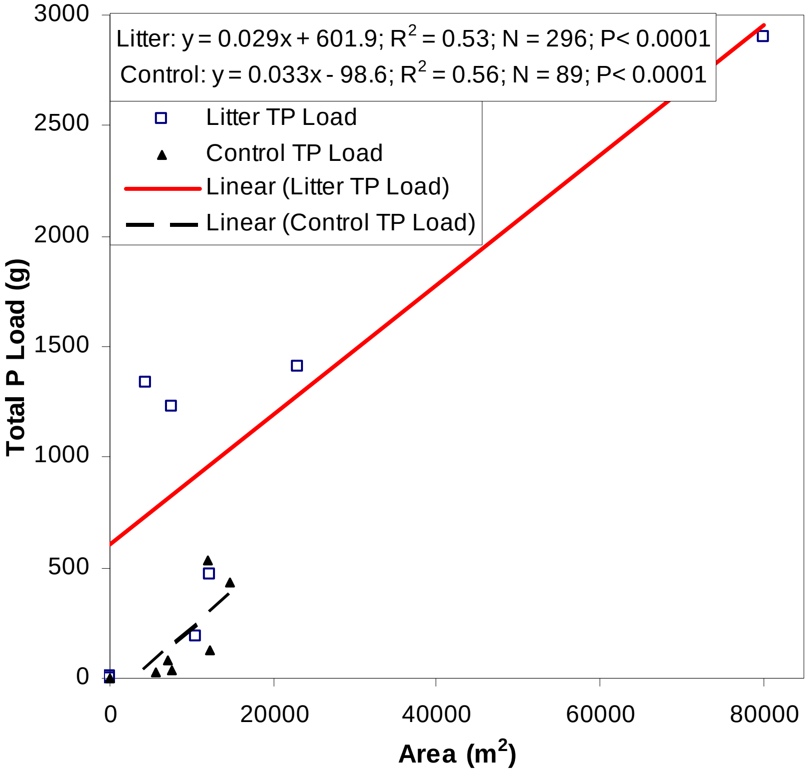


Figure 4-6. The relationship between total P load and area from pastures.

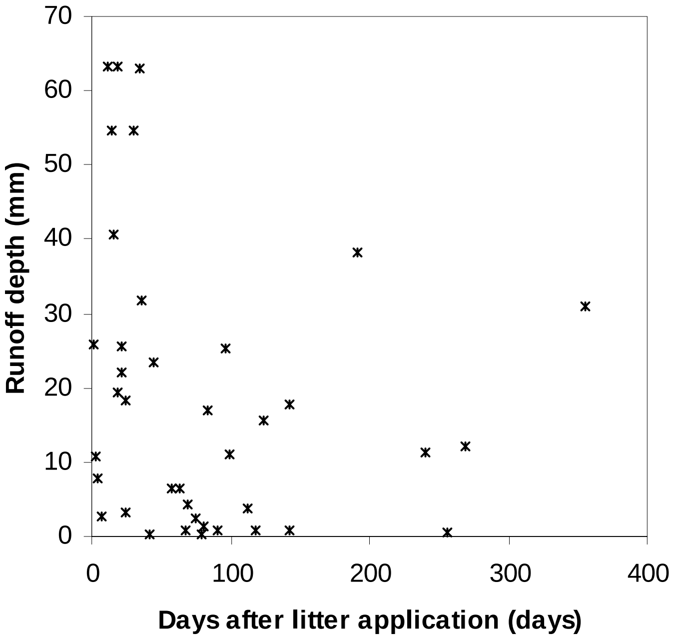


Figure 4-7. No significant (P = 0.05) time scale effect on runoff depth from pastures.

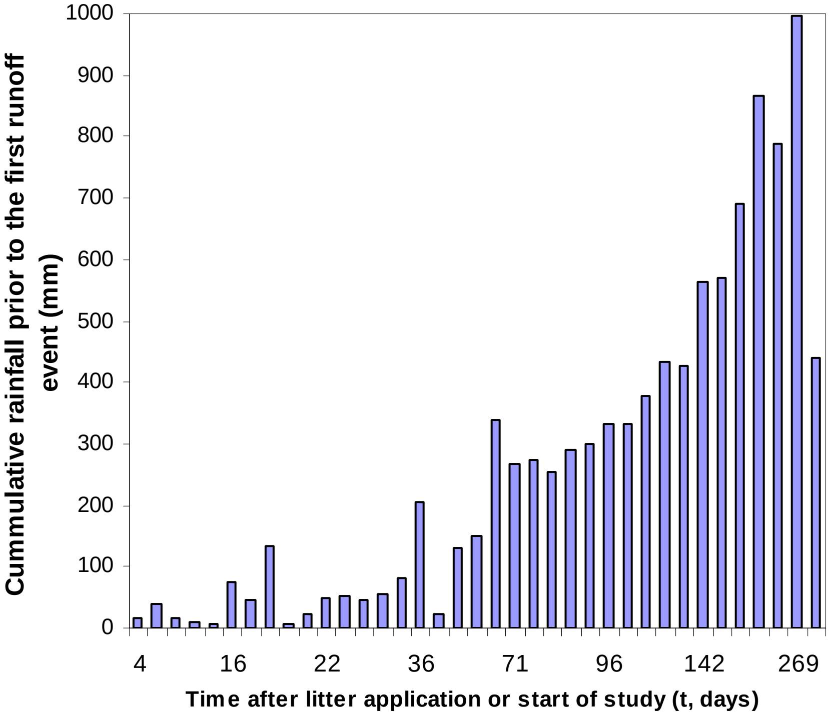


Figure 4-8. Cumulative precipitation prior to runoff event vs. days after litter application for the summarized projects.

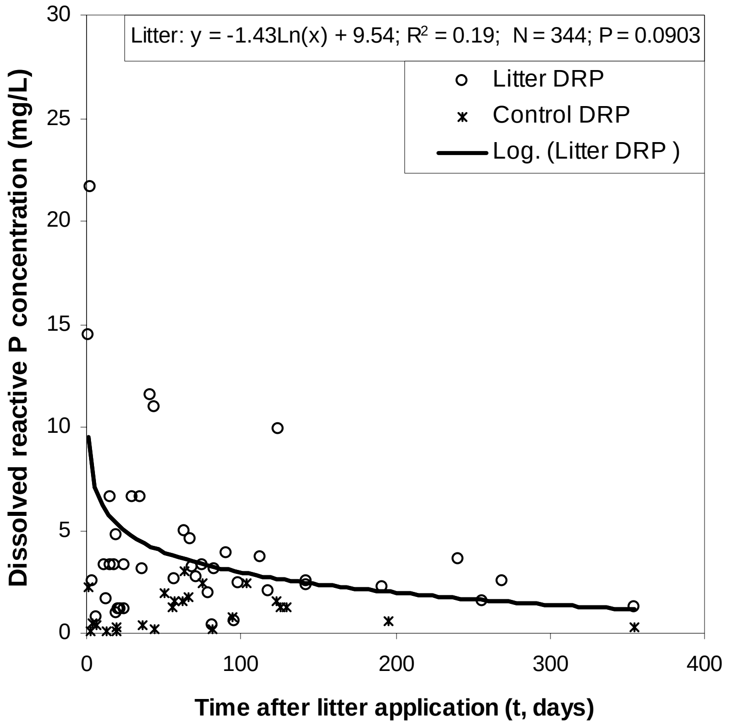


Figure 4-9. Time scale effect on dissolved reactive P concentration in surface runoff from pastures.

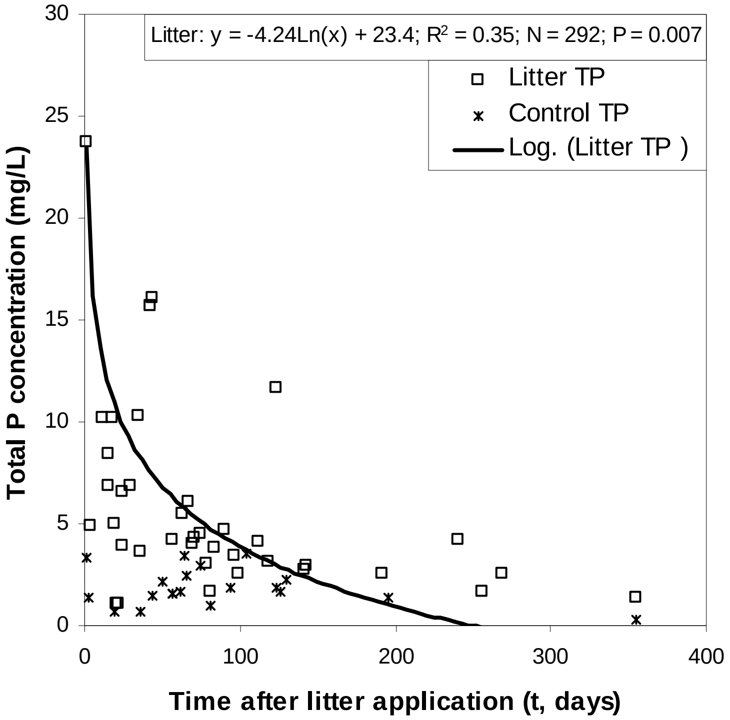


Figure 4-10. Time scale effect on total P concentration in surface runoff from pastures.

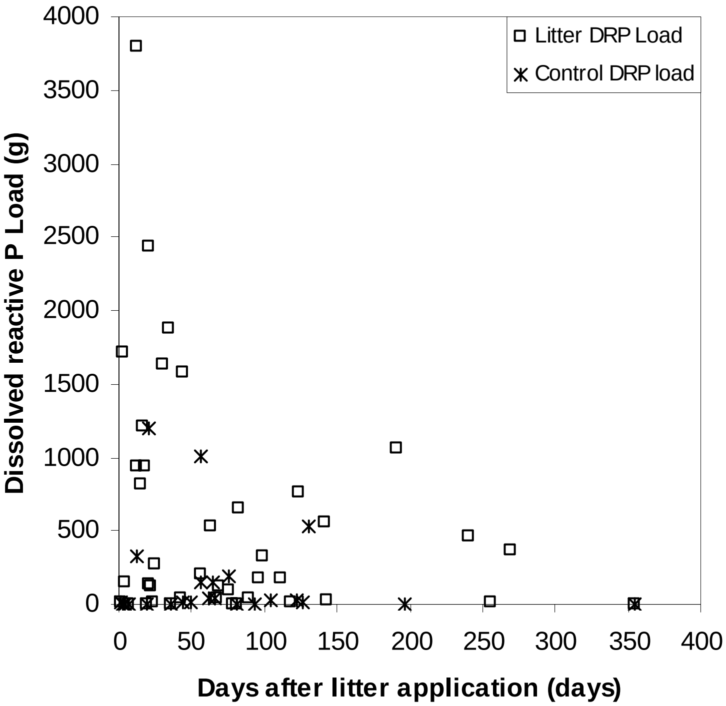


Figure 4-11. No significant (P = 0.10) time scale effect on dissolved reactive P load from pastures despite the visual exponential decreasing trend.

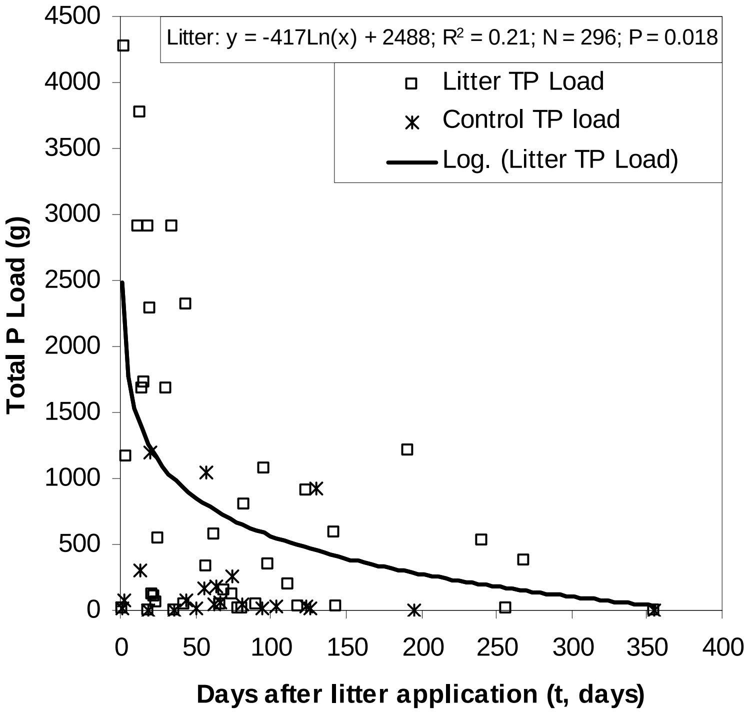


Figure 4-12. Time scale effect on total P load from pastures.

CHAPTER 5

A WATERSHED MODELING APPROACH TO ASSESS THE IMPACTS OF A LAND USE CHANGE AND BMP SCENARIOS ON RUNOFF AND SEDIMENT YIELD FROM THE LEGEDADI RESERVOIR WATERSHED IN CENTRAL ETHIOPIA

5.1. ABSTRACT

The Legedadi Reservoir Watershed (LRW) experiences severe soil erosion owing to the topography, land use practices, population pressure, and prevalent intense rainfall at the time when the land cover is minimal. Moreover, sediment laden runoff and the increasing turbidity of the reservoir have already resulted in a threefold rise in water treatment costs. This clearly suggests that a reduction in sediment yield is imperative. In the absence of plot- and field-scale BMP studies, a watershed modeling approach has much to offer to assess the potential impact of BMP implementation and land use change to meet local water quality goals. Hence, a watershed modeling approach using the Soil and Water Assessment Tool (SWAT) model was employed to investigate the impacts of a land use change and two BMP implementation scenarios on runoff and sediment yield accounting for land use, management, and weather variability. The BMPs were assigned to selected subbasins based on proximity to water bodies, steepness and suitability issues. The SWAT model developed for the watershed was calibrated and validated using flow data obtained from the Sibilu River gauging station. The SWAT model performed well during both the calibration and validation time periods. The impact of the land use change and two BMPs (cultivated land use change to forest, contour strip cropping and terracing in steep areas of the watershed) on runoff and *sediment yield was assessed. Forestation of steep cultivated lands in the upper parts of the watershed had the greatest impact on reducing sediment yield (49%), and surface runoff (11%), and increasing base flow (19%) compared with the existing condition. Both terracing and contour strip-cropping decreased sediment yield by 42% and 6%, respectively, while they both had little impact on the hydrological regime of the watershed compared with the existing conditions. This study showed that a watershed modeling approach is a useful tool to select appropriate BMPs to reduce sediment load to the Legedadi Reservoir.*

5.2. INTRODUCTION

Watershed development related problems differ from place to place based on location in the watershed, hydrology, weather, land use, and land management (Abate, Z., 1994; and Abernethy, 1997). Watershed development based on a modeling approach coordinates all these factors to assess the suitability of a given watershed with its ecological potentials and limitations. Hydrologically, a watershed is an independent entity by itself, which allows all its runoff to reach a particular point, called the watershed outlet. The entire process of watershed development depends on the status of water resources, and the watershed with the distinct hydrological boundary is considered ideal for undertaking investigation of BMP effects on runoff and sediment yield through a modeling effort (McKinney et al., 1999).

The Legedadi Reservoir Watershed (LRW) covers an area of 205 km^2. It drains to the Legedadi Reservoir which was commissioned in 1970 to collect runoff and stream water for drinking water supply. It is located between 38°55’’ and 39°05’ East Longitude, and 9°01’ and 9°15’ North Latitude within the central Ethiopian Highlands (Figure 5-8). The altitude ranges from 2400 to 3227 meters above mean sea level. It plays a major role in drinking water supply to Addis Ababa City where water supply shortage reached a critical stage to cope up with the existing urban growth (Shewaye and Adam, 1999). Typical to the highlands, it is characterized by severe soil erosion and sedimentation. An example of active gully erosion that took place in a single rainy season in the watershed is shown in Figure 5-6.

Water is one of the least-developed natural resources in Ethiopia. A number of constraints have accounted for this underutilization. Some of these are physical, climatic, hydrologic, and resource scarcity related problems. Physical constraints include topographic and geologic, soil erosion and sedimentation, adverse land use change dynamics, and inadequate management practices (Abate, Z., 1994). The climatic and hydrologic constraints include temporal and spatial rainfall/runoff variability, changes in the proportion of the hydrologic cycle (e.g. rainfall-runoff ratio), water quantity and quality. Resource scarcity problems are those problems related to budget and infrastructure needed for watershed development.

Factors that account for the severe soil degradation within the Legedadi reservoir watershed are topography, population density, prevalent traditional land use practices and intense rainfall (Hurni, 1993; Aregay and Chadhokar, 1993; Abate, Z., 1994; and AAWSA, 1999). The topography is dominated by a mountainous environment consisting of fragile and delicate ecosystems that require careful and agro-ecologically sustainable management. However, the existing overpopulation leads to deforestation and overgrazing resulting in accelerated erosion. People employ subsistence land use practices that are highly erosive. These practices include growing food crops on steep slopes without appropriate conservation practices (Figure 5-1), growing food crops such as teff (*Eragrostis tef)* that require fine seedbeds which remain loose and erodible for long periods (Figure 5-2), planting practices that leave the soil bare at times of highly erosive rain, the removal of crop residues after harvest (Figure 5-3), and deforestation and cultivation of extremely steep areas which result in land slides (Figure 5-4).

Soil erosion in the Ethiopian highlands has not only been a continuous threat but currently is a more serious problem than ever before in its severity, extent, and the rate at which it is progressing. Some productive areas have been degraded to the point of no return and more could follow soon if the process is allowed to continue without intervention (Abate, S., 1994). Hurni (1993) estimated an average soil loss of 42 t/ha/year from cropland based on a field experimental study carried out in the Ethiopian highlands (Appendix B-9). This translates to an annual loss of 1.5 billion tones, on a national basis, 80% of which originates from cultivated lands. The onsite effects of soil erosion are reducing cultivable soil depth, soil nutrients, and water holding capacity of the soil thereby creating drought prone conditions (Figures 5-2, 5-3 and 5-6). The offsite effects are increased runoff and velocity of flow, silting of fertile agricultural lands and water bodies (Figures 5-5 and 5-7).

5.2.1. Watershed modeling approach to investigate land use change and BMP effects

As opposed to plot and field scale studies where results from specific treatments can be directly compared with those obtained from controls, investigation of the effect of watershed level BMPs is not easily identifiable (Park et al., 1994; and Santhi et al., 2001). This task becomes even more complex if the watershed involves mixed land uses such as crop, pasture, forest, urban, etc. Long term monitoring data on BMP effectiveness are preferred whenever they are available. Such data are important for cost-benefit analysis and/or improving mathematical models to better predict the effects of BMP implementation (Edwards et al., 1997). To date, a few studies on BMP effectiveness at a watershed scale have been reported, which involved contour strip cropping, minimum tillage, crop rotation, etc. (Edwards et al., 1997; Walker and Graczyk, 1993; and Park et al., 1994). However, statistical procedures or comparative methods used to evaluate BMP effectiveness require long term monitoring data to detect changes due to the BMP implementation (Park et al., 1994). An additional drawback of long term monitoring data is that they are resources intensive and costly. On the other hand, due to the high sediment yield and the rising cost of water treatment of the reservoir water, information on watershed level BMP impacts is not only an imperative but also a good policy guide for decision makers (e.g. AAWSA) to determine whether public resources are to be used to share the cost of BMP implementation in the watershed.

An alternative approach to monitoring is to obtain information on the effect of BMP implementation using watershed models that help to investigate BMP impacts on sediment yield and runoff accounting for land use, management, and weather variability in a given watershed. The Soil and Water Assessment Tool (SWAT) model was chosen for this purpose. SWAT exhibits robustness in estimating stream flows from agricultural watersheds under various climatic conditions (Van Liew, et al., 2003), and it is also a good predictor of sediment and nutrient loading once calibrated (Saleh and Du, 2004). SWAT can also provide quantitative estimates of BMP impacts on watershed runoff and sediment yield which are important determinants of water quality. The Legedadi Reservoir watershed was chosen for this study based on the economic importance of the watershed, high soil erosion rate, water quality issues associated with sediment loading and data availability to undertake the intended study.

5.2.2. Objectives of the Study

The overall objective of this study was to investigate the effect of a land use change and two BMP implementation scenarios (conversion of cultivated land to forest, contour strip-cropping, and terracing) on runoff and sediment yield from the LRW in the central Highlands of Ethiopia using the SWAT model. Specific objectives were: 1) to calibrate and validate the SWAT model for flow and sediment yield under the existing management conditions; and 2) to assess the impacts of two BMP implementation scenarios and a land use change in selected subbasins of the watershed on runoff and sediment yield.

5.3. MATERIALS AND METHODS

5.3.1. The SWAT model

SWAT was developed to predict the effect of different land management practices on water, sediment and agricultural chemical yields in large ungaged basins with varying soils, land use and management conditions over long periods of time (Arnold et al., 1998; and Neitsch et al., 2002). To satisfy these objectives, SWAT is a physically based watershed model that uses readily available inputs, and is capable of simulating long periods for computing the long term effects of management changes. It is also capable of routing runoff, sediment, and nutrients through streams and reservoirs.

There are eight major components in the model. These are hydrology, weather, sedimentation, soil temperature, crop growth, nutrients, pesticides, and agricultural management. The SCS runoff curve number method was used to estimate surface runoff from daily precipitation data. Evapotranspiration (ET) was computed using Penman-Monteith method because of the availability of data required, and its robustness in estimating ET under highly varying daily weather condition. Two methods of channel routing methods are available in SWAT: variable storage and muskingum. The former was used in this study. The reservoir routing was not considered since the only reservoir in the watershed is also the outlet of the watershed.

Simulations undertaken for this study were performed within the ArcView Geographical Information System (ArcView GIS Version 3.3) interfaced for SWAT 2000. This interface has tools that simplify the process of watershed discretization and parameter assignment through the use of spatially explicit data sets representing topography, soils, land use and management (Di Luzio et al., 2002).

5.3.2. The Legedadi Reservoir watershed

The location of the Legedadi Reservoir watershed along with the elevation range is given in Figure 5-8. The watershed has three primary geographic features. These are the Bereh Mountains, the Sendafa Hills, and the Legedadi Plains (AAWSA, 1999). Three weather classes exist corresponding to these three features due to the strong correlation between both annual precipitation and temperature with altitude. Precipitation increases as altitude increases (ranging from 1000 to 1300 mm) where as mean annual temperatures decrease as altitude increases, ranging from 7-10^{o}C and 19-24^{o}C for minimum and maximum temperatures, respectively. The rainfall pattern in the region, including neighboring areas, has a bimodal distribution with strong peaks in the summer months and minor peaks from March to April (Figure 5-10).

The main land use in the watershed is agriculture, the dominant being cultivated (crop land), pasture and forest. The watershed also includes urban (Sendafa town) and water (Legedadi Reservoir). The land use map of the watershed is given in Figure 5-11.

There are four major soil groups in the watershed based on the revised FAO-UNESCO-ISRIC legend of world soil map (AAWSA, 1999). These soils are Vertisols, Luvisols, Leptosols, and Cambisols. The dominant soils of the watershed are shown in Table 5-1 and Figure 5-12. Soil depth varies spatially within the watershed, and it is broadly divided into three classes: shallow (<50 cm), medium (50-100 cm) and deep (>100 cm), which dominate mountainous, hills, and plain areas of the watershed, respectively.

5.3.3. Data acquisition

5.3.3.1. Digital data

A 30 m digital elevation model (DEM) was developed from a digitized contour map of the watershed (1:50000) obtained from the Ethiopian Mapping Authority (EMA, 2003). The 1996 land use and soil maps obtained from AAWSA (1999) were digitized after georeferencing and rectifying them in ArcGIS (Figure 5-11 and 5-12). All digitized data were projected to a common datum (UTM 1983, Zone 37 N projection) for the SWAT model.

5.3.3.2. Soil and land management databases

The soils of the watershed were matched with those in the United States of America based on the FAO-UNESCO soil maps of the world (FAO-UNESCO, 1977; and FAO-UNESCO, 1988), geomorphic and soil maps of Ethiopia (MOA, 1983), and the soil map of the watershed (AAWSA, 1999). The matched soils were then located in the SWAT soil database, and these soils were modified based on the ancillary soil data of the LRW (AAWSA, 1999) to develop the watershed specific soil database (Appendix A-2). Whenever watershed specific information was not available, SWAT default values were used (e.g. soil albido).

The same procedure was employed for the management database. The ancillary data, agro-ecological map of Ethiopia, and information from the Internet were used to modify the SWAT default database to match the cultural practices in the watershed. For crops which weren't included in the SWAT database, management files were generated after modifying a close matching crop using ancillary data for the given crop (e.g. *Eragrostis teff*).

5.3.3.3. Weather data

Daily weather data were prepared from Addis Ababa Observatory (AAO), Ginchi, Holeta, and Sendafa weather stations (January 1, 1975 to December 31, 2001) (Figure 5-10). The Sendafa weather station is located within the study area. Weather elements entered into the model as input were precipitation (mm), maximum and minimum temperature (°C), solar radiation (MJ/m2), average relative humidity (fraction), and wind speed (m/s). These weather elements are highly correlated with altitude, and hence missing data were generated using regression approaches that relate a given weather element to that of its neighboring station. Precipitation isohyets were developed using data from all weather stations shown in Figure 5-10. The isohyets were then used to generate precipitation data for stations in various parts of the study area.

5.3.4. Model calibration and validation

Hydrological flow calculations based on the hydrology similarity method were used to estimate stream flow data for the Legedadi Reservoir watershed. In addition, management practices within the watershed were incorporated into the SWAT model for the watershed using a management tool developed specifically for such purpose. Two statistical (goodness-of-fit) measures were employed for the calibration and validation procedure: Nash-Sutcliffe efficiency (E), and Coefficient of Determination (R^2). E is a measure which indicates how well simulated vs. observed flow data are close to the 1:1 line. The R^2, on the other hand, is a measure of the linear correlation of the data (Legates and McCabe, 1999). Besides these, scatter diagrams and time series plots were also used to evaluate the performance of the model. Information obtained from two consecutive bathymetric surveys of the Legedadi Reservoir (AAWSA, 1999), and soil erosion study within the Ethiopian highlands (Hurni, 1993) were used to calibrate the sediment yield from the watershed.

5.3.5. BMP and land use change scenarios

The calibrated SWAT model was used to assess the long-term effects of a cultivated land use change to forest and BMP implementation scenarios on runoff (flow) and sediment yield using daily historical weather data (1981-2001). The goal was to compare the effect of the different BMP scenarios (future condition) with the current management condition (calibrated and validated) on runoff and sediment yield. Locations within the watershed for the BMP scenarios were selected based on their steepness, proximity to water bodies, and suitability issues. The different scenarios and the subbasins (Figure 5-9, and Table 5-3) subjected to them were:

1. Contour strip-cropping: A technique in which alternate strips of different crops are planted in the same field. Subbasins located close to streams and the reservoir were selected for this BMP scenario. They are 26, 27, 28, 41, 42, 45, 47, 48, 49, 50, 53, and 57 (Tables 5-3, 5-4).
2. Terracing: Terracing helps to reduce soil erosion by shortening the long slope into a series of shorter, more level steps. Slope length, the USLE P factor and the SCS Curve Number (CN2) were changed to simulate terracing BMP effect in the steepest parts of the watershed (Tables 5-3, 5-5). The subbasins selected for this BMP scenario were 3 to 8, and 11 to 14.
3. Land use change from crop to forest: Cultivation in the steeper mountainous areas aggravates soil degradation by leaving the soil bare at the time of the onset of intense rainfall. As a result, conversion of cropped land to forest in these parts of the watershed was considered as an alternative BMP to reduce soil erosion and sediment yield. Cultivated fields subjected to this BMP scenario were located in subbasins 1 to 7, and 11 to 14 (Figure 5-3).

5.4. RESULTS AND DISCUSSIONS

5.4.1. Baseline management simulation

The LRW was divided into 57 subbasins (Figure 5-9) and 399 hydrological response units (HRUs) based on similar land uses and soils by the SWAT model. A threshold area of 200 ha with multiple land use/soil option (10/10%) was employed in the SWAT model. Existing land uses in the watershed were wheat (31.1%), pasture (29.2%), *Eragrostis tef* (20.7%), forest (11.4%), barley (3.4%), water (2.4%), and Urban (Sendafa Town) (1.8%). Crops such as flax, lentils, peas, horse bean, etc. constitute about 1% of the watershed. These crops were left by the model based on the 10% threshold area within the HRU due to their low acreage (Figure 5-11). The dominant soils of the watershed were Vertisols (43.6%), association of Leptosols, Regosols, and Cambols (13.7%), and Cambisols (11.1%) (Figure 5-12). The initial baseline SWAT simulation had a higher base flow and lower total flow compared with the observed flows. To reduce the uncertainty in the SWAT model predictions, calibration and validation procedures were employed.

5.4.2. SWAT model calibration and validation

Watershed models without proper calibration and validation may lead to erroneous predictions (Chu and Shirmohammadi, 2004), resulting in misconception about the models and their ability to simulate land use and/or BMP impacts. Hence, calibration and validation of the LRW SWAT model was carried out prior to undertaking evaluation of the different BMP scenarios to meet the objectives of this study. Calibration is testing the model with known input and output for the purpose of adjusting factors. The model was first calibrated for flow on an annual basis, and then on a monthly basis. The mean monthly observed flow data used for calibration and validation are given in

Appendices B-3 and B-4. Parameters changed to achieve flow and sediment calibration are presented from Appendices B-5 to B-8.

The model was first calibrated using observed data from January 1981 to December 1988. The calibrated model was then run for the rest of observed data (January 1989 - December 1996) for validation purposes. The model required changing appropriate parameters (e.g. soil water (AWC), Curve Number, threshold depth of water in the shallow aquifer and ULSE P) for calibration (Appendices A-2, B-5, B-6, B-7). The statistical measures obtained during the calibration and validation procedures are summarized in Table 5-2. The Nash-Sutcliffe coefficients (E) for the calibration period were 0.56, 0.60 and -0.94 for total, surface and base flows, respectively. The Coefficients of Determination (R^2) for calibration were 0.95, 0.95, and 0.83 for total, surface and base flows, respectively. Figures 5-13 and 5-14 present the time series and scatter plots for the simulated vs. observed flows at the watershed outlet, respectively. The scatter plots are shown along with the 1:1 line. The model evaluation procedures employed for the calibration (statistical measures, time series and scatter plot diagrams) indicated that the SWAT model performed reasonably well for both total and surface flows (Table 5-2, Figures 5-13 and 5-14).

After model calibration, SWAT was run for the remaining data (1988-1996) for validation purpose. As shown in Table 5-2, the Nash-Sutcliffe coefficients (E) for the validation period were 0.95, 0.94 and 0.80 for total, surface and base flows, respectively. The Coefficients of Determination (R^2) for validation were 0.98, 0.98, and 0.94 for total, surface and base flows, respectively. This result indicates that the model performed better during the validation than the calibration period.

The bathymetric survey data shown in Appendix B-8 as obtained from AAWSA (1999), and soil erosion plot studies in the Ethiopian highlands by Hurni (1993) were used to judge the acceptability of the sediment yield predictions by SWAT. The 1979 and

1998 successive bathymetric surveys of the Legedadi Reservoir indicated that the reservoir reduced by 2.1 X 10^6 m^3 over a period of 19 years. This reduction in volume (i.e. sediment deposition), when converted to sediment yield based on a soil bulk density of 1.3 g/cm^3 and reservoir trap efficiency of 65%, gave an average sediment inflow of 12 t/ha/year (Appendix B-8). However, every year about 25X10^6 m^3 sediment-laden runoff water is discharged through the spillway during the peak runoff period (AAWSA, 1999). Moreover, the watershed underwent a dynamic land use change. Forest has been cleared, and more land has been brought under cultivation including mountainous parts since the late 1980s and early 1990s. The watershed is also characterized by high seasonal fluctuation of land cover. The soil erosion rate is severe during the onset of the intense rains when most cultivated lands are bare. It is during this time that most of sediment loading takes place. Once grasses and crops start to grow, land cover increases, and this in turn reduces soil erosion rate. Effects of the aforementioned factors were not considered or can't be detected using the bathymetric survey method. Therefore, the sediment yield should be much higher than 12 t/ha/year.

Hurni (1993) estimated an averaged soil loss rate of 42 t/ha/year from cropland (Appendix B-9). Although this is not a watershed level study and doesn't consider deposition, it is a useful indicator of the soil erosion rate for cultivated fields in the highlands. The LRW watershed experiences severe soil erosion owing to the topography and encroachment of mountainous areas for cultivation and grazing. However, there is a spatial variability in the aggressiveness of the soil erosion rate within the watershed due to the existence of forest and grassland land uses besides cultivated lands. Hence, sediment yield at the reservoir should not exceed 42 t/ha/year.

Final sediment calibration was achieved by adjusting the USLE P factor from 0.9 to 0.7, and BIOMIX from 0.20 to 0.45 (Appendix B-7). The final flow and sediment calibrated model had an averaged watershed sediment yield of 30 t/ha/year at the reservoir (i.e. reservoir inflow). This is acceptable based on the degree of soil erosion taking place within the watershed, erosion susceptibility of the soils, dominance of steeps areas in the watershed (19%; with elevation difference of over 600 m), and intense storms of rainfall during the period of the year when land cover is minimum.

5.4.3. Impacts of a land use change and BMP scenarios on runoff and sediment yield

The impacts of three cultural practices on runoff and sediment yield were investigated. The watershed receives 70 % of its annual precipitation from mid June to mid September (Figure 5-10). This is a period of excess moisture during which most of the annual flows take place. The rest of the year exhibits moisture deficit. There are two problems associated with this hydrological pattern. First, intense precipitation starts during the period when the cultivated land is bare from seedbed preparation or deforestation (Figures 5-3, and 5-4), which results in severe soil erosion (Figure 5.2). The second one is that much of the excess runoff generated from the watershed will be lost since the only reservoir available in the watershed is not capable of harnessing this water. The temporal variation of water availability is one of the challenges faced by the Addis Ababa Water Supply and Sewerage Authority in its effort to supply water to the Addis Ababa metropolitan area. It was hypothesized that cultural practices such as contour strip-cropping, forestation programs in susceptible mountainous area, and terracing at steep areas of the watershed reduce the sediment yield and runoff, and increase base flow in the watershed. This is a desired situation which increases the temporal availability of water in the watershed.

To investigate the effects of the three BMP scenarios, watershed averaged hydrological and sediment yield output for the BMP scenarios were compared with the existing condition simulation. Calibrated and validated hydrology and sediment yield for the current condition are given in Figure 5-15 (1981-2001). A figurative sketch and pictures of the intended BMP scenarios are given in Figures 5-16 and 5-17.

5.4.3.1. Contour strip-cropping

Strip cropping is a practice in which contoured strips of sod are alternated with equal-width strips of row crop or small grain (Neitsch et al., 2002), or it is a technique in which alternate strips of different crops are planted in the same field (Figure 5-16). A contour strip cropping effect was simulated in the SWAT model by changing USLE-P factor and by adding appropriate strip width in the selected subbasins located close to the reservoir or streams (Table 5-3, 5-4 and Figure 5-16). The effect on monthly averaged watershed total, surface, and base flows was minor (Figure 5-18). However, it reduced sediment yield from the watershed by 6%, on average, compared to the existing condition. Sediment that originated from distant and steep parts of the watershed are either deposited enroute to the reservoir or are in stream transport by the time they reached the point of strip BMP implementation. Strip contouring, on the other hand, have a local effect on runoff and sediment yield which didn't have impact on watershed runoff and sediment yield. As a result, strip-cropping had little impact on minimizing watershed runoff and sediment yield from the Legedadi Reservoir watershed.

5.4.3.2. Terracing

Terracing is a method of erosion control accomplished by constructing broad channels across the slope of rolling land (Schwab et al., 1993). It is a soil conservation practice applied to prevent runoff on slopping land from accumulating and causing serious soil erosion (Wheaton and Monke, 2001). The hypothesis behind terrace BMP implementation in the steepest part of the LRW was to reduce the slope length and rill erosion, to prevent formation of gullies, and to allow sediment in runoff to settle, thereby improving the quality of water leaving the field. In order to simulate this effect in the SWAT model, the slope lengths of HRUs in the selected subbasins were reduced by 19% when average slope was less than 10%, 43% otherwise (Table 5-3). Terraces concentrate runoff into channels which is potentially dangerous. A failure in a single terrace might induce a serious of damages to downstream located terraces that are already loaded to full capacity with runoff. To account for this effect, more reduction in slope length (43%) was made in the steeper parts of the watershed. Moreover, curve number and USLE P factor appropriate to graded channel terrace with sod outlets were used in the model (Table 5-5).

This BMP scenario reduced the sediment yield by 42% compared with existing conditions (Figure 5-19) indicating that terrace BMP implementation is effective in reducing sediment yield from the Legedadi reservoir watershed. The effect on surface, base or total flow (Figure 5-18) compared to the existing condition was minor. This can be due to the farthest location of terrace BMP site relative to the watershed outlet. Compared to strip cropping, terracing is a better alternative in reducing sediment yield (Figure 5-19). However, terracing requires additional investment and causes some inconvenience in farming, and thus, it should be considered only when other BMPs singly or in combination will not provide adequate erosion control or water management (Schwab et al., 1993).

5.4.3.3. Cultivated land use change to forest

Compared to its neighboring watersheds that also supply water to the Addis Ababa city, the Legedadi reservoir watershed is dominated by steeps areas (19%), and erodible soils (AAWSA, 1999). Further, encroachment of mountainous parts for grazing and cultivation aggravates the soil erosion process. This BMP scenario (Figure 5-17) was carried out to investigate the effect of forestation (conversion of cultivated lands to forest) in the selected subbasins (Table 5-3, and Figure 5-9). Unlike contour strip cropping and terracing, forestation had an effect on both sediment yield and flows (Figures 5-18 and 5-19). It reduced sediment yield, surface flow, and total flow by 49%, 11% and 4%, respectively. It also increased the base flow by 17%. The reduction in total flow is negligible compared with the calibrated condition (Figure 5-18). From a watershed management perspective, this is a desired situation due to the increased base flow, and reduced runoff and sediment yield during the short period of excess moisture. Most of the severe soil erosion from croplands takes place at these sites due to high rainfall, steep topography and poor management practices. The conversion of these sites to forest will help absorb the energy of the intense rains and reduce their impacts on the soil surface, increase land cover, reduce surface runoff through increased soil infiltration, and hold the soil mass in position.

Conversion of land use leading to a more dense vegetative cover has been mentioned as one of the most effective method to reduce soil erosion (Hurni, 1988), and this study corroborated it. However, implementation requires a number of years to fulfill the anticipated result. Moreover, its use is justified by a number of factors that need to be considered locally which are beyond the scope of this study.

5.5. SUMMARY AND CONCLUSION

A watershed modeling approach was employed to investigate the impacts of three BMP scenarios (contour strip-cropping, terracing and conversion of cultivated land to forest) on runoff and sediment yield in selected subbasins of the Legedadi reservoir watershed in central Ethiopia accounting for land use, management, and weather variability. The different BMPs were assigned based on proximity to water bodies, steepness and suitability issues. The Soil and Water Assessment Tool (SWAT) model that exhibits robustness in estimating stream flows from agricultural watersheds and predicting sediment yield was employed. Digitized topography (30 m DEM), soil, 1996 land use, and weather data (1975-2001) of the Legedadi reservoir watershed were used as input. Soil and management databases were modified to approximate the soils and cultural practices in watershed.

The model was calibrated using stream flow data (1981-1988) obtained from the Sibilu River gauging station based on the hydrological similarity calculation method. The calibrated model was then validated for the period of 1988-1996. Both the calibration and validation periods indicate a good performance of the model as indicated by statistical measures (Table 5-2), time series and scatter plot diagrams (Figures 5-12 and 5.13). The watershed experiences severe soil erosion owing to its topography, land management, population pressure, and intense and excess rainfall that occurs within a few months of the year (Figure 5-9). Of the three BMPs implemented, forestation of cultivated lands in the upper steeper parts of the watershed (Figure 5-8 and Table 5-3) had the greatest impact in reducing both sediment yield (49%), and surface runoff (11%), and in increasing the base flow (19%) compared with the existing condition. Terracing was also effective in reducing sediment yield (42%) while that of contour strip cropping can be considered negligible (6%). Both terracing and strip cropping had little impact on the hydrology of the watershed compared with the existing condition.

The threefold increase in water treatment costs due to the continually increasing turbidity of the Legedadi reservoir (AAWSA, 1999) and highly erosive practices in the watershed that leave the soil bare during the onset of the first intense rainfall, indicate that a reduction in sediment yield is imperative. This study showed that a watershed modeling approach involving different BMP scenarios is a useful tool that has much to offer in rapidly developing plans to reduce sediment yield in the watershed. However, factors such as cost effectiveness and ease of construction and maintenance issues can also influence BMP selection which are beyond the scope of this study.

Table 5-1. List and characteristics of the dominant soil types in the study area. Source: AAWSA (1999)

Soils of the watershed	Texture	Hydrologic Soil Group	Erodibility
Eutric Vertisols	Clay	D	0.200
Vertic Cambisols	Clay	D	0.200
Lithic Leptosols	Clay loam	D	0.225
Eutric Fluvisols	Silt clay	D	0.100
Eutric Fluvisols/ Eutric Cambisols	Silt clay to clay	D	0.100
Eutric Vertisols	Clay	D	0.200
Lithic Leptosols/ Dystric Cambisols	Gravelly clay loam	D	0.225
Chromic Cambisols	Sandy clay loam	C	0.300
Leptosols/Regosols/Cambisols	Clay loam	D	0.249
Eutric Cambisols	Clay loam	D	0.300
Chromic Cambisols	Clay loam	D	0.300
Cambisols and Luvisols	Clay	D	0.100
Leptosols	Clay loam	D	0.150
Eutric Vertisols	Clay	D	0.200
Cambisols	Clay loam to clay	D	0.200
Leptosols/ Cambisols/ Vertisols	Clay loam and clay	D	0.200

Table 5-2. Flow calibration and validation statistics of the Soil and Water Assessment Tool (SWAT) model for the Legedadi Reservoir watershed.

LRW SWAT Model	Time Period	Simulated Flow (m^3/s)			Observed Flow (m^3/s)			Nash Sutcliffe Efficiency (E)			Coefficient of Determination (R^2)		
		TF[1]	SF[2]	BF[3]	TF	SF	BF	TF	SF	BF	TF	SF	BF
Calibration	1981-88	3.92	2.95	0.97	3.91	2.95	0.96	0.56	0.60	-0.94	0.95	0.95	0.83
Validation	1989-96	3.69	2.73	0.96	3.73	2.81	0.92	0.95	0.94	0.80	0.98	0.98	0.94

[1] Total flow
[2] Surface flow
[3] Base flow

Table 5-3. Parameters employed in the SWAT model to simulate effects of a land use change and BMP implementation scenarios in the Legedadi Reservoir watershed.

BMP Implemented	Subbasin Number (Figure 5-9)	Slope length (m)	Average slope (%)	SCS Curve Number (CN2)	USLE P factor	Strip width (m)
Contour-strip cropping	26	25	9	84	0.25	30
	27	91	5	81	0.25	30
	45	37	4	84	0.25	30
	50	61	7	84	0.25	30
	41	37	10	84	0.30	30
	47	37	11	84	0.30	30
	48	25	10	84	0.30	30
	53	49	2	84	0.30	30
	42	20	12	92	0.35	20
	49	24	15	84	0.35	20
	28	18	19	84	0.40	15
	57	18	16	84	0.40	15
Terracing	3	10	16	80	0.14	
	4	10	13	80	0.14	
	5	14	11	80	0.12	
	6	74	3	80	0.10	
	8	14	11	80	0.12	
	11	74	4	80	0.10	
	12	49	6	80	0.10	
	13	14	11	76	0.12	
	14	21	9	80	0.12	
Cultivated land use change to forest	1	24	12	84	0.70	
	2	15	21	84	0.70	
	3	18	20	84	0.70	
	4	18	17	81	0.70	
	5	24	14	84	0.70	
	6	91	4	84	0.70	
	7	37	11	84	0.70	
	11	91	5	84	0.70	
	12	61	8	84	0.70	
	13	24	14	79	0.70	
	14	37	11	84	0.70	

Table 5-4. P factor values, maximum strip width and slope-length limits for contour strip-cropping
Source: Wischmeier and Smith (1978).

Land slope (%)	P_{USLE} values[1]			Strip width (m)	Maximum slope length (m)
	A	B	C		
1 to 2	0.30	0.45	0.60	40	244
3 to 5	0.25	0.38	0.50	30	183
6 to 8	0.25	0.38	0.50	30	122
9 to 12	0.30	0.45	0.60	24	73
13 to 16	0.35	0.52	0.70	24	49
17 to 20	0.40	0.60	0.80	18	37
21 to 25	0.45	0.68	0.90	15	30

[1] P values:

A: For 4-year rotation of row crop, small grain with meadow seeding, and 2 years of meadow. A second row crop can replace the small grain if meadow is established in it.

B: For 4-year rotation of 2 years row crop, winter grain with meadow seeding, and 1-year meadow.

C: For alternate strips of row crop and winter grain

Table 5-5. P factor values for contour-farmed terraced fields
Source: Wischmeier and Smith (1978)

Land slope (%)	Farm planning		Computing sediment yield[3]	
	Contour P factor[2]	Strip crop P factor	Graded channels sod outlets	Steep backslope underground outlets
1 to 2	0.60	0.30	0.12	0.05
3 to 8	0.50	0.25	0.10	0.05
9 to 12	0.60	0.30	0.12	0.05
13 to 16	0.70	0.35	0.14	0.05
17 to 20	0.80	0.40	0.16	0.06
21 to 25	0.90	0.45	0.18	0.06

Slope length is the horizontal terrace interval. The listed values are for contour farming. No additional contouring factor is used in the computation.

[1] Use these values for control of interterrace erosion within specified soil loss tolerances.

[2] These values include entrapment efficiency and are used for control of offsite sediment within limits and for estimating the field's contribution to watershed sediment yield.

Figure 5-1. Land use without soil and water conservation practices in the Ethiopian highlands.

Figure 5-2. Growing crops (e.g. *Eragottis teff*) that require fine seedbed which remain loose and erodible for long periods.

Figure 5-3. Cultivated fields with no crop residue are left exposed to intense rainfall.

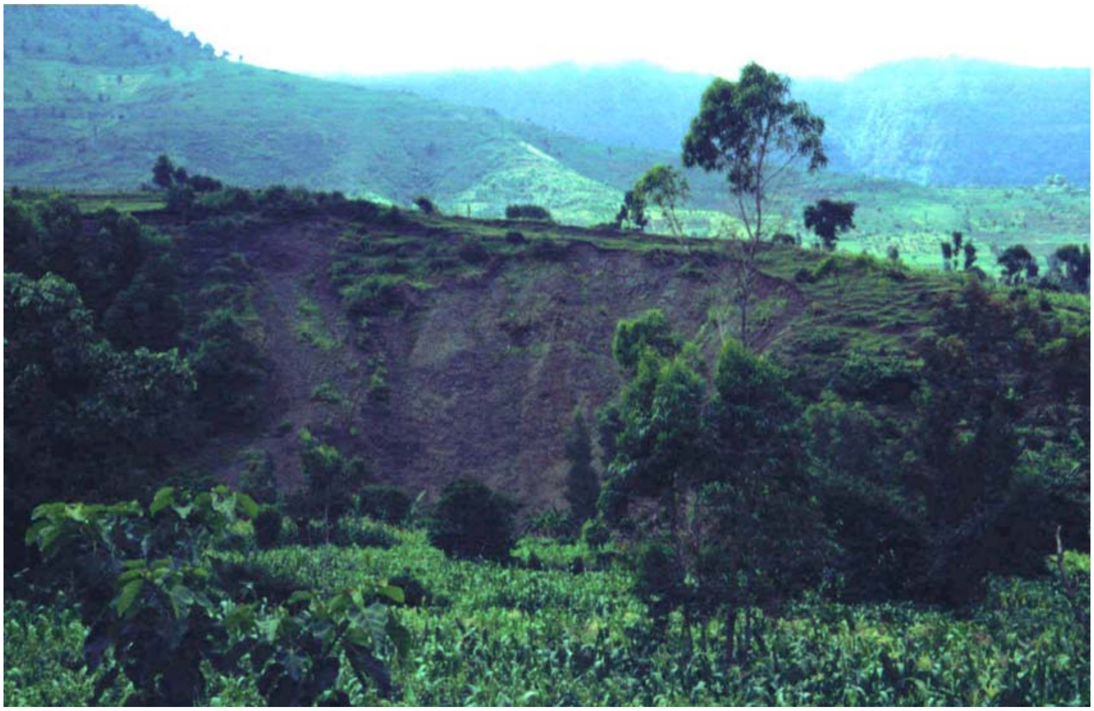


Figure 5-4. Landslide induced by deforestation and cultivation on steep hills (Ethiopian Highlands).

Figure 5-5. Land cultivation near water bodies without buffer strips in the study area.

Figure 5-6. An active gully that shows the severity of soil erosion in the study area.

Figure 5-7. Sedimentation that resulted from severe upstream soil erosion (Ethiopian Highlands, Western Hararghe).

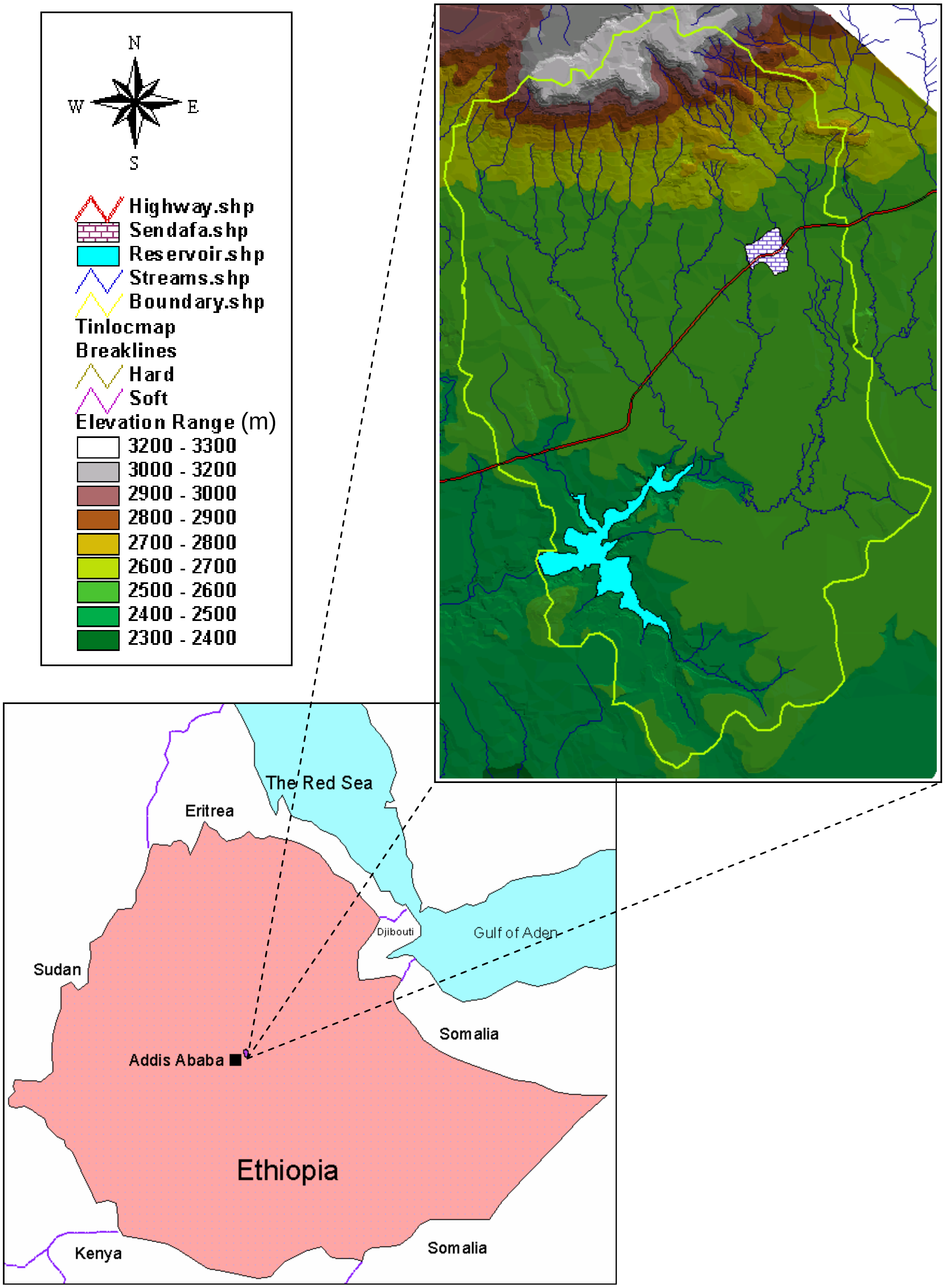


Figure 5-8. Location and digital elevation map of the Legedadi Reservoir Watershed.

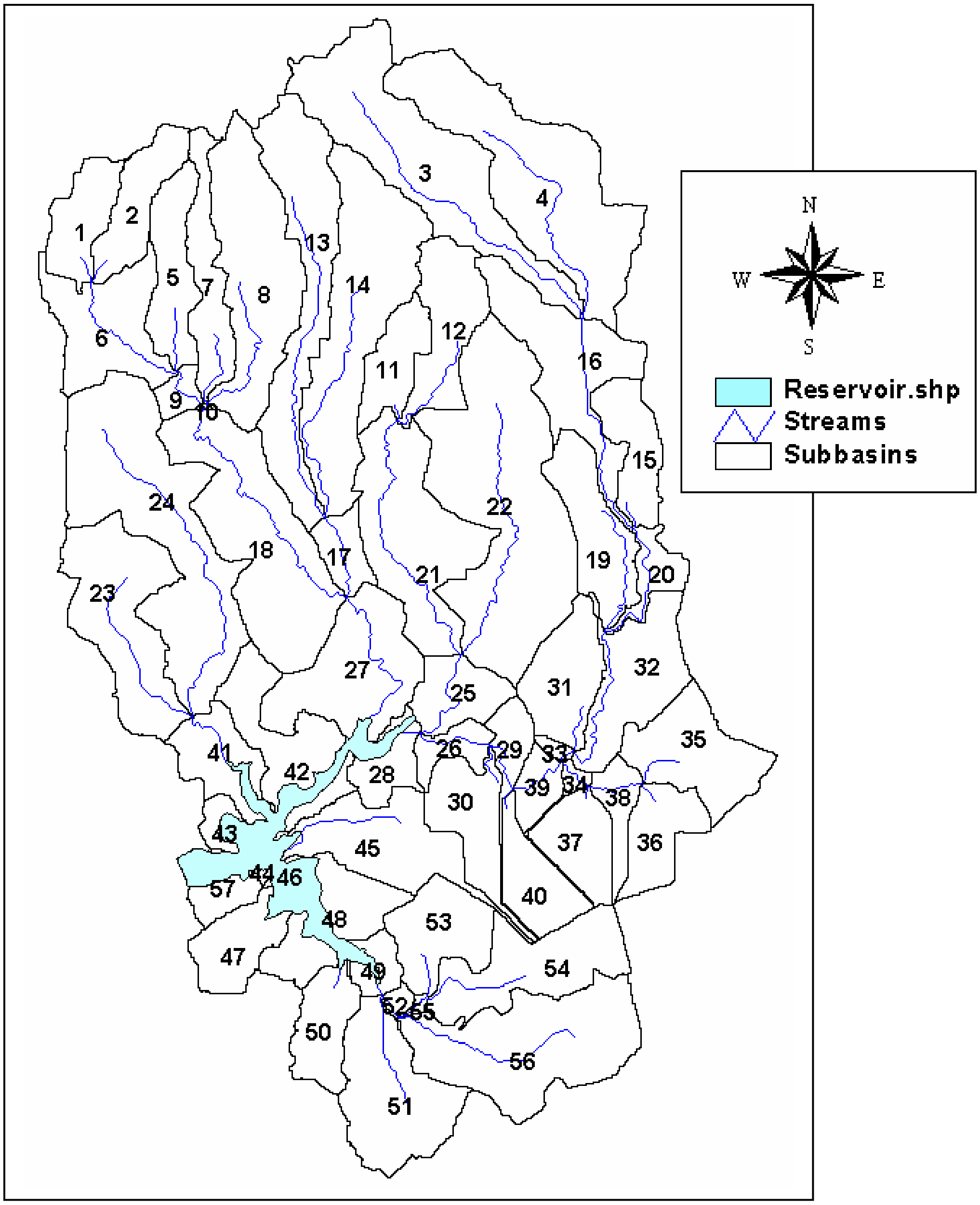
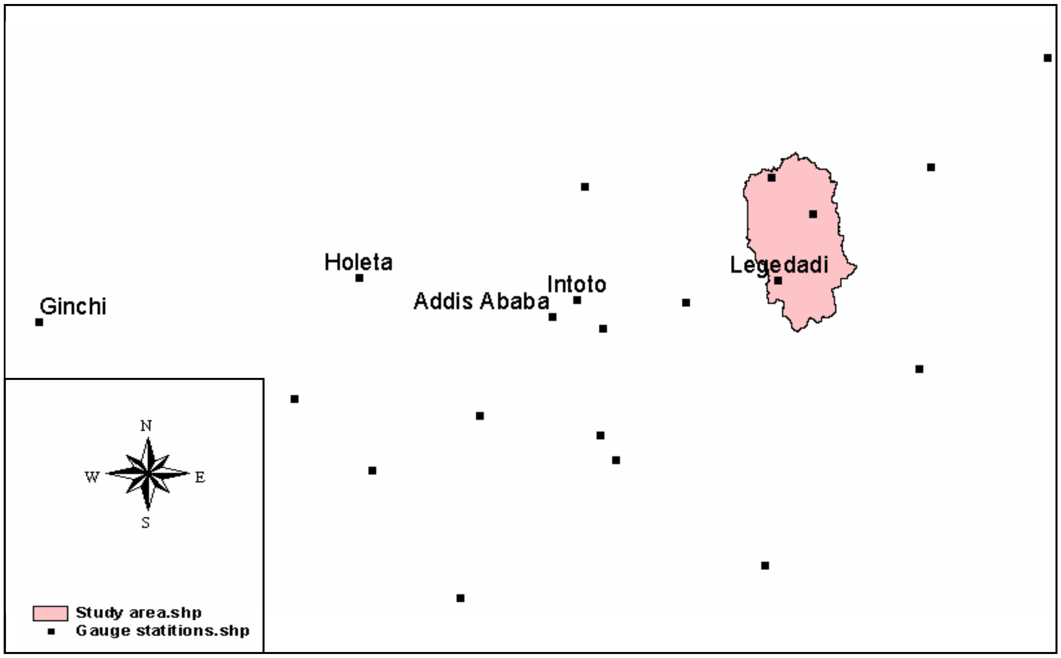
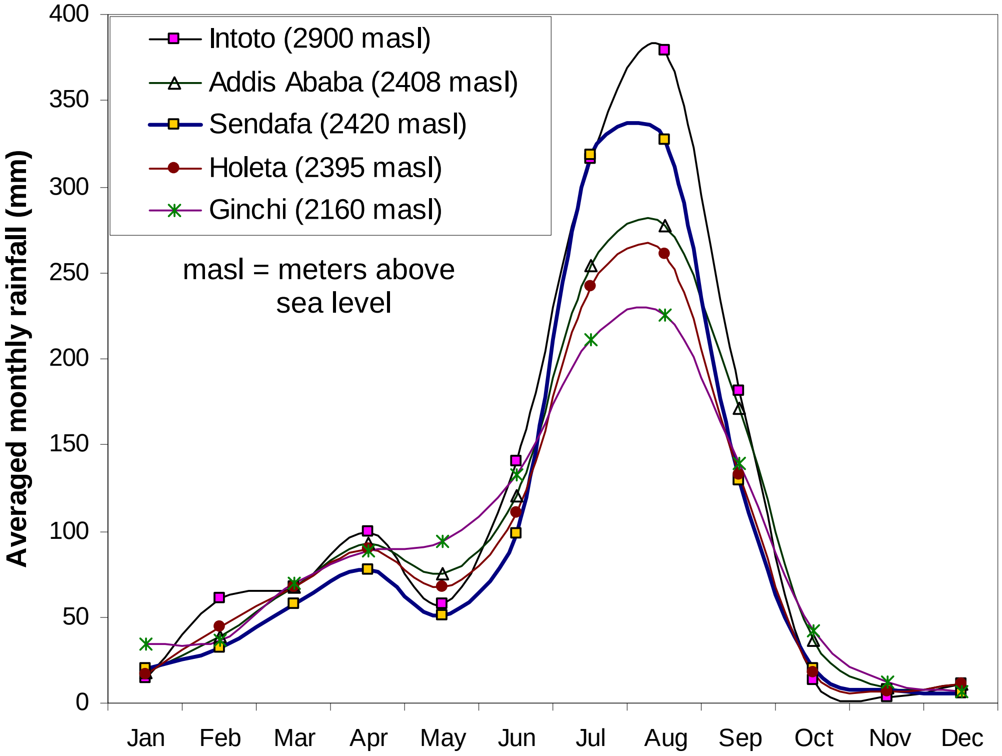


Figure 5-9. SWAT delineated subbasins of the Legedadi Reservoir Watershed in the central Ethiopian Highlands.

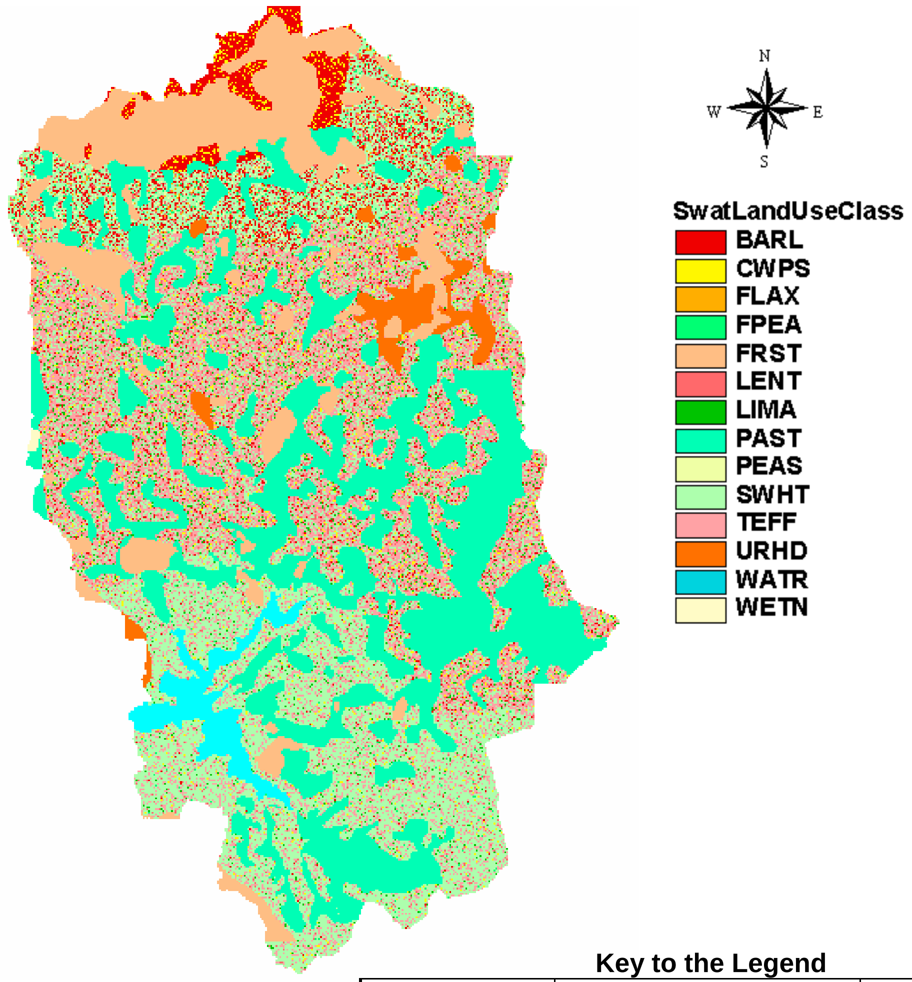


a) Location of stations used for weather data preparations for the study area.



b) Rainfall distribution is correlated to altitude in the study area

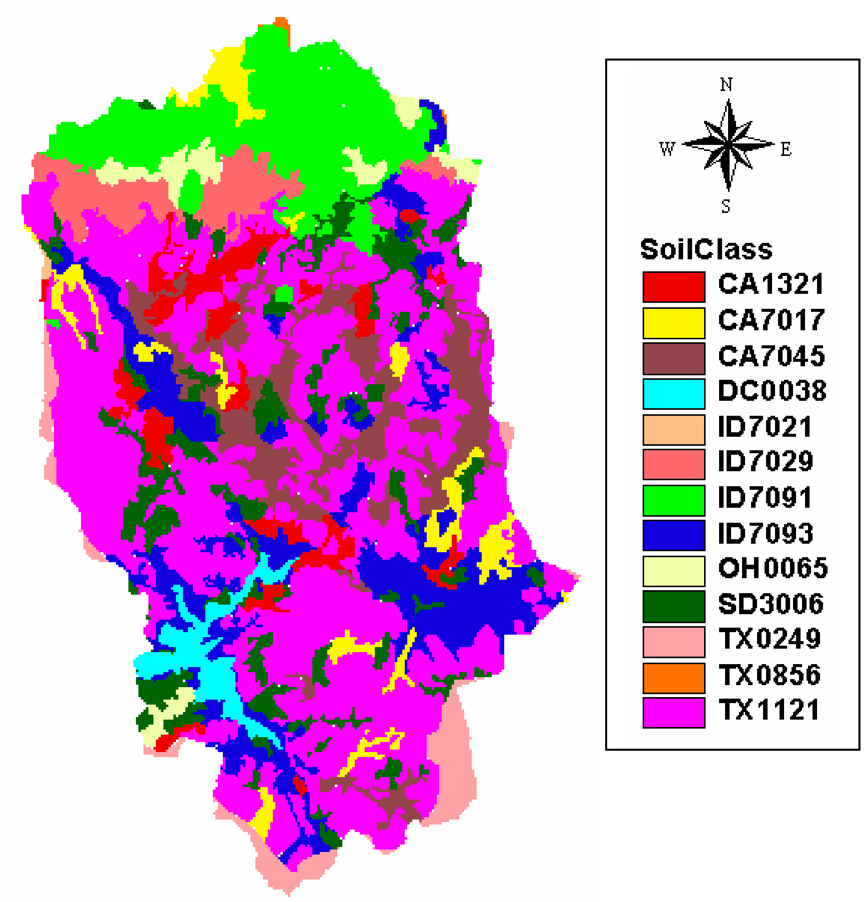
Figure 5-10. Mean monthly rainfall distribution and location map of the weather stations within and around the study area.



Key to the Legend

SWAT Land Use Class	Land use type	Area (ha)	(%)
BARL	Barley	974	5
CWPS	Cow Pea	82	0.4
FLAX	Flax	82	0.4
FPEA	Field pea	72	0.4
FRST	Forest-Mixed	3445	17
LENT	Lentil	410	2
LIMA	Horse Bean	207	1
PAST	Pasture	5290	26
PEAS	Peas	164	1
SWHT	Wheat	5305	26
TEFF	Eragrostis teff	3607	18
URHD	Urban (Sendafa Town)	418	2
WATR	Legedadi Reservoir	447	2
WETN	Wetland forested	10	0.1

Figure 5-11. The 1996 land use in the Legedadi Reservoir Watershed.



Key to the Legend

SWAT Soil Class	Dominant Soil Types	Area (ha)	(%)
CA1321	Leptosols/ Cambisols/ Vertisols	970	5
CA7017	Eutric Fluvisols/Cambisols	796	4
CA7045	Fluvisols/Cambisols	1723	8
DC0038	Legedadi Reservoir	449	2
ID7021*	Cambisols & Luvisols	15	0.1
ID7029	Chromic Cambisols	781	4
ID7091	Leptosols/ Regosols/ Cambisols	2304	11
ID7093	Cambisols	2387	12
OH0065	Vertic Cambisols	433	2
SD3006	Leptosols/ Lithic Leptosols	1777	9
TX0249	Eutric Vertisols	643	3
TX0856*	Eutric Vertisols	16	0.1
TX1121	Eutric Vertisols	8213	40

Figure 5-12. Soil of the Legedadi Reservoir Watershed after matching with the SWAT soil database.

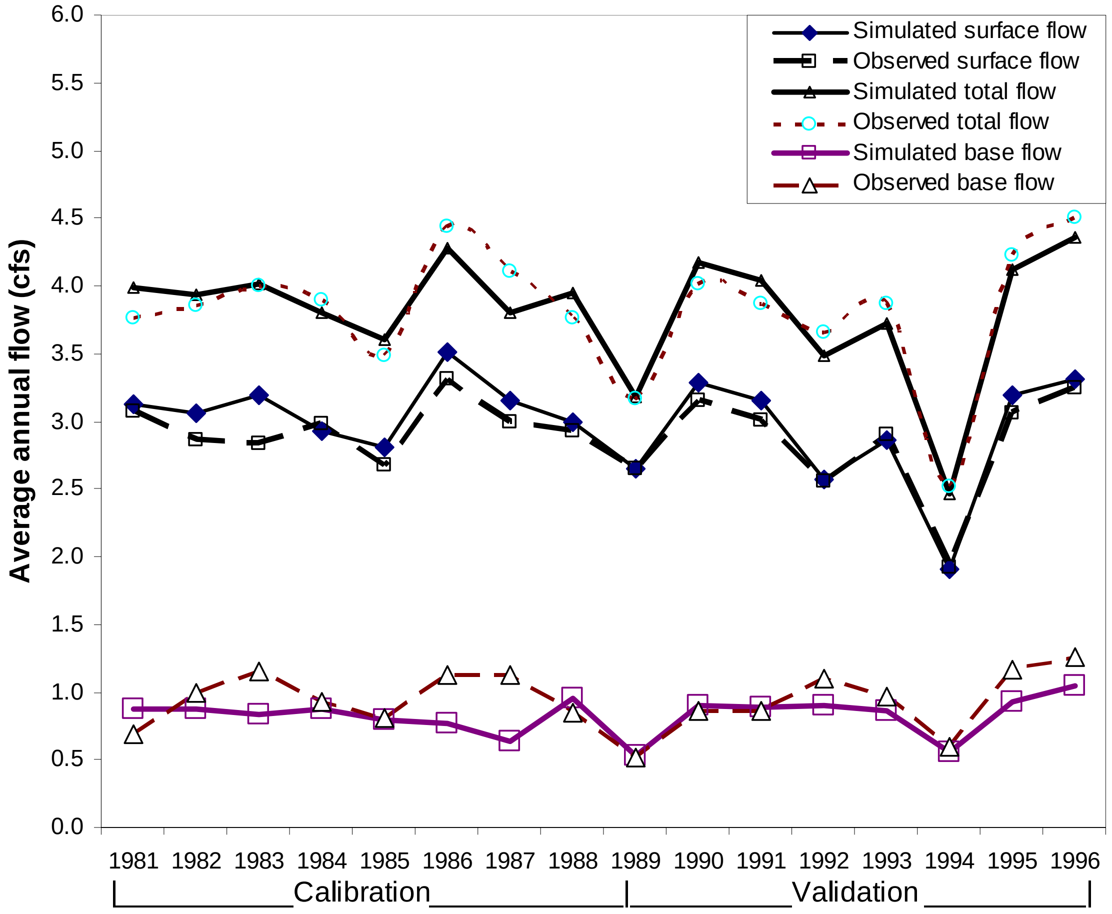
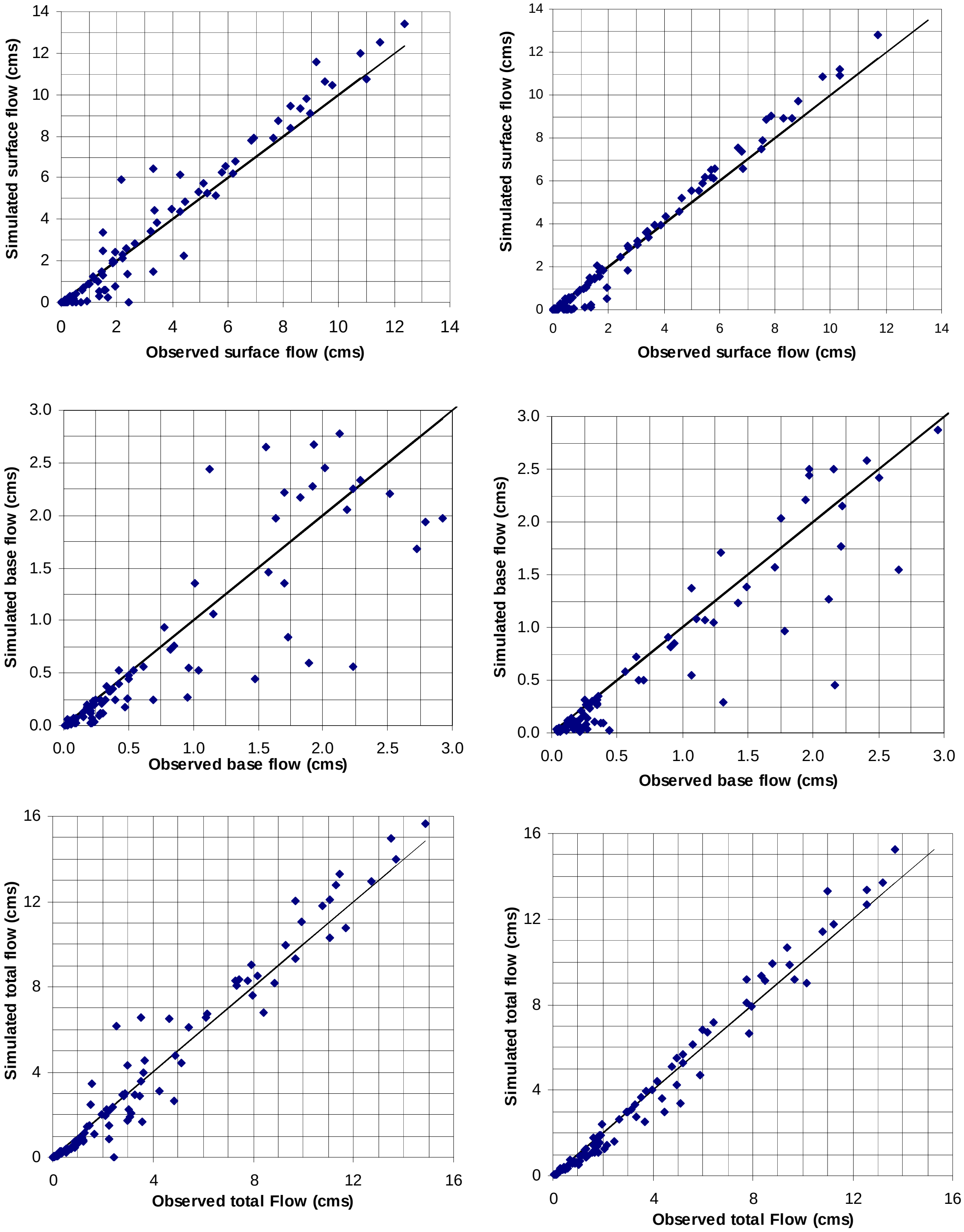


Figure 5-13. Time series plot of annual calibrated and validated flows for existing conditions of the Legedadi Reservoir Watershed.



Calibration

Validation

Figure 5-14. Scatter plots of monthly calibrated and validated flows with 1:1 line for the Legedadi Reservoir Watershed.

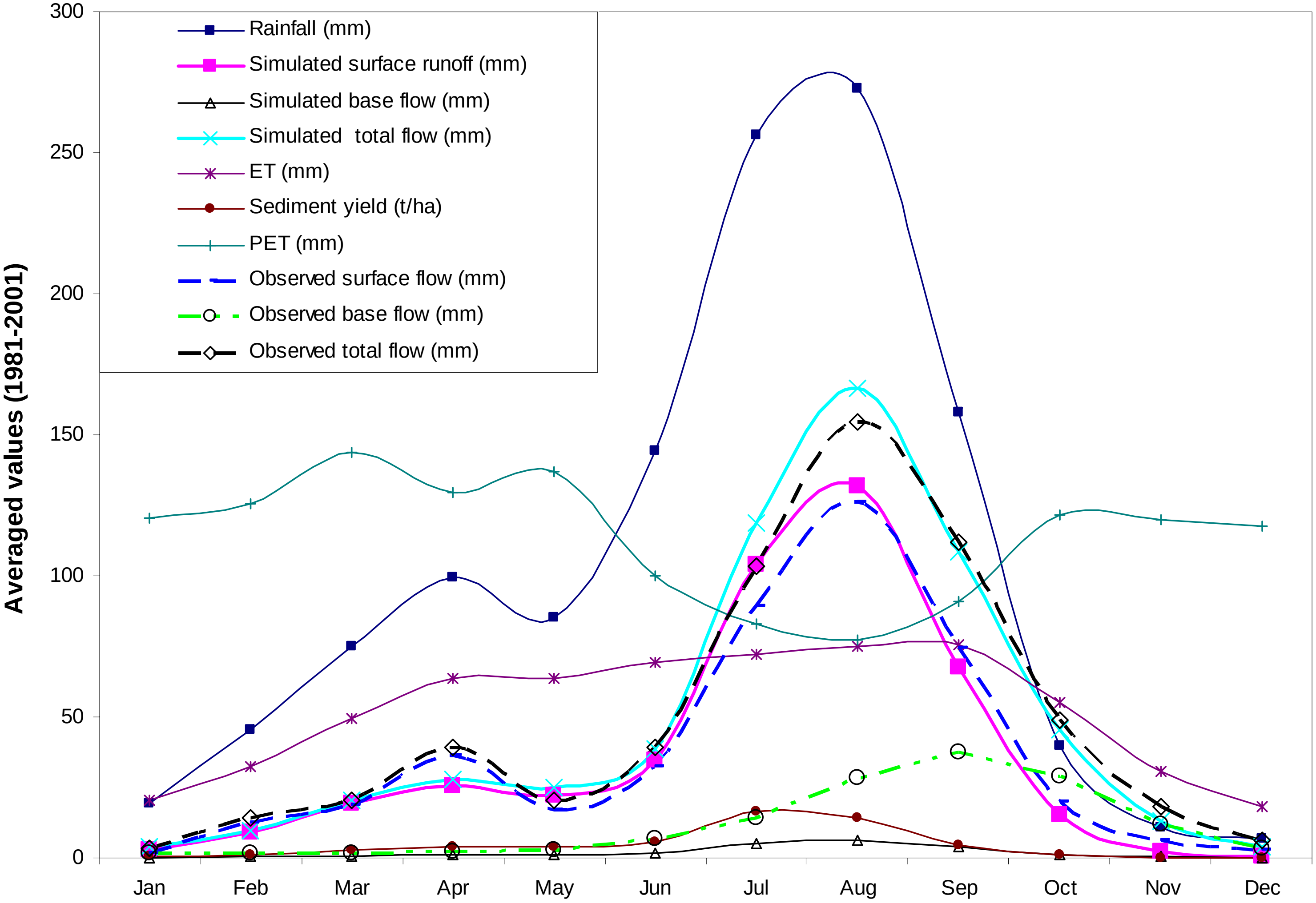


Figure 5-15. Monthly averaged watershed outputs under existing conditions.

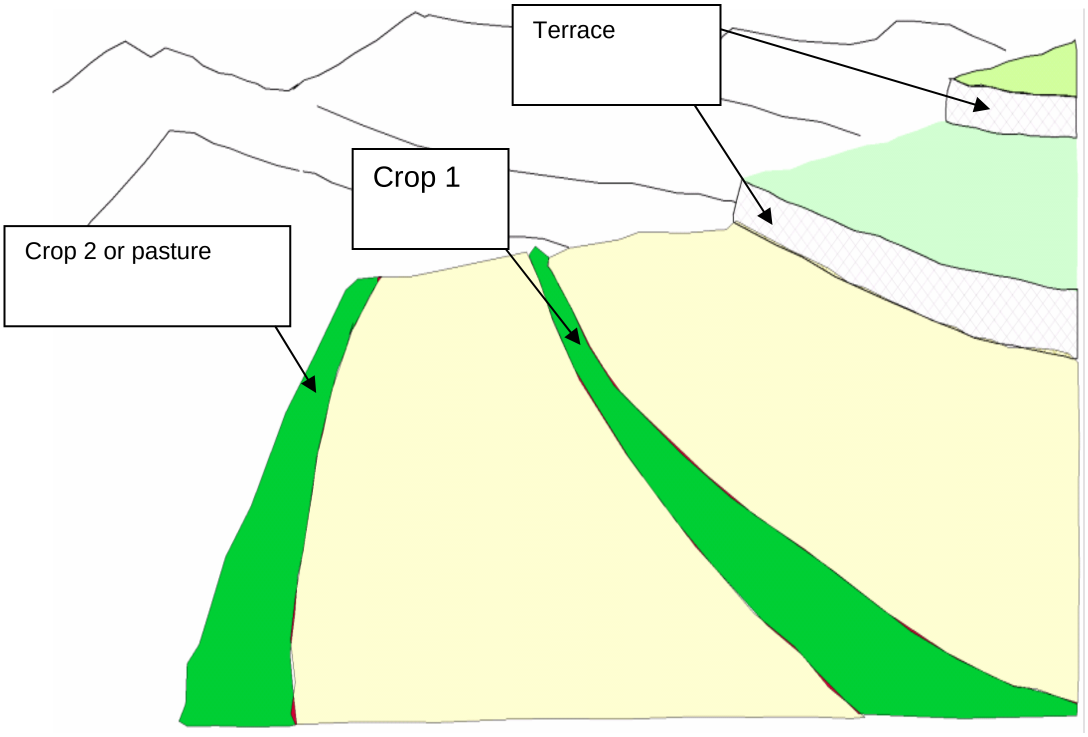


Figure 5-16. Sketch to show contour strip-cropping and terrace BMP implementation. (Strip cropping on the gentle cultivated land to the left, while terraces are used on steeper slopes to right).

Figure 5-17. An example of conversion of cultivated lands to forest as an alternative to reduce runoff and sediment yield in the steeper areas of the Legedadi Reservoir Watershed.

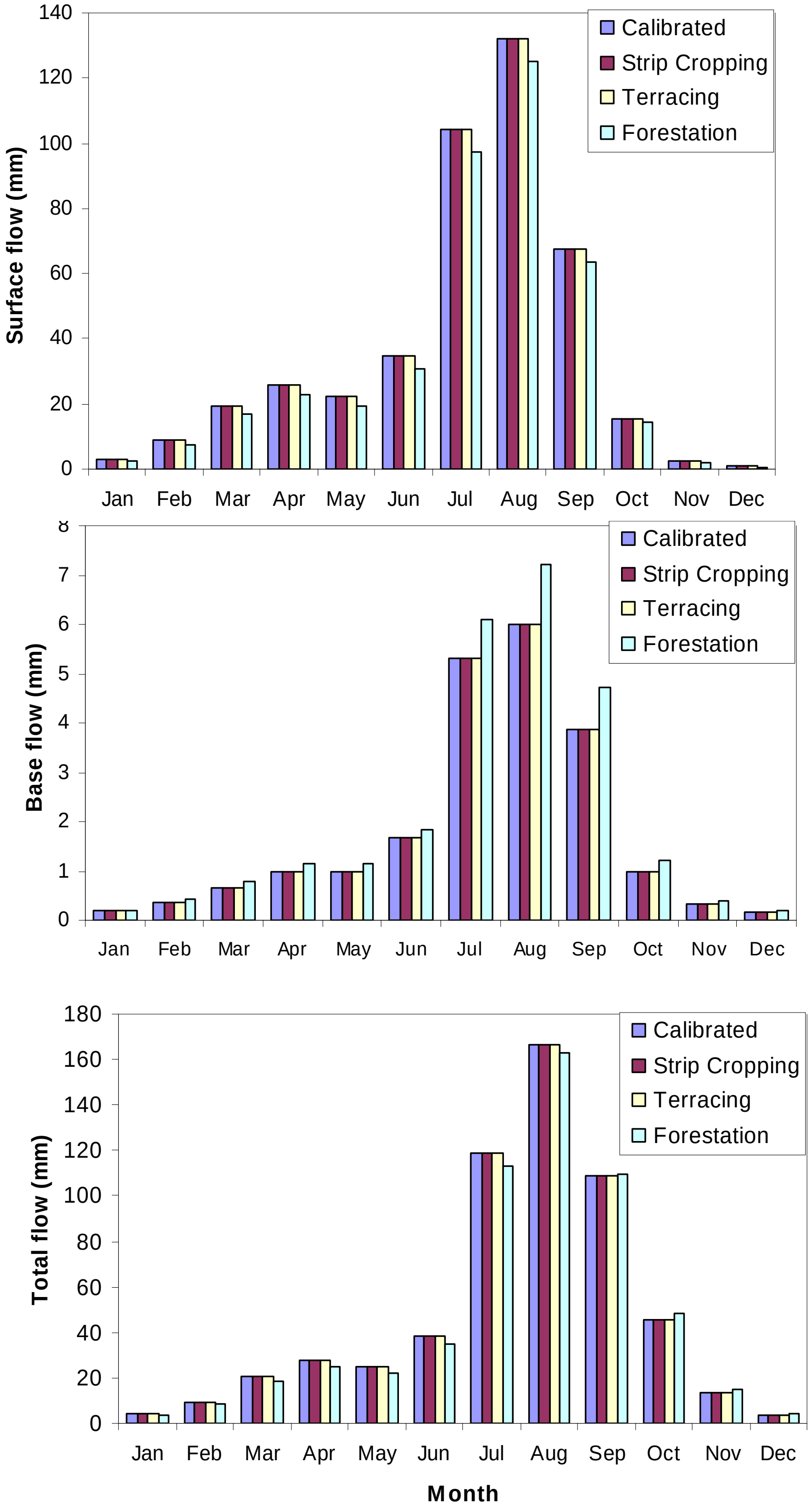


Figure 5-18. Effects of strip-cropping and terrace BMP implementation, and land use change to forest scenarios on watershed flows from the Legedadi Reservoir Watershed.

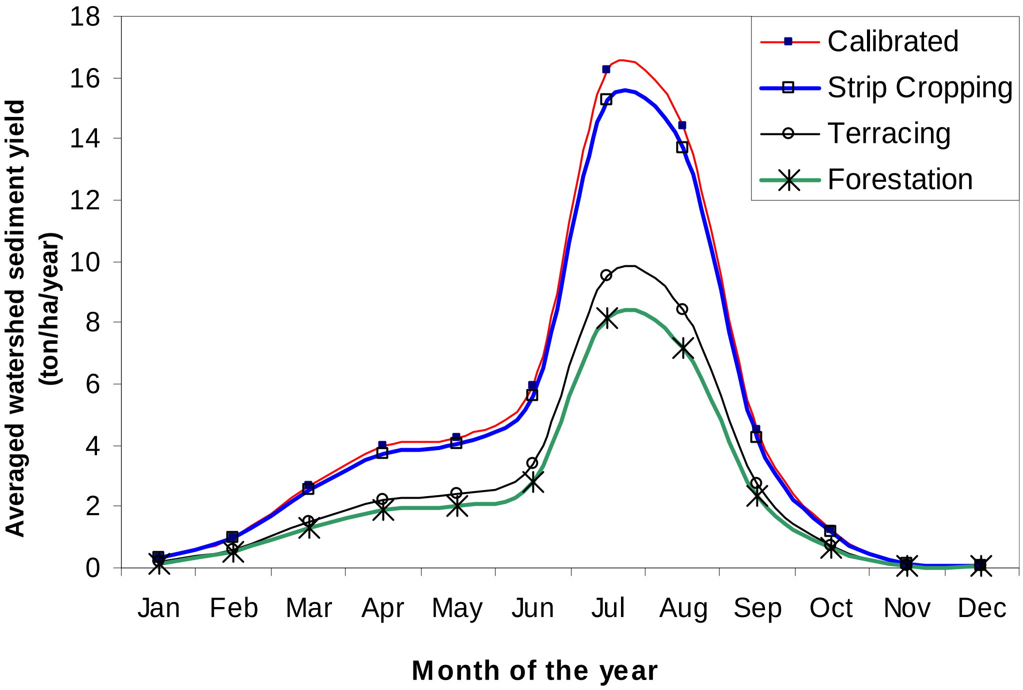


Figure 5-19. Effects of strip-cropping and terrace BMP implementation, and land use change to forest scenarios on watershed sediment yield from the Legedadi Reservoir Watershed

CHAPTER 6

SUMMARY, CONCLUSIONS AND RECOMMENDATIONS

6.1. SUMMARY AND CONCLUSION

6.1.1. Rainfall-runoff sequence effects on P loss from pastures

P loss in surface runoff from well managed pastures is dominated by dissolved reactive P (Edwards and Daniel, 1993), which may result in eutrophication of receiving water bodies. The main objective of this study was to investigate the effects of soil test phosphorus and surface application of poultry litter (P source), rainfall/runoff sequences and time after litter application (P management) on dissolved reactive P in surface runoff from boxes. The study was carried out using a simulated rainfall in a controlled greenhouse experiment in an effort to establish the pasture land use typical of the Ozark Highlands. Rainfall intensity (75 mm/hr) and runoff duration (0.5 h) were held constant through out the experiment. Time to initiate runoff varied from box to box depending on box hydrology and soil infiltration characteristics. Runoff produced from each box was manually recorded at two-minute intervals, and a composite sample was taken at the end of the 30-minute runoff and analyzed for DRP.

Poultry litter, rainfall runoff sequence (RRS), and time after litter application had a highly significant effect on DRP in surface runoff from pastures. The significant STP effect on DRP loss in runoff prior to litter application was masked following litter application. This indicates that litter P served as the primary source of DRP loss in the surface runoff collected from the boxes.

The effect of poultry litter application on DRP loss was also dependent on the time interval between litter application and the first runoff event, and whether there was a non-runoff producing rainfall event during this interval (RRS). A rainfall without runoff reduced significantly the effect of poultry litter application on DRP loss in the first surface runoff event. The highest averaged DRP loss was observed in runoff collected from boxes with the shortest time interval between litter application and first surface runoff event (RRS1; 1 day). More than 50 percent reduction in DRP loss was observed in the first runoff events of consecutive RRS treatments (RRS1 and RRS2, and RRS 2 and RRS3). The longest time interval (RRS3; 7 days) combined with a two non-runoff producing rainfall events resulted in the highest DRP loss reduction (80%) in runoff compared with RRS1. The time trend effect of RRS indicated that litter DRP approached asymptotically control DRP from above. The decrease in DRP loss may be attributed to its movement into the soil with the infiltrating water or its transformation to a less soluble form.

Time to initiate runoff (i.e. difference of runoff and rainfall durations) was found to have a significant effect on DRP loss in surface runoff from the boxes on days 1, 4, and 7 after litter application. This indicates that any practice that reduces surface runoff or increases soil infiltration would minimize the offsite transport of DRP (Figure 3-3). The effect is more significant on DRP from pasture that recently received litter.

An exponential decrease defined the relationship between DRP and time after poultry litter application indicating that poultry litter becomes less available over time for the single application (6.7 Mg/ha). Poultry litter application had a significant effect on DRP loss in surface runoff until 18 days compared to controls. Some time between day 18 and 32 after litter application, the effect of litter was not significant compared with controls although observed litter DRP (0.46 mg/L) was higher than control DRP (0.25 mg/L) at the end of the experiment (Day 62). Time had a highly significant effect on DRP loss in surface runoff from poultry litter received boxes in two ways: time interval between litter application and first runoff event (that ranged from 1 to 7 days) in combination with a rainfall without runoff, and time after litter application (that ranged from 1 to 62 days).

6.1.2. Scale effects on phosphorus loss from pasture systems

Little research has been conducted that integrates temporal and spatial scale effects on P loss from pastures. The scaling study investigated the spatial and temporal scale effects on hydrology and P loss from pastures. In addition to assessing the scale effect, analysis of the overall effects of the independent variables on hydrology, and DRP and TP concentration and load was carried out.

Although some variables had more influence than the others as indicated by the PROC REG analysis (Tables 4-1, 4-2), variability in runoff depth (hydrology) (R^2= 0.70), DRP concentration (R^2= 0.55), DRP load (R^2= 0.31), TP concentration (R^2= 0.65) and TP load (R^2= 0.36) from litter received pastures were explained by variables that were significant at P= 0.1. Similarly, variability in runoff depth (R^2 = 0.81), DRP concentration (R^2 = 0.65), DRP load (R^2= 0.57), TP concentration (R^2= 0.52) and TP load (R^2= 0.50) from control pastures were explained by variables that were significant at P= 0.1.

There were spatial scale effects on DRP and TP concentration from litter received pastures (Table 4-7 and 4-8). Both DRP and TP concentrations decreased as area increased ($r < 0$; $P < 0.0001$; Figures 4-3, 4-4). This may be due to dilution associated with an increase in runoff volume with increasing area. In addition, P transformations and site characteristics, such as hydrology and P adsorption and desorption processes, may contribute to the decrease. It should be noted that there was no spatial scale (area) effect on DRP and TP concentration from the control pastures. This may be due to the difference in P sources, i.e. the soil matrix vs. poultry litter.

Spatial scale effect also existed for runoff depth, DRP and TP load from both litter received and control pastures (Table 4-7, 4-8; Figures 4-5, 4-6). DRP and TP load increased with increasing area. The increase in P load with area is primarily due to increased runoff volume. This is a concern in fields with high runoff potential that received poultry litter.

Temporal scale effect was observed for DRP and TP concentration from both control and litter received pastures. This is mainly due to transformations and downward movement of P resulting from the combined effect of precipitation prior to the first runoff event and time after litter application. This makes less DRP and TP available to surface runoff. Both DRP and TP concentrations decreased exponentially with time. This corroborates the findings in Chapter 3. Moreover, Good (2002) observed a two-fold to six-fold decrease in water extractable P during the first 14 days of laboratory incubation of poultry litter indicating a temporal scale effect. Temporal scale effect existed for TP load, while it didn't for DRP load and hydrology.

The existence of the scale (spatial and temporal) effect suggested that a simple averaging procedure (i.e. homogeneous assumption) may not be an appropriate method to transfer plot- and field-scale studies to larger scales without considering these effects. This calls for the integration of the scale effect on P loss and hydrology in the management of P movement from pastures.

6.1.3. BMP and land use change impacts on watershed runoff and sediment yield

A watershed modeling approach was employed to investigate the impacts of two BMP and a land use change scenarios (contour strip-cropping, terracing and conversion of cultivated land to forest) on runoff and sediment yield in selected subbasins of the Legedadi Reservoir watershed in central Ethiopia accounting for land use, management, and weather variability. The different BMPs were assigned based on proximity to water bodies, steepness and suitability issues. The Soil and Water Assessment Tool (SWAT) model that exhibits robustness in estimating stream flows from agricultural watersheds and predicting sediment yield was employed. Digitized topography (30 m DEM), soil, 1996 land use, and weather data (1975-2001) of the Legedadi Reservoir watershed were used as input. Soil and management databases were modified to approximate the soils and cultural practices in watershed.

The model was calibrated using stream flow data (1981-1988) obtained from the Sibilu River gauging station based on the hydrological similarity calculation method. The calibrated model was then validated for the period of 1988-1996. Both the calibration and validation periods indicate a good performance of the model as indicated by statistical measures (Table 5-2), time series and scatter plot diagrams (Figures 5-12 and 5.13). The watershed experiences severe soil erosion owing to its topography, land management, population pressure, and intense and excess rainfall that occurs within a few months of the year (Figure 5-9). Of the three scenarios, forestation of cultivated lands in the upper steeper parts of the watershed (Figure 5-8 and Table 5-3) had the greatest impact in reducing both sediment yield (49%) and surface runoff (11%), and in increasing the base flow (19%) compared with the existing condition. Terracing was also effective in reducing sediment yield (42%) while that of contour strip cropping can be considered negligible (6%). Both terracing and strip cropping had little impact on the hydrology of the watershed compared with the existing condition.

The threefold increase in water treatment costs due to the continually increasing turbidity of the Legedadi reservoir (AAWSA, 1999) and highly erosive practices in the watershed that leave the soil bare during the onset of the first intense rainfall, indicate that a reduction in sediment yield is imperative. This study showed that a watershed modeling approach involving BMP and land use change scenarios is a useful tool that has much to offer in rapidly developing plans to reduce sediment yield in the watershed. However, factors such as cost effectiveness, ease of construction and maintenance issues can also influence BMP selection which are beyond the scope of this study.

6.2. RECOMMENDATIONS

The objectives of this dissertation were accomplished as described in Chapters 3, 4 and 5, and summarized and concluded in Section 6.1 of this chapter. However, there are a number of recommendations for further improvement or continuing the effort to address the issues investigated in this dissertation in detail. Due to this reason, the following are recommended:

1. Phosphorus loss from pastures was found to be highly affected by rainfall events without runoff, and time interval to the first runoff event. However, little information is available on the effect of time interval with no rainfall prior to the first runoff event. This should be addressed. Moreover, most experiments were carried out by analyzing the total P in litter, a practice followed by many poultry litter analyzing labs. Future experiments should consider analyzing DRP (soluble P) in poultry litter right before application. This may help to more accurately assess the effect of litter P source on P loss from pastures, which is dominated by DRP.
2. Existence of scale effects has been documented in this dissertation. Due to the high variability observed in the summarized studies, it is suggested that further scale studies on P loss from pastures be made. Emphasis should be made on scales ranging from 50 to 10000 m^2. The use of a consistent multiple variable levels for a single scale (plot or field area) is highly recommended. This will allow the investigation of the scale effect at low, medium and high rates of the variable levels. It will also allow the investigation of the effect on the response variables

(e.g. DRP or TP loss) from the interactions of input variables to develop appropriate prediction equations which can then be integrated into water quality models to account for scaling effect in the movement of P from pastures.

3. The scaling study also considered some variables in very simplified units (e.g. grazing rate in animal units per ha) to investigate their impact on dependent variables (e.g. runoff depth). It is suggested that a method be developed to quantify such effects in a more physically meaningful expression. For example, grazing rate in animal units can be related to soil compaction which can then be integrated into runoff and soil erosion determination. A similar approach is needed for BMP amendments such as alum treated litter.
4. This dissertation utilized a watershed modeling approach to investigate the impacts of a land use change and two BMP implementation scenarios in the Legedadi reservoir watershed in central Ethiopia. This adaptation involved modification of existing SWAT soil or management database, which were developed for the United States of America. Although this is the right step to quickly develop a watershed management plan to analyze the effectiveness of watershed level BMP implementation, acquiring watershed representative data are a prerequisite for future studies. Hence soil, crop, and cultural practice databases need to be developed. Moreover, stream flow data and hydrological characteristics need to be revised and evaluated in detail. Moreover, additional monitoring stations need to be installed so that additional site specific flow data can be used in the planning process.

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APPENDIX A. SOIL DATABASE EMPLOYED IN THE SWAT MODEL BASED ON MODIFICATION USING ANCILLIARY DATA

(Supplement to Chapter 5)

A-1. Soil matching in the study area to that in the SWAT database.

Dominant soils of the mapping unit	USDA Soil Classification Equivalent[1]	SWAT Soil Database			
		MUID	SEQN	SWAT Soil Name	S5ID
Leptosols/ Cambisols/ Vertisols	Rockland/Xerochrepts/ Chromoxerert	CA201	18	Cotati	CA1321
Eutric Fluvisols/Cambisols	Xerofluvents/ Xerochrepts	CA145	13	Xerofluvents	CA7017
Eutric Fluvisols	Xerofluvents/ Torrifluvents	CA201	17	Xeric Torrifluvents	CA7045
Fluvisols/Cambisols	Xerofluvents/ Xerochrepts	CA201	17	Xerofluvents	CA7045
Eutric Fluvisols	Xerorthent	CA201	17	Xerofluvents	CA7045
Cambisols & Luvisols	Xerochrepts/ Haploxeralfs/ Haplustalfs	ID369	6	Xerochrepts	ID7021
Eutric Cambisols	Cryochrept	ID033	2	Xerochrepts	ID7029
Dystric Cambisols/ Lithic Leptosols	Dystrochrept	ID033	2	Dystric Cryochrepts	ID7029
Chromic Cambisols	Eutrochrept/ Cryochrept	ID033	2	Dystric Cryochrepts	ID7029
Leptosols/ Regosols/ Cambisols	Rockland/ Xerochrepts/ Xerochrepts	ID348	17	Typic Dystrochrepts	ID7091
Vertic Cambisols	Vertic haploxerolls	ID353	4	Lithic Haploxerolls	ID7093
Cambisols	Xerochrepts	ID353	4	Xerochrepts	ID7093
Chromic Cambisols	Eutrochrept/ Cryochrept	IL042	15	Algiers	OH0065
Lithic Leptosols	Rockland	MT384	12	Rock Outcrop	SD3006
Leptosols	Rockland	MT384	12	Rock Outcrop	SD3006
Eutric Vertisols	Chromoxerert	LA148	9	Boykin	TX0856
Eutric Vertisols	Chromoxerert	KS418	3	Vernon	TX0249
Eutric Vertisols	Chromoxerert	LA159	17	Socagee	TX1121

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[1] Matching of the soils of the study area with that in the USDA Classification System and SWAT soil database was achieved using information obtained from FAO-UNESCO (1977), MOA (1983), and AAWSA (1999).

A-2. SWAT default vs. modified soil database for the Legedadi reservoir watershed.

Default

S5ID	MUID	SEQN	SWAT Soil Name	CMPPCT	NLAYERS	HYDGRP	SOL_ZMX	ANION_EXCL	SOL_CRK	TEXTURE
CA1321	CA201	18	Cotati	2.000	2	D	1727.20	0.500	0.500	FSL-SC
CA7017	CA145	13	Xerofluvents	5.000	3	B	1524.00	0.500	0.500	SL-L-GR--L
CA7045	CA201	17	Xeric torrifluvents	1.000	2	A	1524.00	0.500	0.500	S-GRV-COS
DC0038	AR060	10	Water	2.000	1	-	25.40	0.500	0.500	
ID7029	ID033	2	Cryochrepts	20.000	4	B	1041.40	0.500	0.500	STV-L-GR--L-GRX-SL-UWB
ID7091	ID348	17	Typic dystrochrepts	1.000	4	D	1422.40	0.500	0.500	L-GR--SL-GRV-SL-UWB
ID7093	ID353	4	Xerochrepts	12.000	2	D	203.20	0.500	0.500	GR--LS-UWB
OH0065	IL042	15	Algiers	1.000	3	C	1828.80	0.500	0.500	SIL-SICL-GRV-S
SD3006	MT384	12	Rockoutcrop	1.000	1	D	1524.00	0.500	0.500	WB
TX0249	KS418	3	Vernon	19.000	4	D	2032.00	0.500	0.500	CL-SIC-SH--C-SH--C
TX1121	LA159	17	Socagee	3.000	3	D	2032.00	0.500	0.500	SICL-SICL-CL

Modified

S5ID	MUID	SEQN	SWAT Soil Name	CMPPCT	NLAYERS	HYDGRP	SOL_ZMX	ANION_EXCL	SOL_CRK	TEXTURE
CA1321	CA201	18	Cotati	2.000	2	D	600.00	0.500	0.500	FSL-SC
CA7017	CA145	13	Xerofluvents	5.000	3	D	500.00	0.500	0.500	SL-L-GR--L
CA7045	CA201	17	Xeric torrifluvents	2.000	2	C	1000.00	0.500	0.500	GR--L-WB
DC0038	AR060	10	Water	2.000	1	D	25.40	0.500	0.500	
ID7029	ID033	2	Typic dystrochrepts	20.000	4	D	550.00	0.500	0.000	STV-L-GR--L-GRX-SL-UWB
ID7091	ID348	17	Lithic haploxerolls	1.000	4	D	500.00	0.500	0.500	L-GR--SL-GRV-SL-UWB
ID7093	ID353	4	Xerochrepts	9.000	2	D	1500.00	0.500	0.050	GR--LS-UWB
OH0065	IL042	15	Algiers	1.000	3	C	550.00	0.500	0.500	SIL-SICL-GRV-S
SD3006	MT384	12	Rockoutcrop	1.000	1	D	750.00	0.500	0.500	WB
TX0249	KS418	4	Vernon	19.000	4	D	1150.00	0.500	0.080	CL-SIC-SH--C-SH--C
TX1121	LA159	17	Socagee	3.000	3	D	1200.00	0.500	0.500	SICL-SICL-CL

A-2 continued

Default

S5ID	SOL_Z1	SOL_BD1	SOL_AWC1	SOL_K1	SOL_CBN1	CLAY1	SILT1	SAND1	ROCK1	SOL_ALB1	USLE_K1	SOL_EC1	SOL_Z2
CA1321	558.80	1.58	0.14	18.00	0.29	15.00	19.67	65.33	4.53	0.13	0.32	0.00	1727.20
CA7017	254.00	1.62	0.12	26.00	0.29	12.50	19.65	67.85	9.84	0.13	0.24	1.00	762.00
CA7045	254.00	1.78	0.08	220.00	0.29	5.00	1.48	93.52	8.34	0.13	0.15	0.00	1524.00
DC0038	25.40	0.00	0.00	75.00	0.00	0.00	0.00	0.00	0.00	0.23	0.00	0.00	0.00
ID7029	50.80	1.60	0.08	20.00	1.74	15.00	40.67	44.33	55.65	0.01	0.15	0.00	533.40
ID7091	177.80	1.23	0.15	43.00	1.74	13.00	41.62	45.38	8.58	0.01	0.28	0.00	1041.40
ID7093	177.80	1.48	0.11	600.00	1.45	4.00	15.98	80.02	26.30	0.01	0.05	0.00	203.20
OH0065	508.00	1.33	0.20	3.30	1.74	21.00	52.74	26.26	2.56	0.01	0.37	0.00	1397.00
SD3006	1524.00	1.70	0.05	0.17	0.29	20.00	40.00	40.00	5.25	0.13	0.10	0.00	0.00
TX0249	127.00	1.50	0.17	2.20	0.73	37.50	32.31	30.19	2.89	0.06	0.37	1.00	635.00
TX1121	177.80	1.50	0.21	0.41	1.16	33.50	59.88	6.63	0.00	0.02	0.32	0.00	1016.00

Modified

S5ID	SOL_Z1	SOL_BD1	SOL_AWC1	SOL_K1	SOL_CBN1	CLAY1	SILT1	SAND1	ROCK1	SOL_ALB1	USLE_K1	SOL_EC1	SOL_Z2
CA1321	180.00	1.58	0.15	10.00	0.97	53.80	7.30	38.90	0.60	0.13	0.20	0.00	600.00
CA7017	450.00	1.62	0.15	20.00	0.50	43.00	50.00	7.00	0.00	0.13	0.10	1.00	460.00
CA7045	450.00	1.78	0.14	15.00	0.50	43.00	50.00	7.00	0.00	0.13	0.10	0.00	460.00
DC0038	25.40	0.00	0.00	15.00	0.00	0.00	0.00	0.00	0.00	0.23	0.00	0.00	0.00
ID7029	304.00	1.60	0.10	20.00	4.96	35.00	44.00	21.00	0.00	0.01	0.30	0.00	500.00
ID7091	250.00	1.23	0.12	15.00	1.63	30.00	30.00	40.00	5.00	0.01	0.23	0.00	880.00
ID7093	500.00	1.48	0.12	20.00	4.50	50.00	10.00	40.00	25.51	0.01	0.20	0.00	1100.00
OH0065	355.00	1.33	0.15	7.00	1.58	21.00	52.74	26.26	2.56	0.01	0.30	0.00	1397.00
SD3006	1200.00	1.70	0.15	0.18	0.29	30.00	40.00	30.00	5.25	0.13	0.23	0.00	0.00
TX0249	1200.00	1.50	0.21	15.00	1.16	60.00	20.00	20.00	0.00	0.06	0.20	1.00	1500.00
TX1121	170.00	1.50	0.24	10.00	1.16	76.00	12.00	12.00	0.00	0.02	0.20	0.00	750.00

A-2 continued

Default

S5ID	SOL_BD2	SOL_AWC2	SOL_K2	SOL_CBN2	CLAY2	SILT2	SAND2	ROCK2	SOL_ALB2	USLE_K2	SOL_EC2	SOL_Z3	SOL_BD3
CA1321	1.50	0.10	0.94	0.10	45.00	7.14	47.86	3.97	0.19	0.28	0.00	0.00	0.00
CA7017	1.53	0.14	13.00	0.10	12.50	41.86	45.64	11.39	0.19	0.17	1.00	1524.00	1.54
CA7045	1.78	0.03	190.00	0.10	5.00	3.86	91.14	40.00	0.19	0.15	0.00	0.00	0.00
DC0038	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
ID7029	1.60	0.08	18.00	0.58	15.00	40.67	44.33	51.50	0.08	0.05	0.00	1016.00	1.63
ID7091	1.48	0.06	100.00	0.29	7.50	23.97	68.53	49.60	0.13	0.10	0.00	1397.00	1.48
ID7093	2.50	0.01	34.00	0.48	5.00	25.00	70.00	98.00	0.09	0.00	0.00	0.00	0.00
OH0065	1.45	0.18	1.10	0.58	27.50	52.50	20.00	2.80	0.08	0.37	0.00	1828.80	1.65
SD3006	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
TX0249	1.58	0.14	0.16	0.32	50.00	44.74	5.26	3.03	0.12	0.37	1.00	1600.20	1.67
TX1121	1.50	0.21	0.40	0.39	30.00	63.09	6.91	0.00	0.11	0.32	0.00	2032.00	1.50

Modified

S5ID	SOL_BD2	SOL_AWC2	SOL_K2	SOL_CBN2	CLAY2	SILT2	SAND2	ROCK2	SOL_ALB2	USLE_K2	SOL_EC2	SOL_Z3	SOL_BD3
CA1321	1.70	0.15	6.00	0.48	54.10	9.60	36.30	10.00	0.19	0.28	0.00	900.00	1.78
CA7017	1.52	0.10	26.00	0.22	44.00	45.00	15.00	0.00	0.19	0.17	1.00	820.00	1.85
CA7045	1.52	0.10	15.00	0.22	44.00	45.00	15.00	0.00	0.11	0.00	0.00	820.00	1.85
DC0038	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
ID7029	1.60	0.08	15.00	0.47	23.40	32.00	43.60	7.30	0.08	0.05	0.00	1100.00	1.64
ID7091	1.45	0.06	25.00	1.04	25.00	20.00	55.00	15.00	0.13	0.10	0.00	1000.00	1.48
ID7093	2.50	0.01	33.00	0.48	5.00	25.00	70.00	98.00	0.09	0.00	0.00	0.00	0.00
OH0065	1.45	0.18	1.10	0.58	27.50	52.50	20.00	2.80	0.08	0.37	0.00	1828.80	1.65
SD3006	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
TX0249	1.45	0.18	2.00	0.39	65.00	20.00	15.00	3.03	0.12	0.37	1.00	1600.20	1.67
TX1121	1.65	0.21	7.00	0.39	78.00	11.00	11.00	0.00	0.11	0.32	0.00	1000.00	1.82

A-2 continued

Default

S5ID	SOL_AWC3	SOL_K3	SOL_CBN3	CLAY3	SILT3	SAND3	ROCK3	SOL_ALB3	USLE_K3	SOL_EC3	SOL_Z4	SOL_BD4	SOL_AWC4
CA1321	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
CA7017	0.12	11.00	0.03	12.50	41.86	45.64	25.30	0.22	0.17	1.00	0.00	0.00	0.00
CA7045	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
DC0038	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
ID7029	0.02	13.00	0.15	12.50	19.65	67.85	83.94	0.17	0.05	0.00	1041.40	2.50	0.01
ID7091	0.03	69.00	0.15	6.00	30.48	63.52	74.50	0.17	0.02	0.00	1422.40	2.50	0.01
ID7093	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
OH0065	0.03	350.00	0.19	2.50	1.52	95.98	40.00	0.16	0.10	0.00	0.00	0.00	0.00
SD3006	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
TX0249	0.11	0.40	0.32	50.00	27.77	22.23	6.43	0.12	0.37	5.00	2032.00	1.85	0.09
TX1121	0.18	1.60	0.13	29.00	44.20	26.80	0.00	0.18	0.32	0.00	0.00	0.00	0.00

Modified

S5ID	SOL_AWC3	SOL_K3	SOL_CBN3	CLAY3	SILT3	SAND3	ROCK3	SOL_ALB3	USLE_K3	SOL_EC3	SOL_Z4	SOL_BD4	SOL_AWC4
CA1321	0.08	8.00	0.30	55.70	11.20	33.10	40.00	0.00	0.00	0.00	1200.00	1.82	0.05
CA7017	0.05	31.80	0.37	45.00	40.00	15.00	0.00	0.22	0.17	1.00	0.00	0.00	0.00
CA7045	0.05	31.20	0.37	45.00	40.00	15.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
DC0038	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
ID7029	0.02	31.35	0.40	37.70	39.60	22.70	7.10	0.17	0.05	0.00	0.00	0.00	0.01
ID7091	0.03	39.00	0.36	6.00	30.48	63.52	74.50	0.17	0.02	0.00	0.00	2.50	0.01
ID7093	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
OH0065	0.03	40.50	0.19	2.50	1.52	95.98	40.00	0.16	0.10	0.00	0.00	0.00	0.00
SD3006	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
TX0249	0.11	0.40	0.32	50.00	27.77	22.23	6.43	0.12	0.37	5.00	2032.00	1.85	0.09
TX1121	0.18	5.00	0.13	80.00	11.00	9.00	0.00	0.18	0.32	0.00	0.00	0.00	0.00

A-2 continued

Default

S5ID	SOL_K4	SOL_CBN4	CLAY4	SILT4	SAND4	ROCK4	SOL_ALB4	USLE_K4	SOL_EC4	SOL_Z5	SOL_BD5	SOL_AWC5	SOL_K5
CA1321	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
CA7017	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
CA7045	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
DC0038	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
ID7029	500.00	0.05	5.00	25.00	70.00	98.00	0.21	0.00	0.00	0.00	0.00	0.00	0.00
ID7091	500.00	0.05	5.00	25.00	70.00	98.00	0.21	0.00	0.00	0.00	0.00	0.00	0.00
ID7093	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
OH0065	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
SD3006	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
TX0249	0.35	0.32	50.00	27.77	22.23	20.00	0.12	0.32	5.00	0.00	0.00	0.00	0.00
TX1121	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

Modified

S5ID	SOL_K4	SOL_CBN4	CLAY4	SILT4	SAND4	ROCK4	SOL_ALB4	USLE_K4	SOL_EC4	SOL_Z5	SOL_BD5	SOL_AWC5	SOL_K5
CA1321	5.00	0.00	55.40	8.80	35.80	60.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
CA7017	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
CA7045	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
DC0038	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
ID7029	0.00	0.00	0.00	0.00	0.00	0.00	0.21	0.00	0.00	0.00	0.00	0.00	0.00
ID7091	0.00	0.05	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
ID7093	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
OH0065	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
SD3006	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
TX0249	0.35	0.32	50.00	27.77	22.23	20.00	0.12	0.32	5.00	0.00	0.00	0.00	0.00
TX1121	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

A-2 continued

Default

S5ID	SOL_CBN5	CLAY5	SILT5	SAND5	ROCK5	SOL_ALB5	USLE_K5	SOL_EC5	SOL_Z6	SOL_BD6	SOL_AWC6	SOL_K6	SOL_CBN6
CA1321	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
CA7017	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
CA7045	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
DC0038	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
ID7029	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
ID7091	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
ID7093	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
OH0065	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
SD3006	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
TX0249	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
TX1121	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

Modified

S5ID	SOL_CBN5	CLAY5	SILT5	SAND5	ROCK5	SOL_ALB5	USLE_K5	SOL_EC5	SOL_Z6	SOL_BD6	SOL_AWC6	SOL_K6	SOL_CBN6
CA1321	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
CA7017	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
CA7045	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
DC0038	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
ID7029	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
ID7091	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
ID7093	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
OH0065	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
SD3006	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
TX0249	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
TX1121	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

A-2 continued

Default

S5ID	CLAY6	SILT6	SAND6	ROCK6	SOL_ALB6	USLE_K6	SOL_EC6	SOL_Z7	SOL_BD7	SOL_AWC7	SOL_K7	SOL_CBN7	CLAY7
CA1321	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
CA7017	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
CA7045	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
DC0038	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
ID7029	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
ID7091	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
ID7093	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
OH0065	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
SD3006	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
TX0249	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
TX1121	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

Modified

S5ID	CLAY6	SILT6	SAND6	ROCK6	SOL_ALB6	USLE_K6	SOL_EC6	SOL_Z7	SOL_BD7	SOL_AWC7	SOL_K7	SOL_CBN7	CLAY7
CA1321	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
CA7017	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
CA7045	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
DC0038	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
ID7029	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
ID7091	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
ID7093	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
OH0065	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
SD3006	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
TX0249	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
TX1121	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

A-2 continued

Default

S5ID	SILT7	SAND7	ROCK7	SOL_ALB7	USLE_K7	SOL_EC7	SOL_Z8	SOL_BD8	SOL_AWC8	SOL_K8	SOL_CBN8	CLAY8	SILT8
CA1321	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
CA7017	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
CA7045	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
DC0038	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
ID7029	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
ID7091	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
ID7093	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
OH0065	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
SD3006	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
TX0249	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
TX1121	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

Modified

S5ID	SILT7	SAND7	ROCK7	SOL_ALB7	USLE_K7	SOL_EC7	SOL_Z8	SOL_BD8	SOL_AWC8	SOL_K8	SOL_CBN8	CLAY8	SILT8
CA1321	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
CA7017	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
CA7045	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
DC0038	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
ID7029	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
ID7091	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
ID7093	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
OH0065	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
SD3006	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
TX0249	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
TX1121	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

A-2 continued

Default

S5ID	SAND8	ROCK8	SOL_ALB8	USLE_K8	SOL_EC8	SOL_Z9	SOL_BD9	SOL_AWC9	SOL_K9	SOL_CBN9	CLAY9	SILT9	SAND9
CA1321	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
CA7017	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
CA7045	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
DC0038	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
ID7029	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
ID7091	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
ID7093	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
OH0065	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
SD3006	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
TX0249	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
TX1121	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

Modified

S5ID	SAND8	ROCK8	SOL_ALB8	USLE_K8	SOL_EC8	SOL_Z9	SOL_BD9	SOL_AWC9	SOL_K9	SOL_CBN9	CLAY9	SILT9	SAND9
CA1321	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
CA7017	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
CA7045	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
DC0038	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
ID7029	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
ID7091	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
ID7093	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
OH0065	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
SD3006	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
TX0249	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
TX1121	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

A-2 continued

Default

S5ID	ROCK9	SOL_ALB9	USLE_K9	SOL_EC9	SOL_Z10	SOL_BD10	SOL_AWC10	SOL_K10	SOL_CBN10	CLAY10	SILT10	SAND10	ROCK10
CA1321	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
CA7017	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
CA7045	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
DC0038	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
ID7029	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
ID7091	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
ID7093	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
OH0065	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
SD3006	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
TX0249	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
TX1121	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

Modified

S5ID	ROCK9	SOL_ALB9	USLE_K9	SOL_EC9	SOL_Z10	SOL_BD10	SOL_AWC10	SOL_K10	SOL_CBN10	CLAY10	SILT10	SAND10	ROCK10
CA1321	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
CA7017	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
CA7045	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
DC0038	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
ID7029	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
ID7091	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
ID7093	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
OH0065	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
SD3006	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
TX0249	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
TX1121	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

A-2 continued

Default

S5ID	SOL_ALB10	USLE_K10	SOL_EC10
CA1321	0.00	0.00	0.00
CA7017	0.00	0.00	0.00
CA7045	0.00	0.00	0.00
DC0038	0.00	0.00	0.00
ID7029	0.00	0.00	0.00
ID7091	0.00	0.00	0.00
ID7093	0.00	0.00	0.00
OH0065	0.00	0.00	0.00
SD3006	0.00	0.00	0.00
TX0249	0.00	0.00	0.00
TX1121	0.00	0.00	0.00

Modified

S5ID	SOL_ALB10	USLE_K10	SOL_EC10
CA1321	0.00	0.00	0.00
CA7017	0.00	0.00	0.00
CA7045	0.00	0.00	0.00
DC0038	0.00	0.00	0.00
ID7029	0.00	0.00	0.00
ID7091	0.00	0.00	0.00
ID7093	0.00	0.00	0.00
OH0065	0.00	0.00	0.00
SD3006	0.00	0.00	0.00
TX0249	0.00	0.00	0.00
TX1121	0.00	0.00	0.00

APPENDIX B. DATA AND PARAMETERS FOR FLOW AND SEDIMENT CALIBRATION OF THE SWAT MODEL.

(Supplements to Chapter 5)

B-1. Comparison of the Legedadi Reservoir and Sibilu River Station watersheds

Source: AAWSA (1999; summarized)

Station Variables	Sibilu river station watershed	Legedadi reservoir watershed
Latitude	9^{o}14'N	9^{o}4'12" N
Longitude	38^{o}45' E	38^{o}58'48 E
Average Elevation (m)	2600	2550
Drainage Area (sq. km.)	375	205
Annual rainfall (mm)	1250	1323
Geological formation (%)		
Miocene-Pliocene	30	40
Middle - Miocene	-	60
Oligocene-Miocene	60	-
Middle - Late Oligocene	10	-
Soil Type (%)		
Alluvial Deposits	26.3	26.9
Basic volcanic rocks	6.8	-
Colluvium	31.6	32.5
Intermediate basic volcanic rocks	30.6	32.8
Intermediate acidic volcanic rocks	4.7	7.8

B-2. Hydrologic similarity method employed for flow computation

The recorded stream flow data for the LRW was obtained by extrapolation from the Sibilu River gauging station. This watershed has a very similar soil, geology, topography and weather distribution to the Legedadi Reservoir watershed than any other gauged watershed in the vicinity. This similarity in topography, soil, geology and hydrology was shown in Appendix B-1. The hydrology similarity method was used to obtain stream flow data for LRW. The following equation (AAWSA, 1999) was used to obtain mean monthly stream discharge:

$$Q_i = Q_s * K_1 * K_2 * K_3$$

where:

Q_i = Mean monthly discharges for the ungauged watershed,

Q_s = Mean monthly discharges at the hydrological station of the gauged watershed used for evaluating stream flow for the ungauged watershed,

K_1 = Watershed size comparison coefficient (A_i/A_s), where Ai is area of the ungauged watershed, and As is watershed area of the hydrological station;

K_2 = Mean annual rainfall comparison coefficient (P_i/P_s), where Pi is mean annual rainfall over the ungauged watershed, and Ps is mean annual rainfall over the basin of the hydrological station,

K_3 = Groundwater decrement comparison coefficient (H_s/H_i), where Hs is the average watershed elevation of the hydrological station, and Hi is average watershed elevation of the ungauged watershed.

B-3. Calibration flow data for the Legedadi reservoir watershed based on the hydrological similarity calculation method from the Sibilu River gauging station.

Year	Flow Type	Monthly averaged discharge (Q, cms)											
		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1981	Total	0.06	1.49	1.58	3.55	0.30	0.51	9.68	12.72	9.96	3.26	1.66	0.34
	Surface	0.03	1.44	1.50	3.33	0.12	0.29	9.18	11.02	7.62	1.70	0.51	0.10
	Base	0.03	0.04	0.08	0.22	0.18	0.22	0.50	1.70	2.34	1.56	1.15	0.24
1982	Total	0.52	0.97	1.20	3.67	2.84	2.26	9.28	11.05	7.36	3.62	2.72	0.78
	Surface	0.24	0.74	0.98	3.37	2.35	1.57	8.24	8.82	4.46	1.86	1.33	0.35
	Base	0.28	0.23	0.22	0.30	0.49	0.69	1.04	2.23	2.91	1.76	1.39	0.43
1983	Total	0.24	0.73	2.40	3.50	2.56	2.90	9.70	11.06	8.83	4.24	1.23	0.58
	Surface	0.09	0.51	2.20	3.22	2.16	1.93	7.81	8.26	5.27	1.96	0.38	0.28
	Base	0.15	0.22	0.20	0.29	0.40	0.97	1.89	2.79	3.56	2.29	0.85	0.30
1984	Total	0.13	0.07	0.20	2.46	1.54	5.44	10.77	11.44	9.83	3.13	0.90	0.89
	Surface	0.04	0.03	0.15	2.45	1.51	5.11	9.75	9.51	5.55	0.94	0.28	0.41
	Base	0.09	0.04	0.05	0.01	0.03	0.33	1.02	1.93	4.28	2.19	0.62	0.47
1985	Total	0.13	0.04	0.17	1.06	3.61	1.36	7.43	14.87	8.17	3.46	1.20	0.31
	Surface	0.05	0.01	0.14	1.03	3.46	1.13	6.94	12.35	4.95	1.54	0.38	0.09
	Base	0.09	0.03	0.03	0.03	0.15	0.23	0.50	2.52	3.21	1.92	0.83	0.21
1986	Total	0.10	0.87	2.78	6.14	2.14	4.92	8.43	13.72	9.26	3.88	0.77	0.25
	Surface	0.03	0.79	2.64	5.91	1.86	3.96	6.27	10.80	5.78	1.39	0.23	0.07
	Base	0.07	0.08	0.14	0.23	0.28	0.96	2.17	2.92	3.48	2.50	0.54	0.18
1987	Total	0.11	1.28	3.52	4.86	4.64	2.97	8.41	11.94	7.60	3.09	0.51	0.36
	Surface	0.04	1.19	3.32	4.44	4.26	1.50	6.17	8.96	4.28	1.39	0.15	0.15
	Base	0.07	0.09	0.21	0.43	0.38	1.47	2.23	2.98	3.31	1.70	0.35	0.21
1988	Total	0.09	0.56	0.02	2.23	0.35	1.95	7.28	13.48	11.31	5.12	2.27	0.53
	Surface	0.03	0.49	0.01	2.20	0.27	1.89	6.85	11.46	8.63	2.37	0.69	0.16
	Base	0.05	0.06	0.01	0.04	0.07	0.06	0.43	2.02	2.68	2.75	1.58	0.36

B-4. Validation flow data for the Legedadi reservoir watershed based on the hydrological similarity calculation method from the Sibilu River gauging station.

Year	Flow Type	Monthly averaged discharge (Q, cms)											
		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1988	Total	0.09	0.56	0.02	2.23	0.35	1.95	7.28	13.48	11.31	5.12	2.27	0.53
	Surface	0.03	0.49	0.01	2.20	0.27	1.89	6.85	11.46	8.63	2.37	0.69	0.16
	Base	0.05	0.06	0.01	0.04	0.07	0.06	0.43	2.02	2.68	2.75	1.58	0.36
1989	Total	0.17	2.93	3.26	5.22	0.31	4.98	5.19	7.93	4.75	1.82	0.41	0.95
	Surface	0.05	2.74	3.06	4.99	0.06	4.63	4.55	6.86	3.46	0.58	0.12	0.62
	Base	0.12	0.19	0.20	0.23	0.25	0.35	0.64	1.07	1.30	1.23	0.28	0.33
1990	Total	0.07	3.98	1.62	3.73	0.71	1.88	6.18	15.26	8.35	4.36	1.69	0.40
	Surface	0.02	3.90	1.35	3.39	0.43	1.48	5.48	13.50	5.77	1.95	0.52	0.12
	Base	0.04	0.08	0.28	0.34	0.28	0.40	0.71	1.75	2.58	2.41	1.17	0.28
1991	Total	0.20	1.13	3.55	0.85	0.47	2.99	8.77	13.68	9.37	3.67	1.35	0.32
	Surface	0.07	0.97	3.34	0.57	0.27	2.72	7.88	11.71	6.82	1.17	0.41	0.09
	Base	0.12	0.16	0.21	0.27	0.21	0.27	0.89	1.97	2.55	2.50	0.94	0.22
1992	Total	0.80	0.61	0.89	1.60	1.04	1.77	7.76	12.56	8.47	5.89	2.07	0.37
	Surface	0.54	0.38	0.67	1.38	0.60	1.33	6.68	10.34	5.27	2.71	0.64	0.10
	Base	0.26	0.23	0.22	0.22	0.44	0.44	1.07	2.22	3.20	3.18	1.43	0.27
1993	Total	0.20	1.26	0.14	3.14	1.09	2.66	6.41	12.54	11.25	5.08	2.15	0.50
	Surface	0.08	1.09	0.07	3.03	0.89	2.41	5.85	10.33	8.30	1.93	0.66	0.16
	Base	0.13	0.17	0.07	0.11	0.20	0.25	0.56	2.21	2.96	3.16	1.49	0.35
1994	Total	0.19	0.06	1.28	1.34	0.46	1.90	6.46	8.97	5.61	2.44	1.28	0.22
	Surface	0.06	0.02	1.23	1.29	0.39	1.81	5.71	7.49	3.66	0.73	0.61	0.07
	Base	0.13	0.04	0.05	0.05	0.08	0.09	0.76	1.49	1.94	1.71	0.67	0.15
1995	Total	0.08	1.86	1.78	4.18	1.96	4.97	9.45	11.46	8.77	4.21	1.37	0.57
	Surface	0.03	1.79	1.70	4.04	1.61	3.66	7.67	8.61	5.40	1.39	0.47	0.29
	Base	0.06	0.08	0.08	0.14	0.35	1.31	1.78	2.84	3.37	2.82	0.91	0.29
1996	Total	1.08	0.08	1.26	1.78	1.65	5.99	9.68	13.20	12.78	4.47	1.59	0.51
	Surface	0.71	0.04	1.19	1.67	1.51	5.68	7.56	9.72	8.83	1.38	0.48	0.17
	Base	0.37	0.05	0.07	0.11	0.15	0.31	2.11	3.48	3.96	3.10	1.11	0.34

B-5. Parameters used for the existing condition in the SWAT model.
(Parameters are described following Appendix B-7)

LANDUSE	SOIL	BIOMIX	CN2	USLE_P	SLSUBBSN	GWQMN
PAST	CA1321	0.20	78	1.00	37	0
SWHT	CA1321	0.20	78	1.00	37	0
TEFF	CA1321	0.20	73	1.00	37	0
URHD	CA1321	0.20	81	1.00	91	0
BARL	CA7017	0.20	78	1.00	18	0
PAST	CA7017	0.20	78	1.00	91	0
SWHT	CA7017	0.20	78	1.00	91	0
TEFF	CA7017	0.20	73	1.00	91	0
PAST	CA7045	0.20	73	1.00	122	0
SWHT	CA7045	0.20	75	1.00	122	0
TEFF	CA7045	0.20	66	1.00	122	0
URHD	CA7045	0.20	77	1.00	91	0
WATR	DC0038	0.20	86	1.00	18	0
BARL	ID7029	0.20	78	1.00	15	0
FRST	ID7029	0.20	73	1.00	24	0
PAST	ID7029	0.20	78	1.00	37	0
SWHT	ID7029	0.20	78	1.00	37	0
BARL	ID7091	0.20	67	1.00	24	0
FRST	ID7091	0.20	54	1.00	24	0
PAST	ID7091	0.20	63	1.00	24	0
SWHT	ID7091	0.20	67	1.00	18	0
TEFF	ID7091	0.20	53	1.00	61	0
FRST	ID7093	0.20	73	1.00	91	0
PAST	ID7093	0.20	78	1.00	24	0
SWHT	ID7093	0.20	78	1.00	91	0
TEFF	ID7093	0.20	73	1.00	24	0
URHD	ID7093	0.20	81	1.00	91	0
BARL	OH0065	0.20	75	1.00	24	0
FRST	OH0065	0.20	67	1.00	24	0
PAST	OH0065	0.20	73	1.00	24	0
SWHT	OH0065	0.20	75	1.00	18	0
TEFF	OH0065	0.20	66	1.00	18	0
FRST	SD3006	0.20	73	1.00	61	0
PAST	SD3006	0.20	78	1.00	91	0
SWHT	SD3006	0.20	78	1.00	91	0
TEFF	SD3006	0.20	73	1.00	18	0
URHD	SD3006	0.20	81	1.00	91	0
FRST	TX0249	0.20	73	1.00	61	0
PAST	TX0249	0.20	78	1.00	91	0
SWHT	TX0249	0.20	78	1.00	61	0
TEFF	TX0249	0.20	73	1.00	91	0
FRST	TX1121	0.20	73	1.00	61	0
PAST	TX1121	0.20	78	1.00	24	0
SWHT	TX1121	0.20	78	1.00	24	0
TEFF	TX1121	0.20	73	1.00	18	0
URHD	TX1121	0.20	81	1.00	91	0

B-6. Parameters used for flow calibration and validation of the SWAT model.
(Parameters are described following Appendix B-7)

LANDUSE	SOIL	BIOMIX	CN2	USLE_P	SLSUBBSN	GWQMN
PAST	CA1321	0.20	84	0.90	37	4000
SWHT	CA1321	0.20	84	0.90	37	4000
TEFF	CA1321	0.20	79	0.90	37	4000
URHD	CA1321	0.20	87	0.90	91	4000
BARL	CA7017	0.20	84	0.90	18	4000
PAST	CA7017	0.20	84	0.90	91	4000
SWHT	CA7017	0.20	84	0.90	91	4000
TEFF	CA7017	0.20	79	0.90	91	4000
PAST	CA7045	0.20	79	0.90	122	4000
SWHT	CA7045	0.20	81	0.90	122	4000
TEFF	CA7045	0.20	72	0.90	122	4000
URHD	CA7045	0.20	83	0.90	91	4000
WATR	DC0038	0.20	92	0.90	18	4000
BARL	ID7029	0.20	84	0.90	15	4000
FRST	ID7029	0.20	79	0.90	24	4000
PAST	ID7029	0.20	84	0.90	37	4000
SWHT	ID7029	0.20	84	0.90	37	4000
BARL	ID7091	0.20	84	0.90	24	4000
FRST	ID7091	0.20	79	0.90	24	4000
PAST	ID7091	0.20	84	0.90	24	4000
SWHT	ID7091	0.20	84	0.90	18	4000
TEFF	ID7091	0.20	79	0.90	61	4000
FRST	ID7093	0.20	79	0.90	91	4000
PAST	ID7093	0.20	84	0.90	24	4000
SWHT	ID7093	0.20	84	0.90	91	4000
TEFF	ID7093	0.20	79	0.90	24	4000
URHD	ID7093	0.20	87	0.90	91	4000
BARL	OH0065	0.20	81	0.90	24	4000
FRST	OH0065	0.20	73	0.90	24	4000
PAST	OH0065	0.20	79	0.90	24	4000
SWHT	OH0065	0.20	81	0.90	18	4000
TEFF	OH0065	0.20	72	0.90	18	4000
FRST	SD3006	0.20	79	0.90	61	4000
PAST	SD3006	0.20	84	0.90	91	4000
SWHT	SD3006	0.20	84	0.90	91	4000
TEFF	SD3006	0.20	79	0.90	18	4000
URHD	SD3006	0.20	87	0.90	91	4000
FRST	TX0249	0.20	79	0.90	61	4000
PAST	TX0249	0.20	84	0.90	91	4000
SWHT	TX0249	0.20	84	0.90	61	4000
TEFF	TX0249	0.20	79	0.90	91	4000
FRST	TX1121	0.20	79	0.90	61	4000
PAST	TX1121	0.20	84	0.90	24	4000
SWHT	TX1121	0.20	84	0.90	24	4000
TEFF	TX1121	0.20	79	0.90	18	4000
URHD	TX1121	0.20	87	0.90	91	4000

B-7. Parameters used for sediment calibration of the SWAT model.
(Parameters are described following Appendix B-7)

LANDUSE	SOIL	BIOMIX	CN2	USLE_P	SLSUBBSN	GWQMN
PAST	CA1321	0.45	84	0.70	37	4000
SWHT	CA1321	0.45	84	0.70	37	4000
TEFF	CA1321	0.45	79	0.70	37	4000
URHD	CA1321	0.45	87	0.70	91	4000
BARL	CA7017	0.45	84	0.70	18	4000
PAST	CA7017	0.45	84	0.70	91	4000
SWHT	CA7017	0.45	84	0.70	91	4000
TEFF	CA7017	0.45	79	0.70	91	4000
PAST	CA7045	0.45	79	0.70	122	4000
SWHT	CA7045	0.45	81	0.70	122	4000
TEFF	CA7045	0.45	72	0.70	122	4000
URHD	CA7045	0.45	83	0.70	91	4000
WATR	DC0038	0.45	92	0.70	18	4000
BARL	ID7029	0.45	84	0.70	15	4000
FRST	ID7029	0.45	79	0.70	24	4000
PAST	ID7029	0.45	84	0.70	37	4000
SWHT	ID7029	0.45	84	0.70	37	4000
BARL	ID7091	0.45	84	0.70	24	4000
FRST	ID7091	0.45	79	0.70	24	4000
PAST	ID7091	0.45	84	0.70	24	4000
SWHT	ID7091	0.45	84	0.70	18	4000
TEFF	ID7091	0.45	79	0.70	61	4000
FRST	ID7093	0.45	79	0.70	91	4000
PAST	ID7093	0.45	84	0.70	24	4000
SWHT	ID7093	0.45	84	0.70	91	4000
TEFF	ID7093	0.45	79	0.70	24	4000
URHD	ID7093	0.45	87	0.70	91	4000
BARL	OH0065	0.45	81	0.70	24	4000
FRST	OH0065	0.45	73	0.70	24	4000
PAST	OH0065	0.45	79	0.70	24	4000
SWHT	OH0065	0.45	81	0.70	18	4000
TEFF	OH0065	0.45	72	0.70	18	4000
FRST	SD3006	0.45	79	0.70	61	4000
PAST	SD3006	0.45	84	0.70	91	4000
SWHT	SD3006	0.45	84	0.70	91	4000
TEFF	SD3006	0.45	79	0.70	18	4000
URHD	SD3006	0.45	87	0.70	91	4000
FRST	TX0249	0.45	79	0.70	61	4000
PAST	TX0249	0.45	84	0.70	91	4000
SWHT	TX0249	0.45	84	0.70	61	4000
TEFF	TX0249	0.45	79	0.70	91	4000
FRST	TX1121	0.45	79	0.70	61	4000
PAST	TX1121	0.45	84	0.70	24	4000
SWHT	TX1121	0.45	84	0.70	91	4000
TEFF	TX1121	0.45	79	0.70	18	4000
URHD	TX1121	0.45	87	0.70	91	4000

Descriptions of the parameters given in Appendices B-5 to B-7

LANDUSE	Dominant land use or cover type (SWHT = wheat, TEFF = teff, URHD = Urban or Sendafa town, PAST = pasture, BARL = Barley, and FRST = Forest; Figure 5-11)
SOIL	Dominant soil types in the watershed by S5id (Figure 5-12)
BIOMIX	Biological mixing efficiency.
CN2	Initial SCS runoff curve number for moisture condition II.
USLE_P	USLE equation support practice factor.
SLSUBBSN	Average slope length (m). This is the distance to the point that flow begins to concentrate (i.e. the distance that sheet flow is the dominant surface runoff flow).
GWQMN	Threshold depth of water in the shallow aquifer required for return flow to occur (mm). Groundwater flow to the reach is allowed only if the depth of water in the shallow aquifer is equal to or greater than GWQMN.

B-8. Summary of the 1979 and 1998 bathymetric surveys of the Legedadi reservoir. (AAWSA, 1999)

Bathymetric survey year	Surface area (km^2)	Reservoir volume (10^6 m^3)	Deposited sediment volume (10^6 m^3)	Dry bulk density of soil (kg/m^3)	Trap efficiency (%)	Area (km^2)	Survey interval (years)	Sediment yield (t/ha/yr)
1979	4.98	45.9	-	-	65	205	-	-
1998	4.98	43.8	2.1	1300	65	205	19	12

B-9. Estimated rates of soil loss on slopes in Ethiopia based on land use. Source: Hurni (1993)

Land use type	Estimated soil loss (t/ha/year)
Cropland	42
Perennial crops	8
Pasture	5
Forest	1
Bush land	5
Degraded	70

VITA

Tesfaye Demissie Gebirrye

Candidate for the Degree of

Doctor of Philosophy

Thesis: INVESTIGATING SCALE, RAINFALL-RUNOFF SEQUENCES AND BMP EFFECTS ON PHOSPHORUS, RUNOFF AND SEDIMENT YIELD

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Biographical:

Education: Graduated from Chercher Comprehensive Secondary School, Assebe Teferi, Ethiopia in July 1986; received Bachelor of Science in Agricultural Engineering from Alemaya University of Agriculture, Dire Dawa, Ethiopia in July 1990; received *Diplom* (M. Eng.) in Technology in the Tropics from the University of Applied Sciences Cologne, Cologne, Germany in January 1998; received Master of Science in Agriculture with major in Water Resources and Irrigation Management from the University of Bonn, Bonn, Germany in September 2000; completed the requirements for the Doctor of Philosophy with a major in Biosystems Engineering at Oklahoma State University in December 2004.

Experience: Employed by the Ethiopian Agricultural Research Organization as Junior and Assistant Researcher, Nazareth Research Center, 1990-1995; employed by the Institute for Water Resources and Land Improvement as Graduate Assistant, University of Bonn, 2000; employed by the Department of Biosystems and Agricultural Engineering as a Graduate Research Assistant, Oklahoma State University, 2001 to present.

Professional Memberships: The Society for Engineering in Agriculture, Food and Biological Systems (ASAE); International Association of Hydrological Sciences (IAHS); American Society of Civil Engineers (ASCE); the Honor Society of Phi Kappa Phi.

Name: Tesfaye Demissie Gebirrye Date of Degree: December, 2004

Institution: Oklahoma State University Location: Stillwater, Oklahoma

Title of Study: INVESTIGATING SCALE, RAINFALL-RUNOFF SEQUENCES AND BMP EFFECTS ON PHOSPHORUS, RUNOFF AND SEDIMENT YIELD

Pages in Study: 143 Candidate for the Degree of Doctor of Philosophy

Major Field: Biosystems Engineering

Scope and Methods of Study: 1) Scale effects on phosphorus (P) loss and runoff depth from pastures were investigated by summarizing water quality data from 19 research projects. Spatial (area) and temporal (days after litter application) scales ranged from 0.5 to 80000 m^2 and 1 to 355 days, respectively. 2) Rainfall-runoff sequence (RRS) effects on dissolved reactive P (DRP) in runoff from pastures were studied in a greenhouse experiment using a 2X2X3 factorial arrangement of soil test P (STP), surface application of poultry litter, and RRS. 3) Impacts of two best management practice (BMP) and land use change scenarios (strip-cropping, terrace, forestation) on runoff and sediment yield from the Legedadi Reservoir watershed in central Ethiopia were assessed using the Soil and Water Assessment Tool model.

Findings and Conclusions: 1) Spatial scale had significant effects on runoff depth, DRP and total P (TP) concentration, DRP and TP load from pastures. Exceptions were DRP and TP concentration from control pastures. DRP and TP load increased with area due to an increase in runoff volume. DRP and TP concentrations decreased with area probably due to dilution associated with the increased runoff volume. Temporal scale effect with an exponential decrease existed for DRP and TP concentration from both poultry litter treated and control pastures. The existence of spatial and temporal scale effects suggested that a simple averaging procedure based on homogeneous assumption may not be a suitable method for transferring data from plot- or field-scale study to larger scale. 2) Poultry litter, which masked the significant STP effect on DRP prior to litter application, is the primary source of DRP in runoff immediately following litter application. For consecutive RRS, a rainfall event without runoff reduced litter DRP loss in the first runoff event by more than 50%. Effect of poultry litter application on DRP decreased exponentially with time. 3) Forestation had the greatest impact in reducing sediment yield, and surface runoff, and increasing base flow compared with existing conditions. Although terracing and strip-cropping reduced sediment yield, they had little impact on watershed hydrology. This study showed that a watershed modeling approach, in the absence of plot- and field-data, is a useful tool that can be used in the planning and selection of BMP or land use change to reduce surface runoff and sediment yield.

ADVISOR'S APPROVAL: Dr. Daniel Storm