Simulation of Phosphorus Transport in Vegetative Filter Strips

by

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(ABSTRACT)

This study investigated the effectiveness of vegetative filter strips (VFS) in removing phosphorus from surface runoff. Dissolved and particulate nutrients were treated separately due to differing transport and removal mechanisms. Nutrient transport in VFS appeared to be a function of runoff rate, concentration and size distribution of suspended solids, and biological factors that influence hydrologic and chemical processes in filter strips.

Three sets of experimental field plots were constructed to simulate VFS. Each set consisted of three plots containing sediment and nutrient source areas and 0.0, 4.6, or 9.1 m grass filter strips. Artificial rainfall was applied to the plots, and surface runoff, soil, and plant material samples were collected and physically and chemically analyzed. The VFS reduced surface runoff, suspended solids, and phosphorus losses. Most removal of sediment and phosphorus was accomplished in the first few meters of the VFS. The filter strips did not remove phosphorus as effectively as sediment, due to their ineffectiveness for filtering dissolved phosphorus and sediment-bound phosphorus associated with fine particles. The VFS often increased orthophosphorus losses in surface runoff. Laboratory batch experiments of phosphorus desorption reaction suggested that plant residues, living plant canopy, and soil components of the strips could release dissolved phosphorus to surface runoff. A modified Elovich equation and a diffusion-control model were used to describe the phosphorus release from the plant and soil materials.

A computer model, GRAPH, was developed to simulate phosphorus transport in VFS by incorporating phosphorus transport submodels into the VFS model in SEDIMOT II, a stormwater and sediment transport model. The model considers the effects of advection

processes, infiltration, biological uptake, phosphorus desorption from the soil surface to run-off, the adsorption of dissolved phosphorus to suspended solids in runoff, and the effects of dynamic changes in the sediment size distribution on chemical transport.

GRAPH was verified using the results of the physical plot simulations. The model's predictions and observed phosphorus transport compared favorably. Sensitivity analysis suggested that sediment and phosphorus removal was sensitive to the input parameters in the order: filter length and width, grass spacing, and filter slope and surface roughness. Increased filter width and length and aboveground biomass increased orthophosphorus loss from VFS.

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Chapter 1

Introduction

Soil erosion is a significant factor limiting soil productivity and can also deteriorate water quality if the assimilative capacity of aquatic systems is exceeded. The selective transport of plant available nutrients with surface runoff and sediment has been studied extensively due to its importance to both fertility and water quality. Excessive sediment inflow to aquatic systems can damage spawning sites and the habitats of aquatic organisms, induce turbidity, and thus limit aquatic life and diminish the storage capacity of streams and reservoirs. An increased input of nutrients leads to eutrophic algal blooms in many aquatic systems. Nutrient contributions to water bodies from land runoff have increased relative to municipal and industrial sewage effluents as treatment of the latter has improved. Hence, pollution from land runoff, referred to as nonpoint source pollution, is now receiving considerable attention.

In may cases, agriculture is the principal cause of nonpoint source pollution. Intense agricultural land use increases erodibility by disturbing surface soils. In addition, agricultural application of fertilizers and biocides increases every year as more land is brought into production and existing agricultural land is farmed more intensively. This has resulted in increased transport of these pollutants in stormwater runoff. Urban development also affects

the quality of storm runoff and the concentration of suspended solids and chemicals in the runoff. Several studies have indicated that pollutant contributions from urban stormwater runoff may be more significant than agricultural sources in many areas. Phosphorus and nitrogen in stormwater runoff from thirteen urban catchments representing six homogeneous land uses in the Virginia suburbs of Washington, D.C., were found to be present in sufficient quantity to cause algal blooms (Grizzard *et al.* 1980). Mining and construction activities also have received attention due to their pollution potential. These activities disturb the surface soil and cause concentrated sediment and chemical transport to local aquatic systems, but they are frequently treated as point sources.

Surface runoff and the dislodgement and transport of soil particles are the major processes affecting chemical movement. Since soil particles and organic matter are major transport vectors for many chemical species, erosion must be controlled to reduce the transport of these pollutants, nutrients, pesticides, toxics, pathogens, and other harmful materials to water bodies. Organic matter is preferentially transported by erosion due to its low density, and the organic matter content of eroded material is therefore higher than that of the parent soil (Voroney *et al.* 1981).

Phosphorus is one of the most important and essential nutrients in freshwater bodies. It can cause significant water quality degradation if present in excessive amounts. Phosphorus availability usually limits plant growth in unpolluted natural freshwater bodies, and excessive phosphorus has been found to stimulate eutrophication (Taylor 1967). Dissolved phosphorus is particularly of importance because it is more readily available to aquatic organisms than particulate phosphorus. Eroded soil is usually richer in phosphorus than the A1 horizon because of the element's strong adsorption to fine mineral soil particles (Taylor and Kunishi 1971, Taylor *et al.* 1971) and the nature of the erosion process which selectively transport organics, high cation exchange capacity (CEC) clays, and silt size particles (Singer and Rust 1975).

Best management practices for the control of runoff and sediment are often used to reduce phosphorus inflows into water bodies. Mass movement is controlled by a variety of

physical and/or biochemical factors, such as soil type, topography, vegetation cover, season of the year, climate (especially rainfall), and nutrient availability (Bormann and Likens 1967, Ryden *et al.* 1973, Gorham *et al.* 1979). Identification of these controlling factors is necessary for the successful implementation of management practices designed to prevent or reverse the detrimental impacts of the nonpoint source pollution. Of the several factors involved, vegetation, by modifying the hydrologic response of source areas, is the most significant factor affecting the movement of water, sediment, nutrients and other materials (Sopper 1971). Permanently vegetated areas are particularly effective in nutrient uptake compared to cropland (Peterjohn and Correl 1984, Nikitin and Spirina 1985). Therefore, vegetative areas, referred to as vegetative filter or buffer strips (VFS or VBS), have been promoted in many areas as a means of removing nonpoint source pollutants from surface runoff before runoff reaches water bodies (Sullivan 1986). Vegetative filter strips are planted or indigenous vegetation zones that are located between pollutant source areas and water bodies. They are used to filter runoff, trap soil particles, and protect the soil surface against local scour and erosion. Vegetative filters are also beneficial because they remove fertilizers, pesticides, and microorganisms from upland runoff that otherwise might reach waterways. In addition, the strips often serve as environmental corridors. They provide valuable food, habitat, and travelways for wildlife. As a result, they permit a greater diversity of wildlife, which in turn contributes to a more stable environment, protecting stream water quality and conserving plant and wildlife habitat. These areas also should be considered as a landscape component since they are aesthetically pleasing.

Vegetative filters, however, may conflict with other land uses since they can occupy large land surface areas. Therefore, an appropriate means of determining optimal placement, dimensions, and arrangement of VFS must be developed if they are to be used effectively and economically (Swift 1986). In evaluating the effectiveness of VFS, it is desirable to identify those characteristics which affect the efficiency of nutrient and sediment reduction. One means is to physically or mathematically simulate VFS under a variety of biogeochemical conditions and to evaluate their effectiveness. Unfortunately, current nutrient transport mod-

els are not appropriate for quantitatively evaluating the effectiveness of existing or planned VFS. SEDIMOT II is presently the only physically based design model available for simulating the response of VFS to sediment transport during storm runoff. The model was developed to simulate surface runoff and sediment transport from areas disturbed by surface mining activities and can describe deposition and the particle size distribution of eroded sediment as it travels through VFS. SEDIMOT II may be useful in modeling nutrient transport in surface runoff, for its ability to predict the particle size distribution of transported sediment is essential for modeling nutrient transport. Another useful model is currently under development at the Water Quality and Watershed Research Laboratory, Oklahoma. This empirically data-based model describes dissolved phosphorus transport in surface runoff, but it does not consider VFS.

The primary goal of the research presented here is to assess the effectiveness of VFS in removing phosphorus from surface runoff. The specific objectives of this research are:

1. To develop a computer model for simulating phosphorus trapping in VFS during single storm event by combining SEDIMOT II and the Oklahoma model.

2. To investigate the nutrient trapping mechanisms of VFS.

3. To investigate the response of VFS to runoff, sediment, and phosphorus inputs using experimental field plot studies. The field tests are required for model verification and the development of mathematical phosphorus transport subprocess models.

4. To examine existing phosphorus desorption and adsorption models through laboratory studies for use in parameter selection and model verification.

5. To evaluate the sensitivity of the model to input parameters.

Chapter 2

Literature Review

The design of VFS should be based upon the ability of VFS to remove nonpoint source pollutants such as sediment, nutrients, and other chemically and biologically detrimental agents from surface runoff. Removal mechanisms are, however, not well understood. In this chapter, the potential mechanisms by which the filters remove sediment and nutrients are reviewed. The review is focused on phosphorus but general nutrient removal mechanisms are discussed. In addition, previous VFS research and current sediment and phosphorus transport models are briefly reviewed.

Nutrient Filtering Mechanisms

Nutrient budgets in vegetative areas may be determined by mass balance equations that take into account elemental inputs and outputs and hydrologic, chemical and biological processes (Gorham *et al.* 1979). Because water is a major transport vehicle for nutrients,

hydrologic processes govern the spatial distribution of nutrients. Chemical and biological processes determine the fraction of water-soluble and insoluble chemical forms. Jordan and Kline (1972), therefore, suggest that increased runoff does not necessarily induce correspondingly high losses of nutrients from nutrient-unsaturated soils. Hydrologic, chemical and biochemical phenomena are important for nutrient conservation on land and the water quality of the corresponding aquatic systems (Bormann and Likens 1967, Dillon and Kirchner 1975, Karr and Schlosser 1978, Miller *et al.* 1979, Schlosser and Karr 1981a, b).

Hydrologic Aspects

Considerable losses of soil constituents from land can be attributed to the energy of raindrop splash and overland flow. These two factors are major considerations in the downslope movement of water, sediment, and nutrients (Singer and Rust 1975). Thus, any mechanism decreasing the energy of rainfall and surface runoff contributes to nutrient conservation in terrestrial ecosystems. In general, interception, infiltration, surface retention and detention, and evapotranspiration attenuate runoff discharge and thus its kinetic energy (Huggins and Burney 1982). Runoff discharge from a landscape is highly variable depending on the amount of leaf area and soil water storage capacity (Fahey and Knight 1986). Waring and Schlesinger (1985) classified water storages in vegetative systems into the areas of : (1) foliage, branches, and stems; (2) snowpack; (3) litter layer; (4) soil surface; (5) vegetation; (6) soil root zone; and (7) subsoil. These storages decrease raindrop energy and/or runoff kinetic energy through their effects on hydrologic components.

To begin with, raindrop energy is dissipated when rain is intercepted by plant foliage. The total interception of rainfall consists of water stored on vegetation and that which is directly evaporated from the plant surface into the air (Leonard 1967). The amount of storage and evaporation during precipitation increases with an increased leaf-area index (LAI), de-

fined as the ratio of leaf-area to the soil area it occupies (Marks and Bormann 1972, Wright 1973), when the same geometry and spacing of leaves are assumed. The surface litter layer also is significant because acts as a sponge retaining and re-evaporating incident water, and thus restricting water movement to the soil surface where excess water may generate surface runoff (Moore 1985). The amount and chemical composition of rainwater is modified when it contacts living and/or dead foliage (Fahey and Knight 1986, Knapp and Seastedt 1986). Living foliage and plant detritus were found to intercept approximately 40 percent of rainfall in undisturbed prairie on an annual basis (cited by Knapp and Seastedt 1986). Infiltration and field capacity are directly proportional to the organic matter content of soil, most of which originates from plant materials. Tiessen *et al.* (1984) identified relatively coarse plant debris and colloidal and soluble organic compounds from root exudates, microbial products and litter leachates as major sources of soil organic matter. Wischmeier and Mannering (1965) showed that infiltration increases proportionally to the organic matter content of soil. Robertson and Vitousek (1981) presented data showing that the water-holding capacity of soil increases with the ecosystem succession, which is likely explained by an increase in soil organic matter content (Lola *et al.* 1984). Such hydrologic phenomena may be related to the improvement of soil structural properties. It has been known that organo-mineral associates promote soil structure by functioning as binding agents in soil aggregates (Tisdal and Oades, 1982).

Evapotranspiration occurs at the earth's surface in proportion to the air-exposed area which may be a function of LAI in vegetative areas (Waring and Schlesinger 1985, Fahey and Knight 1986). Greenwood *et al.* (1985) reported that annual evapotranspiration was correlated with leaf area in Australian Eucalyptus forests. Vegetation also tends to roughen the surface of waterways and thus retard surface flow, allowing it to move into the soil (Smith 1974). Plant litter also contributes to surface roughness and thus reduces the transport capacity of surface runoff (Swift 1986). The roughness may be proportional to LAI or the above-ground biomass, and has been expressed as the Manning roughness coefficient by engineers (Kouwen *et al.*, 1969).

In summary, vegetation reduces surface runoff by decreasing the amount of precipitation reaching the soil surface, by increasing infiltration, by roughening the soil surface, and by contributing to rainwater interception and transpiration. Both retardation of flow and decrease in runoff discharge reduce the kinetic energy of runoff, and thus lower its sediment transport capacity. Sediment-bound nutrients can then be removed from runoff in vegetative zones as sediment is deposited due to transport capacity deficits. If nutrients are predominantly sediment-bound, then the deposition process will largely control the effectiveness of the vegetative area for the removal of nutrients from the runoff. The movement of phosphorus from land to water bodies has been found to be strongly dependent on sediment transport processes since it is predominantly sediment-bound (Burwell *et al.*, 1975, Singer and Rust 1975, Mitsch *et al.* 1979, Sharpley and Syers 1979). Burwell *et al.* (1975) reported that at least 95% of annual phosphorus losses were accounted for by sediment transport in most soil cover treatments. With respect to the annual loss of total phosphorus, 76% was in a particulate form for a small agricultural catchment in New Zealand (Bargh 1978). Rigler (1979) and Johnson *et al.* (1976) observed that approximately 75% and 78%, respectively, of phosphorus in streams during storm runoff was particulate. The phosphorus content of suspended solids was found to be 0.12% in a forested and agricultural watershed in New York State (Johnson *et al.* 1976) and 0.2-0.25% in Dartmoor stream (Rigler 1979). In general, clay-sized particles have higher phosphorus concentrations than bulk soil because organic phosphorus and inorganic phosphates are adsorbed by clays (Sharpley 1980). Coarse particulate organic matter (CPOM), however, may also be a significant source of phosphorus. In a woodland stream, CPOM accounted for 60% of the total uptake of phosphorus, FPOM (fine particulate organic matter) for 35%, and aufwuchs for 5% (Newbold *et al.* 1983).

In describing the nutrient retentiveness of forests, Knight *et al.* (1985) have emphasized the hydrologic processes of rainfall interception, evapotranspiration, and hydrograph shape. Ryan and Bormann (1982) claim that the size of the nutrient resorption pool is a function of forest leaf biomass. Their claim has been supported by Hewlett *et al.* (1984) who suggests that the mobility of nutrients appears to be restricted by the ability of ecosystems to evaporate

water on site, which is, in turn, associated with vegetative cover. Soil water storage capacity is associated with LAI due probably to the correlation of LAI and soil organic matter content according to Fahey and Knight (1986). Vegetation decreases runoff, and, in turn erosion and nutrient losses, by enhancing evapotranspiration and infiltration or water storage capacity of a landscape. Finally, Knight et al. (1985) conclude that the leaf area of vegetation, duration of the vernal transpiration, and high carbon/nutrient ratios in the terrestrial forest floor have substantial impacts on nutrient conservation in terrestrial ecosystems.

Chemical and Biochemical Aspects

Biochemical aspects are significant, especially when the long-term effectiveness of buffer areas is considered. Vegetative systems have several biochemical mechanisms to trap and retain nutrients from surface and subsurface flows (Marks and Boramnn 1972, Vitousek and Reiners 1976, Lowrance et al. 1984a, b). Jordan and Herrera (1981) and Herrera et al. (1984) attribute these mechanisms to the structural and functional characteristics of the foliage and root system of plants, and the soil or stand in tropical forests. Vitousek and Melillo (1979) list nine physical or chemical mechanisms by which disturbed forests prevent nitrogen flow into streams: immobilization, prevention of nitrification, nitrate reduction to ammonium, clay fixation, anion adsorption, plant uptake, insufficient precipitation, ammonia volatilization, and nitrate reduction to dinitrogen or nitrogen oxides. Nutrient conservation can also be attributed to the dynamic distribution of diverse biotic and abiotic holders (Odum 1969). This attribution is based upon the nutrient-retentive capacity of plants (Muller and Bormann 1976, Feller 1977, Sollins et al. 1980, Cronan 1980), microbes (Vitousek and Matson 1984, 1985, Yavitt and Fahey 1984) including mycorrhiza (Went and Stark 1968a,b), soil fauna, combined surface root mats (Stark and Jordan 1978) including decaying litter (Fahey 1983, Seastedt 1985), soil organic matter and minerals, and the interactions of these components.

In soil-plant systems, plants apparently affect the spatial pattern of organic matter, nutrients, and other physical and chemical properties of an ecosystem through the cycling of nutrients (Barth and Klemmedson 1978). The incorporation of nutrients into growing biomass consumes water-transportable nutrients in the terrestrial system and thus reduces the transport of nutrients into aquatic systems (Vitousek and Reiners 1975, Lowrance 1981). Golkin and Ewel (1984) report that phosphorus uptake by herbs on the forest floor is proportional to gross productivity. Cole and Rapp (1981) attest that nitrogen uptake and requirement of plants are strongly correlated with biomass production, especially in coniferous species. The uptake by plant roots is one potential sink of nitrate during its downward movement in the soil (Khanna 1981). Thus spring ephemeral plant production has been considered as an important nutrient sink (Muller and Bormann 1976, Blank *et al.* 1980). In addition, vegetation leads to lower concentrations of soluble ions available for losses in drainage water by moderating the soil temperature during the growing season, which reduces the decay rates of plant litters (Mark and Bormann 1972).

Several studies have shown that plant uptake might not be a direct mechanism for nutrient conservation (Likens *et al.* 1978, Gholz *et al.* 1985). More inorganic nitrogen in rainwater is taken up by micorbes on detritus than by living foliage (Seastedt 1985). A simulation model demonstrated that the phosphorus uptake rate is 4 to 5 times higher by microorganisms than by plants in semiarid grasslands (Cole *et al.*, 1977). Microbial immobilization initially accounted for removal of phosphorus added in organic wetlands (Richardson and Marshall 1986). Vitousek and Matson (1984, 1985) report that microbial immobilization is the predominant factor accounting for lower nitrogen losses from a clear-cut Piedmont site in North Carolina. Yavitt and Fahey (1984) also emphasize that microorganisms store nutrients, with an estimated 13% and 7.5% of the total nitrogen in the 01 and 02 layers. Trudinger *et al.* (1979) claim that the microbial role in the nutrient cycle is important because : (i) microorganisms make up the bulk of the mass of the biosphere and their rates of growth are generally several orders of magnitude greater than those of the higher organisms; (ii) microbes carry out many unique reactions of geochemical significance; (iii) the time period

over which microorganisms have colonized earthly environments is four to five times greater than that occupied by higher organisms, and (iv) the microbial world embraces a wider range of environments than that for plant and animals.

Recently the effect of soil microfauna on nutrient cycling processes has been studied. It has been suggested that soil fauna, such as microarthropods, macroarthropods, snails, nematodes, and coligochaets retard the rates of nutrient loss from plant litter by stimulating microfloral growth, which, in turn, leads to nutrient tie-up (Douce and Crossley 1982). Elliott *et al.* (1984) observed that high soil protozoan activity was correlated with large declines in microbial carbon and phosphorus and with increases in mineral nitrogen and extractable inorganic and organic phosphorus. They further noted that protozoan grazing resulted in a high biomass C:N ratio due probably to a shift from a fungal to a bacterial dominated microflora. Mass and nutrient losses from forest litter are enhanced by the comminution of microarthropods, and their feeding activities may stimulate microbes to increase the nutrient retention capacities of forest litter (Seastedt and Crossley 1980, Parker *et al.* 1984). Microbial feeding by soil fauna has been reported to result in increased microbial activities (Baath *et al.* 1981, Woods *et al.* 1982, Parker *et al.* 1984). In these studies, microbial feeding nematodes reduced nitrogen loss through leaching (Baath *et al.* 1981) and caused increased uptake of nitrogen by plants, whose growth was accelerated by the increased mineralization due to bacteria and by NH_4^+-N excretion by nematodes (Ingham *et al.* 1985). According to these studies, soil microfauna function as nutrient-holders and also promote the activities of other holders.

Decomposing leaf litter may also play a significant role in nutrient trapping in vegetative areas. Approximately 60% of the total phosphorus uptake in Walker Branch, a small,first-order woodland stream in east Tennessee, was associated with leaf detritus (Newbold *et al.* 1983). Sorption onto substrates in streams is predominantly a biological process regulated by the quantity of microbes present, whereas physical sorption is generally less than 20% of the phosphorus translocation onto benthic substrates in streams (Gregory 1978). Decaying leaf litter supplies energy or acts as a carbon source to algae, bacteria, and fungi, and these

microorganisms assimilate phosphorus from the water (Gregory 1978, Meyer 1980). In a research of radioactive trace, inorganic phosphate in water was taken up by microbes associated with decomposing leaves rapidly, often in as short a time as 5 minutes. As much as 95% of the radioactive phosphate was removed within 100 m of stream length (Ball and Hooper 1963, cited by Smith 1974 and Gregory 1978). Even though hydrological and biological situations on land are not identical with those within streams, the phosphorus content of dead leaves has been found to increase while leaves are decaying in the terrestrial environment (Gosz et al. 1973, Williams and Gray 1974, Fahey and Knight 1986). The phosphorus source may contain precipitation, upland inflow, and fungal translocation from the humus and upper mineral soil layers (Fahey and Knight 1986). This may be explained by the findings that the addition of organic carbon sources, such as sucrose, dried grass, or cellulose to surface soil, accelerated microbial activity and subsequently increased microbial and organic phosphorus (Hannapel et al., 1964, Chauhan et al. 1979, 1981). Similarly, decaying leaf litter in vegetative filters may act as a good carbon source, attracting organisms and contributing to the formation of a biosurface on the filters, which can remove phosphorus from runoff and upper mineral soil. The biosurface is defined as the biological surface which is exposed to runoff water. If dead litter promotes phosphorus translocation from upper mineral soil to microbes, phosphorus content in mineral soil is relatively low and thus it would indirectly enhance the adsorption of phosphorus onto the mineral from storm runoff. Consequently, it is promising to note that the potential of microbial uptake of phosphorus can be estimated by the quantity and quality of dead litter.

On the other hand, it has been suggested that leaf litter may also contribute to soluble phosphorus in runoff from woodland and farmland (Taylor et al. 1971, Singler and Rust 1975). Under certain conditions, surface runoff can exude a substantial amount of nutrients from vegetative cover and litters (Timmons et al. 1970, Burwell et al. 1975). Covington (1981) suggested that plant debris might behave as a sink for nutrients after a forest was disturbed, whereas it functioned as a source during the rapidly aggrading phase. This phenomena was explained by noting that leaf litters with a high carbon/phosphorus ratio act as phosphorus

sinks, while those with low ratios may release phosphorus. Fuller *et al.* (1956) reported that carbon/phosphorus ratios above 200 initiated the immobilization or biological fixation of phosphorus. This conclusion was supported by data showing that decomposing plant litters of high carbon/phosphorus ratios reduced available phosphorus by immobilizing soluble phosphorus (Gosz *et al.* 1973; Melillo and Aber 1984). This finding was generalized by Staaf and Berg (1982), who suggested that elements limiting microbial growth were trapped in decaying plant litter, while unlimited nutrients were released during the whole decomposition period (Staaf and Berg 1982). Phosphorus is the most limiting element for microbial activity during the decay phase. However, there still is a controversy regarding the major sink of the limiting element. While many studies have considered the increase of microbial biomass as the major phosphorus sink, others have suggested that a large fraction of phosphorus may be immobilized by extracellular reactive compounds, which are produced as microbial enzymes depolymerize the detritus substrates (Melillo and Aber 1984).

The conversion of surface runoff into subsurface flow generally leads to water purification (Nikitin and Spirina 1985). When dissolved nutrients are carried into the soil along with infiltrated water, the filtering capacity of subsurface soil is maximized. Thus soil organic matter may contribute to nutrient retention by increasing infiltration rates and water-holding capacities of soils (Wischmeier and Mannering 1965, Allison 1973, Hollis *et al.* 1977, Robertson and Vitousek 1981). This may be explained by the function of organic materials as binding agents. Organic matter tends to promote water-stable aggregates in soils (Tisdall and Oades 1982). The nutrients in percolated water are more likely to be adsorbed onto soil particles than those nutrients in surface runoff, especially organic matter and clay fraction (Ryden *et al.* 1973). Furthermore, most water retained by organic matter is readily available to plants (Hollis 1977). Therefore, organic matter provides favorable conditions under which plants and microbes can deplete water and nutrients effectively, and then the water- and nutrient-holding capacity is readily recovered. Barbour *et al.* (1980) summarized the role of organic matter in nutrient retention. "Humic substances and other organics play a vital role in nutrient storage, forming complexes with minerals that enhance uptake by plants. Immobilization through decompos-

ition serves to retain nutrients beyond the period of dormancy to the time of growth." In general, phosphorus retention is higher in vegetated than in mineral soils (Radwan *et al.* 1985).

Some phosphorus will be adsorbed to the surface soil of vegetative filter strips while water is running off (Sharpley *et al.* 1981c). It is accepted that soil adsorption accounts for phosphorus retention when biological retention capacity is saturated or disturbed (Wood *et al.* 1984, Richardson 1985, Richardson and Marshall 1986). The adsorption amount will be controlled by soil texture, pH, organic matter, the 'free iron oxides' and 'extractable aluminum' contents of soil (McLean *et al.* 1958), the soil solution temperature, and the runoff rate. Particle size distribution has been reported to account for up to 90% of the distribution of soil phosphorus (Campbell *et al.* 1984, O'Halloran 1985). Clay-sized particles are, in general, responsible for most of the phosphorus content of bulk soils. Phosphorus retention in soils has been known to be closely related to the content of acid-extractable ferric and aluminum ions in soil (Bohn *et al.* 1985). Increasing soil pH decreases exchangeable Al and acetate-extractable Al, and thus to some extent, decreases phosphate retention (Lopez-Hernandez and Burnham 1974b). High soil pH is also related to low soluble phosphorus due to increased reactions between phosphorus and Ca (Adams and Odom 1985). The effects of pH on phosphorus solubility are dependent upon phosphorus compounds (Lindsay and Moreno 1960). Aluminum and iron phosphates become soluble with an increased pH, while calcium phosphates follow an inverse direction. Organic matter can sorb phosphate or else block potential phosphate sorbing sites on inorganic particles, depending upon certain conditions (Lopez-Hernandez and Burnham 1974a). Hence, soil organic matter can show either a positive or a negative relationship with phosphate adsorption. Lopez-Hernandez and Burnham (1974a) reported that about 85% of the variation in phosphate sorptivity could be explained by a multiple regression equation involving free iron oxides, extractable aluminum, organic matter, clay content and pH. However, clay content and pH made a comparatively small contribution in some British and tropical soils. Usually, organic matter, clay content, and soil aggregates are outstandingly important in the transport of adsorbed chemicals.

Summary

The processes affecting nutrient inflows into vegetated soil may include inflows from up-land areas through surface and subsurface waters, soil weathering, nitrogen fixation, particle impaction, and gas adsorption (Gorham *et al*. 1979). Nutrient output processes consist of the removal of dissolved nutrients by surface runoff, erosion, subsurface drainage, and gaseous losses including volatilization and denitrification (Burwell *et al*. 1977). Thus, the fate of nutrients in vegetative areas can be conceptualized as shown in Figure 1. It is believed that each component of an ecosystem plays a role as a nutrient holder, and the nutrient-retentive capacities of whole systems are synergistically promoted by the the interplays of the components. However, if gaseous outputs do not exceed their inputs, the excess of nutrients over the retention capacity of terrestrial systems are destined to eventually flow into aquatic systems via surface and/or subsurface waterways. It is important to note that when forest ecosystems reach steady state production, their ability to trap and retain nutrients from runoff and subsurface water may be negligible (Vitousek and Reiners 1975, Omernik *et al*. 1981, Lewis 1986). There are no permanent nutrient sinks in nature. Existing nutrient sinks are transformed into nutrient sources as circumstances change. In this context, so-called best management practices (BMP's) could be defined as means of promoting the capacity of nutrient sinks in terrestrial systems and of reducing the transformations of sinks to sources. Thus there is a suggestion that appropriate harvest of plants prevents the transformation of vegetal components into inorganic nutrients, which are vulnerable to leaching. Lowrance (1981) claimed that nutrient retentiveness by riparian ecosystems could be continued if biomass accumulation and harvest were maintained with a minimum of soil disturbance during the driest months.

INPUTS   INTERNAL CYCLE   OUTPUTS

```
                    ┌─────────────────────────────────┐
                    │   ┌───────┐         ┌────────┐   │
                    │   │ Plant │────────→│ Animal │   │
upland inflow ──────┼──→│       │         │        │   │ erosion      ──→
                    │   └───────┘         └────────┘   │
                    │                                  │
                    │        ┌─────────┐               │
weathering ─────────┼──→     │ Microbe │               │ leaching     ──→
                    │        └─────────┘               │
  bulk              │                                  │
precipitation ──────┼──→                               │ gaseous output ──→
                    │                                  │
absorption/         │  ┌───────────┐   ┌─────────┐     │ harvest      ──→
impaction ──────────┼─→│ Inorganic │   │ Organic │     │
                    │  │   form    │   │ residue │     │
                    │  └───────────┘   └─────────┘     │
                    └─────────────────────────────────┘
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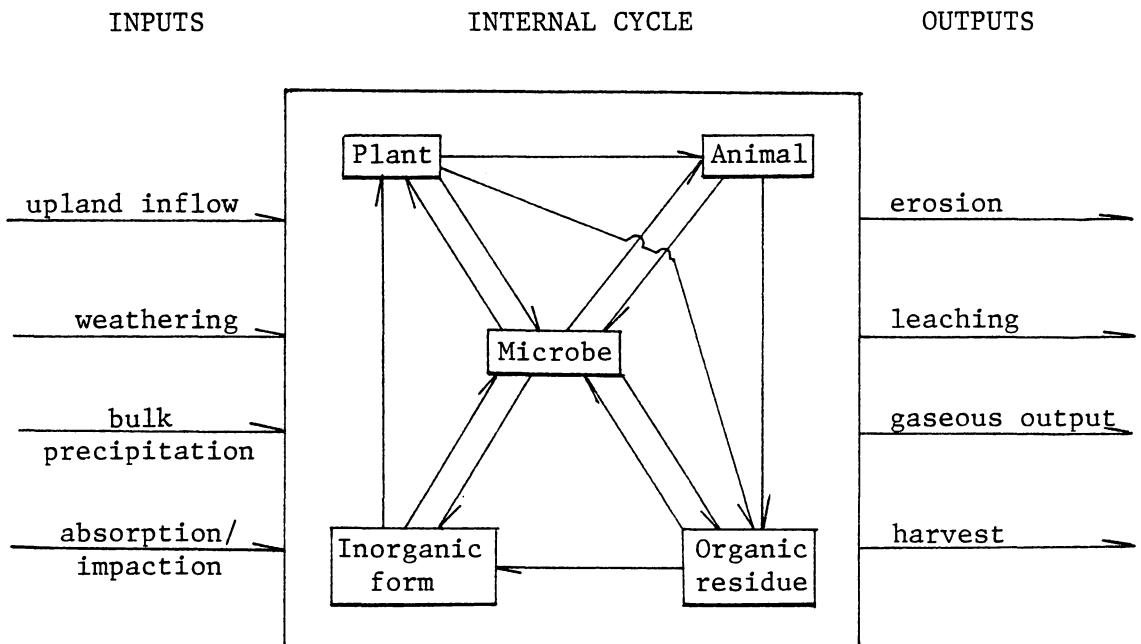
Figure 1.   Nutrient cycle in vegetative filter strips: Modified from Vitousek (1981).

As explained, complex components and processes are associated with the nutrient re-
tention mechanisms in vegetative systems. Some of the components or processes in Figure
1 are directly associated with the nutrient filtering function of VFS during storms. Others may
only indirectly promote the nutrient filtering function. Some exert their influence on nutrient
trapping only during a storm while others continuously deplete the filtered nutrients. For ex-
ample, hydrologic processes predominant during rainfall events. In contrast, biotic compo-
nents consistently take nutrients up and thus reduce nutrient concentrations in the soil
solution, which can trigger more nutrient trapping during storms.

Vegetative Filter Strip Research

Several studies have suggested that VFS reduce runoff discharge and result in reduced
pollution problems associated with agricultural runoff. For example, Westerman and Over-
cash (1980) found that over a 30-month period 21 and 10 percent of the rainfall volume was
generated as runoff from an open dairy lot and neighboring pasture, respectively. They attri-
buted the difference in runoff to the high infiltration and surface storage in the pasture.
Sediment transport in VFS has been extensively investigated by a research group at the Uni-
versity of Kentucky (Tollner *et al.* 1977, Barfield and Albrecht 1982, Hayes *et al.* 1984). The
Kentucky researchers observed that the majority of sediment deposition occurred just upslope
of the filter and within the first meter of the filter until the upper portions of the filter were
buried in sediment. Subsequent flow of sediment into the filter resulted in the advance of a
wedge-shaped deposition of sediment down through the filter. The Kentucky research re-
ported high trapping efficiencies as long as the vegetal media was not submerged, but trap-
ping efficiency decreased dramatically at higher runoff rates that inundated the media. The
results of this VFS research were incorporated into SEDIMOT II, which will be discussed in the

next section. Dickey and Vanderholm (1981) observed significant reductions in runoff and removal of as much as 95 % of nutrients and oxygen-demanding materials by vegetative filters. They also found that a channelized flow reduced filter effectiveness with respect to runoff and nutrient reduction. Young *et al.* (1980) constructed field plots on a 4 percent slope with the upper 13.7 m active feedlot and the lower 27.4 m in a planted area. When a 25-year, 24-hour storm was simulated, on the average, filter strips, reduced the total runoff, suspended solids, nitrogen, and phosphorus by 67, 79, 84, and 83 percent, respectively. The VFS also reduced NH_4-N, PO_4-P, and coliform bacteria but increased NO_3-N in the runoff. They suggested that planted vegetation released NO_3-N into the runoff.

Edwards *et al.* (1983) monitored storm runoff from the outlet of a 243-m² paved feedlot. They also measured and sampled runoff after the feedlot runoff passed through a shallow, concrete settling basin and two consecutive 30 m long by 45 m wide sod filter strips. The first filter reduced the runoff, total suspended solids, nitrogen, and phosphorus by -2, 23, 31, and 29 percent, respectively. The second filter showed less effectiveness in decreasing the same parameters, with additional reductions of -5, 10, 16, and 14 percent, respectively. The reduced effectiveness may be attributed to the selective filtration of easily trapped materials by the settling basin and first filter strip. The total runoff from the filters was greater than the incoming runoff because the rainfall rate during runoff events exceeded the infiltration rate of the filters. This rainfall excess, coupled with the added area of the filters, resulted in the increased runoff. They also suggested that the rainfall in the filter area diluted storm runoff during large storms and that infiltration reduced the transported nutrients to downstream areas.

Sediment and Phosphorus Transport Models

Examples of models currently available to simulate storm runoff and/or sediment transport processes on a watershed or field scale include: USLE, MUSLE, ARM, CSU, CREAMS, ANSWERS, FESHM, and SEDIMOT II (see Dillaha 1981, Wilson *et al.* 1981, Storm 1986). Nutrient transport, however, has not yet been predicted with any reasonable level of accuracy (Sweeney *et al.* 1985). In this section, storm runoff, sediment, and phosphorus transport models will be briefly discussed.

SEDIMOT II

SEDIMOT II (SEdimentology by DIstributed MOdel Treatment) is a simple distributed parameter simulation model developed by a research group at the University of Kentucky. Runoff discharge, sediment yield, particle size distribution, and sediment graphs are predicted for each subwatershed and combined at the watershed outlets. A major feature of SEDIMOT II is that it uses empirical runoff routing techniques to reduce the input data required by common distributed models such as ANSWERS and FESHM. SEDIMOT II is unique in describing the responses of grass filter strips to runoff and sediment inflows. Subroutine GRASS, which describes the performance of grass filter strips, has been developed by several researchers. Toller *et al.* (1976) presented design equations relating the fraction of sediment trapped in simulated vegetal media to the mean flow velocity, flow depth, particle fall velocity, filter length, and the spacing hydraulic radius of the simulated media. Barfield *et al.* (1979) developed a steady-state model for determining the sediment filtration capacity of grass media as a function of flow, sediment load, particle size, flow duration, slope, and media density. Outflow concentrations were found to be primarily a function of slope and media spacing for

a given flow condition. The steady-state model was extended for unsteady flow and non-homogeneous sediment by Hayes *et al.* (1979). These investigators suggested methods for determining the values of hydraulic parameters required by the model for real grasses. Using three different types of grasses, model predictions were found to be in close agreement with laboratory data. Hayes and Hairston (1983) used field data to evaluate the Kentucky model for multiple storm events. Eroded material from fallow cropland was used as a sediment source for the first time. Kentucky 31 tall fescue trimmed to 10 cm was used and the model predictions agreed well with the measured sediment discharge values.

At the present time, SEDIMOT II is the most comprehensive model available for grass filter strip design with respect to sediment removal. Both runoff discharge and sediment size distribution are described by the model, and it is structured so that dissolved and sediment-bound phosphorus transport submodels may be incorporated into the model. While the model has been tested in the laboratory and field in Kentucky, further field testing and verification is required before it can be recommended for widespread use. The model also will require modifications, including the incorporation of chemical transport submodels. The public version of the model produces outputs at less than three points along waterways due to its restrictive dimension statements. The model routes runoff by dividing the travel time in a grass filter segment by a particular time increment. The algorithm's advantage is that it reduces computations in long filter strips and still maintains reasonable accuracy. However, the algorithm can result in significant errors if the value of (travel time)/(time increment) has large decimal portion. The more computations are required for consecutive filter segments, the more serious this problem is. Furthermore, the model does not simulate direct rainfall input to the filter area. If the VFS area has real rainfall input and is large in proportion to the to the drainage source areas, precipitation to the VFS will contribute to the significant portion of total VFS surface runoff. Since the manual of SEDIMOT II (Wilson *et al.* 1981, Warner *et al.* 1981) describes the model in detail, further discussion is omitted here.

Phosphorus Transport Model

A phosphorus transport model is currently under development in Oklahoma (Sharpley *et al.* 1981a, Sharpley *et al.* 1985). Equation [1] is a representative equation used for describing the kinetics of phosphorus desorption from soil, derived by Sharpley *et al.* (1981b), using laboratory batch experiments and theoretically verified by Sharpley and Ahuja (1983), assuming that P desorption is controlled by nonlinear diffusion:

$$P = K \ P_o \ t^\alpha \ W^\beta \qquad [1]$$

where P is the amount of phosphorus desorbed into equilibrating water from soil in time t (μg P/g soil), P_o is the initial amount of desorbable or available phosphorus present in the soil (μg P/g soil), t is the desorption reaction duration (min), W is the water-soil ratio (cm^3/g), and K, α, and β are constants for a given soil. The units of K are $min^{-\alpha}(cm^3/g)^{-\beta}$ but α and β are dimensionless. Assuming that a thin layer of surface soil interacts with surface and subsurface flows, Sharpley *et al.* (1981a) suggested that the average dissolved phosphorus concentration of storm runoff (μg/L) might be given by:

$$P_d = \frac{K \ P_o \ EDI \ D_b \ t^\alpha \ W^\beta}{V} \qquad [2]$$

where P_d is the amount of phosphorus desorbed into stormwater runoff from soil in time t (μg P/L), EDI is the effective depth of interaction between the soil and surface runoff in soluble phosphorus transport (cm), defined as the thickness of surface soil in which soil mass interacts with rainfall and runoff waters, D_b is the bulk density of soil (g/cm^3), and V is the total runoff volume during a storm event (L). The effective depth of interaction between surface soil and runoff can be estimated using the following equations (Sharpley 1985a):

$$\ln \text{EDI} = i + 0.576 \ln(\text{soil loss}) \qquad [3]$$

$$i = -3.130 + 0.017(\text{soil aggregation}) \qquad [4]$$

where the units of EDI and soil loss are mm and kg/ha, respectively. The degree of soil aggregation is represented by the ratio of the proportions of clay-sized material (<2 μm) in dispersed and undispersed soils (Sharpley 1985a). The constants (K, α, and β) may be calculated from the ratio of Fe or clay to organic carbon in acidic soils and $CaCO_3$ or clay to organic carbon in basic calcareous soils (Sharpley, 1983) as follows:

$$K_L = 1.422(\text{clay/organic C})^{-0.829} \qquad [5]$$

$$K_B = 0.630(\text{clay/organic C})^{-0.698} \qquad [6]$$

$$\alpha = 0.815(\text{clay/organic C})^{-0.540} \qquad [7]$$

$$\beta = 0.141(\text{clay/organic C})^{0.429} \qquad [8]$$

The values of K_L and K_B correspond to the K in Equations [1] and [2] when the initial available soil phosphorus (P_o) is represented by labile and Bray-I phosphorus, respectively. Clay and organic carbon contents are expressed as percents in Equations [5] to [8]. The value of W for each runoff event is expressed by the ratio of runoff volume and mass of interacting soil (Sharpley 1985a). The mass of interacting soil is represented by EDI $\times$ D_b per unit area of soil surface. The desorption reaction is assumed to start when rain begins, and thus the desorption reaction time is equal to rainfall duration. This may account for reduced losses

of runoff-transportable dissolved phosphorus in high infiltration areas since initially desorbed phosphorus moves into subsurface soil.

Sharpley et al. (1985) reported that sediment bound phosphorus in runoff could be calculated from the total phosphorus content of surface soil as follows:

$$P_s = TP_s \ S \ PER \qquad\qquad [9]$$

where P_s is the sediment-bound phosphorus in runoff (µg/L), TP_s is the total phosphorus in soil (µg P/g soil), S is the sediment concentration of runoff (g/L), and PER represents the enrichment ratio for particulate phosphorus which is defined as the ratio of the concentration of phosphorus in the sediment (eroded soil) to that in the source soil. The value of PER is more closely associated with runoff and rainfall energy and soil phosphorus status than soil physical properties. Sharpley (1985b) demonstrated that the enrichment ratios varied with phosphorus forms. The following equations may thus be used for bioavailable, Bray I available, inorganic, organic, and total phosphorus:

$$\ln \ (PER) = 1.21 - 0.16 \ \ln \ [\text{soil loss (kg/ha)}] \qquad\qquad [10]$$

for labile phosphorus:

$$\ln \ (PER) = 2.48 - 0.35 \ \ln \ [\text{soil loss (kg/ha)}] \qquad\qquad [11]$$

However, it is doubtful that the experimental results can be universally applied. The model is based upon an intuitively unacceptable assumption: that the water-to-soil ratio is constant during a storm period, and independent of water-travel distance. In addition, the model only determines the average phosphorus load in a particular system. As mentioned

earlier, it is desirable to determine those characteristics which affect the magnitude and timing of the phosphorus load to identify the effectiveness of buffers under several physical conditions. The model does not describe the interactions of dissolved and particulate phosphorus in flowing water. It has been known that the transport of dissolved phosphorus is inversely related to sediment concentration in flowing water due to adsorption onto sediment (McDowell and McGregor 1980, Sharpley *et al.* 1981c). Furthermore, the model does not consider the dynamic change of the fractions of the particle size classes, which is an important parameter in phosphorus desorption and adsorption reactions. Hence, it is not clear how the enrichment of a particular particle size class and the deposition process affects the effectiveness of the filter's function to remove phosphorus from stormwater runoff.

Chapter 3

Experimental Plot Simulation

Experimental research plots were constructed to evaluate the effectiveness of VFS for sediment and phosphorus removals under field conditions. The research plot data also were used to formulate and verify a mathematical model to describe VFS performance.

Experimental Design and Sampling

Three sets of experimental research plots were constructed at the Virginia Tech Prices Fork Agricultural Research Farm, 10 km west of Blacksburg, Virginia. The plots consisted of simulated cattle feedlot or cropland areas (bare soil area) and VFS, as sketched in Figure 2. The plot sets are noted as QF123, QF456, and QF789. The plot set of QF123 is made up of plots QF1, QF2, and QF3, and QF456 and QF789 are referred to in the same way. The physical and chemical properties of the soil at the Research Farm were given by Storm (1986).
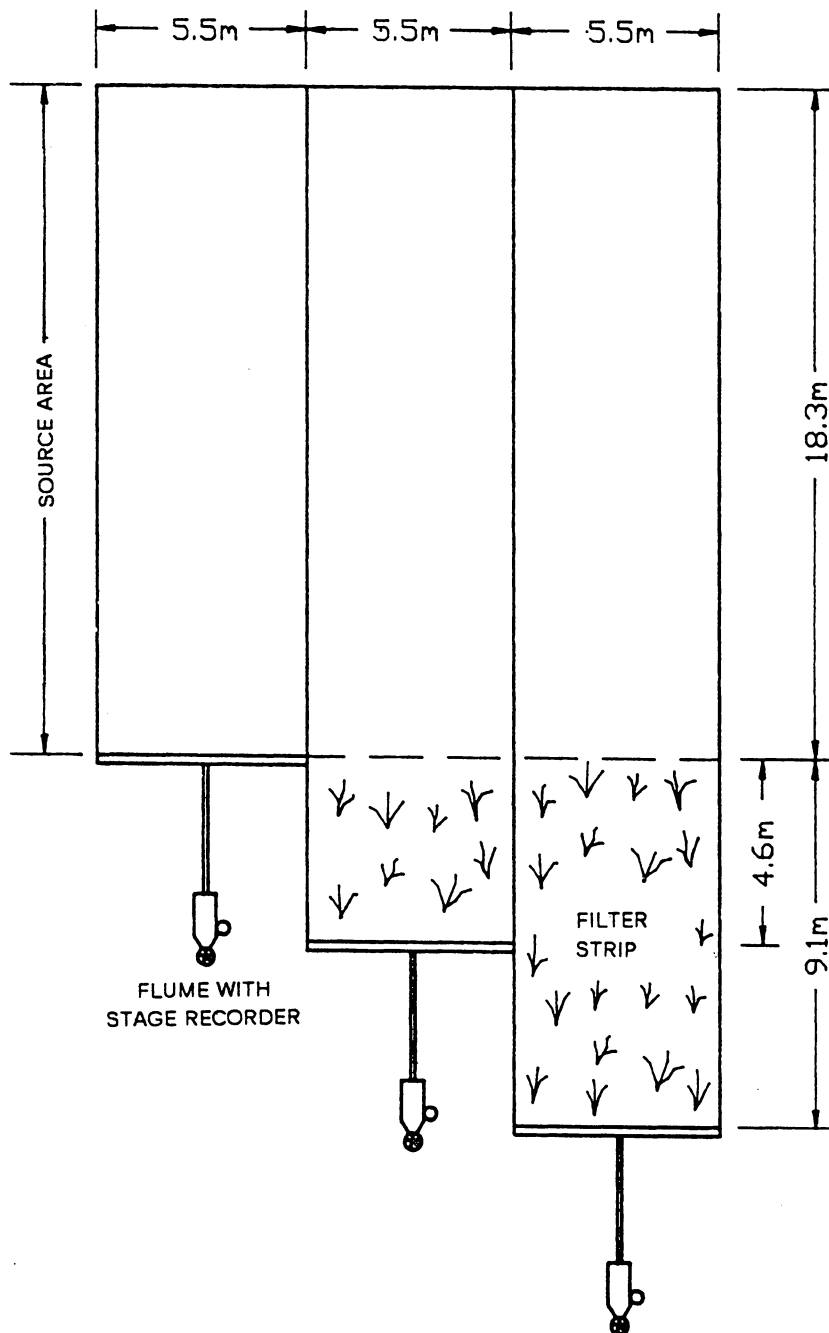
Figure 2. Schematic representation of one experimental field plot set: no filter - QF3,QF6,QF7; 4.6 m filter - QF2,QF5,QF9; 9.1 m filter - QF1,QF4,QF8

The soil in the plots is a Groseclose silt loam. Particle size distribution according to pipette method is 28 % sand, 53 % silt, and 19 % clay (Storm 1986). Organic matter content and pH are 2.6 % and 5.3, respectively. As shown in Table 1 soil particle size fractions of the plot sets were not identical when the standard wet sieve and sedimentation technique (Jackson 1956, Genrich and Bremner 1974) was applied without dispersion of soil aggregates.

The bare soil portion was tilled and compacted using a sheep's foot roller to simulate soil densities found in cattle feedlots. The filter strip vegetation consisted of existing orchard grass (*Dactylis glomerata* L), which was trimmed to 10 cm and then the clipped residues were raked and removed before rainfall was simulated. Each plot was equipped with a H type flume (150 mm) and water level recorder (FW-1) to generate a hydrograph and to facilitate sampling runoff discharge. Fresh dairy manure was applied to the bare soils at a rate of 7500 or 15000 kg/ha (wet weight base) prior to rainfall simulation.

During the fall (October and November) of 1984, artificial rainfall was applied to each plot three different times at two different manure-loading rates. Approximately 100 mm of rainfall was applied to each plot over a two-day period at each manure-loading rate. A one-hour 'dry' run (R1) was applied to each plot. Two 30 minute runs (R1 and R2) separated by a 30-minute rest interval followed R1 24 hours later. A rainfall intensity of approximately 50 mm/hr was used during all simulations. The first simulated rainfall event closely approximates a one hour duration, 2-year recurrence interval storm in Virginia and should represent critical conditions since the manure had just been applied to the plots. The three run sequence of dry, wet and very wet was used because it is a commonly used artificial rainfall sequence for erosion re-search in the United States. A 50 mm/hr rainfall rate is a standard rate, which is used to allow for a direct comparison of results from one location to another. Rainfall rates and uniformity were measured for each simulation by placing 12 to 17 rain gauges within each plot. Rain gauges were read after each rain application to determine the total amount of rainfall and the coefficient of uniformity for each run.

After the feedlot simulations were completed in November, 1984, the plots were covered with clear plastic to protect them from further erosion during the winter. In early April, 1985,

Table 1. Particle size distribution of undispersed soils in experimental plots

| Plot | Particle size fraction (%) | | |
	sand	silt	clay
QF123	45.9	48.6	5.5
QF456	41.2	48.1	10.7
QF789	46.3	49.9	3.9

Sand, silt, and clay represent the sizes of 2000-50 μm, 50-2 μm, and <2 μm, respectively.

the bare were uncovered and prepared for the cropland simulations, referred to Test 3 and 4. The bare portions of the plots were tilled to a depth of 20 to 30 cm with a PTO driven tillter. Granular P_2O_5 and K_2O fertilizer were applied to the plots uniformly by hand at rates of 112 kg/ha. The plots were then tilled again to incorporate the granular fertilizer into the upper 20 to 30 cm of the soil profile. Two to three days before the rainfall simulations began, non-pressurized nitrogen solution was applied to the plots. But in this study, only results concerning phosphorus will be reported. Rainfall simulations and samplings were followed as described for Test 1 and 2. Details for Test 3 and 4 were explained by Dillaha *et al.* (1986a). Physical and chemical characteristics of each plot set and rainfall designed are outlined in Table 2.

Water samples of approximately 300 ml were manually collected from the plot discharge in polyethylene bottles at three-minute intervals throughout the runoff process. A mark was made on the stage recorder charts to precisely record the time and flow rate at which each sample was collected. At the completion of the field collection, the water samples were transported to the laboratory and stored in a refrigerator or frozen for later chemical analysis. Additionally, 15 to 20 liters of runoff samples were taken in buckets during Test 4. The bucket samples were collected when the runoff discharge reached a steady state rate and were used only for the determination of sediment size distribution in the runoff from the research plots. Soil, dead litter, and living plant materials were sampled in the summer of 1986 (April to September) after the plots had been idle since April, 1985.

Laboratory Tests

The runoff samples collected during the rainfall simulation were tested for concentrations of ortho- and total phosphorus, suspended solids, and sediment size distribution. Total- and

Table 2. Experimental plot characteristics and operating conditions

	QF1	QF2	QF3	QF4	QF5	QF6	QF7	QF8	QF9
Filter length (m)	9.1	4.6	0.0	9.1	4.6	0.0	0.0	9.1	4.6
Slope (%)	11	11	11	16	16	16	5	5	5
Cross slope (%)	<1	<1	<1	<1	<1	<1	4	4	4

Filter strip vegetation	- Orchard grass (trimmed to 10 cm height)
Feedlot simulation	- Test 1 (T1): 7500 kg/ha manure (moist weight)
	- Test 2 (T2): 15000 kg/ha manure (moist weight)
Cropland simulation	- Test 3 (T3): 222 kg/ha N
	112 kg/ha K_2O
	112 kg/ha P_2O_4
	- Test 4 (T4): no additional fertilizer
Rainfall intensity	- 50 mm/hr
Rainfall duration	Run1 (R1): 60 min
	Run2 (R2): 30 min
	Run3 (R3): 30 min

Bray I available phosphorus contents, and phosphorus adsorption and/or desorption kinetics were tested for the soil and plant materials to understand the role of the vegetative filter components as nutrient sinks and sources. The phosphorus adsorption tests were additionally performed for soil particle size classes using a particle segregation procedure and laboratory batch experiments. In addition, inorganic phosphorus was extracted from the plant materials after different contact times. Except for the total phosphorus analysis of soils, Total- and orthophosphorus contents in filtrates and extracts were colorimetically measured with a Technicon AutoAnalyzer II. All solution samples were stored in a refrigerator whenever phosphorus measurements were delayed. The experimental results for soil and plant materials are reported on an oven-dried basis (soil: 105° C, plant materials: 55° C for 24 hours).

Runoff Samples

Total suspended solids concentrations (TSS) were determined using the methods described in Methods for Chemical Analysis of Water and Waste (USEPA 1979). Sample volumes of 100 ml size were passed through pre-weighed 0.45 micron glass fiber filters. Filters and residue were then dried for approximately 24 hours at 103° to 105° C, transferred to a desiccator, allowed to cool, and then reweighed on an analytical balance. The change in dry weight was determined and expressed in mg/L after dividing by the sample volume. The bucket runoff samples were used for determination of particle size distribution of the surface runoffs. An entire bucket sample was passed through a series of sieves (mesh size 2.0 - 0.075 mm) to isolate sand sized fractions after the volumes of the runoff samples were determined. Silt and clay size sediments were fractionated following the standard wet sieve and sedimentation technique, which will be explained during the isolation of soil particle size classes in detail. The concentration of each sediment size class was then determined by dividing oven-dried sediment fraction by runoff volume.

Total phosphorus and orthophosphorus concentrations in runoff samples were determined in terms of the procedures described in Methods for Chemical Analysis of Water and Wastes (USEPA 1979). The amounts of total phosphorus (TP) and filterable total phosphorus (TP-F) in runoff samples were determined by digesting original and filtrated samples, respectively. The latter was obtained passing a portion of original water through Whatman 42 filter paper. The samples were digested for two and one-half hours in the presence of H_2SO_4, K_2SO_4 and $HgSO_4$. After the resulting residue cooled, it was diluted to 50 ml and the inorganic phosphorus content was measured. Orthophosphorus (OP) was determined by measuring the phosphorus content in the filtrates of untreated water samples.

Soil and Plant Materials

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Throughout this study soil materials were represented by air-dried and sieved (2 mm) soil samples or their particle size classes obtained by the following segregation procedure. Particle size classes were segregated using the standard wet sieve and sedimentation technique described by Jackson (1956) and Genrich and Bremner (1974). This technique has advantages over the pipette and hydrometer methods since it isolates particle size classes and works when total solid concentrations are unknown.

Sixty grams of air-dry soil were placed in a 1000 ml glass beaker containing a 3.8 cm Teflon-coated stirring bar. No dispersing agent was used since the distribution of natural aggregates was desired for this research. Approximately 150 ml of distilled water was added to the soil, which was allowed to soak for at least 15 minutes. The suspension was then magnetically stirred for 2 minutes. After equilibration for 40 seconds, the supernatant was passed through a 300 mesh sieve to isolate the sand size fraction (> 50 μm). Adding 100 ml of distilled water to the slurry, stirring for 1 minute, equilibrating for 40 seconds, and sieving the supernatant was repeated 3 times. Finally, the whole residue was quantitatively transferred

into the sieve with the aid of a jet of distilled water. The material retained on the sieve was carefully washed with distilled water until no further material passed\through the sieve and then air-dried. The air-dried material was shaken on the 300 mesh sieve for 5 minutes and the material that passed through the sieve was added to the silt sized fraction. The weight and moisture content of the air-dried material retained on the sieve were determined after oven-drying at 105 °C.

The soil suspension was centrifuged to isolate the silt size fraction (50-2 μm) from clay size class. (< 2 μm). Centrifugation time was calculated using the following equation based on Stokes's Law:

$$T = \frac{(63.0 \times 10^8)\ n\ (\log_{10}R/S)}{N^2D^2(S_p - S_w)} \qquad [12]$$

where T is the time for sedimentation in minutes, n is the viscosity of water in poises, R is the rotation radius of centrifuge tube in centimeters, S is the radius of rotation of the centrifuge in rpm, D is the particle diameter in microns, and S_p and S_w are the specific gravity of the soil and water, respectively. In this study a centrifugation time of 2.0 minutes was used to segregate the silt (50-2 μm) and clay sized (<2 μm) particles, using 27 cm for R, 15 cm for S and 2000 rpm for N and assuming that n was 0.00894 poises (25 °C), S_p was 2.65 g/cm³, and S_w was 0.997 g/cm³. After centrifugation, the suspension was carefully decanted and stored for collection of the clay sized soil particles.

The precipitated silt sized fraction was quantitatively transferred to an aluminum dish by agitating the centrifuge tube with an agitator and jetting distilled water into the tube, and then dried at 40° C for 5 days. Dried material was allowed to cool to room temperature until its weight was constant. Clay sized particles (<2 μm) are normally flocculated with $CaCl_2$ from the decanted suspension. After the suspension is centrifuged, the clear supernatant is discarded and the clay pellet washes with acetone into a pre-weighed 100 ml glass beaker (Christensen 1985). However, this procedure may affect the phosphorus sorption kinetics of the isolates since it changes the ionic strength of resulting clay solution. Thus in the present

study, the clay sized particles were settled from the supernatant by centrifuging for 80-minute at 2000 rpm. The clay sized class was collected as done with silt size fraction. Since the silt- and clay-sized fractions were coagulated after drying, they were broken down with a mortar and pestle. Additionally, coarse (2000-37 μm) and fine (<37 μm) size fractions were segregated using wet sieving with a No. 400 mesh sieve. To check the wetness effects of the wet sieving procedure, dry sieving was performed by gently breaking down air-dried soil aggregates with a mortar and pestle until the coarse particle fraction was as much as the air-dried coarse size fraction collected from the wet sieving method. The resulting soil particle size classes were stored at room temperature for testing Bray I available and total phosphorus contents and phosphorus adsorption kinetics. The weights and moisture contents of the air-dried materials were determined by oven-drying at 105 °C for 24 hours.

The initial amount of desorbable phosphorus present in the soil materials was represented by Bray-I available phosphorus of the air-dried and sieved (2 mm) soil samples and their particle size classes (Sharpley 1983). One gram of soil material was extracted with 10 ml of 0.03N NH_4F and 0.025N HCl for 5 minutes. For inorganic phosphorus content measurement, the slurry was centrifuged at 5500 rpm for 5 minutes to facilitate filtering with a Whatman 42 filter paper. Total phosphorus analysis was performed for air-dried and sieved soil samples and some of particle size classes using the procedure described by Sommers and Nelson (1972). Soil materials (0.5 g) were digested with perchloric acid for 75 minutes at 200 °C. The digested soil suspension was cooled to room temperature, diluted to a volume of 50 ml with deionized water, shaken several times, and then allowed to stand overnight. The inorganic phosphorus content of the supernatant was colorimetically determined by the molybdate-blue method after the solution was neutralized with 5 N NaOH (Murphy and Riley 1962).

The time variations of phosphorus desorption and adsorption were examined for the original soil samples and/or its particle size classes and plant materials using laboratory batch experiments. Phosphorus desorption by 0.01 M $CaCl_2$ solution was determined by shaking duplicate soil samples on an end-over-end shaker at 25 °C for 5 minutes to 1 day at a water-to-soil ratio of 50-1 (Sharpley et al. 1981b). The amount of phosphorus desorbed from the soil

was calculated from the increased phosphorus concentration of the supernatant at the pipetting time. Phosphorus desorption tests were applied to air-dried decaying leaves collected monthly from April to September of 1986. The procedure was similar to the phosphorus desorption test for soil except that 0.5 g of dead leaf litters was placed in 25 ml of deionized water in polyethylene bottles and only one extractant sample was taken from each bottle since pipetting changes the water-to-litter ratio. The same procedure was performed for 1.0 g and 2.0 g of fresh decaying leaves and clipped grass blades taken on August 16, 1986, respectively, using a water-to-desorbent ratio of 50-1. The field conditions of plant materials were maintained by collecting the plant materials from the plots just before they were tested, and stored in plastic bags. For the phosphorus adsorption test, either one or one-half gram of soil materials was placed in a KH_2PO_4 in 0.01 M $CaCl_2$ solution, whose phosphorus concentration ranged from 0 to 40 ppm. A solution to soil ratio of 50 was maintained with all soil samples used for the adsorption test. The soil and phosphorus mixture was continually shaken except when approximately 5 ml of the suspension was pipetted into a centrifuge tube according to a predetermined time schedule. After the suspension was centrifuged for 5 minutes at 5500 rpm, the supernatant solution was passed through Whatman 42 filter paper. An aliquot of the filtrate was then collected and stored for the determination of inorganic phosphorus. The amount of phosphorus adsorbed onto soil was determined from the difference in phosphorus concentration of the supernatant at pipetting time and the original phosphorus concentration.

Chapter 4

Mathematical Model Development

Much attention has been paid to mathematical simulations for the successful management of water resources. Describing the behavior of pesticides and nutrients in surface runoff water is one of the major fields where mathematical models have been used extensively. Currently, such chemical transport models are based upon the assumption that chemicals extracted from a thin soil surface are immediately mixed with runoff water and reach an equilibrium. Sharpley *et al.* (1981a) and DeCoursey (1985), however, emphasize that the chemical forms and the equilibrium concentrations of the forms are dynamic, changing with flow conditions, and thus should be described by kinetic properties rather than an instantaneous equilibrium. In addition, existing models do not consider changes in the sediment size distribution in runoff water, which is a prime parameter controlling the adsorption reaction of chemicals, and thus the fractions of their existing forms (Schuman *et al.* 1973a,b).

In this section a conceptual model is developed, which expresses the nutrient exchanges between runoff and the waterway bed and the nutrient-filtering mechanisms in vegetative filter strips. Mathematical models are derived from the conceptual model to describe the transport of dissolved and particulate forms of nutrients separately.

Conceptual Model

Before phosphorus compounds are transported by storm runoff, they must be dissolved or detached from their parent materials to produce dissolved or particulate bound phosphorus (Sharpley *et al.* 1985b). Dislodged phosphorus compounds exist in dynamic equilibrium between their dissolved and particulate bound forms. While some of dislodged phosphorus is deposited on or adsorbed onto the soil surface and vegetation during the runoff process, and some enters into the soil profile with the downward movement of infiltrating water, much phosphorus moves with surface runoff. Consequently, transport processes involve sediment deposition, phosphorus adsorption onto the soil surface, and infiltration of surface runoff. When runoff reaches a vegetative zone, where biogeochemical differences are encountered, the fates of water and materials will change. These changes will trigger the trapping processes corresponding to the effects of vegetation on water infiltration, sediment transport capacity, and nutrient retention. These processes and their interactions and effects on soluble and particulate phosphorus are conceptualized in Figure 3. The biogeochemical conditions of waterways will vary the relative predominance of these processes. For example, on bare soils the dislodgement of nutrients will overwhelm trapping while the opposite tendency is expected in vegetative areas. Accordingly, a comprehensive nutrient routing model must describe the dislodgement, transport, and trapping processes as in modeling the erosion process (Foster 1982).

The dislodgement process is governed by soil and hydrologic characteristics such as the nutrient content of soil, fertilizer management, soil organic matter content, texture and structure, rainfall intensity, runoff velocity and depth, and vegetative cover (Timmons *et al.* 1970,
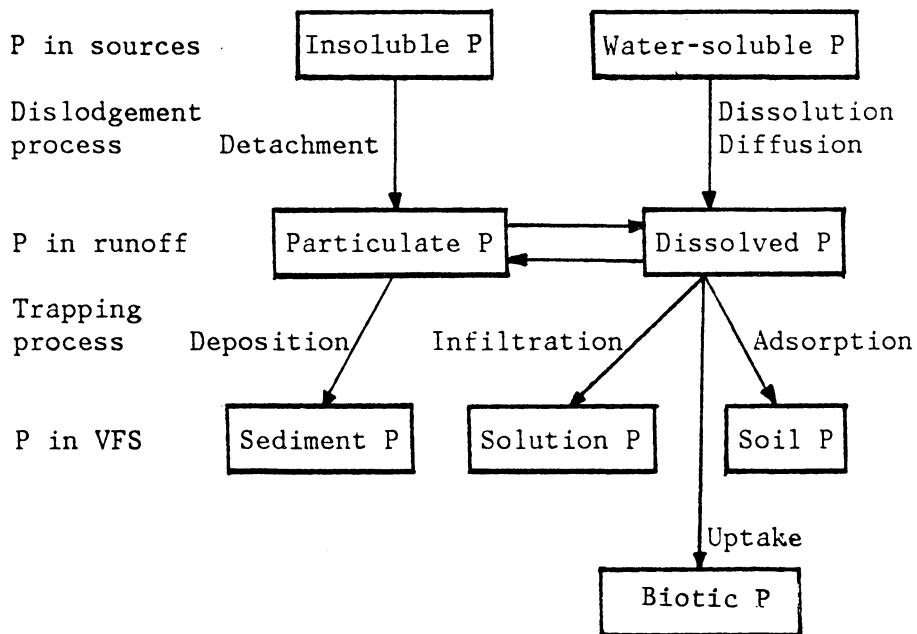
Figure 3.   Schematic diagram of phosphorus movement in nutrient source area and VFS.

White and Williamson 1973, Klausner *et al.* 1974, Singer and Rust 1975). When nutrients are primarily fixed or precipitated into insoluble forms in the soil, erosion may be a major nutrient dislodgement process. Even though much phosphorus is transported in insoluble or particulate bound forms, some portion is soluble in runoff. Soluble phosphorus typically includes inorganic orthophosphate, hydrolyzable polyphosphate, and some organic forms associated with fine colloidal particles, while particulate phosphorus includes insoluble inorganic phosphorus compounds, sorbed or fixed phosphorus, and organic phosphorus in plant and animal matter (Holt *et al.* 1970, Logan 1981). Kinetic factors such as flow rate and turbulence in the moving water will govern the fraction of soluble and sediment-adsorbed phosphorus forms (Taylor and Kunish 1971). The concentrations of existing phosphorus forms will be a function of the equilibrium between labile sediment-associated and dissolved forms as long as there are significant levels of sediment in runoff. These relationships break down through the adsorption reaction when the level of dissolved phosphorus in runoff is high and there are insufficient suspended solids to buffer the soluble phosphorus (Logan 1981). Elwood *et al.*(1981) reported that approximately 34% of the total phosphorus associated with fine particulate organic matter in a woodland stream was exchangeable with phosphate in water. Nutrient trapping processes depend on the nutrient filter mechanisms as explained earlier.

Formulation of the Mathematical Model

In this section, a mathematical model for nonpoint source pollution analysis with respect to vegetative filter strips is developed. The model proposed considers the effects of chemical dispersion, advection process, infiltration, biological decay or uptake, the kinetics of chemical desorption from soil surface to stormwater, the adsorption kinetics of dissolved forms to sediment in runoff, and the dynamic changes of sediment size fractions on chemical transport.

In theory, the model can be used to describe the transport of any chemical species in sediment-laden surface runoff. But the present application was demonstrated for phosphorus transport from nonpoint sources since submodels and the data required are available for phosphorus.

The present discussion is restricted to the case where dispersion is negligible. Dispersion processes will, however, be briefly considered. Major assumptions are that a material exists only in dissolved and particulate or sediment-bound forms in solution (Bormann *et al.*, 1969) and that mass transport velocity is like that of runoff. The latter assumption may become unrealistic as the size of transported materials increases, but this may not cause significant errors since coarse sized particles are not important in transporting materials, especially when they are immediately deposited due to control practices.

Dissolved Constituent Transport

For a unit element of runoff, a mass balance of the dissolved chemical form can be expressed as shown in Figure 4. Hence, the input and output components can be summarized as follows:

Inputs:

Surface runoff inflow $= qC\Delta t$

Input from rain $= Y(t)\Delta x\Delta t$

Desorption from floor $= Z(q,t)\Delta x\Delta t$

Outputs:

Surface runoff outflow $= (q + \Delta q)(C + \frac{\partial C}{\partial x}\Delta x)\Delta t$

Infiltration $= F(t)\overline{C}\Delta x\Delta t$

Adsorption $= X(t,C,S)\Delta t\, V$

Biological uptake $= K_m C\Delta t V$

Surface runoff inflow
$QC\Delta t$

Input from rain
$Y(t)\Delta x\Delta t$

Adsorption onto sediment
$X(t,C,S)\Delta t\ V$

Biological uptake
$K_m C\Delta t V$

Surface runoff outflow
$(Q+\Delta Q)(C+\dfrac{\partial C}{\partial x}\Delta x)\Delta t$

Δx

$F(t)\overline{C}\Delta x\Delta t$
Infiltration

$Z(Q,t)\Delta x\Delta t$
Desorption from floor
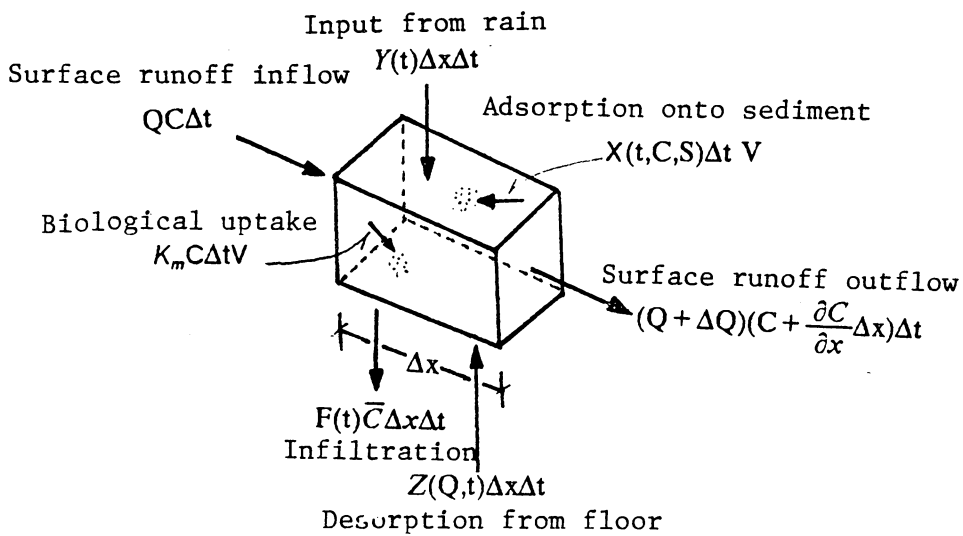
Figure 4. Schematic diagram showing the input-output of a dissolved chemical in an element of surface runoff

When mass conservation is applied to the element volume, the following equation is obtained to describe the concentration of the nutrient with respect to time. It should be noted that the elemental runoff volume, V, is expressed by y times Δx.

$$y\frac{\partial C}{\partial t} + \frac{\partial(qC)}{\partial x} + [F(t) + yK_m]C + yX(t,C,S) - Y(t) - Z(q,t) = 0 \qquad [13]$$

where y = water depth, cm.

C = concentration of dissolved form, $\mu g/cm^3$

$\overline{C}$ = average C value in the element, $\mu g/cm^3$

F = infiltration rate, $cm^3/cm^2/min$

K_m = first-order biological uptake rate, min^{-1}

q = runoff discharge per unit channel width, cm^3/min

S = concentration of sediment-bound form, $\mu g/g$ sediment

V = elemental volume, cm^3

X = adsorption on sediment, $\mu g/cm^3/min$

Y = addition of element from rainfall, $\mu g/cm^2/min$

Z = exchange on soil surface per unit area, $\mu g/cm^2/min$

x = distance in the downstream direction, cm, and

t = time of runoff event, min

If dispersion significantly influences the behavior of the material, e.g., at the boundary of a sludge-applied area or flow-detained area, a term, $yD_c\partial^2C/\partial x^2$ should be subtracted from the left-hand side of the above equation, where D_c is the apparent dispersion coefficient (cm^2/min). Novotny *et al.* (1978) included the dispersion term in a similar model. But this term is negligible for the shallow upland flow case.

Infiltration, F, can be computed by any of numerous infiltration models (Skagg, 1982). Input from rainfall, Y, simply corresponds to the amount of dissolved chemical added with rainfall per unit area for unit time. This value is determined by filtering rainwater and measuring the chemical concentration in the filtrate. This term is usually negligible for phosphorus since the content of this element in precipitation is normally very low (Gosz *et al.*, 1973) except for some cases (Jordan *et al.* 1980, Lewis *et al.* 1985). The K_m term is a first-order constant for the biological uptake rate depending upon the properties of the chemical and soil. For example, vegetative areas may have high values of K_m for nutrients which are required for biological growth.

Nutrient sources in vegetated areas include living plants, dead plant residues, and surface soil components including organic and inorganic constituents. Thus the term, Z, can be determined by summing the nutrient released or desorbed from the nutrient sources, assuming that the release form each source is not influenced by the others. Nutrient release from plant materials has not yet been successfully described (Sharpley 1981). Desorption from surface soil into surface runoff may be described by desorption kinetic equations. Using Equation [1] and assuming that a thin layer of surface soil interacts with surface runoff, phosphorus desorption from soil surface expressed as follows:

$$Z_s = \frac{\partial}{\partial t}(P \times EDI \times D_b)$$

or

$$Z_s = K \times P_o \times D_b \times \frac{\partial}{\partial t}(EDI \times t^\alpha \times W^\beta) \qquad [14]$$

where Z_s is the time variation of phosphorus desorbed into storm runoff from a unit area of soil surface (μg P/cm^2/ min), and EDI and D_b are as defined previously.

The adsorption term, X, is determined from the initial phosphorus content of the soil material and the adsorption reaction rate of sediment in runoff water. It is assumed that sediment is composed of several classes which have uniform physical and chemical properties, and that sediment size is a representative parameter for the adsorption and desorption kinetics of a chemical. Many studies have suggested that several soil properties, including the fractions of soil organic matter (Tiessen and Stewart, 1983; Tiessen et al., 1984), and carbon, nitrogen, phosphorus, and sulfur (Oades and Turchenek, 1978; Anderson et al., 1981; Tiessen et al., 1983; Williams, 1983), can be characterized by the fractionation of soil particle size. Specifically it has been reported that soil phosphorus distribution may be described by particle size distribution with little variation (Campbell et al. 1984, O'Halloran 1985). In general, clay-sized particles often have higher phosphorus concentrations than bulk soil because organic and inorganic phosphates are preferentially adsorbed to clays rather than coarse-sized particles (Syers et al., 1969; Sharpley, 1980). Particle size is also a highly significant parameter affecting the detachment, transport, and deposition processes of sediment (Foster, 1982). Hence, the term X can be expressed as:

$$X_k(t,C,S) = \sum_{k=1}^{n} f_k \frac{\partial S_k}{\partial t} \qquad [15]$$

$$X(t,C,S) = \sum_{k=1}^{n} X_k \qquad [16]$$

where f_k is the concentration of each sediment particle size class per unit volume of runoff (g/cm^3), S_k is the phosphorus concentration of each sediment size class (μg P/g sediment) at time t, t is the adsorption reaction time (min), and n is the number of particle size classes. The values of f_k can be computed using one of several sediment routing models (e.g., SEDIMOT II, ANSWERS).

Many kinetic equations have been reported which describe phosphorus adsorption onto soil particles. A modified Freundlich equation is one of the equations frequently used (Enfield et al., 1976; Bolan et al., 1985).

$$\frac{\partial S_k}{\partial t} = aC^b S_k^c \qquad\qquad [17]$$

where a, b, and c are constants.

Chien and Clayton (1980) suggested that the Elovich equation could be applied to describe the kinetics of phosphate desorption and adsorption in soils.

$$\frac{\partial S_k}{\partial t} = \lambda_k \exp(-\varepsilon_k S_k) \qquad\qquad [18]$$

where λ_k and ε_k are constants for a particular soil size class during any one experiment. The Elovich equation can be applied to both adsorption and desorption reactions and is easily solved. In this study, a modified Elovich equation was used to the transport model. Equation [18] was modified into Equation [19] for the reason which will be discussed in detail below.

$$\frac{\partial S_k}{\partial t} = \frac{1}{\varepsilon_k t} \qquad\qquad [19]$$

Even though both Equation [17] and [19] were incorporated into computer model, the latter was used to verify the submodel due to the ease of finding the related parameter.

Dissolved phosphorus loads for a stormwater runoff event were calculated by integration of the dissolved phosphorus loading curve, which was obtained by plotting the product of flow and phosphorus concentration for every time interval from the beginning of the event in which it occurred (Griffin *et al.* 1980). Thus, the cumulative dissolved phosphorus load which passes a point along a waterway is expressed as follows:

$$L = \int_{t_o}^{t} CQ\,dt \qquad\qquad [20]$$

where L is the cumulative dissolved phosphorus load (mg) at time t after runoff starts, t_o is the runoff starting time, Q is total runoff discharge which is determined by multiplying q by water

channel width (cm³/min), and the other terms are as defined previously. The effectiveness of a nonpoint pollutant management practice is determined by comparing the values of L for runoff influent and effluent of a system.

Sediment-Bound Constituent Transport

When mass conservation is applied to the particulate form of a chemical or nutrient for a particular size class, assuming that some very fine particles are infiltrated into soil pores, the input and output components can be summarized as:

Inputs:

Surface runoff inflow $= qf_kS_k\Delta t$

Input from rainfall $= R_k(t)S_{rk}\Delta x\Delta t$

Detachment $= B_k(q,t)S_{bk}\Delta x\Delta t$

Adsorption to sediment $= X_k\Delta t\ V$

Outputs:

Surface runoff outflow $= (q + \Delta q)[f_kS_k + \dfrac{\partial(f_kS_k)}{\partial x}\Delta x]\Delta t$

Deposition $= D_k(q,t)\overline{S}_k\Delta x\Delta t$

Infiltration $= F(t)\overline{f}_k\overline{S}_k\Delta x\Delta t$

The governing equation is then given by:

$$y\frac{\partial(f_kS_k)}{\partial t} + \frac{\partial(qf_kS_k)}{\partial x} + [D_k(q,t) + F(t)f_k]S_k - yX_k(t,C,S) - B_k(q,t)S_{bk} - R_k(t)S_{rk} = 0 \quad [21]$$

The behavior of a particle size class may then be described as:

$$y\frac{\partial f_k}{\partial t} + \frac{\partial(qf_k)}{\partial x} + D_k(q,t) + F(t)S_k - B_k(q,t) - R_k(t) = 0 \qquad [22]$$

where f_k = concentration of a particle size class, g/cm³

S_k = concentration of sediment-laden chemical for a sediment size fraction, µg/g sediment

$\bar{f}_k$ = average value of f_k in the control element, g/cm³

$\bar{S}_k$ = average value of S_k in the control element, µg/g

R_k = addition of solids from rainfall, g/cm²/min

S_{rk} = concentration of the chemical in the particulates in rainwater, µg/g

B_k = addition of solids due to detachment, g/cm²/min

S_{bk} = concentration of the chemical in the sedimentation-solids, µg/g

D_k = deposition of sediment, g/cm²/min, and

k = a particular particle size class.

The parameters B and D can be estimated by models which route runoff discharge and sediment, such as ANSWERS and SEDIMOT II. The value of S_{bk} is represented by the concentration of the chemical in the initial soil size class. When it is assumed that only fine sized particles exist in the rainwater, the value of R is determined by measuring the concentrations of chemical in unfiltered and filtered rainwater. The difference of the measurements corresponds to the content of the particulate chemical. This value is, however, negligible in the case of phosphorus as noted for the dissolved form.

Total concentrations of sediment-bound chemical and sediment itself are then $\sum_{k=1}^{n} f_k S_k$ and $\sum_{k=1}^{n} f_k$ in µg/cm³ and g/cm³, respectively, where n is the number of sediment size classes. For calculation of cumulative particulate phosphorus load, C is replaced by $\sum_{k=1}^{n} f_k S_k$ in Equation [20].

Potential Applications

The model proposed has many possible applications ranging from small experimental plots to large watersheds, and from surface runoff in the upland areas to river systems. Some studies have used similar models to simulate organic matter (Webster *et al.*, 1979; Webster, 1983) and phosphorus (Newbold *et al.*, 1983) transport in a river system. But these studies did not consider the adsorption kinetics of dissolved elements onto the particulate materials. Novotny (1978) did not take into account the dynamic change of sediment size distribution during runoff discharge and used a simple model for routing particulate phosphorus, which did not include the advection process.

Equations [13] and [21] suggest possible practices for reduction of nonpoint source pollution. The equations show that nonpoint source pollution can be minimized by retarding or detaining runoff discharge. Reduced rainfall inputs (Y and R), desorption (Z), and erosion (B) from soil surface, and/or the initial concentration of chemicals in the upper few cm of the soil surface prior to runoff (S_{bk}), will diminish nonpoint source pollutants entering water bodies. Management practices increasing the infiltration rate of runoff water (F), the adsorption reaction rate (X), and subsequent sediment deposition (D), and biological uptake (K_m) will also lead to successful reduction of nonpoint source pollution. The equations can thus simulate the effectiveness of individual management practices and the significance of each component.

Most significant phosphorus losses in waterways have been found to result from particulate forms. This is ascribed to rapid adsorption of dissolved P onto soil particles when it is applied to an area and onto sediment particles while it is flowing with surface runoff (Kunish *et al.*, 1972; Sharpley *et al.*, 1981c). Consequently, phosphorus movement from land to water is strongly dependent on sedimentation processes (Burwell *et al.*, 1975; Singer and Rust 1975, Sharpley and Syers 1979). Phosphorus removal through sedimentation can be estimated knowing the phosphorus content of the different particle size classes and the amount of sediment deposited. The relevant studies were reviewed in Chapter 2. Those results em-

phasize the significance of the adsorption, sedimentation, and deposition terms in Equations [13] and [21].

In considering Equations [13] and [15] through [19], X apparently reflects the fact that the soluble phosphorus concentration of surface runoff is inversely related to the sediment concentration (McDowell and McGrefor 1980, Sharpley *et al.* 1981c). Sharpley (1980) found that the enrichment ratio (ER) was largely related to runoff and rainfall energy and soil phosphorus status rather than soil physical properties. This indicates that the terms, Z and/or B, are functions of runoff discharge and rainfall energy. Sediment in runoff was more enriched with phosphorus than original soil mass from which it was eroded. This was explained by the fact that the clay-sized soil particles and organic matter have high adsorption capacity for phosphorus and are more easily transported than other soil particles. Also, desorption, Z, increases with increased initial phosphorus content of soil as shown in Equation [14]. Increased desorption from the surface soil to runoff results in a high adsorption rate by Equation [17] and hence high phosphorus enrichment if the value of b is greater than zero. With increased rainfall intensity and soil slope, enrichment will decrease because of less selective sediment transport. The decreasing enrichment may be accounted for by an increased fraction of coarse sized sediment as runoff energy increases. This is associated with Equations [15] through [19]. It is expected that nutrient adsorption is very slow or negligible for coarse sediment compared to the clay-sized fraction (Sharpley and Syers, 1976). This can be verified with phosphorus adsorption tests, and conforms to the observations of Menzel (1980) and Sharpley (1980) who reported that the enrichment ratio and sediment discharge have a negative logarithmic relationship.

Application to Grass Filter Strips

The partial differential equations were solved numerically after being formulated into finite-difference equations with an implicit method. When the governing equations of runoff and sediment discharge are available, those equations would also be transformed into finite-difference forms. The resulting finite-difference equations can then be linearized when boundary conditions are available. The linear system can be solved by any standard method, such as the Gausian elimination method or the matrix inversion method (Chen 1979). Subroutine GRASS of SEDIMOT II has, however, provided the solutions of runoff, sediment discharge, and the fraction of each sediment size class, which were thus treated as the known values in this study.

To more accurately route runoff and sediment during a storm period, an infiltration submodel was incorporated into the public version of SEDIMOT II, which assumed that infiltration was constant during a storm period. A modified Holtan equation was adopted for the present study (Yaramanoglu 1981). The model obtains the volume and rate of infiltration as a function of time by modifying Holtan's original equation, which accounts for the effect of cover condition and soil texture on the infiltration rate (Yaramanoglu 1981, Smolen *et al.* 1984). As explained earlier, the increase in infiltration rate is an important function of vegetative filter strips to remove both dissolved and particulate nutrients from surface runoff. The infiltration equation is given as follows:

$$f = a[A^{1-n} - a(1-n)t]^{n/(1-n)} + f_c \qquad [23]$$

where f is the infiltration rate (cm/hr), a is a coefficient to index the effect of cover condition, A is the available pore space in soil at time $t=0$ (cm), which is the unfilled storage space to a restrictive layer (usually assumed to be the A horizon), n is a coefficient that is assumed to be a function of soil type and is defined as the ratio of potential plant available water to the potential gravitational water in the A horizon, and f_c is the final infiltration rate (cm/hr). Sub-

routine GWATR in the old version of SEDIMOT II accounts for the routing of runoff discharge in grass filter strips. The subroutine, however, does not contain direct rainfall input to the grass filter zone as reviewed earlier. Hence the subroutine was modified to include the direct rainfall input in runoff discharge routing. Interception, evapotranspiration, retention, and detention were not considered in the present study. Those hydrologic components may not significantly reduce the excess water in the clipped grass filter strip during a short period of storm.

Additional submodels were incorporated into SEDIMOT II to simulate phosphorus transport. The public version of SEDIMOT II can not describe runoff discharge and its sediment size distribution at more than three points along a filter slope due to its fixed dimension statements. Hence the model was modified to calculate those values at any point along the waterway. This was accomplished by modifying subroutine GRASS and by adding subroutines PSFR1 and PSFR2. The fractions and concentrations of three sediment size classes can be predicted by PSFR1 and PSFR2, respectively, at any points along waterway and at time interval. Particulate phosphorus contents were estimated for the three soil particle size classes used in SEDIMOT II: coarse (>37 μm), medium (4 to 37 μm), and fine (<4 μm).

Formulation of the Finite Difference Equations

Amein and Fang (1970) and Price (1974) compared the techniques, such as characteristic, explicit, and implicit methods, with which the flood routing equation could be solved. They suggested that the implicit method was unconditionally stable and faster and more accurate than other finite-difference methods. In the present study, the partial differential equations were converted into an equivalent systems of finite difference equations using the implicit method (Chen 1979). Chen (1979) suggested that a function and its partial derivatives could
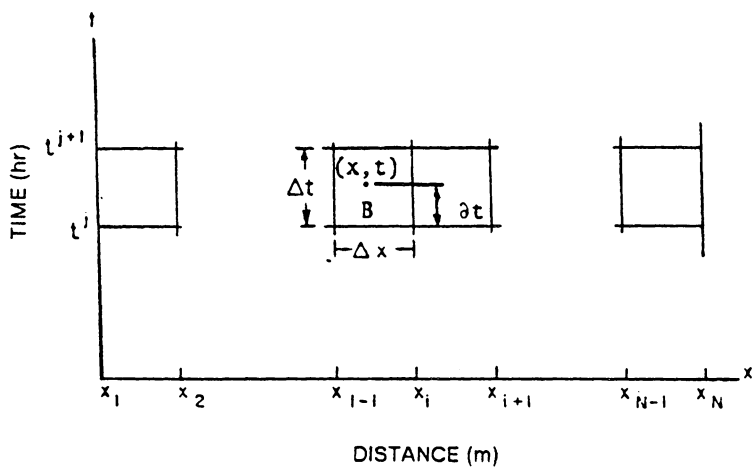
Figure 5. Network for the implicit method: From Chen (1979)

be approximated within a four-point grid formed by the intersections of the space lines x_i and x_{j+i} with the time lines t^j and t^{j+1} as follows (see Figure 5):

$$g \cong \frac{1}{2} \ (g_i^{j+1} + g_{i+1}^{j+1}) \tag{24}$$

$$\frac{\partial g}{\partial x} \cong \frac{1}{\Delta x} \ (g_{i+1}^{j+1} - g_i^{j+1}) \tag{25}$$

and

$$\frac{\partial g}{\partial t} \cong \frac{1}{2\Delta t} \ [(g_i^{j+1} - g_i^j) + (g_{i+1}^{j+1} - g_{i+1}^j)] \tag{26}$$

where g and h represent variables. All the variables are known at all nodes of the networks on the time line t^j. The unknowns on time line t^{j+1} can be found by solving the system of linear algebraic equations formulated from the substitution of the finite-difference approximations into the governing equations. Consequently, each term of Equation [13] can be approximated as follows:

$$y\frac{\partial C}{\partial t} \cong y_{i+1/2}^j \frac{1}{2\Delta t}(C_{i+1}^{j+1} + C_i^{j+1} - C_{i+1}^j - C_i^j) \tag{27}$$

$$\frac{\partial(qC)}{\partial x} \cong q_{i+1/2}^{j+1}\frac{1}{\Delta}x(C_{i+1}^{j+1} - C_{i+1}^{j+1}) + C_{i+1/2}^{j+1}\frac{1}{\Delta x}(q_{i+1}^{j+1} - q_i^{j+1}) \tag{28}$$

$$(F + yK_m)C \cong (F_{i+1/2}^{j+1} + y_{i+1/2}^{j+1}K_m)C_{i+1/2}^{j+1} \tag{29}$$

The known variables were then transformed into other variables as follows:

$$a_g = \frac{1}{4\Delta t}(y_i^{j+1} + y_{i+1}^{j+1}) \tag{30}$$

$$b_g = \frac{1}{\Delta x}(q_i^{j+1} + q_{i+1}^{j+1}) \tag{31}$$

$$c_9 = \frac{1}{2\Delta x}(q_{i+1}^{j+1} - q_i^{j+1})$$ [32]

$$d_9 = \frac{1}{4}[(F_i^{j+1} + F_{i+1}^{j+1}) + K_m(y_i^{j+1} + y_{i+1}^{j+1})]$$ [33]

$$e_9 = (-yX + Y + Z)_{i+1/2}^{j+1}$$ [34]

where the subscript 9 notes that the corresponding variables are related to the routing of dissolved chemical form. Substituting the resulting variables into Equation [13] and arranging:

$$a_9(C_{i+1}^{j+1} + C_i^{j+1} - C_{i+1}^{j} - C_i^{j}) + b_9(C_{i+1}^{j+1} - C_i^{j+1}) + (c_9 + d_9)(C_{i+1}^{j+1} + C_i^{j+1}) = e_9$$ [35]

By redefining some variables as follows:

$$l_9 = a_9 + b_9 + c_9 + d_9$$ [36]

$$m_9 = a_9 - b_9 + c_9 + d_9$$ [37]

$$r_9 = e_9 + a_9 C_i^{j} - m_9 C_i^{j+1}$$ [38]

substituting the resulting variables into Equation [35] and rearranging, the following equation is derived:

$$C_{i+1}^{j+1} = \frac{1}{l_9}(n_9 C_{i+1}^{j} + r_9)$$ [39]

It is assumed that the value of EDI is constant or negligible in terms of Equations [3] and [4] in vegetative filter strips because net soil loss is negative or surface soil is covered with plants (Sharpley, personal communication). The value of EDI is then only a function of soil aggregate or nutrients may not be significantly desorbed from the soil of the filter strips. In this case, Equation [14] can be further expanded for computation of the desorption amount from the soil surface to runoff.

$$Z_s = EDI \ \ D_b \ \ K \ \ P_o \frac{\partial(t^\alpha \ W^\beta)}{\partial t}$$

or

$$Z_s = EDI \ \ D_b \ \ K \ \ P_o(\alpha \ t^{\alpha-1} \ W^\beta + \beta \ t^\alpha \ W^{\beta-1} \frac{\partial W}{\partial t}) \tag{40}$$

where the water-to-soil ratio, W, is defined as the ratio of runoff volume to soil mass in the interacting zone. Runoff volume is calculated multiplying the average runoff discharge by travel time for every filter distance increment. The soil mass is represented by soil volume in the interacting soil (EDI*distance increment) times bulk density (D_b). Time-variation of water-to-soil ratio is proportional to runoff discharge variations in vegetative filter strips where the values of EDI and D_b are constants. Time variation of water-to-soil ratio in a filter segment was then transformed into a finite difference form as follows:

$$\frac{\partial W}{\partial t} \cong \frac{(W^{j+1} - W^j)}{\Delta t} \tag{41}$$

For the adsorption of dissolved phosphorus onto suspended solids, after Equation [17] or [19] was substituted into Equation [15], it was approximated with Equation [42] or [43].

$$X_k = 2^{-1-b_k-c_k} \ a_k \ (f_{i+1}^{j+1} + f_i^{j=1})(C_{i+1}^{j+1} + C_i^{j+1})^{b_k}(S_{i+1}^{j+1} + S_i^{j+1})^{c_k} \tag{42}$$

$$X_k = \frac{1}{2}(f_{i+1}^{j+1} + f_i^{j+1}) \ \frac{1}{\varepsilon_k t} \tag{43}$$

Total adsorption of dissolved phosphorus into suspended solids was approximated after Equation [42] or [43] was substituted into [16]. It is assumed that dissolved phosphorus input from rain is negligible.

The governing equation of particulate phosphorus was approximated by the following Equations [44] through [59].

$$y\frac{\partial fS}{\partial t} = y[f\frac{\partial S}{\partial t} + S\frac{\partial f}{\partial t}]$$

$$\cong y_{i+1/2}^{j+1}f_{i+1/2}^{j+1}\frac{1}{2\Delta t}(S_{i+1}^{j+1} + S_i^{j+1} - S_{i+1}^j - S_i^j) \qquad [44]$$

$$+ y_{i+1/2}^{j+1}S_{i+1/2}^{j+1}\frac{1}{2\Delta t}(f_{i+1}^{j+1} + f_i^{j+1} - f_{i+1}^j - f_i^j)$$

$$\frac{\partial qfS}{\partial x} = qf\frac{\partial S}{\partial x} + qS\frac{\partial f}{\partial x} + fS\frac{\partial q}{\partial x}$$

$$\cong q_{i+1/2}^{j+1}f_{i+1/2}^{j+1}\frac{1}{\Delta x}(S_{i+1}^{j+1} - S_i^{j+1}) + q_{i+1/2}^{j+1}S_{i+1/2}^{j+1}\frac{1}{\Delta x}(f_{i+1}^{j+1} - f_i^{j+1}) \qquad [45]$$

$$+ f_{i+1/2}^{j+1}S_{i+1/2}^{j+1}(q_{i+1}^{j+1} - q_i^{j+1})$$

The value of D is expressed by the quantitative difference of a sediment size class in influent and effluent. Therefore, the third term of Equation [21] is approximated as follows:

$$DS \cong \frac{1}{\Delta x}(f_i^{j+1}q_i^{j+1} - f_{i+1}^{j+1}q_{i+1}^{j+1})S_{i+1/2}^{j+1} \qquad [46]$$

The known variables on line t^j were converted into simple parameters:

$$a_7 = \frac{1}{8\Delta t}(f_{i+1}^{j+1} + f_i^{j+1})(y_{i+1}^{j+1} + y_i^{j+1}) \qquad [47]$$

$$b_7 = \frac{1}{8\Delta t}(y_{i+1}^{j+1} + y_i^{j+1})(f_{i+1}^{j+1} + f_i^{j+1} - f_{i+1}^j - f_i^j) \qquad [48]$$

$$c_7 = \frac{1}{4\Delta x}(q_{i+1}^{j+1} + q_i^{j+1})(f_{i+1}^{j+1} + f_i^{j+1}) \qquad [49]$$

$$d_7 = \frac{1}{4\Delta x}(q_{i+1}^{j+1} + q_i^{j+1})(f_{i+1}^{j+1} - f_i^{j+1}) \qquad [50]$$

$$d_7' = \frac{1}{4\Delta x}(q_{i+1}^{j+1} - q_i^{j+1})(f_{i+1}^{j+1} + f_i^{j+1}) \qquad [51]$$

$$e_7 = \frac{1}{2\Delta x}(f_i^{j+1}q_i^{j+1} - f_{i+1}^{j+1}q_{i+1}^{j+1}) \qquad [52]$$

$$g_7 = (yX_k + BS_b + RS_r)_{i+1/2}^{j+1} \tag{53}$$

Substituting the resulting variables into the partial differential equation [21] and arranging:

$$
\begin{aligned}
(a_7 &+ b_7 + c_7 + d_7 + e_7 + f_7)S_{i+1}^{j+1} \\
&+ (a_7 + b_7 - c_7 + d_7 + e_7 + f_7)S_i^{j+1} - a_7 S_{i+1}^j - a_7 S_i^j = g_7
\end{aligned}
\tag{54}
$$

For convenience, known variables are redefined:

$$l_7 = a_7 + b_7 + c_7 + d_7 + e_7 + f_7 \tag{55}$$

$$m_7 = a_7 + b_7 - c_7 + d_7 + e_7 + f_7 \tag{56}$$

Substituting Equations [55] and [56] into [54]:

$$l_7 S_{i+1}^{j+1} - a_7 S_{i+1}^j = g_7 - m_7 S_i^{j+1} + a_7 S_i^j \tag{57}$$

Redefining known variable set:

$$r_7 = g_7 - m_7 S_i^{j+1} + a_7 S_i^j \tag{58}$$

Substituting the resulting variable into Equation [57] and arranging, the following equation is obtained:

$$S_{i+1}^{j+1} = \frac{1}{l_7}(r_7 + n_7 S_{i+1}^j) \tag{59}$$

It is assumed that the inputs of particulate phosphorus from rainwater and soil dislodgement in vegetative filter strips are negligible. The result of each particle size class can then be summed for computation of the total particulate phosphate concentration.

Cumulative dissolved phosphorus load which passed a point along a flow path can be calculated by numerical integration of Equation [20]. Using the trapezoidal rule, the equation is transformed as follows:

$$L_{i+1} = \frac{\Delta t}{4} \sum_{j=1}^{m} (C_{i+1}^{j} + C_{i+1}^{j+1})(Q_{i+1}^{j} + Q_{i+1}^{j+1}) \qquad [60]$$

where L_{i+1} is the cumulative dissolved phosphorus load (mg) at $(i+1)$th distance step of the flow path, m is the number of time interval, and the other variables are the same as defined previously. For calculation of cumulative particulate phosphorus load, C was replaced by $\sum_{k=1}^{n} f_k S_k$ in Equation [60]. The effectiveness of a nonpoint pollutant management systems was expressed by:

$$PTE = \frac{(L1 - L2)}{L1} \times 100 \qquad [61]$$

where PTE is phosphorus trap efficiency of the management system, and L1 and L2 are the cumulative phosphorus loads of influent and effluent for the management system, respectively.

A computer program was generated with FORTRAN 77, based upon the above finite difference equations, and incorporated into some subprograms of SEDIMOT II. The new program is called GRAPH since it describes phosphorus transport in grass filter strips (GRAssed-strip-PHosphorus). The program is explained in the appendices.

Chapter 5

Results and Discussion

This chapter discusses the results of experimental plot simulation, laboratory batch experiments for phosphorus adsorption and desorption reactions, and mathematical model verification. Nutrient transport will be discussed in relation to runoff discharge and sediment concentration and size distribution since these are the primary functions affecting nutrient transport. For convenience, figures and tables relating to individual parameters, e.g., runoff, sediment, and phosphorus, are placed in the text, while combined tables are found in Appendix A (Tables A-1 through A-5). The soil and plant samples analyzed in this study were assumed to reflect almost the same characteristics as they were for the last cropland simulation (Test 4). Thus model verification was attempted on the cropland simulations.

Experimental Plot Simulations

The rainfall simulator used in this research performed well with respect to application rates and uniformity. The rainfall rate averaged 50.1 mm/hr and ranged from 44.2 mm/hr (QF1T2R3 30-minute run) to 56.8 mm/hr (QF4T2R3 30-minute run). Uniformity coefficients, which are a measure of the uniformity of simulated rain application, were excellent, averaging 93.4 percent and ranging from 80.6 percent to 96.4 percent, with only 5 out of 54 values being less than 90 percent (Dillaha *et al.* 1986b).

Runoff Yield

In Figure 6, the area below each plotted line accounts for the total runoff volume yielded from the corresponding experimental plot due to the one-hour rainfall simulation (Test 4 Run 1). Runoff yield was reduced by VFS, especially in Plots QF1, QF8, and QF9. In this respect, it should be noted that the precipitated rainfall volumes were higher by 25 and 50 percent in the 4.6 m and 9.1 m filter plots, respectively, than in the no-filter plots. The results are consistent with those of Appendices A-1 through A-5. The reduction of runoff volumes is explained by high infiltration and surface storage in VFS due to flow retardation by vegetation cover and soil aggregation improved by high organic matter content (Wischmeier and Mannering 1965, Westerman and Overcash 1980, Loal *et al.* 1984). Figure 6 also demonstrates that runoff starting time was delayed by grassed areas. As shown in Table A-3, the VFS reduced runoff during the initial dry run (T1R1). This indicates that infiltration rates were initially very high in VFS, compared to the bare soil areas. The runoff reduction effect was diminished as rainfall continued (R2 and R3), suggesting that VFS did not contribute increasing final infiltration rate as much as it did to high initial infiltration rate. Consequently, it is expected that
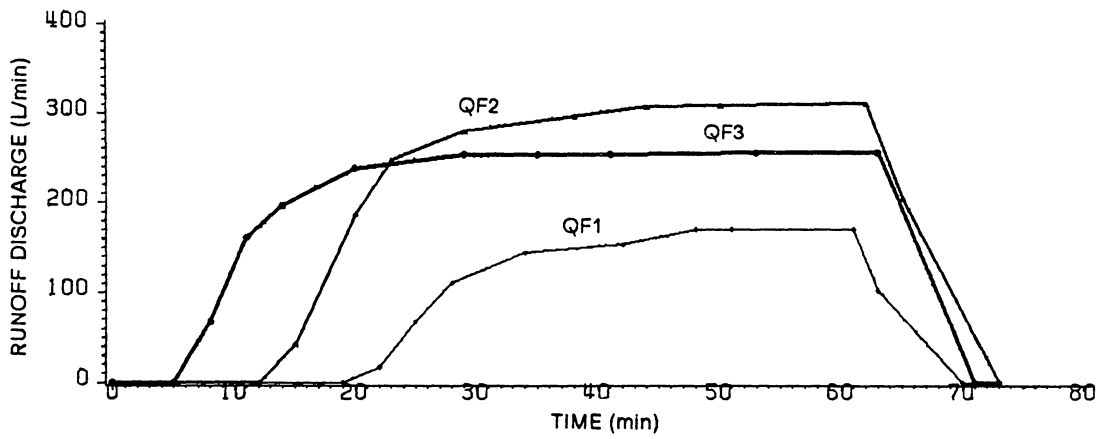
(a) QF123
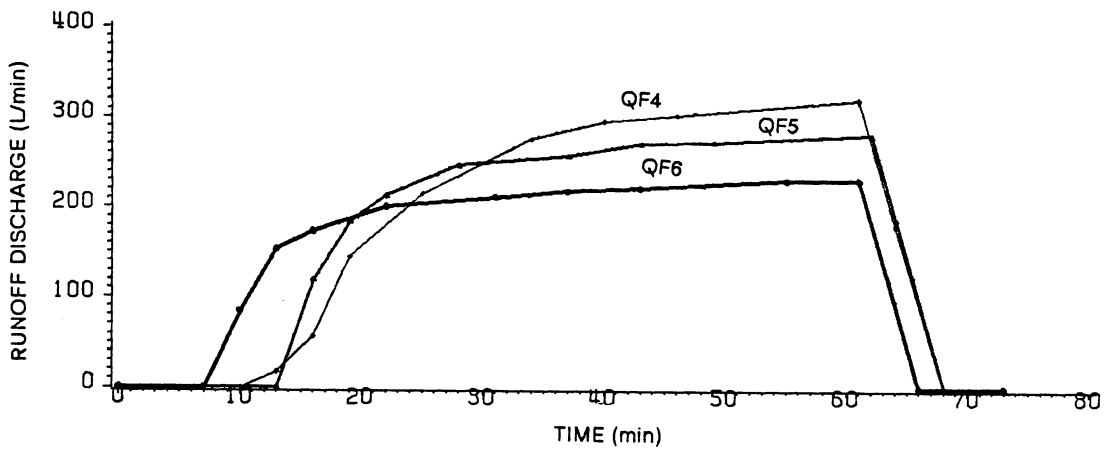
(b) QF456
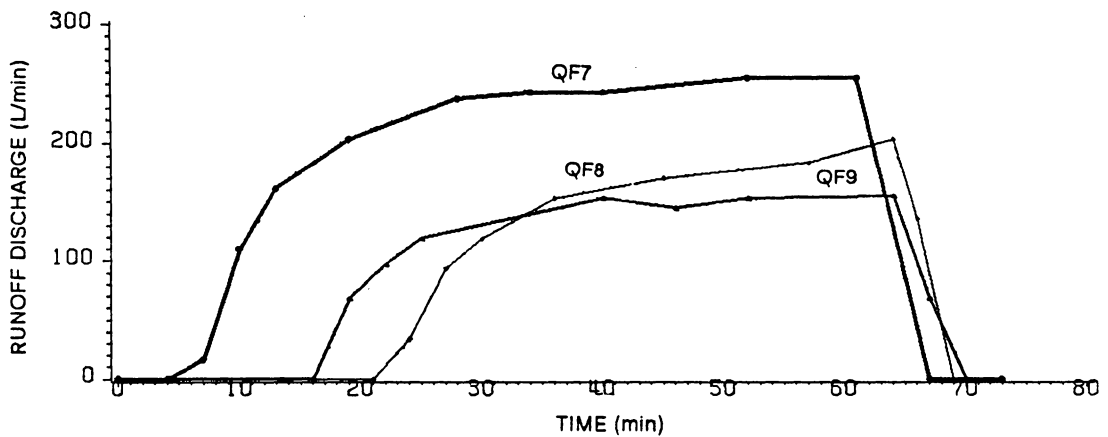
(c) QF789

Figure 6. Hydrograph of runoff discharge, Test 4 and Run 1: QF3, 6, and 7 - no filter; QF2, 5, and 7 - 4.6 m filter; QF1, 4, and 8 - 9.1 m filter (Data from Dillaha *et al.* 1986a)

infiltration is a significant phosphorus removal process once the soil is saturated with moisture.

The cross slope plots (QF789) showed relatively low runoff reduction in the VFS during Test 1 (Table A-5). This may be associated with reduced infiltration due to concentrated flow. The infiltration-contributing area is small when runoff is concentrated in narrow areas. However, runoff reduction was outstanding in QF8 and QF9 during Test 4 (Figure 6). This suggests that cross slope might be modified due to sediment deposition on waterways during Tests 1 through 3 and natural rainfall events.

Sediment Yield

Table 3 demonstrates cumulative particle size distribution of eroded sediment in plot runoff once discharge reached steady state. It is evident that the sediment size distribution is fairly uniform within plots. This result conforms to Sharpley's (1980) observations during rainfall simulation on perforated bottom boxes with dimensions of 100 by 30 by 70 cm. The average cumulative size distribution of eroded sediment was plotted as shown in Figure 7. Both Table 3 and Figure 7 indicate the selective detachment of fine particles in the bare soil portion of the plots and the selective deposition of coarse suspended solids in VFS. The summed clay and silt size fraction (< 50 µm) were greater than 95 percent of the total suspended solids in all but a few cases, showing selective detachment of finer sized particles. The finer size fraction was increased as filter length increased. This verifies that coarse particles are selectively deposited in filters. The relatively low fraction of fines in the QF6 discharge plot suggests that the fraction of coarse sized particles increases as transport capacity increases due to increasing runoff velocity on steep slopes. It is apparent that filter strips made particle size distribution homogeneous even though inflow sediment size distributions were different. The fractions of coarser sized particles increased in the order of QF7, 3, and

Table 3. Cumulative sediment particle size distribution in plot runoff, percent

Sample	Particle size (µm)						
	<0.7	<50	<150	<250	<500	<1000	<2000
QF1T3R3	43.7	99.4	99.6	99.6	99.7	99.9	99.9
QF1T4R1	79.3	97.6	98.5	98.7	99.0	99.5	99.8
QF1T4R3	50.8	92.7	96.7	98.8	99.4	99.6	99.7
QF2T3R1	-	-	99.0	99.2	99.3	99.7	99.9
QF2T3R3	34.6	99.5	99.7	99.8	99.8	99.9	100.0
QF2T4R1	35.8	97.1	98.2	98.9	99.3	99.6	99.9
QF2T4R3	54.8	97.5	98.9	99.1	99.4	99.7	99.9
QF3T3R1	-	-	98.6	98.8	99.2	99.7	99.9
QF3T3R3	-	-	95.6	96.6	97.9	99.2	99.8
QF3T4R1	7.6	70.7	78.7	81.0	86.7	94.4	98.5
QF3T4R3	14.5	91.5	98.2	98.8	99.2	99.6	99.9
QF4T4R1	40.0	99.7	99.9	99.9	100.0	100.0	100.0
QF4T4R2	17.8	96.7	99.4	99.6	99.8	99.9	100.0
QF4T4R3	30.8	98.0	99.5	99.7	99.7	.99.8	99.9
QF5T4R1	32.4	98.0	99.5	99.6	99.8	99.9	100.0
QF5T4R2	32.0	99.4	99.9	100.0	100.0	100.0	100.0
QF5T4R3	14.1	93.9	98.7	99.3	99.7	99.9	100.0
QF6T4R1	12.2	68.2	80.4	85.9	92.5	96.7	98.9
QF6T4R2	12.0	74.3	84.8	89.0	92.9	96.0	98.4
QF6T4R3	10.2	71.8	81.5	85.4	91.9	95.9	98.4
QF8T4R1	59.2	99.4	99.6	99.9	99.9	100.0	100.0
QF8T4R2	47.8	99.7	99.7	99.8	99.8	99.9	100.0
QF8T4R3	40.0	99.0	99.3	99.4	99.5	99.6	99.7
QF9T4R1	34.2	99.0	99.3	99.4	99.6	99.8	99.9
QF9T4R2	29.8	99.4	99.5	99.5	99.6	99.8	99.9
QF9T4R3	32.3	97.3	98.2	98.5	98.8	99.2	99.6
QF7T4R1	25.4	97.2	98.1	98.5	99.0	99.5	99.8
QF7T4R2	16.3	94.9	97.9	98.5	99.0	99.6	99.8
QF7T4R3	15.28	90.5	96.3	97.4	98.5	99.2	99.5
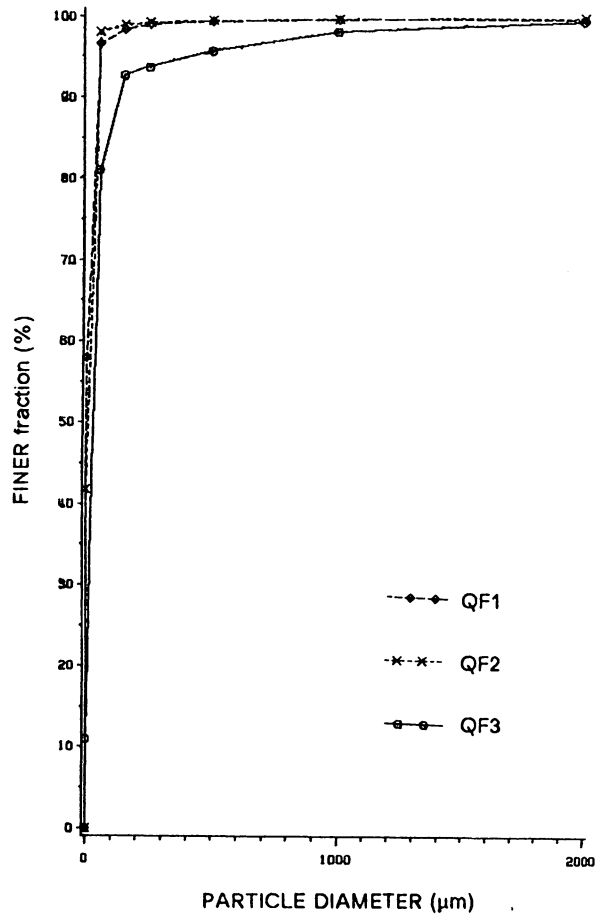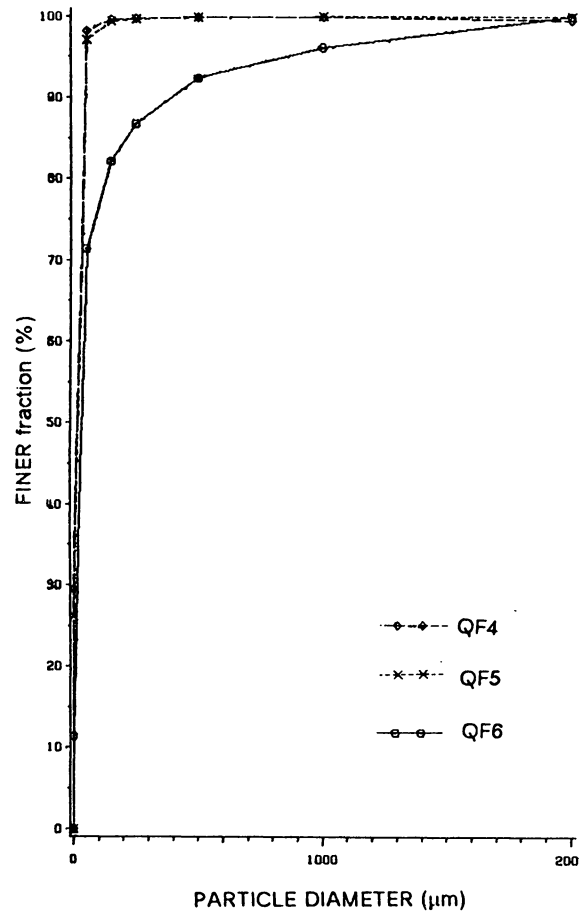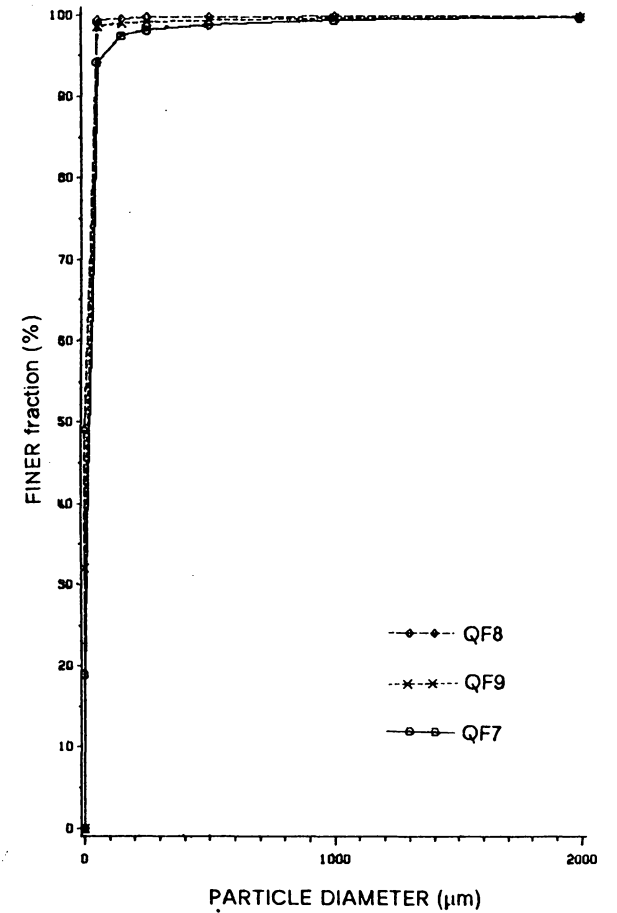
Figure 7. Cumulative sediment particle size distribution in plot runoff: QF1,QF4,QF8 - 9.1 m filter; QF2,QF5,QF9 - 4.6 m filter; QF3,QF6,QF7 - no filter

Results and Discussion

6. Considering the selective deposition of coarse sized particles, one can expect that a filter strip will trap sediment from the plots effectively in the opposite order if the other control conditions are identical.

Total suspended solids were reduced remarkably after runoff passed through the VFS (Figures 8 through 10). In Figure 8, the areas surrounded by plotted lines represent total suspended solids losses. At a glance, TSS was effectively removed in the order of QF123,QF456, and QF789 during Test 4 (cropland simulation). This is consistent with the results of Test 1 and 2 (Tables A-1 through A-5). During Test 1 and 2, TSS loss from the bare plots were 105 g, 235 g, and 77 g by plots for QF3, QF6, and QF7, respectively, while the 4.1 m filter plots, QF2, QF5, and QF9 lost 14, 56, and 54 kg of TSS, respectively (Table A-1). Percent reductions of TSS are summarized in Table 4. The high effectiveness of filters in QF123 is attributed to the relatively lower slope of these plots. Filters in QF456 had a relatively steep slope and their sediment trapping capacity was exceeded by extremely high TSS inputs. Ineffectiveness of QF789 filters was caused by concentrated flow as discussed below.

Doubling filter length increased the effectiveness of sediment removal from surface runoff by approximately 10 percent (Figures 8 to 10 and Tables A-4 and A-5). This supports the suggestion that the area of ponded water within upslope and first few meters of grassed filters account for most of the trapped sediment (Neibling and Alberts 1979). This sediment removal mechanism may be attributed to the selective deposition of large particles at the filter front. This is true until sediment deposition exceeds the sediment-trapping capacity of the upper portion of the VFS. Surface runoff is retarded due to grass resistance and overland flow is ponded at the upslope edge of the filter. This decreases the kinetic energy of the flow and thus sediment-transport capacity. Consequently, large heavier sediment particles and aggregates are selectively deposited at the filter front where sediment transport capacity first drops. As runoff flowed into the filter, the ponded area upslope of the filter was gradually filled with sediment and a triangular sediment wedge developed in the filter front as reported by Tollner *et al.* (1977) and Hayes *et al.* (1984). Once sediment deposition totally submerged the front grasses, a trapezoidal wedge advanced down the filter slope. As the grass became
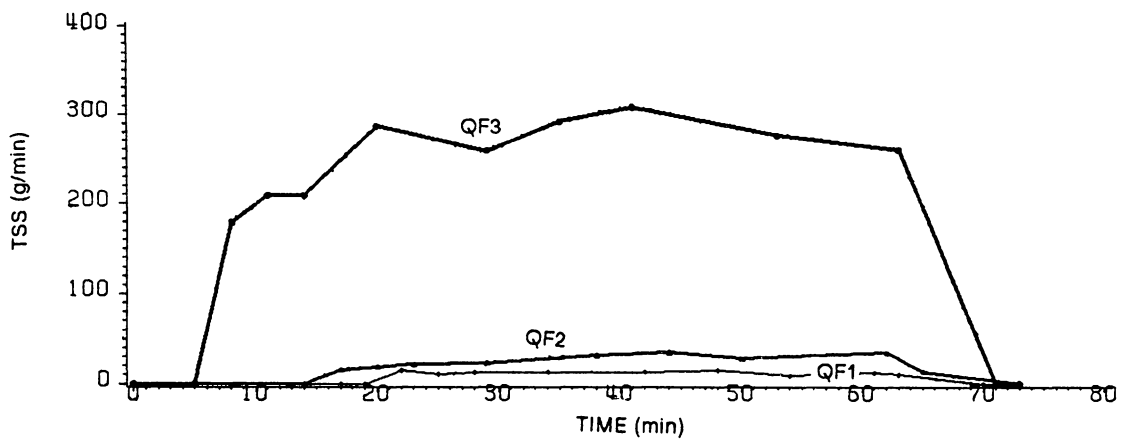
(a) QF123
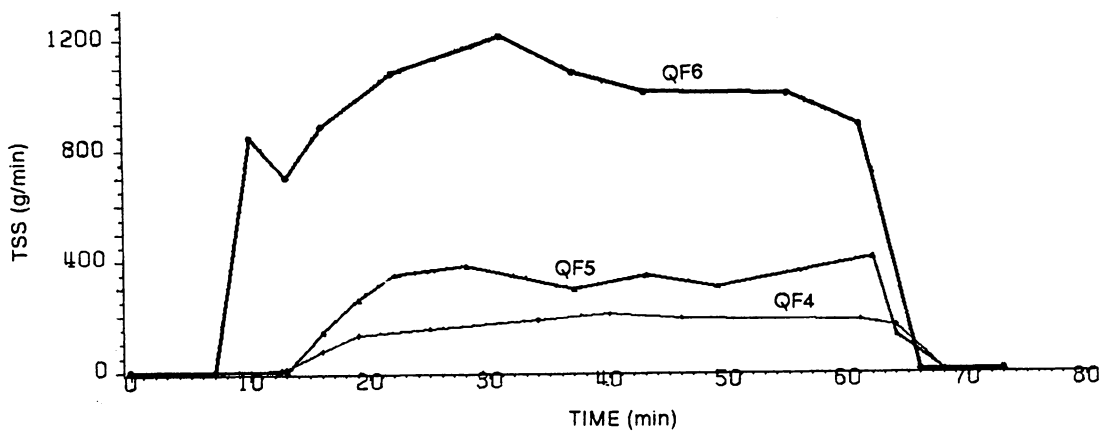
(b) QF456
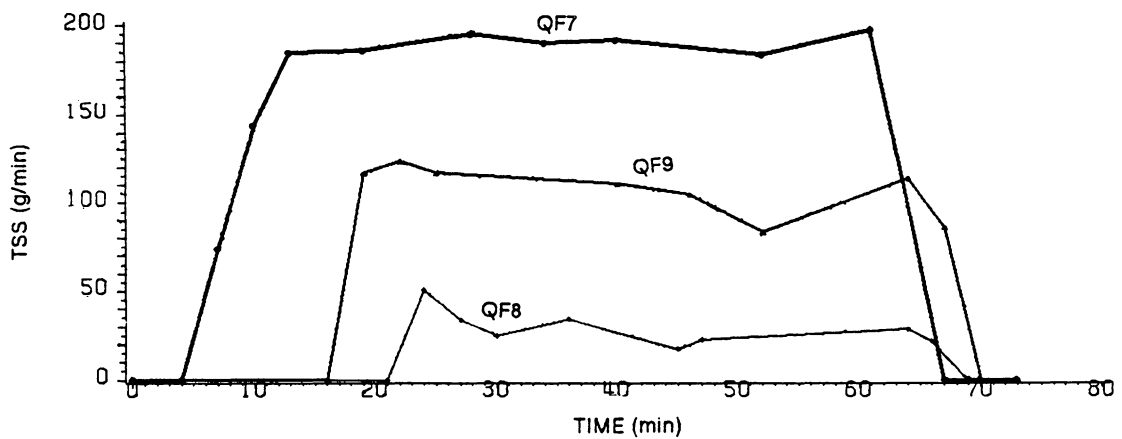
(c) QF789

Figure 8. Total suspended solid discharges, Test 4 Run 1: QF3, 6, and 7 - no filter; QF2, 5, and
9 - 4.6 m filter; QF1, 4, and 8 - 9.1 m filter (Data from Dillaha *et al*.1986a)
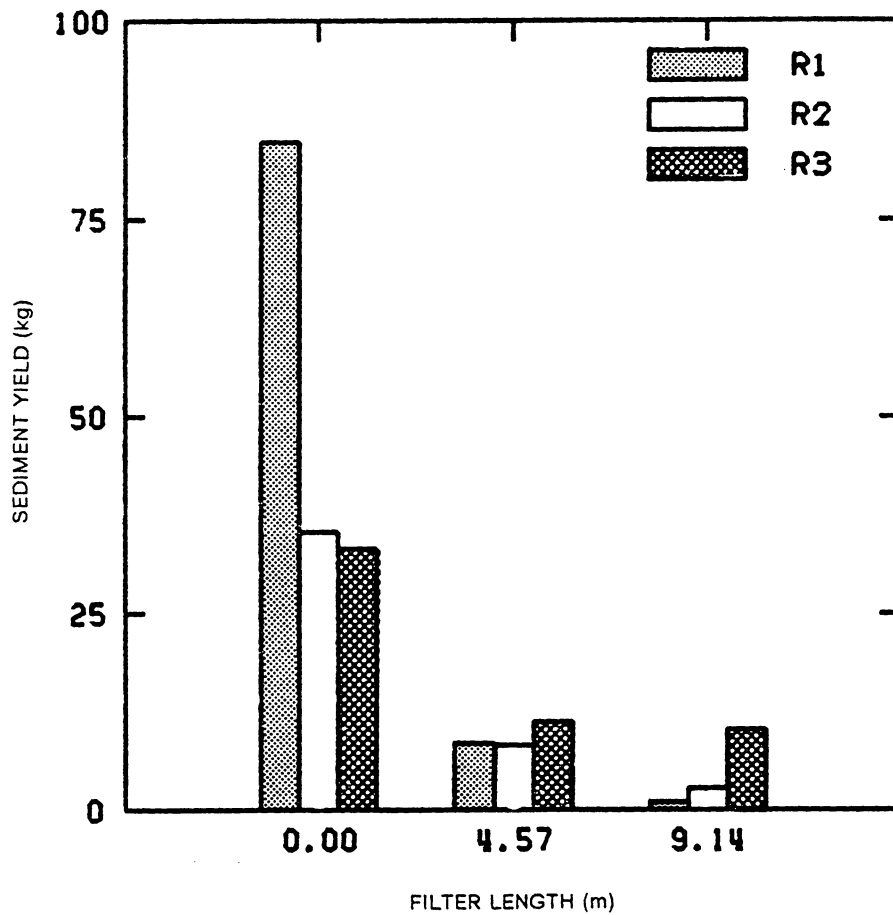
Figure 9. Sediment yields for plots QF4, QF5 and QF6 for Test 1

Results and Discussion
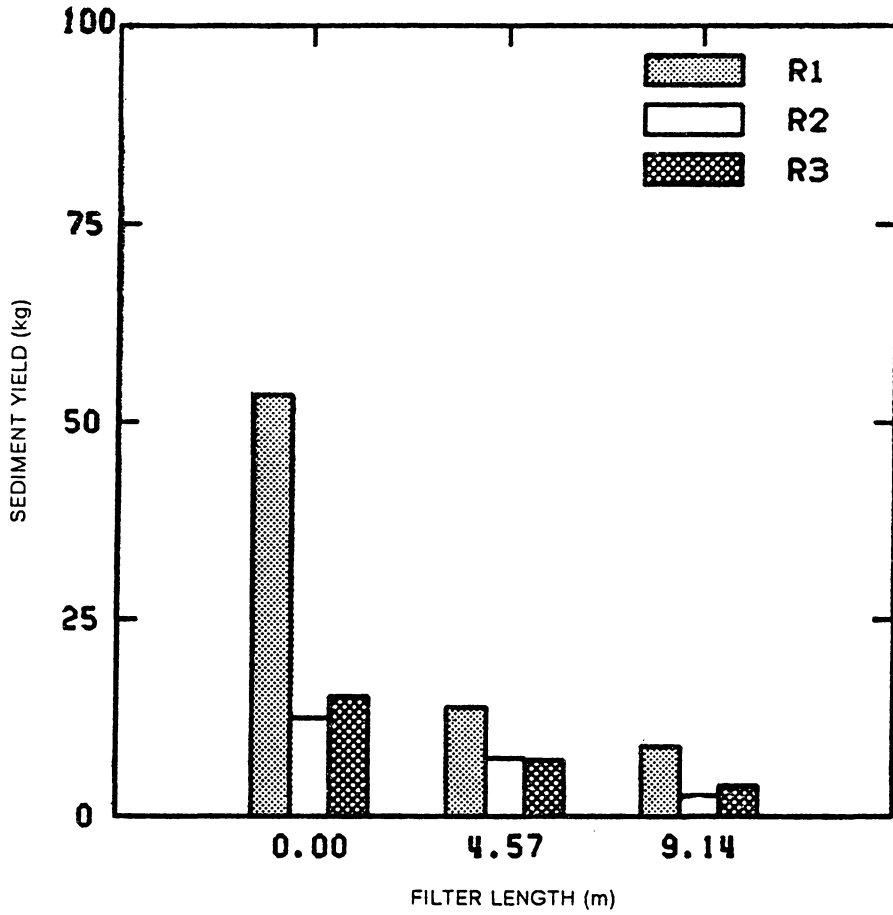
Figure 10. Sediment yields for plots QF4, QF5 and QF6 for Test 2

inundated with sediment, the flow resistance due to vegetation decreased, thus lowering the sediment-filtering capacity, which allowed the sediment wedge to gradually proceed down-slope. This process continued until sediment deposition exceeded the trapping capacity of the grass filter, which is assumed to be a function of filter grass height.

The effectiveness of VFS in removing sediment in runoff decreased as runoff continued (Figure 9 and 10, Table A-3). During Test 1, the 4.6 m and 9.1 m filters reduced TSS by 36 to 87 percent and 60 to 97 percent, respectively. During, Test 2, the effectiveness of the filters was reduced as the corresponding values were 20 to 87 percent and 55 to to 90 percent, re-spectively (Table A-5). The reduced effectiveness is explained by the inundation of grass with sediment and decreased infiltration due to soil moisture saturation. These results suggest that VFS effectiveness may be associated with grass recovery rate after the grasses are inundated by sediment deposition.

Cross slope in plots QF7 through 9 caused concentrated flow and resulted in channelized flow, which made the filters less effective in removing sediment from storm runoff. Concen-trated flow passed through a one-half to one meter wide portion of the VFS, and other parts of the filters did not contribute to the filtration of surface runoff. In addition, the concentrated flow inundated a small portion of the filter, bent the grasses over, and thus lowered the flow retardation effect. Sediment reductions were much lower in the concentrated flow plots than the sheet uniform flow plots (compare Figures 11 and 12 and see Tables A-1 through A-5). Considering that the sediment filtering capacity of VFS, in general, increases as slope angle decreases, plots QF8 and 9 would have been expected to be more effective for sediment re-moval than the other plots because they had the lowest slopes. This indicates that the con-centrated flow was responsible for the poor filter performance in the cross slope plots. In addition, the relatively ineffective sediment trapping in plots QF8 and QF9 can be ascribed to the low fraction of coarse sized particles as explained previously. This study does not identify which, concentrated flow or a lower fraction of coarse sized particles in the inflow to the filter, was the major factor affecting sediment removal in the concentrated flow plots.
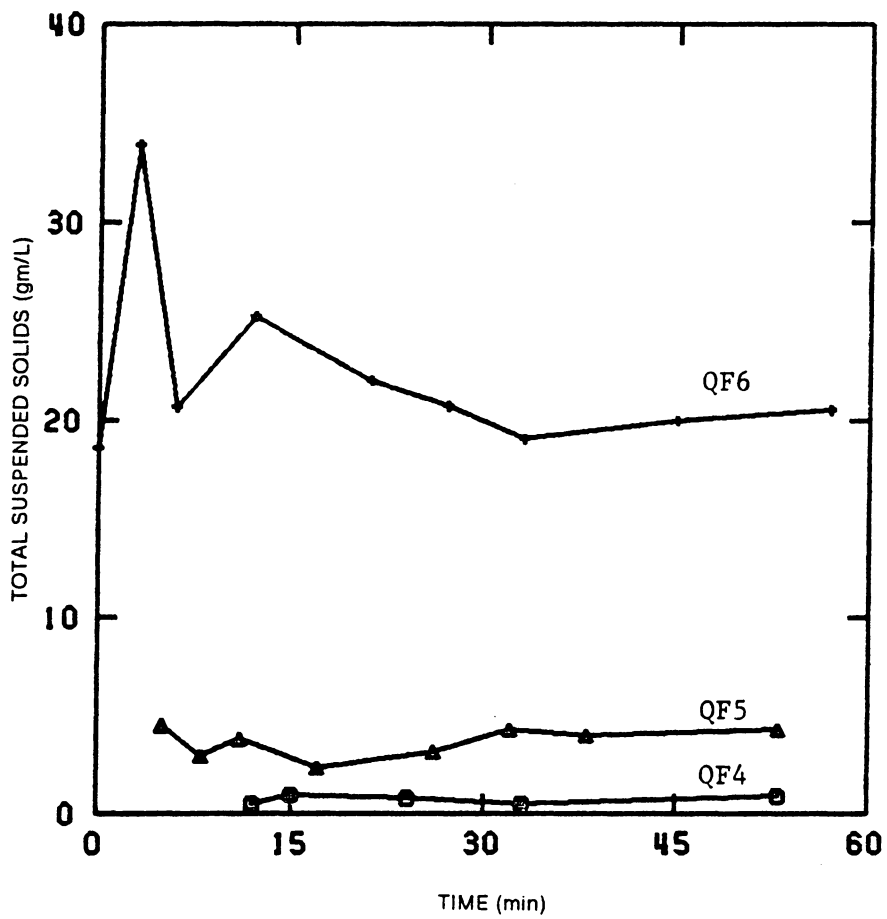
Figure 11. Sediment concentrations for uniform flow plots QF4, QF5, and QF6, Test 1 Run 1
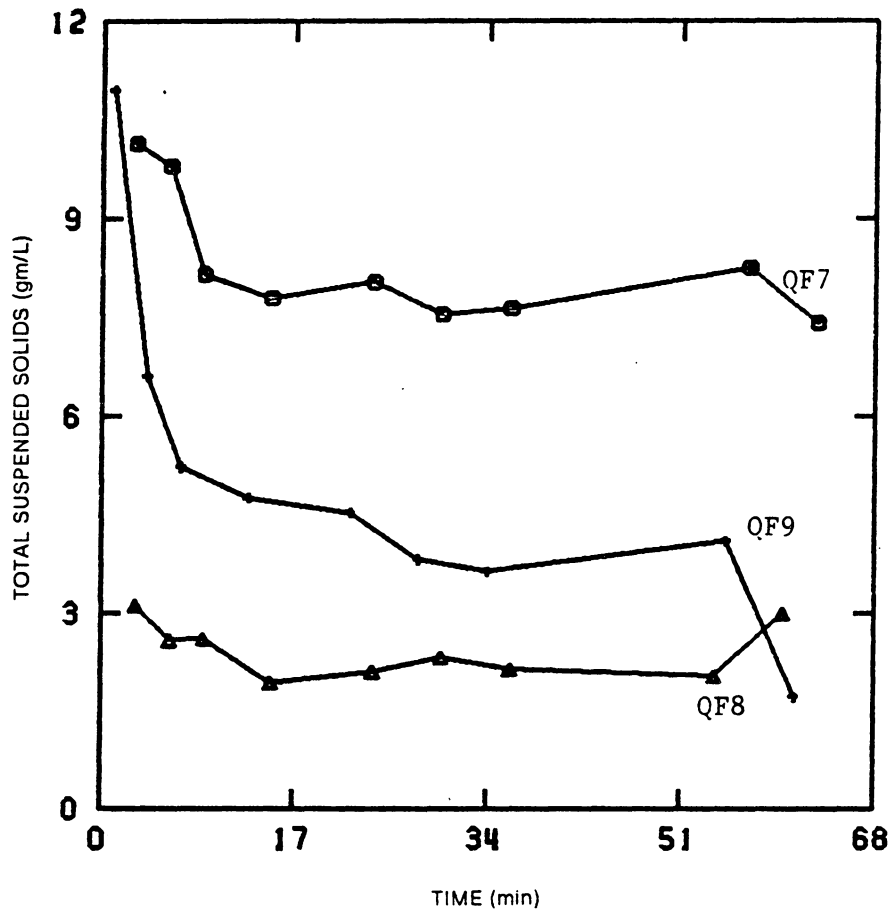
Figure 12. Sediment concentrations for concentrated flow plots QF7, QF8, and QF9, Test 1 Run 1

In grass filters, sediment deposition is influenced by variables such as runoff rate and sediment concentration, filter conditions such as grass height, spacing and stiffness, filter length, slope, soil and type and organic matter content, and their interaction such as the degree of submergence of grasses, flow velocity, and infiltration rate in the filter (Wilson 1967, Barfield and Albrecht 1982). Unfortunately, the physical plot simulations were not designed to separate the roles of these variables in the removal of sediment from plot runoff. The results, however, contribute to the verification of the mathematical simulation.

Phosphorus Yield

In Figure 13, the area below each plotted line represents the total amount of phosphorus lost from the corresponding experimental plots during the rainfall simulation. The vegetative filter strips were remarkedly effective in reducing TP in storm runoff. As shown in Figures 13 and 14, most phosphorus was in the form of TP rather than OP (note different scales). The amounts of OP generally increased after runoff passed through filter strips. The effect of filter length on OP loss is not consistent. The 4.6 m filter released more OP in the runoff than the 9.1 m filter in plot set QF123, while the opposite effect was observed in QF456. In QF789, OP was removed by the filters, but the 4.6 m filter was more effective in removing OP than the 9.2 m filter. This result indicates that OP transport is much more complex in vegetative areas than that of sediment-bound phosphorus. Figures 15 through 17 reemphasized the complexities of OP transport in VFS. In plot sets of QF123 and QF456, OP losses decreased with increasing filter length during Test 1, but they were generally higher from the plots with filters during Test 2. Inconsistent trend was observed from plot QF789 runoff. Dissolved phosphorus losses could increase during Test 2 because considerable sediment-bound phosphorus had been deposited in the the filters during Test 1, and this sediment-bound phosphorus probably
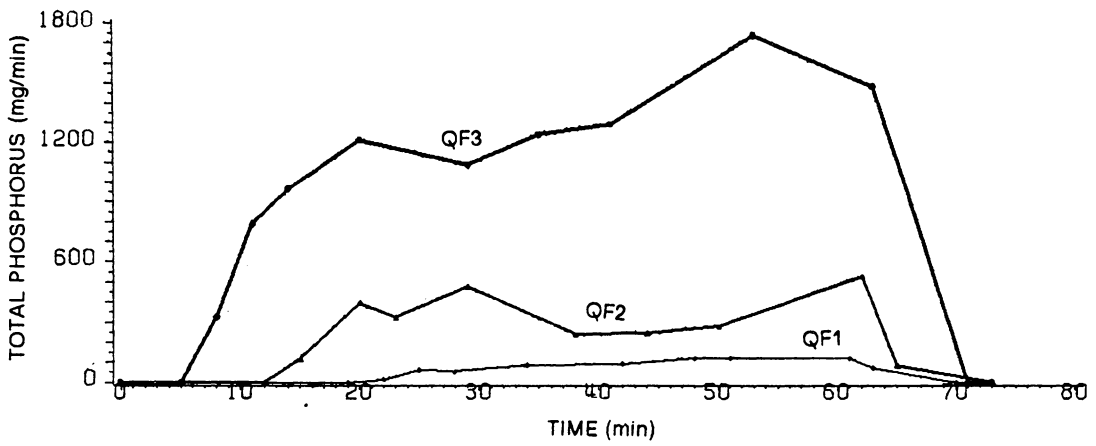
(a) QF123
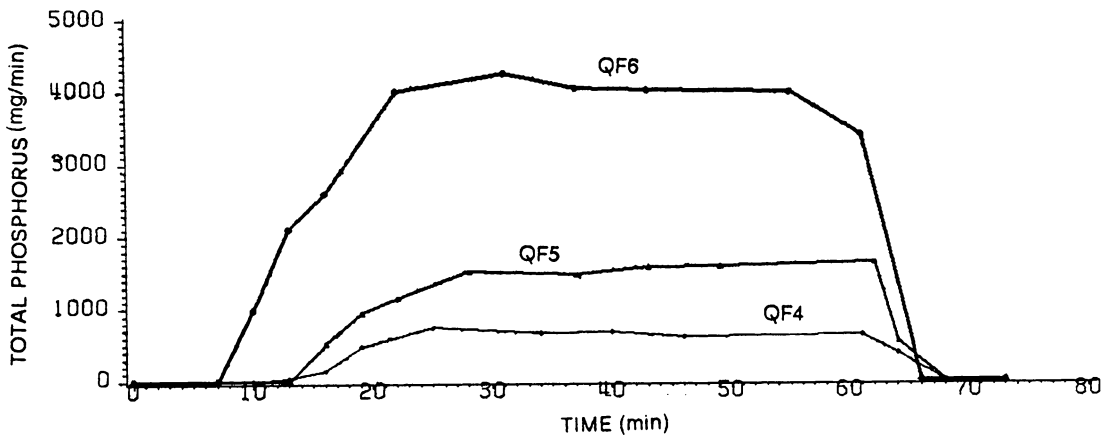
(b) QF456
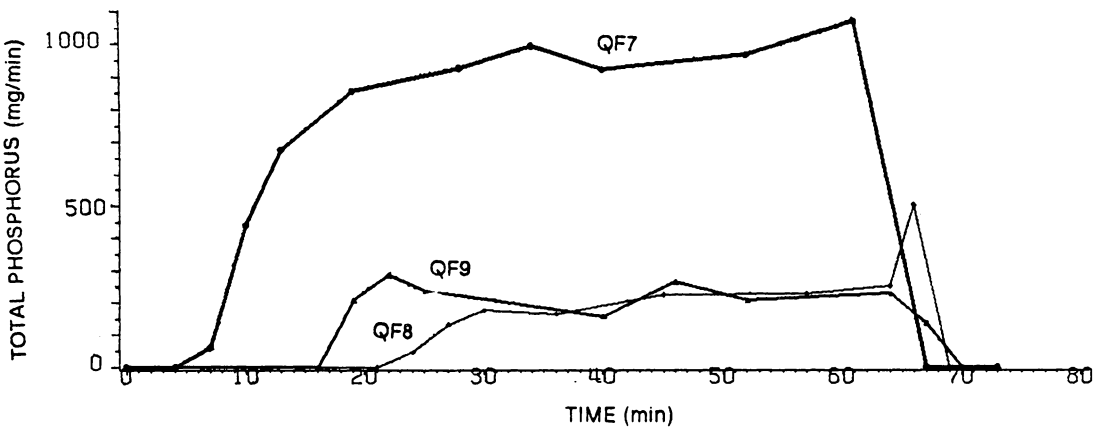
(c) QF789

Figure 13. Total phosphorus discharge, Test 4 Run 1: QF3, 6, and 7 - no filter; QF2, 5, and 7 - 4.6 m filter; QF1, 4, and 8 - 9.1 m filter (Data from Dillaha *et al.* 1986a)

(a) QF123

(b) QF456

(c) QF789
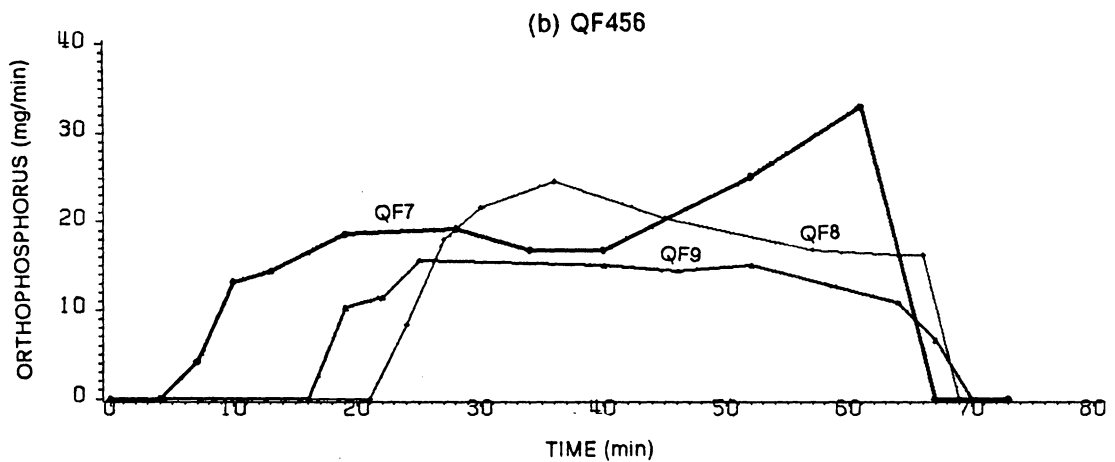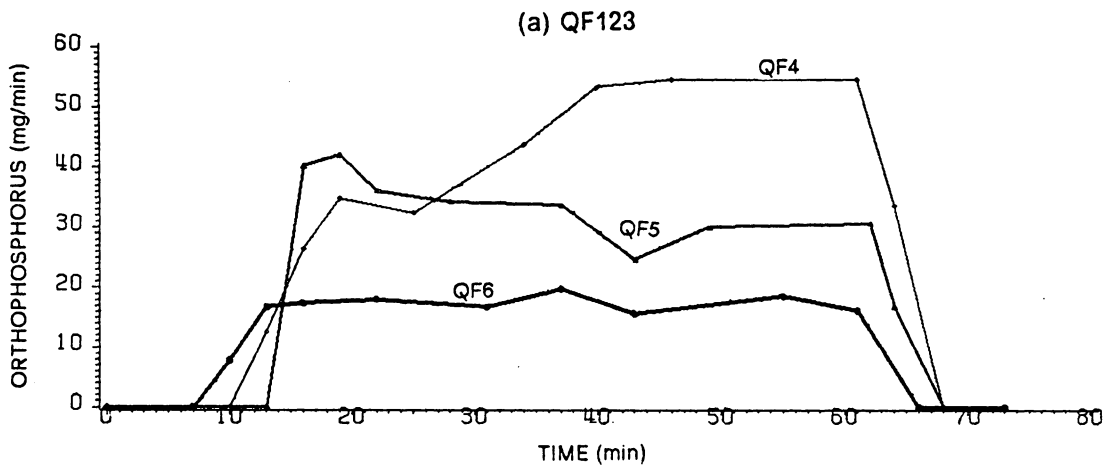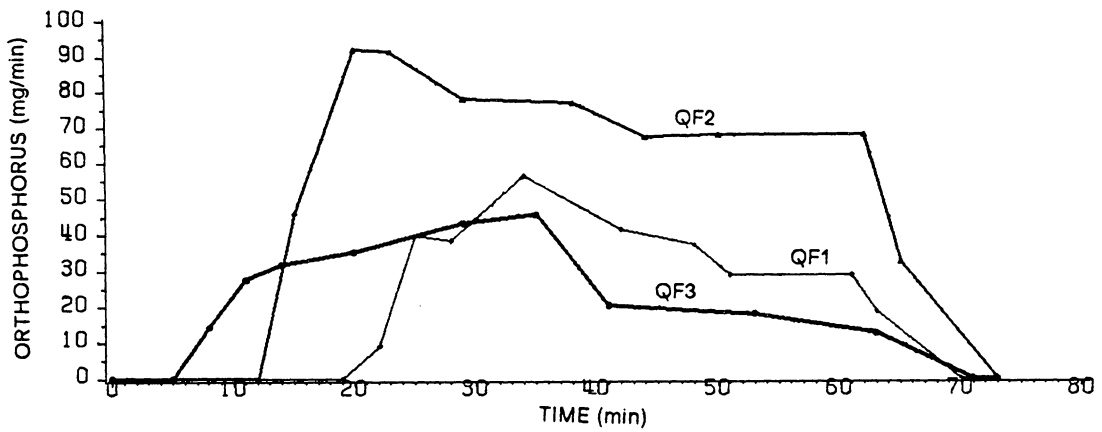
Figure 14. Orthophosphorus discharge, Test 4 Run 1: QF3, 6, and 7 - no filter; QF2, 5, and 7 - 4.6 m filter; QF1, 4, and 8 - 9.1 m filter (Data from Dillaha *et al* 1986a)
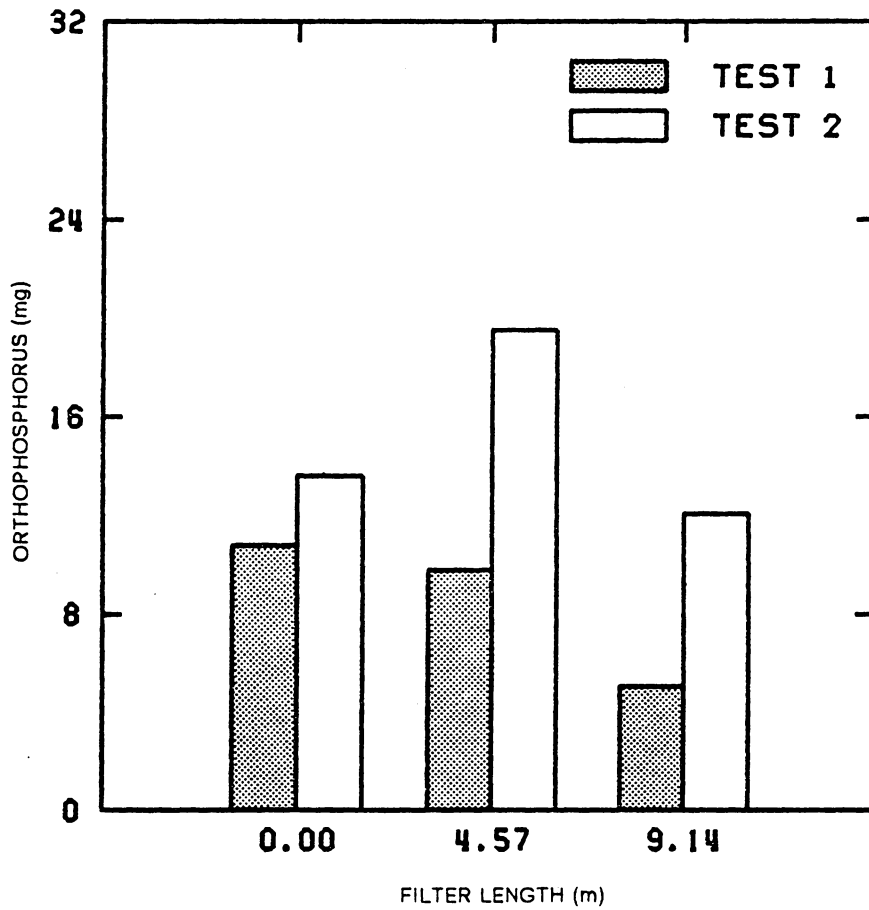
Figure 15. Orthophosphorus loss from plots QF1, QF2, and QF3, Tests 1 and 2
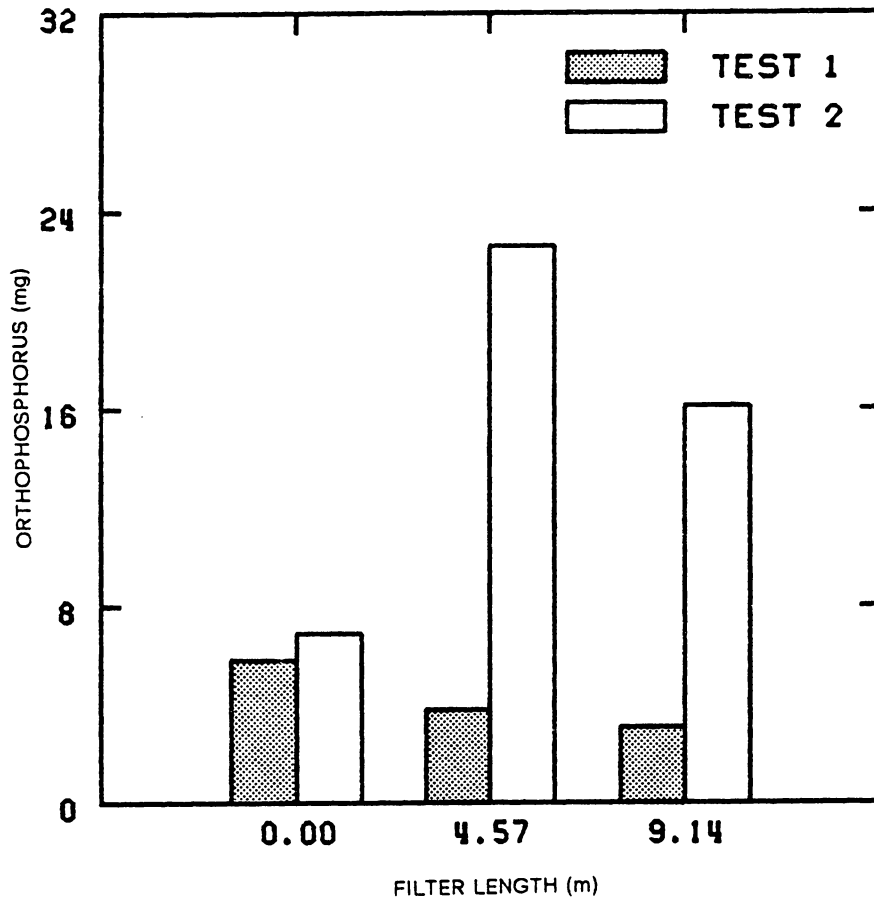
Figure 16. Orthophosphorus loss from plots QF4, QF5, and QF6, Tests 1 and 2
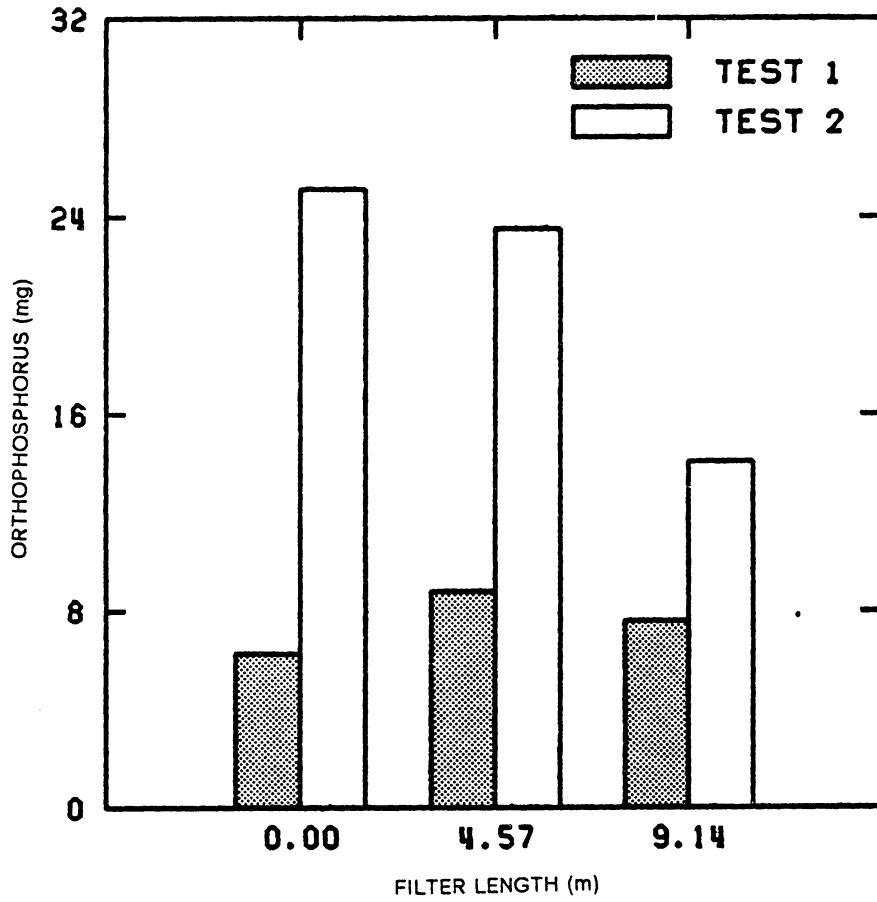
Figure 17. Orthophosphorus loss from plots QF7, QF8, and QF9, Tests 1 and 2

released into solution during Test 2. However, the exact cause of the increased OP release is not explained by the present study.

Total phosphorus losses were highly correlated with sediment losses from the experimental plots during the first 3 simulations. When the Pearson correlation test was applied to the data in Table A-3, total sediment and phosphorus losses had a correlation of 0.654 which is significantly greater than zero at any level greater than 0.0001. This supports the suggestion that most of the phosphorus was lost in the particulate form during a storm period (Schuman *et al.* 1973a, b, Johnson *et al.* 1976, Rigler 1979). The correlation suggests that TP trapping efficiency of VFS will decrease as runoff continues. As described earlier, TSS removal by VFS was reduced as grasses were inundated with deposited sediment. Decreasing TSS trapping efficiency of VFS may well lead to decreasing sediment-bound phosphorus trapping. Table A-5 demonstrates this relation well. Total phosphorus was reduced in the 4.6 m and 9.1 m filters by 33 to 81 percent and 18 to 88 percent during Test 1, respectively. During Test 2, the shorter filter reduced TP by -17 to 27 percent and the longer one reduced TP by 12 to 64 percent.

Percent reductions in phosphorus loss were generally lower than those in sediment loss (Tables A-4 and A-5). The lower effectiveness in phosphorus removal may be accounted for by losses of dissolved phosphorus and the ineffectiveness of the filters in removing silt- and clay-sized particles. Even though high infiltration rates, adsorption onto filter surface soil, and uptake by microorganisms and plant roots induced the removal of dissolved phosphorus in the filter, their total contribution was small over the short simulation time intervals, which were dominated by the removal of particulate phosphorus due to sediment deposition. The silt- and clay-sized particles are particularly enriched with phosphorus due to their much higher phosphorus adsorption capacity (Sharpley 1980).

Figure 18 exhibits approximate phosphorus content of sediment suspended in runoff during the Test 4 Run 1 simulation. The values were calculated by dividing the difference between TP and OP by TSS. The values were overestimated since total phosphorus contained dissolved organic phosphorus. The overestimation is not very large, however, considering
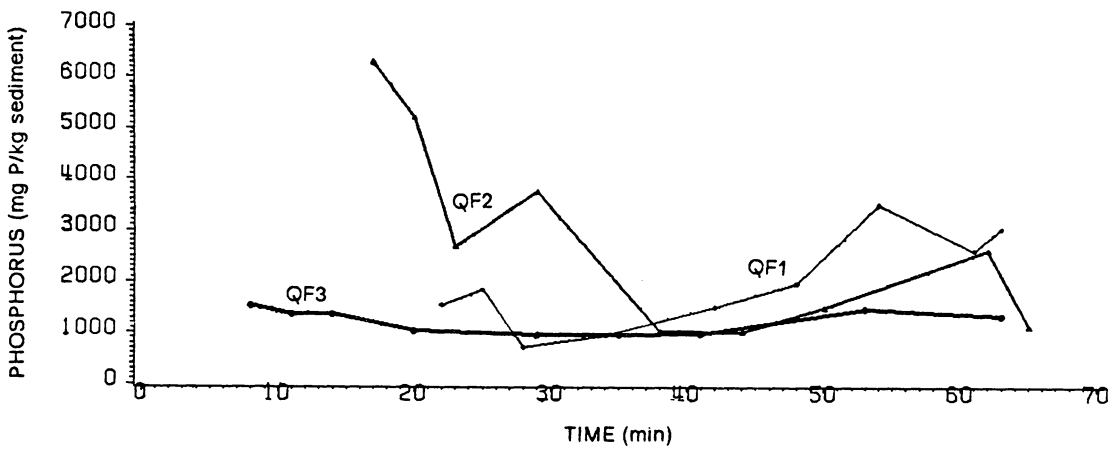
(a) QF123
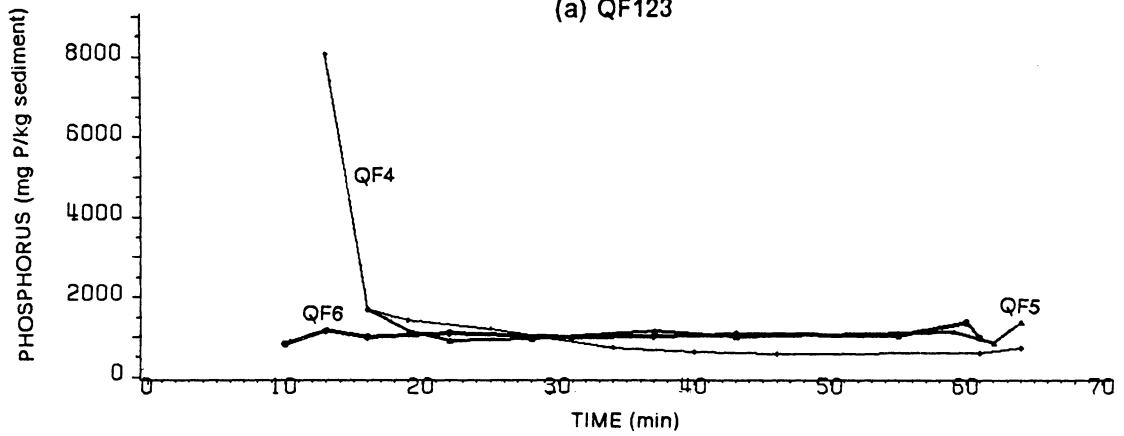
(b) QF456
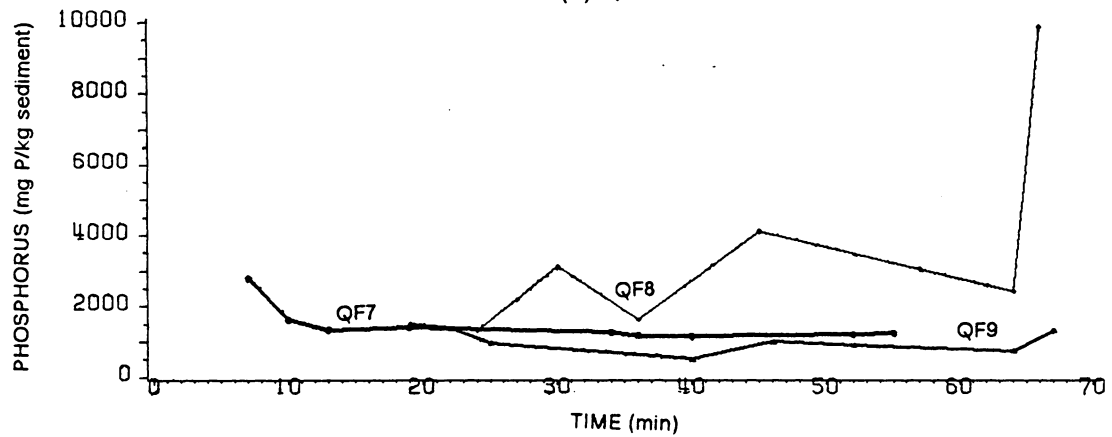
(c) QF789

Figure 18.   Phosphorus content of sediment, plots QF1-9, Test 4 Run 1:   QF3, 6, and 7 - no filter; QF2, 5, and 7 - 4.6 m filter; QF1, 4, and 8 - 9.1 m filter (Data from Dillaha *et al.* 1986a)

that the values of OP and TP-F are almost equal in most cases (see Dillaha *et al.* 1986a). The plotted lines, in general, are slightly concave in Figure 18. This may indicate that runoff has a relatively low kinetic energy at the beginning and end of runoff and contains only very fine sized particles, and thus the phosphorus concentrations of sediment are relatively high (Young *et al.* 1986). The phosphorus concentrations of sediment from the simulated crop areas are relatively consistent during the rainfall simulation, while the values of the filter effluent are highly variable. This indicates that the sediment removal process is very complex in VFS and may be very difficult to model. The complexity may cause problems in the prediction of sediment deposition process in SEDIMOT II and GRAPH.

Total phosphorus losses during the feedlot simulations were reduced by 80 and 63 percent for plots QF1 and 2 and by 57 and 52 percent for plots QF4 and 5, respectively (Table A-4). The cross slope plots had considerably lower reductions, 19 and 2 percent for plots QF8 and 9, respectively. The lower reductions for the cross slope plots are attributed to decreased TSS removal by VFS due to channelized flow. Orthophosphorus and other soluble phosphorus forms were not consistently reduced by VFS. Grass filters with shallow uniform flow were only moderately successful in removing OP during the first set of simulations (Test 1) with reductions of 53 and 47 percent in the 9.1 m filters QF1 and QF4, respectively (Table A-5). The percent reductions were much less during Test 2, decreasing to 11 percent and OP outflow from QF4 was greater than its inflow.

Table 4 indicates that the finer sized particles contributed a large portion of the total phosphorus in soil even if Bray I available phosphorus does not significantly vary with particle size. Since the grass filter did not remove the fine suspended materials from runoff, much particulate phosphorus was lost. Table 4, however, suggests that the vegetation reduced available phosphorus in soil due to biological consumption during the growing season. The lower available phosphorus contents reduced losses of dissolved phosphorus from the filter strip itself as indicated in Equations [1] and [2]. However, vegetation does not significantly alter the total phosphorus content of soil since phosphorus taken up by microorganisms and plant roots is incorporated into the soil part in microbial and organic forms.

Table 4. Comparison of total and Bray I available phosphorus content in plot soils

Soil material[1]	Total (mg P/kg soil)	Bray I (mg P/kg soil)
Soil particle size class by wet sieve (6/11/86)[2]		
QF123 plain	594	36
sand	354	32
silt	502	33
clay	1978	30
QF456 plain	538	30
sand	387	26
silt	386	25
clay	1285	26
QF789 plain	662	37
sand	436	35
silt	532	44
clay	1732	-
Particle size segregation methods in Plot QF789 (6/11/86)		
Dry-sieve segregation		
coarse	516	25
finer	707	36
Wet-sieve segregation		
coarse	617	29
finer	763	40
Bare vs grassed soil for each plot set (8/15/86)		
QF123 bare	613	40
VFS	703	34
QF456 bare	753	33
VFS	627	31
QF789 bare	646	36
VFS	625	26

[1]The segregation of particle size classes was done only on bare soil samples.
[2]The dates in the parentheses indicate the sampling days.

Tables 4 and 5 demonstrate the effect of two different particle size segregation methods on phosphorus parameters. The wet sieving procedure may change physical and chemical properties of soil particles. It is evident that the wet sieving enriched soil particles with available and total phosphorus (Table 4) and accelerated phosphorus adsorption rates for both coarser and finer soil particles (Table 5). It is likely that the wet sieving procedure may switch phosphorus from unavailable into available forms in soil materials. Total phosphorus contents were also increased in the soil particle size classes obtained by the wet sieving method, for unknown reasons. In this study, the wet sieving method was preferred since it makes finer isolation of soil particle classes possible and more closely approximates stormwater runoff conditions than the dry sieving procedure. Tables 5 and 6 demonstrate the possibility that sediment particles adsorb phosphorus from storm runoff. Finer sized particles may dominate coarser ones in both adsorption rate and final amount. The adsorption rates are obviously influenced by the phosphorus concentration of the background solutions.

This study shows that grass filters may potentially act as a phosphorus source to surface runoff (Table 7). As reviewed earlier, there are at least three component nutrient sources in the filters: living grass, dead litter, and surface soil. These components could supply dissolved phosphorus to the runoff passing through grass filters and thus cause higher OP losses in the grassed plots (Figure 14-16). The dissolved phosphorus might be generated by the dissolution of solids deposited on foliage and leaching of substance from the canopy tissues (Fahey and Knight 1986). As losses of OP and silt- and clay-bound-phosphorus increase, TP losses increase correspondingly. As a storm continues, sediment-bound and dissolved phosphorus accumulate in the filter. This may eventually satisfy the phosphorus absorption or adsorption capacity of the biological and geological components of the filters. The filters do not then act as a phosphorus sink. Rather the filter components become a source of phosphorus due to lower flow resistance and the increased kinetic energy of runoff and exposed soil surface, which increases with sediment deposition.

Table 5. Comparison of particle size segregation methods for phosphorus adsorption

Sample[1]	Time (min)				
	5	30	60	180	1440
Initial P concentration of background solution: 1.26 mmol/l					
>37 wet	148.3[2]	151.8	156.4	169.6	173.1
>37 dry	52.0	62.6	95.9	94.9	120.1
<37 wet	189.2	206.3	219.4	288.0	362.2
<37 dry	86.7	112.6	132.9	183.6	215.0
Initial P concentration of background solution: 0.50 mmol/l					
>37 wet	21.1	46.4	72.2	101.5	131.9
>37 dry	55.8	58.3	67.9	71.4	97.7
<37 wet	180.4	234.3	239.9	260.1	309.5
<37 dry	145.8	158.0	194.0	212.2	253.8
Initial P concentration of background solution: 0.25 mmol/l					
>37 wet	42.8	72.4	64.5	65.6	106.9
>37 dry	35.1	44.5	44.2	61.5	86.4
<37 wet	84.8	100.0	105.5	127.6	173.9
<37 dry	66.3	72.0	77.2	93.6	125.5

[1]All samples originated from the bare soil portion of plot QF9.
Sample names represent coarse (>37 µm) or fine (<37 µm) particles
segregated using standard wet (wet) or dry (dry) sieve technique.
[2]The values represent the amounts of phosphorus adsorbed
by soil (mg P/kg soil).

Table 6. Time variation of phosphorus adsorption for soil particle classes

Sample[1]	Time (min)				
	5	30	60	180	1440
Initial P concentration of background solution: 0.16 mmol/l					
silt123	42.8[2]	61.4	68.7	73.1	88.6
silt456	43.7	60.7	63.9	71.6	89.5
silt789	49.2	68.8	77.6	86.4	115.6
clay123	158.3	189.9	-	229.0	-
clay456	145.7	187.5	194.2	208.1	-
clay789	250.5	255.1	-	256.6	-
Initial P concentration of background solution: 0.04 mmol/l					
silt123	11.1	21.6	21.6	29.2	33.6
silt456	14.7	21.7	22.3	29.0	39.3
silt789	17.6	24.6	29.3	35.1	45.4
clay123	53.5	59.7	62.7	63.6	65.5
clay456	51.9	59.2	60.5	63.7	65.9
Initial P concentration of background solution: 0.025 mmol/l					
silt123	2.5	8.1	9.0	9.8	20.3
silt456	6.4	11.6	12.5	11.6	20.4
silt789	2.9	13.3	15.1	18.7	27.3
clay123	33.1	35.9	36.6	37.9	38.3
clay456	33.2	35.8	36.3	37.6	38.0

[1]Silt and clay represent the particle size classes of 2-50 μm and
<2 μm in diameter, respectively.
Sample name numbers identify plots from which soil samples were obtained.
[2]The values represent the amounts of phosphorus adsorbed
by soil (mg P/kg soil).

Table 7. Time variation of phosphorus release from nutrient sources in VFS

Sample	Sampling date	Treatment	time (min)				
			5	30	60	180	1440
Leaf litter	4/11/86	air-dried	121.1[1]	152.7	196.9	252.9	347.6
Leaf litter	5/11/86	air-dried	77.0	161.7	172.6	-	328.3
Leaf litter	7/14/86	air-dried	84.0	124.7	160.3	196.4	321.1
Leaf litter	8/16/86	air-dried	57.7	142.3	180.9	321.7	330.8
Leaf litter	8/16/86	fresh	110.4	220.9	-	260.1	320.6
Living leaf	8/16/86	fresh	12.2	22.4	-	35.1	48.3
Soil(QF123)	8/15/86	air-dried	2.5	3.6	4.1	5.0	5.0
Soil(QF456)	8/15/86	air-dried	3.1	4.7	4.7	5.2	5.4
Soil(QF789)	8/15/86	air-dried	2.6	3.0	3.6	3.8	5.7

[1]The values represent the amounts of phosphorus desorbed from the desorbent (mg P/kg desorbent).

Phosphorus Adsorption and Desorption Kinetics

The parameters or coefficients of phosphorus adsorption and desorption kinetics should be determined for verifying the mathematical transport models. It was assumed that suspended solids passing through the grass filters originated upslope of the filters. Hence phosphorus adsorption kinetics must be identified for the particle size classes of the phosphorus source area soil, while desorption coefficients must be defined for the filter soil.

Adsorption Kinetics

The Elovich equation was integrated assuming that the initial total phosphorus content of the soil (S_o) was zero. Although the assumption is not true in the real world, the Elovich parameters may include the effect of initial soil-particle-bound phosphorus on the adsorption reaction under the given experimental conditions. The integrated form of Equation [18] as given by Van Riemsdijk and de Haan (1981) is:

$$S_k = \frac{1}{\varepsilon_k} \ln \left(t + \frac{1}{\lambda_k \varepsilon_k} \right) + \frac{1}{\varepsilon_k} \ln \lambda_k \varepsilon_k \qquad [62]$$

When $t >> 1/\lambda_k \varepsilon_k$ (see Table 8), the term $1/\lambda_k \varepsilon_k$ can be neglected (Chien and Clayton 1980) with little deviation from the original Elovich equation. This modification facilitates finding the Elovich parameters. When S_k is plotted against $\ln t$, the parameters of λ_k and ε_k can be determined by the slope and intercept of the resulting line. The phosphorus adsorption data of Tables 5 and 6 were thus fitted to Equation [62] using linear regression. Table 8 and Figures 19 and 20 demonstrate that the experimental data can be described by the modified Elovich equation, with the given parameters. Once Equation [62] describes the phosphorus adsorption

Table 8. Elovich adsorption parameters for soil size classes

Sample	P_i* (mg/l)	λ (mg/kg/hr)	ε (kg/mg)	$1/\lambda\varepsilon$ (hr)	R^2
>37 wet	39.0	5.41×10^{14}	0.204	9.07×10^{-15}	0.891
>37 wet	15.6	6.24×10^{2}	0.049	3.29×10^{-2}	0.975
>37 wet	7.8	9.03×10^{3}	0.100	1.11×10^{-3}	0.829
<37 wet	39.0	6.30×10^{4}	0.031	5.16×10^{-4}	0.913
<37 wet	15.6	3.42×10^{5}	0.043	6.83×10^{-5}	0.924
<37 wet	7.8	2.15×10^{4}	0.063	7.43×10^{-4}	0.940
>37 dry	39.0	9.56×10^{3}	0.081	1.30×10^{-2}	0.897
>37 dry	15.6	7.16×10^{4}	0.134	1.04×10^{-4}	0.893
>37 dry	7.8	2.61×10^{3}	0.108	3.55×10^{-3}	0.925
<37 dry	39.0	8.00×10^{3}	0.041	3.04×10^{-3}	0.954
<37 dry	15.6	2.39×10^{5}	0.050	8.40×10^{-5}	0.951
<37 dry	7.8	2.73×10^{4}	0.093	3.95×10^{-4}	0.909
silt123	4.9	3.14×10^{4}	0.127	2.50×10^{-4}	0.977
silt123	1.3	1.15×10^{3}	0.251	3.47×10^{-3}	0.952
silt123	0.8	6.83×10	0.338	4.33×10^{-2}	0.933
silt456	4.9	2.65×10^{4}	0.127	2.98×10^{-4}	0.994
silt456	1.3	1.19×10^{3}	0.229	3.68×10^{-3}	0.980
silt456	0.8	4.68×10^{2}	0.444	4.81×10^{-3}	0.888
silt789	4.9	9.02×10^{3}	0.087	1.28×10^{-3}	0.993
silt789	1.3	1.75×10^{3}	0.200	2.85×10^{-3}	0.995
silt789	0.8	1.36×10^{2}	0.240	3.07×10^{-2}	0.984
clay123	4.9	6.99×10^{5}	0.051	2.85×10^{-5}	0.996
clay123	1.3	1.04×10^{13}	0.483	1.99×10^{-13}	0.866
clay123	0.8	1.12×10^{17}	1.087	8.24×10^{-18}	0.878
clay456	4.9	1.06×10^{6}	0.057	1.65×10^{-5}	0.965
clay456	1.3	1.03×10^{11}	0.410	2.37×10^{-11}	0.920
clay456	0.8	2.08×10^{18}	1.176	4.09×10^{-19}	0.886
clay789	4.9	2.74×10^{85}	0.588	6.19×10^{-86}	0.922

*P_i indicates the initial phosphorus concentration of backgound soluiton.
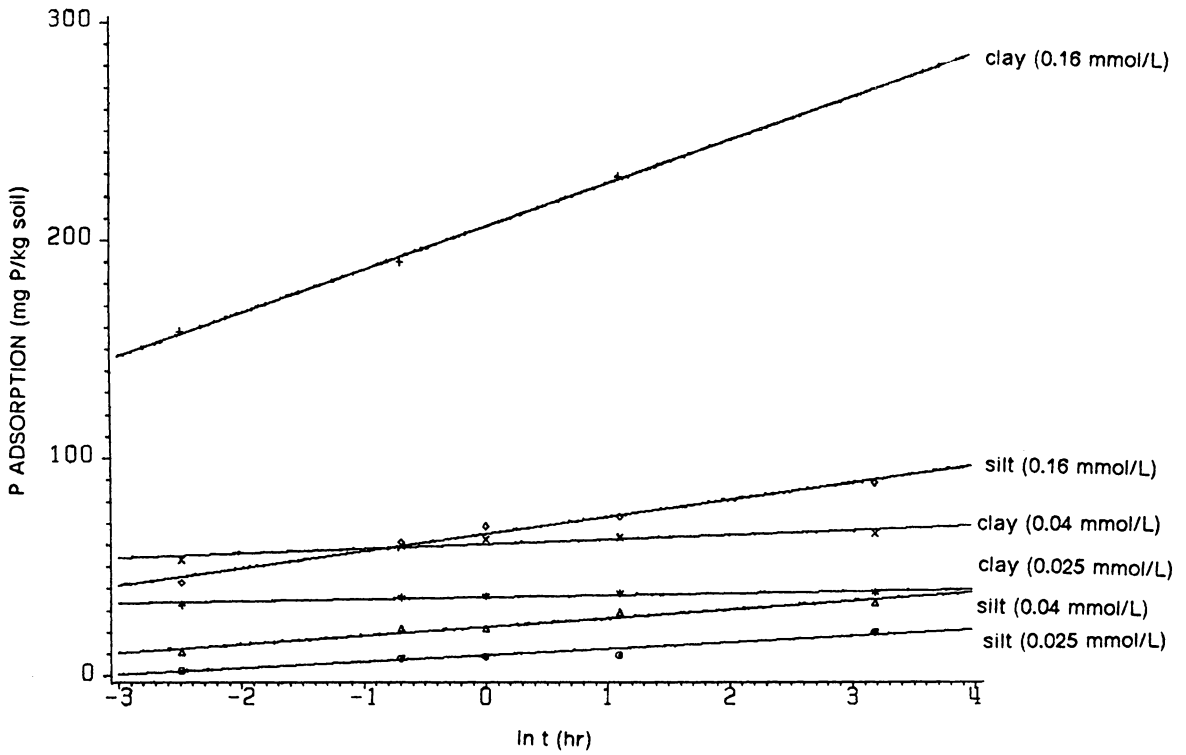
Figure 19. Adsorption of phosphate on silt123 and clay123 as a function of ln t: The solid lines represent linear regression lines. The figures in parentheses indicate the initial phosphorus concentrations of background solution.
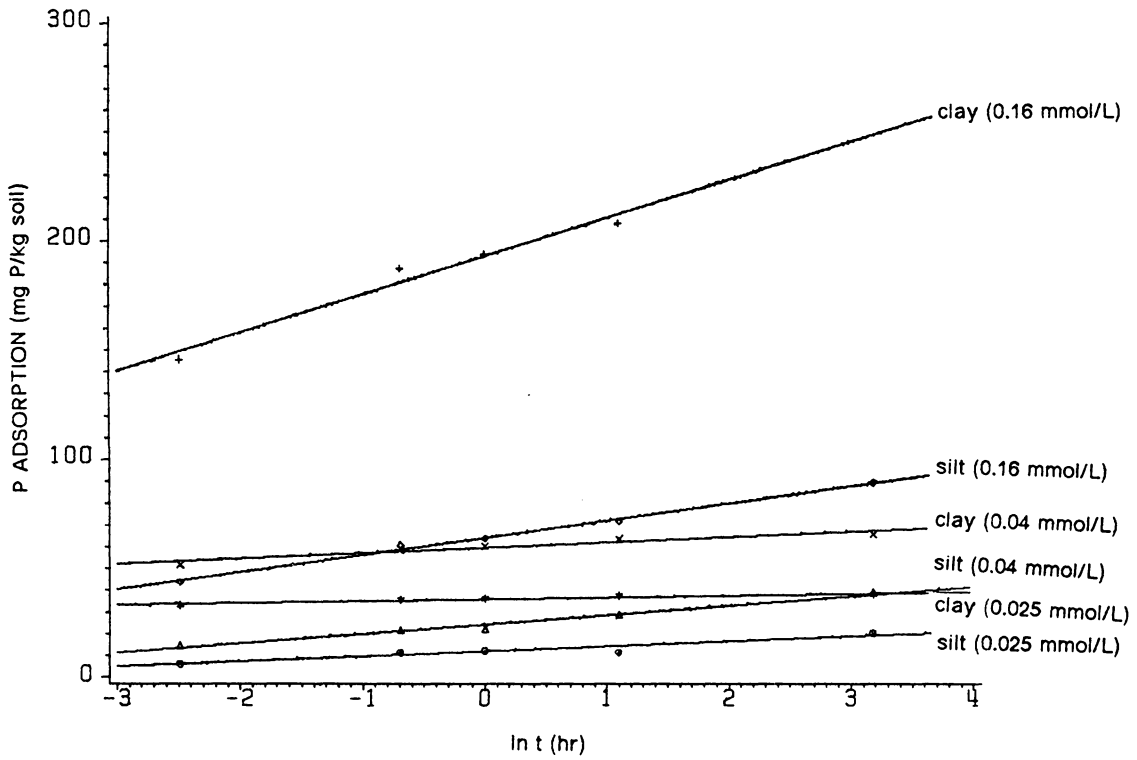
Figure 20. **Adsorption of phosphate on silt456 and clay456 as a function of ln t:** The solid lines represent linear regression lines. The figures in parentheses indicate the initial phosphorus concentrations of background solution.

reaction, its derivative is given by Equation [19], which is a special case of the equation suggested by Kuo and Lotse (1974), the derivative of which can be expressed as:

$$\frac{\partial S_k}{\partial t} = \frac{KP_i}{m}t^{1/m-1}$$

[63]

where K and m are constants, and P_i is the initial phosphorus concentration. Equation [63] is close to Equation [19] when $\varepsilon = m/KP_i$ and m is large. This is consistent with Van Riemsdijk and de Haan (1981) and the data in Table 8. Van Riemsdijk and de Haan (1981) found that the parameters λ and ε vary with initial phosphorus concentration (P_i) and cation species of the background solution. They claimed that the value of ε was inversely related to P_i. Table 8 shows that the values of ε tend to increase as P_i decreases. The effects of P_i were well described by Equations [64] and [65], which were provided by Van Riemsdijk and de Haan (1981), as shown in Table 9. The coefficients of Table 9 were obtained by fitting the logarithmic values of λ and ε to P_i and ln P_i, respectively, with linear regression.

$$\lambda_k = a_k \exp(b_k P_i)$$

[64]

$$\varepsilon_k = c_k P_i^{d_k}$$

[65]

Desorption Kinetics

The desorption data (Table 7) were fitted to Equation [1]. To determine the coefficients, Equation [1] was transformed as follows:

$$\ln \ P = \ln K + \ln P_0 + \beta \ln W + \alpha \ln t$$

[66]

Table 9. Estimated Elovich equation coefficients

Sample*	$\lambda = ae^{bP_i}$			$\varepsilon = cP_i^d$		
	a	b	R^2	c	d	R^2
>37 wet	1.51×10^{-1}	0.882	0.895	0.024	0.503	0.322
<37 wet	6.30×10^4	0.001	0.013	0.150	-0.438	0.985
>37 dry	9.44×10^3	0.012	0.014	0.185	-0.200	0.405
<37 dry	1.41×10^5	-0.064	0.362	0.228	-0.488	0.865
silt123	6.63×10	1.293	0.880	0.295	-0.531	1.000
silt456	2.71×10^2	0.945	0.991	0.332	-0.643	0.930
silt789	1.90×10^2	0.821	0.748	0.219	-0.573	0.986
clay123	1.22×10^{22}	-5.703	0.944	0.743	-1.68	0.999
clay456	2.76×10^{17}	-5.583	0.763	0.729	-1.63	0.996

*Soil materials are identified in the same way as in Tables 5 and 6

The value of α was determined by applying linear regression to the 180-minute reaction data in Table 7 and Equation [66], which had been derived by Sharpley et al. (1981b) with 180-minute reaction data. The clay-to-organic carbon ratio of the soil was estimated by substituting the value of α into Equation [7]. The coefficient β was then determined from Equation [8]. Finally, the value of K was calculated once the values of α , β, and P_o were determined, since the intercept of the linear regression was equal to the first three terms of the right hand side of Equation [66]. The estimates for the coefficients and the R^2 are given in Table 10 (note that R^2 values are only for linear regression to find the values of α). Figure 21 compares the experimental results to Equation [1] using the estimated coefficients.

Table 11 and Figure 22 indicate that the phosphorus desorption kinetics of both the plant and soil materials can be described by the modified Elovich equation when the water-to-desorbent ratio is constant. This result sheds light on the possibility that the processing of decaying plant residues can be indexed by the Elovich parameters for a nutrient cycle study in both terrestrial and aquatic ecosystems. Decaying plant residues tend to have increasing values of λ as they are processed. The Elovich equation fitted the desorption data of this study better than Equation [1] as reaction times increased. However, it is recommended that the role of initial phosphorus content of desorbent and water-to-desorbent ratio (WD) on desorption kinetics be incorporated into the Elovich equation for improvement. Probably a water-to-desorbent ratio effect could be included by multiplying the modified Elovich equation by $(WD/50)^\beta$. The parameters λ and/or ε may involve the effect of initial phosphorus content on the desorbent. Chien and Clayton (1980) claimed that the parameter ε varied with soil type. There is a possibility that the parameter is related to organic matter content and clay fraction and mineralogy as well as the initial phosphorus content in the desorbent.

Table 10. Estimated phosphorus desorption coefficients for Equation [1]

Sample	K	α	β	R^2
Soil(QF123)	0.023	0.194	0.214	0.994
Soil(QF456)	0.034	0.144	0.232	0.760
Soil(QF789)	0.033	0.092	0.257	0.852
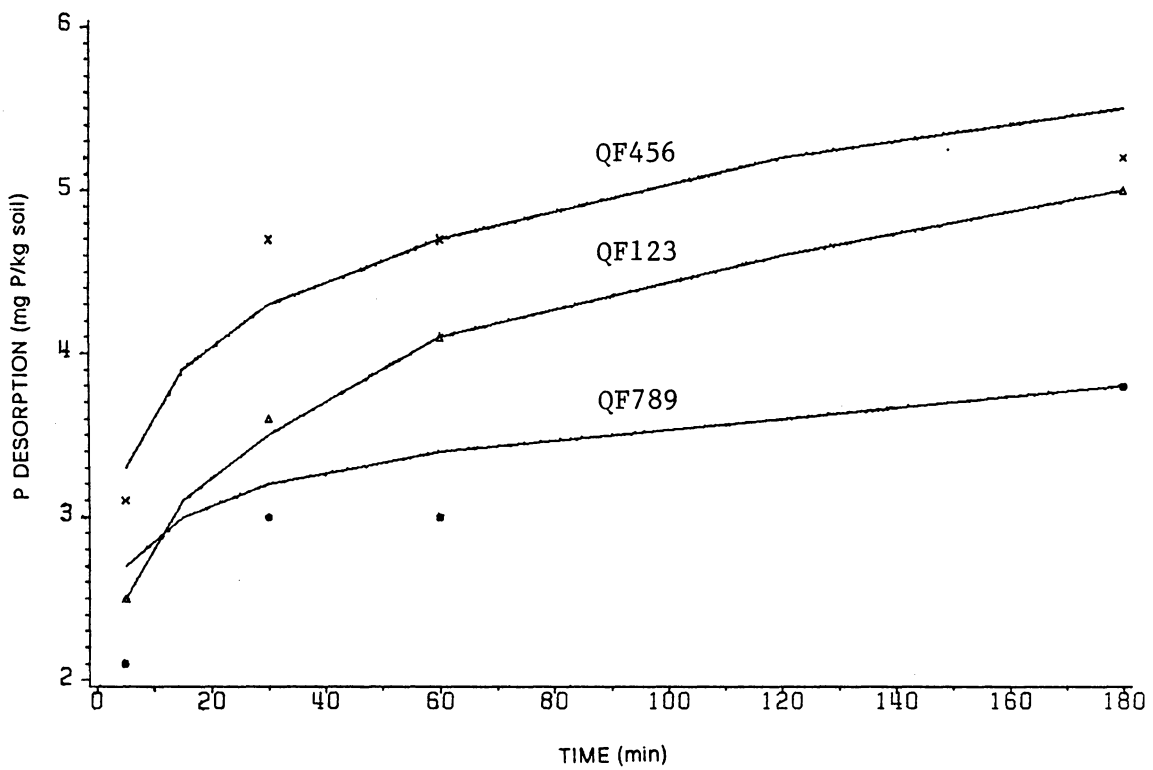
Figure 21   Plot of phosphorus desorption versus reaction time for VFS soils

Table 11. Elovich desorption parameters for plant and soil materials

Sample*	λ (mg/kg/hr)	ε (kg/mg)	$1/\lambda\varepsilon$ (hr)	R^2
Leaf litter	5.80×10^3	0.024	7.15×10^{-3}	0.966
Leaf litter	2.97×10^3	0.023	1.48×10^{-2}	0.993
Leaf litter	2.32×10^3	0.024	1.80×10^{-2}	0.959
Leaf litter	2.17×10^3	0.019	2.42×10^{-2}	0.887
Leaf litter	1.73×10^4	0.028	2.04×10^{-3}	0.947
Living leaf	4.88×10^2	0.156	1.31×10^{-2}	0.999
Soil QF123	2.41×10^3	2.174	1.91×10^{-4}	0.867
Soil QF456	5.87×10^4	2.632	6.48×10^{-6}	0.807
Soil QF789	4.40×10^2	1.852	1.23×10^{-3}	0.919

*Sampling dates and treatment correspond to the order in Table 7
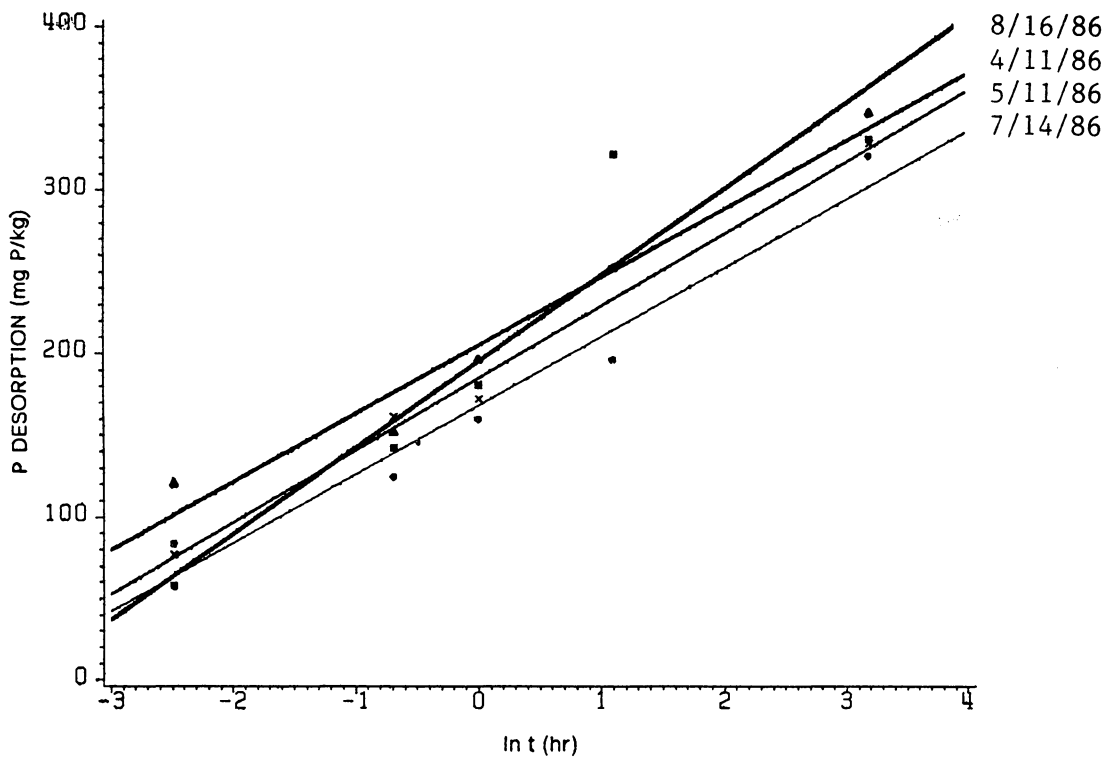
Figure 22. **Desorption of phosphate from leaf litter as a function of ln t:** The solid lines represent linear regression lines. The figures in parentheses indicate the sampling dates.

Model Verification

The model was verified using quantitative and qualitative data from the water, soil, and plant materials collected during Test 4 Run 1 (Dillaha *et al.* 1986a). In this study, the verification was attempted only with the data of plot set QF456 due to potential heterogeneity of the other plot sets. Plot set QF123 contained some alfalfa and dandelion in the vegetative portion, and QF789 had a cross slope and thus caused concentrated flows. Currently the model is not applied to such situations.

Input Data

The required input data include; (1) rainfall intensity and duration, (1) an inflow hydrograph, (3) a sedimentgraph, (4) sediment size distribution, (5) inflow graphs for dissolved and particulate phosphorus, (6) dimensions and hydraulic parameters of grass filter strips, and (7) coefficients of phosphorus desorption and adsorption kinetics for soil.

The runoff discharge, the concentrations of each sediment size, and the dissolved and sediment-bound phosphorus from the plots with no filters were assumed to be the boundary conditions for the filter strips of the other plots in the set. Sediment-bound phosphorus contents were determined by multiplying the concentrations of total phosphorus for each soil particle class by the concentration of each sediment size particle class in storm runoff. This might underestimate real value if soil particles adsorbed dissolved phosphorus before they are detached. In this study, OP was assumed to represent dissolved phosphorus. This replacement may cause lower predicted values for dissolved phosphorus concentrations. However, this underestimation will not be significant because the OP concentrations were not much less than those of TP-F in the experimental plot study. Phosphorus concentrations at

time zero were assumed to be nil along the filter strips. Hydraulic parameters for grass filter strips were determined by the methods described in the SEDIMOT II design manual (Warner *et al.* 1981). Sediment size distribution of inflow runoff was available from Table 1. Infiltration parameters were obtained from Ross *et al.* (1978) and modified when the model underestimated the runoff rate. The coefficients of phosphorus desorption and adsorption kinetics were determined experimentally from soils in the plots as discussed previously (see Tables 9 and 10). It was assumed that the phosphorus content of the rainwater was negligible. Biological uptake during the storm period was neglected since data were not available. Presumably, it should be very small during the short travel time of runoff through the 4.6 m and 9.1 m filters.

Model Validation

Model GRAPH describes several parameters including time variations of infiltration rate, runoff discharge, discharge of each sediment size class, and dissolved and sediment-bound phosphorus discharge in grass filter strips. In addition, sediment and phosphorus trapping efficiency are estimated in terms of the model since the cumulative load for those variables are predictable.

Model GRAPH underestimated runoff yield for experimental plot QF5 and 6 (Figure 23 and Table 12). There are two potential reasons for the underestimation: poor input data and computation errors. The data given by Ross *et al.* (1978) may represent average values of the infiltration parameters: cover coefficient, plant available water, gravitational water, final infiltration rate (f_c), and depth to impeding layer. Most likely a particular area has its own properties depending on weather conditions, topography, and vegetation type and coverage. The underestimation occurred even when no infiltration was assumed in the VFS. This suggests the possibility that infiltration rate was higher in QF6 than in bare soil areas of QF4 and QF6. Computation errors may result from runoff routing and infiltration equations. The continuity
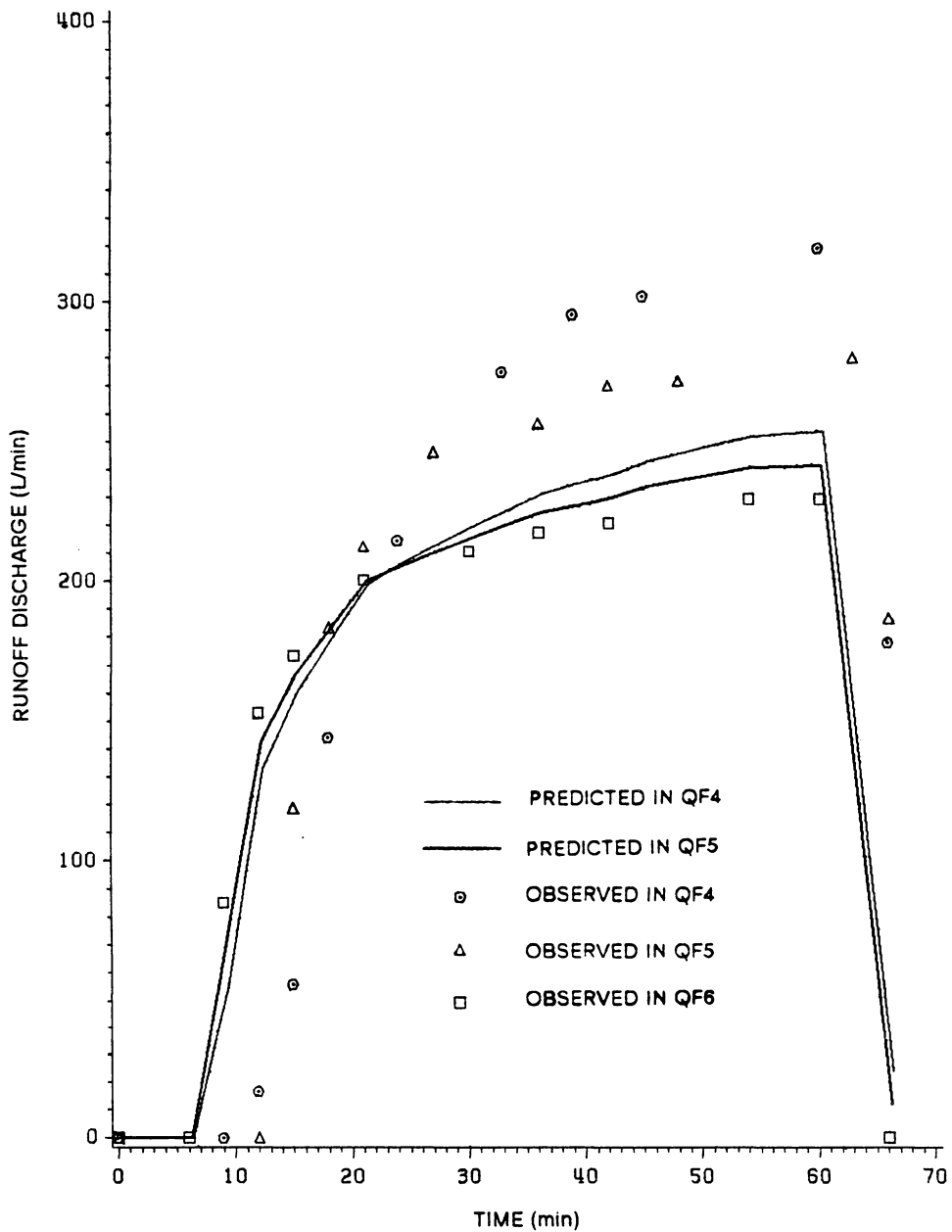
Figure 23. Predicted and observed hydrographs for plot set QF456 during Test 4 Run 1: QF4 - 9.1 m filter; QF5 - 4.6 m filter; QF6 - no filter

Table 12. Simulated runoff, total suspended solids, and phosphorus yield, and particle size distribution for plot set QF456 runoff

Filter length (m)	Runoff volume (L)	TSS[1] (kg)	SP[2] (g)	OP[3] (mg)	Particle size distribution (%)[4]		
					fine	medium	coarse
0.0	11349	191	126	920	31	32	36
4.6	11225 (12365)[5]	70 (67)	66 (67)	1514 (1580)	51	43	6
9.1	11225 (13025)	35 (38)	35 (31)	1547 (2325)	62	33	5

[1]Total suspended solids yield.
[2]Sediment-bound phosphorus yield.
[3]Orthophosphorus yield.
[4]Particle size classes:
   fine (<0.004 mm), medium (0.004 - 0.037 mm), and coarse (>0.037 mm).
[5]The values in parentheses represent observed values.

equation and momentum equation are often solved for the accurate prediction of runoff discharge. In this study, however, a simple difference equation was used to route runoff rate due to the complexity of the momentum equation for VFS. The underestimation may be attributed to the simplifications of the runoff routing equation. In addition, the modified Holtan's infiltration equation has not widely been tested, and this equation should be further verified. It was impossible to determine the cause of the flow discrepancy in the present research because the experimental setup did not measure the discharge rate to each filter. The predicted runoff rate is, however, acceptable when some infiltration parameters are changed.

Sediment transport was overestimated by subroutine GRASS of SEDIMOT II. Figure 24 and Table 12 show the results after the predicted sedimentgraph was adjusted to the observed graph. The adjustment was conducted by decreasing mass outflow load rate (SOFLOW) by 15 percent. Unfortunately, this adjustment was not based on theory but was required for further evaluation of the phosphorus transport model. Despite the adjustment, transport of fine particles was overestimated in this study. The overestimation may cause potential errors for the phosphorus transport model. Hence sediment size distribution was readjusted by assigning a value of 0.003 mm to a representative diameter of fine size class (< 0.004 mm) and by simply inputting a lower fraction of the particle size class less than 0.007 μm. Finally, sediment transport was reasonably described as shown in Figure 24.

Experimental sediment-bound phosphorus contents were determined by subtracting the concentrations of OP from TP in the storm runoff. Model input values for sediment-bound phosphorus were predicted by multiplying the concentrations of sediment particle size classes in runoff by TP in soil particle size classes and by summing. This must lead to smaller predicted values than observed ones as shown in Figure 25. In addition, the underestimation of simulated values might be ascribed to the underestimation of total phosphorus contents for coarse size particles. If higher total phosphorus contents are assigned to only coarse size particles, the model predictions can be improved. In general, model GRAPH described the time variations of sediment-bound phosphorus transport well in this study. However, its validation can not be verified due to the underestimation of runoff yield and the overestimation
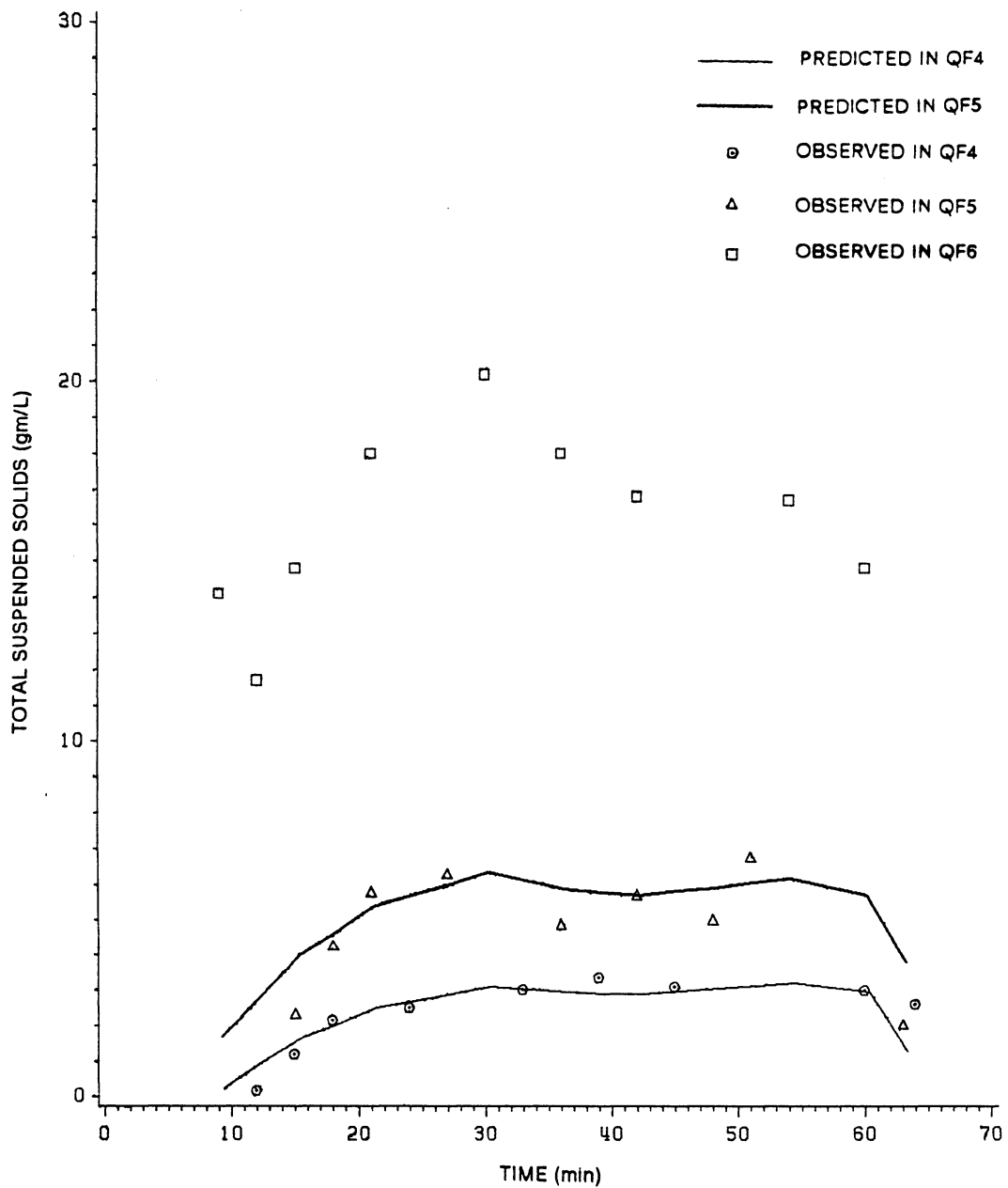
Figure 24. Predicted and observed total suspended solids for plot set QF456, Test 4 Run 1: Predicted values were obtained by lowering mass inflow by 15 percent (see text). QF4 - 9.1 m filter; QF5 - 4.6 m filter; QF6 - no filter.
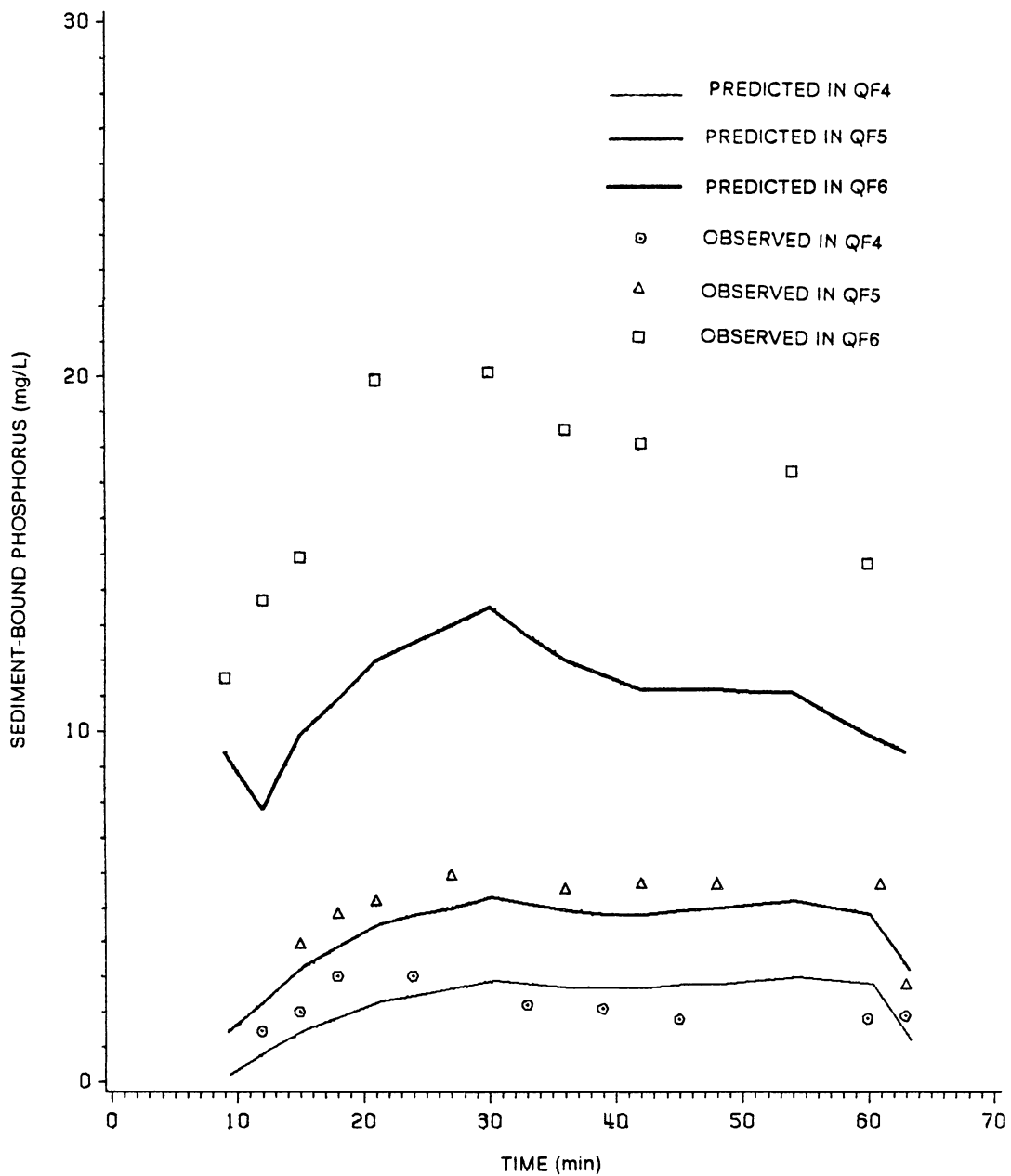
Figure 25. Predicted and observed concentrations of sediment-bound phosphorus for plot set
QF456, Test 4 Run 1: QF4 - 9.1 m filter; QF5 - 4.6 m filter; QF6 - no filter
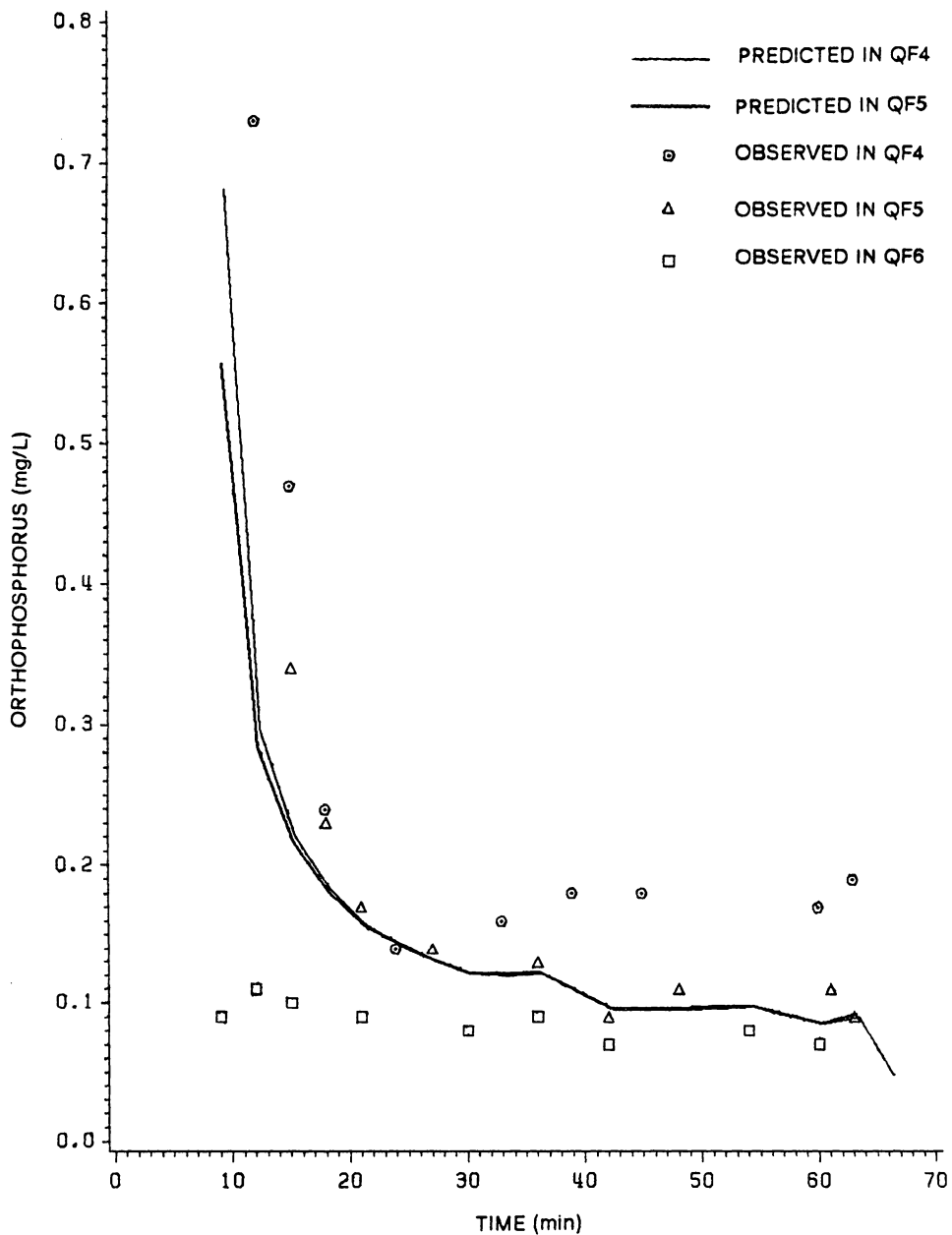
Figure 26. Predicted and observed concentrations of orthophosphorus for plot set QF456, Test 4
Run 1: QF4 - 9.1 m filter; QF5 - 4.6 m filter; QF6 - no filter

of fine suspended solids transport, which should cause the predicted values to deviate from the real ones. Some unknown factors might camouflage the potential deviation, and thus the simulated values were well fitted to the observed ones (Figure 25).

Time dependent variation of orthophosphorus concentration was well predicted by model GRAPH, but orthophosphorus yield was underestimated (Figure 26 and see Table 12). The underestimation was apparently attributed to the lower values of runoff rate as shown previously. The transport of orthophosphorus was sensitive to infiltration rate and the parameters of phosphorus desorption kinetics. Both observed and predicted concentrations of dissolved phosphorus were initially high and tapered off as runoff continued. It is evident that the transport of dissolved phosphorus may be described by the phosphorus desorption kinetics of phosphorus sources, such as soil and plant materials. Infiltration may decrease the quantity of dissolved phosphorus present in runoff, and rainwater diluted storm runoff. Hence, high infiltration led to low dissolved phosphorus concentration. Infiltration rate was high just after rain started, when phosphorus was mostly desorbed from its sources such as soil and plant materials. Consequently, infiltration is an important factor reducing dissolved phosphorus loss in VFS.

Sensitivity Analysis

A sensitivity analysis was performed to identify relatively important factors affecting phosphorus transport in VFS. The sensitivity analysis is helpful in verifying the model validation and in identifying those parameters to which the model is most sensitive. This allows more care to be taken in the estimation of the most sensitive parameters and suggests which parts of the model need to be improved to increase model accuracy.

Thirteen variables relating to filter grass condition, dimensions, and soil phosphorus were chosen. Initially the given values were increased and decreased by 50 percent. Variations

Table 13. Sensitivity of total suspended solids and phosphorus yield to variations in model parameter

Variables[1]	Initial Value	Variation[2] (%)	TSS[3] (kg)	SP[4] (g)	OP[5] (mg)
MN	0.015	50	34.2	34.05	1546.18
		-50	36.5	36.15	1548.59
GHGHTT	4.0	50	35.2	34.98	1547.21
		-50	35.2	34.98	1547.21
LEN	30.0	50	20.4	21.58	1581.54
		-50	69.9	66.31	1514.86
SPACC	0.60	50	36.5	36.13	1547.32
		-50	31.5	31.65	1546.90
SSCC	16.	50	35.7	35.38	1547.66
		-50	33.6	33.56	1546.34
WIDTH	18.	50	20.9	22.04	1883.72
		-50	64.3	61.22	1226.77
MEI	2.	50	35.2	34.98	1547.21
		-50	35.2	34.98	1547.21
PO	31.	50	35.2	34.98	1542.72
		-50	35.2	34.98	1553.57
EDIC	0.1	50	35.2	34.98	1542.51
		-50	35.2	34.98	1552.44
WLEAF	5.35	50	35.2	34.98	1859.57
		-50	35.2	34.98	1239.67
PT(1,1)	387.	50	35.2	35.81	1547.17
		-50	35.2	34.15	1547.17
PT(1,2)	386.	50	35.2	39.06	1547.17
		-50	35.2	30.90	1547.17
PT(1,3)	1258.	50	35.2	47.56	1547.17
		-50	35.2	20.40	1547.17

[1]Variable names are referred to Appendices C and D
[2]Variation from initial value.
[3]Total suspend solids yield.
[4]Sediment-bound phosphorus yield.
[5]Orthophosphorus yield.

of total suspended solids and sediment-bound and orthophosphorus losses were then ob-
served as the parameters were varied. The simulated variations are summarized in Table 13.

Percent deviation and relative sensitivity were determined for the simulated data. Per-
cent deviation and relative sensitivity are defined as follows (Storm 1986):

$$S_p = \frac{\Delta R}{R} \times 100 \qquad \qquad [67]$$

where S_p is the percent deviation, and R is the model result.

$$S_r = \frac{P}{R} \frac{\Delta R}{\Delta P} \qquad \qquad [68]$$

where S_r is the relative sensitivity, and P is the value of the parameter being investigated.
Tables 14 and 15 give the values of S_p and S_r.

Increased Manning's roughness (MN) decreased TSS, SP, and OP yields. This is rea-
sonable since runoff is inversely related to surface roughness. Grass height (GHGHTT) and
stiffness (MEI) variation did not affect sediment and phosphorus transport within the 50 %
variation. Increased filter length (LEN) and width (WIDTH) reduced sediment and sediment-
bound phosphorus yields but increased orthophosphorus yield. Sediment and phosphorus
yields were proportional to grass spacing (SPACC) and filter slope (SSCC). Orthophosphorus
yield was inversely related to increased Bray I available phosphorus concentration of filter soil
(P0) and interacting depth of runoff and filter soils (EDIC). But increased P0 and EDIC in-
creased phosphorus desorption and phosphorus concentration during the storm simulation
except during the recession limb of the hydrograph. Increased aboveground biomass per unit
VFS area (WLEAF) resulted in much orthophosphorus transport but did not affect sediment and
sediment-bound phosphorus. In model GRAPH, WLEAF was independent of GHGHTT and
SPACC even though WLEAF is probably a function of GHGHTT and SPACC in the real world.
This suggests that a functional relationship should be incorporated into the model for more
reasonable situation. The total phosphorus concentration of soil particle size classes influ-
enced sediment-bound phosphorus yield in the order of fine (PT(1,1)), medium (PT(1,2)), and

Table 14. Percent deviation of total suspended solids and phosphorus yield due to changes in input parameters

Variable[1]	Variation[2] (%)	TSS[3] (%)	SP[4] (%)	OP[5] (%)
MN	50	-2.	-3.	-0.
	-50	4.	3.	0.
GHGHTT	50	1.	-0.	0.
	-50	1.	-0.	0.
LEN	50	-42.	-38.	2.
	-50	100.	89.	-2.
SPACC	50	4.	3.	0.
	-50	-10.	-10.	-0.
SSCC	50	2.	1.	0.
	-50	-4.	-4.	-0.
WIDTH	50	-40.	-37.	22.
	-50	84.	75.	-21.
MEI	50	1.	-0.	0.
	-50	1.	-0.	0.
P0	50	1.	-0.	-0.
	-50	1.	-0.	0.
EDIC	50	1.	-0.	-0.
	-50	1.	-0.	0.
WLEAF	50	1.	-0.	20.
	-50	1.	-0.	-20.
PT(1,1)	50	1.	2.	0.
	-50	1.	-2.	0.
PT(1,2)	50	1.	12.	0.
	-50	1.	-12.	0.
PT(1,3)	50	1.	36.	0.
	-50	1.	-42.	0.

[1]Variable names are referred to Appendices C and D
[2]Variation from initial value.
[3]Total suspend solids yield.
[4]Sediment-bound phosphorus yield.
[5]Orthophosphorus yield.

Table 15. Relative sensitivity of the model to changes in model paraments

Variable[1]	Variation[2]	TSS[3]	SP[4]	OP[5]
MN	50	-0.046	-0.054	-0.001
	-50	0.086	0.066	0.002
GHGHTT	50	0.011	-0.001	0.000
	-50	0.011	-0.001	0.000
LEN	50	-0.834	-0.767	0.045
	-50	1.994	1.789	-0.042
SPACC	50	0.086	0.065	0.000
	-50	-0.200	-0.191	-0.000
SSCC	50	0.040	0.022	0.001
	-50	-0.080	-0.082	-0.001
WIDTH	50	-0.806	-0.741	0.435
	-50	1.674	1.498	-0.414
MEI	50	0.011	-0.001	0.000
	-50	0.011	-0.001	0.000
P0	50	0.011	-0.001	-0.006
	-50	0.011	-0.001	0.008
EDIC	50	0.011	-0.001	-0.006
	-50	0.011	-0.001	0.007
WLEAF	50	0.011	-0.001	0.404
	-50	0.011	-0.001	-0.397
PT(1,1)	50	0.011	0.046	0.000
	-50	0.011	-0.049	0.000
PT(1,2)	50	0.011	0.232	0.000
	-50	0.011	-0.234	0.000
PT(1,3)	50	0.011	0.718	0.000
	-50	0.011	-0.834	0.000

[1]Variable names are referred to Appendices C and D
[2]Variation from initial value.
[3]Total suspend solids yield.
[4]Sediment-bound phosphorus yield.
[5]Orthophosphorus yield.

coarse (PT(1,3)) sized particle classes. The order corresponds to that of the fractions after runoff passed through VFS (see Table 12).

The values of S_p and S_r generally indicated consistent sensitivity of investigated parameters to sediment and phosphorus transport in VFS. Filter width and length were found to be important variables for sediment and phosphorus transport. Average grass spacing, Manning's roughness, and filter slope controlled sediment transport, which in turn, governed sediment-bound phosphorus transport in VFS. Orthophosphorus transport was highly affected by the aboveground biomass because grass foliage is a major source of dissolved phosphorus in VFS. Orthophosphorus transport also was sensitive to filter width since aboveground biomass is proportional to filter width. Orthophosphorus transport was much more sensitive to filter width than to filter length.

Model Assumptions and Limitations

Because of the complexities of nutrient transport, there are significant limitations with the model validation presented in this study:

1. The given boundary conditions, which were taken from the water quantity and quality data of the plots without filters, may not provide an accurate indication of the inflow to the filters of the adjacent plots. In order to get more accurate boundary conditions, it might be necessary to concentrate the outflow from bare soil area of each plot, collect samples for analysis disperse the runoff, and then allow it to flow through the filter.

2. Phosphorus contents of soil particle classes were assumed to be the same as that of sediment from the filter entrance since other soil phosphorus data were not available. This assumption may be questionable because soil particles and aggregates probably react with rainwater and runoff before and after they are detached.

3. Soil samples were not analyzed for phosphorus content immediately before rainfall simulations. Total and available phosphorus content of soil may vary from season to season and from year to year. Soil and plant materials should be sampled just before rain starts. Otherwise, the seasonality of initial total and water soluble phosphorus contents and adsorption and desorption reactions for the materials are ignored.

4. The model does not adequately address the interactions and/or competition between soluble organic and inorganic phosphorus during the desorption process or the adsorption reaction. In this study, only orthophosphorus was included in dissolved phosphorus transport model.

5. Experimental determination of the coefficients of phosphorus desorption and adsorption kinetics requires values from natural soil and plant materials. Air drying and wet sieving processes may influence the physical and chemical nature of materials, and thus cause some deviation from natural conditions.

6. Coarse soil aggregates may be broken down during phosphorus desorption and adsorption reaction tests. They may expose additional fine particles, which in turn accelerates the reactions. Consequently phosphorus adsorption rates were higher in coarse soil size isolates than in fine size classes as reaction time increased. Fine size classes might adsorb most phosphorus within 5 minutes. The modified Elovich equation does not describe this initial rapid reaction effect.

7. Laboratory phosphorus solutions do not simulate the characteristics of real world runoff water exactly. The phosphorus sorption test needs to simulate the interactions of runoff, soil surface, and suspended solids. If the adsorption reaction is mechanical (not electrical), turbulence may affect the adsorption rate. Microorganisms may also exert certain influences on the sorption reaction of natural conditions, which may not be included in the laboratory batch experiment. Such microbial influences need further studies.

8. Phosphate is adsorbed onto soil particles competitively with other anions in real runoff (Roy *et al.* 1986). The laboratory batch experiment was performed for pure phosphate solution. The competitive interactions of phosphate and other anions should be included to improve the anion adsorption kinetics.

9. In the present study, it was assumed that the adsorption reaction of each sediment size class was independent of other size classes. There may, however, exist competition or interactions among particle size classes when phosphorus is adsorbed onto sediment transported in surface runoff.

10. The interacting depth of soil surface has been of concern in modeling nutrient transport processes. In this study, it was assumed to be constant in vegetative filter strips according to Sharpley (1985a) who suggested an equation describing the relationship between the interacting depth and soil aggregate and soil loss. The equation, however, is not applicable when soil loss is less than one kg/ha. In the sediment deposition zone, the deposition processes may also influence the interacting depth changing the structure of soil surface. The model should be modified to consider the time variation of EDI.

Chapter 6

Summary and Conclusions

Summary

Experimental plot simulation and mathematical modeling were undertaken to describe phosphorus transport in VFS during a storm period. The experimental plots contained an upland sediment and nutrient source area and/or VFS. The plots had either 0.0, 4.6, or 9.1 m length of VFS. Three sets of the plots were used to evaluate the effect of sediment and phosphorus loading rates on the effectiveness of VFS in removing phosphorus in surface runoff. Surface runoff rates were monitored and water samples were collected as artificial rainfall was applied to the plots. Runoff water, soil, and plant materials were physically and chemically analyzed for TSS, TP, TP-F, and OP or Bray I available phosphorus concentrations, and phosphorus adsorption and desorption reactions to evaluate the performance of the filter strips.

Mathematical equations were formulated to describe the transport of dissolved and particulate phosphorus. In terms of the equations, phosphorus concentrations and loads in

stormwater were quantitatively characterized by hydrologic processes such as runoff discharge, the concentration and size distribution of suspended solids, chemical processes such as phosphorus desorption and adsorption reactions, and biochemical process such as biological uptake. The mathematical equations considered the effects of the advection process, infiltration, chemical desorption from the soil surface to stormwater runoff, adsorption of dissolved chemicals to suspended solids in runoff, the dynamic changes of sediment size fractions on chemical transport, and biological uptake. The equations were incorporated into SEDIMOT II, a stormwater and sediment transport model. The resulting model, GRAPH (GRAssed-strip-PHosphorus) describes phosphorus transport in VFS.

The required input data of GRAPH includes: (1) rainfall intensity and duration, (2) an inflow hydrograph, (3) a sedimentgraph, (4) sediment size distribution, (5) dimensions and hydraulic parameters of grass filter strips, (6) inflow graphs for dissolved phosphorus, (7) phosphorus desorption reaction coefficients for filter soil and adsorption reaction coefficients for sediment source soil, and (8) total phosphorus concentration of each soil particle class. The model GRAPH describes many processes including time variation of infiltration rate, runoff discharge, the discharge of each sediment size class, and dissolved and sediment-bound phosphorus discharge in grass filter strips during a storm period. In addition, sediment and phosphorus trapping efficiency are estimated by the model since the cumulative load for those variables are predicted. Since dissolved and particulate phosphorus were routed separately along the grass filter slope, individual and total phosphorus trapping efficiencies also are predicted.

The experimental plot studies demonstrated that VFS reduced runoff rate, and mass of suspended solids and total phosphorus. The reductions were exceedingly high during initial simulations (Test 1). During Test 1, the 4.6 m filters removed TSS and TP by 36 to 87 percent and 33 to 81 percent from surface runoff, respectively. Doubling of filter length increased TSS and TP removals by 9 to 24 percent and -15 to 7 percent, respectively. Grass filters did not reduce runoff, OP, and TP-F consistently. Subsequent tests (Test 2 to 4) had widely varying effects on runoff, TSS, TP, OP, and TP-F. The laboratory batch experiment showed that

phosphorus adsorption and desorption reaction rates were initially very high and then rapidly reduced as time passed. The modified Elovich equation was used to describe phosphorus adsorption reactions with respect to soil particle classes and desorption from soil and plant materials. Phosphorus desorption reactions also were described by the Oklahoma model in the case of soils.

The model GRAPH did not route runoff and sediment very well, but when the runoff and sediment yields were adjusted to match the observed data, sediment-bound and dissolved phosphorus transport model described phosphorus transport reasonably well. Simulations suggested that total phosphorus loss was governed by TSS and that initially high concentrations of OP in surface runoff passing through VFS could be ascribed to desorption from plant foliage in VFS.

Conclusions

The following conclusions may be drawn from the experimental studies and simulation model developed during the course of this research.

1. A series of partial differential equations were developed to describe sediment-bound and dissolved chemical transport. A numerical procedure was then used to transform the equations into finite difference equations, which were combined with subroutine GRASS of SEDIMOT II. The equations described phosphorus transport in grass filter strips reasonably well when compared with observed data from experimental plot studies. Consequently, the model can be used for evaluating existing VFS and designing new VFS to minimize sediment and phosphorus losses. A sensitivity analysis suggested that sediment and sediment-bound phosphorus transport is largely controlled by filter length

and width, grass spacing, filter slope, and the Manning's roughness coefficient. Orthophosphorus transport was sensitive to aboveground biomass.

2. Subroutine GRASS of SEDIMOT II required extensive modifications for the incorporation of the phosphorus transport submodel. The model was modified to allow time variation in infiltration, rainfall input to the filter area and model output at more than three intermediate points within the filter. Model GRAPH still has limitations: its runoff and sediment transport submodels need to be improved, and it requires input data which are not readily available.

3. Vegetative filter strip effectiveness can be explained by the reduction in raindrop splash and runoff energy. Energy is reduced by interception, flow resistance, and infiltration. Vegetation reduces energy through interception of rainfall and increased surface roughness which retards surface runoff and induces sediment deposition. Sediment deposition is the major sediment-bound phosphorus trapping mechanisms in VFS. Infiltration was found to reduce dissolved phosphorus transport. Increased infiltration in VFS is ascribed to flow retardation due to increased surface roughness caused by vegetation and good soil aggregation due to increased soil organic matter. Dissolved nutrients may be taken up by plants and microorganisms in VFS, but biological uptake was not addressed in this study.

4. Sediment and sediment-bound phosphorus removal was most significant in the upper few meters of VFS. Hence, filter effectiveness in removing sediment and sediment-bound phosphorus was not enhanced proportionally to filter length.

5. Plant residue, living plant canopy, and soil components in VFS can release dissolved phosphorus into surface runoff in VFS. Practices to control phosphorus release from these VFS components may be required. For example, harvesting plant residue after the growing season may be required to maintain phosphorus removal ability. Otherwise,

additional control practices will be required to reduce the loss of dissolved phosphorus from the filter.

6. The phosphorus release from plant and soil materials can be described by a modified Elovich equation and a diffusion-control model.

In summary, VFS can remove sediment and reduce dissolved and sediment-bound phosphorus losses in surface runoff. Under certain circumstances, however, VFS may release dissolved phosphorus to stormwater. Vegetative areas buffer the phosphorus losses from terrestrial systems to water bodies. In addition, the word buffer implies that the vegetative strips reduce the energy of rain drop splash and runoff and retard water flow. However, the word filter does not convey this effect on stormwater and dissolved phosphorus transport. Thus, vegetative buffer strips, may be a more appropriate name than vegetative filter strips when phosphorus transport is considered.

Chapter 7

Future Research Needs

It is recommended that the model and its submodels be further tested before use for VFS design. As discussed in Chapter 5, there are several problems complicating validation of the mathematical model. The chemical transport model is absolutely dependent on the runoff and sediment transport models. The runoff discharge model was improved considerably during this study but additional work is required to improve the sediment transport and particle size distribution aspects of the model. Runoff discharge and the particle size distribution of sediment in runoff are major factors affecting phosphorus transport, both the total amount and the fractions of each chemical form. Chemical desorption kinetics from source materials and adsorption kinetics onto soil particle should be reliable. Unfortunately, universally acceptable kinetic models are not presently available. Specific recommendations for future study include:

1. Presently, the particle size distribution of eroded sediment can not be predicted accurately from its parent soil. More particle size information is required than merely the fractions of primary sand, silt, and clay when runoff and sediment are used in water quality models. Research should be initiated to address these data gaps.

2. The segregation of sediment particle classes is a tedious job. An improved soil and sediment particle size class segregation technique is required to facilitate nutrient transport modeling development.

3. The nutrient filtering capacity of VFS should be tested with different types and conditions of vegetation. Nikitin and Spirana (1985) observed different sediment and nutrient-filtering capacity between natural and artificial protective forests. Meadow vegetation contributed phosphate and potassium to passing runoff water while it trapped all nitrogen compounds. Hopefully, model applicability will be able to be extended to filter strips with composite vegetation and concentrated flow.

4. The overall phosphorus transport model will be improved as the submodels are improved. Recently, it has been suggested that a diffusion-precipitation model describes the phosphate reaction with metal-oxides in soils (Van Riemsdijk *et al.* 1984). Barrow (1983) derived a mechanistic model for describing the sorption and desorption of phosphate by soil, considering variable charge surface, the initial electrostatic potential of soil solution, the diffusion of phosphate into soil particles, and electrostatic potential. These models may well describe phosphorus sorption reactions onto soil particles and should be considered as alternative subprocess models.

5. The current version of GRAPH does not simulate the effects of chemical dispersion and chemical adsorption onto surface soil due to a lack of data. Dispersion may affect chemical transport in the ponding area. Phosphorus desorbed from upland has been found to be adsorbed to surface soil while the water moves downslope (Sharpley *et al.* 1981a). These processes should be investigated for possible inclusion in the model.

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Appendix A

Summarized Water Quality Data for Feedlot

Simulation

Table A-1. Total sediment, phosphorus, and water yield from plots

PLOT	TSS (kg)	TP (gm)	OP (gm)	TP-F (gm)	RUNOFF (mm)
QF1	5.	49.	17.	18.	121.7
QF2	14.	91.	29.	19.	171.2
QF3	105.	248.	24.	28.	161.3
QF4	29.	112.	19.	5.	147.1
QF5	56.	123.	26.	11.	124.7
QF6	235.	257.	13.	7.	148.1
QF8	32.	146.	22.	-	142.2
QF9	54.	177.	32.	-	130.0
QF7	77.	181.	31.	-	141.2

Table A-2. Sediment, phosphorus, and water yield from plots for each test

PLOT/ TEST	TSS (kg)	TP (gm)	OP (gm)	TP-F (gm)	RUNOFF (mm)
QF1T1	2.	19.	5.	6.	52.8
QF2T1	10.	32.	10.	9.	76.7
QF3T1	76.	166.	11.	13.	84.8
QF4T1	14.	18.	3.	5.	53.1
QF5T1	28.	32.	4.	11.	50.5
QF6T1	153.	151.	6.	7.	69.6
QF8T1	20.	56.	8.	-	64.0
QF9T1	32.	46.	9.	-	60.5
QF7T1	50.	69.	6.	-	63.8
QF1T2	3.	30.	12.	12.	68.8
QF2T2	4.	59.	19.	10.	94.5
QF3T2	29.	81.	14.	15.	76.2
QF4T2	15.	94.	16.	-	94.0
QF5T2	29.	91.	23.	-	74.2
QF6T2	81.	107.	7.	-	78.5
QF8T2	12.	90.	14.	-	78.5
QF9T2	21.	131.	23.	-	69.6
QF7T2	27.	112.	25.	-	77.5

Table A-3. Sediment, phosphorus, and water yield from plots for each test and run

PLOT/ TEST/RUN	TSS (kg)	TP (gm)	OP (gm)	TP-F (gm)	RUNOFF (mm)
QF1T1R1	0.8	9.3	2.9	3.2	18.8
QF2T1R1	1.5	16.5	6.5	6.1	31.2
QF3T1R1	42.7	113.0	9.1	10.8	44.2
QF1T1R2	0.6	3.5	0.9	0.9	12.7
QF2T1R2	2.5	7.4	1.7	1.7	21.3
QF3T1R2	15.2	32.8	0.8	1.1	19.8
QF1T1R3	0.8	6.6	1.4	1.7	21.3
QF2T1R3	5.9	7.9	1.6	1.0	24.1
QF3T1R3	17.9	20.4	0.9	1.2	20.8
QF1T2R1	1.5	21.1	6.8	6.5	34.0
QF2T2R1	1.2	30.9	12.4	9.8	49.3
QF3T2R1	12.8	45.1	8.1	9.0	39.6
QF1T2R2	0.1	3.4	2.3	2.8	14.5
QF2T2R2	0.7	13.1	3.4	-	20.8
QF3T2R2	6.9	16.3	2.7	2.8	17.0
QF1T2R3	1.3	5.1	3.0	3.0	20.3
QF2T2R3	1.8	15.3	3.8	-	24.1
QF3T2R3	9.1	20.1	2.8	2.7	19.6

Table A-3 (continued)

PLOT/ TEST/RUN	TSS (kg)	TP (gm)	OP (gm)	TP-F (gm)	RUNOFF (mm)
QF4T1R1	1.0	2.3	0.6	1.0	9.9
QF5T1R1	8.5	12.3	1.5	1.8	16.5
QF6T1R1	84.8	102.5	3.1	4.3	37.1
QF4T1R2	2.7	4.9	0.9	1.4	17.5
QF5T1R2	8.2	8.0	1.1	1.5	16.3
QF6T1R2	35.4	24.6	1.1	1.3	15.0
QF4T1R3	10.2	10.8	1.7	2.2	25.7
QF5T1R3	11.2	11.4	1.2	7.5	17.8
QF6T1R3	33.3	23.5	1.5	1.7	17.8
QF4T2R1	8.9	72.3	11.2	-	46.7
QF5T2R1	13.9	59.8	14.3	-	34.8
QF6T2R1	53.5	73.7	5.5	-	40.1
QF4T2R2	2.6	12.8	2.2	-	22.6
QF5T2R2	7.4	16.7	5.0	-	19.3
QF6T2R2	12.5	17.7	0.8	-	19.0
QF4T2R3	3.9	8.7	2.7	-	24.9
QF5T2R3	7.2	14.4	3.3	-	20.1
QF6T2R3	15.3	15.3	0.6	-	19.3

Table A-3 (continued)

PLOT/ TEST/RUN	TSS (kg)	TP (gm)	OP (gm)	TP-F (gm)	RUNOFF (mm)
QF8T1R1	7.4	33.7	5.3	-	25.9
QF9T1R1	16.1	32.5	6.7	-	30.0
QF7T1R1	22.8	36.1	4.4	-	26.4
QF8T1R2	5.1	11.4	1.1	-	17.0
QF9T1R2	7.4	6.7	1.0	-	14.0
QF7T1R2	13.5	17.9	1.1	-	18.5
QF8T1R3	7.5	11.1	1.2	-	21.1
QF9T1R3	8.6	7.1	1.1	-	16.8
QF7T1R3	14.0	14.8	0.9	-	18.8
QF8T2R1	9.6	79.3	10.5	-	40.9
QF9T2R1	16.1	109.2	20.0	-	37.6
QF7T2R1	14.7	88.3	23.1	-	39.1
QF8T2R2	1.1	3.8	1.6	-	16.8
QF9T2R2	2.3	12.5	1.9	-	15.7
QF7T2R2	5.3	10.7	1.1	-	19.0
QF8T2R3	1.4	6.9	1.9	-	20.8
QF9T2R3	3.0	9.4	1.6	-	16.3
QF7T2R3	6.7	12.7	0.9	-	19.3

Table A-4. Percent reduction in sediment, phosphorus, and water yield by plot

PLOT	TSS	T-P	O-P	TP-F	RUNOFF
QF1	95.	80.	30.	35.	25.
QF2	87.	63.	-20.	33.	-6.
QF3	-	-	-	-	-
QF4	88.	57.	-51.	37.	1.
QF5	76.	52.	-108.	-49.	16.
QF6	-	-	-	-	-
QF8	58.	19.	31.	-	-1.
QF9	31.	2.	-3.	-	8.
QF7	-	-	-	-	-

Negative values indicate percent increase.

Table A-5. Percent reduction in sediment, phosphorus, and water yield by plots and tests

PLOT/ TEST	TSS	T-P	O-P	TP-F	RUNOFF
QF1T1	97.	88.	53.	56.	38.
QF2T1	87.	81.	9.	34.	10.
QF3T1	-	-	-	-	-
QF4T1	91.	88.	47.	37.	24.
QF5T1	82.	79.	34.	-49.	27.
QF6T1	-	-	-	-	-
QF8T1	60.	18.	-21.	-	0.
QF9T1	36.	33.	-40.	-	5.
QF7T1	-	-	-	-	-
QF1T2	90.	64.	11.	16.	10.
QF2T2	87.	27.	-43.	33.	-24.
QF3T2	-	-	-	-	-
QF4T2	81.	12.	-133.	-	-20.
QF5T2	65.	15.	-228.	-	5.
QF6T2	-	-	-	-	-
QF8T2	55.	19.	44.	-	-1.
QF9T2	20.	-17.	6.	-	-10.
QF7T2	-	-	-	-	-

Negative values indicate percent increase.

Appendix B

Program Documentation

This appendix is provided to document the main program, its subroutines, and functions. The main program and Subroutines GRASS through GWATR were either created (C) or modified (M) from those in SEDIMOT II to quantitatively describe phosphorus transport by runoff in VFS. The other subroutines and functions were used without changing the originals in SEDIMOT II.

MAIN PROGRAM (M)

The main program provides rainfall rate (in/hr), some quantitative properties relating to runoff discharge and sediment, and program control variables. Originally the main program calculated most values using rainfall data, geology, and soil properties of an area. Modification of the main program may facilitate incorporating Subroutines of GRAPH into some other program(s), which provide runoff discharge and sediment size distribution at the upper boundary of grass filter strips. The incorporation will be accomplished by providing the input data and adjusting 'COMMON' and 'CALL' statements.

SUBROUTINE GRASS (M)

Subroutine GRASS describes the effectiveness of grass filters to remove stormwater and sediment. A time-dependent infiltration rate model was incorporated into Subroutine GRASS of SEDMOD II, which was also modified to allow more than three filter segment and to eliminate needless repetitive calculations. Input parameters are used to characterize the grass filter. It is called by main program.

SUBROUTINE PSFR1 (C)

Subroutine PSFR1 provides the fractions of sediment size classes along grass filter length during storm runoff coarse (>37 µm), medium (37-4 µm), and finer (<4 µ m). It is called by Subroutine GRASS. This subroutine and PSFR2 were created based on the old version of Subroutine GRASS.

SUBROUTINE PSFR2 (C)

Subroutine PSFR2 calculates the concentrations of the sediment size classes in storm runoff at the corresponding points and times of PSFR1. It is called by Subroutine GRASS.

SUBROUTINE CNVRT (C)

Subroutine CNVRT converts the output variables of the previous filter segment into the input variables of following segment. It is called by Subroutine GRASS.

SUBROUTINE CHMSOL (C)

Subroutine CHMSOL routes the concentrations and loads of dissolved phosphorus in a grass filter strip. It is called by Subroutine GRASS.

SUBROUTINE CHMPRT (C)

Subroutine CHMPRT routes the concentrations and loads of particulate phosphorus in a grass filter strip. It is called by Subroutine GRASS.

SUBROUTINE DESORB (C)

Subroutine DESORB describes the desorption kinetics of phosphorus from the filter surface. It is called by Subroutine CHMSOL.

SUBROUTINE ADSORB (C)

Subroutine ADSORB describes the adsorption kinetics of phosphorus onto each sediment class while stormwater is running the grass filter off. It is called by Subroutine CHMSOL.

SUBROUTINE GWATR (M)

Subroutine GWATR routes the inflow hydrograph through the filter. This subroutine was improved by considering rain input to the filter. The rain input was not included in the original version of SEDIMOT II. It is called by Subroutine GRASS.

SUBROUTINE GWEDGE

Subroutine GWEDGE calculate the flow depth and slope of the sediment wedge. The iterative solution converges using the Secant Method. Subroutine GWEDGE is called by Subroutine GRASS.

SUBROUTINE OUTPUT

Subroutine OUTPUT is used to output arrays of particle size-percent finer hydrographs, and sediment graph values. It is called by the main program and Subroutine GRASS.

SUBROUTINE AVPEAK

Subroutine AVPEAK describes settleable concentration of suspended solids during a period of significant concentration and peak 24 hour period. It is called by the main program and Subroutine GRASS.

SUBROUTINE CHECKI

Subroutine CHECKI check integer input parameters. If the inputs are out of acceptable range, the subroutine will print a warning message and cause the program to abort. If they are out of the expected range but still acceptable, the subroutine will print a warning and keep executing.

SUBROUTINE CHECKR

Subroutine CHECKR has the same function as Subroutine CHECKI except that it checks real parameters instead of integer parameters.

FUNCTION GDEPTH

Function GDEPTH calculate the flow depth of water in a grass filter. An iterative solution is obtained by solving Manning's equation. Function GDEPTH is called by Subroutine GRASS.

FUNCTION PSIZE

Function PSIZE is used to interpolate between tabulated particle size percent finer data. The interpolation is done assuming linear, semi-log scale. Function PSIZE is called by the Subroutine GRASS.

FUNCTION SSCONC

Function SSCONC is used to calculate the settleable solid concentration of effluent. It is called by the Subroutine GRASS.

Appendix C

Input Data File Documentation

This appendix describes input data and their formats. The variables of a data-block in the following table are basically provided on a line of input data file. Since 8 columns are allowed for each variable, more than one consecutive line(s) should be used if there are more than 10 variables in a block.

Variables   Descriptions

MAIN PROGRAM

Header(L)   Job name

ITYPE   Type of rainfall rate (1: constant 2:variable)

IHYDR   Hydrology and/or sedimentology option (1: Hydro. only 2: Both)

NDVPS   Number of data values per particle size distributions

NRPIV	Number of rainfall rate data given every three minutes
NHGP	Number of inflow hydrograph points given every three minutes
P(J)	Rainfall rate every three minutes (in/hr)
INFLOW(J)	Inflow hydrograph of each filter segment (cfs)
CONC(J)	Sediment concentration (mg/L)
PS(I)	Particle size value (mm)
PF(I)	Input percent finer value (%)
PFDIS(I)	Percent of finer particle size distribution entering filter segment (%)
SG	Specific gravity of eroded sediment
SBSG	Submerged bulk specific gravity

SUBROUTINE GRASS

SEG	Number of filter segments with different characteristics
RPRINT	Print control variable
BSG	Bulk specific gravity of deposited sediment
DINT	Initial depth of sediment in depth D (inch)
DELTAX	Filter length increment for iteration (ft)
MN	Grass filter Manning's roughness coefficient (sec/cm$^{1/3}$)
GHGHTT	Grass height (inch)

SUBLEN	Length of grass filter segment (ft)
LEN	Grass filter length (ft)
SPACC	Average grass spacing (inch)
SSCC	Bed slope of grass filter (%)
WIDTH	Grass filter width (ft)
MEI	Grass stiffness factor (N-M Sq)

FA	Coefficient to index the effect of cover conditions
FAW	Plant available water storage (in/in)
FGW	Gravitational water storage (in/in)
DEPTH	Water storage control depth (in)
SA	Initial unfilled storage space to a restrictive layer: A horizon (inch)
FC	Final infiltration rate (in/hr)

SUBROUTINE CHMSOL

KM	First order biological consumption rate constant (min^{-1})
RA	Addition rate of dissolved phosphorus from rain ($\mu g/cm^2/min$)
SOL2(J)	Dissolved P concentration at filter starting line ($\mu g\ P/L$)

SUBROUTINE DESORB

K	Constant K in desorption kinetics ($min^{-\alpha}(cm^3/g)^{-\beta}$)
ALPHA	Constant α in desorption kinetics
BETA	Constant β in desorption kinetics
BD	Bulk density of filter soil (g/cm^3)
P0	Initial P concentration of filter soil ($\mu g/g$ soil)

EDIC	Effective depth of interaction between soil and runoff (cm)
DSA	Degree of soil aggregation

EPSIL	Elovich parameter ε (kg/mg)
WLEAF	Oven-dry (55 °C for 24 hrs) above-ground biomass (g/cm)

* The following two variables are used when the variables K, ALPHA, and BETA are not available and then zeros are assigned to these variables.

CLAY	Content of clay in filter soil (%)
OC	Content of organic carbon in filter soil (%)

SUBROUTINE ADSORB

KIN	Option of P adsorption kinetics (1: modified Elovich, 2: modified Freundlich)
LNA(K)	logarithm of constant a in adsorption kinetics for each sediment size class
B(K)	Constant b in adsorption kinetics for each sediment size class
C(K)	Constant d in adsorption kinetics for each sediment size class
D(K)	Constant d in adsorption kinetics for each sediment size class

* When KIN=1, LNA and B are dummy variables, and when KIN=2, D is a dummy variable.

SUBROUTINE CHMPRT

PT1(1,K)   Phosphorus concentrations of soil particle size classes (µg P/g)

Appendix D

Definitions of Variables in GRAPH

Key variables are provided in this appendix to help a beginner understand the algorithm of model GRAPH. Subscripts 7 and 9 are associated with sediment-bound and dissolved phosphorus transport, respectively. Input variables are omitted since they are referred to in Appendix C.

Variables	Descriptions
A	Coefficient of phosphorus adsorption kinetics
ACDEPD	Cumulated sediment depth in zone D of filter (inches)
ACMASS	Cumulated mass discharged for each slope segment (lb or tons)
ADS	P adsorption rate per unit volume of runoff by each sediment size class (mg/L/min)
AVECON	Arithmetic average settleable concentration during peak 24 hr period (ml/L)
CLAYV	Interpolated ratio for small particle size
COARSE	Portion of particle size distribution finer than 0.037 mm
CORF	Correction factor to account for the accumulation of sediment in zone D

DH   Cumulated sediment depth (inches)

DCOARS   Portion finer than 0.037 mm from particle size distribution existing grass wedge

DELTAT   Time increment of inflow hydrograph and load rate graph (hr)

DELTST   Time increment of routed hydrograph and load rate graph (hr)

DEPTHB   Water depth in zone B of the filter (ft)

DEPTHC   Water depth in zone C of the filter (ft)

DEPTHD   Water depth in zone D of the filter (ft)

DIA   Diameter of the particle in millimeters

DR   Previous structure delivery ratio

DT   Time increment of P adsorption and desorption kinetics (min)

DX   Distance increment of P adsorption and desorption kinetics (ft)

DXC   Distance increment of P adsorption and desorption kinetics (cm)

EFLNT   Effluent sediment concentration (mg/l)

EINC   Constant in Einstein's sediment transport equation

EPS I   Acceptable tolerance in interactive solution

ET   Estimated travel time through the filter segment (min)

ETTME   Estimated travel time through the filter segment (hr)

F1   Concentration of each sediment size class runoff inning a filter segment (kg/L)

F2   Concentration of each sediment size class runoff outing a filter segment (kg/L)

FCLAY   Finer corresponding to 0.004 mm particle

FINER1   Particle size finer distribution of sediment entering filter

FINER3   Particle size finer distribution of sediment existing the filter

FLEN   Length of the filter that suspended particle can settle out (ft)

FN   Ratio of potential plant available water to the potential gravitational water

            in the A horizon

FS   Fraction of sediment in zone D of each representative particle size

FSAND   Portion of particle size distribution corresponding to particle size 0.037 mm

FSILT   Portion of particle size distribution corresponding to particle size 0.012

FTR	Trap efficiency corresponding to each representative particle size
GHGHT	Grass height (ft)
HR	Spacing hyrdraulic radius of the filter (ft)
IATTME	Travel time through the filter in terms of skipped subscripts
ICLAY	Lower subscript corresponding to particle size of 0.004 mm
ICLAY1	Upper subscript corresponding to particle size of 0.004 mm
IHP	Subscript corresponding to the peak outflow discharge
INFIL	Grass filter infiltration rate (in/hr)
INFVOL	Infiltration volume of each plug of inflow (ft³/ft)
IO	Subscript of outflow hydrograph and load rate graph
IPRINT	Print control variable
IS	Subscript corresponding to the slope segment
ISAND	Lower subscript corresponding to a particle size of 0.037 mm
ISAND1	Upper subscript corresponding to a particle size of 0.037 mm
ISILT	Lower subscript of particle size finer than 0.012 mm
ISILT1	Upper subscript of particle size finer than 0.012 mm
ISP	Subscript corresponding to the peak load rate
KERROR	Error check variable
KERR2	Error check variable
LMASS	Sediment mass discharged for each inflow plug (lb)
LVOL	Cumulated infiltration volume (ac-ft)
MCONST	Mass continue constant expressed in 115.385*DELTST/BSG
NFALLS	Number fall of each representative particle
NPSD	Number of particle size distributions
NR	Spacing hydraulic radius of the filter
NRE	Reynold's Number of the flow in zone D
NRHP	Number of routed hydrograph points
NUMSEG	Number of slope segments

OFLOW	Outflow hydrograph values (cfs)
OTE	Trap efficiency of each inflow plug
OUTPK	Peak outflow discharge rate (cfs)
OVOL	Total outflow runoff volume (ac-ft)
PCLSS1	Concentration of each sediment size class at entering line (mg/L)
PCLSS2	Concentration of each sediment size class at leaving line (mg/L)
PD(1)	Mean diameter of the clay sized particle (0.004 mm)
PD(2)	Mean diameter of the silt sized particle (0.012 mm)
PD(3)	Mean diameter of the sand sized particle (by FNC PSIZE)
PD3	Medium diameter of coarse sized particles (mm)
PDCLAY	Diameter of clay size (0.002 mm)
PEFLNT	Peak effluent concentration (mg/L)
PFSET	Defines the percent finer larger than 0.037 mm for each particle size distribution
PKSGRA	Peak sediment load rate (lb/sec)
PLOAD	Cumulative load of phosphorus passed a point during a storm period (mg)
PT	Concentration of phosphorus in each sediment size class (mg/kg)
QPEAK	Peak runoff discharge (cfs)
QSC	Sediment load rate in zone C of particles greater than 0.037 mm (lb/ft/sec)
QSI	Sediment load rate at the start of filter of particles greater than 0.037 mm (lb/ft/sec)
QSTOT	Total sediment load in zone C (lb/ft/sec)
QSU	Sediment load rate at the start of deposition wedge of particle greaterthan 0.037 mm
QTOTAL	Total runoff volume (ac-ft)
QWB	Discharge on the sediment wedge face (cfs/ft)
QWC	Discharge in zone C (cfs/ft)
QWD	Discharge in zone D (cfs/ft)
RA	Dissolved chemical input rate from rainwater, (mg/cm²/ min)
RAIN	Rainfall rate over the entire plot (in/hr)
RDEPTH	Peak flow depth in the filter (ft and inch)

RPRINT   Real value corresponding to integer IPRINT

RQ   Peak discharge per unit width

RTIMP   Time of routed peak discharge (hrs)

SANDV   Interpolation constant for a particle size of 0.037 mm

SEE   Equilibrium slope of sediment wedge

SGRAPH   Inflow load rate graph (lbm/sec)

SOFLOW   Outflow load rate graph (lbm/sec)

SOL   Concentration of dissolved phosphorus in storm runoff (mg/L)

SPAC   Average grass spacing (ft)

SPARA   Previous routed peak discharge (cfs)

SPEAK   Peak concentration (mg/L)

SSC   Grass filter slope (ft/ft)

SSCONV   Peak settleable concentration (ml/L)

SSCONM   Peak settleable concentration (ml/L)

TAREA   Total drainage area (acres)

TADS   Total P adsorption rate per unit volume of runoff by all sediment size class (mg/L/min)

TCONC   Average settleable concentration during a period of significant concentratio (ml/L)

TCOEF(D)   Correction factor for the trap efficiency of suspended sediment

TE   Trap efficiency of each segment (%)

TIME   Travel time through the filter segment (hrs)

TIMEC   Period of significant concentration (hrs)

TIMPC   Time to peak concentration (hrs)

TIMPH   Time to peak discharge (hrs)

TOTINM   Total inflow mass (tons)

TPT   Concentration of sediment-bound in storm runoff (mg/L)

TRAP   Cumulation of trap efficiency of each particle size in zone D

TTME   Filter travel time (hrs)

TWCONC   Volume weighted average settleable concentration during a period of significant

concentration (ml/L)

VCR	Critical shear velocity of stiff grass (ft/sec)
VCR1	Critical shear velocity of elastic grass (ft/sec)
VD	Fluid velocity in zone D (ft/sec)
VISC	Kinetic viscosity (0.00895 cm²/ sec)
VS(1)	Settling velocity of clay-sized particles (ft/sec)
VS(2)	Settling velocity of silt-sized particles (ft/sec)
VS(3)	Settling velocity of sand-sized particles (ft/sec)
VSL	Logarithic value of VS
VSTAR	Shear velocity (ft/sec)
WCONC	Volume weighted average settleable concentration during peak 24 hour period (ml/L)
WD1	Water depth of storm runoff inflowing into a filter segment (cm)
WD2	Water depth of storm runoff leaving a filter segment (cm)
WQ1	Storm runoff discharge inflowing a filter segment (cm³/ft/min)
WQ2	Storm runoff discharge leaving a filter segment (cm³/ft/min)
WS	Water-to-soil ratio in filter segment (kg/L)
WTRAP	Total trap efficiency of sediment wedge
XPREV	Location of leading point of sediment deposition wedge (ft)
YPREV	Height of sediment deposition wedge (ft)
YTOTAL	Total sediment mass (tons)
Z	Phosphorus desorption rate for soil (and grass foliage) (µg/cm²/min)
ZLEAF	Phosphorus desorption rate for grass foliage (µg/cm²/min)

Appendix E

Computer Program

```
C  ********************************************************************
C  ********************************************************************
C     THIS IS THE MAIN PROGRAM
C  ********************************************************************
C  ********************************************************************
C
      REAL HEADER(15),INFLOW,INFIL(502),LNA,LNADS
      COMMON /RAINF / TIME(502),RAIN(502),VOLINF
      COMMON /LARRAY/ OFLOW(502),SOFLOW(502),CONC(502),INFLOW(1002),
     1                SGRAPH(1002)
      COMMON /PARTDA/ PS(15),PFDIS(15),NDVPC,IHYDR,NPSD
      COMMON /SRETRN/ DELTST,NRHP,ACMASS,OVOL,OUTPK,IHP,ISP,PEFLNT
      COMMON /ERODE1/ PFSET(10),ISAND,ISILT,ICLAY,ISAND1,SANDV
      COMMON /SSCON1/ SBSG,SILTV,ISILT1
      COMMON /WATER / WQ1(502),WD1(502),WQ2(502),WD2(502),
     1                WQAVG(502),WDAVG(502)
      COMMON /SEDIM2/ PCLSS1(502,3),PCLSS2(502,3)
      COMMON /SEDIM3/ VS(3),FS(3),FTR(3),FINER1(15),FINER3(15),PD(3)
      COMMON /CHEM1 / SOL1(502),SOL2(502)
      COMMON /CHEM2 / PT1(502,3),PT2(502,3),PTCON(502,3),TPT(502)
      COMMON /DESRB / EDI(502),WS(502),Z(502)
      COMMON /ADSRB1/ LNA(3),B(3),C(3),D(3)
      COMMON /ADSRB2/ ADS(502,3),LNADS(502,3),TADS(502)
C
C *** ASSUMED VISCOSITY (CM**2/SEC) AT 25 C (60 F) ***
```

```
      VISCOS = 0.00895
C
C *** INPUT AND OUTPUT HEADER CARD ******
      READ(5,5100) ( HEADER(I),I=1,15 )
 5100 FORMAT( 15A4 )
      WRITE(6,5200) ( HEADER(I) ,I = 1,15)
 5200 FORMAT(///15X,42('*') //
     1 22X,'FILTER IDENTIFICATION CODE'/20X,30('-')/20X,15A4//
     2 15X,42('*')//)
C
      READ(5,5010)ITYPE,IHYDR,NDVPC,NRPIV,NHGP
 5010 FORMAT(10I8)
      CALL CHECKI(ITYPE,1,2,1,
     1'CONSTANT OR VARIABLE RAIN RATE     ')
      CALL CHECKI(IHYDR,1,2,1,
     1'HYROLOGY ONLY OR BOTH              ')
      CALL CHECKI(NDVPC,2,15,2,
     1'NO. OF VALUES PER DISTRIBUTION     ')
C
      DELTAT = 0.05
      READ(5,5012) SG,SBSG
 5012 FORMAT(10F8.4)
      CALL CHECKR(SG,1.0,3.0,2.5,
     1'SPECIFIC GRAVITY                   ')
      CALL CHECKR(SBSG,1.00,1.75,1.25,
     1'SUBMERGED BULK SPECIFIC GRAVITY    ')
C
C *** RAINFALL RATE (IN/HR) EVERY 3 MINUTES AFTER RAIN START ***
      IF(ITYPE.EQ.1)READ(5,5012) P
      IF(ITYPE.EQ.2)READ(5,5012) (RAIN(J),J=1,NRPIV)
      NR = NHGP + 10
      TIME(1)=0.0
      DO 300 J = 2,NR
        TIME(J) = TIME (J-1) + DELTAT
        IF(ITYPE.EQ.1) RAIN(J) = P
        IF(J.GE.NRPIV) RAIN(J) = 0.0
  300 CONTINUE
C
      WRITE(6,5027)
 5027 FORMAT(/3X,20('*'),' INPUT RAINFALL PATTERN ',20('*')///,
     1      20X,31('-'),/20X,'VALUE',5X,'TIME(HR)',2X,'RATE(IN/HR)',
     2      /20X,31('-')/)
      WRITE(6,5028)(J,TIME(J),RAIN(J),J=1,NRPIV,2)
 5028 FORMAT(22X,I2,5X,F7.2,5X,F7.2)
C
C *** INFLOW HYDROGRAPH AND SEDIMENTGRAPH EVERY 3 MININUTES
C     FROM THE RAIN STARTING TIME
C
      READ(5,5012)(INFLOW(J),J=1,NHGP)
```

```
          READ(5,5012)(CONC(J),J=1,NHGP)
C
       QPEAK  = 0.0
       QTOTAL = 0.0
       YTOTAL = 0.0
       DO 350 J = 1, NHGP
          IF(INFLOW(J).GT.QPEAK) QPEAK = INFLOW(J)
          SGRAPH(J) = ( 62.4 * CONC(J) * INFLOW(J) ) / 1000000.0
C %%%     SGRAPH(J) = (62.4*SG*CONC(J)*INFLOW(J))/(999551.9*SG - CONC(J))
          IF(J.LE.1) GOTO 350
          ACWTER = INFLOW(J) + INFLOW(J-1)
C                  / 2.0 * DELTAT * 3600.0 ( 6 LINES BELOW TO REDUCE CAL. )
          ACMAS1 = SGRAPH(J) + SGRAPH(J-1)
C                  / 2.0 * DELTAT * 3600.0 ( 4 LINES BELOW TO REDUCE CAL. )
          QTOTAL = QTOTAL + ACWTER
          YTOTAL = YTOTAL + ACMAS1
  350 CONTINUE
       FACTOR = 1800.0 * DELTAT
       QTOTAL = QTOTAL * FACTOR
       YTOTAL = YTOTAL * FACTOR
C *** CHANGE THE UNITS FROM FT**3 AND LB TO AC-FT AND TONS, RESPECTIVELY
       QTOTAL = QTOTAL * 0.092903 / 4046.8
       YTOTAL = YTOTAL * 0.000454
       NHGP1 = NHGP + 1
       DO 400 J = NHGP1,NR
          INFLOW(J) = 0.000
          CONC(J) = 0.000
  400 CONTINUE
C
C *** SEDIMENT SIZE DISTRIBUTION
       READ(5,5012)(PS(I),I=1,NDVPC)
       READ(5,5012)(PFDIS(I),I=1,NDVPC)
C
C *** DETERMINE UPPER BOUND INDEX FOR SAND, SILT, AND CLAY PART. ****
C
       DO 140 I = 1,NDVPC
           IF( PS(I) .LE.  0.0 ) PS(I) = 0.0001
           IF( PS(I) .GE. 0.037 ) ISAND = I
           IF( PS(I) .GE. 0.012 ) ISILT = I
           IF( PS(I) .GE. 0.004 ) ICLAY = I
  140 CONTINUE
C
C **** DETERMINE THE PERCENT FINER VALUE OF LARGE PARTICLES ******
       ISAND1 = ISAND + 1
       ISILT1 = ISILT + 1
       ICLAY1 = ICLAY + 1
C
       IF( ICLAY1 - NDVPC ) 160,160,150
  150 WRITE(6,6000)
 6000 FORMAT(//2(5X,57('*')/)/10X,'WARNING:  A PARTICLE SIZE'/
```

```
      1 10X,'DISTRIBUTION SHOULD HAVE AT LEAST ONE SIZE'/
      2 10X,'SMALLER THEN 0.004 MM'//2(5X,57('*')/),
      3 ' THIS WILL CAUSE A FATAL ERROR IF THE GRASS FILTER OR'/
      4 ' CHECKDAM IS USED'/)
C
  160 SANDV = ALOG10(0.037/PS(ISAND1))/ALOG10(PS(ISAND)/PS(ISAND1))
      SILTV = ALOG10(0.012/PS(ISILT1))/ALOG10(PS(ISILT)/PS(ISILT1))
C     DO 170 I = 1,NPSD
C         PFSET(I) = PF(I,ISAND1) + SANDV*(PF(I,ISAND)-PF(I,ISAND1))
C 170 CONTINUE
C
      CALL OUTPUT(PS,PFDIS,INFLOW,CONC,TIME,NDVPC,NHGP,502,IHYDR)
C
      WRITE (6,7000) QTOTAL,YTOTAL
 7000 FORMAT(//3X,'***** TOTAL RUNOFF VOLUME            = ',F12.6,
      1        ' AC-FT ****',//3X,'***** TOTAL SEDIMENT MASS      ',
      2        '       = ',F12.6,' TONS  ****')
C
      CALL GRASS(NR,DELTAT,YTOTAL,QTOTAL,QPEAK,NHGP,SG,VISCOS)
      STOP
      END
C
C *******************************************************************
C *******************************************************************
      SUBROUTINE GRASS(NR,DELTAT,YTOTAL,QTOTAL,QPEAK,NHGP,SG,VISC)
C *******************************************************************
C *******************************************************************
C
      REAL LEN,MN,INFIL(502),MEI,LNA,LNADS
      REAL LMASS,NRE,NFALLS,MCONST,INFVOL,INFLOW,LVOL
      COMMON /RAINF / TIME(502),RAIN(502),VOLINF
      COMMON /LARRAY/ OFLOW(502),SOFLOW(502),EFLNT(502),INFLOW(1002),
      1                SGRAPH(1002)
      COMMON /PARTDA/ PS(15),PFDIS(15),NDVPC,IHYDR,NPSD
      COMMON /SRETRN/ DELTST,NRHP,ACMASS,OVOL,OUTPK,IHP,ISP,PEFLNT
      COMMON /ERODE1/ PFSET(10),ISAND,ISILT,ICLAY,ISAND1,SANDV
      COMMON /FILTER/ WIDTH,MN,SSC,SPAC,EPS
      COMMON /WATER / WQ1(502),WD1(502),WQ2(502),WD2(502),
      1                WQAVG(502),WDAVG(502)
      COMMON /SEDIM1/ COARSE,FSAND,FSILT,FCLAY
      COMMON /SEDIM2/ PCLSS1(502,3),PCLSS2(502,3)
      COMMON /SEDIM3/ VS(3),FS(3),FTR(3),FINER1(15),FINER3(15),PD(3)
      COMMON /CHEM1 / SOL1(502),SOL2(502)
      COMMON /CHEM2 / PT1(502,3),PT2(502,3),PTCON(502,3),TPT(502)
      COMMON /DESRB / EDI(502),WS(502),Z(502)
      COMMON /ADSRB1/ LNA(3),B(3),C(3),D(3)
      COMMON /ADSRB2/ ADS(502,3),LNADS(502,3),TADS(502)
C
C *** STATEMENT FUNCTION USED TO ESTIMATE LOG SETTLING VELOCITY AND
```

```
C *** TRAP EFFICIENCY CORRECTION FACTOR FOR ZONE D **********
C
      VSL(DIA) = -0.34246272 * (ALOG10(DIA)) ** 2 + 0.98912185
     1           * ALOG10(DIA) + 1.146128
      TCOEF(DH) = 0.5*EXP( -3.0*DH ) + 0.5*EXP( 15.0*( 0.2*DH-DH**2 ) ) )
C
C *** INITIALIZE VALUES ***
C
      TOTINM = YTOTAL
      DELTST = DELTAT
      EINC = (6.4617E+07) * SG / ( SG-1.0 ) ** 3.07
C *** SETTLING VELOCITIES FOR SILT AND CLAY PARTICLES ***
      PD(1) = 0.004
      PD(2) = 0.012
      PDCLAY = 0.003
      VS(1) = 0.0178889 * ( SG-1.0 ) * PDCLAY ** 2 / VISC
      VS(2) = 10.0 ** VSL(PD(2)) / 30.48
      ICLAY1 = ICLAY + 1
      CLAYV = ALOG10(PD(1)/PS(ICLAY1)) / ALOG10(PS(ICLAY)/PS(ICLAY1))
C
C *** INPUT GRASS FILTER DATA ***
C       RPRINT= 1.0-SUMMARY TABLE,2.0-OUTPUT ARRAYS,3.0-PLOT VALUES,
C               4.0-PHOSPHORUS,5.0-NO PRINT
C *** DELTAX IN FEET
C
      READ(5,5100)SEG,RPRINT,BSG,DINIT,DELTAX
 5100 FORMAT(5F8.2)
      CALL CHECKR(RPRINT,1.,5.,1.,
     1'GRASS FILTER PRINT OPTION          ')
      CALL CHECKR(BSG,0.5,3.0,1.25,
     1'GRASS FILTER BULK SPECIFIC GRAVITY ')
      CALL CHECKR(DINIT,0.0,0.8,0.0,
     1'INITIAL DEPTH OF SEDIMENT          ')
      NUMSEG = INT ( SEG )
      IPRINT = INT( RPRINT )
      MCONST = 115.385 * DELTST / BSG
C
C
C
C *** LOOP THROUGH EACH SEGMENT WITH DIFFERENT VARIABLE(S)  ***
C
      WRITE(6,5000)
 5000 FORMAT(////3X,30('* ')//24X,'GRASS FILTER RESULTS'//3X,30('* ')/)
C
      IS = 0
  120 CONTINUE
      IS =IS + 1
C
C *** ENTER SLOPE IN PERCENT,GRASS HEIGHT,GRASS SPACING IN INCHES,
```

```
C *** LENGTH AND WIDTH IN FEET  *****
C
      READ(5,5010)MN,GHGHTT,SUBLEN,LEN,SPACC,SSCC,WIDTH,MEI
 5010 FORMAT(8F8.4)
      CALL CHECKR(MN,.003,.17,-1.,
     1'GRASS FILTER MANNING''S ROUGHNESS     ')
      CALL CHECKR(GHGHTT,0.1,9.0,-2.,
     1'GRASS HEIGHT                        ')
      CALL CHECKR(SUBLEN,1.0,500.,-2.,
     1'GRASS FILTER LENGTH                 ')
      CALL CHECKR(SPACC,0.1,3.0,-2.,
     1'AVERAGE GRASS SPACING               ')
      CALL CHECKR(SSCC,.01,20.,-2.,
     1'GRASS FILTER SLOPE                  ')
      CALL CHECKR(WIDTH,1.0,500.,-2.,
     1'GRASS FILTER WIDTH                  ')
      CALL CHECKR(MEI,.002,250.,-2.,
     1'GRASS STIFFNESS FACTOR              ')
        IF(IPRINT.NE.4)DELTAX=SUBLEN
        GHGHT = GHGHTT / 12.0
        SPAC = SPACC / 12.0
        SSC = SSCC / 100.0
        IF( MN ) 140,140,160
  140     WRITE(6,5300)
 5300     FORMAT(//2(5X,57('*')/)/10X,'WARNING: INPUT ERROR.  EITHER '
     1 /10X,'MANNING ROUGHNESS COEFFICIENT,SLOPE OR GRASS'/10X,
     2      'HEIGHT HAS BEEN INPUTTED AS ZERO.  THE VARIABLE'
     3 /10X,'IN ERROR HAS BEEN ASSIGNED AN ARBITUARY NUMBER'//
     4      2(5X,57('*')/)/)
          MN = 0.001
  160   IF( GHGHT ) 180,180,200
  180     WRITE(6,5300)
          GHGHT = 0.05
  200   IF( SSC ) 220,220,240
  220     WRITE(6,5300)
          SSC = 0.01
  240 CONTINUE
C
      WRITE(6,5310)
 5310 FORMAT(//12X,'***** GRASS FILTER PROPERTIES *****')
      WRITE(6,5400) IS,MN,SSCC,SPACC,GHGHTT,WIDTH,MEI
 5400 FORMAT(//21X,'SEGMENT NUMBER = ',I2,/21X,19('-')//,
     1 /5X,'MANNING''S FRICTION FACTOR',5X,'=',F9.4,
     2 /5X,'CHANNEL SLOPE',17X,'=',F9.4,2X,'PERCENT',
     3 /5X,'GRASS SPACING',17X,'=',F9.4,2X,'INCH',
     4 /5X,'GRASS HEIGHT',18X,'=',F9.4,2X,'INCH',
     5 /5X,'FILTER WIDTH',18X,'=',F9.4,2X,'FEET',
     6 /5X,'STIFFNESS COEFFICIENT',9X,'=',F9.4,2X,'N-M SQ')
C
C *** CALCULATE INFILRATION RATE
```

```
C     WRITE(6,5410)
C5410 FORMAT(///12X,'*** POTENTIAL INFILTRATION RATE ***'/,
C    1       /18X,22('-')/,20X,'TIME  INFILTRATION',
C    2       /18X,' (HR)   RATE(IN/HR)'/,18X,22('-')/)
C
      READ(5,5010)FA,FAW,FGW,DEPTH,SA,FC
      FN = FAW / FGW
C
C *** REDEFINE SOME TERMS FOR REDUCING CALCULATION ***
      FN1 = 1 - FN
      SA1F = SA**FN1
      FA1F = FA*FN1
      FN1F = FN/FN1
C
      DO 250 J = 1, NR
        INFIL(J) = FA*(SA1F - FA1F*TIME(J))**FN1F + FC
C       WRITE(6,5420) TIME(J),INFIL(J)
C5420   FORMAT(14X,F10.2,F11.2)
  250 CONTINUE
C
C
C *** LOOP THROUGH EACH SUBSEGMENT WITH IDENTICAL VARIABLES ***
C *** ISUB IS THE NUMBER OF LOOP FOR WRITING OUTPUTS
C *** ITT=NUMBER OF LOOP, I.E., FILTER DISTANCE = ITT*DELTAX
      ITOTAL=INT(LEN/DELTAX + 0.001)
      ISUB=INT(SUBLEN/DELTAX + 0.001)
C
      ITT=0
  260 CONTINUE
C
C *** INITIALIZE VALUES *****
C
      EPS = 0.1 / WIDTH
      IF( 0.01*QPEAK/WIDTH .LT. EPS) EPS = 0.01 * QPEAK / WIDTH
      VCR = ( 0.23 * MEI ** 0.106 ) * 3.281
      VCR1 = ( 0.028 + 6.33 * MEI ** 2.0 ) * 3.281
      IF( VCR1 .LT. VCR ) VCR = VCR1
      SCONST = SQRT( 32.2 * SSC )
      KERROR = 0
      KERR2 = 0
      XPREV = 0.0
      YPREV = 0.0
      SEE = 0.0
      DEPTHB = 0.1
      DEPTHC = 0.1
      DEPTHD = 0.1
      ACDEPD = DINIT
      ACMASS = 0.0
      OUTPK = 0.0
      PKSGRA = 0.0
```

```
      PEFLNT = 0.0
      LVOL = 0.0
      CORF = TCOEF( ACDEPD )
C
      IF(ITT.NE.0) GOTO 280
C *** ROUTING OF COARSE, FSILT, AND FCALY AT FILTER ENTRANCE ***
      WRITE(6,5450)
 5450 FORMAT(///,15X,'*** INPUT DATA AT FILTER STARTING POINT ***',
     1        /15X,43('-')/)
C
C *** CALCULATE THE FRACTIONS OF COARSER, MEDIUM, AND FINER SIZED
C     PARTICLES ENTERING FILTER
      CALL PSFR1(ITT,ISUB,NDVPC,PFDIS,FINER1,FINER3,CLAYV,ICLAY1,IHYDR)
C
C *** CALCULATE THE AMOUNTS OF RUNOFF AND THE SEDIMENT SIZE CLASSES
      CALL PSFR2(ITT,ISUB,INFLOW,EFLNT,NHGP,TIME,502,IHYDR)
C
C *** DETERMINE THE INPUT VALUES FOR ROUTING PHOSPHORUS
      CALL CNVRT(IS,ITT,NHGP,3,502)
C
  280 RF = FSAND + COARSE / 2.0
      PD3 = PSIZE(FINER1,PS,RF,NDVPC)
C *** ESTIMATE TRAVEL TIME THROUGH THE FILTER ******
      RQ = QPEAK / WIDTH
      RDEPTH = ( 1.962 * RQ * MN / SQRT(SSC) ) ** 0.6
      RDEPTH = GDEPTH(RQ,RDEPTH,MN,SSC,SPAC,EPS)
      ETTME = DELTAX * RDEPTH / RQ / 3600.0
      ATTME =  ETTME/DELTST
      IATTME = INT( ATTME )
      TTME = FLOAT(IATTME) * DELTST
      VSTAR = SQRT( RDEPTH ) * SCONST
C
      IF( VSTAR .LT. VCR ) GO TO 300
          REQD = VCR * VCR / SCONST / SCONST
          DV1 = ( REQD*SPAC / (2.0*REQD+SPAC) ) ** 0.6667
          REQQ = 1.49 * REQD * DV1 * SQRT( SSC ) / MN
          REQW = QPEAK / REQQ + 0.1
          WRITE(6,5500) REQW
 5500 FORMAT(//2(5X,57('*')/)/10X,'NOTE: FOR THE GIVEN INPUT',
     1 ' CONDITIONS, PREDICTED FLOW '/10X,
     2 'VELOCITIES WILL CAUSE THE GRASS TO TOPPLE.  A'/10X,
     3 'FILTER WIDTH OF ',F8.2,' FEET SHOULD'/10X,
     4 'SUFFICIENTLY REDUCES THIS FLOW VELOCITY'//2(5X,57('*')/)/)
C
  300 IF( RDEPTH .LT. GHGHT ) GO TO 320
C
      DV1 = ( GHGHT*SPAC / (2.0*GHGHT+SPAC) ) ** 0.6667
      TEMP = 1.49 * GHGHT * DV1 * SQRT( SSC ) / MN
      TEMP2 = QPEAK / TEMP
      WRITE(6,5600) TEMP,TEMP2
```

```
 5600 FORMAT(/2(5X,57('*')/)/10X,'NOTE: MAXIMUM DISCHARGE POSSIBLE'/
     1 10X,'WITHOUT INUDATING THE GRASS IS EQUAL TO:'/
     2 15X,'DISCHARGE / FOOT FILTER WIDTH = ',F10.4,' CFS/FT'/
     3 10X,'FOR PEAK DISCHARGE ENTERING THIS SEGMENT THE'/10X,
     4 'REQUIRED FILTER WIDTH IS EQUAL TO:'/15X,'WIDTH= ',F10.4,
     5 ' FEET' //2(5X,57('*')/) )
C
  320 CONTINUE
      NRHP = NHGP + IATTME
C *** INITIALIZE VALUES FOR FLOW TO REACH OUTLET ********
      DO 340 I = 1,IATTME
         OFLOW(I) = 0.0
         SOFLOW(I) = 0.0
         EFLNT(I) = 0.0
  340 CONTINUE
C
C ***** MAJOR SEDIMENT AND WATER ROUTING LOOP *****
C
      DO 840 I = 1,NHGP
C
C *** ROUTE THE INFLOW HYDROGRAPH POINT TO END OF SEGMENT ******
C
         IO = I + IATTME
         INFLOW(I) = INFLOW(I) / WIDTH
         SGRAPH(I) = SGRAPH(I) / WIDTH
C      .
         CALL GWATR(I,IO,ETTME,DELTST,DELTAX,INFIL,INFLOW(I),OFLOW(IO))
C
C *** CHECK FOR POSSIBLE ERROR OR ZERO VALUES ************
      IF( OFLOW(IO) * WIDTH - 0.0006 ) 360,360,380
  360    OFLOW(IO) = 0.0
         SOFLOW(IO) = 0.0
         EFLNT(IO) = 0.0
         IF(INFLOW(I).GT.0.0)LVOL=LVOL+INFLOW(I)*WIDTH*DELTST/12.1
         GO TO 840
C
  380    CONTINUE
         LVOL = LVOL + INFVOL * WIDTH / 43560.0
         IF( SGRAPH(I) ) 400,400,420
  400    SOFLOW(IO) = 0.0
         EFLNT(IO) = 0.0
         OFLOW(IO) = OFLOW(IO) * WIDTH
         GO TO 840
C
  420    IF( KERROR ) 460,460,440
  440    SOFLOW(IO) = SGRAPH(I)
         GO TO 740
C *** DETERMINE DISCHARGE AT INTERMEDIATE POINTS ********
  460    QWC = INFLOW(I) - XPREV * (INFLOW(I) - OFLOW(IO))/ DELTAX
         QWB = ( QWC + INFLOW(I) ) / 2.0
```

```
          QWD = ( QWC + OFLOW(IO) ) / 2.0
C ***** CALCULATE VALUES AT THE BOTTOM OF THE WEDGE *****
          DEPTHC = GDEPTH(QWC,DEPTHC,MN,SSC,SPAC,EPS)
C
          IF ( GHGHT - DEPTHC ) 480,480,500
   480    KERROR = KERROR + 1
          SOFLOW(IO) = SGRAPH(I)
          WRITE(6,5700) IS
  5700    FORMAT(//2(5X,57('*')/)/10X,'CAUTION: GRASS IS ASSUMED'/
     1    10X,'TO HAVE FALLEN OVER IN SEGMENT = ',I2/10X,
     2    'IF THIS UNACCEPTABLE POSSIBLE CORRECTION TECHNIQUES INCLUDE:'/
     3    15X,'(1) INCREASE FILTER WIDTH'/15X,
     4    '(2) PLACE FILTER IN SMALLER SUBBASIN'//2(5X,57('*')/)/)
          GO TO 740
C
   500    HR = DEPTHC * SPAC / ( 2.0*DEPTHC + SPAC )
C *** CHECK FOR CRITICAL VELOCITY ********
          VSTAR = SQRT( DEPTHC) * SCONST
          IF( VCR - VSTAR ) 480,480,520
C
C **** SEDIMENT TRANSPORT CAPACITY AS BEDLOAD CALCULATED ***
C
   520    QSC = EINC * ( HR*SSC ) ** 3.57 / PD3 ** 2.07
          QSU = COARSE * SGRAPH(I)
C
          IF (QSU - QSC) 540,540,560
   540    QSC = QSU
          GO TO 640
C *** CHECK FOR TRIANGULAR OR TRAPEZOIDAL WEDGE ******
   560    IF (YPREV - GHGHT) 580,620,620
C *** QSI= SEDIMENT LOAD AT START OF DEPOSITION ******
   580    QSI = QSU - SEE * (QSU - QSC) / (SEE + SSC)
          CALL GWEDGE(QSI,QSC,QWB,DEPTHB,EINC,PD3,
     1    MN,SPAC,SSC,EPS,SEE)
          XPREV = SQRT( (QSU - QSC) * SSC * MCONST / SEE /
     1    (SEE + SSC)    + XPREV ** 2)
          YPREV = SQRT((QSU - QSC) * MCONST * SEE * SSC
     1    / (SSC + SEE) + YPREV ** 2)
C
          IF ( XPREV - DELTAX ) 640,600,600
   600    KERROR = KERROR + 1
          SOFLOW(IO) = SGRAPH(I)
          WRITE(6,5800) IS
  5800    FORMAT(//2(5X,57('*')/)/10X,'CAUTION: THE FILTER IS FILLED WITH'
     1    /10X,'SEDIMENT IN SEGMENT = ',I2,'.  IF THIS IS'/10X,
     2    'UNACCEPTABLE POSSIBLE CORRECTION TECHNIQUES INCLUDE:'/15X,
     3    '(1) INCREASE FILTER WIDTH'/15X,'(2) INCREASE FILTER LENGTH'/
     4    15X,'(3) PLACE FILTER IS SMALLER SUBBASIN'//2(5X,57('*')/)/)
```

```
          GO TO 740
C
C *** TRAPEZOIDAL WEDGE ****************
   620    XPREV = (QSU-QSC) * MCONST / ( 2.0 * GHGHT) + XPREV
          IF ( XPREV - DELTAX ) 640,600,600
   640    CONTINUE
C
C *** CALCULATE TRAP EFFICIENCY IN THE WEDGE *****
C
          IF (COARSE .LE. 0.0) QSU = 1.0
          WTRAP = ( (QSU - QSC) / QSU ) * COARSE
C ***** CALCULATE NEW COARSE PARTICLE SIZE *****
          DCOARS = 1.0 - WTRAP - FSAND
          RF = FSAND + DCOARS / 2.0
          PD(3) = PSIZE(FINER1,PS,RF,NDVPC)
          VS(3) = 10.0 ** VSL( PD(3) ) / 30.48
C ***** CALCULATE FALL LENGTH;SEDIMENT PORTION EACH PARTICLE *****
          FLEN = DELTAX -  XPREV
          QSTOT = QSC + SGRAPH(I) * FSAND
          IF( QSTOT ) 400,400,660
   660    FS(1) = FCLAY * SGRAPH(I) / QSTOT
          FS(2) = FSILT * SGRAPH(I) / QSTOT
          FS(3) = QSC / QSTOT
C ***** DETERMINE FALL DEPTH *****
          DEPTHD = GDEPTH(QWD,DEPTHD,MN,SSC,SPAC,EPS)
          HR = DEPTHD * SPAC / (2.0 * DEPTHD + SPAC)
          VD = 1.49 * SQRT(SSC) * HR ** 0.6667 / MN
          NRE = 929.03 * VD * HR / VISC
C
C ***** CALCULATE TRAP EFFICIENCY IN REMAINING FILTER LENGTH *****
C
          RTRAP = 0.0
          DO 700 J=1,3
             NFALLS = VS(J) * FLEN / QWD
             DV1 = 0.00105 * NRE**0.82 * NFALLS**(-0.91)
             IF( DV1 .LT. 10.0) GO TO 680
                  DV1 = 10.0
   680    FTR(J) = CORF * EXP(- DV1 )
             RTRAP = RTRAP + FTR(J) * FS(J)
   700    CONTINUE
C *** ACCOUNT FOR MASS LOSS DUE TO INFILTRATION ********
          DV1 = (QWC-OFLOW(IO)) * (1.0-RTRAP) / (2.0*QWD)
          SOFLOW(IO) = QSTOT * (1.0-RTRAP-DV1) / (1.0+DV1)
C %%% TO ADJUST UNDERESTIMATION OF SEDIMENT TRAPPING EFFICIENCY
          SOFLOW(IO) = SOFLOW(IO) * 0.85
C
          ACDEPD = ACDEPD + 12.*(QSTOT-SOFLOW(IO))*(MCONST/2.)/FLEN
C
          IF( ACDEPD .LT. 1.5 ) GO TO 720
          IF( KERR2 .GE. 1 ) GO TO 740
```

```
         KERR2 = 2
         CORF = 0.0
         WRITE(6,5900)
 5900    FORMAT(//2(5X,57('*')/)/10X,'CAUTION: ZONE D IN FILTER IS'/
      1  10X,'FILLED TO MAXIMUM DEPOSITION DEPTH.  NO MORE SEDIMENT'/
      2  10X,'IS TRAPPED IN THIS ZONE.  IF THIS IS UNACCEPTABLE'/
      3  10X,'POSSIBLE CORRECTION TECHNIQUES INCLUDE:'/15X,
      4  '(1) INCREASE FILTER LENGTH OR FILTER WIDTH'/15X,
      5  '(2) PLACE FILTER IN SMALLER SUBBASIN'/2(5X,57('*')/)/)
         GO TO 740
  720    CORF = TCOEF( ACDEPD )
C
C **** CALCULATE OVERALL TRAP EFFICIENCY ********
C
  740    CONTINUE
         OTRAP = 1.0 - SOFLOW(IO)/SGRAPH(I)
         LMASS = SOFLOW(IO) * DELTST * 3600.0 * WIDTH
C        IF(IO.LE.1) GOTO 750
C        LMASS = (SOFLOW(IO)+SOFLOW(IO-1))/2.0 * DELTST * 3600.0 * WIDTH
  750    ACMASS = ACMASS + LMASS
         IF( 1.0 - OTRAP ) 760,760,780
  760       EFLNT(IO) = 0.0
            OFLOW(IO) = OFLOW(IO) * WIDTH
            GO TO 840
C ***** CALCULATE WEIGHTED PARTICLE SIZE  *****
  780    DO 800 J=1,NDVPC
            DV1 = FINER1(J) / (1.0-OTRAP)
            IF ( DV1 .GT. 1.0) DV1 = 1.0
            FINER3(J) = FINER3(J) + DV1 * LMASS
  800    CONTINUE
C *** CALCULATE EFLUENT CONCENTRATION AND CHECK PEAK VALUES ****
         SOFLOW(IO) = SOFLOW(IO) * WIDTH
         OFLOW(IO) = OFLOW(IO) * WIDTH
         EFLNT(IO) = (SOFLOW(IO)/(SOFLOW(IO)/SG/62.4+OFLOW(IO)))*16018.46
         IF( EFLNT(IO) .GT. PEFLNT) PEFLNT = EFLNT(IO)
         IF( OUTPK .GT. OFLOW(IO) ) GO TO 820
            OUTPK = OFLOW(IO)
            IHP = IO
  820    IF( PKSGRA .GT. SOFLOW(IO) ) GO TO 840
            PKSGRA = SOFLOW(IO)
            ISP = IO
C
C *** END OF SEDIMENT AND WATER ROUTING LOOP
C
  840 CONTINUE
C
C *** DETERMINE WEIGHTED PARTICLE SIZE AND OUTPUT SUMMARY TABLES ***
C
         DO 860 I = 1,NDVPC
            IF( ACMASS .LE. 0.0 ) GO TO 860
```

```
              PFDIS(I) = ( FINER3(I)/ACMASS ) * 100.0
              IF( PFDIS(I) .GT. 99.9 ) PFDIS(I) = 100.0
        860 CONTINUE
              ACMASS = ACMASS / 2000.0
              OVOL = QTOTAL - LVOL
              IF( YTOTAL ) 880,880,900
        880 TE = 0.0
              GO TO 920
        900 TE = ( 1.0 - ACMASS/YTOTAL ) * 100.0
        920 CONTINUE
      C
              IF( IPRINT .EQ. 3 ) GO TO 930
      C
              RDEPTH = RDEPTH * 12.0
              SSCONV = SSCONC(PFDIS,PS,NDVPC,PEFLNT,SSCONM,IHYDR)
      C
              IF(MOD(ITT,ISUB).NE.0) GOTO 930
      C *** CUMLEN IS THE DISTANCE OF FILTER CONSIDERED
              CUMLEN=(ITT+1)*DELTAX
              CETIME=(ITT+1)*ETIME
              WRITE(6,6300)
       6300 FORMAT(///22X,'***** SUMMARY TABLE *****',/21X,27('-'))
              WRITE(6,6400) CUMLEN,SG,BSG,VISC,VCR,RDEPTH,CETIME,LVOL,
             1 XPREV,ACDEPD,OVOL,OUTPK,PEFLNT,SSCONV,SSCONM,ACMASS,TE
       6400 FORMAT(/5X,'CUMULATIVE FILTER LENGTH',9X,'=',F11.2,2X,'FEET',
             2/5X,'SPECIFIC GRAVITY OF SEDIMENT',5X,'=',F11.2,
             3/5X,'BULK SPECIFIC GRAVITY',12X,'=',F11.2,
             4/5X,'VISCOSITY',24X,'=',F11.4,2X,'CM**2/SEC',
             5/5X,'CRITICAL PRONE VELOCITY',10X,'=',F11.4,2X,'FT/S',
             6/5X,'PEAK FLOW DEPTH',18X,'=',F11.2,2X,'INCH',
             7/5X,'FILTER TRAVEL TIME',15X,'=',F11.4,2X,'HR',
             8/5X,'INFILTRATION VOLUME',14X,'=',F11.4,2X,'ACRE-FT'
             A/5X,'WEDGE LOCATION',19X,'=',F11.2,2X,'FEET',
             B/5X,'SEDIMENT DEPTH ZONE D',12X,'=',F11.4,2X,'INCH',
             C/5X,'OUTFLOW RUNOFF VOLUME',12X,'=',F11.2,2X,'ACRE-FT',
             D/5X,'PEAK DISCHARGE RATE',14X,'=',F11.2,2X,'CFS',
             E/5X,'PEAK EFFLUENT CONCENTRATION',6X,'=',F11.2,2X,'MG/L',
             F/5X,'PEAK SETTLEABLE CONCENTRATION',4X,'=',F11.4,2X,'ML/L',
             G/5X,'PEAK SETTLEABLE CONCENTRATION',4X,'=',F11.2,2X,'MG/L',
             H/5X,'TOTAL MASS DISCHARGED',12X,'=',F11.2,2X,'TONS',
             I/5X,'TRAP EFFICIENCY IN ADDED SEGMENT',3X,'=',F9.2,2X,'PERCENT')
              IF(IHYDR.EQ.1)GO TO 930
              CALL AVPEAK(TWCONC,WCONC,TCONC,AVECON,TIMEC,OFLOW,EFLNT,NRHP,502,
             1            DELTAT,SSCONV,PEFLNT)
              WRITE(6,6401)TIMEC,TWCONC,WCONC,TCONC,AVECON
       6401 FORMAT(5X,'PERIOD OF SIGNIFICAT CONCENTRATION =',3X,F6.2,2X,
             1          'HRS'/5X,'VOLUME WEIGHTED AVERAGE SETTLEABLE'/7X,
             2          'CONCENTRATION DURING PERIOD OF'/7X,'SIGNIFICANT',
             3          ' CONCENTRATION',8X,'=',F9.2,2X,'ML/L'/5X,'VOLUME',
             4          ' WEIGHTED AVERAGE SETTLEABLE'/7X,'CONCENTRATION',
```

```
     5          ' DURING PEAK 24 HOUR'/7X,'PERIOD',27X,'=',F9.2,2X,
     6          'ML/L'/5X,'ARITHMETIC AVERAGE SETTLEABLE'/7X,
     7          'CONCENTRATION DURING PERIOD OF'/7X,'SIGNIFICANT',
     8          ' CONCENTRATION',8X,'=',F9.2,2X,'ML/L'/5X,
     9          'ARITHMETIC AVERAGE SETTLEABLE'/7X,'CONCENTRATION',
     A          ' DURING PEAK 24 HOUR'/7X,'PERIOD',27X,'=',F9.2,2X,
     B          'ML/L')
C
      WRITE(6,5410)
 5410 FORMAT(///13X,'*** POTENTIAL INFILTRATION RATE ***'/,
     1          /18X,22('-')/,20X,'TIME   INFILTRATION',
     2          /18X,' (HR)   RATE(IN/HR)'/,18X,22('-')/)
C
      DO 922 J = 1, NRHP
         WRITE(6,5420) TIME(J),INFIL(J)
 5420    FORMAT(14X,F10.2,F11.2)
  922 CONTINUE
C
  930 CONTINUE
C
C *** CALCULATE THE FRACTIONS OF COARSER, MEDIUM, AND FINER SIZED
C     PARTICLES LEAVING FILTER SEGMENT
      CALL PSFR1(ITT,ISUB,NDVPC,PFDIS,FINER1,FINER3,CLAYV,ICLAY1,IHYDR)
C
C *** CALCULATE THE AMOUNT OF RUNOFF AND THE SEDIMENT SIZE CLASSES
      CALL PSFR2(ITT,ISUB,OFLOW,EFLNT,NRHP,TIME,502,IHYDR)
C
      IF(IPRINT.NE.4) GOTO 940
C *** ROUTE PHOSPHORUS: CHANGE TIME UNIT FROM HOUR TO MIN ***
      DT = 3.0
      ET = 60.0 * ETTME
      DX = DELTAX
C
C *** CHMSOL SHOULD PRECEDE CHMPRT IN CALLING PROGRAM
      CALL CHMSOL(ITT,ISUB,DT,DX,WIDTH,ET,TIME,INFIL,NRHP,3,502,IHYDR)
      CALL CHMPRT(ITT,ISUB,DT,DX,WIDTH,TIME,NRHP,3,502,IHYDR)
C
  940 CONTINUE
C *** OUTPUT OF ACCUMULATED SEGMENT RESULT ********
      IF(TOTINM.LE.0.) GOTO 980
      IF(MOD(ITT,ISUB).NE.0) GOTO 950
      IF( IPRINT .EQ. 3 ) RETURN
      IF( IPRINT .EQ. 1 ) RETURN
      CALL OUTPUT(PS,PFDIS,OFLOW,EFLNT,TIME,NDVPC,NRHP,502,IHYDR)
C
      WRITE (6,7000) OVOL,ACMASS
      WRITE (9,7000) OVOL,ACMASS
 7000 FORMAT(//3X,'***** TOTAL RUNOFF VOLUME                 = ',F12.6,
     1          ' AC-FT ****',//3X,'***** TOTAL SEDIMENT MASS          ',
```

```
      2          '       = ',F12.6,' TONS  ****')
C
         OTE = ( 1.0 - ACMASS/TOTINM ) * 100.0
         WRITE(6,6500) OTE
 6500 FORMAT(//3X,'***** OVERALL SEDIMENT TRAP EFFICIENCY  = ',
     1         F12.2, ' %  *******'/)
C
C *** CONVERT VALUES FOR NEXT DISTANCE INREMENT ********
C    * WATER AND SEDIMENT VALUSES
  950 NHGP = NRHP
      YTOTAL = ACMASS
      QTOTAL = OVOL
      DO 970 I = 1,NRHP
         INFLOW(I) = OFLOW(I)
         SGRAPH(I) = SOFLOW(I)
  970 CONTINUE
C    * PHOSPHORUS VALUES ***
      CALL CNVRT(IS,ITT,NRHP,3,502)
C
      ITT=ITT+1
      IF(ITT.LT.ITOTAL) GO TO 260
C *** LOOP END OF SUBSEGMENT WITH IDENTICAL VARIABLES ***
C
C
      IF(IS.LT.NUMSEG) GO TO 120
C *** LOOP END OF SEGMENT WITH DIFFERENT VARIABLE(S)  ***
C
C
C
  980 CONTINUE
      RETURN
      END
C
C ********************************************************************************
C ********************************************************************************
      SUBROUTINE PSFR1(IT,IC,ND,PFDIS,F1,F3,CLAYV,ICLAY1,IHYDR)
C ********************************************************************************
C ********************************************************************************
C
C    F1 AND F3 CORRESPOND TO FINER1 AND FINER3, RESPECTIVELY
C
      DIMENSION F1(ND),F3(ND),PFDIS(ND)
      COMMON /ERODE1/ PFSET(10),ISAND,ISILT,ICLAY,ISAND1,SANDV
      COMMON /SEDIM1/ COARSE,FSAND,FSILT,FCLAY
C
      DO 100 I = 1,ND
         F1(I) = PFDIS(I) / 100.0
         F3(I) = 0.0
  100 CONTINUE
C
```

```
      FSAND = F1(ISAND1) + SANDV * ( F1(ISAND)-F1(ISAND1) )
      FCLAY = F1(ICLAY1) + CLAYV * ( F1(ICLAY)-F1(ICLAY1) )
      COARSE = 1.0 - FSAND
      FSILT = FSAND - FCLAY
C
      IF(MOD(IT,IC).NE.0) RETURN
      WRITE(6,5000)
 5000 FORMAT(////15X,'*** PARTICLE SIZE FRACTION OF SEDIMENT ***'//,
     A15X,'SIZE,MM',11X,'>0.037   0.037>   <0.004'/)
      WRITE(6,5100) COARSE,FSILT,FCLAY
 5100 FORMAT(15X,'SIZE FRACTION',2X,3F9.4/)
      RETURN
      END
C
C ***********************************************************************
C ***********************************************************************
      SUBROUTINE PSFR2(IT,IC,WQ,SQ,NHGP,TIME,LSIZE,IHYDR)
C ***********************************************************************
C ***********************************************************************
C
      REAL MN,WQ(LSIZE),SQ(LSIZE),TIME(LSIZE)
      COMMON /FILTER/ WIDTH,MN,SSC,SPAC,EPS
      COMMON /WATER / WQ1(502),WD1(502),WQ2(502),WD2(502),
     1                WQAVG(502),WDAVG(502)
      COMMON /SEDIM1/ COARSE,FSAND,FSILT,FCLAY
      COMMON /SEDIM2/ PCLSS1(502,3),PCLSS2(502,3)
C
      IF(MOD(IT,IC).NE.0) GO TO 100
      WRITE(6,5200)
 5200 FORMAT(////17X,'*** HYDROGRAPH AND SEDIMENT GRAPH ***'//)
      IF(IHYDR.EQ.2)WRITE(6,5300)
 5300 FORMAT(7X,55('-'),/8X,'TIME     DISCHARGE          COARSE',
     1       6X,'MEDIUM        FINERS',/8X,'(HR)  (CM3/FT/MIN)',
     2       3(6X,'(MG/L)'),/7X,55('-')/)
      IF(IHYDR.EQ.1)WRITE(6,5400)
 5400 FORMAT(15X,'TIME      DISCHARGE',1X,'*******',2X,'TIME',4X,
     1       'DISCHARGE'/15X,'(HR) (CM3/FT/MIN)',5X,'*',5X,
     2       '(HR) (CM3/FT/MIN)',/12X,22('-')/)
C
  100 CONTINUE
      DO 120 J = 1,NHGP
        WQ2(J) = WQ(J) / WIDTH
        WD2(J) = ( 1.962 * WQ2(J) * MN / SQRT(SSC) ) ** 0.6
C       WD2(J) = GDEPTH(WQ2,WD2,MN,SSC,SPAC,EPS)
C *** CONVERT UNIT FROM CFS TO CM3/MIN
        WQ2(J) = 1699010.8 * WQ2(J)
        WD2(J) = 30.48 * WD2(J)
        PCLSS2(J,1) = COARSE * SQ(J)
        PCLSS2(J,2) = FSILT * SQ(J)
        PCLSS2(J,3) = FCLAY * SQ(J)
```

```
      IF(MOD(IT,IC).NE.0) GOTO 120
      IF(IHYDR.EQ.2)WRITE(6,5700)TIME(J),WQ2(J),(PCLSS2(J,K),K=1,3)
 5700   FORMAT(6X,F6.2,2X,F10.2,2X,3F12.2)
  120 CONTINUE
      RETURN
      END
C
C ******************************************************************************
C ******************************************************************************
      SUBROUTINE CNVRT(IS,IT,NHGP,N,LS)
C ******************************************************************************
C ******************************************************************************
C
C *** THIS SUBPROGRAM PROVIDES THE KNOWN INPUT VARIABLES
C     FOR FOLLOWING FILTER SEGMENT
C
      COMMON /WATER / WQ1(502),WD1(502),WQ2(502),WD2(502),
     1                WQAVG(502),WDAVG(502)
      COMMON /SEDIM2/ F1(502,3),F2(502,3)
      COMMON /CHEM1 / SOL1(502),SOL2(502)
      COMMON /CHEM2 / PT1(502,3),PT2(502,3),PTCON(502,3),TPT(502)
C
C *** CONVERT VALUES FOR NEXT DISTANCE INCREMENT ***
C   - AT FILTER STARTING POINT SOL1 AND PT1 ARE DEFINED BY INPUT DATA
C   - ONLY AT THE ENTERING POINT, IS = 1 AND IT = 0
      DO 200 J = 1, NHGP
        WQ1(J) =  WQ2(J)
        WD1(J) =  WD2(J)
        IF((IS.NE.1).AND.(IT.NE.0)) SOL1(J) = SOL2(J)
        DO 100 K = 1, N
          F1(J,K) = F2(J,K)
          IF((IS.NE.1).AND.(IT.NE.0)) PT1(J,K) = PT2(J,K)
  100   CONTINUE
  200 CONTINUE
      RETURN
      END
C
C ******************************************************************************
C ******************************************************************************
      SUBROUTINE CHMSOL(IT,IC,DT,DX,WIDTH,ET,TIME,INFIL,NHGP,N,LS,IHYDR)
C ******************************************************************************
C ******************************************************************************
C
      REAL INFIL(LS),KM,L9,M9,LNA,LNADS,TIME(LS)
      COMMON /WATER / WQ1(502),WD1(502),WQ2(502),WD2(502),
     1                WQAVG(502),WDAVG(502)
      COMMON /SEDIM2/ F1(502,3),F2(502,3)
      COMMON /CHEM1 / SOL1(502),SOL2(502)
      COMMON /CHEM2 / PT1(502,3),PT2(502,3),PTCON(502,3),TPT(502)
      COMMON /CHEM3 / PLOAD7,PLOAD9,PLIN7,PLIN9,PLOUT7,PLOUT9
```

```
      COMMON /DESRB / EDI(502),WS(502),Z(502)
      COMMON /ADSRB1/ LNA(3),B(3),C(3),D(3)
      COMMON /ADSRB2/ ADS(502,3),LNADS(502,3),TADS(502)
C
C *** INITIALIZE DISSOLVED P CONCENTRATIONS AND LOAD AT TIME = 0
      SOL2(1) = 0.0
      PLOAD9 = 0.
      IF(IT.NE.0) GO TO 200
C *** INITIAL VALUES OF DISSOLVED P AT FILTER STARTING LINE ***
      READ (5,1000) KM,RA
      READ (5,1000) (SOL1(J),J=1,NHGP)
 1000 FORMAT(10F8.4)
      WRITE(6,2000)
 2000 FORMAT(////13X,'*** CONC OF DISSOLVED P AT ENTERING POINT ***'///,
     1 /20X,30('-'),/20X,'TIME (HR)      CONC OF P (MG/L)',/20X,30('-')/)
C
      DO 100 J = 1, NHGP
         WRITE(6,3000) TIME(J),SOL1(J)
         WRITE(8,3000) TIME(J),SOL1(J)
 3000    FORMAT(20X,F6.2,7X,F12.4)
C
C *** INTEGRATING (CONC*DISCHARGE) CURVE IN RESPECT WITH TIME ***
         IF(J.EQ.NHGP) GO TO 100
         PLOAD9 = PLOAD9 + (SOL1(J) + SOL1(J+1)) * (WQ1(J) + WQ1(J+1))
C                * DT/2./2./1000. (COMING 2 LINES BELOW TO RDUCE CLCLTN)
  100 CONTINUE
C
      PLIN9 = (PLOAD9 * WIDTH ) * (DT / 4000.)
      WRITE(6,6000) PLIN9
C
C *** REINITIALIZE P LOAD VALUE FOR THE FOLLOWING SEGMENT ***
      PLOAD9 = 0.
  200 CONTINUE
C
      DO 300 J = 1, NHGP
         WQAVG(J) = (WQ1(J) + WQ2(J)) / 2.
         WDAVG(J) = (WD1(J) + WD2(J)) / 2.
  300 CONTINUE
C
      CALL DESORB (IT,IC,DX,DT,ET,TIME,WQAVG,NHGP,LS,IHYDR)
      CALL ADSORB (IT,IC,TIME,NHGP,N,LS,IHYDR)
C
      DXC = 30.48 * DX
      NHGP1 = NHGP - 1
      DO 400 J = 1, NHGP1
         A9 = WDAVG(J+1) / DT / 2.
         B9 = WQAVG(J+1) / DXC
         C9 = (WQ2(J+1) - WQ1(J+1)) / DXC / 2.
         D9 = ( ( INFIL(J+1) + INFIL(J) ) * 2.54 / 60.0 / 2.0
     1        + KM * WDAVG(J+1) ) / 2.0
```

```
           E9 = ( - WDAVG(J+1) * TADS(J+1) + RA + Z(J+1))
           L9 = A9 + B9 + C9 + D9
           IF(L9.EQ.0.0) GOTO 320
           M9 = A9 - B9 + C9 + D9
           R9 = E9 + A9 * SOL1(J) - M9 * SOL1(J+1)
           SOL2(J+1) = ( A9 * SOL2(J) + R9 ) / L9
           IF(SOL2(J+1).LT.0) SOL2(J+1) = 0.0
           GO TO 340
  320      SOL2(J+1) = 0.0
  340      CONTINUE
C
           IF(MOD(IT,IC).NE.0) GOTO 400
           PLOAD9 = PLOAD9 + (SOL2(J) + SOL2(J+1)) * (WQ2(J) + WQ2(J+1))
C                    * DT/2./2./1000.0 (BELOW 10 LINES)
  400 CONTINUE
C
      IF(MOD(IT,IC).NE.0) RETURN
      WRITE (6,4000)
 4000 FORMAT(////10X,'*** ROUTING OF DISSOLVED CHEMICALS  ***'///,15X,
     130('-'),/15X,'TIME (HR)   DISSOLVED P (MG/L)',/15X,30('-')/)
C
      DO 500 J = 1, NHGP
         IF(IHYDR.EQ.2) WRITE(6,5000)TIME(J),SOL2(J)
         IF(IHYDR.EQ.2) WRITE(8,5000)TIME(J),SOL2(J)
 5000    FORMAT(12X,F10.2,6X,F10.4)
  500 CONTINUE
C
      PLOUT9 = ( PLOAD9 * WIDTH ) * (DT / 4000.)
C
C *** CALCULATE DISSOLVED P TRAPPING EFFICIENCY ***
      PTE = 100 * (PLIN9 - PLOUT9) / PLIN9
      WRITE(6,6000) PLOUT9
      WRITE(9,6000) PLOUT9
C
 6000 FORMAT(////3X,'******* CUMULATIVE DISSLOVED P LOAD    =',
     1       F8.2,' MG  *******')
      WRITE(6,7000) PTE
 7000 FORMAT(///3X,'******* DISSOLVED P TRAPPING EFFICIENCY =',
     1       F8.2,' %   *******'//)
      RETURN
      END
C
C ***************************************************************************
C ***************************************************************************
      SUBROUTINE DESORB (IT,IC,DX,DT,ET,TIME,WQAVG,NHGP,LS,IHYDR)
C ***************************************************************************
C ***************************************************************************
C
      REAL K,WQAVG(NHGP),TIME(LS)
```

```
      COMMON /DESRB / EDI(502),WS(502),Z(502)
C
      IF((MOD(IT,IC).EQ.0).AND.(IHYDR.EQ.2)) WRITE (6,1000)
 1000 FORMAT(////15X,'*** CHANGE OF DESORPTION VARIABLES ***'///,12X,
     1 44('-')/,12X,'TIME         EDI    WATER/SOIL  P DESORPTION'/,
     2 12X,'(HR)        (CM)      (L/KG)    (UG/CM2/MIN)'/,
     3 12X,44('-')/)
C
      IF(IT.NE.0) GO TO 100
C *** DEFINE CONSTANTS ***
C     ASSIGN ZEROS TO K, ALPHA, AND BETA WHEN DIRECTLY UNAVAILABLE
C
      READ(5,2000) K,ALPHA,BETA,BD,P0,EDIC,DSA
      READ(5,2000) EPSIL,WLEAF
C
      IF(ABS(K).GT.0) GOTO 100
      READ (5,2000) CLAY,OC
 2000 FORMAT(10F8.4)
      COC = CLAY/OC
      K = 0.63 * COC**(-0.699)
      ALPHA = 0.915 * COC ** (-0.540)
      BETA = 0.141 * COC ** 0.429
C
  100 CONTINUE
C
      FACTOR = ET * 1000.0 / ( 30.48 * 30.48 * DX * BD )
      WS(1) = 0.0
      DO 200 J = 2, NHGP
        EDI(J) = EDIC
        IF(EDI(J).LE.0.0) EDI(J) = EXP(-3.130 + 0.017 * DSA )
        COEF = K * BD * EDI(J) * P0
        WS(J) = FACTOR * WQAVG(J) / EDI(J)
        IF(WS(J).LE.0.0) GOTO 150
C  *** ALL COEFFICIENTS WERE DETERMINED WITH TIME UNIT OF MINUTES ***
        Z(J) = COEF*(ALPHA*((60.*TIME(J))**(ALPHA-1.)) * (WS(J)**BETA)
     1          + BETA*((60.0*TIME(J))**ALPHA) * (WS(J)**(BETA-1))*(WS(J)
     2          - WS(J-1)) / DT )
C  *** P DESORPTION FORM LIVING LEAVES ***
        ZLEAF = (1./ ( EPSIL * TIME(J) * 60.0 ) ) * WLEAF
        Z(J) = Z(J) + ZLEAF
        GOTO 170
  150   Z(J) = 0.0
  170   CONTINUE
        IF(Z(J).LE.0.0) Z(J) = 0.0
        IF(MOD(IT,IC).NE.0) GOTO 200
        IF(IHYDR.EQ.2) WRITE(6,3000) TIME(J),EDI(J),WS(J),Z(J)
 3000   FORMAT(12X,F4.2, F11.2,F12.2,F13.4)
  200 CONTINUE
      RETURN
```

```
      END
C
C ********************************************************************
C ********************************************************************
      SUBROUTINE ADSORB(IT,IC,TIME,NHGP,N,LS,IHYDR)
C ********************************************************************
C ********************************************************************
C
      REAL TIME(LS),LNLAM,LNA,LNADS
      COMMON /SEDIM2/ F1(502,3),F2(502,3)
      COMMON /CHEM1 / SOL1(502),SOL2(502)
      COMMON /CHEM2 / PT1(502,3),PT2(502,3),PTCON(502,3),TPT(502)
      COMMON /ADSRB1/ LNA(3),B(3),C(3),D(3)
      COMMON /ADSRB2/ ADS(502,3),LNADS(502,3),TADS(502)
C
      IF(IT.NE.0) GO TO 200
C *** KIN=1 (ELOVICH KINETICS), KIN=2 (MODEIFIED FREUNDLICH)
      READ(5,1000) KIN
 1000 FORMAT(I8)
      DO 100 K =1, N
        READ(5,2000) LNA(K),B(K),C(K),D(K)
 2000   FORMAT(4F8.3)
  100 CONTINUE
  200 CONTINUE
C
      IF(MOD(IT,IC).EQ.0) WRITE (6,3000)
 3000 FORMAT(////11X,'***** CHANGE OF ADSORPTION VARIABLES *****'///,7X,
     152('-'),/7X,'TIME       ADS1       ADS2       ADS3      TOTAL',
     2/7X,'(HR)    (MG/L/MIN) (MG/L/MIN) (MG/L/MIN) (MG/L/MIN)'/,
     37X,52('-')/)
C
      DO 400 J = 2, NHGP
        TADS(J) = 0.
C *** CALCULATE ADSORPTION AMT BY EACH PARTICLE SIZE CLASSES
C     K=1 COARSE(>37 MICRONS), K=2 MEDIUM (37-4), K=3 (<4)
C
        DO 300 K =1, N
C *** NO ADSORPTION WHEN NO SEDIMENT OR DISCHARGE ***
          IF(TIME(J).LE.0.0) GO TO 260
          IF(SOL1(J).LE.0.0) GO TO 260
          IF((F1(J,K)+F2(J,K)).LE.0) GO TO 260
          GO TO ( 210,230 ), KIN
  210     EPSIL = C(K) * SOL1(J)**D(K)
C ***  EPSILON DETERMINED EXPERIMENTALLY WITH TIME UNIT OF HOUR ***
          ADS(J,K) = 1./ ( EPSIL * TIME(J) * 60.0 )
     1               * (F1(J,K) + F2(J,K)) / 2.0 / 1000000.0
          GOTO 280
  230     LNADS(J,K) = 0.6931 * ( -1. - B(K) - C(K) ) + LNA(K)
     1               + ALOG( F1(J,K) + F2(J,K) )
     2               + B(K) * ALOG( SOL1(J) + SOL2(J) )
```

```
     3                       + C(K) * ALOG( PT1(J,K) + PT2(J,K) )
C
   250     ADS(J,K) = EXP(LNADS(J,K)) / (60.0 * 1000000.)
           GO TO 280
   260     ADS(J,K) = 0.0
   280     TADS(J) = TADS(J) + ADS(J,K)
   300   CONTINUE
C
       IF(MOD(IT,IC).NE.0) GOTO 400
       IF(IHYDR.EQ.2) WRITE(6,4000) TIME(J),(ADS(J,K),K=1,N),TADS(J)
 4000   FORMAT(5X,F6.2,4F12.4)
  400 CONTINUE
      RETURN
      END
C
C ********************************************************************
C ********************************************************************
      SUBROUTINE CHMPRT(IT,IC,DT,DX,WIDTH,TIME,NHGP,N,LS,IHYDR)
C ********************************************************************
C ********************************************************************
C
      REAL L7,M7,LNA,LNADS,TIME(502)
      COMMON /WATER / WQ1(502),WD1(502),WQ2(502),WD2(502),
     1                WQAVG(502),WDAVG(502)
      COMMON /SEDIM2/ F1(502,3),F2(502,3)
      COMMON /CHEM1 / SOL1(502),SOL2(502)
      COMMON /CHEM2 / PT1(502,3),PT2(502,3),PTCON(502,3),TPT(502)
      COMMON /CHEM3 / PLOAD7,PLOAD9,PLIN7,PLIN9,PLOUT7,PLOUT9
      COMMON /DESRB / EDI(502),WS(502),DES(502)
      COMMON /ADSRB1/ LNA(3),B(3),C(3),D(3)
      COMMON /ADSRB2/ ADS(502,3),LNADS(502,3),TADS(502)
C
C *** ASSUMED THAT INPUT FROM RAIN IS NEGLIGIBLE   ***
C     ASSUMED THAT DISLODGEMENT IS NEGLIGIBLE IN FILTER STRIPTS ***
      DATA RR,SR,BB,SB/4*0./
C
C *** INITIALIZE TOTAL PARTICULATE PHOSPHORUS CONCENTRATIONS
      DO 100 J = 1, NHGP
         TPT(J) = 0.
  100 CONTINUE
      PLOAD7 = 0.
C
      IF(IT.NE.0) GO TO 500
C *** INPUT DATA OF PARTICULATE P AT FILTER STARTING LINE ***
C *** PT1 IN MG P/KG SOIL MATERIAL
C
       READ(5,1000)(PT1(1,K),K=1,N)
 1000   FORMAT(10F8.2)
      DO 300 K = 1, N
         DO 200 J = 1, NHGP
```

```
                PT1(J,K) = PT1(1,K)
                PTCON(J,K) = PT1(J,K) * F1(J,K) / 1000000.0
                TPT(J)=TPT(J) + PTCON(J,K)
   200    CONTINUE
   300 CONTINUE
C
      WRITE(6,2000)
 2000 FORMAT(////7X,'*** CONC OF PARTICULATE P AT ENTERING POINT ***'
     1///7X,50('-'),/8X,'TIME                   PARTICULATE P (MG P/L)'/,8X,
     2'(HR)        COARSE      MEDIUM        FINER      TOTAL'/,7X,50('-'),/)
C
      DO 400 J = 1, NHGP
         WRITE(6,3000) TIME(J),(PTCON(J,K),K=1,N),TPT(J)
         WRITE(8,3000) TIME(J),TPT(J)
 3000    FORMAT(7X,F6.2,4F10.2)
         IF(J.EQ.NHGP) GO TO 400
         PLOAD7 = PLOAD7 + (TPT(J) + TPT(J+1)) * (WQ1(J) + WQ1(J+1))
C    1            * DT / 4. / * WIDTH ( BELOW 4 LINES )
   400 CONTINUE
C
C *** CHANGE UNIT FROM MILIGRAMS P TO GRAM P ***
C     PLIN7 = PLOAD7 / 1000. * ( DT / 4000.0 ) * WIDTH   IS EQUAL TO
      PLIN7 = PLOAD7 * WIDTH * DT / 4000000.0
      WRITE(6,6000) PLIN7
C
C *** REINITIALIZE TOTAL PHOSPHORUS FOR THE FOLLOWING SEGMENT ***
      DO 450 J = 1, NHGP
         TPT(J) = 0.
   450 CONTINUE
      PLOAD7 = 0.
   500 CONTINUE
      IF(MOD(IT,IC).EQ.0) WRITE (6,4000)
C
 4000 FORMAT(////12X,'*** ROUTING OF PARTICULATE PHOSPHORUS ***',///,
     116X,53('-'),/6X,'TIME (HR)                   PARTICULATE P (MG P/L)',
     2/18X,'COARSE        MEDIUM          FINER        TOTAL',/6X,53('-'),/)
C
C *** K REPRESENTS NUMBER OF PARTICLE SIZE CLASSES ***
C     K=1 COARSE (>37 MICRONS(, K=2 MEDIUM (37-4), K=3 FONER (<4)
C
      DXC = 30.48 * DX
      DO 700 K = 1, N
         PT2(1,K) = 0.
         NHGP1 = NHGP - 1
         DO 600 J = 1, NHGP1
            A7 = (F2(J+1,K) + F1(J+1,K)) * WDAVG(J+1) / DT / 4.0
            B7 = A7 - (F2(J,K) + F1(J,K))* WDAVG(J+1) / DT / 4.0
            C7 = WQAVG(J+1) * (F2(J+1,K)+F1(J+1,K)) / DXC / 2.0
            D7 = WQAVG(J+1) * (F2(J+1,K)-F1(J+1,K)) / DXC / 2.0
            E7 = (WQ2(J+1) - WQ1(J+1)) * (F2(J+1,K)+F1(J+1,K)) / DXC / 4.0
```

```fortran
          F7 = (F1(J+1,K)*WQ1(J+1) - F2(J+1,K)*WQ2(J+1)) / DXC / 2.0
          G7 = BB*SB + RR*SR + ADS(J+1,K) * WQAVG(J+1)
          L7 = A7 + B7 + C7 + D7 + E7 + F7
          IF(L7.LE.0.) GOTO 520
          M7 = A7 + B7 - C7 + D7 + E7 + F7
          R7 = G7 - M7*PT1(J+1,K) + A7*PT1(J,K)
          PT2(J+1,K) = (R7 + A7*PT2(J,K)) / L7
          GOTO 540
  520     PT2(J+1,K) = 0.0
  540     PTCON(J+1,K) = PT2(J+1,K) * F2(J+1,K) / 1000000.0
          TPT(J+1) = TPT(J+1) + PTCON(J+1,K)
C
          IF(MOD(IT,IC).NE.0) GOTO 500
          PLOAD7 = PLOAD7 + (TPT(J) + TPT(J+1)) * (WQ2(J) + WQ2(J+1))
C     1               * DT / 4. / 1000.0 *WIDTH ( BELOW 8 LINES )
  600   CONTINUE
  700 CONTINUE
C
      IF(MOD(IT,IC).NE.0) RETURN
      DO 800 J = 1, NHGP
        IF(IHYDR.EQ.2) WRITE(6,5000) TIME(J),(PTCON(J,K),K=1,3),TPT(J)
        IF(IHYDR.EQ.2) WRITE(8,5000) TIME(J),TPT(J)
 5000   FORMAT(5X,F6.2,4F12.2)
  800 CONTINUE
C
C *** CHANGE UNIT FROM MILIGRAMS P TO GRAMS
C     PLOUT7 = PLOAD7 / 1000. * (DT / 4000.0 ) * WIDTH
      PLOUT7 = PLOAD7 * WIDTH * DT / 4000000.0
      SPTE = 100 * (PLIN7 - PLOUT7) / PLIN7
      TPTE = 100 * (1000.0 * ( PLIN7 - PLOUT7 ) + ( PLIN9  - PLOUT9 ))
     1        / (1000.0 * PLIN7 + PLIN9)
C
      WRITE(6,6000) PLOUT7
      WRITE(9,6000) PLOUT7
 6000 FORMAT(////3X,'***** CUMULATIVE PARTICULATE PLOAD    = ',
     1       F10.2,' GRAMS ****'/)
C
      WRITE(6,7000) SPTE
 7000 FORMAT(/3X,'***** PARTICULATE P TRAPPING EFFICIENCY = ',
     1       F10.2,' % *****'/)
C
      WRITE(6,8000) TPTE
 8000 FORMAT(/3X,'***** TOTAL P TRAPPING EFFICIENCY       = ',
     1       F10.2,' % *****'/)
      RETURN
      END
C
C ****************************************************************************
C ****************************************************************************
```

```
      FUNCTION SSCONC(PF,PS,NDVPC,SPEAK,SSCONM,IHYDR)
C *************************************************************************
C *************************************************************************
C
      REAL MASS,PF(15),PS(15)
      COMMON /SSCON1/ SBSG,SILTV,ISILT1
      COMMON /ERODE1/PFSET(10),ISAND,ISILT,ICLAY,ISAND1,SANDV
C
C *** INITIALIZE VARIABLES ******
C
      VC = 3.604E-04
      MASS = SPEAK
      FC = ( PF(ISILT1) + SILTV * ( PF(ISILT) - PF(ISILT1) ) )   / 100.0
      SSCONM = MASS * ( 1.0-FC )
      FINER = FC
      DELW = 0.10
      I200 = INT( FC/DELW + 0.00001) + 1
C
C **** LOOP FOR FRACTION FINER VALUES *******
C
      DO 200 I = 1,I200
         FINER = FINER - DELW
         IF( FINER .LT. 0.0 ) DELW = FINER + DELW
         Z = (FINER + (DELW/2.0) ) * 100.0
         DI = PSIZE(PF,PS,Z,NDVPC)
         VSI = 2.81 * DI ** 2.0
         SSCONM = SSCONM + MASS * DELW * ( VSI/VC ) ** 3.0
  200 CONTINUE
      SSCONC = SSCONM / ( SBSG * 1000.0 )
      RETURN
      END
C
C *************************************************************************
C *************************************************************************
      FUNCTION PSIZE(PFORF,PS,Z,NDVPC)
C *************************************************************************
C *************************************************************************
C
      COMMON / WARN1 / IWARN
      REAL PFORF(15),PS(15)
      IF( PFORF(1) ) 120,120,100
  100 IF (Z - PFORF(NDVPC)) 120,140,160
  120 PSIZE = 0.0001
      RETURN
  140 PSIZE = PS(NDVPC)
      RETURN
  160 CONTINUE
C
      IF( Z .LE. PFORF(1) ) GO TO 180
```

```
      IF( IWARN .NE. 1 ) GO TO 180
C
      WRITE(6,5000)
 5000 FORMAT(//2(5X,57('*')/)/10X,'CAUTION: COARSE PARTICLE SIZE'/
     1 10X,'HAS EXCEEDED THE MAXIMUM INPUTTED PARTICLE SIZE.  VALUE'/
     2 10X,'ESTIMATED BY EXTRAPOLATION OF THE LOG SLOPE BETWEEN THE'/
     3 10X,'LARGEST TWO PARTICLE SIZES.  IF THIS IS UNACCEPTABLE'/
     4 10X,'CORRECTION TECHNIQUE INCLUDES ENTERING A LARGER PARTICLE'/
     5 10X,'SIZE.'//2(5X,57('*')/)/)
      IWARN=2
C
  180 DO 200 I=2,NDVPC
         IH = I
         IF (PFORF(I) - Z) 220,200,200
  200 CONTINUE
  220 CONTINUE
      IF( PFORF(IH-1) - PFORF(IH) .GT. 0.01 ) GO TO 240
         PSIZE = PS(IH)
         RETURN
  240 EF = (Z - PFORF(IH-1)) / (PFORF(IH) - PFORF(IH-1))
      PSIZE = PS(IH-1) * (PS(IH) / PS(IH-1)) ** EF
      RETURN
      END
C
C *****************************************************************
C *****************************************************************
      SUBROUTINE GWATR(I,IO,ET,DT,DX,INFIL,Q1,Q2)
C *****************************************************************
C *****************************************************************
C
      REAL INFIL(502),INFLR,INFVOL
      COMMON /RAINF / TIME(502),RAIN(502),VOLINF
C
C *** CALCULATE THE RAIN AND INFILTRATION VOLUMES DURING THE PERIOD
C     [((IO-I)*DT) OR ET] TRAVELLING FILTER LENGTH OF DX
C **1 VOLUMES PER UNIT AREA (INCHES)
      RAINV = 0.0
      INFVOL = 0.0
      IF(ET.LT.DT) GOTO 200
C
C   * TO REDUCE CACULATION FOR MEANA*DT = ((A1 + A2)/2) * DT
      UNIT1 = DT / 2.
      IO1 = IO - 1
      DO 100 II = I, IO1
         RAINV = RAINV + (RAIN(II) + RAIN(II+1)) * UNIT1
         INFVOL = INFVOL + (INFIL(II) + INFIL(II+1)) * UNIT1
  100 CONTINUE
C
  200 DIFF = ET-((IO-I)*DT)
      RAINR = RAIN(IO) + (RAIN(IO+1) - RAIN(IO)) * DIFF / DT
```

```
         INFLR = INFIL(IO) + (INFIL(IO+1) - INFIL(IO)) * DIFF / DT
         RAINV = RAINV + ( RAIN(IO) + RAINR ) * DIFF / 2.0
         INFVOL= INFVOL + (INFIL(IO) + INFLR) * DIFF / 2.0
C
C **2 CALCULATE ACCUMULATED VOLUMES OF RAIN AND INFILTRATION (FT**3)
C      AT THE AREA OF DX * 1
         VOLFAC = DX / 12.
         RAINV = RAINV * VOLFAC
         INFVOL = INFVOL * VOLFAC
C
         TI = ET * 3600.0
         VOLIN = Q1 * TI + RAINV
         Q2 = (VOLIN - INFVOL) / TI
         IF(Q2.LE.0.0) Q2 = 0.0
         DO 500 II = I, IO
            IF(Q2.LE.0.0) INFIL(II) = INFVOL / VOLFAC / ET
     500 CONTINUE
         RETURN
         END
C
C ******************************************************************
C ******************************************************************
         SUBROUTINE GWEDGE(QSI,QSC,QOBS,DEPTH,EK,PD,MN,SPAC,SSC,EPS,SEE)
C ******************************************************************
C ******************************************************************
C      .
         REAL MN,NZERO
         QSB = (QSI + QSC) / 2.0
         RSSET = ( QSB * PD ** 2.07 / EK ) ** 0.28
         C1 = SQRT(RSSET) * 1.49 / MN
         ODEPTH = 0.9 * DEPTH
         HR = ODEPTH * SPAC /(2.0 * ODEPTH + SPAC)
         OZERO = QOBS-C1 * ODEPTH * HR ** 0.166667
         DO 120 I=1,25
            HR = (DEPTH * SPAC) / (2.0 * DEPTH + SPAC)
            NZERO = QOBS - C1 * DEPTH * HR ** 0.16667
            IF (ABS(NZERO) - EPS) 140,140,100
     100    HV1 = DEPTH
            DEPTH = DEPTH - NZERO * (DEPTH - ODEPTH)/(NZERO - OZERO)
            IF (DEPTH .LT. 0.0)  DEPTH = HV1/10.0
            OZERO = NZERO
            ODEPTH = HV1
     120 CONTINUE
         WRITE(6,5000)
    5000 FORMAT(/2X,'*** DEPTH ON WEDGE FACE DID NOT CONVERGE AFTER 25 ',
        1'ITERATIONS ***')
     140 SST = (QOBS * MN / (DEPTH * HR ** 0.6667)) ** 2
         SEE = SST - SSC
C
         IF (SEE) 160,160,180
```

```
   160 SEE = 0.05
       QSC = QSI
       WRITE(6,5100)
  5100 FORMAT(/2X,'*** EQUILIBRIUM SLOPE NEGATIVE ***')
C
   180 RETURN
       END
C
C  *********************************************************************
C  *********************************************************************
       FUNCTION GDEPTH(QOBS,DEPTH,MN,SC,SPAC,ESP)
C  *********************************************************************
C  *********************************************************************
C
       REAL MN,NZERO
       C1 = 1.49 * SPAC ** 0.6667 * SQRT(SC) / MN
       ODEPTH = 0.9 * DEPTH
       OZERO = QOBS - C1 *ODEPTH ** 1.66667/(2.0*ODEPTH + SPAC)** 0.6667
       DO 120 I=1,25
          NZERO=QOBS-C1*DEPTH ** 1.6667 / (2.0 * DEPTH + SPAC) ** 0.66667
          IF (ABS(NZERO) - ESP) 140,140,100
   100    HV1 = DEPTH
          DEPTH = DEPTH - NZERO*(DEPTH - ODEPTH)/(NZERO - OZERO)
          IF (DEPTH .LT. 0.0)  DEPTH = HV1/10.0
          OZERO = NZERO
          ODEPTH = HV1
   120 CONTINUE
       WRITE(6,5000)
  5000 FORMAT(/2X,'*** CAUTION:  DEPTH FAILED TO CONVERGE AFTER 25',
      1'ITERATIONS ***')
   140 CONTINUE
       GDEPTH = DEPTH
       RETURN
       END
C
C  *********************************************************************
C  *********************************************************************
       SUBROUTINE OUTPUT(PS,PFDIS,WQ,SQ,TIME,NDVPC,NHGP,LSIZE,IHYDR)
C  *********************************************************************
C  *********************************************************************
C
       DIMENSION PS(15),PFDIS(15),WQ(LSIZE),SQ(LSIZE),TIME(LSIZE)
C
       IF(IHYDR.EQ.1)GOTO 101
       WRITE(6,5000)
  5000 FORMAT(///11X,'*** PARTICLE SIZE DISTRIBUTION OF SEDIMENT ***'//)
       IND=(NDVPC-1)/6+1
       DO 100 I=1,IND
       K=I*6
       K2=K-5
```

```
      IF (K.GT.NDVPC) K=NDVPC
      WRITE(6,5100) (PS(J),J=K2,K)
 5100 FORMAT(1X,'SIZE,MM',7X,6F9.4)
      WRITE(6,5200) (PFDIS(J),J=K2,K)
 5200 FORMAT(1X,'PERCENT FINER',1X,6F9.4/)
  100 CONTINUE
  101 WRITE(6,5300)
 5300 FORMAT(////13X,'*** HYDROGRAPH AND SEDIMENT GRAPH ***'///)
      IF(IHYDR.EQ.2)WRITE(6,5400)
 5400 FORMAT(15X,33('-'),/16X,'TIME',6X,'DISCHARGE',4X,'SED DISC',
     1        /16X,'(HR)',8X,'(CFS)',7X,'(MG/L)',/15X,33('-')/)
      IF(IHYDR.EQ.1)WRITE(6,5500)
 5500 FORMAT(15X,'TIME',4X,'DISCHARGE',1X,'*******',2X,'TIME',4X,
     1        'DISCHARGE'/15X,'(HR)',6X,'(CFS)',5X,'*',5X,'(HR)',
     2        6X,'(CFS)',/12X,44('-')/)
C
      DO 120 I=1,NHGP
        IF(IHYDR.EQ.2)WRITE(6,5700)TIME(I),WQ(I),SQ(I)
 5700   FORMAT(14X,F6.2,4X,F9.4,3X,F11.2)
        IF(IHYDR.EQ.1)WRITE(6,5750)TIME(I),WQ(I)
 5750   FORMAT(13X,F6.2,4X,F9.3)
  120 CONTINUE
      RETURN
      END
C
C*******************************************************************************
C*******************************************************************************
      SUBROUTINE AVPEAK(TWCONC,WCONC,TCONC,AVECON,TIME,W,C,NHP,LSIZE,
     1                  TI,PSML,PCMG)
C*******************************************************************************
C*******************************************************************************
C
      INTEGER FSED
      REAL W(LSIZE),C(LSIZE)
C
C ***   LOOP TO FIND FIRST OCCURENCE OF SIGNIFICANT SEDIMENT--FSED
C
      DO 200 I=1,NHP
        IF(C(I) .GE. .001)GO TO 300
  200 CONTINUE
  300 FSED=I
C
C***   LOOP TO FIND LAST OCCURENCE OF SIGNIFICANT SEDIMENT--LSED
      DO 400 I=FSED,NHP
        IF(C(I) .LT. 0.001)GO TO 500
        IH=I
  400 CONTINUE
  500 LSED=IH
C
```

```
C***    DETERMINE TIME OF SIGNIFICANT SEDIMENT CONCENTRATION--TIME
C
       TIME=(LSED-FSED)*TI
C
C ***    NEXT SET OF STATEMENTS DETERMINES AVERAGE CONCENTRATION
C ***    OVER ENTIRE SIGNIFICANT RUNOFF PERIOD.
C ***    TWCONC--VOLUME WEIGHTED; TCONC--ARITHMETIC
C
       TWSED=0.0
       TCFS=0.0
       TSED=0.0
       DO 900 I=FSED,LSED
         WSED=W(I)*C(I)
         TWSED=TWSED+WSED
         TCFS=TCFS+W(I)
         TSED=TSED+C(I)
  900 CONTINUE
       IF(TCFS .EQ. 0.0) TCFS=1.0
       TWCONC=TWSED/TCFS
       IF(TIME .EQ. 0.0) TCONC=0.0
       IF(TIME .EQ. 0.0) GO TO 100
       TCONC=TSED/(TIME/TI)
C
C ***    THE NEXT SET OF STATEMENTS DETERMINES AVERAGE CONCENTRATION
C ***    OVER ALL 24 HOUR PERIODS FROM FSED TO LSED AND WHICH OF
C ***    THOSE 24 HOUR AVERAGE CONCENTRATIONS IS GREATEST.
C ***    WCONC--VOLUME WEIGHTED; AVECON--ARITHMETIC
C
  100 I24=INT(24/TI)+FSED
       IF(I24 .GE .LSED)I24=LSED
       AVECON=0.0
       WCONC=0.0
  800 TSED24=0.0
       TCFS24=0.0
       SED24=0.0
       DO 600 I=FSED,I24
         WSED24=W(I)*C(I)
         TSED24=TSED24+WSED24
         TCFS24=TCFS24+W(I)
         SED24=SED24+C(I)
  600 CONTINUE
       IF(TCFS24 .EQ. 0.0) TCFS24=1.0
       X=TSED24/TCFS24
       Y=SED24/(24./TI)
       IF(X .GE. WCONC)WCONC=X
       IF(Y .GE. AVECON)AVECON=Y
       I24=I24+1
       IF(I24 .GT. LSED)GO TO 700
       FSED=FSED+1
```

```
      GO TO 800
C
C ***   THE NEXT STATEMENTS CONVERT CONCENTRATIONS FROM
C ***   TOTAL MG/L TO SETTLEABLE ML/L
C
  700 IF(PCMG .EQ. 0.0) PCMG=1.0
      TWCONC=TWCONC*(PSML/PCMG)
      WCONC=WCONC*(PSML/PCMG)
      TCONC=TCONC*(PSML/PCMG)
      AVECON=AVECON*(PSML/PCMG)
      RETURN
      END
C ***********************************************************************
C ***********************************************************************
      SUBROUTINE CHECKI(N,L1,L2,NDEF,MESSAG)
C ***********************************************************************
C ***********************************************************************
      REAL MESSAG(9)
      IF(N.EQ.-1.AND.NDEF.NE.-1)GO TO 11
      IF(N.EQ.-1)WRITE(6,6007)(MESSAG(K),K=1,9)
 6007 FORMAT(//1X,27('|'),'  W A R N I N G  ',27('|')
     1//1X,9A4/' DOES NOT HAVE A DEFAULT VALUE.'/'  PLEASE CORRECT AND',
     2' REINPUT DATA'//,72('|')/)
      IF(N.EQ.-1)STOP
      IF(N.GE.L1.AND.N.LE.L2)GO TO 20
      ILEN=10
      WRITE(6,6000)(MESSAG(K),K=1,9)
 6000 FORMAT(//1X,27('|'),'  W A R N I N G  ',27('|'))//1X,9A4/' IS NOT',
     1' WITHIN THE EXPECTED LIMITS. THE')
      IF(NDEF.NE.-1)WRITE(6,6001)L1,L2,NDEF
 6001 FORMAT(' VALUE MUST BE NO SMALLER THAN ',I2,' AND NO LARGER',
     1' THAN ',I3,'. SEDIMOT'/' USES THE DEFAULT VALUE OF ',I3,'.'/
     2/,72('|')/)
      IF(NDEF.NE.-1)GO TO 11
      IF(NDEF.EQ.-1)WRITE(6,6003)L1,L2
 6003 FORMAT(' THE VALUE MUST BE NO SMALLER THAN ',I2,' AND',
     1' NO LARGER THAN ',I3,'.'/' PLEASE CORRECT AND REINPUT'
     2//,72('|')/)
      IF(NDEF.EQ.-1)STOP
   11 N=NDEF
   20 RETURN
      END
C
C ***********************************************************************
C ***********************************************************************
      SUBROUTINE CHECKR(R,R1,R2,RDEF,MESSAG)
C ***********************************************************************
C ***********************************************************************
      REAL MESSAG(9)
      IF(R.EQ.-1 .AND.RDEF.GE.0.)GO TO 11
```

```
      IF(R.EQ.-1)WRITE(6,6007)(MESSAG(K),K=1,9)
6007  FORMAT(//1X,27('|'),' W A R N I N G ',27('|')
     1//1X,9A4/' DOES NOT HAVE A DEFAULT VALUE.'/' PLEASE CORRECT AND',
     2' REINPUT DATA'//,72('|')/)
      IF(R.EQ.-1)STOP
      IF(R.GE.R1.AND.R.LE.R2)GO TO 20
      WRITE(6,6000)(MESSAG(K),K=1,9)
6000  FORMAT(//1X,27('|'),' W A R N I N G ',27('|')//1X,9A4/' IS NOT',
     1' WITHIN THE EXPECTED LIMITS. THE')
      IF(RDEF.GE.0.)WRITE(6,6002)R1,R2,RDEF
6002  FORMAT(' VALUE MUST BE NO SMALLER THAN ',F7.4,
     1' AND NO LARGER THAN ',F7.2,'. SEDIMOT'/' USES THE DEFAULT',
     2' VALUE OF ',F8.3,'.'//,72('|')/)
      IF(RDEF.GE.0.)GO TO 11
      IF(RDEF.EQ.-1.)WRITE(6,6004)R1,R2
6004  FORMAT(' VALUE MUST BE NO SMALLER THAN ',F7.4,
     1' AND NO LARGER THAN ',F7.2,'.'/' PLEASE CORRECT AND',
     2' REINPUT DATA'//72('|')/)
      IF(RDEF.EQ.-1.)STOP
6012  IF(RDEF.EQ.-2.AND.R.LT.R1)GO TO 6008
      GO TO 6009
6008  WRITE(6,6010)R1,R2
6010  FORMAT(' VALUE MUST BE NO SMALLER THAN ',F7.4,
     1' AND IF POSSIBLE SHOULD NOT EXCEED'/1X,F7.2,
     2'. PLEASE CORRECT AND REINPUT DATA.'/1X,72('|')/)
      STOP
6009  IF(RDEF.EQ.-2.AND.R.GT.R2)WRITE(6,6005)R1,R2,R
6005  FORMAT(' VALUE MUST BE NO SMALLER THAN ',F7.4,
     1' AND IF POSSIBLE SHOULD NOT EXCEED'/1X,F9.3,'. SEDIMOT',
     2' WILL CONTINUE WITH THE VALUE ENTERED,',F10.4,' ,BUT IT'/
     3' MAY CAUSE INACCURACIES OR EVEN TERMINATION LATER IN',
     4' THE PROGRAM',//1X,72('|')/)
      IF(RDEF.EQ.-2.AND.R.GT.R2)GO TO 20
      IF(RDEF.EQ.-3.)WRITE(6,6011)R
6011  FORMAT(' VALUE ',F8.3,' IS EITHER OUT OF LIMITS ACCEPTABLE',
     1' TO SEDIMOT,'/' OUT OF THE RANGE OF POSSIBLE VALUES DUE TO',
     2' THE ANSWER TO A PREVIOUS'/' QUESTION, OR NOT IN PROPER',
     3' SEQUENCE. PLEASE CORRECT AND RE-INPUT DATA'//,72('|')/)
      IF(RDEF.EQ.-3.)STOP
   11 R=RDEF
   20 RETURN
      END
```

Appendix F
Example Input Data and Output

Example Input Data

In order to illustrate a typical input data file, input parameters were matched with example input values in each set of parameters and variable letters or numbers. Definitions of input parameters is referred to Appendix C.

```
HEADER(1) - HEADER(15)
QF456 T4 R1 AT PRICE FORK FARM

   ITYPE    HYDR   NDVPC   NRPIV   NHGP
       1       2       9      23      23

      SG    SBSG
    2.65    1.25

       P
     2.0

   INFLOW(1) - (INFLOW(23)
   0.000   0.000   0.000   0.050   0.090   0.102   0.110   0.118   0.120   0.122
   0.124   0.126   0.128   0.129   0.130   0.132   0.133   0.134   0.135   0.135
   0.1350  0.068   0.000

   CONC(1) - CONC(23)
   0.0000    0.000    0.000  14100.  11700.  14800.  16400.  18000.  18733.  19467.
 20200.0   19100.   18000.  17400.  16800.  16775.  16750.  16725.  16700.  15750.
 14800.0   14100.    0.00

     PS(1) - PS(9)
```

```
          5.0        2.       1.        .5       .25       .15      .050     .0007  0.0001

PFDIS(1) - PFDIS(9)
100.0       98.9       96.7      92.5      85.9      80.43     68.2       6.0       0.

     SEG   RPRINT      BSG      DINT    DELTAX
     1.0       4.      1.25       0.       15.

      MN   GHGHTT   SUBLEN       LEN     SPACC      SSCC    WIDTH       MEI
   0.015     4.00    15.00     30.00      0.60      16.0     18.0       2.0

      FA      FAW      FAG     DEPTH        SA        FC
    0.40     0.24     0.10      8.00      3.00      0.24

      KM       RA
     0.0      0.0

SOL(1) - SOL(23)
     0.0     0.00    0.000      0.09      0.11      0.10     0.095     0.090    0.0867    0.0833
  0.0800    0.085     0.09      0.08    0.0700    0.0725    0.0750    0.0775    0.0800    0.0750
  0.0700   0.0700    0.000

       K    ALPHA     BETA        BD        PO      EDIC       DSA
   0.034   0.0144    0.232      2.65      31.0     0.100      0.00

   EPSIL    WLEAF
   0.156     5.35

     KIN
       1

  LNA(1)     B(1)     C(1)      D(1)
   0.000    0.000    0.024     0.053

  LNA(2)     B(2)     C(2)      D(2)
   0.000    0.000    0.332    -0.643

  LNA(3)     B(3)     C(3)      D(3)
   0.000    0.000    0.000    -1.630

 PT(1,1) PT(1,2) PT(1.3)
   387.0    386.0   1285.0
```

Example Output

****

FILTER IDENTIFICATION CODE

QF456 T4 R1 AT PRICE FORK FARM

****

********************** INPUT RAINFALL PATTERN **********************

VALUE	TIME(HR)	RATE(IN/HR)
1	0.00	0.00
3	0.10	2.00
5	0.20	2.00
7	0.30	2.00
9	0.40	2.00
11	0.50	2.00
13	0.60	2.00
15	0.70	2.00
17	0.80	2.00
19	0.90	2.00
21	1.00	2.00
23	1.10	2.00

*** PARTICLE SIZE DISTRIBUTION OF SEDIMENT ***

SIZE,MM	5.0000	2.0000	1.0000	0.5000	0.2500	0.1500
PERCENT FINER	100.0000	98.9000	96.7000	92.5000	85.9000	80.4300

SIZE,MM	0.0500	0.0007	0.0001
PERCENT FINER	68.2000	6.0000	0.0000

*** HYDROGRAPH AND SEDIMENT GRAPH ***

TIME (HR)	DISCHARGE (CFS)	SED DISC (MG/L)

```
         --------------------------------

         0.00        0.0000          0.00
         0.05        0.0000          0.00
         0.10        0.0000          0.00
         0.15        0.0500      14100.00
         0.20        0.0900      11700.00
         0.25        0.1020      14800.00
         0.30        0.1100      16400.00
         0.35        0.1180      18000.00
         0.40        0.1200      18733.00
         0.45        0.1220      19467.00
         0.50        0.1240      20200.00
         0.55        0.1260      19100.00
         0.60        0.1280      18000.00
         0.65        0.1290      17400.00
         0.70        0.1300      16800.00
         0.75        0.1320      16775.00
         0.80        0.1330      16750.00
         0.85        0.1340      16725.00
         0.90        0.1350      16700.00
         0.95        0.1350      15750.00
         1.00        0.1350      14800.00
         1.05        0.0680      14100.00
         1.10        0.0000          0.00
```

***** TOTAL RUNOFF VOLUME   =   0.009178 AC-FT ****

***** TOTAL SEDIMENT MASS   =   0.191139 TONS ****

* *

                     GRASS FILTER RESULTS

* *

               ***** GRASS FILTER PROPERTIES *****

               SEGMENT NUMBER = 1

   MANNING'S FRICTION FACTOR   =   0.0150

```
CHANNEL SLOPE                =  16.0000  PERCENT
GRASS SPACING                =   0.6000  INCH
GRASS HEIGHT                 =   4.0000  INCH
FILTER WIDTH                 =  18.0000  FEET
STIFFNESS COEFFICIENT        =   2.0000  N-M SQ
```

*** INPUT DATA AT FILTER STARTING POINT ***

*** PARTICLE SIZE FRACTION OF SEDIMENT ***

SIZE,MM	>0.037	0.037>	<0.004
SIZE FRACTION	0.3619	0.3242	0.3140

*** HYDROGRAPH AND SEDIMENT GRAPH ***

TIME (HR)	DISCHARGE (CM3/FT/MIN)	COARSE (MG/L)	MEDIUM (MG/L)	FINERS (MG/L)
0.00	0.00	0.00	0.00	0.00
0.05	0.00	0.00	0.00	0.00
0.10	0.00	0.00	0.00	0.00
0.15	4719.47	5102.43	4570.57	4426.99
0.20	8495.05	4233.93	3792.60	3673.46
0.25	9627.73	5355.74	4797.48	4646.77
0.30	10382.84	5934.74	5316.12	5149.13
0.35	11137.96	6513.74	5834.77	5651.48
0.40	11326.73	6779.00	6072.37	5881.62
0.45	11515.51	7044.61	6310.30	6112.08
0.50	11704.30	7309.87	6547.91	6342.22
0.55	11893.07	6911.80	6191.34	5996.85
0.60	12081.85	6513.74	5834.77	5651.48
0.65	12176.24	6296.62	5640.28	5463.10
0.70	12270.63	6079.49	5445.79	5274.71
0.75	12459.41	6070.45	5437.68	5266.87
0.80	12553.80	6061.40	5429.58	5259.02

```
0.85     12648.19      6052.35      5421.47      5251.17
0.90     12742.57      6043.30      5413.37      5243.32
0.95     12742.57      5699.52      5105.43      4945.05
1.00     12742.57      5355.74      4797.48      4646.77
1.05      6418.48      5102.43      4570.57      4426.99
1.10         0.00         0.00         0.00         0.00
```

***** SUMMARY TABLE *****

```
CUMULATIVE FILTER LENGTH          =      15.00  FEET
SPECIFIC GRAVITY OF SEDIMENT      =       2.65
BULK SPECIFIC GRAVITY             =       1.25
VISCOSITY                         =      0.0089  CM**2/SEC
CRITICAL PRONE VELOCITY           =      0.8122  FT/S
PEAK FLOW DEPTH                   =       0.08  INCH
FILTER TRAVEL TIME                =      0.0035  HR
INFILTRATION VOLUME               =      0.0001  ACRE-FT
WEDGE LOCATION                    =       0.00  FEET
SEDIMENT DEPTH ZONE D             =      0.1602  INCH
OUTFLOW RUNOFF VOLUME             =       0.01  ACRE-FT
PEAK DISCHARGE RATE               =       0.14  CFS
PEAK EFFLUENT CONCENTRATION       =    6321.93  MG/L
PEAK SETTLEABLE CONCENTRATION     =       1.5424  ML/L
PEAK SETTLEABLE CONCENTRATION     =    1927.94  MG/L
TOTAL MASS DISCHARGED             =       0.07  TONS
TRAP EFFICIENCY IN ADDED SEGMENT  =      63.41  PERCENT
PERIOD OF SIGNIFICAT CONCENTRATION =      0.90  HRS
```
VOLUME WEIGHTED AVERAGE SETTLEABLE
   CONCENTRATION DURING PERIOD OF
   SIGNIFICANT CONCENTRATION   =   1.34 ML/L
VOLUME WEIGHTED AVERAGE SETTLEABLE
   CONCENTRATION DURING PEAK 24 HOUR
   PERIOD   =   1.34 ML/L
ARITHMETIC AVERAGE SETTLEABLE
   CONCENTRATION DURING PERIOD OF
   SIGNIFICANT CONCENTRATION   =   1.34 ML/L
ARITHMETIC AVERAGE SETTLEABLE
   CONCENTRATION DURING PEAK 24 HOUR
   PERIOD   =   0.05 ML/L

*** POTENTIAL INFILTRATION RATE ***

```
          TIME    INFILTRATION
          (HR)    RATE(IN/HR)
```

```
----------------------

     0.00      5.79
     0.05      4.74
     0.10      3.97
     0.15      3.41
     0.20      2.96
     0.25      2.60
     0.30      2.31
     0.35      2.08
     0.40      1.88
     0.45      1.72
     0.50      1.58
     0.55      1.46
     0.60      1.35
     0.65      1.26
     0.70      1.18
     0.75      1.11
     0.80      1.05
     0.85      0.99
     0.90      0.94
     0.95      0.90
     1.00      0.86
     1.05      0.82
     1.10      0.79
```

*** PARTICLE SIZE FRACTION OF SEDIMENT ***

SIZE,MM	>0.037	0.037>	<0.004
SIZE FRACTION	0.0578	0.4270	0.5152

*** HYDROGRAPH AND SEDIMENT GRAPH ***

TIME (HR)	DISCHARGE (CM3/FT/MIN)	COARSE (MG/L)	MEDIUM (MG/L)	FINERS (MG/L)
0.00	0.00	0.00	0.00	0.00
0.05	0.00	0.00	0.00	0.00
0.10	0.00	0.00	0.00	0.00

0.15	3895.60	97.55	720.74	869.51
0.20	7935.61	161.25	1191.36	1437.27
0.25	9277.84	228.88	1691.00	2040.04
0.30	10202.09	268.64	1984.80	2394.49
0.35	11095.88	310.24	2292.11	2765.22
0.40	11399.90	327.52	2419.77	2919.23
0.45	11685.61	345.92	2555.70	3083.22
0.50	11956.76	365.40	2699.65	3256.88
0.55	12216.18	352.49	2604.25	3141.79
0.60	12466.05	339.24	2506.38	3023.72
0.65	12613.66	332.94	2459.80	2967.53
0.70	12754.73	328.23	2425.00	2925.55
0.75	12984.70	335.36	2477.72	2989.15
0.80	13115.62	341.08	2519.98	3040.12
0.85	13242.59	348.54	2575.12	3106.65
0.90	13366.17	355.23	2624.48	3166.20
0.95	13392.43	341.67	2524.35	3045.40
1.00	13416.16	327.90	2422.57	2922.62
1.05	7113.59	219.87	1624.41	1959.71
1.10	672.82	0.00	0.00	0.00

*** CONC OF DISSOLVED P AT ENTERING POINT ***

TIME (HR)	CONC OF P (MG/L)
0.00	0.0000
0.05	0.0000
0.10	0.0000
0.15	0.0900
0.20	0.1100
0.25	0.1000
0.30	0.0950
0.35	0.0900
0.40	0.0867
0.45	0.0833
0.50	0.0800
0.55	0.0850
0.60	0.0900
0.65	0.0800
0.70	0.0700
0.75	0.0725
0.80	0.0750
0.85	0.0775

```
                    0.90           0.0800
                    0.95           0.0750
                    1.00           0.0700
                    1.05           0.0700
                    1.10           0.0000
```

******* CUMULATIVE DISSLOVED P LOAD   = 919.55 MG *******

*** CHANGE OF DESORPTION VARIABLES ***

```
--------------------------------------------------
TIME        EDI     WATER/SOIL  P DESORPTION
(HR)        (CM)      (L/KG)    (UG/CM2/MIN)
--------------------------------------------------

0.05        0.20       0.00       0.0000
0.10        0.20       0.00       0.0000
0.15        0.20     124.13       3.9498
0.20        0.20     236.74       2.9361
0.25        0.20     272.39       2.3100
0.30        0.20     296.59       1.9208
0.35        0.20     320.35       1.6474
0.40        0.20     327.45       1.4341
0.45        0.20     334.28       1.2750
0.50        0.20     340.91       1.1477
0.55        0.20     347.37       1.0435
0.60        0.20     353.69       0.9567
0.65        0.20     357.18       0.8819
0.70        0.20     360.57       0.8190
0.75        0.20     366.60       0.7658
0.80        0.20     369.85       0.7168
0.85        0.20     373.04       0.6747
0.90        0.20     376.18       0.6372
0.95        0.20     376.56       0.6024
1.00        0.20     376.90       0.5723
1.05        0.20     194.97       0.3994
1.10        0.20       9.69       0.0000
```


***** CHANGE OF ADSORPTION VARIABLES *****

TIME (HR)	ADS1 (MG/L/MIN)	ADS2 (MG/L/MIN)	ADS3 (MG/L/MIN)	TOTAL (MG/L/MIN)
0.05	0.0000	0.0000	0.0000	0.0000
0.10	0.0000	0.0000	0.0000	0.0000
0.15	0.0137	0.0002	0.0000	0.0139
0.20	0.0086	0.0002	0.0000	0.0087
0.25	0.0088	0.0001	0.0000	0.0089
0.30	0.0081	0.0001	0.0000	0.0083
0.35	0.0077	0.0001	0.0000	0.0078
0.40	0.0070	0.0001	0.0000	0.0071
0.45	0.0065	0.0001	0.0000	0.0066
0.50	0.0061	0.0001	0.0000	0.0062
0.55	0.0052	0.0001	0.0000	0.0053
0.60	0.0045	0.0001	0.0000	0.0046
0.65	0.0040	0.0001	0.0000	0.0041
0.70	0.0037	0.0001	0.0000	0.0037
0.75	0.0034	0.0000	0.0000	0.0035
0.80	0.0032	0.0000	0.0000	0.0032
0.85	0.0030	0.0000	0.0000	0.0030
0.90	0.0028	0.0000	0.0000	0.0029
0.95	0.0025	0.0000	0.0000	0.0026
1.00	0.0023	0.0000	0.0000	0.0023
1.05	0.0020	0.0000	0.0000	0.0021
1.10	0.0000	0.0000	0.0000	0.0000

*** ROUTING OF DISSOLVED CHEMICALS ***

TIME (HR)	DISSOLVED P (MG/L)
0.00	0.0000
0.05	0.0000
0.10	0.0000
0.15	0.5641
0.20	0.2859
0.25	0.2167
0.30	0.1821
0.35	0.1577
0.40	0.1432
0.45	0.1316
0.50	0.1219

```
           0.55            0.1215
           0.60            0.1220
           0.65            0.1090
           0.70            0.0965
           0.75            0.0963
           0.80            0.0966
           0.85            0.0971
           0.90            0.0979
           0.95            0.0918
           1.00            0.0859
           1.05            0.0886
           1.10            0.0005
```

******* CUMULATIVE DISSLOVED P LOAD   = 1516.48 MG *******

******* DISSOLVED P TRAPPING EFFICIENCY = -64.92 %   *******

*** CONC OF PARTICULATE P AT ENTERING POINT ***

| TIME | | PARTICULATE P (MG P/L) | | |
| (HR) | COARSE | MEDIUM | FINER | TOTAL |

0.00	0.00	0.00	0.00	0.00
0.05	0.00	0.00	0.00	0.00
0.10	0.00	0.00	0.00	0.00
0.15	1.97	1.76	5.69	9.43
0.20	1.64	1.46	4.72	7.82
0.25	2.07	1.85	5.97	9.90
0.30	2.30	2.05	6.62	10.97
0.35	2.52	2.25	7.26	12.04
0.40	2.62	2.34	7.56	12.53
0.45	2.73	2.44	7.85	13.02
0.50	2.83	2.53	8.15	13.51
0.55	2.67	2.39	7.71	12.77
0.60	2.52	2.25	7.26	12.04
0.65	2.44	2.18	7.02	11.63
0.70	2.35	2.10	6.78	11.23

0.75	2.35	2.10	6.77	11.22
0.80	2.35	2.10	6.76	11.20
0.85	2.34	2.09	6.75	11.18
0.90	2.34	2.09	6.74	11.17
0.95	2.21	1.97	6.35	10.53
1.00	2.07	1.85	5.97	9.90
1.05	1.97	1.76	5.69	9.43
1.10	0.00	0.00	0.00	0.00

***** CUMULATIVE PARTICULATE PLOAD   =   126.31 GRAMS ****

*** ROUTING OF PARTICULATE PHOSPHORUS ***

| TIME (HR) | PARTICULATE P (MG P/L) | | | |
	COARSE	MEDIUM	FINER	TOTAL
0.00	0.00	0.00	0.00	0.00
0.05	0.00	0.00	0.00	0.00
0.10	0.00	0.00	0.00	0.00
0.15	0.04	0.28	1.11	1.42
0.20	0.06	0.46	1.85	2.37
0.25	0.09	0.65	2.62	3.36
0.30	0.10	0.77	3.08	3.95
0.35	0.12	0.88	3.55	4.56
0.40	0.13	0.93	3.75	4.81
0.45	0.13	0.99	3.96	5.08
0.50	0.14	1.04	4.18	5.37
0.55	0.14	1.01	4.04	5.18
0.60	0.13	0.97	3.89	4.99
0.65	0.13	0.95	3.81	4.89
0.70	0.13	0.94	3.76	4.82
0.75	0.13	0.96	3.84	4.93
0.80	0.13	0.97	3.91	5.01
0.85	0.13	0.99	3.99	5.12
0.90	0.14	1.01	4.07	5.22
0.95	0.13	0.97	3.91	5.02
1.00	0.13	0.94	3.76	4.82
1.05	0.09	0.63	2.52	3.23
1.10	0.00	0.00	0.00	0.00

```
***** CUMULATIVE PARTICULATE PLOAD        =       66.31 GRAMS ****


***** PARTICULATE P TRAPPING EFFICIENCY =       47.51 %  *****


***** TOTAL P TRAPPING EFFICIENCY         =       46.70 %  *****
```

*** PARTICLE SIZE DISTRIBUTION OF SEDIMENT ***

```
SIZE,MM          5.0000    2.0000    1.0000    0.5000    0.2500    0.1500
PERCENT FINER  100.0000  100.0000  100.0000  100.0000  100.0000  100.0000

SIZE,MM          0.0500    0.0007    0.0001
PERCENT FINER  100.0000   18.0599    0.0000
```

*** HYDROGRAPH AND SEDIMENT GRAPH ***

TIME (HR)	DISCHARGE (CFS)	SED DISC (MG/L)
0.00	0.0000	0.00
0.05	0.0000	0.00
0.10	0.0000	0.00
0.15	0.0413	1687.80
0.20	0.0841	2789.88
0.25	0.0983	3959.92
0.30	0.1081	4647.93
0.35	0.1176	5367.57
0.40	0.1208	5666.51
0.45	0.1238	5984.84
0.50	0.1267	6321.93
0.55	0.1294	6098.53
0.60	0.1321	5869.35
0.65	0.1336	5760.27
0.70	0.1351	5678.78

```
        0.75        0.1376        5802.24
        0.80        0.1390        5901.18
        0.85        0.1403        6030.31
        0.90        0.1416        6145.91
        0.95        0.1419        5911.41
        1.00        0.1421        5673.09
        1.05        0.0754        3803.99
        1.10        0.0071           0.00
```

***** TOTAL RUNOFF VOLUME   =   0.009121 AC-FT ****

***** TOTAL SEDIMENT MASS   =   0.069936 TONS ****

***** OVERALL SEDIMENT TRAP EFFICIENCY =   63.41 % *******

***** SUMMARY TABLE *****

```
CUMULATIVE FILTER LENGTH         =      30.00   FEET
SPECIFIC GRAVITY OF SEDIMENT     =       2.65
BULK SPECIFIC GRAVITY            =       1.25
VISCOSITY                        =      0.0089   CM**2/SEC
CRITICAL PRONE VELOCITY          =      0.8122   FT/S
PEAK FLOW DEPTH                  =       0.08    INCH
FILTER TRAVEL TIME               =      0.0071   HR
INFILTRATION VOLUME              =      0.0001   ACRE-FT
WEDGE LOCATION                   =       0.00    FEET
SEDIMENT DEPTH ZONE D            =      0.0396   INCH
OUTFLOW RUNOFF VOLUME            =       0.01    ACRE-FT
PEAK DISCHARGE RATE              =       0.15    CFS
PEAK EFFLUENT CONCENTRATION      =    3205.99    MG/L
PEAK SETTLEABLE CONCENTRATION    =      0.6010   ML/L
PEAK SETTLEABLE CONCENTRATION    =     751.24    MG/L
TOTAL MASS DISCHARGED            =       0.04    TONS
TRAP EFFICIENCY IN ADDED SEGMENT =      49.63    PERCENT
PERIOD OF SIGNIFICAT CONCENTRATION =     0.90    HRS
VOLUME WEIGHTED AVERAGE SETTLEABLE
   CONCENTRATION DURING PERIOD OF
   SIGNIFICANT CONCENTRATION     =       0.51    ML/L
VOLUME WEIGHTED AVERAGE SETTLEABLE
   CONCENTRATION DURING PEAK 24 HOUR
   PERIOD                        =       0.51    ML/L
ARITHMETIC AVERAGE SETTLEABLE
   CONCENTRATION DURING PERIOD OF
   SIGNIFICANT CONCENTRATION     =       0.50    ML/L
```

ARITHMETIC AVERAGE SETTLEABLE
CONCENTRATION DURING PEAK 24 HOUR
PERIOD   =   0.02   ML/L

*** POTENTIAL INFILTRATION RATE ***

TIME (HR)	INFILTRATION RATE(IN/HR)
0.00	5.75
0.05	4.71
0.10	3.95
0.15	3.41
0.20	2.96
0.25	2.60
0.30	2.31
0.35	2.08
0.40	1.88
0.45	1.72
0.50	1.58
0.55	1.46
0.60	1.35
0.65	1.26
0.70	1.18
0.75	1.11
0.80	1.05
0.85	0.99
0.90	0.94
0.95	0.90
1.00	0.86
1.05	0.82
1.10	0.79

*** PARTICLE SIZE FRACTION OF SEDIMENT ***

SIZE,MM	>0.037	0.037>	<0.004
SIZE FRACTION	0.0453	0.3347	0.6200

*** HYDROGRAPH AND SEDIMENT GRAPH ***

TIME (HR)	DISCHARGE (CM3/FT/MIN)	COARSE (MG/L)	MEDIUM (MG/L)	FINERS (MG/L)
0.00	0.00	0.00	0.00	0.00
0.05	0.00	0.00	0.00	0.00
0.10	0.00	0.00	0.00	0.00
0.15	3071.73	11.07	81.82	151.59
0.20	7376.18	44.61	329.57	610.59
0.25	8927.94	73.72	544.63	1009.03
0.30	10021.33	92.98	686.96	1272.71
0.35	11053.79	113.77	840.56	1557.28
0.40	11473.07	122.18	902.70	1672.40
0.45	11855.69	131.08	968.43	1794.18
0.50	12209.22	140.40	1037.32	1921.81
0.55	12539.29	137.14	1013.24	1877.21
0.60	12850.27	133.51	986.37	1827.41
0.65	13051.09	131.89	974.46	1805.35
0.70	13238.84	130.84	966.67	1790.91
0.75	13509.98	134.97	997.22	1847.52
0.80	13677.44	138.02	1019.73	1889.23
0.85	13836.99	141.78	1047.51	1940.68
0.90	13989.77	145.22	1072.95	1987.82
0.95	14042.29	139.80	1032.84	1913.51
1.00	14089.74	134.26	991.97	1837.80
1.05	7808.68	57.38	423.90	785.35
1.10	1345.64	0.00	0.00	0.00

*** CHANGE OF DESORPTION VARIABLES ***

TIME (HR)	EDI (CM)	WATER/SOIL (L/KG)	P DESORPTION (UG/CM2/MIN)
0.05	0.20	0.00	0.0000
0.10	0.20	0.00	0.0000
0.15	0.20	100.39	3.9431
0.20	0.20	220.61	2.9457
0.25	0.20	262.31	2.3143
0.30	0.20	291.38	1.9238
0.35	0.20	319.14	1.6496

```
          0.40        0.20        329.56        1.4358
          0.45        0.20        339.19        1.2764
          0.50        0.20        348.19        1.1488
          0.55        0.20        356.68        1.0445
          0.60        0.20        364.76        0.9575
          0.65        0.20        369.78        0.8827
          0.70        0.20        374.52        0.8196
          0.75        0.20        381.74        0.7663
          0.80        0.20        386.04        0.7172
          0.85        0.20        390.17        0.6750
          0.90        0.20        394.15        0.6376
          0.95        0.20        395.28        0.6028
          1.00        0.20        396.31        0.5726
          1.05        0.20        215.00        0.4104
          1.10        0.20         29.08        0.0000
```

***** CHANGE OF ADSORPTION VARIABLES *****

TIME (HR)	ADS1 (MG/L/MIN)	ADS2 (MG/L/MIN)	ADS3 (MG/L/MIN)	TOTAL (MG/L/MIN)
0.05	0.0000	0.0000	0.0000	0.0000
0.10	0.0000	0.0000	0.0000	0.0000
0.15	0.0003	0.0000	0.0000	0.0003
0.20	0.0004	0.0000	0.0000	0.0005
0.25	0.0005	0.0001	0.0000	0.0005
0.30	0.0005	0.0000	0.0000	0.0005
0.35	0.0005	0.0000	0.0000	0.0005
0.40	0.0004	0.0000	0.0000	0.0005
0.45	0.0004	0.0000	0.0000	0.0005
0.50	0.0004	0.0000	0.0000	0.0004
0.55	0.0004	0.0000	0.0000	0.0004
0.60	0.0003	0.0000	0.0000	0.0003
0.65	0.0003	0.0000	0.0000	0.0003
0.70	0.0003	0.0000	0.0000	0.0003
0.75	0.0003	0.0000	0.0000	0.0003
0.80	0.0002	0.0000	0.0000	0.0003
0.85	0.0002	0.0000	0.0000	0.0003
0.90	0.0002	0.0000	0.0000	0.0002
0.95	0.0002	0.0000	0.0000	0.0002
1.00	0.0002	0.0000	0.0000	0.0002
1.05	0.0001	0.0000	0.0000	0.0001
1.10	0.0000	0.0000	0.0000	0.0000

*** ROUTING OF DISSOLVED CHEMICALS ***

```
-------------------------------
TIME (HR)   DISSOLVED P (MG/L)
-------------------------------
   0.00           0.0000
   0.05           0.0000
   0.10           0.0000
   0.15           0.6890
   0.20           0.3002
   0.25           0.2217
   0.30           0.1839
   0.35           0.1582
   0.40           0.1430
   0.45           0.1310
   0.50           0.1211
   0.55           0.1206
   0.60           0.1211
   0.65           0.1081
   0.70           0.0956
   0.75           0.0955
   0.80           0.0958
   0.85           0.0963
   0.90           0.0971
   0.95           0.0911
   1.00           0.0852
   1.05           0.0876
   1.10           0.0006
```

******* CUMULATIVE DISSLOVED P LOAD   = 1543.31 MG *******

******* DISSOLVED P TRAPPING EFFICIENCY = -67.83 %   *******

*** ROUTING OF PARTICULATE PHOSPHORUS ***

```
-----------------------------------------------------
TIME (HR)              PARTICULATE P (MG P/L)
            COARSE     MEDIUM     FINER      TOTAL
-----------------------------------------------------

  0.00       0.00       0.00       0.00       0.00
  0.05       0.00       0.00       0.00       0.00
  0.10       0.00       0.00       0.00       0.00
  0.15       0.00       0.03       0.19       0.23
  0.20       0.02       0.13       0.78       0.93
  0.25       0.03       0.21       1.29       1.53
  0.30       0.04       0.26       1.63       1.94
  0.35       0.04       0.32       2.00       2.37
  0.40       0.05       0.35       2.15       2.54
  0.45       0.05       0.37       2.30       2.73
  0.50       0.05       0.40       2.47       2.92
  0.55       0.05       0.39       2.41       2.86
  0.60       0.05       0.38       2.35       2.78
  0.65       0.05       0.38       2.32       2.75
  0.70       0.05       0.37       2.30       2.73
  0.75       0.05       0.38       2.37       2.81
  0.80       0.05       0.39       2.43       2.87
  0.85       0.05       0.40       2.49       2.95
  0.90       0.06       0.41       2.55       3.02
  0.95       0.05       0.40       2.46       2.91
  1.00       0.05       0.38       2.36       2.80
  1.05       0.02       0.16       1.01       1.20
  1.10       0.00       0.00       0.00       0.00
```

***** CUMULATIVE PARTICULATE PLOAD   =   34.98 GRAMS ****

***** PARTICULATE P TRAPPING EFFICIENCY =   72.31 %   *****

***** TOTAL P TRAPPING EFFICIENCY   =   71.29 %   *****

*** PARTICLE SIZE DISTRIBUTION OF SEDIMENT ***

```
SIZE,MM          5.0000    2.0000    1.0000    0.5000    0.2500    0.1500
PERCENT FINER  100.0000  100.0000  100.0000  100.0000  100.0000  100.0000
```

```
SIZE,MM          0.0500   0.0007   0.0001
PERCENT FINER  100.0000  35.7822   0.0000
```

*** HYDROGRAPH AND SEDIMENT GRAPH ***

TIME (HR)	DISCHARGE (CFS)	SED DISC (MG/L)
0.00	0.0000	0.00
0.05	0.0000	0.00
0.10	0.0000	0.00
0.15	0.0325	244.48
0.20	0.0781	984.77
0.25	0.0946	1627.38
0.30	0.1062	2052.66
0.35	0.1171	2511.61
0.40	0.1216	2697.27
0.45	0.1256	2893.68
0.50	0.1293	3099.53
0.55	0.1328	3027.59
0.60	0.1361	2947.28
0.65	0.1383	2911.71
0.70	0.1403	2888.42
0.75	0.1431	2979.71
0.80	0.1449	3046.99
0.85	0.1466	3129.97
0.90	0.1482	3205.99
0.95	0.1488	3086.15
1.00	0.1493	2964.04
1.05	0.0827	1266.63
1.10	0.0143	0.00

***** TOTAL RUNOFF VOLUME   =   0.009064 AC-FT ****

***** TOTAL SEDIMENT MASS   =   0.035225 TONS ****

***** OVERALL SEDIMENT TRAP EFFICIENCY   =   81.57 % *******