STREAM NUTRIENT RETENTION IN THE LAKE EUCHA-SPAVINAW BASIN

By

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PREFACE

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CHAPTER 1

INTRODUCTION

BACKGROUND

The fate of nutrients within a stream ecosystem plays a major role in determining the quantity and form of nutrients that are transported downstream. While upstream movements exists, net fluxes of nutrients are predominately downstream (Allan 1995). Nutrient cycling and the downstream transport of nutrients are interrelated (Newbold et al. 1983) and have been defined as 'spiraling' (Newbold et al. 1981, Webster and Patten 1979). The term, spiraling, incorporates both the transformation and downstream movement of nutrients in streams. The nutrient cycle begins downstream from the last cycle, thus producing a spiral pathway through the stream ecosystems (Newbold et al. 1981). The length of the spiral consists of two parts: nutrient uptake length (S_w) and turnover length (S_p *sensu* Stream Solute Workshop 1990). S_w is the distance a nutrient molecule travels in the water column before uptake by the stream benthos (Newbold et al. 1983), and is a relative measure of the efficiency with which the stream uses the nutrients supplied, i.e. nutrient retention efficiency (Newbold et al. 1981). S_p is the sum of distances traveled in the various particulate forms (Newbold 1992).

Various methods are available to measure nutrient retention efficiency, such as laboratory analysis, stream mesocosms and whole-stream studies. The advantage of the whole-stream approach is hydrologic, chemical and biological attributes of streams are integrated into the study (Stream Solute Workshop 1990). Assessment of nutrient retention in various flow regimes and climatic conditions can provide information with regard to the timing, magnitude and form of nutrients transported from the stream ecosystem (Meyer et al. 1988). This is accomplished by short-term in-stream solute injections using a conservative solute to quantify hydrological parameters, such as average velocity, dispersion, transient storage area and exchange rate, and a non-conservative solute to quantify nutrient dynamics.

THE PROBLEM

Lakes Eucha and Spavinaw are two impoundments on Spavinaw Creek with Lake Spavinaw downstream of Lake Eucha. Lake Spavinaw was impounded in 1924, and Lake Eucha was established in 1952 to provide a regulated source of water to the downstream reservoir. The Eucha-Spavinaw Basin is primarily forest and pasture, and is in the Ozark Plateau of northwest Arkansas and northeastern Oklahoma where the underlying geology is karstic. Agricultural practices include grazing cattle, small dairies, confined animal operations, land application of animal wastes and some row crops. The basin also contains two rural wastewater treatment plants (WWTP) in Gravette and Decatur, Arkansas.

Lakes Eucha and Spavinaw supply half of the drinking water to the City of Tulsa, Oklahoma. Recently, the cost of drinking water treatment, and taste and odor problems have increased. The taste and odor problems were associated with geosmin, an organic compound derived from blue-green algae. In 1997, the Oklahoma Conservation Commission (OCC 1997) reported increases in average annual total P (TP) and NO_3-N concentration of three and two times, respectively, in Lake Eucha from 1975 to 1995. Beaty Creek and Spavinaw Creek are the two primary tributaries to Lake Eucha and constitute approximately 85% of the P loading into the reservoir (OCC 1997). Nutrient loading in Beaty Creek emanates from diffuse pollution and in Spavinaw Creek originates from a combination of diffuse and point source pollution (OCC 1997).

Watershed modeling of nutrient loading is being conducted for the Eucha-Spavinaw Basin. This modeling provides an estimation of nutrient loading to streams from the upland areas, but it does not incorporate in-stream processes. These stream processes can be significant in selecting appropriate management for terrestrial and aquatic ecosystems. The sinks and/or sources of nutrient within streams can retain and/or export nutrients into the water column. Whole-stream investigations into these processes can provide insight into the effects of point sources and watershed alterations on nutrient retention in the Lake Eucha-Spavinaw Basin. The transport and transformation of nutrients are important in understanding water quality impact.

PURPOSE OF THE STUDY

Lotic ecosystems are resilient, and the adverse effects of pollution are often not observed until the problem is excessive. In the Lake Eucha basin, stream nutrient retention is assessed in systems receiving variable amounts of point source and diffuse pollution. A comparison within and among streams impacted with various amounts of nonpoint source (agriculture) and point source pollution can give insights into potential effects on Lake Eucha water quality. This process will aide in the identification of management strategies for the Lake Eucha-Spavinaw Basin because streams are a link between aquatic and terrestrial ecosystems and in-stream processes are impacted by watershed alterations (Meyer et al. 1988). Temporal and spatial variability in stream nutrient dynamics can alter downstream impacts and may require the selection of site and time specific management strategies to address water quality problems. Streams and the receiving water body can be more sensitive to N and/or P enrichment during certain seasons; Conversely, streams may be able to withstand increased nutrient loads without increasing export to the receiving water body at a particular time.

OBJECTIVES OF THE STUDY

1. Assess the impact of Columbia Hollow (essentially Decatur WWTP) on nutrient retention in Spavinaw Creek during summer baseflow (CHAPTER III).

2. Assess the impact of the Decatur WWTP on nutrient retention in CH and the influence of seasonal and hydrologic variability on nutrient retention (CHAPTER IV).

3. Compare stream nutrient retention in three agricultural watersheds with a varying degree of impact (CHAPTER V).

CHAPTER 2

LITERATURE REVIEW

NUTRIENT CYCLING AND SPIRALING

In a stream ecosystem nutrient cycling consists of abiotic and biotic uptake of dissolved nutrients from the water column and the subsequent processing and movement through the food web eventually leading to regeneration in the dissolved inorganic form (Newbold, 1992). As the nutrient cycles between the abiotic and biotic components the nutrient is subject to downstream displacement, and the cycle produces a spiral with this longitudinal displacement (Webster and Patten, 1979). Spiraling length (S) is the downstream distance required to complete this nutrient cycle or spiral (Elwood et al., 1983). S is the combination of the average distance travelled by a nutrient in the dissoved form [uptake length, S_w] and the distance travelled by a nutrient in the various particulate forms before regeneration into dissolved inorganic form [turnover length, S_p] ($S = S_w + S_p$, Stream Solute Workshop, 1990).

Newbold et al. (1981) developed these indices and reported field measurements of S using radiotracers. This experiment involved release of ^{32}P (as carrier-free PO_4) and ^{3}H (as water). ^{32}P concentrations were measured at sampling stations increasing in distance from the radiotracer release point and corrected for dilution using ^{3}H data. Uptake of ^{32}P at each point downstream stream is proportional to ^{32}P remaining in the water column at that point. The proportion (C_x/C_o) of ^{32}P remaining in the water is assumed to decrease exponentially with distance (x) from the release [$C_x/C_o = \exp(-kx)$ where C = ^{3}H corrected concentration of ^{32}P, x = distance downstream from injection point, o = most upstream site below injection point and k = uptake rate constant]. Then, the average distance (S_w) travelled by $^{32}PO_4$ molecule is calculated as $S_w = -1/k$.

Release of radiotracers were used to estimate S (e.g. see Mullholland et al., 1985; Newbold et al., 1983). These results indicated that S_w is the major component of S, and S_w averaged over 90% of the distance in the nutrient spiral (Mullholland et al., 1985; Newbold et al., 1983). S is an index of the efficiency of nutrient retention, and because S_w is the greatest component of S, S_w can be used as an index of the relative importance of nutrient utilization and transport in the stream ecosystem (Mulholland et al., 1985; Newbold et al., 1983). Because S_p, and therefore S, can only be estimated using radiotracer experimental releases, S_w has become the most explored parameter of nutrient spirals (Webster and Ehrman, 1996).

Mulholland et al. (1990) compared S_w calculated from radiotracer $^{33}PO_4$ and stable PO_4 releases. Results indicated two important issues: (1) stable PO_4 releases overestimated S_w compared to radiotracer and (2) S_w increased with the level of stable PO_4 additions (see also Hart et al. 1992). However, since radiotracer releases would be of limited use due to public concerns over radiation exposure, Mullholland et al. (1990) proposed that stable PO_4 additions still present a reasonable method for comparing nutrient retention between streams. Furthermore, these authors suggested that increases in ambient PO_4 concentration need to remain within the range of concentrations in which the relationship between uptake and solute concentration is linear to calculate S_w accurately. Research using stable nutrient additions has flourished over the past decade, and the purpose of these additions is to estimate and compare stream nutrient retention efficiency by measuring S_w.

NUTRIENT UPTAKE LENGTH METHODS

Whole-stream nutrient addition studies integrate the physical, chemical and biological attributes of a stream ecosystem and provide an understanding of the natural ecological environment and the hydrologic properties of the stream (Stream Solute Workshop, 1990). In nutrient additions, injection solutions are composed of a conservative tracer (hydrologic tracers such as Br^- or Cl^-) and non-conservative ions (nutrients such as NH_4, NO_3 and/or PO_4). Dynamics of conservative ions are limited to advection (water velocity) and dispersion (molecular diffusion and turbulence) processes. However, the nature of downstream transport of non-conservative ions is more complicated because of abiotic and biotic interactions between the dissolved ions in the water and the stream benthos (Stream Solute Workshop, 1990). Abiotic processes include adsorption, desorption, precipitation, and dissolution; biotic processes include algal and microbial uptake, bio-transformation and mineralization. Nutrient concentrations are corrected for ambient conditions, and hydrologic tracers are used to correct for downstream dilution of the dissolved nutrient in short-term nutrient additions (e.g. see Martí and Sabater, 1996), such that:

$$[Nutrient_x]_{corr} = \frac{[tracer_o]-[tracer_b]}{[tracer_x]-[tracer_b]}\left([nutrient_x]-[nutrient_b]\right)$$

where corr = background and dilution corrected nutrient concentration, o = up-stream most sampling station below injection point, x = downstream sampling stations, b = ambient concentrations at point x. The corrected nutrient concentrations are expressed as the proportion of the nutrient remaining in solution from the most up-stream sampling station. Nutrient uptake per unit stream length (k, uptake rate constant) is calculated as the slope of the regression line relating the natural logarithm of the corrected proportion of nutrient remaining in the water to distance.

$$\ln\left(\frac{[Nutrient_x]_{corr}}{[Nutrient_o]}\right) = -kx$$

S_w is the negative inverse of the uptake rate constant (-1/k).

Nutrient additions must be conducted in study reaches long enough to measure differences in concentration between downstream sampling stations (Martí, 1995), and study reaches must also be representative of the dominant channel morphology in order to extrapolate S_w to the entire stream (Stream Solute Workshop, 1990). Duration of the nutrient additions depends on time needed to reach equilibrium at the sampling station most downstream of the injection point, but the duration should not be long enough to allow regeneration or substrate release of the nutrient back into the water column (Mulholland et al., 1990; Stream Solute Workshop, 1990). Durations less than a few hours are usually sufficient to reach equilibrium and short enough to avoid significant regeneration.

Nutrient and tracer concentrations are considered in 'equilibrium' throughout the reach when conductivity or conservative tracer concentration measurements establish a plateau at the most downstream sampling station (Martí, 1995; Stream Solute Workshop, 1990). The tracer is injected at levels great enough to induce ca. 25 µS cm^{-1} increase in conductivity at the downstream end of the study reach, and conductivity measurements are recorded with time as the pulse of injection solution passes the most downstream sampling point. When the system reaches a plateau in conductivity and is in 'equilibrium', samples are taken at the downstream sampling stations. Nutrient concentrations are corrected for background, normalized for dilution using the hydrologic tracer and the proportion of the corrected, and the normalized nutrient concentration remaining in the water at each site is used to calculate S_w (e.g. see D'Angelo et al., 1991; Martí, 1995; Stream Solute Workshop, 1990). Again, nutrients must be added at concentrations high enough to detect the nutrient addition (Martí, 1995), but low enough not to saturate the stream biotic community (Mulholland et al., 1990; Stream Solute Workshop, 1990).

Co-injection of conservative and non-conservative ions estimates uptake of the non-conservative ion and the hydrologic properties of the stream reach such as average water velocity, dispersion and subsurface water exchange. The relation between conductivity and time provides valuable information about transient storage and subsurface inputs in the stream reach. Several simulation models are available which use the relationship between conductivity and time to estimate average water velocity, dispersion, the rate of solute exchange with the transient storage zone and the size of the transient storage zone (e.g. see Bencala and Walters, 1983; D'Angelo et al., 1993; Stream Solute Workshop, 1990). These parameters reflect differences in stream size, flow and morphology and are useful when comparing temporal and spatial differences in nutrient retention (D'Angelo et al., 1993).

PHOSPHORUS

P is present in either the dissolved or particulate form in streams. The dissolved inorganic form of P in streams is orthophosphate, PO_4. Soluble reactive P (SRP) is the dissolved form of P typically measured in streams and lakes, and includes PO_4 and some portion of the highly reactive fraction of dissolved organic P (DOP) or colloidal P in water (i.e., ascorbic acid method after Murphy and Riley 1962). True PO_4 concentrations have constituted between 4-76% of SRP in various streams and rivers (summarized by Newbold, 1992).

PO_4 is a highly reactive molecule and is adsorbed and desorbed by stream sediments through a processes collectively referred to as the phosphate buffer mechanism (Froelich, 1988). The ability of stream sediments to adsorb or desorb

P is often characterized in terms of their equilibrium P concentration (EPC_0 *sensu* Froelich, 1988). EPC_0 is the PO_4 concentration of ambient stream water at which there is no net adsorption nor desorption of PO_4. This EPC_0 has been linked to the maintenance of PO_4 or SRP concentrations in streams (Klotz, 1988, 1991; Meyer, 1979; Taylor and Kunishi, 1971). By this mechanism, sediments are a source or sink of P depending on ambient P conditions in the stream ecosystem. If PO_4 (or SRP) in the water column is below the EPC_0 then the sediments may release P until an equilibrium is established between the sediments and water column P levels. However, if the stream water PO_4 (or SRP) is above the EPC_0 then the sediments may absorb P. Suspended sediments may contribute to any inequality observed between SRP and EPC_0 of the benthic sediments (House et al., 1995). Froelich (1988) postulated that water column PO_4 (or SRP) may fluctuate around the sediment EPC_0 in a stream ecosystem. Newbold (1992) questioned whether the sediments are controlling PO_4 levels or are stream PO_4 levels determining sediment EPC_0, but such predictions require further research.

Temporal and spatial (longitudinal) variation in SRP was observed in Hoxie Gorge Creek, New York, and concentrations were correlated with sediment EPC_0 (Klotz, 1988, 1991). Spatial changes in EPC_0 were associated with variations in exchangeable Al in the sediments as influenced by ionic strength and dissolved Ca^{2+} concentration (Klotz, 1988), whereas annual changes in EPC_0 were not correlated with exchangeable Al or Fe but organic matter and ATP activity in the sediments (Klotz, 1991). Other researchers found no difference in EPC_0 and sediments of varying particle size distribution and organic matter content (Hill, 1982; Meyer, 1979), whereas Haggard et al. (1999) observed significant positive correlation between EPC_0 and the percent of silt in the sediments. The adsorption of PO_4 may increase bioavailability and serve as a transient or temporary storage zone of P within the stream ecosystem (Tate et al., 1995). In general, abiotic buffering or control of water column P concentrations through adsorption and desorption is relatively important in streams with an abundance of finer particle sediments, with a large difference between EPC_0 and stream PO_4, and where biotic uptake may already be saturated (Newbold, 1992). However, biotic processes may regulate P concentrations in streams with minimal abiotic influence such as systems with coarse sediments and low ambient PO_4 concentrations (Newbold, 1992).

Several studies have demonstrated P removal by algae (Lock et al., 1990), heterotrophic microbial and fungal communities associated with leaf detritus (Elwood et al., 1981; Suberkropp, 1998), macrophytes (Pelton et al., 1998), and bryophytes (Meyer, 1979). Biological uptake of PO_4 is typically expressed by Michaelis-Menton kinetics:

$$U = U_{\max}\left(\frac{C}{K_s + C}\right)$$

where U = uptake rate at concentration C, U_{max} = maximum uptake rate, K_s = nutrient concentration at ½ U_{max}, and may be saturated at PO_4 concentrations less than 5 µg L^{-1} (Bothwell, 1985). Algal and microbial communities can exhibit luxury consumption of PO_4; that is, they can assimilate PO_4 at a greater rate than cell growth requires so that U_{max} can vary greatly depending on the accumulation of PO_4 in the cells (Newbold, 1992). Periphyton biomass increases as PO_4 concentrations increase (Bothwell, 1989); although periphyton biomass can increase with long-term additions of PO_4, the short-term response is limited to biotic uptake kinetics and should become saturated at low PO_4 concentrations (Mulholland et al., 1990). Typically, as periphyton biomass increases, the importance of internal P cycling within the biofilm increases (Paul and Duthie, 1989). After PO_4 has been assimilated by the biotic community it may be excreted or released into the stream as DOP or particulate organic P (POP), or even regenerated directly as PO_4 (Allan, 1995).

NITROGEN

The N cycle is more complex than the P cycle because the processes of N_2 fixation and denitrification involve exchange between the water and atmosphere and dissolved inorganic N (DIN) forms are involved in biologically mediated redox reactions (Newbold, 1992). Also, DIN in streams is typically NH_4 and/or NO_3, and these two forms of DIN differ in their biological availability and abiotic reactivity. For example, preferential uptake of $^{15}NH_4$ compared to $^{15}NO_3$ was observed in river phytoplankton (Stanley and Hobbie, 1981). NO_3 assimilation following a large scouring flood was observed in a desert stream (Grimm 1987), and several investigation have also shown uptake of both experimentally injected NO_3 (Munn and Meyer, 1990; Sebetich et al., 1984; Triska et al., 1989a) and NH_4 in streams (Martí and Sabater, 1996; Richey et al., 1985). NH_4 is similar to PO_4 because it is subject to abiotic adsorption to sediments (Munn and Meyer, 1990; Triska et al., 1994) whereas NO_3 is non-reactive with sediments. In general, sediment particles are negatively charged which explains the adsorption of NH_4 but PO_4 is either adsorbed or chemisorbed to micro-sites of positive charge, especially in Al and Fe oxides (McBride, 1994). Triska et al. (1994) suggested riparian or stream sediments can serve as a transient storage zone for NH_4. Biotic uptake of either form of DIN should conform to Michaelis-Menton kinetics as previously described.

N bio-transformations can be categorized as either structural synthesis or energy yielding reactions. N_2 fixation and assimilation are structural synthesis reactions, whereas the energy producing reactions are nitrification (conversion of NH_4 to NO_3) and denitrification (conversion of NO_3 to N_2). The oxidation of NH_4 to NO_3 occurs under oxic conditions, and has been observed in the hyporheic zone of desert streams (Jones et al., 1995). Nitrification in the hyporheic zone is influenced by the mineralization of organic-N to NH_4 in benthic sediments and import of NH_4 and dissolved organic N from the surface water of the stream (Holmes et al. 1994). Richie et al. (1985) observed removal of reduced forms of N (i.e., NH_4 and urea) during experimental injections in a forested headwater stream and an increase in NO_3 suggesting nitrification.

Denitrification requires anoxic conditions and may occur in deep stream sediments (Allan, 1995) or in the riparian ecosystem (Peterjohn and Correl, 1984;

Jacobs and Gilliam, 1985). Although denitrification requires anoxic conditions, it has been observed in micro-zones in oxic sediments (summarized by Newbold, 1992). While nitrification results in a transformation in the form of DIN ($NH_4 \rightarrow NO_3$), denitrification results in a loss of N from the aquatic ecosystem to the atmosphere as well as a chemical transformation ($NO_3 \rightarrow N_2$).

TEMPORAL AND SPATIAL VARIABILITY IN NUTRIENT RETENTION

Stream nutrient retention is influenced by abiotic and biotic processes within the stream and also the upland area. The relative contribution of these processes is determined by the individual basin (stream, riparian and watershed) characteristics (Meyer et al., 1988). Nutrient retention has been used as a measure of ecosystem stability (Minshall et al., 1983). Ecosystem stability is defined by two properties: resistance and resilience. Resistance is the ecosystem's ability to withstand perturbation, and resilience is the time required for an ecosystem to recover from perturbation. Ecosystems that are more resistant to change and more resilient are considered to be more stable; therefore, ecosystems with high nutrient retention efficiency may be more stable. Given the numerous processes and potential interaction between these processes, no single experiment assessing all factors regulating nutrient retention is possible (Triska et al., 1989a), and variation in nutrient cycling or spiraling (most importantly S_w) and ecosystem stability are typical explained by variations in the parameters described below.

Among local factors governing stream nutrient retention, discharge or velocity, temperature, algal uptake, allochthonous inputs and transient storage appear to be the most important whereas on a larger spatial scale geology may be most important. Geology may be a major determinant in absolute and relative nutrient concentrations in streams by influencing water chemistry, nutrient ratios and geomorphic structures or channel form (Dillon and Kirchner, 1975; Munn and Meyer, 1990; Valett et al., 1996). For example, Dillon and Kirchner (1975) observed that P export was greater in catchments of volcanic origin compared to plutonic or sedimentary catchments. Clearly no single factor is responsible for nutrient assimilation but stream nutrient retention is regulated by a complex interaction of abiotic and biotic mechanisms (D'Angelo and Webster, 1991) as constrained by parent geology, local morphology and environmental conditions (D'Angelo et al., 1991; Martí and Sabater, 1996; Munn and Meyer, 1990; Valett et al., 1996). These abiotic and biotic interactions are not limited to channel processes because hyporheic and parafluvial zone processes may be sources or sinks of nutrients (Triska et al., 1989b). The individual processes associated with nutrient retention in streams are influenced by the spatial heterogeneity of different habitats or patches typical of small streams (Pringle et al., 1988); substrate patchiness may result in heterogeneous patterns of nutrient retention (Aumen et al., 1990).

Discharge and velocity may control nutrient retention (D'Angelo and Webster, 1991; Martí and Sabater, 1996; Meyer, 1979). D'Angelo et al. (1991) observed that S_w varied with average velocity in artificial streams with similar discharge. Typically, nutrient removal efficiency of streams increases as discharge or velocity decreases, and increases in discharge or velocity result in a loss of retentive ability (Meyer, 1979). Nutrients accumulate during low flow because uptake mainly occurs in association with particulate organic materials and the transport of this material depends upon discharge (Allan, 1995). The hydrologic regime influences biotic accumulation of nutrients because it serves as a physical control over biomass accrual and organic matter export (Allan, 1995). Grimm (1987) observed an initial increase in nutrient retention followed by a decline with time after the biological community was reset by an episodic flood event. Overall, the importance of biotic regulation of nutrient dynamics can be reduced by changes in stream flow that increase the downstream transport of organic matter and nutrients (D'Angelo et al., 1991). Temporal changes in stream nutrient retention may be linked to the annual variability in the discharge regime within each individual basin.

The theoretical framework for nutrient spiraling and nutrient transport (Newbold et al., 1981) incorporates hydrologic factors such as dispersion and average water velocity. In fact the Stream Solute Workshop (1990) defined S_w = -u/k where u is average stream velocity determined by hydrologic tracers; thus, as stream average stream velocity increases so does S_w. It has been suggested that S_w can be normalized for velocity (S_w/u), and this value allows comparison across sampling dates within a stream or between streams. However, most investigators still use S_w when comparing nutrient retention in the literature (e.g., see Table 7 in

Martí and Sabater, 1996).

Subsurface and surface flow interaction is another hydrologic regulator over nutrient retention in streams. The exchange of surface water across the benthic sediment-water interface in streams is especially important since the abiotic and biotic mechanisms of nutrient retention operate almost exclusely in this region and the hyporheic zone. Therefore, hydrologic conditions that favor increased contact between benthic sediments and/or the algal and heterotrophic microbial community increase nutrient retention. Specific areas of interaction between the benthic substrate and water column exist. These regions of subsurface water upwelling and surface water downwelling result from changes in the streambed and contribute to different ecological processes. Sites of downwelling are associated with increased hyporheic and parafluvial mineralization and nitrification (Holmes et al., 1994; Jones et al., 1995), whereas areas of upwelling are sites of increased nutrient retention by biological communities from nutrient rich hyporheic zones (Valett et al., 1994). Mulholland et al. (1997) suggested the hyporheic zone may also serve as an important site for nutrient uptake and temporary storage of surface water nutrients (see also Triska et al., 1989b). Subsurface zones are important stream subsystems in the processes of nutrient assimilation and regeneration.

Transient storage zones are defined as zones where water is retarded compared to stream water advection (Webster and Ehrman, 1996), and may also be significant factors in stream nutrient retention. Transient storage parameters such as dispersion (D), transient storage zone size (A_s) and exchange rate (α) are used to compare tracer and nutrient dynamics in streams with various discharge, order or watershed characteristics or over the annual cycle (Bencala and Walters, 1983; D'Angelo et al., 1993). These transient storage zones allow for increased contact between nutrients and potential retention sites, and this increased residence time often translated to increased nutrient retention in streams. The relative importance of these zones varies between streams and within a single stream as a function of discharge. Lower discharge typically favors increased exchange between transient storage zones and the water column. Consequently, the importance of transient storage in nutrient dynamics may fluctuate seasonally as discharge rises and falls. Examples of transient storage zones are the hyporheic zone, pools and back-water eddies (Webster and Ehrman, 1996).

Another important physical factor regulating nutrient retention is temperature. Temperature can control nutrient retention by regulating the metabolic rate of the biological community and adsorption-desorption dynamics. Increasing levels of exchangeable P in benthic sediments have been associated with increased stream water temperatures, and may reduce biotic uptake from the water column, thus increasing P availability in the sediment P pool. Temperature can indirectly control S_w because biotic uptake or transformation increases logarithmically with temperature (D'Angelo et al., 1991; Elwood et al., 1981). Temperature may act as a primary physical and environmental control of nutrient retention because in some streams biotic uptake was responsible for most of nutrient retention (D'Angelo et al., 1991; Elwood et al., 1981). However, the control of temperature in streams may be influenced by the amount of riparian shading.

Riparian shading may also inhibit light penetration into the stream; thus, nutrient retention may be reduced because photoautotrophic organisms are light limited within the selected stream reach. Furthermore, variation in local climatic conditions can control S_w by stimulating or inhibiting photoautotrophic activity.

Autochthonous (algal and microbial communities) production increases with increasing nutrient concentrations (Bothwell, 1989). Algae and heterotrophic microbes have been associated with nutrient retention in streams (Elwood et al., 1981; Lock et al., 1990). Furthermore, algal and microbial communities may be responsible for most of the nutrient retention in some streams (D'Angelo et al., 1991; Elwood et al., 1981; Mulholland et al., 1985). Allochthonous input of materials may also be a regulating factor in the temporal variability nutrient retention in streams. Leaf litter and its associated microbial community can retain a considerable portion of P injected into streams (Elwood et al., 1981). P uptake by the microbes on the leaf litter was rapid in the beginning of decomposition then decreased and stabilizes several weeks after the litter initially entered the stream (Mulholland et al., 1984). Mulholland et al. (1985) compiled several years of radiotracer P and organic matter data for a small woodland stream in Tennessee and observed an inverse relationship between S_w for P and organic matter (as CPOM) in the stream. At small spatial scales in streams woody debris may be important site of nutrient retention (Aumen et al., 1990); on a larger scale large woody debris can increase the size of the transient storage zone, thus increasing nutrient retention. Therefore, seasonal and spatial patterns of allochthonous input into streams may also be a primary determinant in the temporal and spatial variation in nutrient retention.

The animal community also influences nutrient cycling or spiraling in many ways. Algal grazing can reduce or increase productivity and nutrient assimilation. In a stream mesocosm study, snails consumed periphyton and reduced biomass (Mulholland et al., 1983). Cell-specific uptake rates were enhanced by grazing activity but overall nutrient uptake was reduced, i.e. nutrient spiraling was shortest in the stream without snails (Mulholland et al., 1983). Lack of grazing activity can also influence nutrient cycling; in laboratory streams without snails periphytic biomass accrual increased the importance of internal nutrient cycling and reduce nutrient assimilation from the water column (Mulholland et al., 1994). Bothwell (1989) suggested that stream periphyton communities can be nutrient limited in streams with higher nutrient concentrations than biologically required for optimum growth because nutrient diffusion into the periphytic matrix is regulating nutrient availability. Grazing activity can also increase the rate of regeneration and downstream transport of nutrients associated with particulate matter (Allan, 1995). Similarly, shredders increase the rate of conversion from large to small particles possibly increasing particulate matter export from a stream reach (Mulholland et al., 1985b) whereas filter feeding organisms actually reduce transport of particles. Migration and movement of members of the animal community can result in either input or export of nutrients.

In general, nutrient retention has been investigated in nutrient depleted headwater forested streams (e.g. see D'Angelo and Webster, 1991; Elwood et al., 1981; Meyer, 1979, Mulholland et al., 1985a, 1990; Munn and Meyer, 1990; Newbold et al., 1983; Sebetich et al., 1984; Tate et al., 1995) and desert stream ecosystems (Grimm, 1987; Grimm et al., 1981). Tate (1990) assessed the variations and controls of N in prairie streams which were typically N and P co-limited. Several researchers have used input/output relationship between sampling points in higher order streams to assess nutrient retention (Dorioz et al., 1998; Stanley and Hobbie, 1981). In the last decade nutrient retention studies have flourished but few have been conducted in eutrophic or nutrient rich streams (e.g. see Meals et al., 1999), although Meyer (1999) presented nutrient retention data from a wide variety of streams in forested, urban and agricultural sub-basins. Nutrient retention is important because it defines the ability of a stream to retain and recycle nutrients. The efficiency of the stream can determine its productivity and trophic nature of the lotic ecosystem (D'Angelo and Webster, 1991) and ultimately the timing and form of nutrient transport to downstream aquatic ecosystems (Meyer et al., 1988). However, abiotic and biotic retention of nutrients in streams is probably not a significant buffer of annual nutrient flux through stream ecosystems (Meyer and Likens, 1979). That is, nutrient retention studies can be used to understand and evaluate the effects of stream, riparian or land use changes on in-stream processes but are not indicative of annual nutrient transport to receiving water bodies. However, these studies can provide insight into the timing of nutrient transport since a high nutrient retention efficiency suggests that the nutrient transport is retarded compared to the downstream transport of water (Newbold, 1992). The more cycles completed before the nutrient is transported downstream the greater the chance the nutrient is not in a bioavailable state, or at least less bioavailable when reaching downstream aquatic ecosystems. Mulholland et al. (1992) observed an upstream-downstream linkage between nutrient supply and nutrient limitation. Therefore, streams that exhibit high nutrient retention efficiency have less chance to degrade downstream water quality. Investigation of nutrient retention in agricultural sub-basins is needed to understand the dynamics of nutrients in eutrophic lotic ecosystems and the effects of various agricultural practices on in-stream abiotic and biotic processes.

LIMITATIONS

The limitations of the solute injection methodology may be characterized as theoretical, stable vs. radiotracers or other isotopes, temporal and spatial variability, and extrapolation from reach to entire stream systems. In the following discussion I will attempt to describe these limitations further.

Solute injection studies first used radiotracers [^{32}P as carrier free $^{32}PO_4$ and ^{3}H as tritiated water] by Newbold et al. (1981) in Walker Branch, Tennesse, and with heavy N [^{15}N as either $^{15}NO_3$ or $^{15}NH_4$] by future investigators. With environmental concerns concentrating on P transport in 1990's, Mullholland et al. (1990) compared S_w from radiotracer and stable PO_4 injections in Walker Branch.

However, since radiotracer releases would be of limited use due to public concerns over the release of radioactive materials into water supplies, Mullholland et al. (1990) proposed that stable PO_4 additions still present a reasonable method for comparing nutrient retention between streams. This presents possibly the greatest limitation of the use of whole-stream solute injections because periphyton growth may be saturated at concentrations as low as 5 µg L^{-1} (Bothwell, 1985). In streams, where P transport and retention is of greatest concern, levels would typically be above this, but recent research has indicated a linear relationship between S_w and increasing PO_4 additions within a relatively large range of nutrient enrichment (5-50 µg L-1; Haggard et al., 2000). In streams dominated by abiotic uptake ambient S_w may be estimated as the y intercept of this linear relationship. However, this idea remains to be tested.

Another problem with stable PO_4 additions is that turnover lengths can not be calculated. Few studies (e.g., see Newbold et al., 1983) have investigated the complete spiral of P through a stream ecosystem. S_w has no temporal dimension. Streams may exhibit high nutrient retention (low S_w) but the nutrient may be cycled through the particulate forms quickly, or streams may exhibit low nutrient retention (high S_w) but the completion of spiral takes a considerable amount of time.

Multiple factors have been suggested as regulators in nutrient retention. The question is: how do you compare results from these studies if S_w is dependent on so many variables? Some clear interpretations of temporal variability exist, such as autumn is a period of high allochthonous input and associated nutrient retention but winter may be similar to summer in temperate streams (Mullholland et al., 1985). However, spike additions in a eutrophic stream in the northeast United States showed no net (long-term) retention during winter whereas long-term retention occurred in summer (Meals et al., 1999). Another question might be how do you extrapolate results from the study reach to the entire stream? This possible limitation may be overcome by selecting study reaches with similar characteristics to those prevalent in the stream as a whole (Stream Solute Workshop, 1990). Care must be taken when comparing results from solute injection studies within and among streams and/or over seasons.

Despite these pitfalls S_w is a good descriptor for comparison of nutrient retention in streams because it incorporates actual stream processes (Stream Solute Workshop, 1990). Stream ecosystems are conditioned by upland watershed characteristics (Meyer et al., 1988) and S_w should reflect the degree with which the watershed and stream ecosystem is disturbed.

CHAPTER III

EFFECT OF A POINT SOURCE INPUT ON STREAM NUTRIENT RETENTION

ABSTRACT: We examined the effect of a point source (PS) input on nutrient retention in Spavinaw Creek, AR, during summer baseflow in 1998 and 1999. Nutrient uptake lengths, S_w, for soluble reactive phosphorus (SRP) and NO_3-N were estimated in a reach above and below the PS input. The PS was used as the nutrient source in the reach below, but the reach above required a short-term nutrient addition. In order to examine specific mechanisms of P retention, sediment samples were collected and analyzed for particle size, exchangeable P (Ex-P) and P Sorption Index (PSI). Control S_w for SRP was 0.75 km in the reach above the confluence, but S_w in the reach below the confluence ranged from 9.0 - 31 km for SRP and 3.1 - 12 km for NO_3-N. S_w-SRP was significantly correlated with discharge whereas S_w-NO_3-N was correlated to NO_3-N additions from the PS. Benthic sediments exhibited little natural buffering capacity (low PSI) above the PS, but buffering capacity was further reduced by P loading from the PS. Ex-P in the sediments also increased three fold below the PS. P retention in Spavinaw Creek was apparently regulated by the physical process of flow whereas N retention was controlled by flow and the level of N enrichment and possibly biotic uptake and transformation. The PS dramatically reduces nutrient retention in Spavinaw Creek.
(**KEYS TERMS**: aquatic ecosystems, phosphorus, nitrogen, nutrient retention, sediments, point source pollution.)

INTRODUCTION

The Clean Water Act in 1972 initiated control measures on point sources of pollution. As further regulation of point source (PS) pollution became less viable economically and significant water quality impairment remained, more attention has focused on diffuse sources of pollution, especially agricultural nonpoint source (NPS) pollution (Smith et al., 1987; Carpenter et al., 1998). However, recent investigations have shown whole-stream nutrient retention is greatly reduced in PS impacted systems compared to less impacted streams (Haggard et al., In review; Martí et al., 1999). Several investigators have shown substantial decreases in benthic sediment P buffering capacity and increases in extractable P in sediments below a PS discharge (e.g., see Dorioz et al., 1998; House and Denison, 1998). Furthermore, PS releases are responsible for sediment deoxygenation up to 20 km below the PS release (Rutherford et al., 1991), heavy metal and volatile organic carbon contamination, and altered community structure of benthic and hyporheic organisms (Birge et al., 1989, Hunt 1999).

Despite extensive regulation, PS inputs often have pronounced impacts on stream ecosystems. Few PSs have strict regulations regarding nutrient loading, especially for P, and this is true in facilities in rural areas in the Ozark Plateau of Oklahoma and Arkansas. Spavinaw Creek, AR, is a primary tributary of Lakes Eucha and Spavinaw, OK, which supply half the drinking water to the City of Tulsa, OK (Figure 1). Recently, the cost of chemicals used in drinking water treatment has doubled and taste and odor problems associated with geosmin have increased

(City of Tulsa, personal communication). The Oklahoma Conservation Commission reported increases in average annual total P (TP) and NO_3-N of three and two fold, respectively, in Lake Eucha from 1975 to 1995 (OCC, 1997). Nutrient loading from Spavinaw Creek originates from both NPS and PS pollution (OCC, 1997).

The objective of this study was to assess the effects of a PS input on Spavinaw Creek. Specifically, we examined the ability of Spavinaw Creek to retain nutrients from this PS through a combined approach of estimating whole-system nutrient retention, and through smaller-scale experiments examining the ability of benthic sediments to remove nutrients from the water.

STUDY SITE DESCRIPTION

Lakes Eucha and Spavinaw are two impoundments on Spavinaw Creek with Lake Spavinaw being downstream of Lake Eucha (Figure 1). Lake Spavinaw was impounded in 1924, and completely filled in 1928. Lake Eucha was established in 1952 to provide a regulated source of water to the downstream reservoir, and the impoundment began supplying Lake Spavinaw in 1956. The Eucha-Spavinaw Basin is primarily forest and pasture in upland areas, and is located in the karstic Ozark Plateau of northwestern Arkansas and northeastern Oklahoma. Primary agricultural practices in the basin include grazing cattle, confined animal operations and land application of animal wastes. The basin also contains two rural wastewater treatment plants (WWTP) in Gravette and Decatur, Arkansas. The City of Decatur (Pop. 1013) is located in northwest Arkansas, and the WWTP is a secondary treatment facility. A major input into this facility is a poultry processing and rendering plant. The treatment plant is composed of a high rate bio-filtration system followed by approximately 5 ha of stabilization ponds. Two ponds containing surface aerators are in parallel and are followed by a finishing pond with baffles and a re-circulation line. WWTP effluent has limits on carbonaceous biochemical oxygen demand (CBOD), NH_4-N and NO_3-N of 10, 15 and 10 mg L^{-1}, respectively. Currently, the facility is required to report levels of TP in the effluent but no discharge permits for P are in place. Average discharge (Q) and TP from the WWTP was 1.3 MGD and 7.1 mg L^{-1} from November 1997 to 1999 [All information regarding this WWTP was attained in public documents provided by the City of Tulsa, OK, and the Arkansas Department of Pollution Control and Ecology (ADPCE, 1985; 1997)].

The effluent of the WWTP discharges into Columbia Hollow, a 3rd order tributary to Spavinaw Creek (Figure 1). Spavinaw Creek is a 5th order stream throughout the reach selected above and below the confluence of Columbia Hollow (stream order estimated using 1:24,000 United States Geological Survey topography maps and includes perennial and intermittent streams). Riparian zones in Spavinaw Creek varied from extensive forest vegetation and almost complete shading to pastures and no canopy within the 3.5 km study reach below the confluence. Several large pools, long runs and riffles are present, which is representative of Spavinaw Creek. Spavinaw Creek has relatively low SRP (<30 µg L^{-1}) and high NO_3-N, ca. 2 - 3.5 mg L^{-1}, above the confluence with Columbia

Hollow, while NH_4-N is generally below detection limits (<30 µg L^{-1}). N:P ratios and artificial growth substrates (Matlock Periphytometer, unpublished data) indicate Spavinaw Creek is P limited above Columbia Hollow. Within the selected study reach, no visible lateral inflows were observed. One sampling site was selected upstream of the confluence of Spavinaw Creek and Columbia Hollow in both streams, and 6 sites were selected downstream of the confluence in Spavinaw Creek. The riffle immediately below the confluence (approximately 0.2 km) was the first sampling station, and sites further downstream were selected at increasing distances from the confluence, up to a distance of 3.5 km. No sites were chosen further downstream to avoid the influence of other tributaries. A second 400 m study reach was selected approximately 0.5 km above the confluence to estimate background nutrient retention. The reach was sufficiently upstream of Columbia Hollow to avoid any influence the tributary would have on nutrient processes within Spavinaw Creek.

MATERIALS AND METHODS

Nutrient Retention Methods

Uptake length (S_w) is the average distance an atom or molecule travels in its dissolved form before being removed from the water column (Newbold et al., 1981), and is an estimate of whole-reach nutrient use relative to transport (Martí and Sabater, 1996). Short values of S_w (e.g., 1-100 m) denote high nutrient retention within a stream reach. S_w is commonly estimated by artificially elevating the ambient nutrient concentration in a stream reach by injecting small amounts of a concentrated nutrient solution plus a tracer, such as Cl^-, and measuring the downstream decline in the nutrient relative to the tracer (Webster and Ehrman, 1996). In these studies, the addition of solutes is used as a tool to examine whole-stream reach retention. The addition is small but large enough to detect a measurable difference in concentration in the water column without altering normal nutrient processes in the stream (Stream Solute Workshop, 1990). In the present study, we have reversed the perspective. We used whole-reach retention to examine the effects of solute injection; specifically, the point source input from Columbia Hollow was used to assess S_w in Spavinaw Creek. Despite the reversal of perspectives, the methods for estimating S_w are the same, and S_w was calculated based on the downstream decline in nutrient concentrations. Specifically,

$$C_x = C_o e^{-kx}$$

$$S_w = -\frac{1}{k}$$

where C_x is the nutrient concentration at distance x from injection point, C_o is the nutrient concentration at most upstream site below injection point, x is the downstream distance from injection point, and k is the downstream nutrient change coefficient. Nutrient concentrations below Columbia Hollow were corrected for background (upstream) conditions, then S_w was calculated as the negative inverse slope of the regression line relating the fraction of nutrient remaining in the water column (C_x/C_o) to distance downstream. S_w during baseflow conditions in the impacted study reach in Spavinaw Creek was estimated on three dates in 1998 (13, 27 Aug and 10 Sept) and in 1999 (9, 26 Aug and 9 Sept).

We estimated ambient (control) nutrient retention in Spavinaw Creek by an artificial solute injection in a 400 m study reach above the Columbia Hollow confluence. Five sampling sites were selected within this reach, with the first site approximately 100 m below the injection point. Before injection began, background surface water samples were collected at all five sites. The injection solution was delivered via a peristaltic pump and an apparatus consisting of eight pressure-compensating 15 L h^{-1} emitters. The solution contained NaH_2PO_4 and NaCl, and was dispensed into the stream at a constant rate. The increase, plateau and decrease in conductivity were recorded (YSI Model 30 SCT Meter) with time at the most downstream site. Plateau P and Cl^- concentrations were corrected for background conditions, and Cl^- data were used to correct for dispersion and dilution (e.g., see Martí and Sabater, 1996). Background NO_3-N retention was not measured because previous injections in adjacent tributaries indicated reaches greater in length were needed to estimate S_w (Haggard, unpublished data).

In both study reaches, surface water samples were collected at three points across a transect perpendicular to stream flow at each site. Samples were filtered on site through a 0.5 µm glassfiber filter (Gelman Syringe Filters), acidified to pH 2 using 6N H_2SO_4 and stored on ice. Temperature (YSI Model 30 SCT Meter), conductivity and pH (Oakron pH Tester 2) were measured at a single point on each transect within the impacted reach or at the most downstream site in the control reach. Q was estimated using transect width, depth and velocity measurements in the impacted reach. Stream velocity across the transect was measured using fixed period averaging by an electromagnetic flow meter (Marsh-McBirney, Inc., Flo-Mate Model 2000).

Nutrient loads were estimated above Columbia Hollow, from Columbia Hollow and below Columbia Hollow using mean concentration and calculated Q. Surface and subsurface contributions from Columbia Hollow were determined by observed differences in Q and nutrient loading comparing above Columbia Hollow, from Columbia Hollow and below Columbia Hollow. Subsurface concentrations of the nutrients were estimated from the differences in observed nutrient loading.

Sediment Methods

Benthic sediments were collected upstream and at all 6 sites downstream of Columbia Hollow on 27 Aug 1998 in Spavinaw Creek. Sediments from the top 2-10 cm of the streambed were collected using a trowel. Three composite samples were taken along three transects perpendicular to stream flow in the general vicinity of surface water sampling point at each site (i.e., one composite per transect and three transects per site), stored in plastic bags on ice and kept in the dark until return to the laboratory. Sediments were then sieved (4.5 mm), and the remaining fraction used in laboratory procedures.

Sediment particle size analysis was determined using the hydrometer method and dry sieve analysis (ASTM, 1985). Readily exchangeable or loosely adsorbed P (Ex-P) in the benthic sediments was determined via a modification of the methods of Ruttenburg (1990). Ten - 15 g of wet sediment was saturated with 50 ml of 1 M $MgCl_2$, and shaken at low speed for 1 hour. A 15 ml aliquot was removed, filtered (0.45 µm membrane) and analyzed for SRP. We measured the P Sorption Index (PSI) to measure the P sorption ability or buffering capacity of benthic sediments in Spavinaw Creek (Bache and Williams, 1971; Klotz, 1988). Ten - 15 g of wet sediment were incubated with a solution of 2 mg PO_4-P L^{-1} for 1 hr and were shaken vigorously for 10 s every 15 min. An aliquot was removed and processed as previously described. PSI was calculated as the amount of P adsorbed per unit dry weight of sediment divided by the logarithm of the P concentration in the water. After extraction and sorption procedures, sediments were transferred to a pre-weighed aluminum dish and oven-dried at 80 C for 48 h.

Laboratory Methods

Samples were analyzed for SRP colorimetrically using the molybdate blue method (after Murphy and Riley, 1962). Nitrate-N, NH_4-N and Cl^- were determined colorimetrically using a Lachat QuikChem 9000 automated ion analyzer. NO_3-N was analyzed using cadmium-copper reduction (QuikChem Method 10-107-04-1-A). NH_4-N was determined by alkaline phenol, sodium hypochlorite and nitroprusside reaction (QuikChem Method 10-107-06-1-B). Cl^- was analyzed using mercuric thiocyanate (QuikChem Method 10-117-07-1-C).

Statistical Analysis

Differences among sites were evaluated using a one-way analysis of variance (ANOVA) for appropriately transformed variables (e.g., absolute values - ln transformation, proportions - arcsin square root transformation). Simple linear regression of the natural logarithm of the proportion of the nutrient remaining in dissolved form and distance was used for S_w calculations. Relationships among variables were examined using Pearson correlation coefficients. In all cases, significance was set at $P=0.05$, and marginal significance was reported at $0.05<P<0.10$.

RESULTS

Discharge

Baseflow in Spavinaw Creek was higher in 1999 than 1998 because of an extended spring rainy season (Table 1). Although no precipitation was observed between sampling dates in 1998, one rain event occurred in 1999 on the evening of 26 August, increasing stream stage <0.2 m. In both years, discharge decreased with time and in the downstream direction. Surface input from Columbia Hollow into Spavinaw Creek accounted for only a small fraction (7 - 43%) of the increase in discharge measured below the confluence, thus indicating substantial subsurface input.

Nutrient Concentrations, Loads and Retention

Despite its small size, Columbia Hollow had a pronounced impact on dissolved N and P in Spavinaw Creek, increasing the concentrations of SRP and NO_3-N approximately 8 - 25 fold and 1.1 - 1.4 fold, respectively (Table 1). SRP and NO_3-N in Spavinaw Creek above Columbia Hollow were significantly higher (ln transformed, $p<0.05$) in 1999 than 1998. Columbia Hollow inputs into Spavinaw Creek decreased atomic N:P ratios from >200 above Columbia Hollow to <13 in 1998 and to 24 - 35 in 1999 below Columbia Hollow. N:P ratios increased asymptotically with distance from Columbia Hollow on all dates.

Surface water inputs from Spavinaw Creek and Columbia Hollow were responsible for approximately 16 and 58% of SRP and NO_3-N loads in 1998 and for 44 and 79% of the loads in 1999, respectively. The remaining nutrient loads were probably subsurface contributions from Columbia Hollow. The approximated mean subsurface SRP concentration in Columbia Hollow (1.56 mg L^{-1}) was significantly less than the mean surface concentration in 1998 (ln transformed, $p<0.05$) whereas no significant difference was observed in 1999 (approximated mean subsurface SRP 1.08 mg L^{-1}). The same relationship was observed between surface and subsurface NO_3-N concentrations with approximated mean subsurface NO_3-N concentration of 4.25 and 4.60 mg L^{-1} in 1998 and 1999, respectively. Although surface SRP concentrations were significantly different between years in Columbia Hollow (ln transformed, $P<0.05$), estimated subsurface concentrations were not significantly different between years. A similar relation for NO_3-N was observed.

NO_3-N and SRP concentrations in Spavinaw Creek decreased exponentially with distance from Columbia Hollow in 1998 and 1999 (Figure 2). Mean S_w for SRP (S_w-SRP) was 9.6 and 23 km and mean S_w-NO_3-N was 11 and 7.8 km in the summers of 1998 and 1999, respectively (Table 1). S_w-SRP increased exponentially ($r=0.96$, $p<0.05$) as discharge increased (Figure 3), but decreased exponentially ($r=0.97$, $p<0.05$) with the change in concentration (ΔSRP, i.e., Spavinaw Creek below Columbia Hollow minus Spavinaw Creek above Columbia Hollow) in Spavinaw Creek (Figure 4). When normalized for variation in Q, S_w/Q-SRP was relatively constant, regardless of ΔSRP. Interestingly, S_w-NO_3-N decreased with increasing flow and asymptotically increased with increasing ΔNO_3-N (Figures 3 and 4). However, S_w/Q-NO_3-N increased significantly ($r=0.98$, $p<0.05$) as ΔNO_3-N increased (Figure 5).

In the Spavinaw Creek control reach above Columbia Hollow, SRP was ca. 0.030 mg L^{-1} before the injection began at all sampling sites. SRP concentration increased by 0.018 mg L^{-1} 100 m below the injection point, and approximately 63% of injected SRP remained in the water column at the most downstream sampling site. Control S_w-SRP was approximately 0.75 km.

Benthic Sediments

Phosphorus buffering capacity, as PSI, of the benthic sediments in Spavinaw Creek above Columbia Hollow was significantly greater than immediately below Columbia Hollow ($p<0.05$, Table 2). PSI increased with log-distance below the confluence ($r=0.82$, $p<0.05$), and no significant difference in PSI was observed between Spavinaw Creek sediments above Columbia Hollow and greater than 0.5 km below Columbia Hollow. Ex-P in Spavinaw Creek was significantly higher below Columbia Hollow compared to above ($p<0.05$). No gradient was observed in Ex-P with distance downstream. The amount of SRP present in one g of sediment relative to the amount present in one g of water (ratio of P distribution between sediment and water phases after Triska et al., 1994) was ca. 21 for Spavinaw Creek above Columbia Hollow and ranged from 1.9 - 3.0 in the study reach below the confluence. The ratio increased log-linearly downstream ($r=0.99$, $p<0.05$), disregarding the site 2.5 km from the Columbia Hollow. Particle size distribution in the benthic sediments was variable, with no evident downstream trend, but the fraction of clay and silt was less than 0.11 at all sites and averaged 0.04 (Table 2). The finer fractions of the sediment were not significantly correlated with PSI or exchangeable P.

DISCUSSION

Nutrient retention in streams is influenced by landscape processes (Meyer et al., 1988) and within-stream variation in channel forms and habitat (Aumen et al. 1990; D'Angelo and Webster 1991; Martí and Sabater 1996; Munn and Meyer 1990). Undoubtedly, differences between the control and impacted study reaches exist; however, the most prominent difference is from an anthropogenic nutrient source, the Decatur WWTP. Although the WWTP conduit (Columbia Hollow) is a highly agricultural catchment and potentially impacted by diffuse sources, the Decatur WWTP is the greatest nutrient contributing source under baseflow conditions. The $Q_{7/10}$ for Columbia Hollow at the WWTP outfall is 0 L s^{-1} (ADPCE, 1985). SRP and NO_3-N concentrations within 4 km of the WWTP exceeded 6 and 10 mg L^{-1} in Columbia Hollow, respectively, during the summer of 1997 (Hunt, 1999), which is reflective of extreme nutrient enrichment and WWTP effluent dominance in Columbia Hollow. Furthermore, Columbia Hollow input significantly increased nutrient concentrations in Spavinaw Creek in this study.

With respect to water input, most of the nutrients entering Spavinaw Creek from Columbia Hollow were delivered via surface, rather than subsurface discharge. The fraction of the nutrient load from subsurface flow was less than the fraction of water contributed and mean subsurface nutrient concentrations were less than surface water in Columbia Hollow, suggesting the hyporheic zone may be an important site of nutrient retention. In fact, several investigators have demonstrated that hyporheic zones are important sites of nutrient uptake and retention in stream ecosystems (e.g., Mulholland et al., 1997; Triska et al., 1989).

Not only did nutrient concentrations increase in the water column and sediments below Columbia Hollow, but Spavinaw Creek virtually has no ability to retain these added nutrients. S_w-SRP (23 km, 26 August 1999) in the impacted reach was over 30 times longer than S_w-SRP in the reach above Columbia Hollow in Spavinaw Creek (0.75 km). Nutrient retention in Spavinaw Creek below

Columbia Hollow is also 1-2 orders of magnitude less than un- or less impacted streams (see Table 7 in Martí and Sabater, 1996). Further, mean S_w-SRP below Columbia Hollow was 17 km, over twice as long as summertime uptake length measured below a PS in the River Way, UK (Haggard et al., In review) and even greater than the upper end of the range (0.14 - 14 km) reported by Martí et al. (1999) for WWTP-impacted streams in Spain.

Nutrient retention is influenced by several factors. Q and velocity have previously been reported to affect S_w in artificial and natural streams (D'Angelo et al., 1991; D'Angelo and Webster, 1991; Martí and Sabater, 1996; Valett et al., 1996). In this highly impacted system, a similar relation was observed with S_w-SRP but not for S_w-NO_3-N. P retention likely increases at lower discharge because exchange across the sediment-water interface increases (Bencala, 1983), which in turn increases the potential for abiotic or biotic uptake. S_w-SRP normalized for variations in Q was not related to the level of SRP addition as previously reported (Mulholland et al., 1990; Hart et al., 1992), but flow normalized S_w-NO_3-N did increase with increasing NO_3-N enrichment. In short, whole-reach P retention was regulated by hydrological factors, i.e. flow, whereas NO_3-N retention was regulated by flow and the level of enrichment and biotic uptake or transformation in Spavinaw Creek. NO_3-N, unlike P, is not retained through sediment (abiotic) adsorption, and the major retentive processes are biotic which are typically saturated at concentrations greater than 0.1 mg L-1 in Ozark streams (Lohman et al., 1991). Although low N:P ratios suggests N limitation of biota below Columbia Hollow, the amount of N in the water column is several orders of magnitude greater than reported limiting NO_3-N concentrations (Grimm and Fisher, 1986; Lohman et al., 1991).

Several processes can remove nutrients from the water column in streams, including biotic uptake (Meyer, 1979; Lock et al., 1990), movement of water through transient storage zones (Valett et al., 1996), denitrification (Duff and Triska, 1990) and abiotic sorption by sediments (Klotz, 1988; Triska et al., 1994). Several studies have demonstrated sediment regulation of water column P (Haggard et al., 1999; Klotz, 1988; Meyer, 1979). In Spavinaw Creek below Columbia Hollow, sediment P storage (Ex-P) increased, whereas potential buffering capacity decreased within 0.5 km downstream of Columbia Hollow. These observations are similar to other studies in WWTP impacted streams (House and Denison, 1998; Dorioz et al., 1998) and support the hypothesis that benthic sediment adsorption is an important contributor to P removal in highly impacted ecosystems. However, while sediment adsorption may attenuate some of the P load from the WWTP, these abiotic (and biotic) processes are clearly not significant buffers of P fluxes given S_w in the km range.

Although S_w is influenced by stream morphology and discharge (D'Angelo and Webster, 1991; Martí and Sabater, 1996; Munn and Meyer, 1990), the 3.5 km reach in Spavinaw Creek below Columbia Hollow includes a wide variety of channel forms, riparian zones and other anthropogenic influences. Consequently, our measurement of mean S_w is an accurate assessment of average nutrient retention and can be used to estimate the proportion of nutrients from Columbia Hollow (essentially Decatur WWTP) reaching the headwaters of Lake Eucha during baseflow. In one S_w, 63% of the solute is removed from the water column. Using the S_w range for each constituent, we estimate 0.1 - 17% of NO_3-N and 9 - 50% of SRP additions from Columbia Hollow reach the headwaters of Lake Eucha 22 km downstream without being subjected to any retention processes in Spavinaw Creek under baseflow conditions. Interestingly, under high summer baseflow the greatest fraction of SRP (50%) is reaching the reservoir but the lowest fraction of NO_3-N (0.1%). It should be noted that one important limitation of using S_w is that no temporal dimension with regard to nutrient release or regeneration is integrated (Maltchik et al., 1994). Therefore, removal of dissolved nutrients from the PS in Spavinaw Creek provides a temporary buffer, and essentially all P inputs from Columbia Hollow eventually reach Lake Eucha.

CONCLUSIONS

No single factor is responsible for nutrient retention in lotic ecosystems; instead, this process is governed by complex interactions of abiotic and biotic processes (D'Angelo et al., 1991). Nonetheless, discharge and the level of nutrient enrichment dominated SRP and NO_3-N retention efficiency, respectively, in this system. However, this assessment is limited to one period in the annual cycle, and other watershed, riparian or in-stream processes may exert a greater control over nutrient retention over time. Perhaps the most important finding in this study is the pronounced impact that Columbia Hollow has on P retention in Spavinaw Creek. P retention efficiency in Spavinaw Creek was reduced by a factor of 30 below Columbia Hollow, and S_w was in the km range. Our results are similar to observations in other WWTP impacted streams (Haggard et al., In review; Martí et al., 1999). It appears that km scale S_w are the norm below WWTPs and that it may be premature to minimize attention given to nutrients from PS inputs. The impact of PS inputs reduces the stream's ability to withstand and recover from other anthropogenic disturbances such as diffuse pollution; therefore, watershed management should consider PS influences on stream nutrient retention.

Table 1. Discharge, surface water nutrient concentrations, S_w and S_w/Q in Spavinaw Creek and Columbia Hollow. CH denotes Columbia Hollow. Above denotes measurements in Spavinaw Creek at a site above or upstream of Columbia Hollow. Below denotes measurements in Spavinaw Creek at a site below or downstream of Columbia Hollow.

Date	Q (L s^{-1})			SRP (mg L^{-1})			NO_3-N (mg L^{-1})			S_w (km)		S_w/Q (m·s L^{-1})	
Summer 98	Above	CH	Below	Above	CH	Below	Above	CH	Below	SRP	NO_3-N	SRP	NO_3-N
10 Aug	480	14	680	0.022	2.54	0.449	2.15	5.64	2.76	10	12	15	18
27 Aug	380	12	500	0.021	2.60	0.501	2.04	5.94	2.75	9.4	11	19	23
10 Sept	270	11	420	0.021	2.67	0.531	1.97	5.56	2.65	9.0	9.6	22	23
Summer 99	Above	CH	Below	Above	CH	Below	Above	CH	Below	SRP	NO_3-N	SRP	NO_3-N
9 Aug	1110	86	1310	0.031	1.39	0.239	3.57	5.37	3.80	31	3.1	24	2.4
26 Aug	640	50	970	0.025	1.82	0.291	3.41	5.61	3.77	23	11	24	11
9 Sept	790	68	1010	0.028	1.75	0.321	3.16	5.14	3.52	17	9.4	17	9.3

Table 2. Benthic sediment particle size, exchangeable P, PSI, sediment/water distribution of P ratio, and water column SRP in Spavinaw Creek on 27 August 1998.

Site	Particle Size (%)				Ex-P	PSI	SRP	Ratio
	Gravel*	Sand#	Silt†	Clay‡	μg g^{-1}	log(C)·X^{-1}	mg L^{-1}	
Above	78	20	0.9	0.4	0.44	1.83	0.02	21
CH	84	15	0.8	0.8	2.34	1.39	2.60	0.9
0.2 km$	72	26	1.3	0.4	1.11	1.53	0.50	2.2
0.4 km	30	59	8.0	2.9	1.20	1.69	0.46	2.6
0.8 km	66	25	7.6	1.4	1.20	1.92	0.43	2.8
1.1 km	60	36	3.5	0.7	1.19	1.70	0.40	3.0
2.5 km	82	17	1.1	0.2	0.69	1.98	0.37	1.9
3.5 km	77	21	1.6	0.5	1.21	1.89	0.34	3.5

Ratio = distribution of P between sediments and water column, Above = upstream or background conditions, CH = Columbia Hollow, $ = downstream distance from Spavinaw Creek and Columbia Hollow confluence, * = particles between 2 - 4.5 mm, # = particles between 0.05 - 2 mm, † = particles between 0.002 - 0.05 mm, ‡ = particles < 0.002 mm from USDA Classification system.

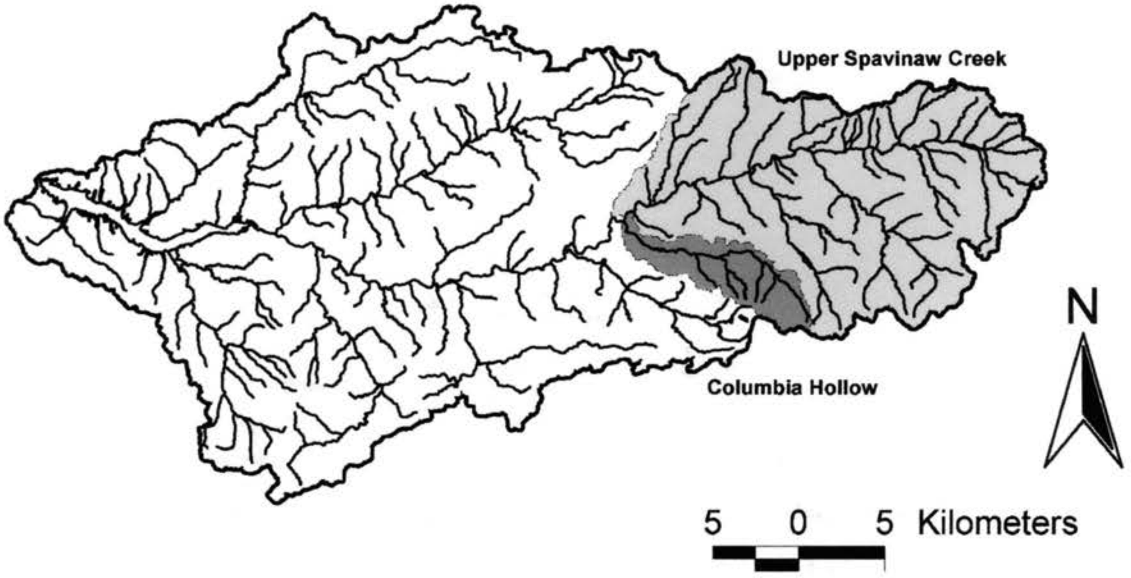

Figure 1. General map of study reaches in Spavinaw Creek located in the Ozark Plateau of northwestern Arkansas.

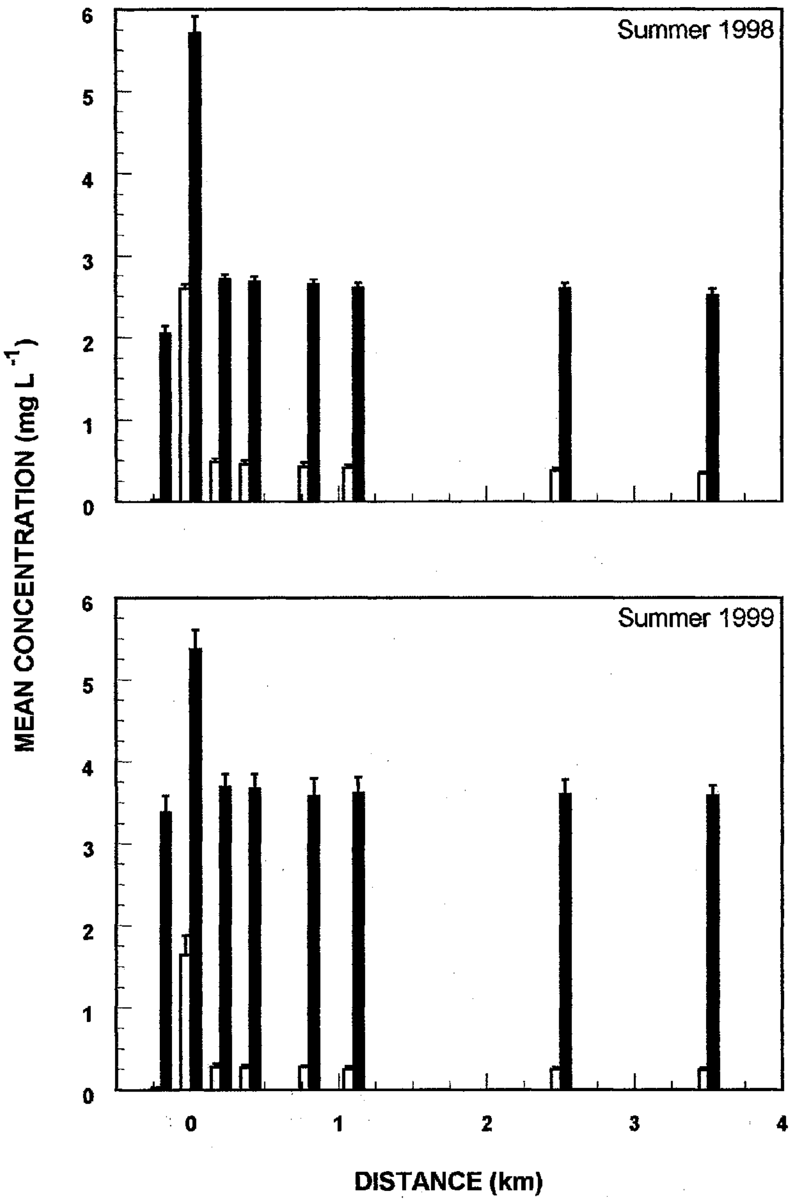

Figure 2. Mean and standard deviation of NO_3-N and SRP concentrations in the water column in Spavinaw Creek during summer 1998 and 1999. Distance less than zero is Spavinaw Creek above Columbia Hollow, zero distance is Columbia Hollow, and distances greater than zero are Spavinaw Creek below Columbia Hollow (■ = NO_3-N and □ = SRP).

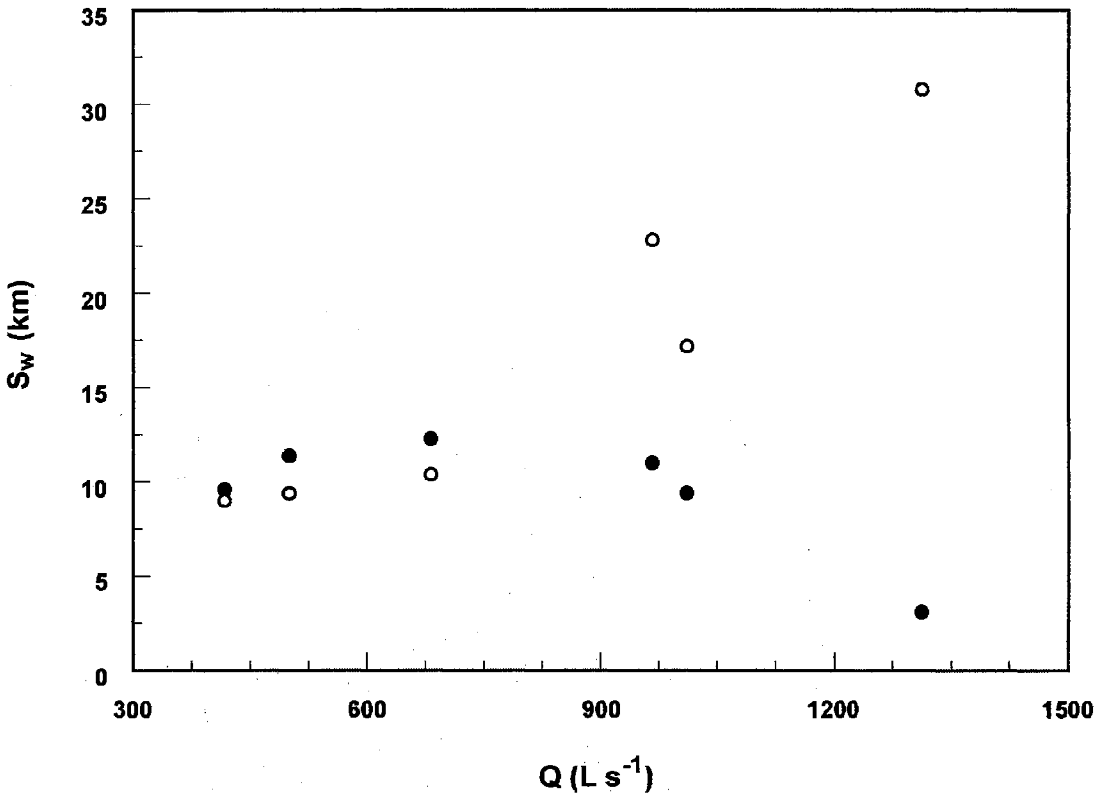

Figure 3. Nutrient uptake length (S_w) as a function of discharge (Q) in Spavinaw Creek below Columbia Hollow confluence (● = NO_3-N and ○ = SRP).

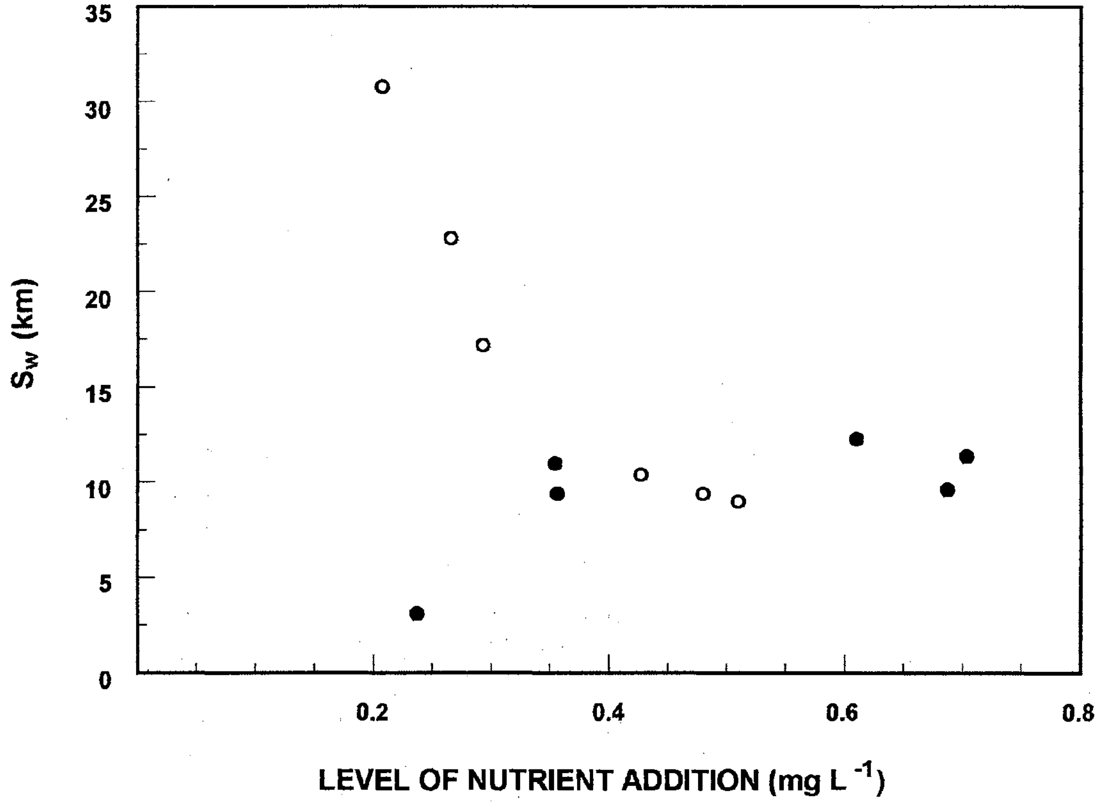

Figure 4. Nutrient uptake length (S_w) as a function of the level of nutrient addition in Spavinaw Creek from Columbia Hollow (● = NO_3-N and ○ = SRP).

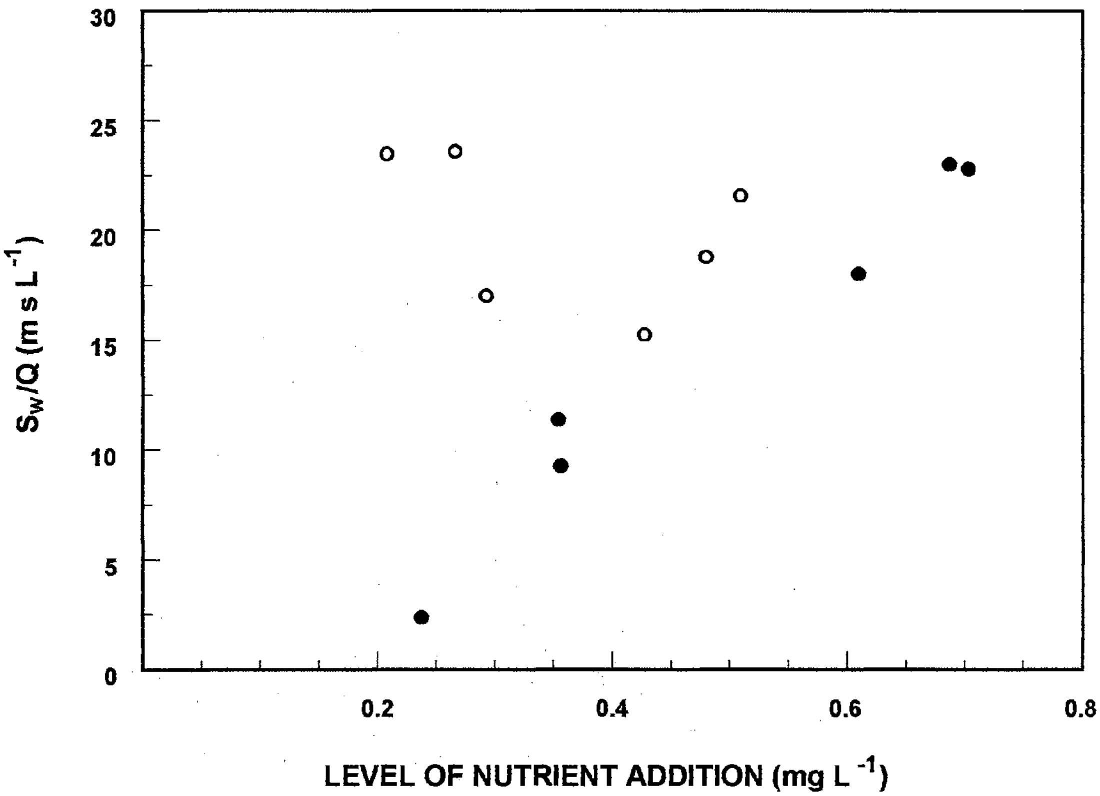

Figure 5. Flow normalized nutrient uptake length (S_w/Q) as a function of the level of nutrient addition in Spavinaw Creek from Columbia Hollow (● = NO_3-N and ○ = SRP).

CHAPTER IV

VARIATION IN STREAM NUTRIENT RETENTION BELOW A POINT SOURCE

ABSTRACT: Nutrient retention was examined in a point source (PS) impacted stream in the Ozark Plateau in Oklahoma. Usually, solute injections have been used to assess uptake lengths (S_w), but we used the PS as the solute injection source and examined S_w as a result of the PS input. S_w was estimated for NH_4-N, NO_3-N, DIN and SRP in a 3 km reach below the PS. No temporal pattern was evident in S_w-SRP whereas S_w-NH_4-N was typically shorter in summer and autumn compared to winter. On all dates, NO_3-N concentration increased with distance from the PS source (negative S_w-NO_3-N via nitrification). S_w-DIN varied widely (negative to positive) depending upon use of both DIN species by stream biota. Normalizing for variations in discharge, this system was most retentive of SRP and NH_4-N during summer whereas the longest (or negative) S_w were observed in winter. SRP and NH_4-N retention decreased with increasing additions from the PS source; thus, variation in stream discharge regime and PS inputs can impact nutrient transport from this stream to downstream aquatic ecosystems. Fluctuation in seasonal patterns of nutrient retention should be considered in water quality management because these processes can influence the timing, magnitude and form of nutrients transported (Meyer et al., 1988) from the PS.

(**KEYS WORDS:** phosphorus, nitrogen, retention, point source, aquatic ecology)

INTRODUCTION

In the last twenty years, environmental and water quality issues have focused on diffuse sources of pollution, especially confined animal operations and land application of animal wastes (e.g., see Carpenter et al., 1998; Scott et al., 1998). The potential for localized non-point source (NPS) pollution impact is escalating as agricultural land use in catchments increases and agricultural practices become more intensive and centralized. However, despite the nationwide reduction of point source (PS) pollution following the Clean Water Act of 1972, PS pollution remains a risk to the quality of our nation's and the world's water supplies.

In particular, the impact of waste water treatment plant (WWTP) effluent on stream nutrient retention can be profound; nutrient uptake lengths (S_w *sensu* Newbold et al., 1981) below PS inputs are in the km scale (e.g., see Haggard et al. In review; Martí et al., 1999), several orders of magnitude greater than less disturbed systems. In northeastern Oklahoma, stream nutrient retention efficiency was reduced 30 fold by PS inputs into Spavinaw Creek, even after approximately 9 km of natural (in-stream) treatment in a 3rd order tributary (Haggard et al., In preparation), the focus of the present study. PS impacts in this basin are of particular importance because Spavinaw Creek is a primary tributary to Lake Eucha, Oklahoma, which serves as a municipal water supply for the City of Tulsa, Oklahoma, and several other smaller communities. Water treatment chemical costs and taste and odor problems have increased in the past few years (personal communication, City of Tulsa), and PS inputs have been identified as a major nutrient contributor to Spavinaw Creek and to Lake Eucha (OCC, 1997).

Nutrient retention, measured by S_w, can be utilized to determine the impact of disturbances on stream ecosystems (Meyer et al., 1988). Traditionally, short-term nutrient additions have been used to assess S_w, but we reversed the perspective and used S_w to assess PS inputs in a small 3rd order stream; the PS served as the mechanism of solute injection. Using S_w, we assessed the impact of PS inputs and hydrologic conditions on seasonal patterns of nutrient retention.

MATERIALS AND METHODS

Study Site Description

The PS-impacted stream, Columbia Hollow, is in northwest Arkansas (Figure 6), and the WWTP discharge with secondary treatment originates from the City of Decatur, Arkansas. The facility receives wastewater from the city with a population of approximately 1000 and a major poultry processing and rendering plant. Mean discharge from the WWTP was 1.3 MGD between November 1997 to 1999 (City of Tulsa), and effluent has limits on discharge of carbonaceous biochemical oxygen demand (CBOD), NH_4-N and NO_3-N of 10, 15 and 10 mg L^{-1}, respectively. No regulations currently exist for P (ADPCE, 1985, 1997) but average P concentrations in the effluent are approximately 7 mg L^{-1} (City of Tulsa). The effluent of the WWTP discharges into Columbia Hollow, a 3rd order tributary to Spavinaw Creek (stream order determined using 1:24,000 United States Geological Survey topography maps and includes perennial and intermittent streams).

The Columbia Hollow watershed is ca. 18 km^2 (above the most downstream sampling site) and land use is predominately agriculture (73% pasture) consisting of poultry, swine and cattle operations with land application of animal waste to pastures. The portion of the sub-watershed above the WWTP outfall is dominated by urban-suburban land use (only 4% of study watershed). Columbia Hollow is a typical Ozark Mountain stream with chert gravel bottoms and karst topography in the upland areas. During summer drought conditions, stream surface flow may be entirely composed of WWTP effluent in the upper reaches because the reported $Q_{7/10}$ is 0 m^3 s^{-1} (ADPCE 1985). Columbia Hollow is a 2nd and 3rd order stream throughout the ~3 km study reach selected above and below the WWTP. The most upstream sampling site below the WWTP was approximately 0.3 km from the point of discharge. The most downstream station was 2.7 km, and 4 additional sites were chosen in between these two sampling stations. A seventh site was selected sufficiently upstream of WWTP effluent and served as an estimate of background physicochemical and nutrient conditions. Approximately 0.8 km downstream from the WWTP substantial groundwater input was observed. In addition, a 2nd order tributary inflow occurs 2.2 km downstream where Columbia Hollow becomes 3rd order.

Nutrient Uptake Length Calculations

The theory behind S_w calculations is the decline in solute concentration in the water column is proportional to the uptake by the stream benthos; thus S_w is reflective of the utilization of nutrients with regard to nutrient supply, i.e. an index of stream nutrient retention efficiency (Newbold 1992). In the present study, we are using S_w to assess the impact of nutrient inputs from the Decatur WWTP on nutrient retention in Columbia Hollow, specifically soluble reactive P (SRP), NH_4-N, NO_3-N and dissolved inorganic N (DIN = NH_4-N + NO_3-N). S_w is calculated as the inverse slope of the regression line relating distance and the natural logarithm of the proportion of nutrient concentration remaining in the water (e.g., see Stream Solute Workshop, 1990; Webster and Ehrman, 1996). In order to assess the retention of nutrient inputs from the Decatur WWTP in Columbia Hollow, nutrient concentrations were corrected for background conditions (i.e., upstream site) and Cl^- inputs from the PS were used to correct for downstream dilution from ground water and lateral inputs. In this study, background correction does not allow calculation of S_w if upstream nutrient concentrations are greater than the concentrations immediately below the WWTP. In fact, in Columbia Hollow NO_3-N concentrations upstream of the WWTP outfall were greater than NO_3-N concentrations below the WWTP discharge on some occasions.

Positive S_w denotes net nutrient retention in the reach; shorter S_w suggest greater nutrient retention efficiency than longer S_w (Newbold et al., 1981). However, negative S_w suggest net export from the reach. The lower the absolute value of negative S_w indicates greater export. Statistically insignificant linear regressions between normalized concentration and downstream distance suggest no net retention or export within the reach, i.e. the slope is not significantly different from zero.

Field Procedures

Columbia Hollow was sampled approximately monthly from June 1999 to February 2000. Surface water samples were collected at three points across a transect perpendicular to stream flow at each site. Water samples were filtered on site (0.7 µm glassfiber filter, Whatman GF/F), and acidified ($pH \leq 2$ H_2SO_4) for preservation. Samples were put on ice, stored in the dark until return to the laboratory, and analyzed with 48 hrs. Electrical conductivity (YSI Model 30 SCT Meter), temperature, and pH (Oakron pH Tester 2) was measured at a single point at each sampling site. Discharge (Q) calculations were made using width, depth and velocity. Velocity was measured using an electromagnetic flow meter (Flo-Mate 2000, Marsh-McBirney, Inc., Frederick, MD).

Laboratory Procedures

Upon return to the laboratory samples, nutrient and tracer analysis were conducted on a Latchet QuikChem 9000 (Milwaukee, WI). Samples were analyzed for soluble reactive P (SRP) colorimetrically using the molybdate and ascorbic acid method (QuikChem Method 10-115-01-1A). Nitrate-N was analyzed using cadmium-copper reduction (QuikChem Method 10-107-04-1-A). Ammonia-N was determined by the alkaline phenol, sodium hypochlorite and nitroprusside reaction (QuikChem Method 10-107-06-1-B). Chloride was analyzed using mercuric thiocyanate (QuikChem Method 10-117-07-1-C).

RESULTS

Stream Flow and Water Chemistry

Stream flow decreased with time (June to February) on our selected sampling dates (Table 3). We estimated that the WWTP discharge was responsible for between 17 and 83% of the surface flow during this study; the lowest percentage occurred during the highest stream flows. Stream discharge increased on all dates from the sampling site immediately below the WWTP to the most downstream station because of groundwater or lateral inputs.

SRP and NH_4-N concentrations were significantly higher below the WWTP than above on all sampling dates (T-test on ln transformed data, $P<0.01$). However, NO_3-N concentrations below the WWTP were not consistently above or below background NO_3-N concentrations (Table 4); on individual sampling dates NO_3-N concentrations below the WWTP were significantly higher and lower, and even similar (T-test on ln transformed data, $P<0.01$). DIN concentrations were significantly higher below the WWTP (T-test ln transformed data, $P < 0.01$) except in July when DIN concentrations were similar ($P=0.061$). pH significantly decreased below the WWTP (Two-Factor ANOVA, $P<0.01$) whereas temperature and conductivity significantly increased (Two-Factor ANOVA, $P<0.001$) (Table 4).

Nutrient Uptake Length and Rate

P retention, expressed as S_w-SRP, was variable between sampling dates but similar in summer and fall, whereas in winter S_w-SRP was negative in December and January (Figure 7). When S_w was normalized by flow (S_w/Q), P retention was highest in the summer (Figure 8). Disregarding the negative values, a positive correlation was observed between S_w-SRP and Q ($R=0.82$, $P<0.05$); however, the significance of the relationship disappeared when a single outlier with high Q was excluded from analysis. Neglecting the negative values, S_w/Q-SRP increased exponentially with the level of P enrichment (ΔSRP, i.e. above WWTP minus immediately below WWTP) ($R=0.88$, $P<0.05$) (Figure 9). ΔSRP decreased exponentially with increasing stream flow ($R=0.84$, $P<0.05$); ΔSRP was highest when the percent of surface flow attributable to WWTP effluent was lowest.

NO_3-N concentrations were similar above and below the PS input but concentrations increased with distance downstream; however, background (above PS) concentrations permitted calculation of S_w on only four sampling dates and all four were negative. NO_3-N concentrations above the PS inputs were lowest in the fall whereas below PS inputs no temporal trend was observed. Increases in NO_3-N concentrations coincided with proportional decreases in NH_4-N when S_w-DIN regressions were insignificant. On some occasions NO_3-N increases were greater than NH_4-N losses resulting in negative S_w-DIN and vice versa. However, nitrification alone may not be responsible for downstream increases in NO_3-N concentrations because groundwater inputs 0.8 km from the PS input usually had higher NO_3-N concentrations than stream surface water. DIN retention (as S_w-DIN) was highly variable between and within seasons. S_w-DIN was shortest in winter whereas S_w/Q-DIN was shortest in summer but in this season the greatest production of DIN, as NO_3-N, also occurred on 11 August 1999 (Figures 7 and 8).

S_w-NH_4-N was similar in the summer and fall and longest during winter (Figure 7). However, S_w/Q-NH_4-N suggested retention was higher in the summer compared to fall (Figure 8). S_w-NH_4-N and S_w/Q-NH_4-N displayed only a marginal positive correlation with ΔNH_4-N (R=0.67, P=0.07 and R=0.69, P=0.06, repectively) (Figure 10) but was positively correlated with NH_4-N concentrations measured 2.7 km below the WWTP (R=0.92, P<0.01). NH_4-N concentrations 2.7 km below the WWTP also increased exponentially with the level of addition (ΔNH_4-N) from the WWTP (R=0.92, P<0.01).

DISCUSSION

Phosphorus Retention

The sheer magnitude of S_w-SRP in this study is not surprising given that previous investigations have shown S_w-SRP in the km scale below WWTP (e.g., see Haggard et al., In Review; Martí et al. 1999). Although S_w-SRP did not demonstrate a temporal trend, S_w/Q-SRP was shortest in the summer and longest in the winter in Columbia Hollow. A similar observation was made in a

PS-impacted stream in the U.K. in which P retention was highest in summer and negligible in winter (Haggard et al., In Review), although this investigation was limited to a single sampling date in each season. The shortest S_w-SRP in Columbia Hollow coincided with periods of high temperature and biotic productivity, i.e. summer. This observation agrees with previous investigations in low-impacted systems (e.g., see Martí and Sabater, 1996; Webster et al. 1991) whereas other studies have observed the shortest S_w-SRP in the fall (Mulholland et al., 1985, 1990). Therefore, streams may have the ability to buffer increasing P loads from PSs in the summer more efficiently.

Regardless of the season, P uptake in streams is via a combination of abiotic and biotic processes. House and Denison (1997, 1998) observed that abiotic (sediment) uptake was not sufficient to account for total P loss from the water column below a PS. Therefore, seasonal fluctuations in aquatic biota in PS impacted streams can influence nutrient uptake and transport. For example, the periphytic matrix or biofilm in streams is composed of autotrophic and heterotrophic organisms and can uptake P from the water column (Lock et al., 1990). This biofilm is typically most productive during the summer season. Furthermore, in autumn heterotrophic microbes associated with leaf litter and other organic matter are responsible for significant phosphorus retention in headwater streams (Elwood et al., 1981; Mullholland et al., 1985). Therefore, seasonal fluctuations in biotic uptake and production can substantially influence P retention below a WWTP and subsequent transport to downstream aquatic ecosystems.

Hydrologic discharge regime and seasonal variability can also influence P retention. Several investigators have observed that the shortest S_w occurs during the lowest flow (Martí and Sabater, 1996; Mullholland et al., 1985, 1990) and a positive correlation between P uptake and average velocity or discharge has been shown (D'Angelo and Webster, 1991; D'Angelo et al., 1991). In contrast, S_w-SRP was similar during high and low flows in Columbia Hollow. In fact, when normalizing S_w for variations in Q, P retention was highest during summer compared to fall. S_w-SRP increased with increasing discharge from the PS, and although S_w-SRP was not significantly related to Q in this study, combining our results with data from Spavinaw Creek (Chapter III) produced a exponential increase in S_w-SRP with Q ($R=0.83$, $P<0.05$) (Figure 11). Thus, on a larger scale nutrient retention below a WWTP is reduced during periods of elevated baseflow.

The level of phosphorus enrichment (ΔSRP) can also influence S_w-SRP. Several investigations have shown an increase in S_w-SRP associated with increasing ΔSRP (see Mulholland et al., 1990; Hart et al., 1992). In Columbia Hollow, S_w/Q-SRP increased with increasing phosphorus additions from the PS (i.e., ΔSRP), neglecting negative S_w estimations. In fact, inclusion of data from Spavinaw Creek (Chapter III) produced a very similar exponential increase in S_w/Q-SRP with ΔSRP ($R=0.97$, $P<0.05$) (Figure 9). This evidence suggests that increasing levels of P additions from the PS (Decatur WWTP) significantly reduces the retention efficiency of the receiving streams. Furthermore, in Spavinaw Creek S_w-SRP was 30 times longer below Columbia Hollow compared to above Columbia Hollow demonstrating the magnitude of effect of PS pollution during summer baseflow (Chapter III). The level of P addition from the PS decreased exponentially with increasing stream flow which possibly explains the lack of seasonal variation or significant relationship between S_w-SRP and ΔSRP.

Negative S_w-SRP occurred during low flow and reduced biotic activity (i.e., winter) and also during minimal input from the PS. Minimum input of SRP, i.e. ΔSRP, should result in increased P retention, but a negative S_w-SRP was observed. During these sampling dates, benthic substrates were black suggesting Mn reduction in the hyporheic zone or groundwater and subsequent oxidation at the sediment-water interface. Reduction of Fe and Mn oxides can result in a release of P (Moore and Reddy, 1994) and possibly increased P concentration in hyporheic zone but oxidation of reduced Mn at the sediment-water interface can result in increased adsorption and co-precipitation.

SRP concentrations were approximately 1.83 and 2.03 mg L^{-1} on 22 December 1999 and 28 January 2000, respectively, throughout the downstream 2 km of the study reach. The stabilization of SRP concentrations suggests that water column P concentrations were possibly regulated by the sediment P buffer mechanism (see Froelich, 1988). In fact, Popova (2000) observed sediment regulation of SRP concentrations among streams within the Lake Eucha Basin. Therefore, benthic sediments in Columbia Hollow may release P and maintain elevated SRP concentrations even when WWTP inputs of P are minimal.

Nitrogen Retention

Nitrification of reduced N additions have been observed in long-term additions in low-impacted streams (Richey et al., 1985) and in PS impacted systems (Martí et al., 1999). In this study, nitrification of reduced N forms in the PS inputs were not solely responsible for the downstream increases in NO_3-N concentration. Ground water NO_3-N concentrations approximately 0.8 km below the PS were usually greater than that measured immediately upstream in Columbia Hollow and always greater than NO_3-N concentrations observed above the PS (data not shown). Discharge increased from 0.3 km below the PS to the most downstream sampling site within our study reach suggesting substantial ground water input since lateral inputs were minimal.

It appears that the WWTP did not substantially increase NO_3-N concentrations immediately below its discharge except on two occasions (October and January) when NO_3-N concentrations increased 5-6 mg L^{-1}. On these dates and in December, nitrification of reduced N from the PS and ground water inputs produced NO_3-N concentrations exceeding 10 mg L^{-1} at the most downstream sampling site. Furthermore, on all sampling dates NO_3-N concentrations exceeded 6 mg L^{-1} 2.7 km from the PS.

For the dissolved nutrients examined, S_w was shortest for NH_4-N suggesting this reach was most efficient in retaining NH_4-N. S_w-NH_4-N in this study were generally longer than the lengths reported in other studies for low-impacted systems (Martí and Sabater, 1996; Munn and Meyer, 1990), although the difference was not as profound as observed with S_w-SRP. However, the above discussions have shown that a bio-transformation reaction may result in the loss of most of the NH_4-N from the water column. Thus, NH_4-N and NO_3-N retention are not independent in aquatic systems, and possibly S_w-DIN should be used to describe the retention efficiency of inorganic N below PS.

Furthermore, S_w-NH_4-N increased with increasing ΔNH_4-N; thus, additions from the PS significantly reduced NH_4-N retention which can affect NO_3-N levels in the downstream portion of Columbia Hollow and Spavinaw Creek. In Columbia Hollow, increases in NH_4-N can result in increased production of NO_3-N and increased NO_3-N loading to Spavinaw Creek where NO_3-N retention significantly decreased with increasing NO_3-N addition from Columbia Hollow (Chapter III).

CONCLUSIONS

Stream nutrient retention is governed by a myriad of processes including water velocity and discharge (D'Angelo et al., 1991; D'Angelo and Webster, 1991), transient storage and lithology (Munn and Meyer, 1990; Valett et al., 1996), sediment sorption and desorption (Klotz, 1991; Haggard et al. 1999), precipitation and dissolution (House and Denison, 1997), biotic uptake (Lock et al., 1990, Mulholland et al., 1985), and bio-transformation (Richey et al. 1985).

In Columbia Hollow and Spavinaw Creek (the receiving stream), nutrient retention is apparently regulated by variations in discharge and the level of nutrient addition from the WWTP. Although NO_3-N additions from the PS were typically small, nitrification of reduced N forms and groundwater inputs increased NO_3-N concentrations downstream from the PS in Columbia Hollow. Furthermore, the level of NO_3-N additions from Columbia Hollow (essentially Decatur WWTP) were significantly correlated to flow normalized S_w-NO_3-N in Spavinaw Creek (Chapter III).

Nutrient retention in lotic ecosystems is an important aspect in watershed water quality management of PS pollution because variation in retention alters the timing, magnitude and form of nutrient transport to downstream aquatic ecosystems (Meyer et al. 1988), i.e. in this study Lake Eucha. This investigation shows the impact that the Decatur WWTP has on stream nutrient retention; furthermore, km-scale S_w have been observed worldwide in PS-impacted streams (e.g. see Haggard et al., In review; Martí et al., 1999). In this watershed PS source inputs reduce nutrient retention substantially, and a portion of the nutrient inputs travels ~32 km through the water column of Columbia Hollow and then Spavinaw Creek without being temporarily retained by in-stream processes. This reduction in nutrient retention depletes the ability of Columbia Hollow and Spavinaw Creek to recover and withstand other perturbations.

Table 3. Discharge in Columbia Hollow above the wastewater treatment plant and 0.3 and 2.7 km downstream from its effluent release.

	Discharge ($L\ s^{-1}$)			
Date	above†	0.3 km‡	2.7 km	WWTP#
17 June 1999	162	215	242	53
23 July 1999	85	103	226	18
11 August 1999	47	67	114	20
21 October 1999	15	88	108	73
11 November 1999	20	46	80	27
22 December 1999	27	54	121	27
28 January 2000	14	59	83	45
29 February 2000	14	26	45	12

† denotes above wastewater treatment plant discharge, ‡ denotes distance downstream of point of discharge from wastewater treatment plant, # denotes estimated discharge from wastewater treatment plant, i.e. above minus 0.3 km below.

Table 4. Mean and standard deviation of physicochemical properties in Columbia Hollow above and below the Decatur wastewater treatment plant discharge from June 1999 to February 2000.

Site (km)	pH	Temp (°C)	Cond (μS cm^{-1})	SRP (mg L^{-1})	NO_3-N (mg L^{-1})	NH_4-N (mg L^{-1})
above†	8.6 (0.6)	16.7 (6.4)	226 (32)	0.19 (0.21)	4.80 (1.45)	0.02 (0.03)
0.3‡	7.4 (0.1)	19.5 (7.3)	467 (97)	5.07 (2.72)	5.47 (2.55)	4.95 (2.90)
0.8	7.5 (0.1)	19.4 (7.5)	453 (83)	4.91 (2.64)	5.82 (2.38)	4.09 (2.61)
1.3	7.4 (0.2)	17.4 (7.4)	406 (61)	3.49 (1.86)	7.45 (1.75)	1.51 (1.29)
1.7	7.6 (0.5)	16.9 (6.1)	404 (61)	3.50 (1.88)	7.75 (1.89)	1.11 (1.13)
2.1	7.7 (0.2)	16.5 (6.0)	396 (60)	3.40 (1.75)	8.06 (1.97)	0.72 (0.83)
2.7	7.5 (0.1)	15.8 (6.1)	386 (59)	3.02 (1.33)	8.24 (2.04)	0.31 (0.35)

Temp denotes temperature; Cond denotes conductivity; † denotes above wastewater treatment plant discharge in Columbia Hollow, ‡ denotes distance below point of discharge from wastewater treatment plant, () denote standard deviation.

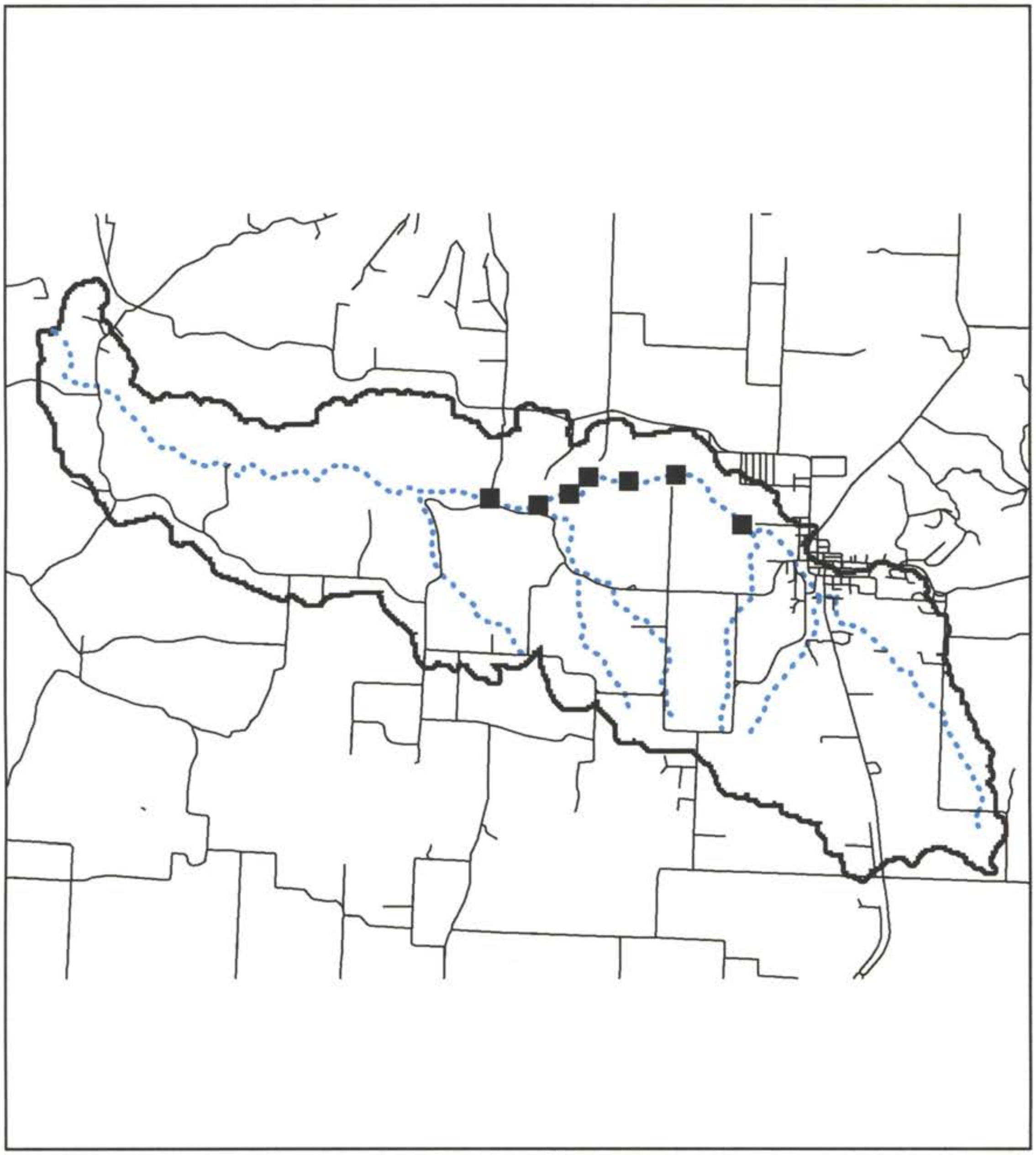

Figure 6. Map of Columbia Hollow in the Ozark Plateau of northeastern Oklahoma and northwestern Arkansas.

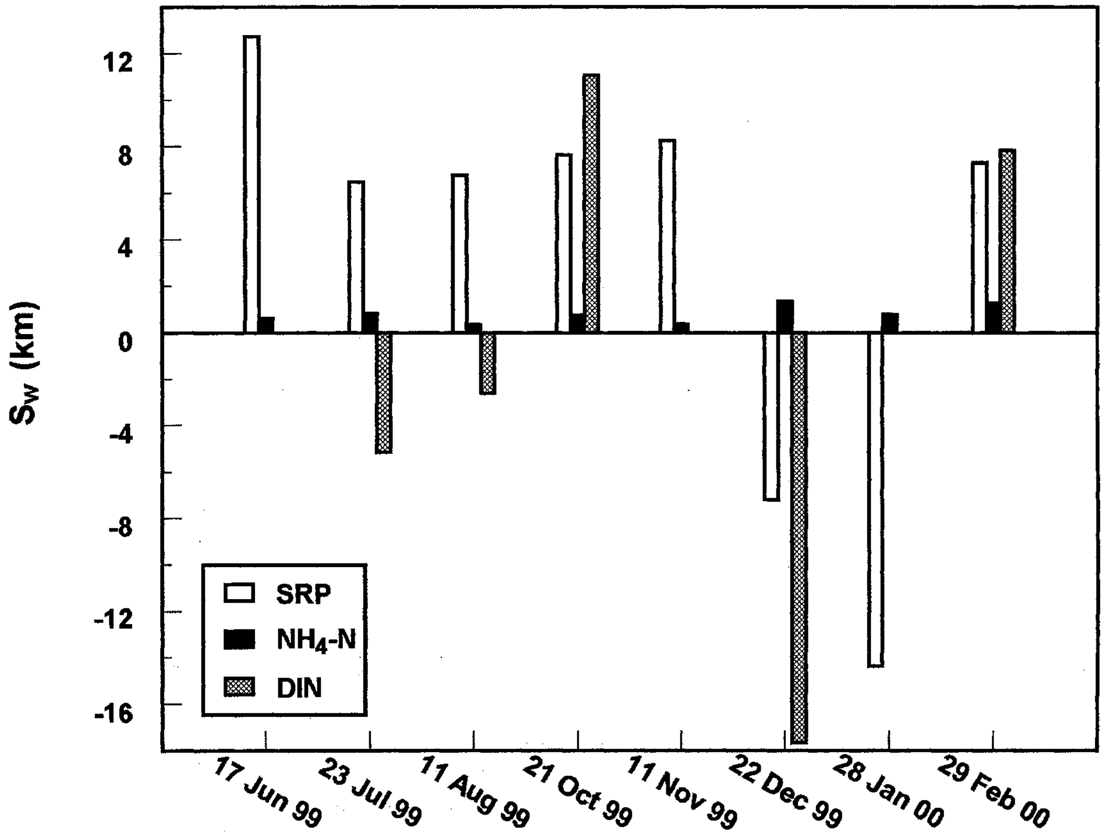

Figure 7. Nutrient uptake length in Columbia Hollow from June 1999 to February 2000.

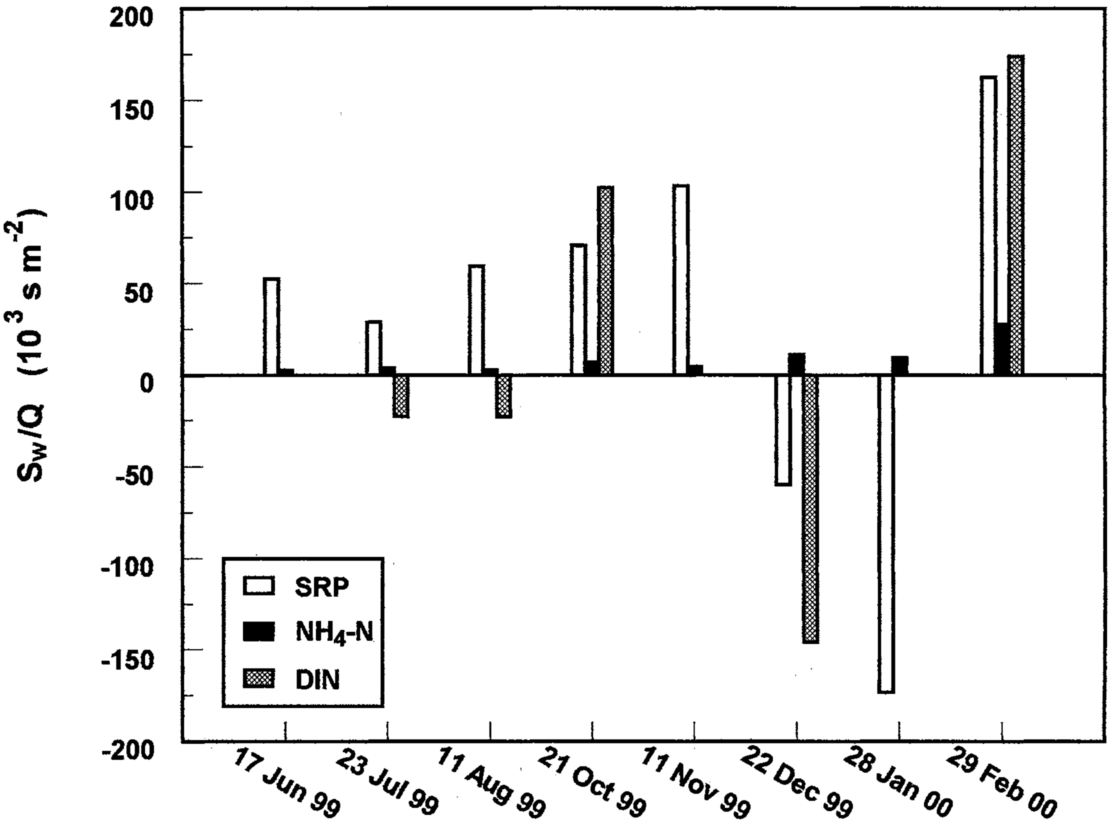

Figure 8. Flow normalized nutrient uptake length in Columbia Hollow from June 1999 to February 2000.

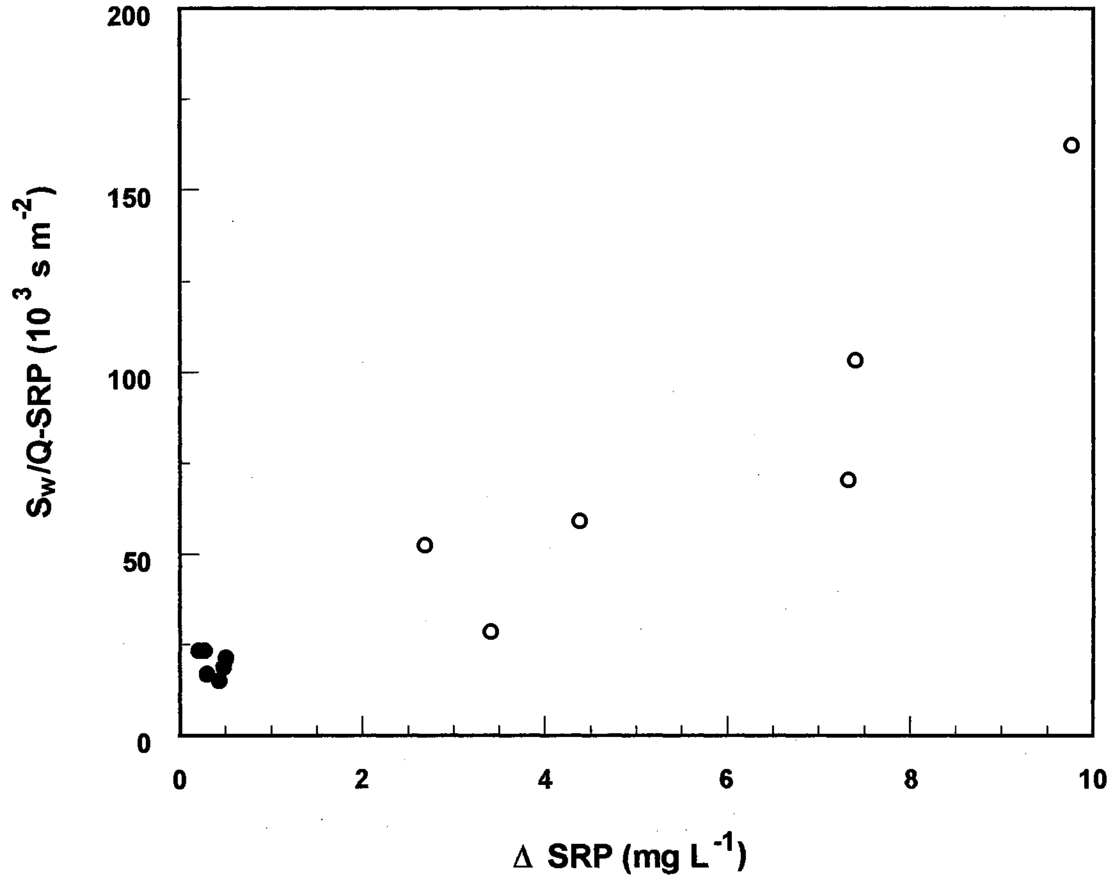

Figure 9. Relationship between flow normalized uptake length for SRP and the level of SRP addition from the wastewater treatment plant (filled in symbols denote data from Chapter III).

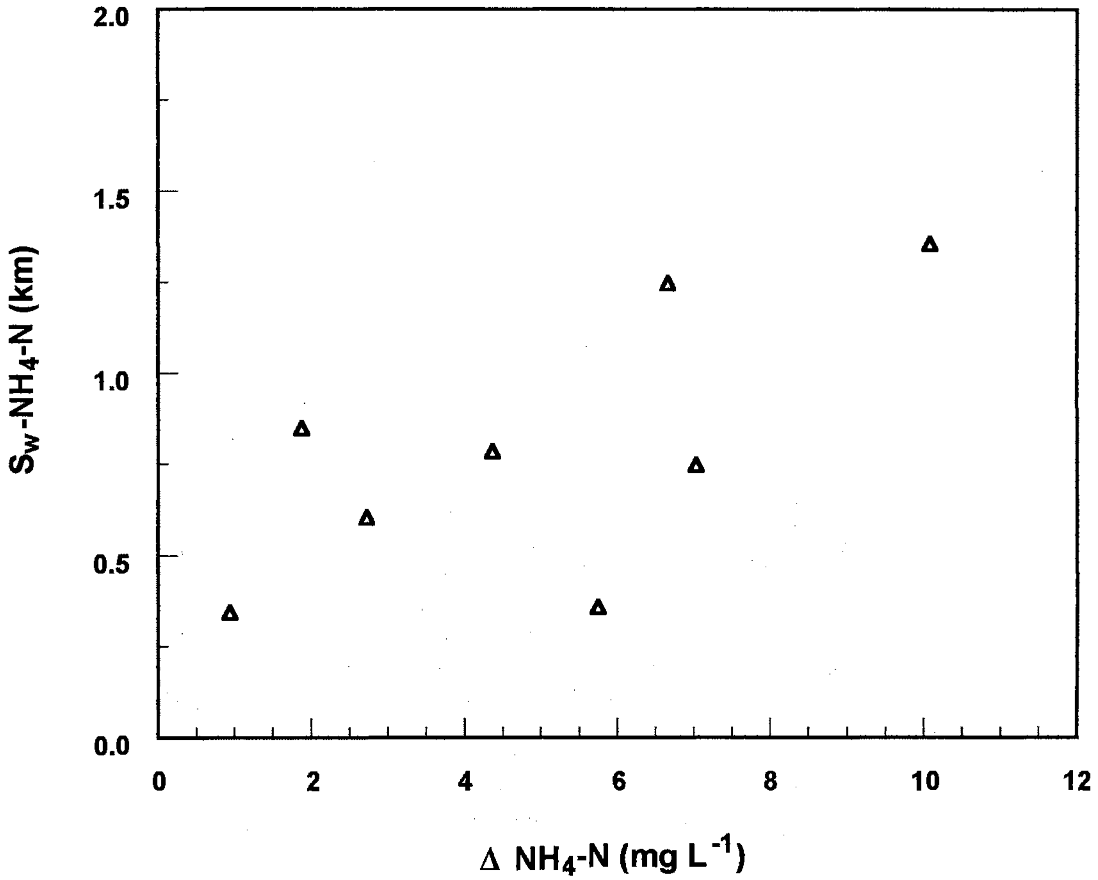

Figure 10. Relationship between uptake length for NH_4-N and the level of NH_4-N addition from the wastewater treatment plant.

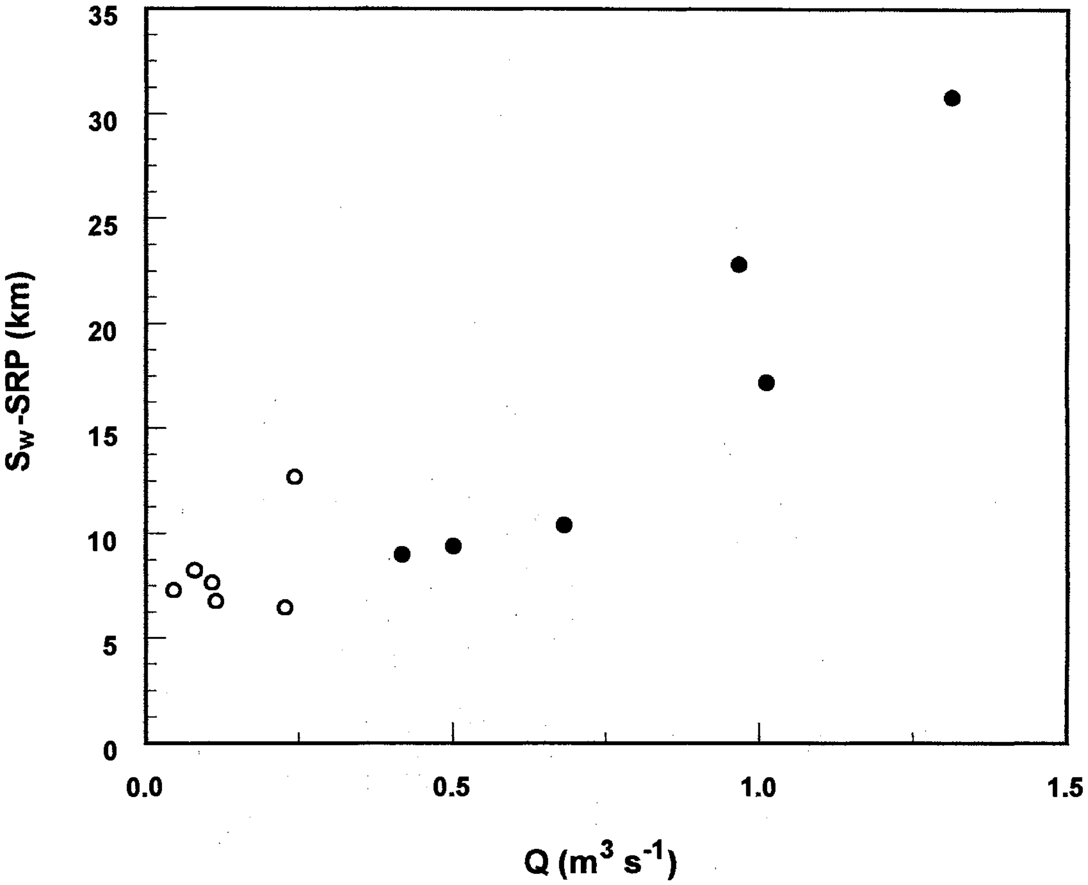

Figure 11. Relationship between uptake length for SRP and flow in Columbia Hollow and Spavinaw Creek (filled in symbols denote data from Chapter III).

CHAPTER V

STREAM NUTRIENT RETENTION IN THREE NORTHEASTERN OKLAHOMA AGRICULTURAL CATCHMENTS

ABSTRACT: Stream nutrient retention was examined in three adjacent agricultural catchments (Cherokee Creek, Cloud Creek and Dry Creek) in the Ozark Plateau. Retention efficiency was measured using short-term nutrient and tracer injections to estimate nutrient uptake length (S_w) during summer 1999 and winter 2000. A one-dimensional transport model was used to estimate hydrologic properties. S_w-NO_3-N regressions were insignificant suggesting NO_3-N retention is negligible whereas S_w-NH_4-N was 94 and 200 m in Cloud Creek and Dry Creek, respectively. NH_4-N is efficiently retained while NO_3-N is not in these systems. S_w-SRP was significant during the summer but not in winter for all streams. S_w-SRP was positively correlated with discharge and average water velocity and negatively correlated with transient storage properties in Cherokee Creek. Variation in catchment land use was not a major determinant in P retention but stream hydrology, such as discharge and transient storage, was a regulating factor. Therefore, land use changes which alter stream hydrology may have a greater impact on P retention in these streams, i.e. deforestation and elimination of riparian zones. Watershed management should consider stream hydrology and the effect of land use changes on its properties to maintain or meet water quality goals.

(**KEYWORDS:** Aquatic ecology, Nutrient retention, Transient storage, Streams)

INTRODUCTION

In the last 25 years, non-point source (NPS) pollution has become a substantial problem and has been identified as the cause of anthropogenic eutrophication in lakes, reservoirs, rivers and streams (Carpenter et al., 1998). Non-point sources are spatially and temporally variable; however, it is clear that agricultural land use is a major contributor to nutrient loading from diffuse sources (Sharpley et al., 1994; Carpenter et al., 1998). In northeast Oklahoma, the issue of NPS nutrient loading has become a major environmental concern due to the rapid growth of confined animal operations, particularly poultry and swine industries.

Evidence exists which shows that high levels of agricultural land use in catchments is associated with increased nutrient loading to streams (Newman, 1996); how does this effect in-stream nutrient processes? Investigating the effect of changes in catchment land use on stream nutrient retention is essential for downstream water quality management. While in-stream processes are not significant buffers of annual nutrient fluxes (Meyer and Likens, 1979), differences in seasonal nutrient retention in streams may influence the timing, magnitude and form of nutrients transported downstream (Meyer et al., 1988) and can impact watershed management strategies and goals.

Nutrient cycling in streams involves longitudinal displacement of a nutrient molecule during a cycle and has been described as ‘spiraling’ (Newbold et al., 1981; Webster and Patten, 1979). The length required to complete one spiral, the spiraling length, is composed of two parts: uptake length (S_w) and turnover length (S_p) (Stream Solute Wokshop, 1990). S_w is the average distance a nutrient molecule travels in the water column before removal, and S_p is the distance required for a nutrient molecule to be regenerated or released from the particulate form (Newbold, 1992). S_p requires the use of isotopes for calculation (e.g., see Newbold et al., 1981, 1983; Mulholland et al., 1985) whereas S_w can be estimated by stable nutrient additions (Mulholland et al., 1990; Webster and Ehrman, 1996).

As the nutrient molecule travels downstream it may cycle from the dissolved inorganic form back into the particulate form and back into the dissolved inorganic form many times, and the number of cycles depends upon the spiraling length. Spiraling length is a measure of the nutrient retention efficiency of the stream, that is the degree to which nutrient transport is inhibited compared to conservative solutes (Martí and Sabater, 1996). S_w generally constitutes greater than 90% of the spiraling length (Newbold et al., 1983; Mulholland et al., 1985), and has been described as an index of stream utilization of nutrients supplied by the terrestrial ecosystem (Newbold et al., 1981).

In the last decade S_w has been widely used to assess nutrient retention in streams. Several studies have shown spatial variation in S_w within and among streams (Aumen et al., 1990; D'Angelo and Webster, 1991; Martí and Sabater, 1996; Munn and Meyer, 1990), and others have examined temporal variation in

S_w (Martí and Sabater, 1996; Mulholland et al., 1985; Webster et al., 1991). Spatial variation in S_w may result from differences in channel form, local environmental conditions, watershed land use and physiographic features whereas temporal variation was largely related to temperature, hydrology and allochthonous inputs into the stream ecosystem.

In this study, spatial and seasonal variations in nutrient retention during summer and winter seasons were examined in three streams draining adjacent agricultural catchments in northeastern Oklahoma. These seasons were selected because warmer temperatures are associated with increased biotic activity whereas winter is the dormant season. Our objectives were (1) to compare stream soluble reactive P (SRP) and NO_3-N retention in summer and winter, (2) to compare NH_4-N and NO_3-N retention and (3) to evaluate the importance of hydrologic properties and catchment land use on nutrient retention.

STUDY SITE DESCRIPTIONS

The Lake Eucha-Spavinaw Basin is one of several high priority basins within the State of Oklahoma, and is located in Ozark Plateau in northeastern Oklahoma and northwest Arkansas (Figure 12). Lake Eucha was constructed in the 1950's to provide a constant source of water to Lake Spavinaw several km downstream on Spavinaw Creek; this impoundment serves as a municipal water supply to the City of Tulsa, Oklahoma. Lake Eucha has experienced substantial increases in nutrient concentrations over the last 25 years (Oklahoma Conservation Commission, 1997). Furthermore, taste and odor problems and the cost of water treatment chemicals have increased (City of Tulsa, personal communication).

Three streams within the Lake Eucha-Spavinaw Basin were selected to conduct short-term nutrient injections to estimate nutrient uptake length. Dry Creek, Cloud Creek and Cherokee Creek are in adjacent catchments with Dry Creek draining into Lake Eucha and Cloud Creek and Cherokee Creek draining into Spavinaw Creek upstream of the riverine zone of Lake Eucha (Figure 12). These streams were selected because the proportion of agricultural land use varies from extensive confined animal operations and high percent pasture in Cloud Creek and Cherokee Creek to fewer confined animal operations and lower percent pasture in Dry Creek (Figure 12, Table 5). A study reach approximately 200 m long was selected in lower basin flood plains in 3rd or 4th order sections in each stream (stream order determined using 1:24000 United States Geological Survey topography maps and includes perennial and intermittent streams). Stream substrate is cobble with only a small fraction of fine sediments. The streams have large gravel beds lateral to the stream channel, and riparian zones are composed primarily of sycamore trees in Dry Creek and a mix of sycamore trees and other hardwoods in Cloud Creek and Cherokee Creek. The riparian zone vegetation did not appear to substantially reduce insolation in these systems. Dry Creek and Cherokee Creek have large cool season grass pastures on either side of the stream up-slope of the riparian zone whereas Cloud Creek has an area of underbrush and forest. The dominant soils in the riparian and upland terrestrial ecosystems are shallow silt loams. The reaches selected in Dry Creek and Cherokee Creek are also long-term water quality monitoring sites for the City of Tulsa, and the reach selected in Cloud Creek is approximately 1 km upstream of a long-term monitoring site. Short-term nutrient additions were performed in the summer of 1999 and in the following winter. Summer injections were conducted on 19 and 27 July and on 3 and 19 August 1999 and winter injections were conducted on 6, 14 and 21 January 2000.

METHODS

Nutrient Injections and S_w Calculation

On all sampling dates, nutrients and a hydrologic tracer were injected into the stream using a peristaltic pump which delivered a solution enriched with PO_4-P, NO_3-N and Cl^- ions to eight pressure compensating emitters through clear polyvinyl plastic tubing. On 6 January 2000 NH_4-N was also used in the injection solution. Cl^- is a conservative element in most streams and was used to quantify dilution and mixing (Bencala et al., 1987). Emitters varied in their discharge rate from 4-15 L h^{-1}, depending upon stream flow and level of nutrient enrichment desired in the stream. The injection apparatus was placed just upstream of a riffle during the short-term nutrient additions to induce complete mixing of the injection solution and stream water. Background water samples were collected prior to the injection at five sampling stations. The solution was released into the stream at a constant rate until conductivity measurements at the most downstream station stabilized, and injections lasted less than 2 hrs. Plateau water samples were taken approximately 10-15 min after conductivity measurements stabilized. Conductivity (YSI Model 30 Meter) was recorded from the time injection started to the return to background levels and was used to estimate various hydrologic parameters of the stream reach.

Nutrients typically exhibit an exponential decline in concentration during short-term addition experiments, and the concentration remaining in the water column is proportional to uptake by the stream benthos (Newbold, 1992). Nutrient concentrations are corrected for background levels at each site and then for losses due to dilution using Cl^- data. Corrected concentrations were then expressed as the proportion remaining in solution from the most upstream sampling station below the injection point. S_w was calculated:

$$[Nutrient_x]_{corr} = \frac{[tracer_o]-[tracer_b]}{[tracer_x]-[tracer_b]}\left([nutrient_x]-[nutrient_b]\right)$$

$$\ln\left(\frac{[Nutrient_x]_{corr}}{[Nutrient_o]}\right) = -kx$$

$$S_w = -\frac{1}{k}$$

Water samples were collected at the most downstream sampling station then at the station immediately upstream and continued to the most upstream station throughout the study reach. This technique was used to avoid influencing nutrient and tracer concentrations by disturbing the stream benthos and collection of all samples was accomplished in less than ten min. Both background and plateau water samples were collected in this manner. Three water samples were taken along a transect perpendicular to stream flow with 60 mL polyethylene syringes and filtered immediately (Whatman GF/F glassfiber filters). Filtered water samples were acidified to pH 2 and stored on ice and in the dark until return to the laboratory. Temperature and pH (Oakron pH Testr2) was measured prior to the injection and at plateau conditions at the most downstream sampling point.

Laboratory Methods

Upon return to the laboratory, samples were allowed to adjust to room temperature before nutrient and tracer analysis were conducted on a Latchet QuikChem 9000 (Milwaukee, WI). NO_3-N was determined using cadmium-copper reduction (QuikChem Method 10-107-04-1-A), and NH_4-N was determined by the alkaline phenol, sodium hypochlorite and nitroprusside reaction (QuikChem Method 10-107-06-1-B). Chloride was analyzed using mercuric thiocyanate (QuikChem Method 10-117-07-1-C). SRP was determined by the ascorbic acid method after Murphy and Riley (1962).

Hydrologic Parameters

We used Cl^- measurements to estimate discharge (Q) at the most upstream station. Average velocity (u) was calculated as reach length divided by the time required to reach half the plateau conductivity at the most downstream sampling site (Martí, 1995). A one-dimensional solute transport model (OTIS-P: Runkel, 1998) was used to simulate conservative solute transport (Cl^-) in these streams. This model accounts for the influence of transient storage on Cl^- transport and provides an automated means of estimating transient storage properties. Figure 13 presents a conceptual model of transient storage in a stream (see Figure 1 D'Angelo et al. (1991) for a theoretical representation of a chloride curve influenced by advection, dispersion and transient storage). Conductivity measurements were converted to Cl^- concentration assuming a linear relationship between background and plateau conductivity and Cl^- concentration and used in OTIS-P. Variation in Cl^- concentration with time at the most downstream station was used to estimate the cross sectional area of the transient storage zone (A_s), the transient storage exchange coefficient (α) and dispersion (D). OTIS-P provides statistical optimization of modeled hydrologic parameters using a nonlinear least squares method (Runkel, 1998).

RESULTS AND DISCUSSION

Water Chemistry and Nutrient Concentrations

Table 6 displays all physicochemical parameters and ambient nutrient concentrations. Dry Creek had relatively low baseflow SRP concentrations compared to the streams in this basin (unpublished data, City of Tulsa), whereas Cloud Creek and Cherokee Creek had significantly higher SRP concentrations (ln transformed, ANOVA, $P<0.05$). SRP concentrations were similar between summer and winter in all streams. In contrast, NO_3-N concentrations significantly increased in winter compared to summer in Dry Creek and Cloud Creek but decreased significantly in Cherokee Creek (ln transformed, ANOVA, $P<0.05$).

Seasonal variations in stream NO_3-N concentration have been attributed to biotic uptake and denitrification in the riparian zone and terrestrial ecosystem (Jacobs and Gilliam, 1985; Peterjohn and Correl, 1984). However, in-stream processes may also be a major determinant in regulation of seasonal and diel variation in NO_3-N concentrations in streams (Tate, 1990). Higher winter concentrations may result from slower biotic processes in the winter due to decreased temperature. It appears that riparian and/or in-stream processes may reduce summer NO_3-N concentrations in Dry Creek and Cloud Creek, but these processes may not be substantial in Cherokee Creek, but with only one winter sampling date, we can not be sure. However, many factors can influence seasonal surface water nutrient concentrations such as changes in fertilizer and animal waste applications, in-stream disturbances from animals, and effects of hydrology such as karst features.

Several investigators have shown maintenance of water column P concentrations by benthic sediments (Meyer, 1979; Klotz 1988, 1991; Haggard *et al.*, 1999). In fact, SRP concentrations in the water column of Lake Eucha tributaries have been correlated to the equilibrium phosphate concentration (EPC) of the benthic sediments (Popova, 2000). EPC has been shown to be dominated by physical processes (Klotz, 1998; Baldwin, 1996); however, abiotic or biotic dominance of EPC can vary between streams (Munn and Meyer, 1990). Therefore, the lack of seasonal difference between SRP concentrations in these streams suggests that regulation of P maybe via in-stream processes such as benthic sediment EPC.

SRP (and NO_3-N) concentrations appeared to be related to the proportion of agricultural land use (%pasture) in the catchments. This result is not surprising because several investigations have shown a positive relationship between stream nutrient concentrations and the proportion of agricultural land use in the catchment (e.g., see McFarland and Hauck, 1999; Omernik, 1977; Petersen, 1992). This relationship has also been observed throughout the Ozark Plateau streams (Petersen et al., 1998) and in particular in streams draining the Beaver Lake Basin, an adjacent watershed (Haggard et al., In preparation).

Nutrient Retention

Whereas P is subject to both abiotic and biotic processes, NO_3-N retention is driven by biotic uptake or transformation. In 10 of 12 experiments, there was no statistically significant downstream increase or decrease in NO_3-N concentration after dilution corrections during short-term injections (regression slope not different than zero, $P>0.10$). In the remaining two experiments, S_w for NO_3-N (S_w-NO_3-N) was marginally significant in the summer. S_w-NO_3-N was negative (-4000 m, $P=0.08$) in Dry Creek, possibly from nitrification of mineralized N in the hyporheic zone (e.g., see Jones et al., 1995), and 3120 m in Cherokee Creek ($P=0.06$, Figure 14). Overall, in these streams NO_3-N retention is not sufficient to be detected by our methods. However, other studies have observed significant NO_3-N retention (Triska et al., 1989; Munn and Meyer 1990; Valett et al., 1996). Previously reported S_w-NO_3-N in other streams were typically several orders of magnitude less than that observed in Cherokee Creek.

Evidence of N limitation in streams within the Ozark Plateau was observed when NO_3-N concentrations were less than 0.1 mg L^{-1} (Lohman et al., 1991), but in our study stream NO_3-N concentrations were at least five times greater and biotic uptake is probably saturated. Therefore, NO_3-N is simply transported through the stream ecosystem without any significant removal from the water column by in-stream processes. The magnitude of NO_3-N concentrations in these stream is not surprising given that the primary agricultural use of pastures is for land application of animal wastes. Soils in this catchment are shallow and the underlying geology is karstic; thus, nitrification of reduced forms of N in land-applied animal wastes increases soil solution and ground water NO_3-N concentrations (Hubbard and Sheridan, 1989) which in turn may increase stream NO_3-N concentrations.

Although NH_4-N concentrations in the water column are below detection limits (<0.030 mg L^{-1}), it is possible that NH_4-N adsorbed to benthic sediments can serve as a bioavailable N reserve (Triska et al., 1994). In these streams sediment-bound NH_4-N was greater than 0.75 μg NH_4-N g^{-1} dry sediment (Popova, 2000). NH_4-N and NO_3-N were co-injected on 6 January 2000 during a short-term addition in Cloud Creek and Dry Creek because benthic sediments may adsorb NH_4-N and/or some stream organisms may preferentially uptake NH_4-N over NO_3-N. NH_4-N retention was significant in both streams (S_w-NH_4-N = 94 and 200 m in Cloud Creek and Dry Creek, respectively) (Figure 14) but NO_3-N retention was not. S_w-NH_4-N observed in this study is within the range of reported values for other streams (32-900 m; see Table 7 in Martí and Sabater, 1996).

Summer SRP retention was significant ($\alpha = 0.05$) with S_w-SRP ranging from 200 to 900 m (Table 6, Figure 15). Our results are comparable to the range of reported values (5-697 m; see Table 7 in Martí and Sabater, 1996). However, in winter S_w-SRP regressions indicated no statistically significant decrease in concentrations on all sampling dates in all three streams. This clear seasonal difference was most likely because of reduced biological retention resulting from the temperature decrease, approximately 10°C. Similar results were observed in spike P additions in a eutrophic stream in northeastern USA (Meals et al., 1999); these authors suggested that long-term retention of P was via biological processes where short-term retention was via sediment adsorption. However, in our systems abiotic sorption was not significant most likely because benthic sediment P buffering capacity and exchangeable P were lower in the winter than in the summer and there are few fine sediments (Popova, 2000). Also, the short duration of our experiments may not permit equilibration between the benthic sediment EPC and water column P concentrations.

Variations in S_w among or within seasons are often the product of temporal variations in discharge. During summer in these systems, S_w-SRP decreased with decreasing average velocity or discharge in Dry Creek and Cloud Creek (n=2), but the positive correlation between S_w-SRP and ln transformed u was insignificant in Cherokee Creek (R=0.95, n=3, P=0.20). However, S_w-SRP and Q were moderately, positively correlated (R=0.99, n=3, P=0.10) (Figure 16). Several investigations have shown similar positive relations between S_w and average velocity and/or discharge (e.g., see D'Angelo and Webster, 1991; Martí and Sabater, 1996; Valett et al., 1996).

Hydrologic Properties

In transient storage zones, movement of water and nutrients is typically retarded compared to average water velocity leading to increased residence times. Thus, transient storage zones increase the opportunity for abiotic and/or biotic retention of nutrients in the stream ecosystem and S_w typically decreases with increasing transient storage (Valett et al., 1996). Parent lithology has been shown to influence the nature and size of the hyporheic zone in streams (Valett et al., 1996). Recent investigations have shown the importance of the hyporheic zone and transient storage in nutrient retention (Mulholland et al., 1997; Valett et al., 1996). The hyporheic zone may be a sink or source of the nutrients depending on dominant processes, i.e. nitrification of reduced N (Richey et al., 1985) or biotic uptake (Triska et al., 1989b).

In this study, Cherokee Creek was constrained by shallow bedrock underneath benthic substrates and had the smallest storage cross-sectional area, A_s (ln transformed, ANOVA, $P<0.05$). In Cherokee Creek, the size of the transient storage zone decreased with increasing average velocity or discharge (ln transformed, $R=-0.98$, $n=4$, $P<0.05$) and in Dry Creek a moderately, negative correlation was observed between As and average velocity ($R=-0.92$, $n=4$, $P=0.08$), but no significant correlation was observed in Cloud Creek (Figure 17). Several investigations have shown negative correlations between A_s and velocity or discharge (Morrice et al., 1997; Valett et al., 1996). In contrast, A_s in Cloud Creek was larger during the high baseflow injections in summer and winter compared to that measured in the subsequent low baseflow injection. A possible explanation is that the injection in Cloud Creek during higher flow had an increased wetted perimeter. Thus, surface and ground water may interact on a larger interface across the stream cross-section; therefore, the hyporheic zone was larger. In these streams, the hyporheic zone probably constitutes the greatest proportion of transient storage area because there are few backwater pools, side channels or large woody debris.

Nutrient retention has been shown to be positively correlated to A_s or relative transient storage (A_s/A where A is the average cross-sectional area of the surface water above the streambed) (e.g., see Valett et al., 1996). In this study, the number of significant S_w-SRP regressions limits trend investigations to Cherokee Creek where S_w-SRP was decreased with increasing A_s ($R=-0.99$, $n=3$, $P<0.05$) (Figure 18). The size of the transient storage and discharge (and average velocity) were also significantly correlated in Cherokee Creek; therefore, we examined the relationship between S_w normalized for discharge (or average velocity) and A_s. Our results displayed a marginally significant negatively correlation ($R=-0.72$, $n=7$, $P=0.07$) between A_s and discharge but the negative correlation was significant between A_s and average velocity ($R=-0.76$, $n=7$, $P<0.05$). These results suggest that both transient storage and average velocity (and flow) are both important determinants of SRP retention in Cherokee Creek.

Nutrient retention in streams can be conditioned by catchment characteristics and alterations (Meyer et al., 1988). In these catchments, nonpoint source pollution from land application of animal wastes is potentially the greatest nutrient contributor to the streams. We expected to observe a gradient between land use and nutrient retention but it appears that stream hydrology, i.e. transient storage area and discharge, have the greatest influence. Unlike absolute SRP concentrations, S_w-SRP was similar between Cloud Creek and Dry Creek despite the large differences in catchment land use (Table 5 and 6). Furthermore, S_w-SRP was shorter in Cloud Creek compared to Cherokee Creek despite similar proportions of pasture in the upland areas (63 and 66%, respectively). These similarities or differences in S_w-SRP may reflect the variations in the transient storage parameters A_s and A_s/A (Table 7). Our results further support the findings of Meyer et al. (1999), where transient storage was more important than proportion of any one land use category, i.e. agriculture, forest or urban. However, if land use changes the hydrologic characteristics of the stream, then S_w can be affected (Meyer et al., 1999). In addition, no long-term S_w data (from short-term injections) exists in any catchment which has undergone major land use changes. These data will help substantiate the effects of land use changes on nutrient and hydrologic retention within stream ecosystems.

CONCLUSIONS

Injected NO_3-N is transported through these streams without any significant retention but NH_4-N is efficiently retained. Furthermore, SRP retention was significant in summer but not winter suggesting biological processes may play a large role in stream P retention. If biological processes are an important factor in nutrient retention then spatial and temporal patterns in

P (and NH_4-N) retention should parallel variations in stream biotic productivity. Furthermore, these variations in stream biota and nutrient retention should be considered in the water quality management strategies of downstream aquatic ecosystems. In addition, several investigations have clearly shown temporal variation in nutrient concentrations and retention exists in streams because of fluctuations in biotic processes (Klotz, 1991), organic matter and its associated microbial community (Mulholland et al., 1985) and hydrology (Valett et al., 1996).

In our study, stream hydrology (velocity, discharge and transient storage area) was the most important determinant in regulating nutrient retention within and among streams during the summer season despite large differences in catchment land use between streams. However, the ambient nutrient concentrations in these streams did agree with the proportion of agricultural land use (%pasture) in each catchment. Furthermore, land use changes which alter stream hydrology will impact nutrient retention, especially during periods of high biotic activity (Meyer et al., 1999). Thus, catchment level water quality management should not only consider temporal variations in biological processes and nutrient retention, but also the effects of catchment land use on stream hydrology.

Table 5. Catchment characteristics upstream of study reaches and stream order for Cherokee Creek, Cloud Creek and Dry Creek.

Catchment	Latitude*	Longitude*	Area (km^2)	Agri (%)	For (%)	Urb (%)	Stream Order
Cherokee	36.19.16	94.39.57	50	66	32	2	3rd
Cloud	36.18.20	94.44.40	47	63	36	1	3rd
Dry	36.18.56	94.50.02	51	24	76	<1	4th

* denotes location of experimental study reach for each stream; Agri denotes land use in pasture; For denotes land use in forest and woodland; Urb denotes land use in urban-suburban.

Table 6. Physicochemical properties, average ambient nutrient concentrations, and SRP uptake length for Cherokee Creek, Cloud Creek and Dry Creek.

Date	pH	Temp (°C)	Cond (µS cm^{-1})	NO_3-N (mg L^{-1})	SRP (mg L^{-1})	S_w-SRP (m)
Cherokee Creek						
07-27-99	7.5	20	244	2.65	0.030	900
08-03-99	-	18	242	2.66	0.028	580
08-19-99	7.0	21	266	-	0.032	200
01-14-00	7.5	13	287	2.32	0.028	-
Cloud Creek						
07-19-99	-	21	150	1.58	0.029	339
07-27-99	7.2	22	158	1.54	0.032	257
01-06-00	7.3	12	164	1.93	0.032	-
01-21-00	7.3	11	171	1.78	0.027	-
Dry Creek						
07-19-99	-	19	189	0.52	0.006	371
08-03-99	-	20	209	0.60	0.012	248
01-06-00	7.5	11	223	0.94	0.011	-
01-14-00	7.3	11	224	0.85	0.010	-

Temp denotes tempertaure; Cond denotes conductivity; S_w-SRP denotes SRP uptake length; - denotes missing data or insignificant S_w regressions.

Table 7. Hydrologic parameters in Cherokee Creek, Cloud Creek and Dry Creek.

Date	Q (m^3 s^{-1})	u (m s^{-1})	A_s (m^2)	A (m^2)	D (s m^{-2})	α (10^{-3} s^{-1})	Length (m)
Cherokee Creek							
07-27-99	0.14	0.17	0.2	0.8	0.87	1.0	197
08-03-99	0.12	0.09	0.5	1.3	1.30	9.3	197
08-19-99	0.12	0.08	0.8	1.4	0.77	0.2	197
01-14-00	0.14	0.13	0.3	1.0	0.51	0.2	197
Cloud Creek							
07-19-99	0.14	0.12	4.6	1.1	2.00	0.4	150
07-27-99	0.11	0.07	1.4	1.6	0.80	0.2	150
01-06-00	0.14	0.16	3.1	0.9	1.65	0.5	150
01-21-00	0.08	0.06	0.6	1.3	0.21	0.7	150
Dry Creek							
07-19-99	0.14	0.17	1.8	0.8	7.04	0.2	201†
08-03-99	0.11	0.11	3.4	1.1	0.23	0.2	159
01-06-99	0.13	0.14	2.8	1.0	0.47	0.3	159
01-14-00	0.09	0.11	2.7	0.8	0.35	0.2	159

Q denotes discharge; u denotes average water velocity; A_s denotes absolute transient storage zone; A denotes average cross-sectional area of stream (Q/u); D denotes dispersion coefficient; Length denotes length of study reach from injection point to most downstream sampling site; † study reach included a pool between injection point and first sampling site and subsequent injections did not include this feature whereas sampling points remained fixed.

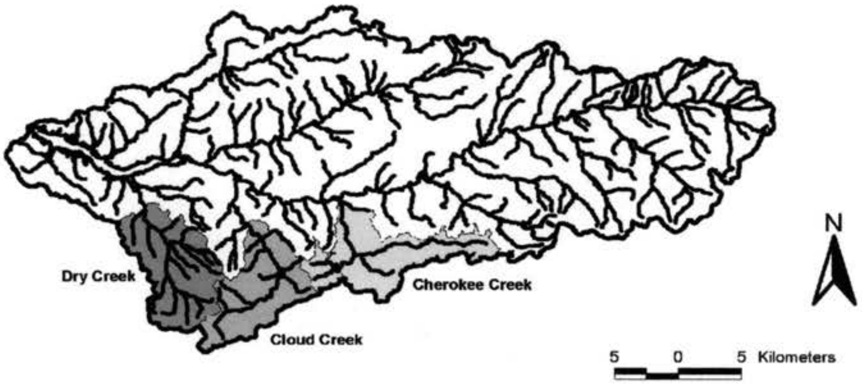

Figure 12. Lake Eucha Basin and Cherokee Creek, Cloud Creek, and Dry Creek catchments.

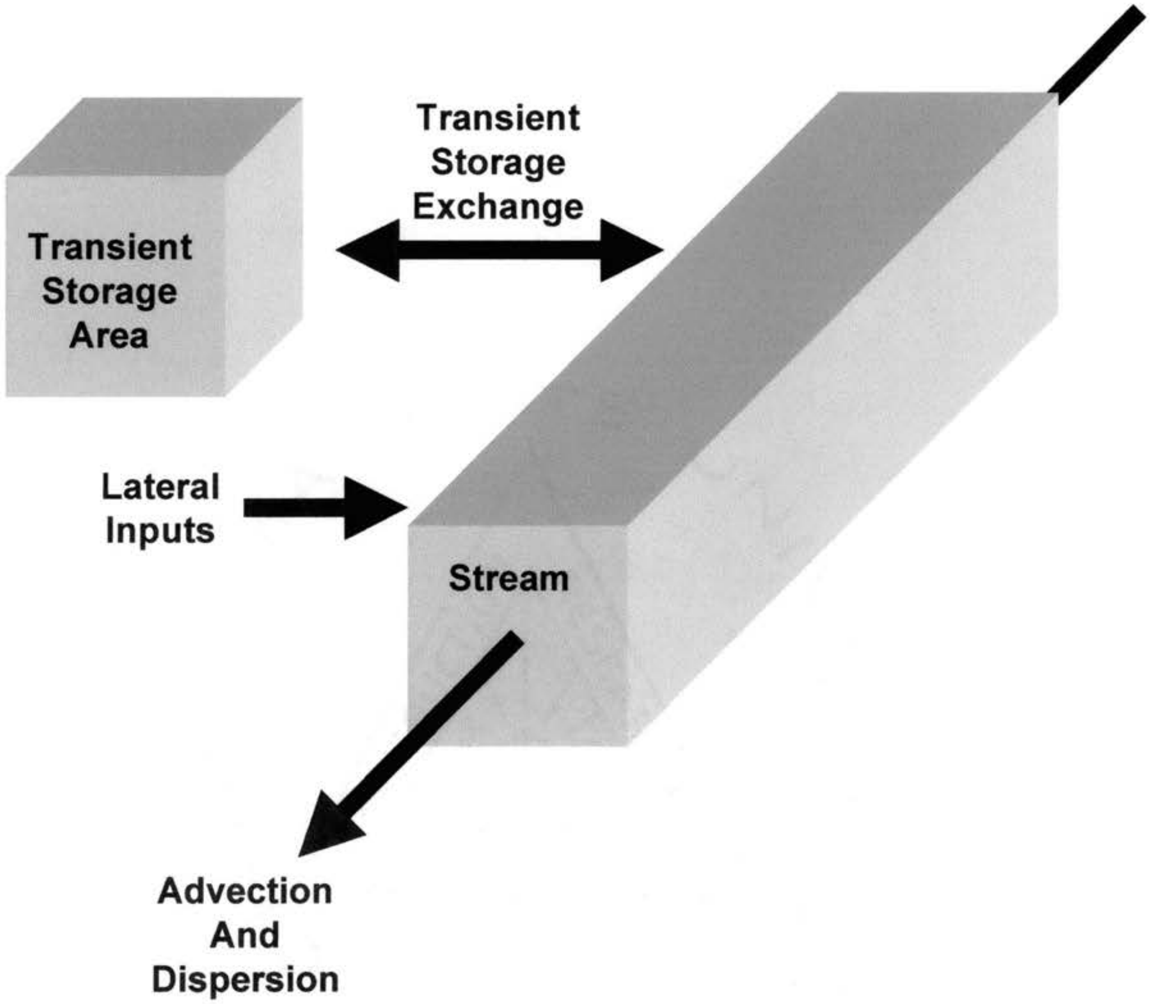

Figure 13. Conceptual model of transient storage and the main channel of the stream.

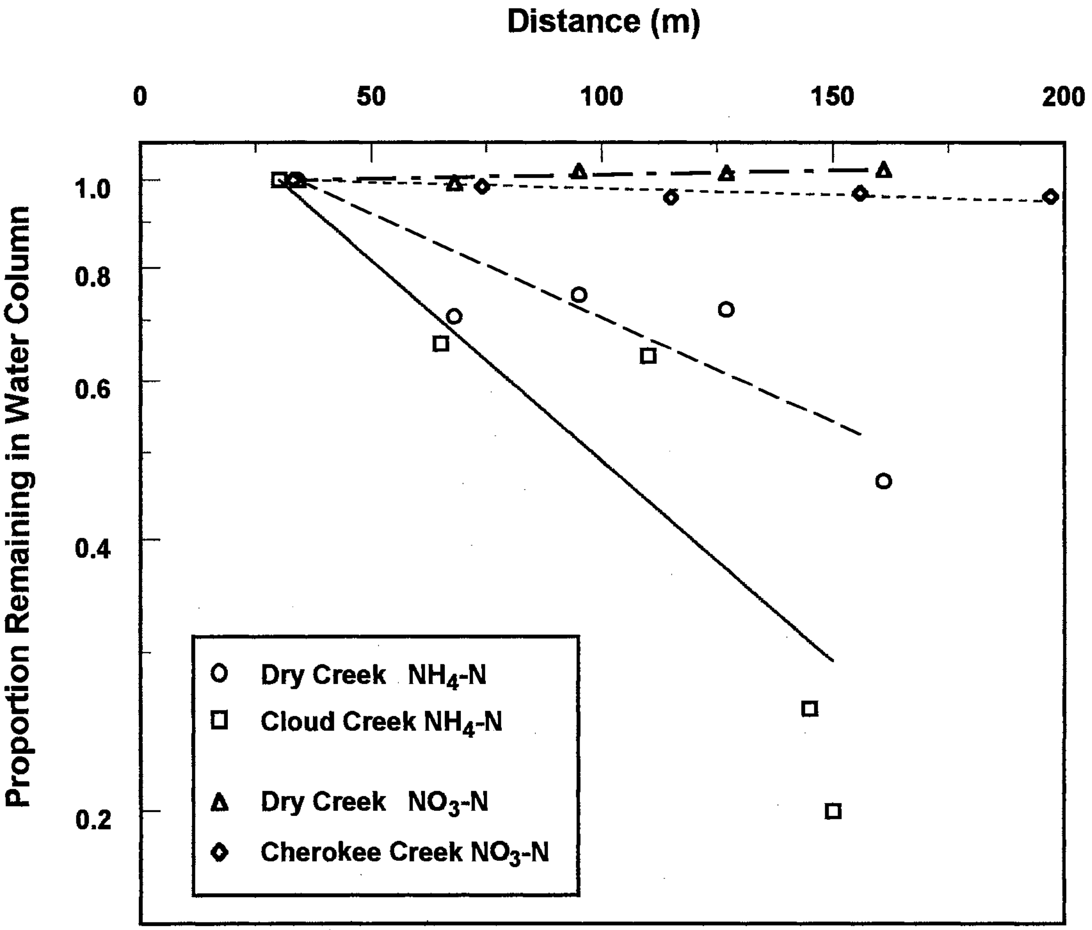

Figure 14. Proportion of inorganic N remaining in the water column as a function of distance downstream from injection point. Sampling dates for S_w-NO_3-N are 3 August 1999 in Cherokee Creek and 19 July 1999 in Dry Creek, and S_w-NH_4-N are from 6 January 2000. Linear regression represents the exponential decline in concentration with distance from which slope and S_w are derived.

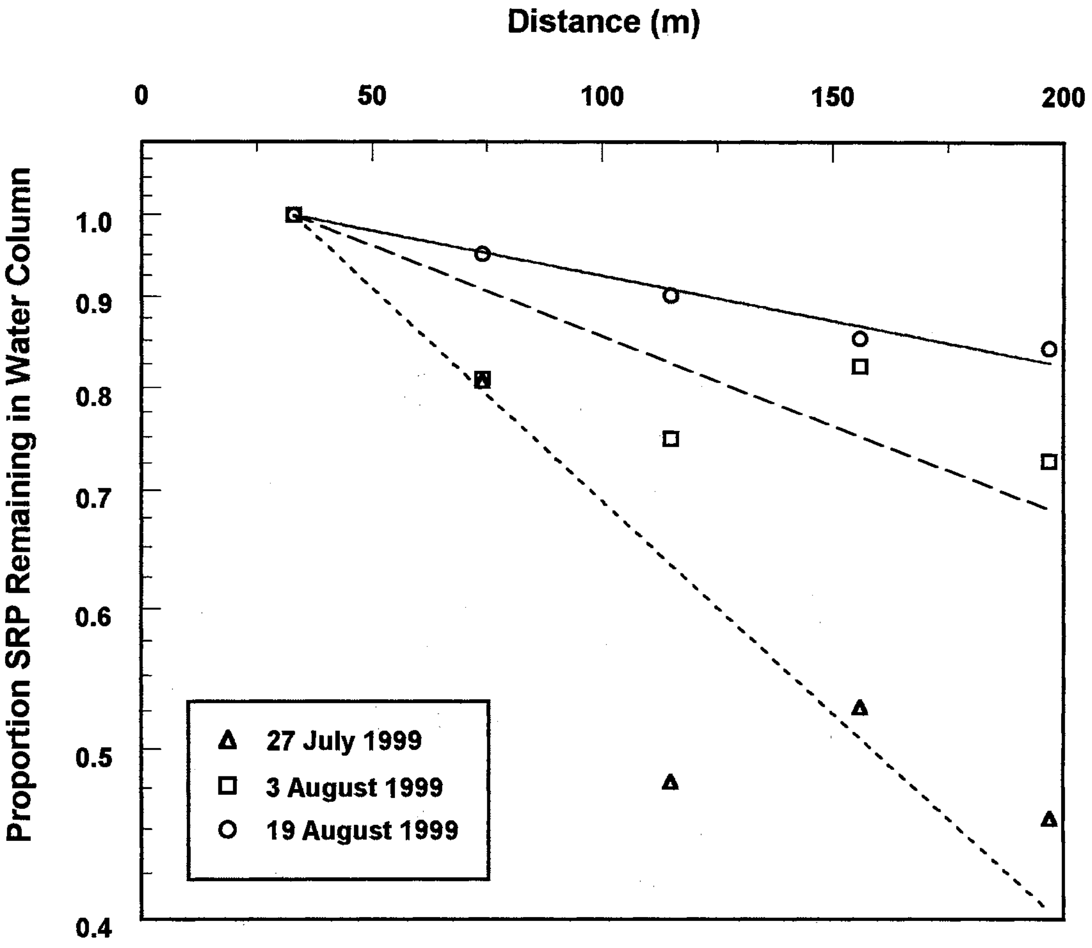

Figure 15. Proportion of SRP remaining in the water column as a function of distance downstream from injection point through summer in Cherokee Creek. Linear regression represents the exponential decline in concentration with distance from which slope and S_w are derived.

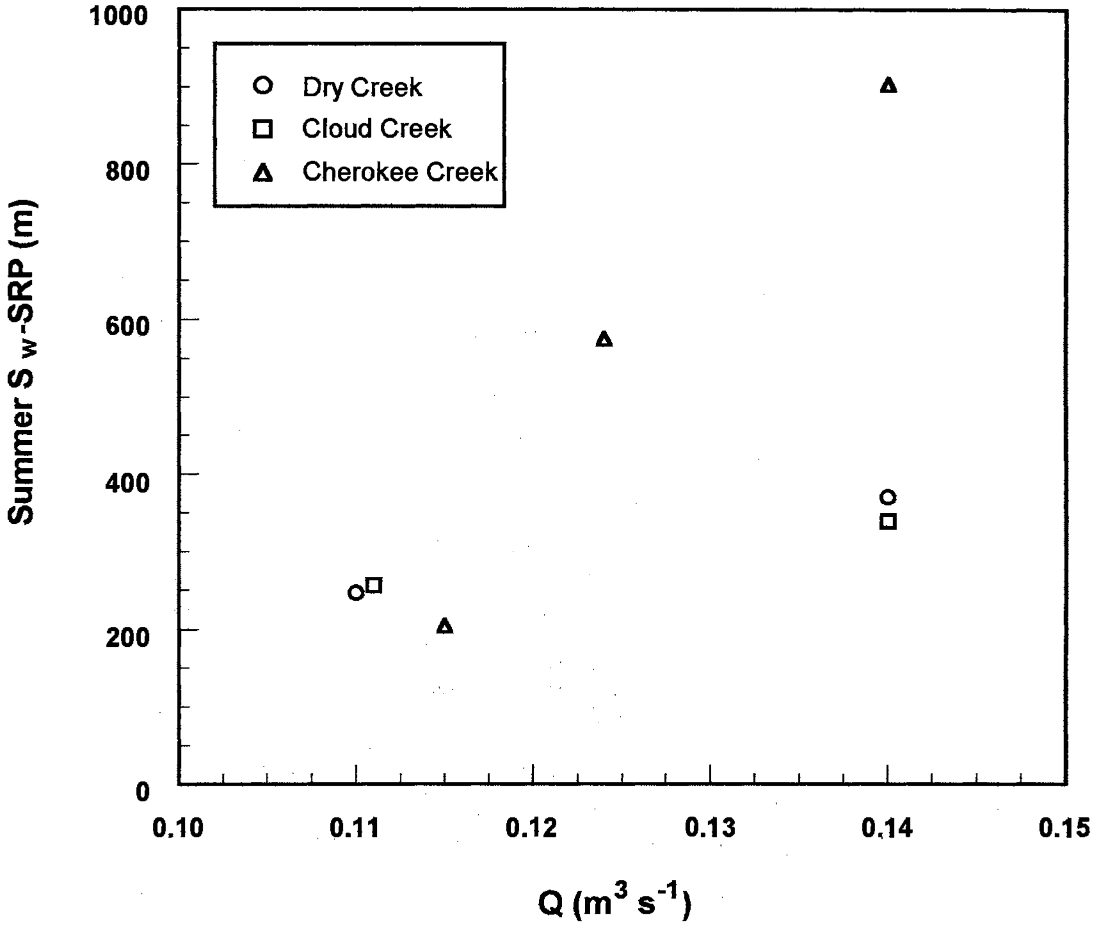

Figure 16. Relationship between summer SRP uptake length and stream flow in Cherokee Creek, Cloud Creek and Dry Creek.

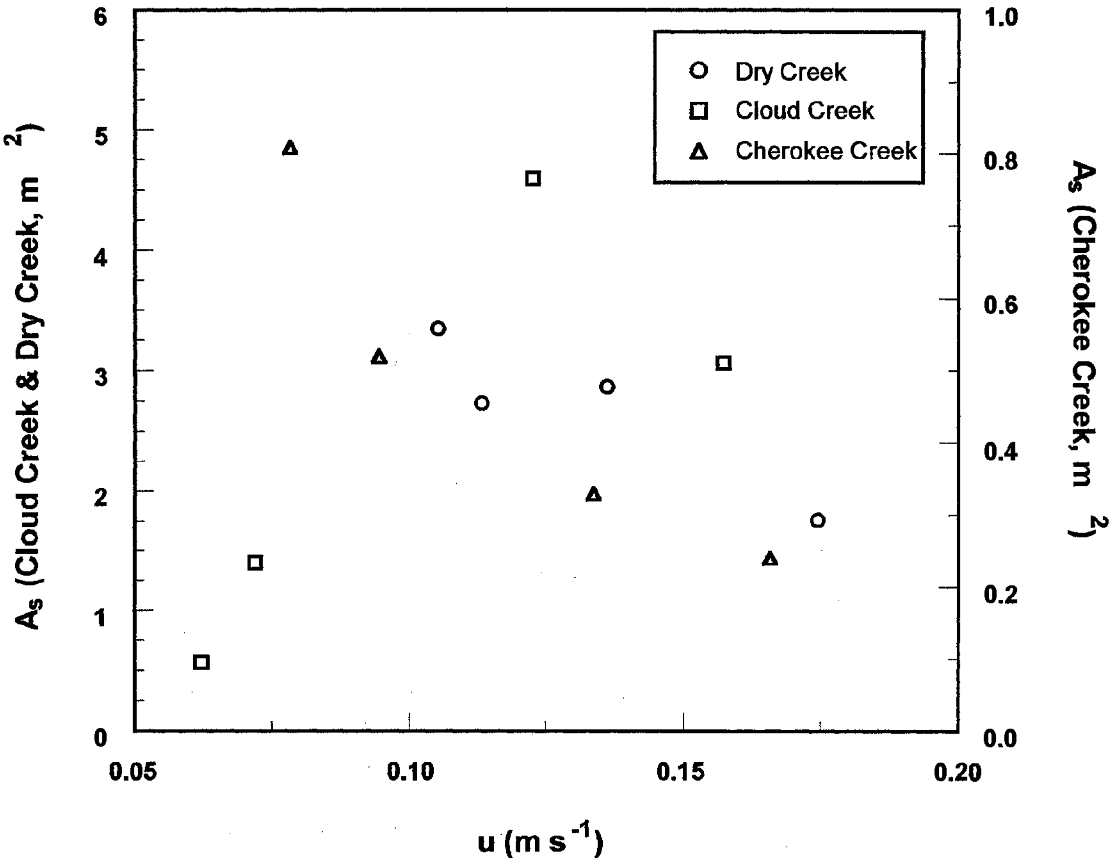

Figure 17. Relationship between transient storage area and average water velocity in Cherokee Creek, Cloud Creek and Dry Creek.

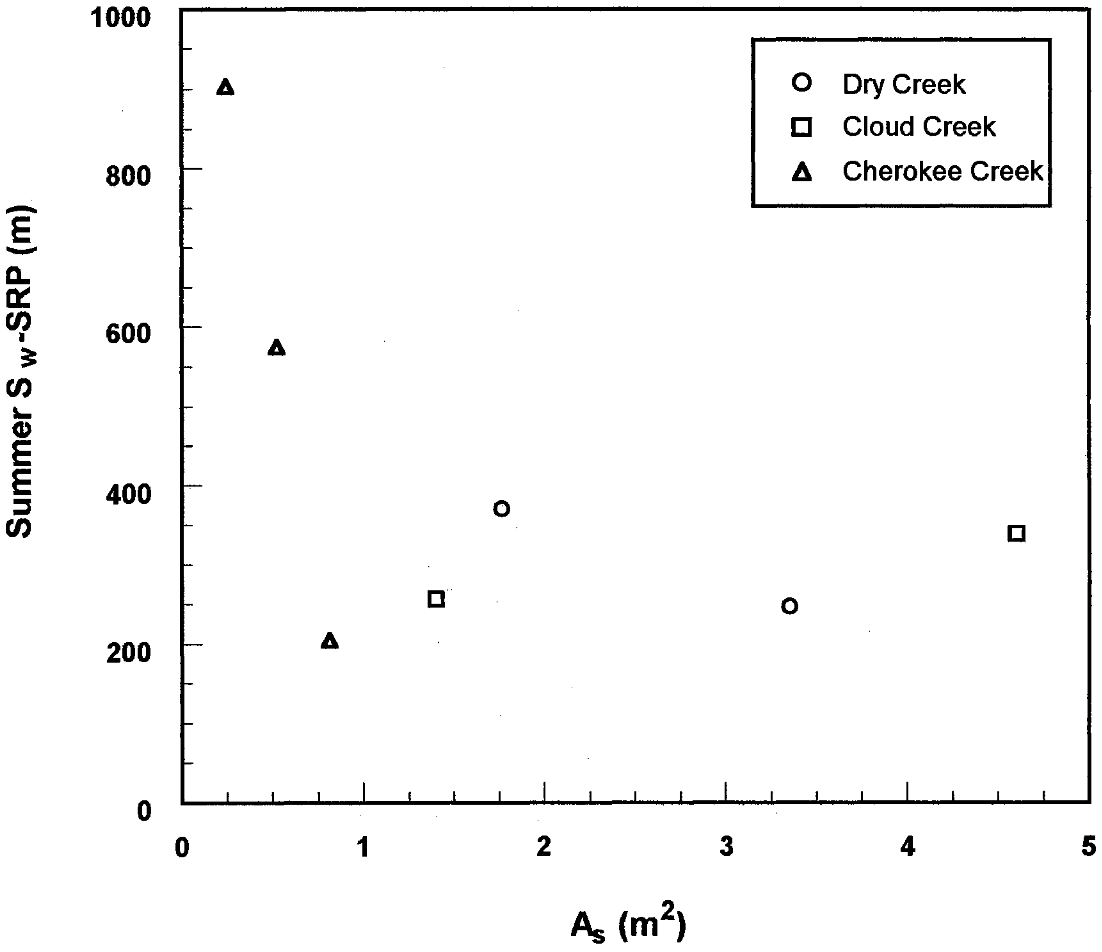

Figure 18. Relationship between summer SRP uptake length and transient storage area in Cherokee Creek, Cloud Creek and Dry Creek.

CHAPTER VI

SUMMARY, CONCLUSIONS AND RECOMMENDATIONS

SUMMARY

Nutrient retention was examined in point source (PS) and nonpoint source (NPS) impacted streams in the Lake Eucha Basin in the Ozark Plateau of northeastern Oklahoma and northwestern Arkansas. Three NPS impacted streams (Cherokee Creek, Cloud Creek and Dry Creek) were selected to assess nutrient retention in streams draining watersheds with various land use proportions. The PS used in this investigation was a secondary wastewater treatment plant (WWTP) in Decatur, Arkansas. The effluent of the WWTP discharges into a third order stream, Columbia Hollow, which is a tributary of Spavinaw Creek. The effects of the WWTP on nutrient retention were investigated in both Columbia Hollow and Spavinaw Creek.

A widely used indicator of nutrient retention is nutrient uptake length, S_w. S_w is a measure of the nutrient retention efficiency of streams with respect to nutrient supply (Newbold et al., 1981). S_w for NO_3-N, NH_4-N and soluble reactive P (SRP) were measured using standard solute injection experiments, and hydrologic parameters were quantified using a conservative tracer, Cl^-. These whole-stream enrichment studies were conducted in Cherokee Creek, Cloud Creek and Dry Creek during the summer of 1999 and winter of 2000. Traditionally, solute injections are used to assess S_w, but in Columbia Hollow and Spavinaw Creek S_w was used to examine the PS inputs. Despite the reversal of perspective, S_w calculations are the same and are based on the downstream decline in the proportion of nutrient remaining in the water column

from the injection source. Nutrient uptake lengths were measured in Spavinaw Creek during the summers of 1998 and 1999, and in Columbia Hollow on an approximate monthly basis from June 1999 to February 2000. In order to examine specific mechanisms of P retention in Spavinaw Creek, sediment samples were analyzed for exchangeable P (Ex-P) and P Sorption Index (PSI) in summer 1998.

In NPS impacted streams S_w for NO_3-N (S_w-NO_3-N) within the study reaches was generally insignificant in summer and winter whereas S_w-SRP was significant in summer but not in winter. During winter co-injection of both dissolved inorganic N (DIN) species, S_w-NH_4-N was significant whereas S_w-NO_3-N was not. S_w-SRP was positively associated with discharge or average water velocity and negatively associated with transient storage area (in Cherokee Creek). Variation in watershed land use was apparently not a major factor in nutrient retention but appeared to be related to absolute nutrient concentrations. Hydrologic variables, such as discharge or average velocity and transient storage, controlled nutrient retention. Although the range of discharge was similar between streams, the relationship between S_w-SRP and discharge and average velocity suggests it is an important determinant of nutrient spiraling within a stream. Transient storage did not vary between Cloud Creek and Dry Creek and both had similar P retention efficiencies. On the other hand, transient storage was much smaller in Cherokee Creek, and the range in S_w-SRP values was much greater 200 - 900 m.

In Columbia Hollow, NO_3-N concentration increased with distance from the WWTP indicating nitrification of reduced N forms. S_w-DIN varied widely (negative to positive) depending on the use of both DIN species by the stream biota. Normalizing for variations in discharge, NH_4-N and SRP retention was highest in summer then autumn and winter. The retention efficiency of NH_4-N and SRP decreased with increasing additions from the WWTP. S_w-SRP was negative during winter when input from the WWTP was minimal. It appears that P previously adsorbed by benthic sediments was being released back into the water column, maintaining SRP concentrations at elevated levels (ca. 2 mg L^{-1}). In Columbia Hollow S_w estimations for NH_4-N were generally less than 2 km whereas S_w-SRP was often greater than 5 km (when positive).

In Spavinaw Creek, NH_4-N concentrations were generally less than the detection limit (0.030 mg L^{-1}), but NO_3-N concentrations were significantly increased by Columbia Hollow (essentially WWTP effluent) and S_w-NO_3-N ranged from 3.3 to 9.9 km. SRP concentrations in Spavinaw Creek also increased significantly below Columbia Hollow, and S_w-SRP ranged from 7.3 to 25 km whereas S_w-SRP measured in Spavinaw Creek above the influence of Columbia Hollow (background S_w) was approximately 0.6 km, over 30 times shorter than S_w-SRP measured below Columbia Hollow a few days before. S_w-SRP was positively associated with discharge whereas S_w-NO_3-N was positively associated with the magnitude of NO_3-N additions from Columbia Hollow. Benthic sediments exhibited little natural buffering capacity (low PSI) above

Columbia Hollow, but this minimal capacity was further reduced by P loading from Columbia Hollow. Benthic sediment Ex-P also increased 3 fold below Columbia Hollow. S_w-SRP values from both in Columbia Hollow and Spavinaw Creek increased exponentially with discharge, and flow normalized S_w-SRP exponentially increased with P additions from the WWTP.

CONCLUSIONS

PS inputs from the Decatur WWTP overload Columbia Hollow and Spavinaw Creek because these streams are unable to retain the nutrient additions. S_w measured in these streams were in the km scale, several orders of magnitude greater than S_w measured in less impacted streams, including the NPS impacted streams measured in this study. Overall P retention in both Spavinaw Creek and Columbia Hollow was governed by discharge and the degree of P enrichment from the WWTP. NO_3-N retention in Spavinaw Creek and NH_4-N retention in Columbia Hollow were regulated by the level of N additions from the WWTP. Thus, variations in discharge and PS inputs can substantially impact nutrient transport from PS impacted streams to downstream aquatic environments. Fluctuations in the seasonal patterns of nutrient retention should be considered in water quality management because these processes can influence the timing, quantity and quality of nutrients transported from the PS.

In the NPS impacted streams, variation in catchment land use was not a major determinant in nutrient retention in Cherokee Creek, Cloud Creek and Dry Creek; instead stream hydrology was the dominant regulating factor of nutrient uptake. Therefore, land use changes that alter stream hydrology can impact nutrient retention in this system (Meyer et al., 1999). However, NPS pollution is responsible for a large fraction of the nutrient loading, especially during surface runoff events. Regardless, watershed management strategies should consider stream hydrology and the potential impact of land use alterations on its properties to maintain or meet water quality goals. Particularly in the Lake Eucha Basin, watershed management should address PS inputs because the impact of WWTP effluents on lotic ecosystems substantially reduces their ability to withstand and recover from other disturbances, such as NPS pollution.

In the last 25 years water quality concerns have focused on NPS pollution but this shift of focus may be premature given that PS pollution reduces stream nutrient retention by orders of magnitude, i.e. km-scale S_w. The impact of PS pollution on nutrient retention is not just a local or regional concern but is an international problem.

RECOMMENDATIONS

Further investigations within the Eucha-Spavinaw Basin should examine nutrient retention across a gradient of stream size and watershed land use to ascertain the effects of increased agriculture and watershed alterations. Investigations should also be expanded to include variations over the annual cycle and through succession following floods. Specific mechanisms or processes of nutrient uptake should also be studied within a particular nutrient's cycle or spiral. For example, NH_4-N retention in Columbia Hollow was similar to other streams despite high levels of enrichment, but P retention was reduced by several orders of magnitude. Furthermore, N transformations in Columbia Hollow resulted in NO_3-N increases in Spavinaw Creek despite minimal NO_3-N inputs from the PS. Although one nutrient may be of concern (or of more concern) in this basin such as P, another nutrient may be a problem further downstream, i.e. N loading into the Gulf of Mexico, so N and P should be examined simultaneously.

Long-term monitoring of nutrient retention within PS impacted streams should be conducted; thus, remediation of these systems could be monitored if future actions are taken to reduce PS inputs within this basin. In fact, P limits on WWTP effluent should be included in the current National Pollution Discharge Elimination System Permit.

Future investigations should not just focus on surface water chemistry because several studies have shown the importance of other ecotones within the stream system, such as hyporheic or riparian zones. Processes in the total stream ecosystem interact to produce changes in surface water chemistry. In this basin the significance of these other compartments are not completely known.

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APPENDIX

SPAVINAW CREEK

Spavinaw Creek Raw Data

13-Aug-98

Site	SRP (mg L^{-1})	NO_3-N (mg L^{-1})
1 1	0.023	2.14
1 2	0.022	2.16
1 3	0.022	2.15
2 1	0.419	2.74
2 2	0.461	2.77
2 3	0.467	2.77
3 1	0.394	2.73
3 2	0.423	2.71
3 3	0.423	2.71
4 1	0.375	2.67
4 2	0.384	2.70
4 3	0.386	2.68
5 1	0.370	2.66
5 2	0.373	2.85
5 3	0.375	2.65
6 1	0.330	2.67
6 2	0.344	2.62
6 3	0.353	2.66
7 1	0.303	2.67
7 2	0.328	2.58
7 3	0.324	2.61
D 1	2.436	5.68
D 2	2.809	5.62
D 3	2.381	5.65

27-Aug-98

Site	SRP (mg L^{-1})	NO_3-N (mg L^{-1})
1 1	0.023	2.05
1 2	0.020	2.06
1 3	0.021	2.02
2 1	0.472	2.69
2 2	0.505	2.77
2 3	0.527	2.78
3 1	0.475	2.72
3 2	0.453	2.73
3 3	0.455	2.70
4 1	0.428	2.72
4 2	0.427	2.68
4 3	0.427	2.67
5 1	0.403	2.61
5 2	0.391	2.64
5 3	0.408	2.63
6 1	0.371	2.61
6 2	0.376	2.64
6 3	0.371	2.63
7 1	0.348	2.56
7 2	0.338	2.55
7 3	0.341	2.53
D 1	2.544	5.96
D 2	2.636	5.94
D 3	2.619	5.92

10-Sep-98

Site	TRP (mg L^{-1})	SRP (mg L^{-1})	NO_3-N (mg L^{-1})
1 1	0.022	0.023	1.97
1 2	0.022	0.018	1.95
1 3	0.022	0.023	1.98
2 1	0.533	0.528	2.63
2 2	0.539	0.534	2.65
2 3	0.546	0.533	2.68
3 1	0.509	0.511	2.59
3 2	0.529	0.498	2.60
3 3	0.529	0.501	2.61
4 1	0.484	0.473	2.60
4 2	0.499	0.491	2.58
4 3	0.489	0.480	2.60
5 1	0.472	0.460	2.53
5 2	0.479	0.460	2.54
5 3	0.472	0.458	2.54
6 1	0.400	0.411	2.54
6 2	0.427	0.411	2.53
6 3	0.430	0.414	2.52
7 1	0.368	0.355	2.44
7 2	0.380	0.371	2.42
7 3	0.383	0.366	2.40
D 1	2.679	2.630	5.56
D 2	2.537	2.655	5.57
D 3	2.621	2.688	5.55

9-Aug-99

Site	SRP (mg L^{-1})	NO_3-N (mg L^{-1})
1 1	0.030	3.558
1 2	0.031	3.575
1 3	0.032	3.564
2 1	0.238	3.822
2 2	0.245	3.799
2 3	0.235	3.788
3 1	0.230	3.818
3 2	0.231	3.802
3 3	0.232	3.772
4 1	*	*
4 2	*	*
4 3	*	*
5 1	0.228	3.740
5 2	0.229	3.751
5 3	0.226	3.747
6 1	0.213	3.766
6 2	0.225	3.716
6 3	0.226	3.692
7 1	0.214	3.623
7 2	0.210	3.677
7 3	0.220	3.613
D 1	1.375	5.399
D 2	1.391	5.302
D 3	1.396	5.415

28-Aug-99

Site	SRP (mg L^{-1})	NO_3-N (mg L^{-1})
1 1	0.025	3.41
1 2	0.026	3.41
1 3	0.024	3.42
2 1	0.289	3.81
2 2	0.291	3.74
2 3	0.293	3.74
3 1	0.277	3.73
3 2	0.280	3.76
3 3	0.283	3.77
4 1	0.272	3.73
4 2	0.269	3.74
4 3	0.275	3.71
5 1	0.256	3.72
5 2	0.261	3.70
5 3	0.266	3.71
6 1	0.259	3.66
6 2	0.257	3.66
6 3	0.263	3.71
7 1	0.250	3.64
7 2	0.248	3.70
7 3	0.247	3.69
D 1	1.795	5.63
D 2	1.819	5.59
D 3	1.834	5.60

9-Sep-99

Site	TRP (mg L^{-1})	SRP (mg L^{-1})	NO_3-N (mg L^{-1})
1 1		0.028	3.15
1 2	0.028	0.027	3.14
1 3		0.027	3.19
2 1		0.305	3.47
2 2	0.320	0.319	3.52
2 3		0.337	3.55
3 1		0.288	3.46
3 2	0.309	0.304	3.49
3 3		0.314	3.45
4 1		0.294	3.43
4 2	0.298	0.296	3.46
4 3		0.297	3.43
5 1		0.280	3.43
5 2	0.291	0.287	3.44
5 3		0.282	3.40
6 1		0.273	3.42
6 2	0.274	0.276	3.40
6 3		0.277	3.37
7 1		0.256	3.38
7 2	0.268	0.264	3.39
7 3		0.262	3.42
D 1		1.529	5.11
D 2	1.851	1.819	5.14
D 3		1.893	5.16

TRP - Total Reactive Phosphorus
SRP - Soluble Reactive Phosphorus
NO_3-N - Nitrate-N

Site 1 - Upstream of Columbia Hollow
Site 2 - Downstream of Columbia Hollow (0.2 km)
Site 3 - 0.4 km downstream
Site 4 - 0.8 km downstream
Site 5 - 1.1 km downstream
Site 6 - 2.5 km downstream
Site 7 - 3.5 km downstream
Site D - Columbia Hollow

Tripilicate Samples Per Site

Spavinaw Creek Raw Data

13-Aug-98

Site	pH	Cond (uS cm^{-1})	Temp (deg C)	Q (L s^{-1})
1	7.1	272	22	479
2	7.1	318	21	682
3	6.7	334	23	495
4	7.0	335	23	574
5	7.3	295	27	656
6	6.9	315	24	556
7	6.9	338	24	588
D	7.1	470	19	14

27-Aug-98

Site	pH	Cond (uS cm^{-1})	Temp (deg C)	Q (L s^{-1})
1	7.2	306	24	375
2	7.4	325	24	500
3	7.2	290	24	397
4	7.4	305	24	508
5	7.8	295	27	499
6	7.3	300	26	483
7	7.7	300	26	445
D	7.2	454	23	12

10-Sep-98

Site	pH	Cond (uS cm^{-1})	Temp (deg C)	Q (L s^{-1})
1	7.3	289	22	267
2	6.8	335	22	417
3	7.1	310	23	317
4	7.2	309	23	394
5	7.2	300	24	361
6	7.3	299	24	423
7	7.4	299	24	372
D	7.0	466	21	11

9-Aug-99

Site	pH	Cond (uS cm^{-1})	Temp (deg C)	Q (L s^{-1})
1	8.0	282	23	1110
2	7.9	291	22	1312
3	7.9	290	23	976
4				
5	8.1	296	23	1237
6	8.2	300	24	1432
7	8.3	301	24	1231
D	7.5	344	20	86

26-Aug-99

Site	pH	Cond (uS cm^{-1})	Temp (deg C)	Q (L s^{-1})
1	7.7	281	21	643
2	7.7	295	21	966
3	7.7	299	22	855
4	7.7	301	22	744
5	7.8	300	22	895
6	7.7	302	23	914
7	7.7	302	23	705
D	7.5	368	19	50

9-Sep-99

Site	pH	Cond (uS cm^{-1})	Temp (deg C)	Q (L s^{-1})
1	7.8	273	20	791
2	7.7	291	20	1011
3	7.8	294	21	857
4	7.9	298	22	1132
5	8.0	298	22	1012
6	8.2	299	22	1167
7	8.3	299	22	1006
D	7.5	368	19	68

Cond - Conductivity
Temp - Temperature
Q - Discharge

Site 1 - Upstream of Columbia Hollow
Site 2 - Downstream of Columbia Hollow (0.2 km)
Site 3 - 0.4 km downstream
Site 4 - 0.8 km downstream
Site 5 - 1.1 km downstream
Site 6 - 2.5 km downstream
Site 7 - 3.5 km downstream
Site D - Columbia Hollow

Tripilicate Samples Per Site

Uptake Length Calculations - Spavinaw Creek 13 August 1998

Site	Distance (km)	SRP_{corr} (mg L^{-1})	NO_3-N_{corr} (mg L^{-1})	Ln(SRP_{corr})	Ln(NO_3-N_{corr})
2	0.2	0.427	0.610	0.000	0.000
3	0.4	0.391	0.567	-0.086	-0.074
4	0.8	0.360	0.533	-0.171	-0.134
5	1.1	0.351	0.503	-0.196	-0.192
6	2.5	0.320	0.500	-0.287	-0.199
7	3.5	0.296	0.437	-0.364	-0.334

SRP Uptake Length (km)
10.4

NO3 Uptake Length (km)
12.3

SRP Uptake Length Regression
SUMMARY OUTPUT

Regression Statistics	
Multiple R	0.948142839
R Square	0.898974844
Adjusted R Square	0.873718555
Standard Error	0.046824372
Observations	6

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	1	0.078040839	0.078040839	35.594099	0.00396402
Residual	4	0.008770087	0.002192522		
Total	5	0.086810926			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 95.0%*	*Upper 95.0%*
Intercept	-0.06744874	0.027329009	-2.46802731	0.0690929	-0.14332639	0.0084289	-0.14332639	0.00842891
X Variable 1	-0.095772035	0.01605276	-5.966079003	0.003964	-0.14034173	-0.0512023	-0.140341735	-0.05120234

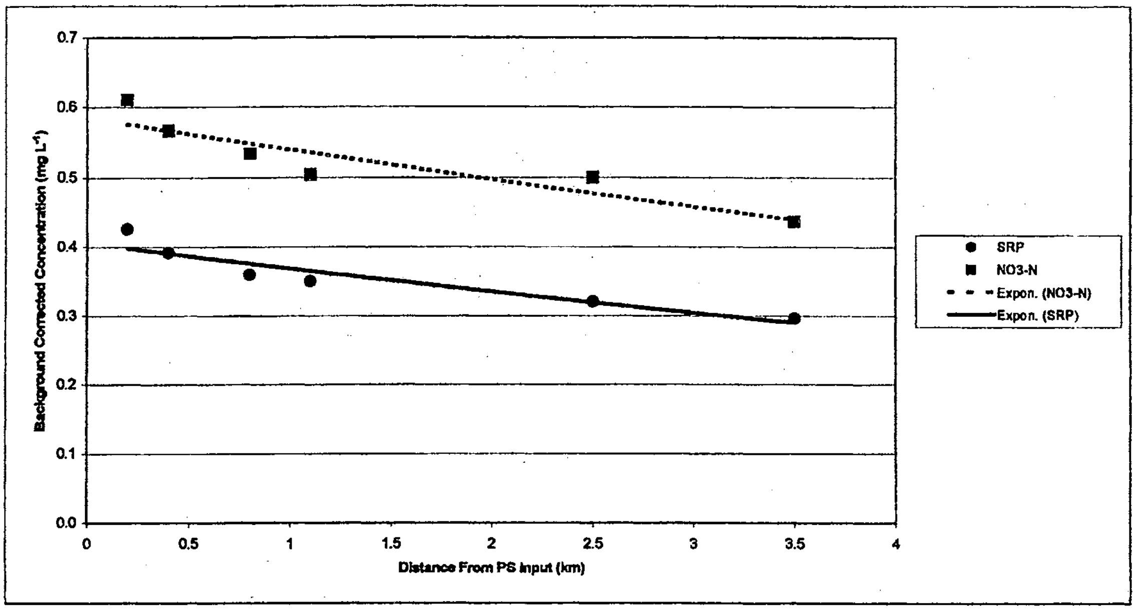
NO_3-N Uptake Length Regression
SUMMARY OUTPUT

Regression Statistics	
Multiple R	0.921529629
R Square	0.849218857
Adjusted R Square	0.811521071
Standard Error	0.050073107
Observations	6

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	1	0.056485229	0.056485229	22.528164	0.0089948
Residual	4	0.010029264	0.002507316		
Total	5	0.066514493			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 95.0%*	*Upper 95.0%*
Intercept	-0.056425005	0.029225131	-1.930701561	0.1257139	-0.13756714	0.0247171	-0.137567144	0.024717134
X Variable 1	-0.081476908	0.017166521	-4.746384346	0.0089948	-0.12914091	-0.0338169	-0.12914091	-0.03381691



Uptake Length Calculations - Spavinaw Creek 27 August 1998

Site	Distance (km)	SRP_{corr} (mg L^{-1})	NO_3-N_{corr} (mg L^{-1})	Ln(SRP_{corr})	Ln(NO_3-N_{corr})
2	0.2	0.480	0.703	0.000	0.000
3	0.4	0.440	0.673	-0.088	-0.044
4	0.8	0.406	0.647	-0.167	-0.084
5	1.1	0.379	0.583	-0.235	-0.187
6	2.5	0.351	0.583	-0.312	-0.187
7	3.5	0.321	0.503	-0.402	-0.335

SRP Uptake Length (km)
9.4

NO3 Uptake Length (km)
11.4

SRP Uptake Length regression
SUMMARY OUTPUT

Regression Statistics	
Multiple R	0.946772142
R Square	0.896377489
Adjusted R Square	0.670471862
Standard Error	0.052992702
Observations	6

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	1	0.097169271	0.097169271	34.601651	0.0041744
Residual	4	0.011232906	0.002808228		
Total	5	0.108402176			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 95.0%*	*Upper 95.0%*
Intercept	-0.070807002	0.03092915	-2.28932909	0.0839191	-0.15668027	0.0150663	-0.156680265	0.015066262
X Variable 1	-0.106866657	0.018167443	-5.882316815	0.0041744	-0.15730767	-0.0564256	-0.15730767	-0.05642564

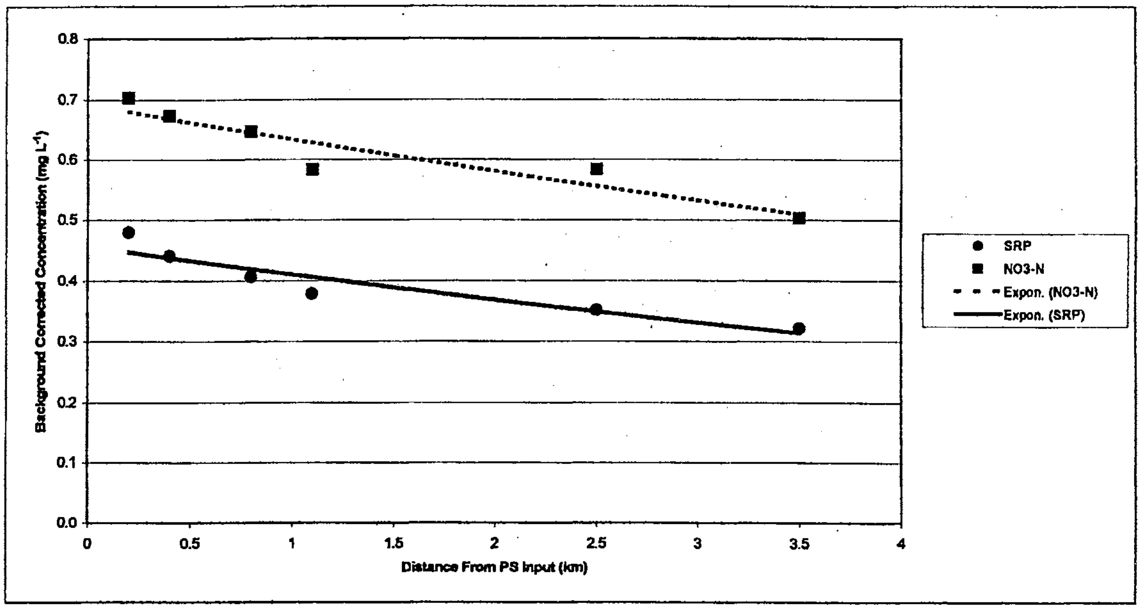
NO_3-N Uptake Length Regression
SUMMARY OUTPUT

Regression Statistics	
Multiple R	0.936042755
R Square	0.876176039
Adjusted R Square	0.845220049
Standard Error	0.047965351
Observations	6

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	1	0.065118131	0.065118131	28.303925	0.00600498
Residual	4	0.0092027	0.002300675		
Total	5	0.074320831			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 95.0%*	*Upper 95.0%*
Intercept	-0.032946617	0.02799494	-1.176877548	0.3044943	-0.11067319	0.04478	-0.110673193	0.044779959
X Variable 1	-0.087484017	0.016443921	-5.320143366	0.006005	-0.13313976	-0.0418283	-0.133139756	-0.04182828



Uptake Length Calculations - Spavinaw Creek 10 September 1998

Site	Distance (km)	SRP_{corr} (mg L^{-1})	NO_3-N_{corr} (mg L^{-1})	Ln(SRP_{corr})	Ln(NO_3-N_{corr})
2	0.2	0.510	0.687	0.000	0.000
3	0.4	0.482	0.633	-0.057	-0.081
4	0.6	0.460	0.627	-0.104	-0.091
5	1.1	0.438	0.570	-0.153	-0.186
6	2.5	0.391	0.563	-0.267	-0.198
7	3.5	0.343	0.453	-0.398	-0.415

SRP Uptake Length (km)
9.0

NO3 Uptake Length (km)
9.6

SRP Uptake Length Regression
SUMMARY OUTPUT

Regression Statistics	
Multiple R	0.991544861
R Square	0.983161211
Adjusted R Square	0.978951514
Standard Error	0.021284034
Observations	6

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	1	0.105799048	0.105799048	233.546776	0.00010693
Residual	4	0.00181204	0.00045301		
Total	5	0.107611088			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 95.0%*	*Upper 95.0%*
Intercept	-0.027547693	0.01242241	-2.217580379	0.090856413	-0.0620379	0.006942518	-0.062037904	0.006942518
X Variable 1	-0.111511236	0.007296787	-15.28223727	0.000106932	-0.13177041	-0.091252065	-0.131770408	-0.09125206

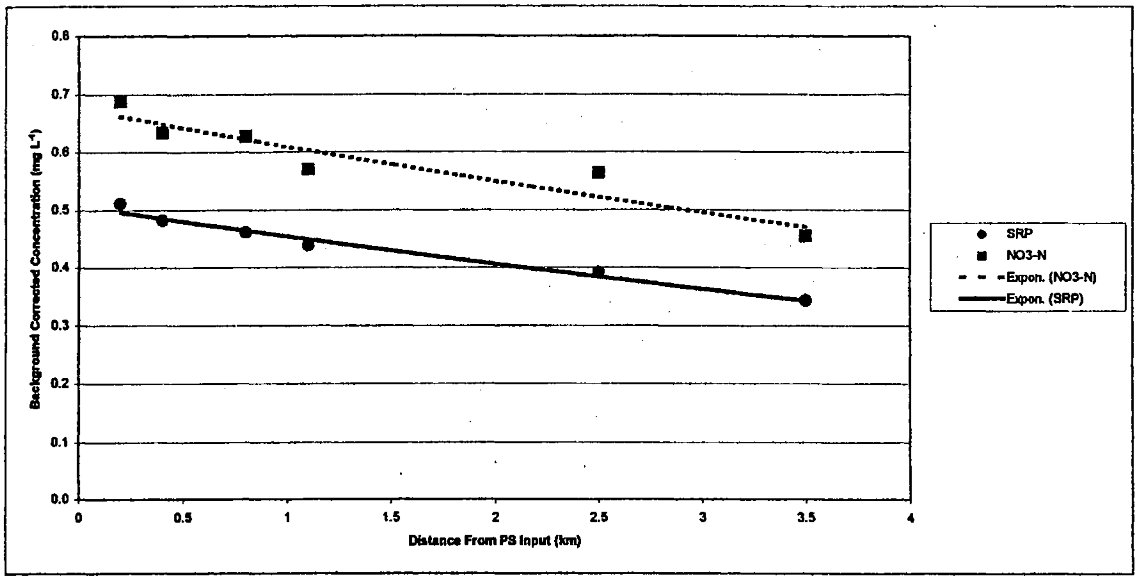
NO_3-N Uptake Length Regression
SUMMARY OUTPUT

Regression Statistics	
Multiple R	0.938449578
R Square	0.88068761
Adjusted R Square	0.850859513
Standard Error	0.055645836
Observations	6

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	1	0.091424308	0.091424308	29.52543695	0.00556609
Residual	4	0.012385836	0.003096459		
Total	5	0.103810144			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 95.0%*	*Upper 95.0%*
Intercept	-0.0358307	0.03247765	-1.103241797	0.331830048	-0.1260033	0.054341897	-0.126003298	0.054341897
X Variable 1	-0.103659377	0.019077015	-5.433731402	0.005566091	-0.15662577	-0.050692981	-0.156625772	-0.05069298



Uptake Length Calculations - Spavinaw Creek 9 August 1999

Site	Distance (km)	SRP_{corr} (mg L^{-1})	NO_3-N_{corr} (mg L^{-1})	Ln(SRP_{corr})	Ln(NO_3-N_{corr})
2	0.2	0.208	0.237	0.000	0.000
3	0.4	0.200	0.232	-0.038	-0.024
4	0.8				
5	1.1	0.196	0.180	-0.058	-0.275
6	2.5	0.190	0.159	-0.089	-0.402
7	3.5	0.184	0.072	-0.125	-1.199

SRP Uptake Length (km)
30.8

NO3 Uptake Length (km)
3.1

SRP Uptake Length Regression
SUMMARY OUTPUT

Regression Statistics	
Multiple R	0.965587268
R Square	0.932358772
Adjusted R Square	0.909811696
Standard Error	0.0143346
Observations	5

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	1	0.008496968	0.008496968	41.351649	0.00762356
Residual	3	0.000616442	0.000205481		
Total	4	0.00911341			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 95.0%*	*Upper 95.0%*
Intercept	-0.018236396	0.009323007	-1.956063783	0.1454098	-0.04790639	0.0114336	-0.047906393	0.011433601
X Variable 1	-0.032484793	0.005051655	-6.430524788	0.0076236	-0.04856143	-0.0164082	-0.048561429	-0.01640816

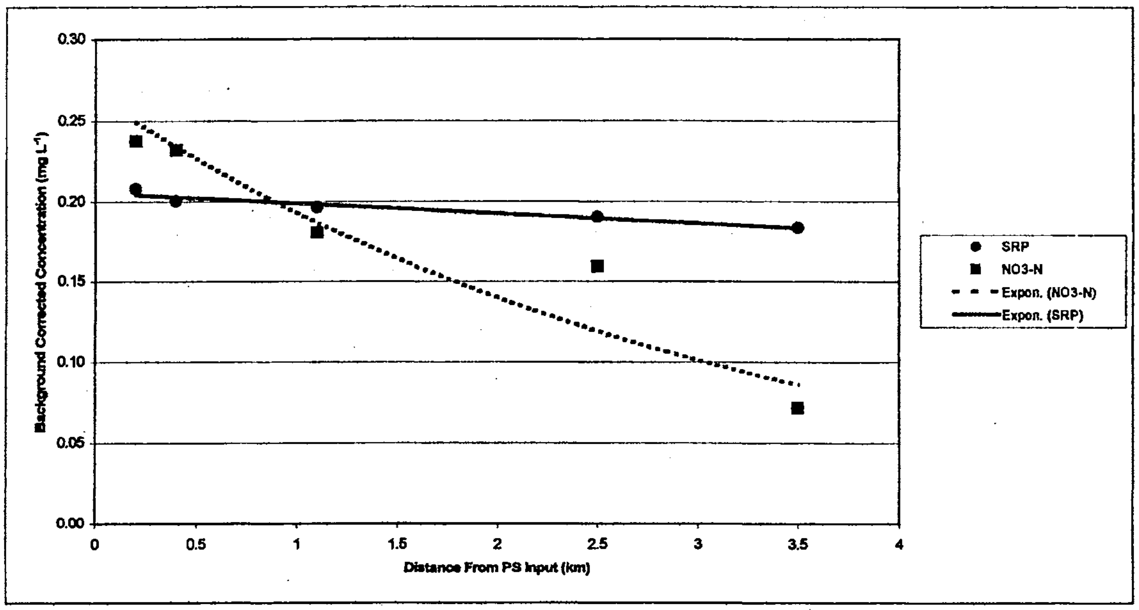
NO_3-N Uptake Length Regression
SUMMARY OUTPUT

Regression Statistics	
Multiple R	0.933977496
R Square	0.872313963
Adjusted R Square	0.82975195
Standard Error	0.201337168
Observations	5

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	1	0.830804007	0.830804007	20.49513	0.02016153
Residual	3	0.121609966	0.040536655		
Total	4	0.952413973			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 95.0%*	*Upper 95.0%*
Intercept	0.050363427	0.130946651	0.384610275	0.726171	-0.36636765	0.4670945	-0.366367649	0.467094503
X Variable 1	-0.321216176	0.070953214	-4.527154696	0.0201615	-0.54702118	-0.0954112	-0.547021182	-0.09541117



Uptake Length Calculations - Spavinaw Creek 26 August 1999

Site	Distance (km)	SRP_{corr} (mg L^{-1})	NO_3-N_{corr} (mg L^{-1})	Ln(SRP_{corr})	Ln(NO_3-N_{corr})
2	0.2	0.266	0.354	0.000	0.000
3	0.4	0.255	0.341	-0.043	-0.036
4	0.8	0.247	0.317	-0.075	-0.111
5	1.1	0.236	0.296	-0.119	-0.177
6	2.5	0.235	0.263	-0.125	-0.295
7	3.5	0.223	0.263	-0.175	-0.296

SRP Uptake Length (km)
22.8

NO3 Uptake Length (km)
11.0

SRP Uptake Length Regression
SUMMARY OUTPUT

Regression Statistics	
Multiple R	0.906769969
R Square	0.822231777
Adjusted R Square	0.777789722
Standard Error	0.029715309
Observations	6

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	1	0.01633656	0.01633656	18.501209	0.01263259
Residual	4	0.003531998	0.000883		
Total	5	0.019868559			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 95.0%*	*Upper 95.0%*
Intercept	-0.03623127	0.017343317	-2.089062315	0.1049419	-0.08438414	0.0119216	-0.084384138	0.011921598
X Variable 1	-0.043818556	0.010187274	-4.301303217	0.0126326	-0.07210302	-0.0155341	-0.072103023	-0.01553409

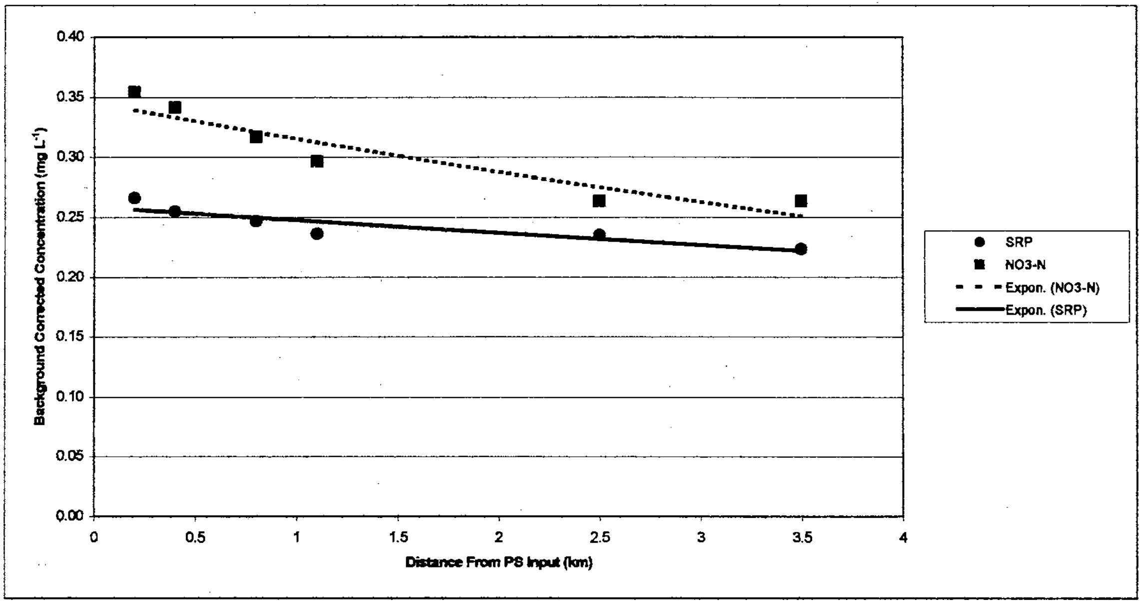
NO_3-N Uptake Length Regression
SUMMARY OUTPUT

Regression Statistics	
Multiple R	0.939137067
R Square	0.88197843
Adjusted R Square	0.852473038
Standard Error	0.048599642
Observations	6

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	1	0.070602927	0.070602927	29.89211	0.00544372
Residual	4	0.009447701	0.002361925		
Total	5	0.080050628			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 95.0%*	*Upper 95.0%*
Intercept	-0.041692955	0.028365144	-1.469865825	0.215541	-0.12044738	0.0370615	-0.120447382	0.037061472
X Variable 1	-0.09109386	0.016661374	-5.46736772	0.0054437	-0.13735335	-0.0448344	-0.137353347	-0.04483437



Uptaka Length Calculations - Spavinaw Creek 9 September 1999

Site	Distance (km)	SRP_{corr} (mg L^{-1})	NO_3-N_{corr} (mg L^{-1})	Ln(SRP_{corr})	Ln(NO_3-N_{corr})
2	0.2	0.293	0.356	0.000	0.000
3	0.4	0.274	0.304	-0.064	-0.156
4	0.8	0.268	0.282	-0.087	-0.231
5	1.1	0.255	0.263	-0.136	-0.302
6	2.5	0.247	0.237	-0.168	-0.405
7	3.5	0.233	0.235	-0.226	-0.415

SRP Uptake Length (km)
17.2

NO3 Uptake Length (km)
9.4

SRP Uptake Length Regression
SUMMARY OUTPUT

Regression Statistics	
Multiple R	0.938818085
R Square	0.881379396
Adjusted R Square	0.851724245
Standard Error	0.031040253
Observations	6

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	1	0.02863606	0.02863606	29.720955	0.00550033
Residual	4	0.003853989	0.000963497		
Total	5	0.032490049			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 95.0%*	*Upper 95.0%*
Intercept	-0.043361775	0.01811662	-2.393480436	0.0748842	-0.09366168	0.006938129	-0.09366168	0.006938129
X Variable 1	-0.05601421	0.010641504	-5.451692824	0.0055003	-0.08755982	-0.028468598	-0.087559822	-0.0284686

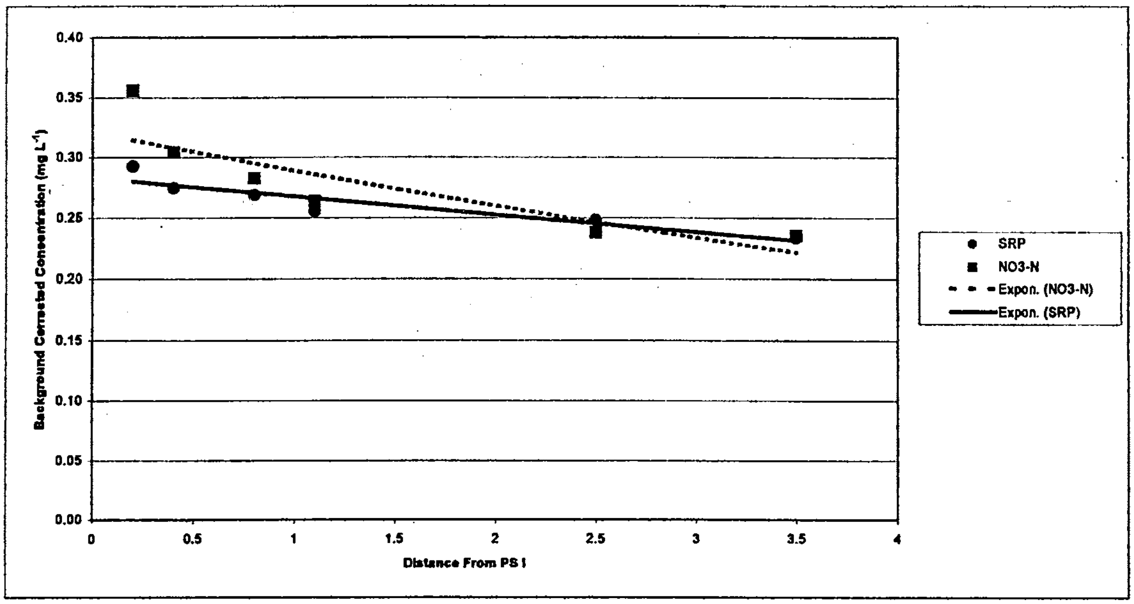
NO_3-N Uptake Length Regression
SUMMARY OUTPUT

Regression Statistics	
Multiple R	0.876135244
R Square	0.767612966
Adjusted R Square	0.709516208
Standard Error	0.085386998
Observations	6

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	1	0.096332734	0.096332734	13.212664	0.02206352
Residual	4	0.029163757	0.007290939		
Total	5	0.125496492			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 95.0%*	*Upper 95.0%*
Intercept	-0.122115571	0.049836056	-2.450345829	0.0704191	-0.26048293	0.016251788	-0.26048293	0.016251788
X Variable 1	-0.106405652	0.029273153	-3.634922875	0.0220635	-0.18768112	-0.025130182	-0.187681121	-0.02513018



COLUMBIA HOLLOW

Columbia Hollow Raw Data (1 of 2)

17-Jun-99

Site	DIN (mg L^{-1})	NO_3-N (mg L^{-1})	NH_4-N (mg L^{-1})	Cl^- (mg L^{-1})	SRP (mg L^{-1})
CH-2	7.07	7.01	0.06	20.67	1.94
CH-2	7.07	7.00	0.07	20.92	1.94
CH-2	7.11	7.05	0.06	20.42	1.96
CH-3	7.48	7.34	0.14	21.68	2.15
CH-3	7.54	7.39	0.15	21.84	2.16
CH-3	7.46	7.32	0.14	21.79	2.11
CH-4	7.50	7.19	0.31	21.83	2.11
CH-4	7.34	7.05	0.29	21.74	2.13
CH-4	7.36	7.05	0.31	22.15	2.11
CH-5	7.37	6.85	0.52	21.74	2.15
CH-5	7.40	8.87	0.53	21.92	2.14
CH-5	7.49	8.91	0.58	22.32	2.12
CH-6	7.57	5.58	1.99	23.44	2.67
CH-6	7.51	5.54	1.97	22.95	2.66
CH-6	7.45	5.51	1.94	23.91	2.65
CH-7	7.82	5.10	2.72	23.15	2.73
CH-7	7.79	5.04	2.75	23.36	2.75
CH-7	7.78	5.04	2.74	23.19	2.75
UP-CH	5.34	5.34	0.00	6.69	0.06
UP-CH	5.37	5.37	0.00	6.65	0.06
UP-CH	5.41	5.39	0.02	6.76	0.06
GW-6	8.65	8.65	0.00	21.37	0.77
GW-6	8.62	8.62	0.00	21.40	0.75
GW-6	8.58	8.58	0.00	21.55	0.75

23-Jul-99

Site	DIN (mg L^{-1})	NO_3-N (mg L^{-1})	NH_4-N (mg L^{-1})	Cl^- (mg L^{-1})	SRP (mg L^{-1})
CH-2	6.79	6.65	0.14	25.50	1.88
CH-2	6.73	6.62	0.11	26.45	1.93
CH-2	6.78	6.65	0.13	24.15	1.88
CH-3	6.84	6.56	0.29	26.08	2.33
CH-3	6.83	6.56	0.27	26.54	2.22
CH-3	6.85	6.57	0.28	26.41	2.19
CH-4	6.85	6.40	0.45	28.18	2.33
CH-4	6.90	6.34	0.55	31.81	2.37
CH-4	6.82	6.35	0.46	29.52	2.37
CH-5	6.81	6.19	0.62	28.29	2.40
CH-5	6.76	6.15	0.62	30.48	2.33
CH-5	6.77	6.15	0.62	*	2.36
CH-6	6.21	4.70	1.51	30.11	3.27
CH-6	6.27	4.76	1.51	29.59	3.28
CH-6	6.22	4.77	1.45	29.58	3.30
CH-7	6.51	4.64	1.87	29.07	3.42
CH-7	6.61	4.69	1.92	*	3.45
CH-7	6.57	4.66	1.91	33.65	3.55
UP-CH	4.45	4.41	0.04	5.87	0.07
UP-CH	4.45	4.42	0.03	5.66	0.06
UP-CH	4.49	4.46	0.03	5.68	0.06
GW-6	7.39	7.37	0.02	21.42	0.76
GW-6	7.40	7.36	0.04	21.39	0.76
GW-6	8.40	8.38	0.02	21.45	0.59

11-Aug-99

Site	DIN (mg L^{-1})	NO_3-N (mg L^{-1})	NH_4-N (mg L^{-1})	Cl^- (mg L^{-1})	SRP (mg L^{-1})
CH-2	6.37	6.33	0.04	31.64	2.62
CH-2	6.41	6.30	0.11	27.28	2.65
CH-2	8.45	6.39	0.07	29.94	2.67
CH-3	6.31	6.24	0.07	29.56	2.86
CH-3	6.26	6.19	0.07	29.72	2.88
CH-3	6.22	6.15	0.06	30.50	2.89
CH-4	6.16	6.09	0.07	29.99	2.86
CH-4	6.19	6.12	0.07	30.90	2.87
CH-4	6.20	6.12	0.08	31.22	2.87
CH-5	6.35	6.23	0.12	30.81	2.86
CH-5	6.37	6.22	0.15	29.73	2.90
CH-5	6.37	6.25	0.13	31.03	2.87
CH-6	5.41	4.94	0.47	36.90	4.41
CH-6	5.37	4.91	0.46	35.83	4.35
CH-6	5.13	4.74	0.39	34.95	4.32
CH-7	5.61	4.59	1.02	35.16	4.54
CH-7	5.60	4.58	1.02	35.23	4.61
CH-7	5.60	4.59	1.01	38.08	4.50
UP-CH	4.32	4.24	0.08	5.95	0.18
UP-CH	4.35	4.26	0.09	6.10	0.16
UP-CH					
GW-6	7.38	7.33	0.05	22.63	0.75
GW-6	7.53	7.49	0.04	22.40	0.83
GW-6	7.44	7.40	0.04	22.67	0.81

21-Oct-99

Site	DIN (mg L^{-1})	NO_3-N (mg L^{-1})	NH_4-N (mg L^{-1})	Cl^- (mg L^{-1})	SRP (mg L^{-1})
CH-2	11.16	10.87	0.29	51.49	4.46
CH-2	11.19	10.89	0.30	57.78	4.45
CH-2	11.19	10.89	0.30	52.84	4.48
CH-3	11.38	10.82	0.56	55.15	4.94
CH-3	11.37	10.83	0.54	62.28	4.95
CH-3	11.48	10.92	0.56	60.86	4.96
CH-4	11.26	10.13	1.13	55.30	4.99
CH-4	11.25	10.13	1.12	54.34	4.92
CH-4	11.30	10.25	1.05	51.37	4.91
CH-5	11.45	9.42	2.03	55.77	4.95
CH-5	11.28	9.40	1.88	52.31	4.94
CH-5	11.32	9.47	1.85	52.75	4.97
CH-6	14.30	8.96	5.34	57.01	7.16
CH-6	14.38	8.91	5.47	65.34	7.19
CH-6	14.23	8.92	5.31	63.36	7.17
CH-7	15.57	8.37	7.20	69.06	7.39
CH-7	15.42	8.46	6.96	67.63	7.31
CH-7	15.31	8.37	6.94	66.86	7.46
UP-CH	3.16	3.16	0.00	11.27	0.07
UP-CH	3.16	3.16	0.00	11.22	0.07
UP-CH	3.13	3.13	0.00	11.28	0.06
GW-6	8.62	6.62	0.00	30.35	0.88
GW-6	6.53	6.53	0.00	30.04	0.90
GW-6	6.33	6.33	0.00	30.20	0.92

Columbia Hollow Raw Data (2 of 2)

11-Nov-99

Site	DIN (mg L^{-1})	NO$_3$-N (mg L^{-1})	NH$_4$-N (mg L^{-1})	Cl$^-$ (mg L^{-1})	SRP (mg L^{-1})
CH-2	6.22	6.22	0.00	47.67	3.66
CH-2	6.21	6.21	0.00	47.67	3.74
CH-2	6.19	6.20	0.00	47.44	4.01
CH-3	6.21	6.19	0.01	48.73	4.09
CH-3	6.14	6.15	0.00	48.84	4.05
CH-3	6.26	6.24	0.03	48.97	4.09
CH-4	6.27	6.12	0.15	49.89	4.49
CH-4	6.20	6.09	0.11	48.68	4.44
CH-4	6.24	6.11	0.12	49.03	4.35
CH-5	6.43	5.81	0.63	49.71	4.40
CH-5	6.47	5.80	0.67	49.00	4.42
CH-5	6.40	5.89	0.51	49.44	4.48
CH-6	7.54	3.04	4.50	63.56	7.27
CH-6	7.30	3.06	4.24	63.95	7.41
CH-6	7.60	3.10	4.49	63.74	7.25
CH-7	8.26	2.54	5.71	84.91	7.65
CH-7	8.29	2.46	5.83	66.00	7.57
CH-7	8.30	2.53	5.77	65.03	7.50
UP-CH	3.07	3.03	0.04	16.56	0.15
UP-CH	3.11	3.07	0.04	18.55	0.24
UP-CH	3.10	3.10	0.00	16.74	0.12
GW-6	6.43	6.44	-0.01	32.01	1.12
GW-6	5.98	5.98	0.00	32.82	1.17
GW-6	6.24	6.23	0.01	31.97	1.02

22-Dec-99

Site	DIN (mg L^{-1})	NO$_3$-N (mg L^{-1})	NH$_4$-N (mg L^{-1})	Cl$^-$ (mg L^{-1})	SRP (mg L^{-1})
CH-2	10.99	9.98	1.01	38.50	1.86
CH-2	11.29	10.25	1.04	38.95	1.82
CH-2	10.97	9.92	1.05	38.84	1.86
CH-3	11.66	9.37	2.28	40.07	1.85
CH-3	11.45	9.19	2.26	40.42	1.84
CH-3	11.56	9.29	2.26	41.87	1.84
CH-4	11.73	8.49	3.24	41.14	1.85
CH-4	11.56	8.35	3.21	40.47	1.83
CH-4	11.82	6.56	3.26	40.75	1.83
CH-5	11.72	7.76	3.96	43.98	1.78
CH-5	11.62	7.76	3.86	40.37	1.76
CH-5	11.83	7.80	4.02	40.64	1.81
CH-6	13.70	4.83	8.87	49.80	2.22
CH-6	13.59	4.96	8.64	50.27	2.26
CH-6	13.87	4.91	8.96	50.50	2.26
CH-7	14.51	4.19	10.32	50.48	2.20
CH-7	14.19	4.21	9.99	51.42	2.25
CH-7	14.08	4.15	9.94	51.18	2.24
UP-CH	4.84	4.84	0.00	19.85	0.07
UP-CH	4.82	4.82	0.00	20.79	0.07
UP-CH	4.83	4.82	0.01	21.99	0.07
GW-6	9.33	9.30	0.03	22.89	0.78
GW-6	9.21	9.18	0.02	22.67	0.76
GW-6	9.02	8.98	0.04	21.42	0.84

28-Jan-00

Site	DIN (mg L^{-1})	NO$_3$-N (mg L^{-1})	NH$_4$-N (mg L^{-1})	Cl$^-$ (mg L^{-1})	SRP (mg L^{-1})
CH-2	11.73	11.47	0.26	49.87	2.06
CH-2	11.26	11.09	0.17	48.71	2.08
CH-2	11.38	11.21	0.17	48.69	2.09
CH-3	11.72	11.17	0.55	50.55	2.04
CH-3	11.31	10.76	0.55	50.12	1.98
CH-3	12.04	11.45	0.59	51.38	2.07
CH-4	12.23	11.22	1.01	52.53	2.03
CH-4	12.13	11.14	0.99	51.26	2.04
CH-4	12.06	11.16	0.90	51.27	2.03
CH-5	12.35	10.93	1.43	51.64	1.97
CH-5	12.20	10.90	1.29	51.73	1.99
CH-5	12.34	10.99	1.35	53.19	2.01
CH-6	14.79	10.36	4.43	66.77	2.62
CH-6	14.25	10.30	3.94	66.79	2.64
CH-6	15.21	10.42	4.79	66.80	2.64
CH-7	14.85	10.44	4.41	66.77	2.62
CH-7	15.11	10.60	4.51	67.98	2.77
CH-7	15.04	10.72	4.33	69.05	2.73
UP-CH	4.43	4.41	0.02	14.65	0.12
UP-CH	4.55	4.46	0.10	15.01	0.11
UP-CH	4.55	4.51	0.04	15.56	0.12

29-Feb-00

Site	DIN (mg L^{-1})	NO$_3$-N (mg L^{-1})	NH$_4$-N (mg L^{-1})	Cl$^-$ (mg L^{-1})	SRP (mg L^{-1})
CH-2	8.24	7.51	0.73	35.9	5.47
CH-2	8.20	7.49	0.71	35.6	5.44
CH-2	8.19	7.47	0.72	35.4	5.54
CH-3	8.83	6.90	1.93	39.0	7.09
CH-3	8.87	6.96	1.91	39.7	7.00
CH-3	8.84	6.93	1.91	39.4	7.00
CH-4	9.08	6.49	2.59	40.8	7.47
CH-4	9.09	8.54	2.55	41.5	7.40
CH-4	9.00	6.43	2.57	41.2	7.46
CH-5	9.24	6.27	2.97	41.1	7.31
CH-5	9.33	6.36	2.97	41.0	7.45
CH-5	9.30	6.31	2.99	41.3	7.33
CH-6	9.98	4.10	5.88	43.6	9.62
CH-6	10.07	4.16	5.91	45.0	9.74
CH-6	10.07	4.27	5.79	44.0	9.56
CH-7	10.40	3.73	6.67	44.6	9.89
CH-7	10.40	3.74	6.66	43.6	9.90
CH-7	10.40	3.76	6.84	44.6	9.84
UP-CH	5.47	5.47	0.00	7.5	0.117
UP-CH	5.31	5.31	0.00	7.4	0.109
UP-CH	5.38	5.38	0.00	7.5	0.124

UP-CH - Upstream of Decatur wastewater treatment plant
CH-7 - Downstream of Decatur wastewater treatment plant (0.3 km)
CH-6 - 0.8 km downstream
GW-6 - groundwater sepage 0.8 km downstream
CH-5 - 1.3 km downstream
CH-4 - 1.7 km downstream
CH-3 - 2.1 km downstream
CH-2 - 2.7 km downstream

DIN - Dissolved Inorganic Nitrogen
NO$_3$-N - Nitrate-N
NH$_4$-N - Ammonium-N
Cl$^-$ - Chloride
SRP - Soluble Reactive Phosphorus

Triplicate Samples Per Site

Date	Site	Temp (deg C)	pH	Cond (uS cm^{-1})
17-Jun-99	CH-2	17.8	7.5	286
17-Jun-99	CH-3	18.7	7.5	293
17-Jun-99	CH-4	19.5	7.3	299
17-Jun-99	CH-5	19.9	7.3	301
17-Jun-99	CH-6	22.0	7.4	305
17-Jun-99	CH-7	21.8	7.4	311
17-Jun-99	UP-CH	19.6	7.8	199
23-Jul-99	CH-2	23.0	7.5	318
23-Jul-99	CH-3	23.8	7.7	333
23-Jul-99	CH-4	24.2	7.5	341
23-Jul-99	CH-5	24.3	7.4	342
23-Jul-99	CH-6	27.3	7.5	358
23-Jul-99	CH-7	26.5	7.5	351
23-Jul-99	UP-CH	24.3	8.9	183
11-Aug-99	CH-2	24.1	7.4	377
11-Aug-99	CH-3	24.5	7.6	384
11-Aug-99	CH-4	24.7	7.5	386
11-Aug-99	CH-5	24.9	7.3	386
11-Aug-99	CH-6	29.5	7.3	427
11-Aug-99	CH-7	30.5	7.3	435
11-Aug-99	UP-CH	25.3	8.1	208
21-Oct-99	CH-2	16.1	7.4	417
21-Oct-99	CH-3	16.9	7.5	432
21-Oct-99	CH-4	17.7	7.3	439
21-Oct-99	CH-5	18.2	7.2	446
21-Oct-99	CH-6	20.6	7.3	534
21-Oct-99	CH-7	20.7	7.3	593
21-Oct-99	UP-CH	16.5	8.7	204

Date	Site	Temp (deg C)	pH	Cond (uS cm^{-1})
11-Nov-99	CH-2	16.1	7.5	375
11-Nov-99	CH-3	16.6	7.6	381
11-Nov-99	CH-4	17.1	7.4	388
11-Nov-99	CH-5	17.6	7.2	395
11-Nov-99	CH-6	20.2	7.4	479
11-Nov-99	CH-7	20.7	7.4	536
11-Nov-99	UP-CH	15.9	8.1	269
22-Dec-99	CH-2	8.7	7.5	430
22-Dec-99	CH-3	9.3	7.6	429
22-Dec-99	CH-4	9.8	7.5	446
22-Dec-99	CH-5	10.4	7.3	447
22-Dec-99	CH-6	10.2	7.5	495
22-Dec-99	CH-7	10.3	7.5	479
22-Dec-99	UP-CH	10.1	9.1	267
28-Jan-00	CH-2	7.1	7.5	457
28-Jan-00	CH-3	7.9	8.0	462
28-Jan-00	CH-4	7.9	8.8	467
28-Jan-00	CH-5	9.6	7.7	469
28-Jan-00	CH-6	9.3	7.7	529
28-Jan-00	CH-7	9.6	7.6	537
28-Jan-00	UP-CH	6.6	9.4	243
29-Feb-00	CH-2	13.3	7.7	428
29-Feb-00	CH-3	14.0	7.7	455
29-Feb-00	CH-4	14.3	7.5	464
29-Feb-00	CH-5	14.6	7.5	463
29-Feb-00	CH-6	15.7	7.5	495
29-Feb-00	CH-7	16.0	7.5	494
29-Feb-00	UP-CH	15.2	8.5	237

Temp - Temperature
Cond - Conductivity

Uptake Length Calculations - Columbia Hollow 17 June 1999

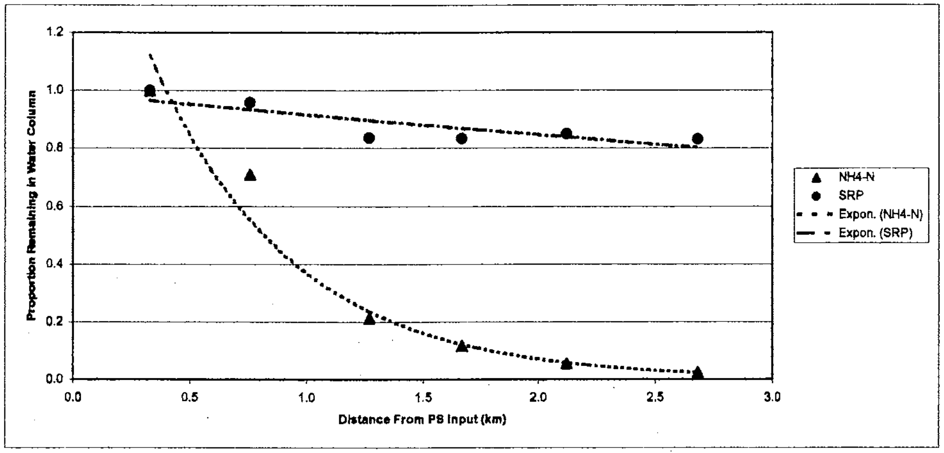
Proportion Remaining From PS Input

Distance (km)	DIN	NO$_3$-N	NH$_4$-N	SRP
2.66	0.84		0.02	0.83
2.12	0.96		0.05	0.85
1.67	0.91		0.12	0.83
1.27	0.91		0.21	0.84
0.76	0.87		0.71	0.96
0.33	1.00		1.00	1.00

Natural Logarithm of Proportion Remaining

Distance (km)	DIN	NO$_3$-N	NH$_4$-N	SRP
2.66	-0.18		-3.71	-0.18
2.12	-0.04		-2.90	-0.16
1.67	-0.10		-2.14	-0.18
1.27	-0.09		-1.55	-0.18
0.76	-0.14		-0.34	-0.04
0.33	0.00		0.00	0.00

	DIN	NO$_3$-N	NH$_4$-N	SRP
Sw (km)	25.70		0.61	12.72
P value	0.286		3.3E-05	0.038



DIN Uptake Length Regression
SUMMARY OUTPUT

Regression Statistics	
Multiple R	0.52201838
R Square	0.27250319
Adjusted R Square	0.09062899
Standard Error	0.08172391
Observations	6

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	1	0.005708307	0.005708	1.498306	0.2880983
Residual	4	0.015239362	0.00381		
Total	5	0.020947669			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 95.0%*	*Upper 95.0%*
Intercept	-0.0464502	0.044182025	-1.051336	0.352423	-0.169119	0.0762191	-0.1691194	0.07621905
X Variable 1	-0.0389105	0.031788234	-1.224053	0.288098	-0.127169	0.049348	-0.127169	0.04934798

NH$_4$-N Uptake Length Regression
SUMMARY OUTPUT

Regression Statistics	
Multiple R	0.99526875
R Square	0.99059571
Adjusted R Square	0.98824464
Standard Error	0.15623024
Observations	6

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	1	10.26396586	10.28397	421.3376	3.327E-05
Residual	4	0.09763155	0.024408		
Total	5	10.36159743			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 95.0%*	*Upper 95.0%*
Intercept	0.11263542	0.111629738	1.008993	0.370057	-0.197654	0.4233252	-0.1976543	0.4233252
X Variable 1	-1.6515561	0.080459643	-20.52651	3.33E-05	-1.874946	-1.428164	-1.8749463	-1.42616381

SRP Uptake Length Regression
SUMMARY OUTPUT

Regression Statistics	
Multiple R	0.83733004
R Square	0.70112159
Adjusted R Square	0.62640199
Standard Error	0.04981574
Observations	6

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	1	0.023285645	0.023	9.3834	0.03754
Residual	4	0.009926433	0.002		
Total	5	0.033212278			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 95.0%*	*Upper 95.0%*
Intercept	-0.0352642	0.035656151	-0.99	0.3784	-0.134287	0.0637169	-0.1342873	0.06371886
X Variable 1	-0.0785665	0.025655449	-3.063	0.0375	-0.14962	-0.007357	-0.1496196	-0.00735741

Uptake Length Calculations - Columbia Hollow 23 July 1999

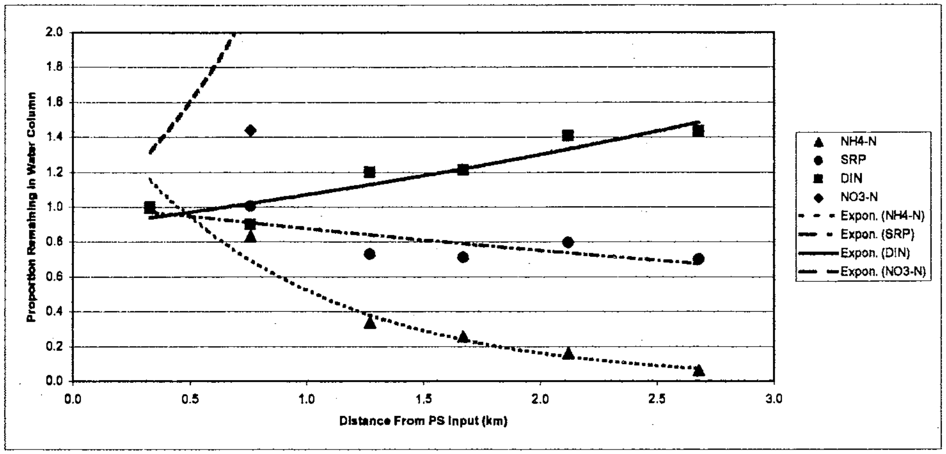
Proportion Remaining From PS Input

Distance (km)	DIN	NO_3-N	NH_4-N	SRP
2.68	1.43	12.41	0.06	0.70
2.12	1.41	11.40	0.16	0.80
1.67	1.21	8.64	0.26	0.71
1.27	1.20	6.07	0.34	0.73
0.76	0.90	1.44	0.83	1.01
0.33	1.00	1.00	1.00	1.00

Natural Logarithm of Proportion Remaining

Distance (km)	DIN	NO_3-N	NH_4-N	SRP
2.68	0.36	2.52	-2.76	-0.35
2.12	0.34	2.43	-1.83	-0.23
1.67	0.19	2.18	-1.35	-0.34
1.27	0.18	2.09	-1.08	-0.31
0.76	-0.10	0.37	-0.18	0.01
0.33	0.00	0.00	0.00	0.00

	DIN	NO_3-N	NH_4-N	SRP
Sw (km)	-5.14	-0.86	0.85	6.48
P value	0.010	0.013	2.E-04	0.053



DIN Uptake Length Regression
SUMMARY OUTPUT

Regression Statistics	
Multiple R	0.91531817
R Square	0.83780736
Adjusted R Square	0.7972592
Standard Error	0.08313744
Observations	6

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	1	0.142812516	0.143	20.682	0.0104529
Residual	4	0.027847333	0.007		
Total	5	0.170459849			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 95.0%*	*Upper 95.0%*
Intercept	-0.0608092	0.059509848	-1.018	0.388	-0.225835	0.104817	-0.2258353	0.10461701
X Variable 1	0.19462389	0.042816349	4.548	0.0105	0.0757484	0.3135014	0.0757464	0.31350138

NO_3-N Uptake Length Regression
SUMMARY OUTPUT

Regression Statistics	
Multiple R	0.90462993
R Square	0.81835532
Adjusted R Square	0.77294415
Standard Error	0.53042297
Observations	6

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	1	5.070185622	5.07	18.021	0.0132095
Residual	4	1.125394109	0.281		
Total	5	6.195579731			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 95.0%*	*Upper 95.0%*
Intercept	0.27370451	0.379677216	0.721	0.5109	-0.780451	1.3278596	-0.7804508	1.32785984
X Variable 1	1.15964467	0.273171463	4.245	0.0132	0.4011975	1.9180918	0.40119753	1.91809181

NH_4-N Uptake Length Regression
SUMMARY OUTPUT

Regression Statistics	
Multiple R	0.98985723
R Square	0.97942144
Adjusted R Square	0.9742768
Standard Error	0.16557104
Observations	6

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	1	5.218952231	5.219	190.38	0.0001599
Residual	4	0.109855071	0.027		
Total	5	5.328807302			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 95.0%*	*Upper 95.0%*
Intercept	0.14334377	0.118515889	1.209	0.2931	-0.18571	0.4723973	-0.1857098	0.47239731
X Variable 1	-1.1785345	0.085270217	-13.8	0.0002	-1.413283	-0.939786	-1.4132831	-0.93978593

SRP Uptake Length Regression
SUMMARY OUTPUT

Regression Statistics	
Multiple R	0.80646884
R Square	0.65038843
Adjusted R Square	0.56298554
Standard Error	0.10983797
Observations	6

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	1.	0.089774299	0.09	7.4413	0.0525583
Residual	4	0.048257521	0.012		
Total	5	0.13803182			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 95.0%*	*Upper 95.0%*
Intercept	-0.0273543	0.078622115	-0.348	0.7454	-0.245645	0.1909381	-0.2456447	0.19093815
X Variable 1	-0.1543082	0.058567308	-2.728	0.0526	-0.311365	0.0027481	-0.3113646	0.00274815

Uptake Length Calculations - Columbia Hollow 11 August 1999

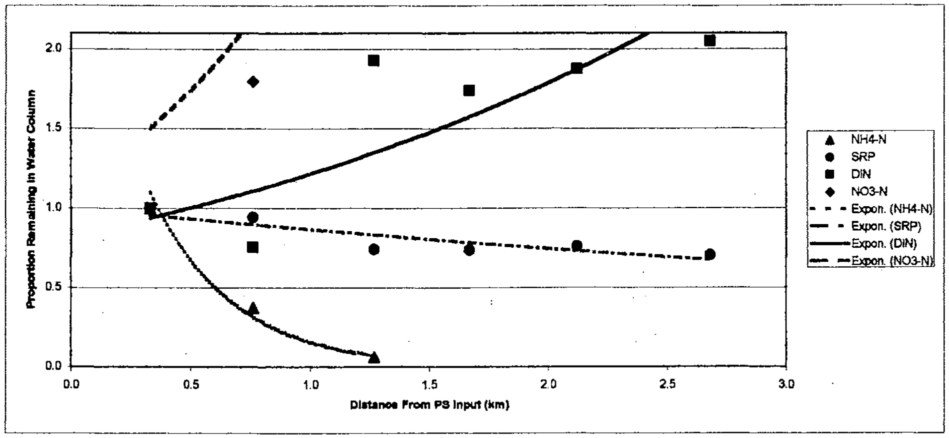
Proportion Remaining From PS Input

Distance (km)	DIN	NO_3-N	NH_4-N	SRP
2.68	2.05	7.77		0.71
2.12	1.87	7.13		0.76
1.67	1.74	6.61		0.74
1.27	1.93	7.10	0.07	0.74
0.76	0.75	1.80	0.38	0.94
0.33	1.00	1.00	1.00	1.00

Natural Logarithm of Proportion Remaining

Distance (km)	DIN	NO_3-N	NH_4-N	SRP
2.68	0.72	2.05		-0.35
2.12	0.63	1.96		-0.27
1.67	0.55	1.89		-0.31
1.27	0.66	1.96	-2.72	-0.30
0.76	-0.28	0.59	-0.98	-0.06
0.33	0.00	0.00	0.00	0.00

	DIN	NO_3-N	NH_4-N	SRP
Sw (km)	-2.60	-1.14	0.34	6.75
P value	0.054	0.027	0.072	0.022



DIN Uptake Length Regression
SUMMARY OUTPUT

Regression Statistics	
Multiple R	0.80379937
R Square	0.64609343
Adjusted R Square	0.55761679
Standard Error	0.27687998
Observations	6

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	1	0.55982179	0.56	7.3024	0.0539657
Residual	4	0.306650093	0.077		
Total	5	0.866471883			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 95.0%*	*Upper 95.0%*
Intercept	-0.0619234	0.198190927	-0.312	0.7703	-0.612191	0.488344	-0.6121907	0.48834401
X Variable 1	0.38533451	0.142595066	2.702	0.054	-0.010574	0.7812428	-0.0105737	0.78124276

NO_3-N Uptake Length Regression
SUMMARY OUTPUT

Regression Statistics	
Multiple R	0.8624597
R Square	0.74383673
Adjusted R Square	0.67979591
Standard Error	0.50081409
Observations	6

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	1	2.913223629	2.913	11.615	0.0270751
Residual	4	1.003259016	0.251		
Total	5	3.916482645			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 95.0%*	*Upper 95.0%*
Intercept	0.40471017	0.356483155	1.129	0.322	-0.590601	1.400021	-0.5906007	1.40002103
X Variable 1	0.87902235	0.257922668	3.408	0.0271	0.1629127	1.595132	0.16291268	1.59513202

NH_4-N Uptake Length Regression
SUMMARY OUTPUT

Regression Statistics	
Multiple R	0.99389195
R Square	0.9874237
Adjusted R Square	0.97484739
Standard Error	0.21853342
Observations	3

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	1	3.74961111	3.75	78.515	0.0715437
Residual	1	0.047756857	0.048		
Total	2	3.797367966			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 95.0%*	*Upper 95.0%*
Intercept	0.09669208	0.195978309	0.493	0.7062	-2.393438	2.5868219	-2.3934378	2.58682194
X Variable 1	-2.9097563	0.328383533	-8.861	0.0715	-7.082247	1.2627342	-7.0822468	1.26273423

SRP Uptake Length Regression
SUMMARY OUTPUT

Regression Statistics	
Multiple R	0.87760416
R Square	0.77018905
Adjusted R Square	0.71273632
Standard Error	0.0785234
Observations	6

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	1	0.082657983	0.083	13.406	0.0215543
Residual	4	0.024663697	0.006		
Total	5	0.10732166			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 95.0%*	*Upper 95.0%*
Intercept	-0.0445568	0.056207116	-0.793	0.4723	-0.200613	0.1114995	-0.2006131	0.11149953
X Variable 1	-0.148066	0.040440068	-3.661	0.0218	-0.260346	-0.035786	-0.2603459	-0.0357881

Uptake Length Calculations - Columbia Hollow 21 October 1999

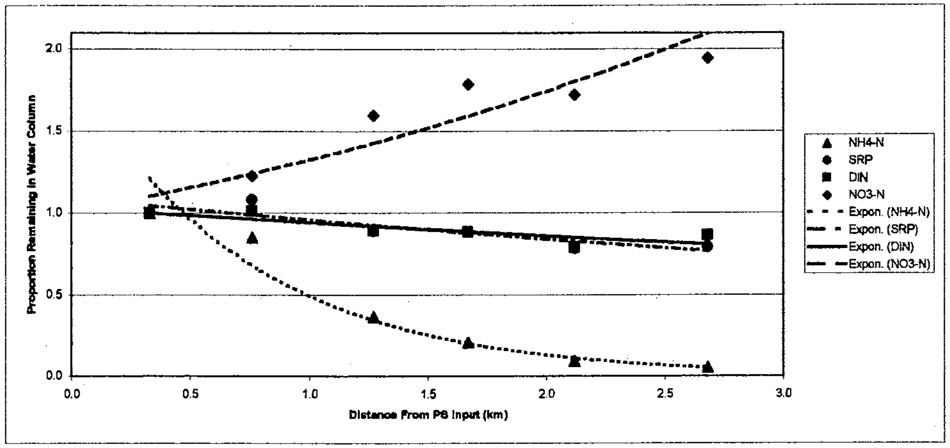
Proportion Remaining From PS Input

Distance (km)	DIN	NO_3-N	NH_4-N	SRP
2.68	0.86	1.95	0.06	0.79
2.12	0.79	1.72	0.09	0.78
1.67	0.88	1.78	0.21	0.89
1.27	0.89	1.60	0.36	0.89
0.76	1.01	1.23	0.85	1.08
0.33	1.00	1.00	1.00	1.00

Natural Logarithm of Proportion Remaining

Distance (km)	DIN	NO_3-N	NH_4-N	SRP
2.68	-0.15	0.67	-2.89	-0.23
2.12	-0.24	0.54	-2.36	-0.24
1.67	-0.13	0.58	-1.57	-0.12
1.27	-0.11	0.47	-1.01	-0.11
0.76	0.01	0.21	-0.16	0.08
0.33	0.00	0.00	0.00	0.00

	DIN	NO3	NH4	SRP
Sw (km)	11.07	-3.85	0.75	7.63
P value	0.040	0.007	1E-04	0.016



DIN Uptake Length Regression

SUMMARY OUTPUT

Regression Statistics	
Multiple R	0.83194884
R Square	0.69213886
Adjusted R Square	0.61517358
Standard Error	0.05847889
Observations	6

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	1	0.030751545	0.031	8.9929	0.0399868
Residual	4	0.013678188	0.003		
Total	5	0.044429733			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 95.0%*	*Upper 95.0%*
Intercept	0.00207169	0.04185781	0.049	0.9629	-0.114144	0.1162876	-0.1141445	0.11628764
X Variable 1	-0.0903122	0.030116001	-2.999	0.04	-0.173928	-0.006697	-0.1739278	-0.00669662

NH_4-N Uptake Length Regression

SUMMARY OUTPUT

Regression Statistics	
Multiple R	0.99057893
R Square	0.98124286
Adjusted R Square	0.97655332
Standard Error	0.17893898
Observations	6

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	1	6.699853027	6.7	209.25	0.0001326
Residual	4	0.128073776	0.032		
Total	5	6.827926802			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 95.0%*	*Upper 95.0%*
Intercept	0.18840169	0.128083248	1.471	0.2153	-0.167215	0.5440167	-0.1672149	0.54401673
X Variable 1	-1.3330478	0.092153772	-14.47	0.0001	-1.588908	-1.077187	-1.588908	-1.07718714

NO_3-N Uptake Length Regression

SUMMARY OUTPUT

Regression Statistics	
Multiple R	0.93166217
R Square	0.8679944
Adjusted R Square	0.834993
Standard Error	0.1036558
Observations	6

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	1	0.282598885	0.283	26.302	0.0068455
Residual	4	0.042977937	0.011		
Total	5	0.325576822			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 95.0%*	*Upper 95.0%*
Intercept	0.09864022	0.07419677	1.329	0.2545	-0.107363	0.3048439	-0.1073635	0.3048439
X Variable 1	0.2737777	0.053383346	5.129	0.0068	0.1255815	0.4219939	0.12558146	0.42199394

SRP Uptake Length Regression

SUMMARY OUTPUT

Regression Statistics	
Multiple R	0.89494688
R Square	0.80093348
Adjusted R Square	0.75116682
Standard Error	0.06344923
Observations	6

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	1	0.064790432	0.065	16.094	0.015974
Residual	4	0.016103219	0.004		
Total	5	0.080893652			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 95.0%*	*Upper 95.0%*
Intercept	0.04551758	0.045417014	1.002	0.373	-0.080581	0.1716157	-0.0805805	0.17161589
X Variable 1	-0.1310897	0.032676766	-4.012	0.016	-0.221815	-0.040364	-0.2218152	-0.04036417

Uptake Length Calculations - Columbia Hollow 11 November 1999

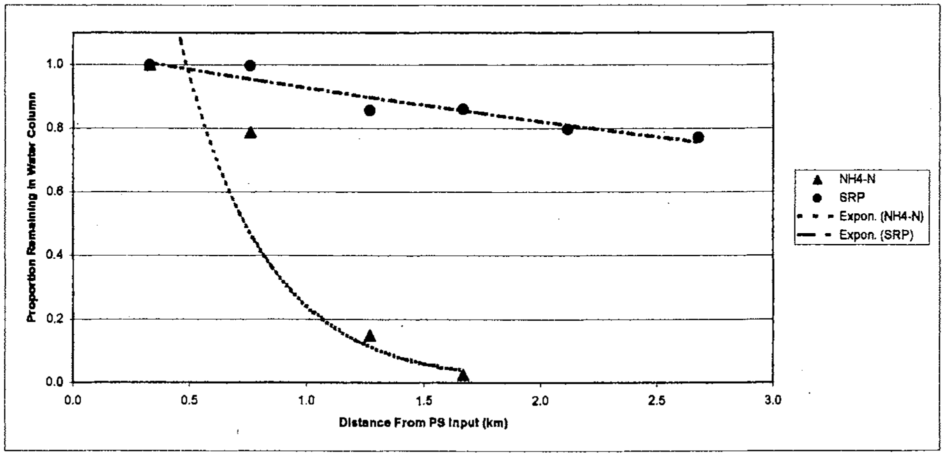
Proportion Remaining From PS Input

Distance (km)	DIN	NO_3-N	NH_4-N	SRP
2.68	0.94			0.77
2.12	0.91			0.80
1.67	0.90		0.03	0.86
1.27	0.96		0.15	0.86
0.76	0.87		0.79	1.00
0.33	1.00		1.00	1.00

Natural Logarithm of Proportion Remaining

Distance (km)	DIN	NO_3-N	NH_4-N	SRP
2.68	-0.06			-0.26
2.12	-0.10			-0.23
1.67	-0.10		-3.63	-0.15
1.27	-0.04		-1.90	-0.16
0.76	-0.14		-0.24	0.00
0.33	0.00		0.00	0.00

	DIN	NO_3-N	NH_4-N	SRP
Sw (km)	76.22		0.36	8.26
P value	0.662		4E-02	0.002



DIN Uptake Length Regression
SUMMARY OUTPUT

Regression Statistics	
Multiple R	0.22946996
R Square	0.05266564
Adjusted R Square	-0.184168
Standard Error	0.05264366
Observations	6

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	1	0.000616277	6E-04	0.2224	0.6616062
Residual	4	0.01108542	0.003		
Total	5	0.011701698			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 95.0%*	*Upper 95.0%*
Intercept	-0.0580687	0.037662378	-1.541	0.1982	-0.162692	0.0465546	-0.1626919	0.04655461
X Variable 1	-0.012765	0.027111646	-0.472	0.6616	-0.08806	0.0624697	-0.0880597	0.0624897

NH_4-N Uptake Length Regression
SUMMARY OUTPUT

Regression Statistics	
Multiple R	0.96098919
R Square	0.92350023
Adjusted R Square	0.88525034
Standard Error	0.57130494
Observations	4

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	1	7.880301013	7.88	24.144	0.0390108
Residual	2	0.652778674	0.326		
Total	3	8.533079687			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 95.0%*	*Upper 95.0%*
Intercept	0.43256622	0.476761607	0.907	0.46	-1.616862	2.4839942	-1.6168617	2.48399419
X Variable 1	-2.7685923	0.563450258	-4.914	0.039	-5.192925	-0.34426	-5.1929248	-0.34425961

SRP Uptake Length Regression
SUMMARY OUTPUT

Regression Statistics	
Multiple R	0.95963399
R Square	0.9208974
Adjusted R Square	0.90112175
Standard Error	0.03444855
Observations	6

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	1	0.055261474	0.055	46.567	0.0024112
Residual	4	0.004746611	0.001		
Total	5	0.060008286			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 95.0%*	*Upper 95.0%*
Intercept	0.00565612	0.024658304	0.229	0.8296	-0.062806	0.0741167	-0.0628085	0.07411869
X Variable 1	-0.1210666	0.017741241	-6.824	0.0024	-0.170324	-0.071809	-0.1703243	-0.07180889

Uptake Length Calculations - Columbia Hollow 22 December 1999

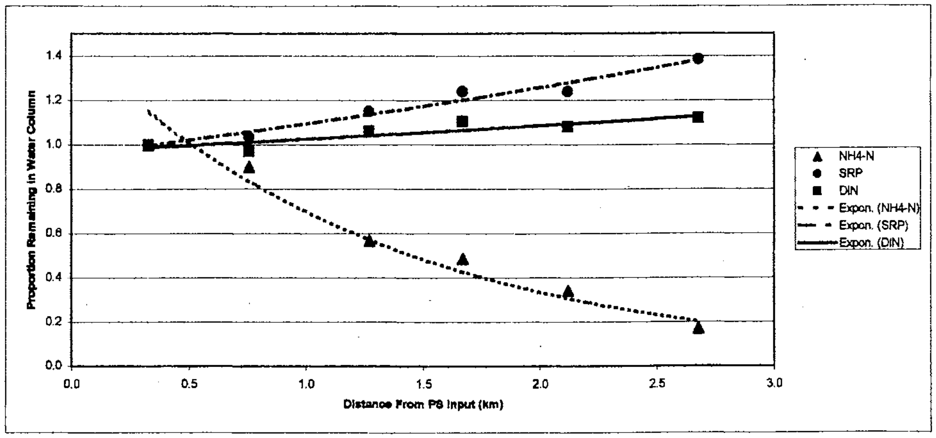
Proportion Remaining From PS Input

Distance (km)	DIN	NO_3-N	NH_4-N	SRP
2.68	1.12		0.17	1.39
2.12	1.08		0.34	1.24
1.67	1.10		0.49	1.24
1.27	1.06		0.57	1.15
0.76	0.97		0.90	1.04
0.33	1.00		1.00	1.00

Natural Logarithm of Proportion Remaining

Distance (km)	DIN	NO_3-N	NH_4-N	SRP
2.68	0.11		-1.76	0.33
2.12	0.08		-1.08	0.22
1.67	0.10		-0.72	0.21
1.27	0.06		-0.57	0.14
0.76	-0.03		-0.11	0.04
0.33	0.00		0.00	0.00

	DIN	NO_3-N	NH_4-N	SRP
Sw (km)	-17.65		1.36	-7.21
P value	0.023		5E-04	4E-04



DIN Uptake Length Regression
SUMMARY OUTPUT

Regression Statistics	
Multiple R	0.87326838
R Square	0.762597664
Adjusted R Square	0.70324708
Standard Error	0.030686238
Observations	6

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	1	0.012099231	0.012	12.849	0.0230736
Residual	4	0.003766581	9E-04		
Total	5	0.015865812			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 95.0%*	*Upper 95.0%*
Intercept	-0.01245278	0.021965236	-0.57	0.60106	-0.073438	0.0485326	-0.0734382	0.04853262
X Variable 1	0.056648954	0.015803623	3.585	0.02307	0.012771	0.1005269	0.01277097	0.10052694

NH_4-N Uptake Length Regression
SUMMARY OUTPUT

Regression Statistics	
Multiple R	0.98124555
R Square	0.96284283
Adjusted R Square	0.953553537
Standard Error	0.14051662
Observations	6

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	1	2.046577277	2.047	103.651	0.0005243
Residual	4	0.078979662	0.02		
Total	5	2.125556958			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 95.0%*	*Upper 95.0%*
Intercept	0.13620185	0.100581917	1.354	0.24714	-0.143059	0.4154626	-0.1430589	0.4154628
X Variable 1	-0.73676177	0.072367022	-10.2	0.00052	-0.937685	-0.535838	-0.9376852	-0.5356363

SRP Uptake Length Regression
SUMMARY OUTPUT

Regression Statistics	
Multiple R	0.983200779
R Square	0.966683773
Adjusted R Square	0.958354716
Standard Error	0.025002821
Observations	6

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	1	0.072554882	0.073	116.062	0.000421
Residual	4	0.002500564	6E-04		
Total	5	0.075055446			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 95.0%*	*Upper 95.0%*
Intercept	-0.0033453	0.017897041	-0.19	0.86062	-0.053036	0.046345	-0.0530356	0.04634496
X Variable 1	0.138722314	0.012876624	10.77	0.00042	0.102971	0.1744736	0.102971	0.17447363

Uptake Length Calculations - Columbia Hollow 26 January 1999

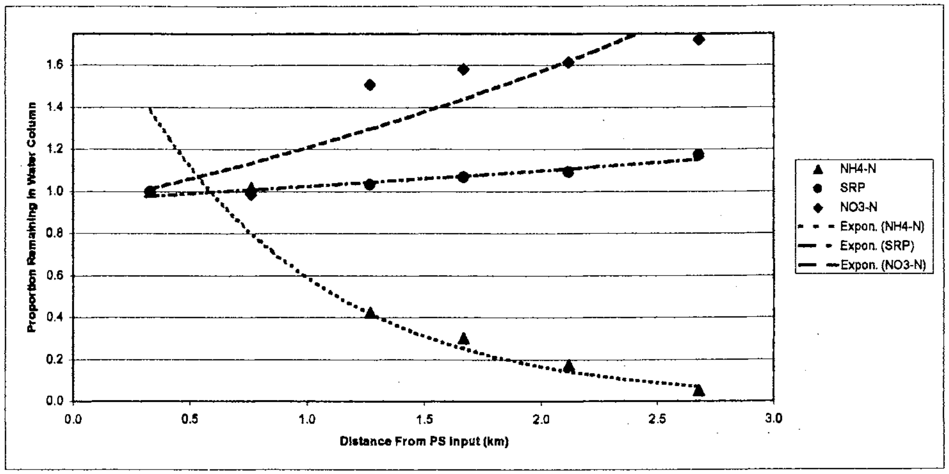
Proportion Remaining From PS Input

Distance (km)	DIN	NO_3-N	NH_4-N	SRP
2.66	1.03	1.72	0.05	1.17
2.12	1.02	1.62	0.17	1.09
1.67	1.05	1.56	0.30	1.07
1.27	1.06	1.51	0.43	1.03
0.76	1.00	0.98	1.02	0.99
0.33	1.00	1.00	1.00	1.00

Natural Logarithm of Proportion Remaining

Distance (km)	DIN	NO_3-N	NH_4-N	SRP
2.66	0.03	0.54	-2.96	0.16
2.12	0.02	0.48	-1.76	0.09
1.67	0.05	0.46	-1.20	0.07
1.27	0.06	0.41	-0.65	0.03
0.76	0.00	-0.02	0.02	-0.01
0.33	0.00	0.00	0.00	0.00

	DIN	NO_3-N	NH_4-N	SRP
Sw (km)	-66.64	-3.82	0.79	-14.37
P value	0.429	0.014	0.001	0.002



DIN Uptake Length Regression

SUMMARY OUTPUT

Regression Statistics	
Multiple R	0.40227944
R Square	0.16162675
Adjusted R Square	-0.0477141
Standard Error	0.02492661
Observations	6

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	1	0.000479862	5E-04	0.7723	0.429131
Residual	4	0.002485363	6E-04		
Total	5	0.002965245			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 95.0%*	*Upper 95.0%*
Intercept	0.01131063	0.017642631	0.634	0.5606	-0.036228	0.06065	-0.0382284	0.06065002
X Variable 1	0.01126161	0.012637477	0.879	0.4291	-0.024361	0.0469242	-0.024361	0.04692424

SUMMARY OUTPUT

Regression Statistics	
Multiple R	0.90216769
R Square	0.81394299
Adjusted R Square	0.76742874
Standard Error	0.12153663
Observations	6

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	1	0.25847724	0.258	17.499	0.0138629
Residual	4	0.059084606	0.015		
Total	5	0.317561646			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 95.0%*	*Upper 95.0%*
Intercept	0.01406636	0.086996023	0.162	0.8794	-0.227472	0.2556066	-0.2274716	0.25560856
X Variable 1	0.26183287	0.062592196	4.183	0.0139	0.0880487	0.435617	0.08804871	0.43561702

NH_4-N Uptake Length Regression

SUMMARY OUTPUT

Regression Statistics	
Multiple R	0.97464937
R Square	0.9499414
Adjusted R Square	0.93742675
Standard Error	0.28305587
Observations	6

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	1	6.081684282	6.082	75.906	0.0009558
Residual	4	0.320462492	0.08		
Total	5	6.402146774			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 95.0%*	*Upper 95.0%*
Intercept	0.32558599	0.202611831	1.607	0.1833	-0.236955	0.8881272	-0.2369552	0.88812723
X Variable 1	-1.27006	0.14577571	-8.712	0.001	-1.674799	-0.865321	-1.6747991	-0.86532067

SRP Uptake Length Regression

SUMMARY OUTPUT

Regression Statistics	
Multiple R	0.96564537
R Square	0.93247099
Adjusted R Square	0.91558873
Standard Error	0.01818492
Observations	6

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	1	0.01826534	0.018	55.234	0.0017501
Residual	4	0.001322765	3E-04		
Total	5	0.019588106			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 95.0%*	*Upper 95.0%*
Intercept	-0.0228281	0.013016762	-1.754	0.1543	-0.058969	0.0133124	-0.0589685	0.0133124
X Variable 1	0.06960283	0.009385359	7.432	0.0018	0.0438004	0.0958053	0.04380037	0.09560529

Uptake Length Calculations - Columbia Hollow 28 January 2000

Proportion Remaining From PS Input

Distance (km)	DIN	NO_3-N	NH_4-N	SRP
2.68	1.03	1.72	0.05	1.17
2.12	1.02	1.62	0.17	1.09
1.67	1.05	1.58	0.30	1.07
1.27	1.06	1.51	0.43	1.03
0.76	1.00	0.98	1.02	0.99
0.33	1.00	1.00	1.00	1.00

Natural Logarithm of Proportion Remaining

Distance (km)	DIN	NO_3-N	NH_4-N	SRP
2.68	0.03	0.54	-2.96	0.16
2.12	0.02	0.48	-1.76	0.09
1.67	0.05	0.46	-1.20	0.07
1.27	0.06	0.41	-0.65	0.03
0.76	0.00	-0.02	0.02	-0.01
0.33	0.00	0.00	0.00	0.00

	DIN	NO_3-N	NH_4-N	SRP
Sw (km)	-88.64	-3.62	0.79	-14.37
P value	0.429	0.014	0.001	0.002

DIN Uptake Length Regression

SUMMARY OUTPUT

Regression Statistics	
Multiple R	0.40227944
R Square	0.16162875
Adjusted R Square	-0.0477141
Standard Error	0.02492681
Observations	6

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	1	0.000479662	5E-04	0.7723	0.429131
Residual	4	0.002485383	6E-04		
Total	5	0.002965245			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 95.0%*	*Upper 95.0%*
Intercept	0.01131063	0.017642631	0.634	0.5606	-0.038226	0.06065	-0.0382284	0.06065002
X Variable 1	0.01128161	0.012837477	0.879	0.4291	-0.024361	0.0469242	-0.024361	0.04692424

NH_4-N Uptake Length Regression

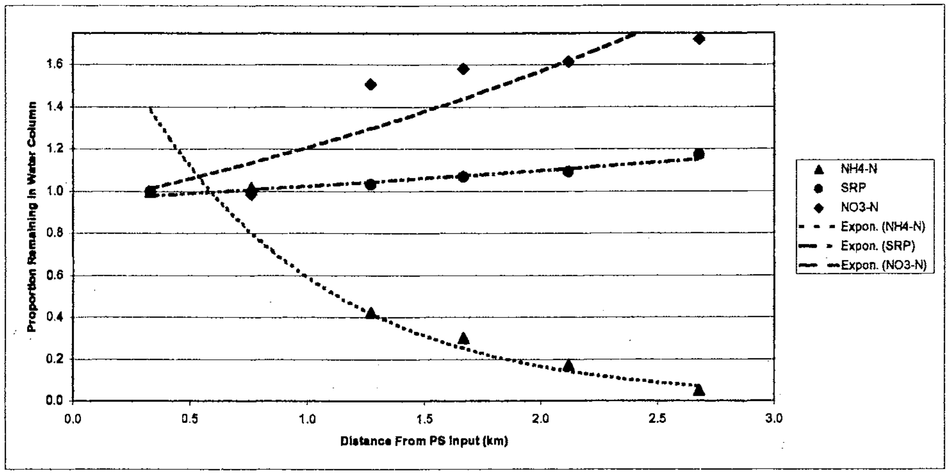
SUMMARY OUTPUT

Regression Statistics	
Multiple R	0.97464937
R Square	0.9499414
Adjusted R Square	0.93742675
Standard Error	0.28305587
Observations	6

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	1	6.081664282	6.082	75.906	0.0009556
Residual	4	0.320482492	0.08		
Total	5	6.402146774			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 95.0%*	*Upper 95.0%*
Intercept	0.32558599	0.202611631	1.607	0.1833	-0.236955	0.8881272	-0.2369552	0.88812723
X Variable 1	-1.27008	0.14577571	-8.712	0.001	-1.674799	-0.865321	-1.8747991	-0.86532067



SUMMARY OUTPUT

Regression Statistics	
Multiple R	0.90218769
R Square	0.81394299
Adjusted R Square	0.76742874
Standard Error	0.12153663
Observations	6

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	1	0.25647724	0.256	17.499	0.0138829
Residual	4	0.059064606	0.015		
Total	5	0.317561848			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 95.0%*	*Upper 95.0%*
Intercept	0.01406638	0.086996023	0.162	0.8794	-0.227472	0.2556066	-0.2274716	0.25560656
X Variable 1	0.26163287	0.062592196	4.183	0.0139	0.0860467	0.435617	0.08604871	0.43561702

SRP Uptake Length Regression

SUMMARY OUTPUT

Regression Statistics	
Multiple R	0.96564537
R Square	0.93247099
Adjusted R Square	0.91558873
Standard Error	0.01618492
Observations	6

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	1	0.01626534	0.016	55.234	0.0017501
Residual	4	0.001322765	3E-04		
Total	5	0.019588106			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 95.0%*	*Upper 95.0%*
Intercept	-0.0228281	0.013016782	-1.754	0.1543	-0.058969	0.0133124	-0.0589685	0.0133124
X Variable 1	0.06960263	0.009365359	7.432	0.0018	0.0438004	0.0956053	0.04360037	0.09560529

Uptake Length Calculations - Columbia Hollow 29 February 2000

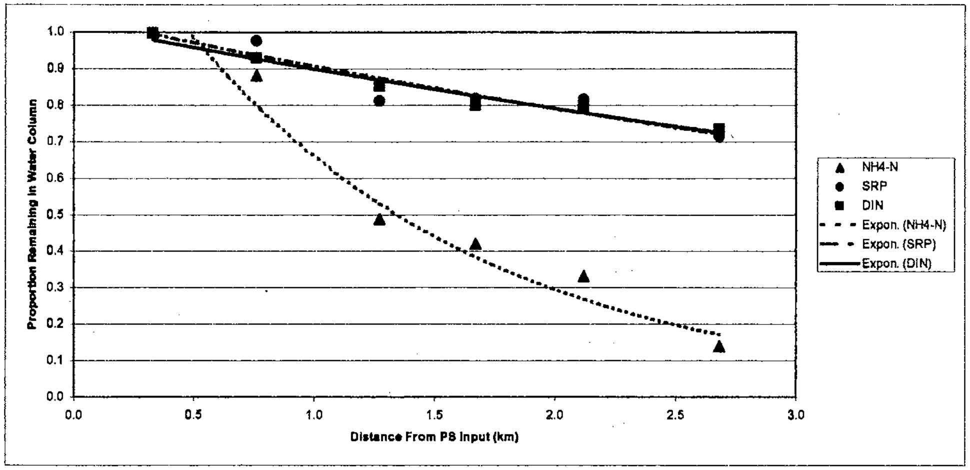
Proportion Remaining From PS Input

Distance (km)	DIN	NO_3-N	NH_4-N	SRP
2.88	0.73		0.14	0.72
2.12	0.80		0.33	0.82
1.67	0.80		0.42	0.82
1.27	0.85		0.49	0.81
0.76	0.93		0.88	0.98
0.33	1.00		1.00	1.00

Natural Logarithm of Proportion Remaining

Distance (km)	DIN	NO_3-N	NH_4-N	SRP
2.88	-0.31		-1.96	-0.33
2.12	-0.23		-1.10	-0.20
1.67	-0.22		-0.86	-0.20
1.27	-0.18		-0.71	-0.21
0.76	-0.07		-0.13	-0.02
0.33	0.00		0.00	0.00

	DIN	NO_3-N	NH_4-N	SRP
Sw (km)	7.84		1.25	7.31
P value	0.001		9E-04	6E-03



DIN Uptake Length Regression
SUMMARY OUTPUT

Regression Statistics	
Multiple R	0.980444141
R Square	0.961270713
Adjusted R Square	0.951588391
Standard Error	0.024883415
Observations	6

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	1	0.061374471	0.061	99.281	0.0005699
Residual	4	0.002472756	6E-04		
Total	5	0.063847229			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 95.0%*	*Upper 95.0%*
Intercept	-0.02028625	0.017797254	-1.14	0.31797	-0.069699	0.029127	-0.0696994	0.02912695
X Variable 1	-0.12756714	0.012804829	-9.96	0.00057	-0.163139	-0.092035	-0.1631391	-0.0920352

NH_4-N Uptake Length Regression
SUMMARY OUTPUT

Regression Statistics	
Multiple R	0.975590359
R Square	0.951776549
Adjusted R Square	0.939720687
Standard Error	0.175112118
Observations	6

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	1	2.420856857	2.421	78.9472	0.0008885
Residual	4	0.122657016	0.031		
Total	5	2.543513873			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 95.0%*	*Upper 95.0%*
Intercept	0.120371627	0.125345404	0.96	0.39128	-0.227644	0.4683872	-0.2276435	0.46838718
X Variable 1	-0.80130446	0.09018394	-8.89	0.00089	-1.051696	-0.550913	-1.0516957	-0.5509132

SRP Uptake Length Regression
SUMMARY OUTPUT

Regression Statistics	
Multiple R	0.93659155
R Square	0.877203731
Adjusted R Square	0.846504664
Standard Error	0.0496825
Observations	6

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	1	0.070531346	0.071	28.5743	0.0059035
Residual	4	0.009873403	0.002		
Total	5	0.080404749			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 95.0%*	*Upper 95.0%*
Intercept	-0.0052302	0.035562776	-0.15	0.89019	-0.103966	0.0935061	-0.1039665	0.0935061
X Variable 1	-0.13677417	0.025588828	-5.35	0.0059	-0.207815	-0.065734	-0.2078147	-0.0657336

CHEROKEE CREEK, CLOUD CREEK, AND DRY CREEK

Agricultural Catchment Streams - Summer Injection Raw Data

19-Jul-99 Dry Creek all units in mg L^{-1}

Sample	Site	Location	SRP	Nitrate-N	Ammonia-N	Chloride
bg	1	1	0.007	0.54	0.01	6.17
bg	1	2	0.006	0.53	0.01	6.49
bg	1	3	0.007	0.54	0.02	6.46
bg	2	1	0.006	0.52	0.01	6.30
bg	2	2	0.005	0.53	0.05	8.38
bg	2	3	0.005	0.52	0.02	6.49
bg	3	1	0.005	0.53	0.08	6.50
bg	3	2	0.005	0.52	0.07	6.45
bg	3	3	0.005	0.47	0.05	6.47
bg	4	1	0.005	0.51	0.07	6.47
bg	4	2	0.005	0.52	0.03	6.50
bg	4	3	0.005	0.51	0.07	6.46
bg	5	1	0.005	0.51	0.05	6.46
bg	5	2	0.006	0.51	0.05	6.49
bg	5	3	0.006	0.52	0.01	6.73
plateau	1	1	0.028	1.38	0.10	12.88
plateau	1	2	0.024	1.42	0.06	12.76
plateau	1	3	0.024	1.42	0.05	12.31
plateau	2	1	0.021	1.32	0.08	12.45
plateau	2	2	0.021	1.32	0.05	12.23
plateau	2	3	0.023	1.39	0.07	12.15
plateau	3	1	0.020	1.34	0.06	12.20
plateau	3	2	0.020	1.33	0.06	12.19
plateau	3	3	0.020	1.32	0.03	12.34
plateau	4	1	0.019	1.36	0.08	12.48
plateau	4	2	0.020	1.33	0.05	12.16
plateau	4	3	0.019	1.33	0.05	12.13
plateau	5	1	0.017	1.31	0.01	11.95
plateau	5	2	0.017	1.32	0.05	12.01
plateau	5	3	0.017	1.29	0.04	12.22

3-Aug-99 Dry Creek all units in mg L^{-1}

Sample	Site	Location	SRP	Nitrate-N	Ammonia-N	Chloride
bg	1	1	0.010	0.60	0.01	8.43
bg	1	2	0.010	0.60	0.02	8.04
bg	1	3	0.011	0.81	0.01	8.30
bg	2	1	0.013	0.60	0.00	8.19
bg	2	2	0.011	0.60	0.03	8.21
bg	2	3	0.011	0.60	0.03	8.13
bg	3	1	0.012	0.59	0.03	8.37
bg	3	2	0.011	0.60	0.06	8.15
bg	3	3	0.011	0.60	0.02	8.38
bg	4	1	0.011	0.59	0.02	8.25
bg	4	2	0.013	0.60	0.04	8.23
bg	4	3	0.013	0.60	0.07	8.60
bg	5	1	0.013	0.57	0.04	8.32
bg	5	2	0.011	0.58	0.03	8.44
bg	5	3	0.013	0.60	0.03	8.47
plateau	1	1	0.031	2.43	0.02	21.41
plateau	1	2	0.032	2.46	0.04	21.68
plateau	1	3	0.030	2.45	0.03	21.51
plateau	2	1	0.027	2.15	0.04	19.39
plateau	2	2	0.026	2.18	0.03	19.75
plateau	2	3	0.027	2.06	0.05	18.64
plateau	3	1	0.027	2.15	0.03	19.55
plateau	3	2	0.026	2.08	0.03	19.17
plateau	3	3	0.025	2.01	0.03	18.69
plateau	4	1	0.026	2.16	0.03	19.60
plateau	4	2	0.025	2.08	0.04	19.11
plateau	4	3	0.023	2.06	0.03	18.83
plateau	5	1	0.022	2.12	0.04	19.73
plateau	5	2	0.021	1.98	0.01	18.44
plateau	5	3	0.019	1.12	0.03	*

19-Jul-99 Cloud Creek all units in mg L^{-1}

Sample	Site	Location	SRP	Nitrate-N	Ammonia-N	Chloride
bg	1	1	0.026	1.56	0.03	5.75
bg	1	2	0.027	1.58	0.03	5.98
bg	1	3	0.028	1.57	0.04	5.83
bg	2	1	0.027	1.57	0.06	5.88
bg	2	2	0.027	1.68	0.04	6.02
bg	2	3	0.029	1.58	0.03	8.04
bg	3	1	0.030	1.61	0.08	6.12
bg	3	2	0.030	1.57	0.02	5.91
bg	3	3	0.030	1.58	0.07	5.90
bg	4	1	0.031	1.59	0.05	6.07
bg	4	2	0.031	1.59	0.02	5.97
bg	4	3	0.029	1.58	0.01	5.93
bg	5	1	0.032	1.60	0.06	6.06
bg	5	2	0.031	1.58	0.00	6.00
bg	5	3	0.034	1.59	0.02	5.96
plateau	1	1	0.058	3.24	0.02	13.08
plateau	1	2	0.051	2.82	0.00	11.06
plateau	1	3	0.042	2.26	0.00	9.26
plateau	2	1	0.052	3.02	0.01	12.27
plateau	2	2	0.048	2.89	0.03	12.11
plateau	2	3	0.048	2.59	0.01	10.18
plateau	3	1	0.044	2.46	0.00	9.52
plateau	3	2	0.045	2.68	0.02	11.23
plateau	3	3	0.045	2.60	0.01	10.57
plateau	4	1	0.042	2.50	0.01	9.46
plateau	4	2	0.042	2.39	0.01	9.48
plateau	4	3	0.042	2.41	0.02	9.44
plateau	5	1	0.041	2.37	0.02	9.20
plateau	5	2	0.041	2.37	0.01	9.50
plateau	5	3	0.040	2.17	0.02	8.88

27-Jul-99 Cloud Creek all units in mg L-1

Sample	Site	Location	SRP	Nitrate-N	Ammonia-N	Chloride
bg	1	1	0.030	1.54	0.00	6.62
bg	1	2	0.030	1.52	0.01	6.60
bg	1	3	0.029	1.49	0.01	6.51
bg	2	1	0.033	1.51	0.01	6.60
bg	2	2	0.030	1.49	0.01	8.59
bg	2	3	0.032	1.51	0.01	6.62
bg	3	1	0.034	1.53	0.02	6.64
bg	3	2	0.034	1.51	0.00	6.51
bg	3	3	0.033	1.53	0.02	6.38
bg	4	1	0.033	1.55	0.01	6.88
bg	4	2	0.033	1.53	0.05	6.67
bg	4	3	0.034	1.85	0.10	8.53
bg	5	1	0.033	1.53	0.07	6.81
bg	5	2	0.032	1.52	0.04	6.83
bg	5	3	0.032	1.53	0.01	6.64
plateau	1	1	0.062	4.34	0.01	22.40
plateau	1	2	0.063	4.45	0.04	21.36
plateau	1	3	0.064	4.55	0.03	22.43
plateau	2	1	0.064	4.64	0.01	22.59
plateau	2	2	0.065	4.66	0.04	23.13
plateau	2	3	0.063	4.61	0.03	22.87
plateau	3	1	0.056	4.09	0.03	19.89
plateau	3	2	0.054	4.57	0.07	21.86
plateau	3	3	0.051	4.56	0.00	21.95
plateau	4	1	0.049	3.61	0.04	16.78
plateau	4	2	0.047	3.59	0.05	16.79
plateau	4	3	0.050	3.51	0.05	18.79
plateau	5	1	0.039	3.36	0.05	19.53
plateau	5	2	0.046	3.50	0.03	17.10
plateau	5	3	0.044	2.92	0.03	13.50

27-Jul-99 Cherokee Creek all units in mg L-1

Sample	Site	Location	SRP	Nitrate-N	Ammonia-N	Chloride
bg	1	1	0.030	2.67	0.04	7.61
bg	1	2	0.030	2.66	0.01	8.74
bg	1	3	0.031	2.66	0.01	7.53
bg	2	1	0.030	2.67	0.00	7.42
bg	2	2	0.031	2.65	0.00	7.53
bg	2	3	0.031	2.65	0.03	7.82
bg	3	1	0.030	2.66	0.03	7.41
bg	3	2	0.030	2.66	0.03	7.47
bg	3	3	0.030	2.66	0.03	7.40
bg	4	1	0.031	2.62	0.02	7.46
bg	4	2	0.032	2.65	0.00	7.49
bg	4	3	0.031	2.64	0.02	7.40
bg	5	1	0.031	2.64	0.03	*
bg	5	2	0.029	2.64	0.01	7.81
bg	5	3	0.030	2.65	0.01	7.67
plateau	1	1	0.052	4.70	0.01	17.73
plateau	1	2	0.053	4.99	0.00	19.97
plateau	1	3	0.055	5.36	0.01	20.99
plateau	2	1	0.049	4.70	0.01	17.42
plateau	2	2	0.050	4.70	0.01	17.54
plateau	2	3	0.048	4.55	0.03	16.94
plateau	3	1	0.048	4.64	0.01	17.41
plateau	3	2	0.049	4.54	0.00	17.24
plateau	3	3	0.046	4.53	0.03	16.57
plateau	4	1	0.049	4.64	0.00	17.80
plateau	4	2	0.047	4.64	0.02	17.04
plateau	4	3	0.049	4.61	0.00	17.46
plateau	5	1	0.045	4.53	0.01	16.72
plateau	5	2	0.046	4.59	0.01	17.10
plateau	5	3	0.046	4.56	0.03	17.33

3-Aug-99 Cherokee Creek all units in mg L-1

Sample	Site	Location	SRP	Nitrate-N	Ammonia-N	Chloride
bg	1	1	0.028	2.69	0.10	8.18
bg	1	2	0.028	2.65	0.04	7.98
bg	1	3	0.027	2.62	0.03	7.90
bg	2	1	0.027	2.61	0.06	7.95
bg	2	2	0.028	2.63	0.04	7.93
bg	2	3	*	2.68	0.07	8.14
bg	3	1	0.029	2.65	0.04	7.82
bg	3	2	0.027	2.67	0.04	7.86
bg	3	3	0.029	2.64	0.04	7.88
bg	4	1	0.029	2.67	0.03	7.92
bg	4	2	0.030	2.66	0.00	7.93
bg	4	3	0.026	2.66	0.02	8.02
bg	5	1	0.030	2.67	0.06	8.00
bg	5	2	0.029	2.66	0.01	7.87
bg	5	3	0.030	2.67	0.03	8.55
plateau	1	1	0.061	5.83	0.03	25.45
plateau	1	2	0.063	5.95	0.03	25.74
plateau	1	3	0.061	6.10	0.03	26.21
plateau	2	1	0.056	5.58	0.04	24.11
plateau	2	2	*	5.38	0.01	22.88
plateau	2	3	0.049	5.09	0.05	21.48
plateau	3	1	0.050	5.34	0.08	22.80
plateau	3	2	0.051	5.20	0.04	22.11
plateau	3	3	0.046	4.90	0.06	20.68
plateau	4	1	0.050	5.20	0.04	21.89
plateau	4	2	0.051	5.17	0.02	21.89
plateau	4	3	0.050	5.17	0.05	22.06
plateau	5	1	0.047	5.00	0.01	21.38
plateau	5	2	0.048	5.07	0.03	21.55
plateau	5	3	0.050	5.14	0.02	21.90

19-Aug-99 Cherokee Creek

Sample	Site	Location	SRP	Chloride
bg	1	1	0.028	7.72
bg	1	2	0.028	7.09
bg	1	3	0.030	7.33
bg	2	1	0.030	6.77
bg	2	2	0.029	7.43
bg	2	3	0.029	7.23
bg	3	1	0.033	7.05
bg	3	2	0.033	7.38
bg	3	3	0.034	7.44
bg	4	1	0.034	7.23
bg	4	2	0.033	7.67
bg	4	3	0.034	7.46
bg	5	1	0.034	7.59
bg	5	2	0.034	7.65
bg	5	3	0.034	7.38
plateau	1	1	0.053	19.97
plateau	1	2	0.045	22.54
plateau	1	3	0.039	13.59
plateau	2	1	0.045	16.85
plateau	2	2	0.043	18.57
plateau	2	3	0.039	16.91
plateau	3	1	0.040	17.15
plateau	3	2	0.041	17.03
plateau	3	3	0.040	16.35
plateau	4	1	0.041	15.99
plateau	4	2	0.040	16.28
plateau	4	3	0.042	16.35
plateau	5	1	0.039	14.60
plateau	5	2	0.039	15.38
plateau	5	3	0.041	16.20

Agricultural Catchment Streams - Winter Injection Raw Data

6-Jan-00 Dry Creek all units in mg L^{-1}

Sample	Site	Location	SRP	Nitrate-N	Ammonia-N	Chloride
bg	1	1	0.011	0.96	0.00	10.13
bg	1	2	0.012	0.94	0.00	9.99
bg	1	3	0.011	0.94	0.00	10.11
bg	2	1	0.012	0.93	0.00	9.99
bg	2	2	0.011	0.94	0.00	9.97
bg	2	3	0.011	0.94	0.00	10.23
bg	3	1	0.011	0.93	0.00	10.39
bg	3	2	0.011	0.94	0.00	9.68
bg	3	3	0.011	0.96	0.00	10.32
bg	4	1	0.011	0.95	0.00	9.80
bg	4	2	0.010	0.93	0.00	9.99
bg	4	3	0.010	0.93	0.00	10.41
bg	5	1	0.011	0.92	0.00	9.75
bg	5	2	0.011	0.93	0.00	9.51
bg	5	3	0.012	0.94	0.00	9.77
plateau	1	1	0.021	1.78	0.12	18.37
plateau	1	2	0.022	1.79	0.12	18.80
plateau	1	3	0.022	1.80	0.12	19.21
plateau	2	1	0.019	1.64	0.06	17.81
plateau	2	2	0.019	1.65	0.07	18.30
plateau	2	3	0.021	1.67	0.09	17.10
plateau	3	1	0.019	1.64	0.07	17.11
plateau	3	2	*	1.66	0.07	17.62
plateau	3	3	0.019	1.61	0.09	17.90
plateau	4	1	0.019	1.63	0.07	17.14
plateau	4	2	0.018	1.62	0.08	16.62
plateau	4	3	0.018	1.62	0.05	18.15
plateau	5	1	0.017	1.61	0.06	16.82
plateau	5	2	0.017	1.61	0.07	16.58
plateau	5	3	0.015	1.60	0.01	17.13

14-Jan-00 Dry Creek all units in mg L^{-1}

Sample	Site	Location	SRP	Nitrate-N	Ammonia-N	Chloride
bg	1	1	0.011	0.86	0.00	10.32
bg	1	2	0.011	0.88	0.00	10.37
bg	1	3	0.010	0.85	0.02	10.33
bg	2	1	0.010	0.83	0.02	9.82
bg	2	2	0.008	0.84	0.02	9.95
bg	2	3	0.009	0.84	0.02	9.67
bg	3	1	0.009	0.86	0.03	10.28
bg	3	2	0.009	0.85	0.01	10.36
bg	3	3	0.010	0.85	0.01	10.43
bg	4	1	0.010	0.86	0.01	10.30
bg	4	2	0.010	0.86	0.01	10.33
bg	4	3	0.009	0.85	0.01	10.17
bg	5	1	0.009	0.85	0.01	10.37
bg	5	2	0.009	0.87	0.00	10.44
bg	5	3	0.010	0.85	0.01	10.32
plateau	1	1	0.039	2.03	0.02	26.04
plateau	1	2	0.042	2.14	0.00	26.33
plateau	1	3	0.043	2.12	0.00	25.69
plateau	2	1	0.036	1.88	0.00	23.16
plateau	2	2	0.033	1.85	0.01	22.42
plateau	2	3	0.036	1.91	0.00	23.20
plateau	3	1	0.034	1.88	0.00	23.14
plateau	3	2	0.034	1.88	0.00	22.98
plateau	3	3	0.034	1.81	0.00	21.92
plateau	4	1	0.034	1.85	0.01	23.11
plateau	4	2	0.033	1.80	0.01	23.04
plateau	4	3	0.034	1.85	0.00	23.36
plateau	5	1	0.033	1.84	0.00	23.12
plateau	5	2	0.021	1.52	0.00	19.46
plateau	5	3	0.029	1.76	0.00	22.49

6-Jan-00 Cloud Creek all units in mg L^{-1}

Sample	Site	Location	SRP	Nitrate-N	Ammonia-N	Chloride
bg	1	1	0.032	1.93	0.00	5.81
bg	1	2	0.032	1.92	0.00	5.69
bg	1	3	0.033	1.92	0.00	5.80
bg	2	1	0.036	1.92	0.00	5.59
bg	2	2	0.031	1.91	0.00	5.61
bg	2	3	0.031	1.92	0.00	5.75
bg	3	1	0.030	1.92	0.00	5.94
bg	3	2	0.032	1.94	0.00	5.67
bg	3	3	0.030	1.92	0.00	5.55
bg	4	1	0.031	1.96	0.00	5.80
bg	4	2	0.030	1.94	0.00	5.83
bg	4	3	0.033	1.96	0.00	6.02
bg	5	1	0.033	1.92	0.00	5.85
bg	5	2	0.032	1.94	0.00	5.62
bg	5	3	0.030	1.94	0.00	5.92
plateau	1	1	0.057	3.65	0.24	22.86
plateau	1	2	0.037	2.18	0.01	8.76
plateau	1	3	0.054	3.28	0.18	19.23
plateau	2	1	0.051	3.03	0.11	17.12
plateau	2	2	0.047	2.79	0.07	15.16
plateau	2	3	0.040	2.55	0.02	12.21
plateau	3	1	0.046	2.91	0.09	16.28
plateau	3	2	0.043	2.69	0.05	13.58
plateau	3	3	0.040	2.53	0.03	11.74
plateau	4	1	0.038	2.56	0.00	12.66
plateau	4	2	0.040	2.66	0.03	13.45
plateau	4	3	0.040	2.68	0.03	13.41
plateau	5	1	0.038	2.50	0.00	11.97
plateau	5	2	0.039	2.42	0.01	11.93
plateau	5	3	0.039	2.62	0.03	11.84

21-Jan-00 Cloud Creek all units in mg L-1

Sample	Site	Location	SRP	Nitrate-N	Ammonia-N	Chloride
bg	1	1	0.027	1.77	0.00	6.62
bg	1	2	0.029	1.77	0.00	6.53
bg	1	3	0.028	1.79	0.00	6.40
bg	2	1	0.028	1.75	0.00	6.42
bg	2	2	0.027	1.75	0.00	6.33
bg	2	3	0.028	1.77	0.00	6.51
bg	3	1	0.025	1.74	0.00	6.37
bg	3	2	0.026	1.77	0.00	6.24
bg	3	3	0.026	1.75	0.00	6.57
bg	4	1	0.029	1.83	0.00	6.84
bg	4	2	0.029	1.74	0.00	6.38
bg	4	3	0.027	1.78	0.00	6.18
bg	5	1	0.027	1.79	0.00	6.50
bg	5	2	0.027	1.77	0.00	6.47
bg	5	3	0.029	1.76	0.00	6.28
plateau	1	1	0.189	5.34	0.00	35.22
plateau	1	2	0.205	5.02	0.00	33.31
plateau	1	3	0.180	4.88	0.00	30.54
plateau	2	1	0.168	4.54	0.00	28.53
plateau	2	2	0.181	4.87	0.00	30.82
plateau	2	3	0.157	4.46	0.00	28.48
plateau	3	1	0.161	4.55	0.00	28.74
plateau	3	2	0.153	4.42	0.00	27.43
plateau	3	3	0.129	4.13	0.00	25.50
plateau	4	1	0.151	4.41	0.00	27.88
plateau	4	2	0.154	4.38	0.00	27.76
plateau	4	3	0.156	4.33	0.00	27.89
plateau	5	1	0.145	4.26	0.00	25.86
plateau	5	2	0.153	4.35	0.00	27.02
plateau	5	3	0.156	4.53	0.00	27.14

14-Jan-00 Cherokee Creek all units in mg L-1

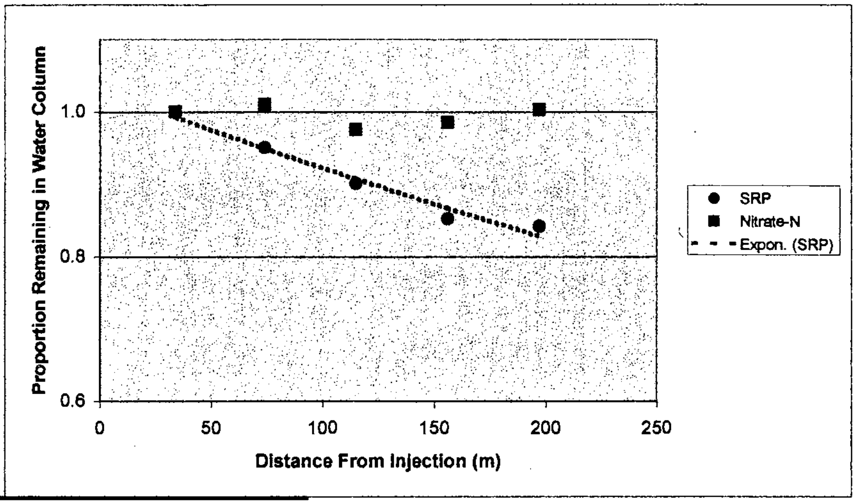
Sample	Site	Location	SRP	Nitrate-N	Ammonia-N	Chloride
bg	1	1	0.030	2.36	0.00	10.08
bg	1	2	0.030	2.32	-0.02	9.39
bg	1	3	0.028	2.36	0.01	9.52
bg	2	1	0.028	2.36	0.01	9.25
bg	2	2	0.028	2.37	0.01	8.96
bg	2	3	0.029	2.34	0.00	9.35
bg	3	1	0.027	2.31	-0.02	9.58
bg	3	2	*	2.30	0.00	9.36
bg	3	3	0.027	2.29	0.00	9.10
bg	4	1	0.028	2.31	0.00	9.08
bg	4	2	0.029	2.29	-0.02	9.19
bg	4	3	0.028	2.27	-0.02	9.41
bg	5	1	0.028	2.28	0.00	9.30
bg	5	2	0.029	2.31	0.00	9.26
bg	5	3	0.030	2.31	0.00	9.24
plateau	1	1	0.064	3.67	0.01	24.43
plateau	1	2	0.071	3.98	0.01	27.30
plateau	1	3	0.069	3.85	0.01	25.81
plateau	2	1	0.053	3.23	0.01	20.84
plateau	2	2	0.066	3.87	0.00	25.97
plateau	2	3	0.056	3.37	0.00	21.43
plateau	3	1	0.055	3.39	0.01	21.10
plateau	3	2	0.060	3.54	0.02	23.03
plateau	3	3	0.062	3.63	0.01	23.16
plateau	4	1	0.062	3.58	0.01	24.34
plateau	4	2	0.060	3.54	0.01	24.26
plateau	4	3	0.055	3.50	-0.01	23.20
plateau	5	1	0.055	3.52	0.00	22.77
plateau	5	2	0.058	3.55	0.01	22.73
plateau	5	3	0.060	3.53	0.01	23.40

bg = background
site: 1 most upstream, 5 downstream
location: 1 left middle looking upstream, 2 middle, 3 right middle

Cherokee Creek - 27 July 1999

Proportion Remaining in the Water Column

Distance (m)	SRP	Nitrate-N	Ln(SRP)	Ln(Nitrate-N)
34	1.00	1.00	0.00	0.00
74	0.95	1.01	-0.05	0.01
115	0.90	0.98	-0.10	-0.02
156	0.85	0.98	-0.16	-0.02
197	0.84	1.00	-0.17	0.00



SRP Uptake Length Regression
SUMMARY OUTPUT

Regression Statistics	
Multiple R	0.984438145
R Square	0.969118462
Adjusted R Square	0.958824616
Standard Error	0.014708164
Observations	5

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	1	0.020368487	0.02037	94.1454211	0.002324928
Residual	3	0.00064899	0.00022		
Total	4	0.021015478			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 95.0%*	*Upper 95.0%*
Intercept	-0.006852541	0.011355603	-0.60345	0.588781802	-0.04299117	0.02928609	-0.042991172	0.02928609
X Variable 1	-0.001106096	0.000113997	-9.70286	0.002324928	-0.00146889	-0.00074331	-0.001468885	-0.000743306

Nitrate-N Uptake Length Regression
SUMMARY OUTPUT

Regression Statistics	
Multiple R	0.21794488
R Square	0.047499971
Adjusted R Square	-0.270000039
Standard Error	0.015930893
Observations	5

ANOVA

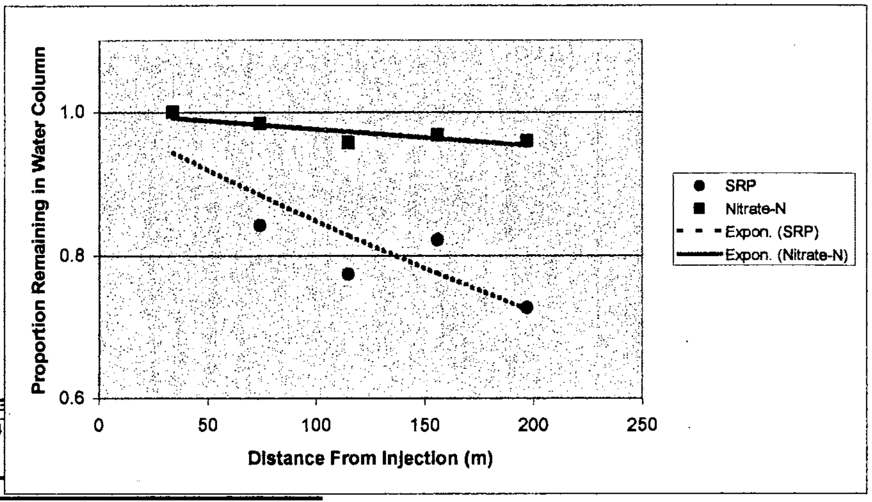
	df	*SS*	*MS*	*F*	*Significance F*
Regression	1	3.79691E-05	3.8E-05	0.149606202	0.724716727
Residual	3	0.00076138	0.00025		
Total	4	0.000799349			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 95.0%*	*Upper 95.0%*
Intercept	-0.001613183	0.012299625	-0.13116	0.903952437	-0.04075611	0.037529749	-0.040756114	0.037529749
X Variable 1	-4.77584E-05	0.000123474	-0.38679	0.724716727	-0.00044071	0.000345191	-0.000440707	0.000345191

Cherokee Creek - 3 August 1999

Proportion Remaining in the Water Column

Distance (m)	SRP	Nitrate-N	Ln(SRP)	Ln(Nitrate-N)
34	1.00	1.00	0.00	0.00
74	0.84	0.98	-0.17	-0.02
115	0.77	0.96	-0.25	-0.04
156	0.82	0.97	-0.20	-0.03
197	0.73	0.96	-0.32	-0.04



SRP Uptake Length Regresion

SUMMARY OUTPUT

Regression Statistics	
Multiple R	0.872393945
R Square	0.761071195
Adjusted R Square	0.681428261
Standard Error	0.067469559
Observations	5

ANOVA

	df	SS	MS	F	Significance F
Regression	1	0.043500452	0.0435	9.556041561	0.053659714
Residual	3	0.013656424	0.00455		
Total	4	0.057156876			

	Coefficients	Standard Error	t Stat	P-value	Lower 95%	Upper 95%	Lower 95.0%	Upper 95.0%
Intercept	-0.001656489	0.067375464	-0.02459	0.981929176	-0.21607549	0.212762507	-0.216075486	0.212762507
X Variable 1	-0.001616522	0.000522929	-3.09128	0.053659714	-0.00328072	4.76725E-05	-0.003280716	4.76725E-05

Nitrate-N Uptake Length Regresion

SUMMARY OUTPUT

Regression Statistics	
Multiple R	0.843226563
R Square	0.711031037
Adjusted R Square	0.614708049
Standard Error	0.011387734
Observations	5

ANOVA

	df	SS	MS	F	Significance F
Regression	1	0.000957267	0.00096	7.381737764	0.072737208
Residual	3	0.000389041	0.00013		
Total	4	0.001346309			

	Coefficients	Standard Error	t Stat	P-value	Lower 95%	Upper 95%	Lower 95.0%	Upper 95.0%
Intercept	0.001007022	0.011371852	0.08855	0.935016703	-0.03518332	0.037197365	-0.03518332	0.037197365
X Variable 1	-0.000239801	8.82616E-05	-2.71694	0.072737208	-0.00052069	4.1087E-05	-0.000520689	4.1087E-05

Cherokee Creek - 20 August 1999

Proportion Remaining in the Water Column

Distance (m)	SRP	Ln(SRP)
34	1.000	0.00
74	0.808	-0.21
115	0.479	-0.74
156	0.528	-0.64
197	0.456	-0.78

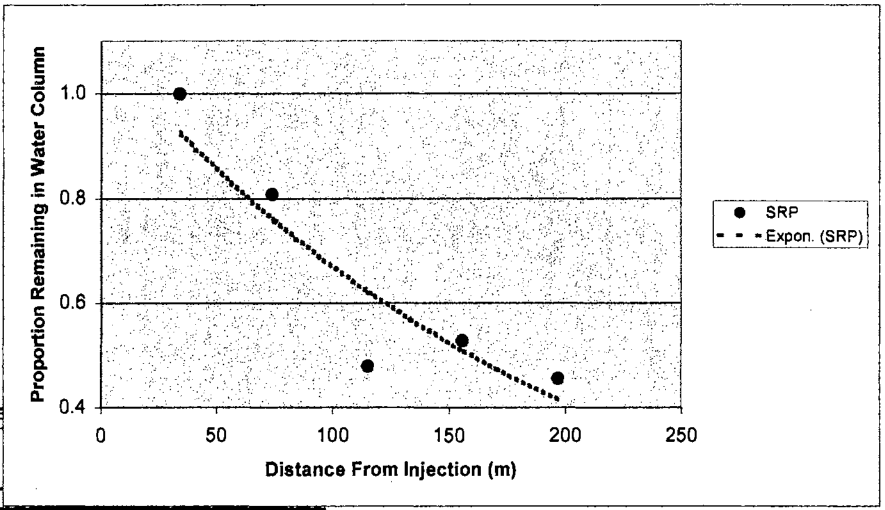
SRP Uptake Length regression
SUMMARY OUTPUT

Regression Statistics	
Multiple R	0.904893914
R Square	0.818832996
Adjusted R Square	0.758443995
Standard Error	0.171074659
Observations	5

ANOVA

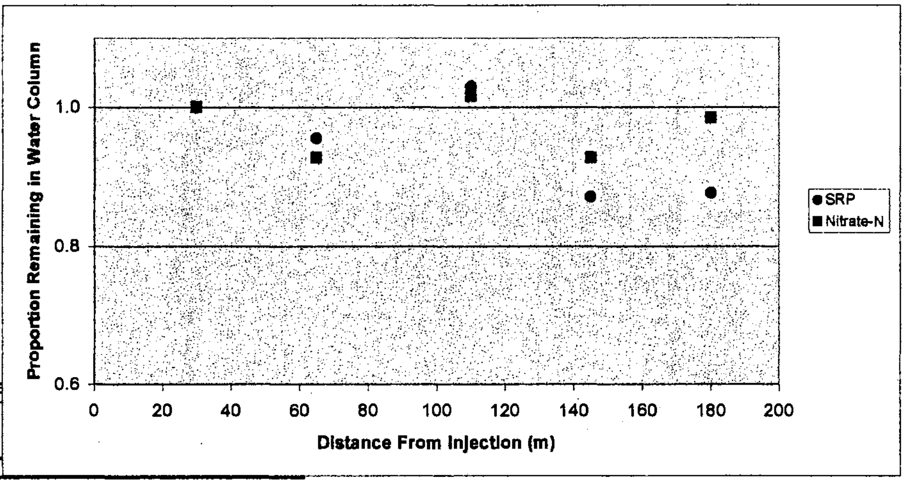
	df	*SS*	*MS*	*F*	*Significance F*
Regression	1	0.396833979	0.3968	13.55931	0.03470178
Residual	3	0.087799617	0.0293		
Total	4	0.484633595			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 95.0%*	*Upper 95.0%*
Intercept	-0.07815476	0.132080109	-0.5917	0.595666	-0.49849301	0.34218349	-0.498493011	0.342183491
X Variable 1	-0.004882464	0.001325929	-3.6823	0.034702	-0.00910217	-0.0006628	-0.009102166	-0.000662762



Cherokee Creek - 14 January 2000
Proportion Remaining in the Water Column

Distance (m)	SRP	Nitrate-N	Ln(SRP)	Ln(Nitrate-N)
30	1.00	1.00	0.00	0.00
65	0.96	0.93	-0.04	-0.08
110	1.03	1.02	0.03	0.02
145	0.87	0.93	-0.14	-0.08
180	0.88	0.98	-0.13	-0.02



SRP Uptake Length Regression
SUMMARY OUTPUT

Regression Statistics	
Multiple R	0.719088668
R Square	0.517088513
Adjusted R Square	0.356118017
Standard Error	0.060809899
Observations	5

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	1	0.011878652	0.01188	3.21231857	0.17099507
Residual	3	0.011093531	0.0037		
Total	4	0.022972184			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 95.0%*	*Upper 95.0%*
Intercept	0.039418905	0.06009123	0.65598	0.55865581	-0.1518184	0.2306562	-0.151818388	0.230656198
X Variable 1	-0.000906044	0.000505522	-1.7923	0.17099507	-0.0025148	0.00070275	-0.002514842	0.000702754

Nitrate-N Uptake Length Regression
SUMMARY OUTPUT

Regression Statistics	
Multiple R	0.089335641
R Square	0.007980857
Adjusted R Square	-0.322692191
Standard Error	0.04923737
Observations	5

ANOVA

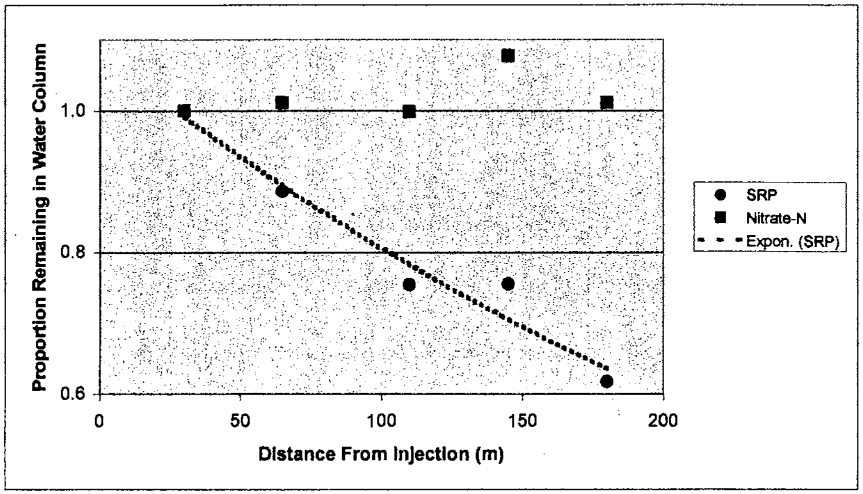
	df	*SS*	*MS*	*F*	*Significance F*
Regression	1	5.85114E-05	5.9E-05	0.02413519	0.88640581
Residual	3	0.007272856	0.00242		
Total	4	0.007331467			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 95.0%*	*Upper 95.0%*
Intercept	-0.023263888	0.048655469	-0.4781	0.6652347	-0.1781074	0.13157967	-0.178107449	0.131579674
X Variable 1	-6.35896E-05	0.000409318	-0.1554	0.88640581	-0.0013662	0.00123904	-0.001366223	0.001239043

Cloud Creek - 19 July 1999

Proportion Remaining in the Water Column

Distance (m)	SRP	Nitrate-N	Ln(SRP)	Ln(Nitrate-N)
30	1.00	1.00	0.00	0.00
65	0.89	1.01	-0.12	0.01
110	0.76	1.00	-0.28	0.00
145	0.76	1.08	-0.28	0.07
180	0.62	1.01	-0.48	0.01



SRP Uptake Length Regression
SUMMARY OUTPUT

Regression Statistics	
Multiple R	0.972908444
R Square	0.946550841
Adjusted R Square	0.928734455
Standard Error	0.048737204
Observations	5

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	1	0.126195988	0.1262	53.128105	0.005331041
Residual	3	0.007125945	0.00238		
Total	4	0.133321933			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 95.0%*	*Upper 95.0%*
Intercept	-0.007962993	0.037725577	-0.21108	0.846352363	-0.12802273	0.112096744	-0.12802273	0.112096744
X Variable 1	-0.00295317	0.00040516	-7.2889	0.005331041	-0.00424257	-0.00166377	-0.004242571	-0.00166377

Nitrate-N Uptake Length Regression
SUMMARY OUTPUT

Regression Statistics	
Multiple R	0.425414874
R Square	0.180977815
Adjusted R Square	-0.09202958
Standard Error	0.032823978
Observations	5

ANOVA

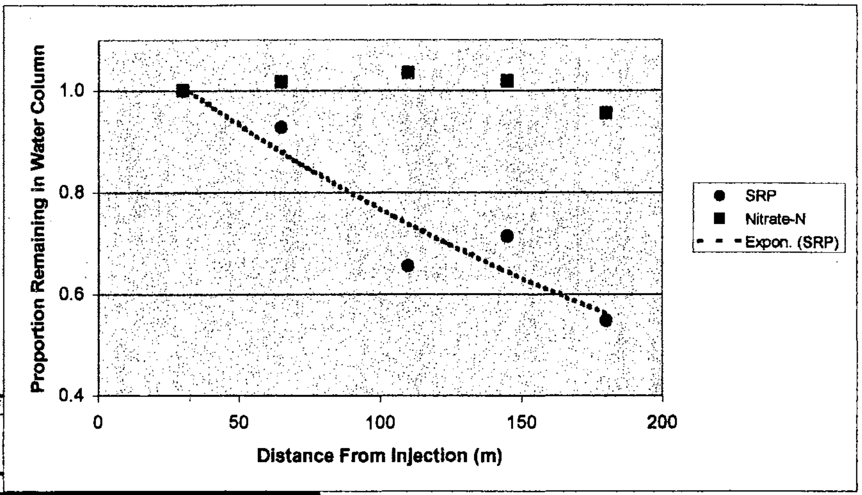
	df	*SS*	*MS*	*F*	*Significance F*
Regression	1	0.000714222	0.00071	0.662904441	0.475157889
Residual	3	0.003232241	0.00108		
Total	4	0.003946463			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 95.0%*	*Upper 95.0%*
Intercept	0.001814444	0.025407767	0.07141	0.947563346	-0.07904448	0.082673374	-0.079044485	0.082673374
X Variable 1	0.000222168	0.000272871	0.61419	0.475157889	-0.00064623	0.001090566	-0.000646229	0.001090566

Cloud Creek - 27 July 1999

Proportion Remaining in the Water Column

Distance (m)	SRP	Nitrate-N	Ln(SRP)	Ln(Nitrate-N)
30	1.00	1.00	0.00	0.00
65	0.93	1.02	-0.07	0.02
110	0.66	1.03	-0.42	0.03
145	0.71	1.02	-0.34	0.02
180	0.55	0.95	-0.60	-0.05



SRP Uptake Length Regression

SUMMARY OUTPUT

Regression Statistics	
Multiple R	0.941427943
R Square	0.886286572
Adjusted R Square	0.848382096
Standard Error	0.096745751
Observations	5

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	1	0.218850465	0.21885	23.38210854	0.016866179
Residual	3	0.028079221	0.00936		
Total	4	0.246929686			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 95.0%*	*Upper 95.0%*
Intercept	0.009388173	0.074887129	0.12536	0.908164394	-0.22893632	0.247712665	-0.228936319	0.247712665
X Variable 1	-0.003889014	0.000804262	-4.8355	0.016866179	-0.00644854	-0.00132949	-0.006448537	-0.00132949

Nitrate-N Uptake Length Regression

SUMMARY OUTPUT

Regression Statistics	
Multiple R	0.444529074
R Square	0.197606098
Adjusted R Square	-0.069858536
Standard Error	0.031893935
Observations	5

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	1	0.000751537	0.00075	0.738812062	0.453244331
Residual	3	0.003051669	0.00102		
Total	4	0.003803206			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 95.0%*	*Upper 95.0%*
Intercept	0.021789235	0.024887856	0.88259	0.442451669	-0.05677862	0.100357086	-0.056778615	0.100357086
X Variable 1	-0.000227898	0.000265139	-0.85954	0.453244331	-0.00107169	0.000615894	-0.00107169	0.000615894

Cloud Creek - 8 january 2000

Proportion Remaining in the Water Column

Distance (m)	SRP	Nitrate-N	Ammonia-N	Ln(SRP)	Ln(Nitrate-N)	Ln(Ammonia-N)
30	1.00	1.00	1.00	0.00	0.00	0.00
65	0.88	0.99	0.66	-0.13	-0.01	-0.41
110	0.99	1.00	0.64	-0.01	0.00	-0.44
145	0.75	0.96	0.26	-0.29	-0.04	-1.33
180	0.76	0.98	0.20	-0.27	-0.02	-1.59

SRP Uptake Length Regression

SUMMARY OUTPUT

Regression Statistics	
Multiple R	0.791239748
R Square	0.62606034
Adjusted R Square	0.501413786
Standard Error	0.097949264
Observations	5

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	1	0.04818793	0.04818793	5.022685	0.11084487
Residual	3	0.028782175	0.00959406		
Total	4	0.076970104			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 95.0%*	*Upper 95.0%*
Intercept	-0.003473207	0.075818722	-0.0458094	0.966341	-0.24476244	0.23781603	-0.244762445	0.23781603
X Variable 1	-0.001824882	0.000814267	-2.2411347	0.110845	-0.00441625	0.000766482	-0.004416246	0.000766482

Nitrate-N Uptake Length Regression

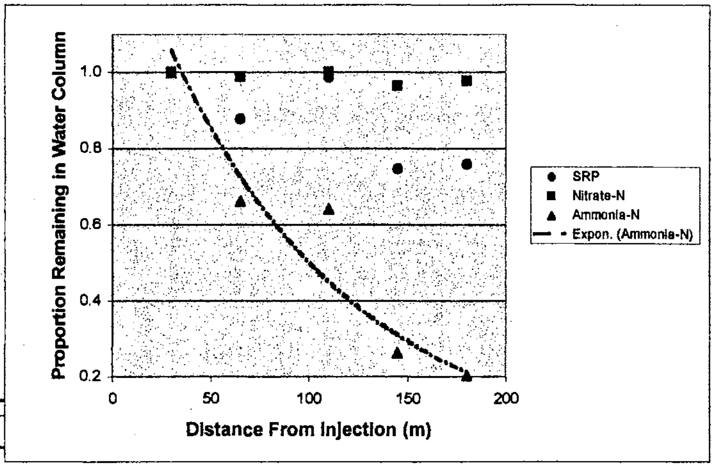
SUMMARY OUTPUT

Regression Statistics	
Multiple R	0.688645626
R Square	0.474232798
Adjusted R Square	0.298977063
Standard Error	0.013195219
Observations	5

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	1	0.000471143	0.00047114	2.705947	0.19852426
Residual	3	0.000522341	0.00017411		
Total	4	0.000993484			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 95.0%*	*Upper 95.0%*
Intercept	-0.00051124	0.010213807	-0.0500533	0.963226	-0.03301648	0.031994001	-0.033016481	0.031994001
X Variable 1	-0.000180444	0.000109694	-1.6449764	0.198524	-0.00052954	0.000168651	-0.000529539	0.000168651



Ammonia-N Uptake Length Regression

SUMMARY OUTPUT

Regression Statistics	
Multiple R	0.953392063
R Square	0.908956426
Adjusted F	0.878608567
Standard E	0.234643562
Observatic	5

ANOVA

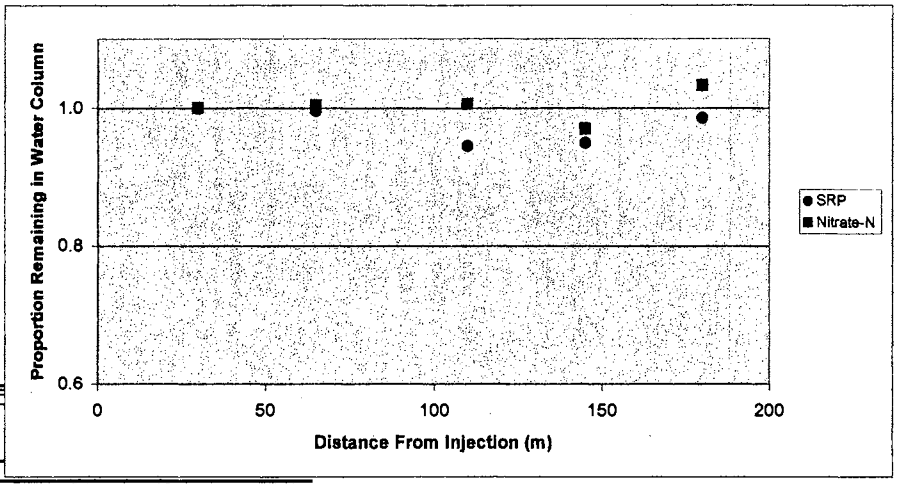
	df	*SS*	*MS*	*F*	*Significance F*
Regressior	1	1.649044224	1.649	29.95125	0.011994
Residual	3	0.165172803	0.0551		
Total	4	1.814217027			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 95.0%*	*Upper 95.0%*
Intercept	0.056330266	0.18162847	0.3101	0.776751	-0.52169313	0.63435366	-0.521693131	0.634353662
X Variable	-0.010675344	0.001950628	-5.4728	0.011994	-0.01688312	-0.00446757	-0.016883118	-0.004467571

Cloud Creek - 21 January 2000

Proportion Remaining in the Water Column

Distance (m)	SRP	Nitrate-N	Ln(SRP)	Ln(Nitrate-N)
30	1.00	1.00	0.00	0.00
65	1.00	1.00	0.00	0.00
110	0.95	1.01	-0.06	0.01
145	0.95	0.97	-0.05	-0.03
180	0.99	1.03	-0.01	0.03



SRP Uptake Length Regression
SUMMARY OUTPUT

Regression Statistics	
Multiple R	0.496508207
R Square	0.246520399
Adjusted R Square	-0.004639468
Standard Error	0.026759069
Observations	5

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	1	0.000702821	0.0007	0.98152783	0.39485694
Residual	3	0.002148143	0.00072		
Total	4	0.002850964			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 95.0%*	*Upper 95.0%*
Intercept	-0.008399669	0.020713156	-0.4055	0.71228079	-0.07431824	0.0575189	-0.074318238	0.0575189
X Variable 1	-0.000220388	0.000222452	-0.9907	0.39485694	-0.00092833	0.00048755	-0.000928331	0.000487555

Nitrate-N Uptake Length Regression
SUMMARY OUTPUT

Regression Statistics	
Multiple R	0.18727865
R Square	0.035073293
Adjusted R Square	-0.286568943
Standard Error	0.025344539
Observations	5

ANOVA

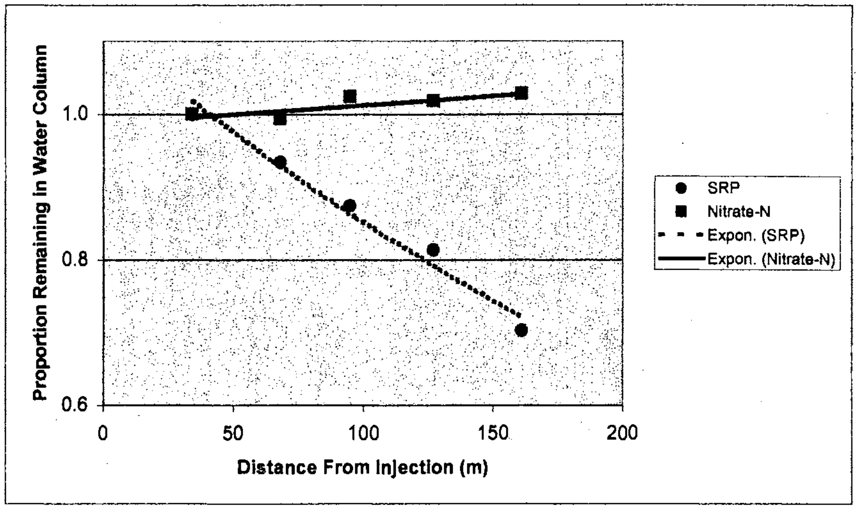
	df	*SS*	*MS*	*F*	*Significance F*
Regression	1	7.00442E-05	7E-05	0.10904442	0.76295072
Residual	3	0.001927037	0.00064		
Total	4	0.001997081			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 95.0%*	*Upper 95.0%*
Intercept	-0.003388092	0.019618223	-0.1727	0.87388037	-0.06582209	0.05904591	-0.065822093	0.059045908
X Variable 1	6.95748E-05	0.000210693	0.33022	0.76295072	-0.00060095	0.00074009	-0.000600945	0.000740095

Dry Creek - 19 July 1999

Proportion Remaining in the Water Column

Distance (m)	SRP	Nitrate-N	Ln(SRP)	Ln(Nitrate-N)
34	1.00	1.00	0.00	0.00
68	0.93	0.99	-0.07	-0.01
95	0.88	1.02	-0.13	0.02
127	0.81	1.02	-0.21	0.02
161	0.70	1.03	-0.35	0.03



SRP Uptake Length Regression
SUMMARY OUTPUT

Regression Statistics	
Multiple R	0.986151157
R Square	0.972494105
Adjusted R Square	0.963325473
Standard Error	0.025931628
Observations	5

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	1	0.071325037	0.0713	106.067528	0.00195231
Residual	3	0.002017348	0.0007		
Total	4	0.073342385			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 95.0%*	*Upper 95.0%*
Intercept	0.01825082	0.02016319	0.9052	0.4321071	-0.04591751	0.08241915	-0.045917509	0.082419149
X Variable 1	-0.002696414	0.000261816	-10.299	0.00195231	-0.00352963	-0.0018632	-0.003529628	-0.001863199

Nitrate-N Uptake Length Regression
SUMMARY OUTPUT

Regression Statistics	
Multiple R	0.8270272
R Square	0.683973989
Adjusted R Square	0.578631985
Standard Error	0.009615723
Observations	5

ANOVA

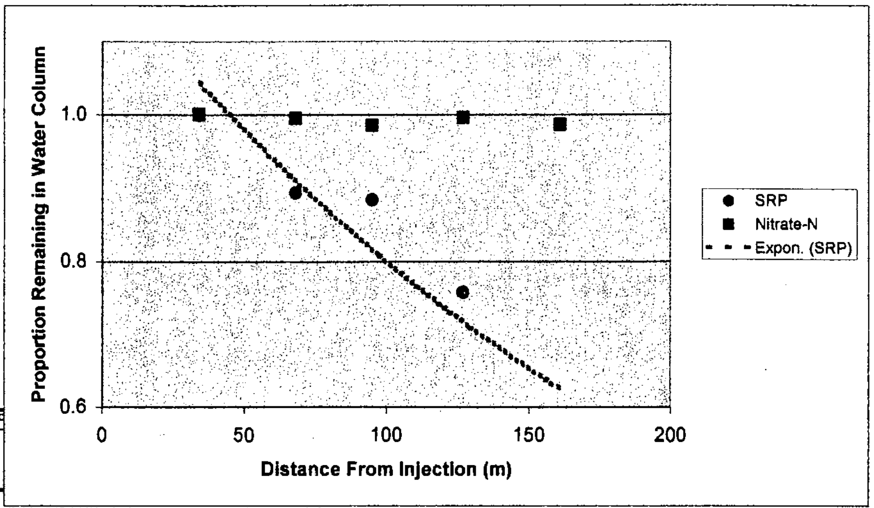
	df	*SS*	*MS*	*F*	*Significance F*
Ragression	1	0.000600346	0.0006	6.49288949	0.08408115
Residual	3	0.000277386	9E-05		
Total	4	0.000877733			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 95.0%*	*Upper 95.0%*
Intercept	-0.003199851	0.007476725	-0.428	0.69753375	-0.02699415	0.02059445	-0.026994148	0.020594446
X Variable 1	0.000247381	9.70839E-05	2.5481	0.08408115	-6.1584E-05	0.00055635	-6.15837E-05	0.000556346

Dry Creek - 3 August 1999

Proportion Remaining in the Water Column

Distance (m)	SRP	Nitrate-N	Ln(SRP)	Ln(Nitrate-N)
34	1.00	1.00	0.00	0.00
68	0.89	0.99	-0.11	-0.01
95	0.88	0.99	-0.12	-0.01
127	0.76	1.00	-0.28	0.00
161	0.58	0.99	-0.54	-0.01



SRP Uptake Length Regression
SUMMARY OUTPUT

Regression Statistics	
Multiple R	0.950187333
R Square	0.902855969
Adjusted R Square	0.870474625
Standard Error	0.075772151
Observations	5

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	1	0.160082124	0.16008	27.8819796	0.0132456
Residual	3	0.017224257	0.00574		
Total	4	0.177306381			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 95.0%*	*Upper 95.0%*
Intercept	0.043310456	0.05891679	0.73511	0.51552407	-0.14418924	0.23081015	-0.144189239	0.230810152
X Variable 1	-0.004039587	0.000765024	-5.2803	0.0132456	-0.00647424	-0.0016049	-0.006474237	-0.001604936

Nitrate-N Uptake Length Regression
SUMMARY OUTPUT

Regression Statistics	
Multiple R	0.671318675
R Square	0.450668764
Adjusted R Square	0.267558352
Standard Error	0.005531749
Observations	5

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	1	7.53129E-05	7.5E-05	2.4611859	0.21469958
Residual	3	9.18007E-05	3.1E-05		
Total	4	0.000167114			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 95.0%*	*Upper 95.0%*
Intercept	-0.00213145	0.004301223	-0.4955	0.65424208	-0.01581987	0.01155697	-0.015819873	0.011556972
X Variable 1	-8.78194E-05	5.58506E-05	-1.5688	0.21469958	-0.00026536	9.0122E-05	-0.000265361	9.01224E-05

Dry Creek - 6 january 2000
Proportion Remaining in the Water Column

Distance (m)	SRP	Nitrate-N	Ammonia-N	Ln(SRP)	Ln(Nitrate-N)	Ln(Ammonia-N)
34	1.00	1.00	1.00	0.00	0.00	0.00
68	1.00	0.97	0.71	0.00	-0.03	-0.35
95	1.02	0.97	0.75	0.02	-0.03	-0.29
127	0.98	0.98	0.72	-0.02	-0.02	-0.33
161	0.64	0.97	0.46	-0.45	-0.03	-0.77

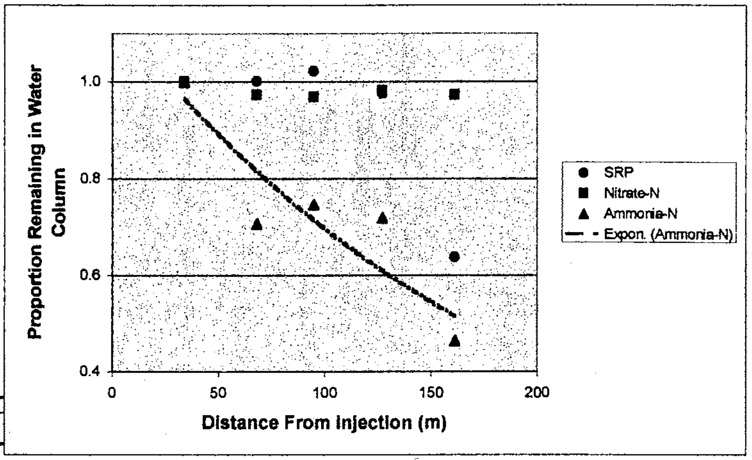
SRP Uptake Length Regression
SUMMARY OUTPUT

Regression Statistics	
Multiple R	0.740079587
R Square	0.547717795
Adjusted R Square	0.39695706
Standard Error	0.155914252
Observations	5

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	1	0.088316172	0.0883162	3.633027	0.15271861
Residual	3	0.072927762	0.0243093		
Total	4	0.161243934			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 95.0%*	*Upper 95.0%*
Intercept	0.099554845	0.121231443	0.8211966	0.471713	-0.2862581	0.485367764	-0.286258075	0.485367764
X Variable 1	-0.003000445	0.001574169	-1.9060501	0.152719	-0.0080102	0.002009268	-0.008010157	0.002009268



Nitrate-N Uptake Length Regression
SUMMARY OUTPUT

Regression Statistics	
Multiple R	0.591773416
R Square	0.350195776
Adjusted R Square	0.133594368
Standard Error	0.011886903
Observations	5

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	1	0.000228525	0.0002285	1.616775	0.29316859
Residual	3	0.000424038	0.0001413		
Total	4	0.000652563			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 95.0%*	*Upper 95.0%*
Intercept	-0.011548749	0.009244241	-1.2492912	0.300155	-0.0409681	0.017870578	-0.040968076	0.017870578
X Variable 1	-0.000152627	0.000120035	-1.2715247	0.293169	-0.0005346	0.000229378	-0.000534632	0.000229378

Ammonia-N Uptake Length Regression
SUMMARY OUTPUT

Regression Statistics	
Multiple R	0.890651013
R Square	0.793259227
Adjusted R Square	0.724345635
Standard Error	0.143631703
Observations	5

ANOVA

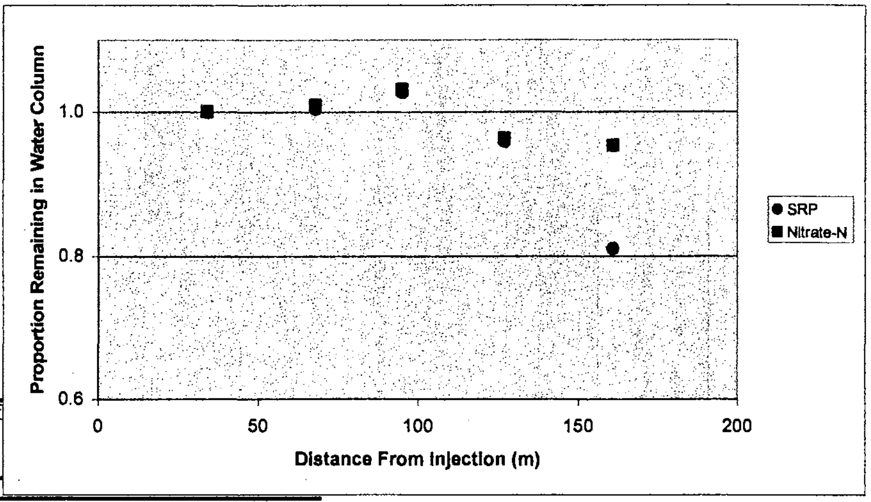
	df	*SS*	*MS*	*F*	*Significance F*
Regression	1	0.237471159	0.2375	11.51093	0.04266755
Residual	3	0.061890198	0.0206		
Total	4	0.299361357			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 95.0%*	*Upper 95.0%*
Intercept	-0.03603272	0.111681122	-0.3226	0.768147	-0.3914522	0.31938679	-0.391452228	0.319386768
X Variable 1	-0.004920066	0.00145016	-3.3926	0.042688	-0.0095351	-0.000305	-0.009535125	-0.000305007

Dry Creek - 14 January 2000

Proportion Remaining in the Water Column

Distance (m)	SRP	Nitrate-N	Ln(SRP)	Ln(Nitrate-N)
34	1.00	1.00	0.00	0.00
68	1.00	1.01	0.00	0.01
95	1.03	1.03	0.03	0.03
127	0.96	0.96	-0.04	-0.04
161	0.81	0.95	-0.21	-0.05



SRP Uptake Length Regression

SUMMARY OUTPUT

Regression Statistics	
Multiple R	0.780182257
R Square	0.608684355
Adjusted R Square	0.478245806
Standard Error	0.069626748
Observations	5

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	1	0.022622386	0.02262	4.666445324	0.119553644
Residual	3	0.014543652	0.00485		
Total	4	0.037166038			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 95.0%*	*Upper 95.0%*
Intercept	0.051844058	0.054138419	0.95762	0.408899875	-0.12044871	0.224136831	-0.120448715	0.224136831
X Variable 1	-0.00151857	0.000702978	-2.1602	0.119553644	-0.00375576	0.000718622	-0.003755761	0.000718622

Nitrate-N Uptake Length Regression

SUMMARY OUTPUT

Regression Statistics	
Multiple R	0.693282508
R Square	0.480640635
Adjusted R Square	0.307520847
Standard Error	0.027584609
Observations	5

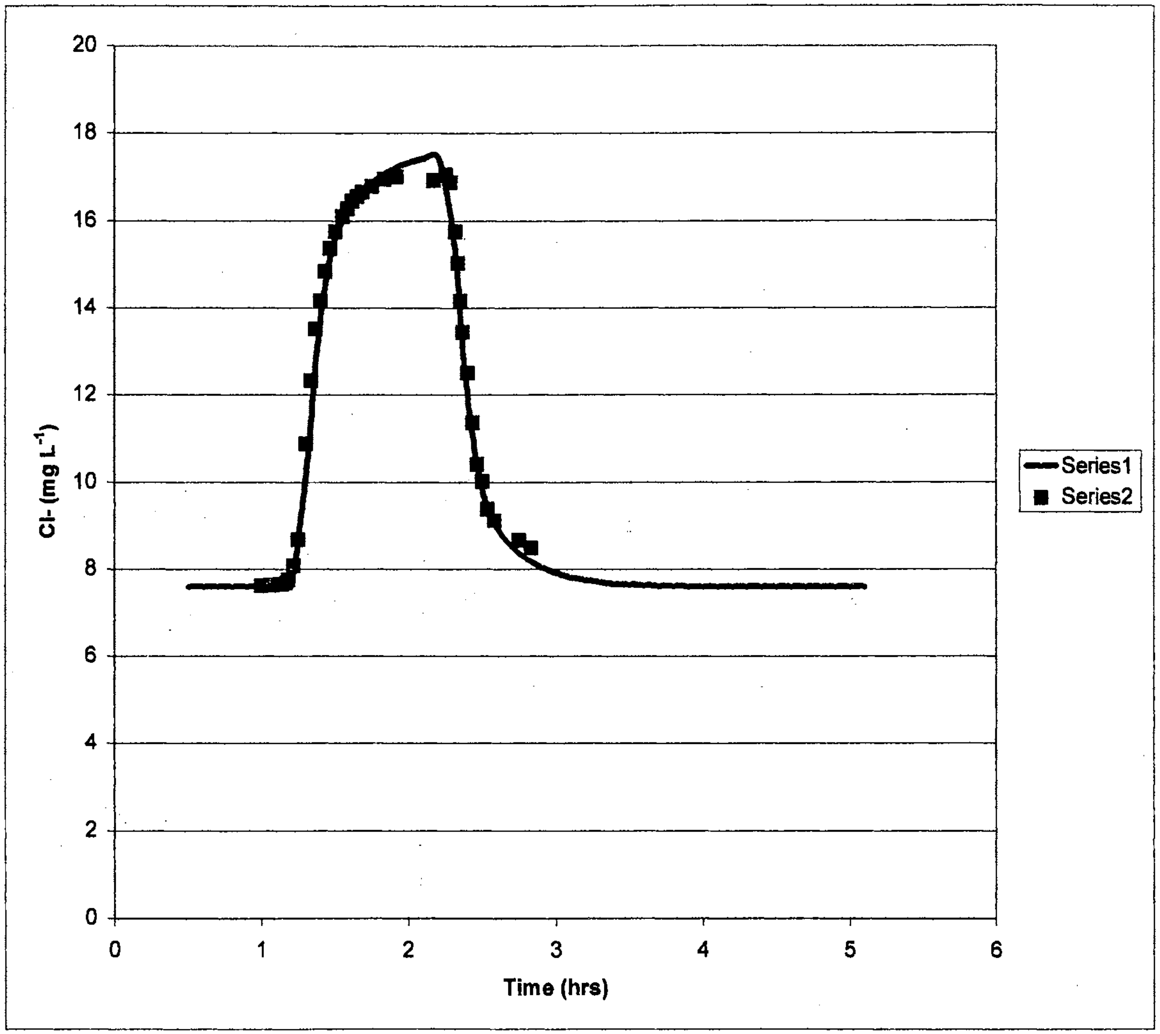
ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	1	0.002112552	0.00211	2.776347178	0.194256434
Residual	3	0.002282732	0.00076		
Total	4	0.004395284			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 95.0%*	*Upper 95.0%*
Intercept	0.019956773	0.021448469	0.93045	0.420771005	-0.04830189	0.088215437	-0.04830189	0.088215437
X Variable 1	-0.000464055	0.000278505	-1.66624	0.194256434	-0.00135038	0.000422272	-0.001350381	0.000422272

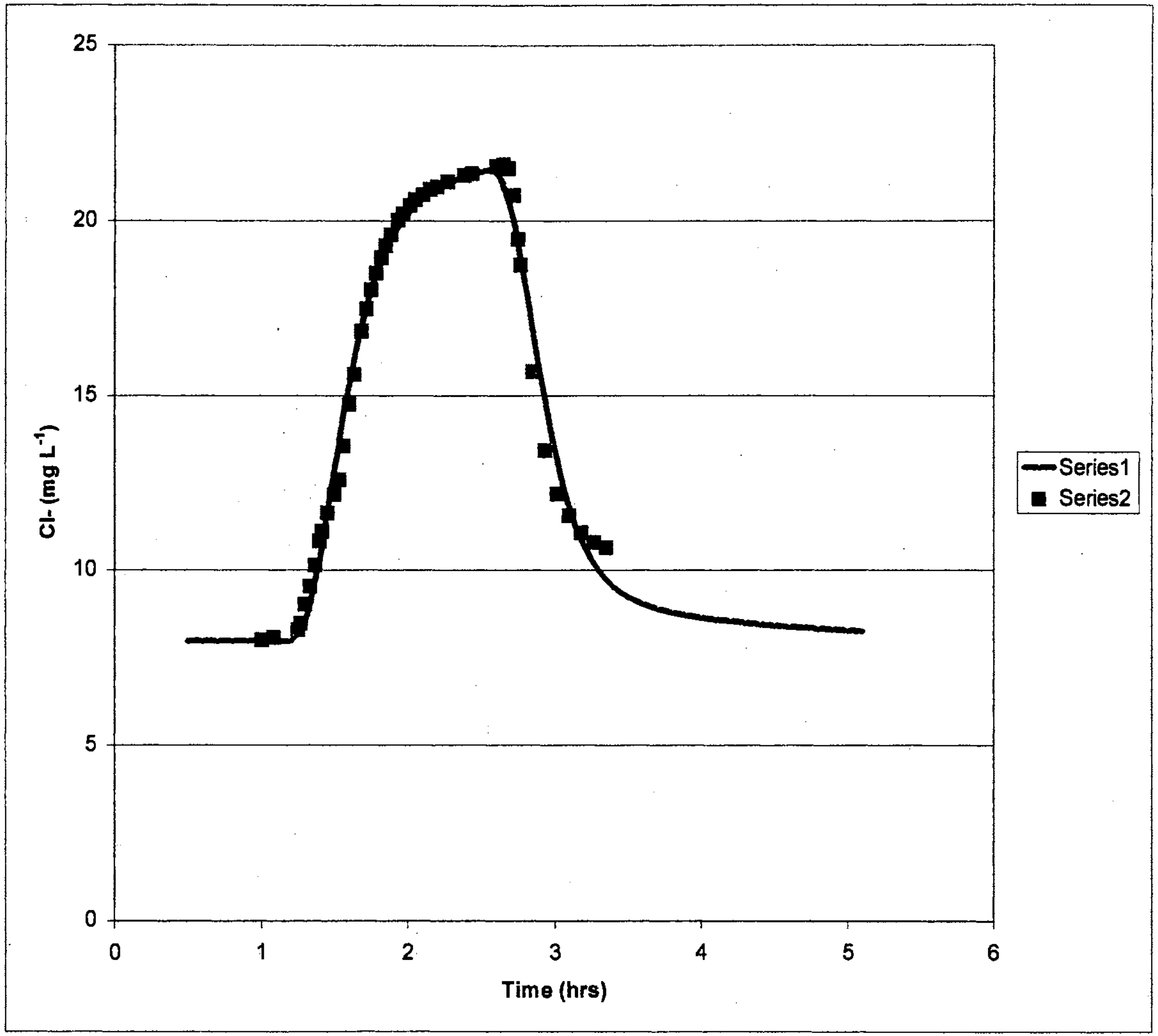
27-Jul-99 Cherokee Creek

Observed Data - Series 2		OTIS Modeled Data- Series 1	
Time (hrs)	Cl- (mg L^{-1})	Time (hrs)	Cl- (mg L^{-1})
1.00	7.61	0.50	7.61
1.07	7.63	0.60	7.61
1.13	7.65	0.70	7.61
1.17	7.67	0.80	7.61
1.18	7.75	0.90	7.61
1.22	8.07	1.00	7.61
1.25	8.68	1.10	7.61
1.30	10.88	1.20	7.72
1.33	12.32	1.30	10.13
1.37	13.51	1.40	13.82
1.40	14.16	1.50	15.61
1.43	14.83	1.60	16.35
1.47	15.37	1.70	16.76
1.50	15.74	1.80	17.03
1.55	16.10	1.90	17.21
1.58	16.28	2.00	17.34
1.62	16.46	2.10	17.43
1.65	16.56	2.20	17.46
1.68	16.65	2.30	15.78
1.75	16.79	2.40	11.95
1.83	16.95	2.50	9.82
1.92	17.01	2.60	8.97
2.17	16.91	2.70	8.53
2.25	17.05	2.80	8.25
2.28	16.87	2.90	8.05
2.32	15.74	3.00	7.92
2.33	15.03	3.10	7.82
2.35	14.16	3.20	7.76
2.37	13.45	3.30	7.71
2.40	12.50	3.40	7.68
2.43	11.35	3.50	7.66
2.47	10.40	3.60	7.64
2.50	10.00	3.70	7.63
2.53	9.37	3.80	7.63
2.58	9.11	3.90	7.62
2.75	8.66	4.00	7.62
2.83	8.48	4.10	7.62
		4.20	7.61
		4.30	7.61
		4.40	7.61
		4.50	7.61
		4.60	7.61
		4.70	7.61
		4.80	7.61
		4.90	7.61
		5.00	7.61
		5.10	7.61



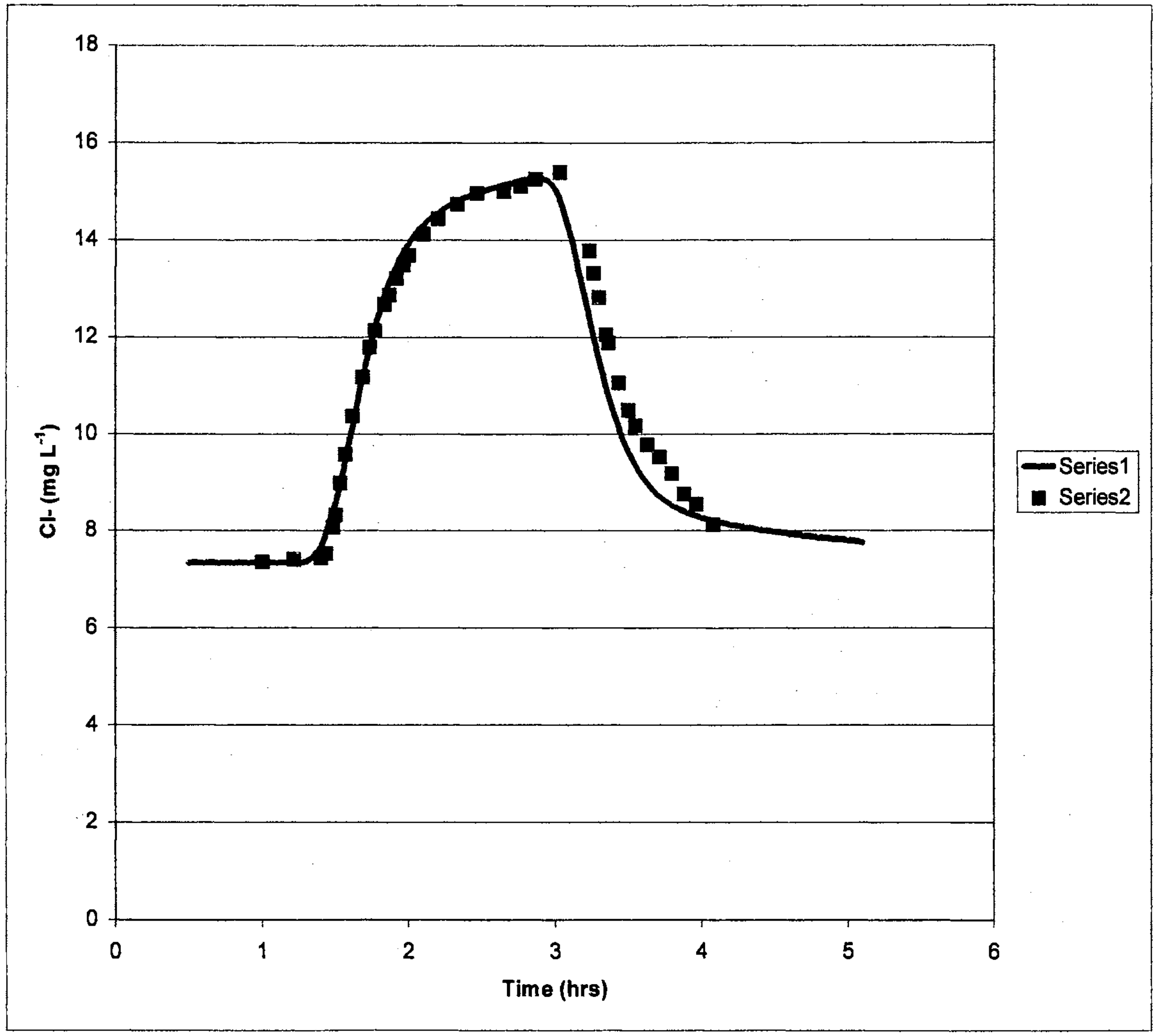
3-Aug-99 Cherokee Creek

Observed Data - Series 2		OTIS Modeled Data- Series 1	
Time (hrs)	Cl- (mg L^{-1})	Time (hrs)	Cl- (mg L^{-1})
1.00	8.00	0.50	8.00
1.08	8.08	0.60	8.00
1.25	8.28	0.70	8.00
1.27	8.47	0.80	8.00
1.30	9.02	0.90	8.00
1.33	9.53	1.00	8.00
1.37	10.14	1.10	8.00
1.40	10.82	1.20	8.02
1.42	11.11	1.30	8.56
1.45	11.64	1.40	10.34
1.50	12.17	1.50	12.87
1.53	12.58	1.60	15.33
1.56	13.55	1.70	17.28
1.60	14.74	1.80	18.67
1.63	15.60	1.90	19.61
1.68	16.85	2.00	20.24
1.72	17.47	2.10	20.66
1.75	18.02	2.20	20.94
1.78	18.49	2.30	21.15
1.82	18.93	2.40	21.30
1.85	19.29	2.50	21.42
1.88	19.59	2.60	21.36
1.93	20.01	2.70	20.31
1.97	20.20	2.80	18.12
2.02	20.43	2.90	15.81
2.05	20.60	3.00	13.45
2.10	20.75	3.10	11.84
2.15	20.90	3.20	10.74
2.20	20.96	3.30	10.02
2.27	21.11	3.40	9.56
2.38	21.30	3.50	9.25
2.43	21.35	3.60	9.05
2.60	21.54	3.70	8.91
2.65	21.60	3.80	8.81
2.68	21.49	3.90	8.73
2.72	20.73	4.00	8.66
2.75	19.46	4.10	8.61
2.77	18.74	4.20	8.56
2.85	15.69	4.30	8.51
2.93	13.42	4.40	8.47
3.02	12.19	4.50	8.44
3.10	11.56	4.60	8.41
3.18	11.07	4.70	8.37
3.27	10.78	4.80	8.35
3.35	10.64	4.90	8.32
		5.00	8.30
		5.10	8.27



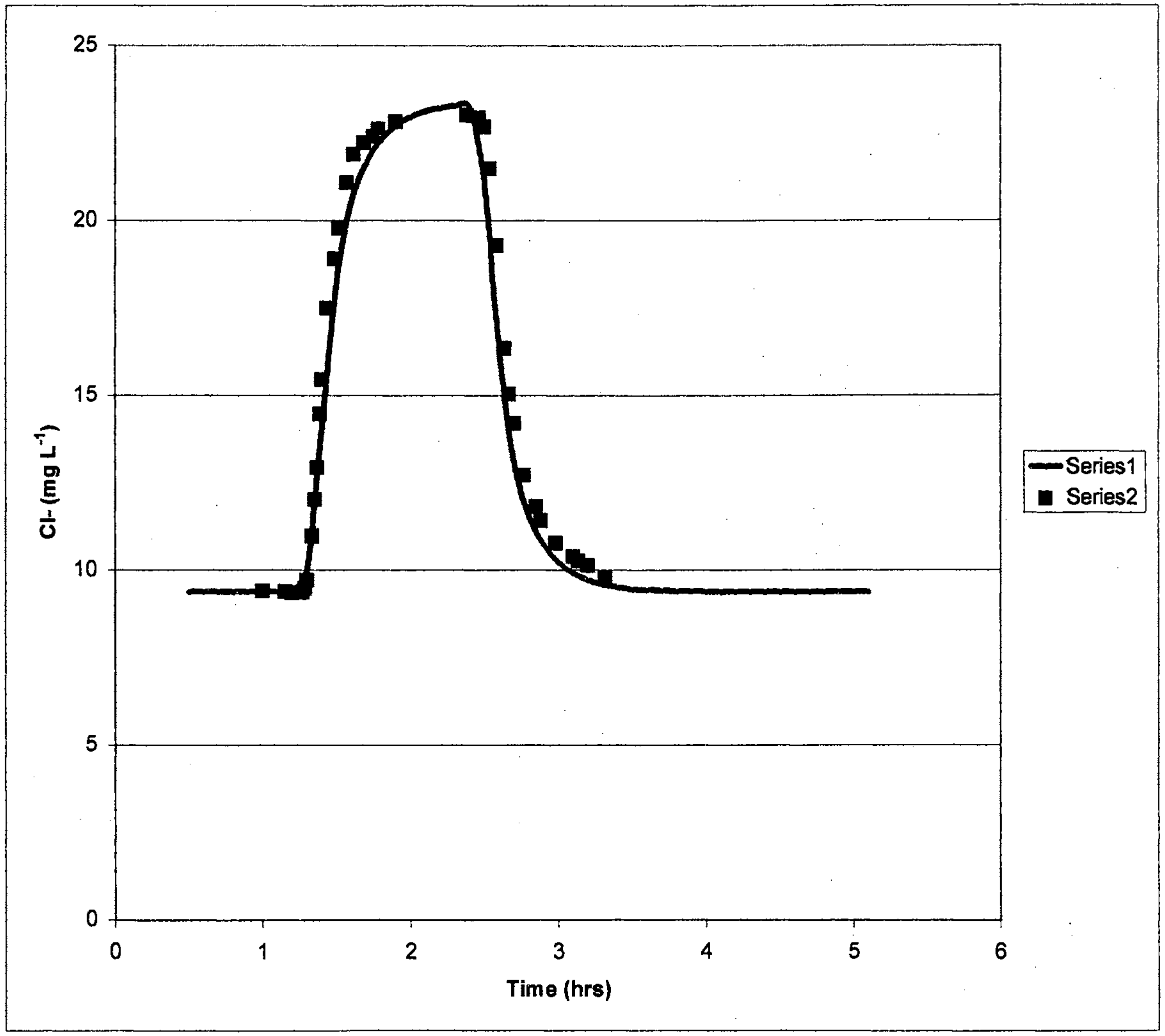
19-Aug-99 Cherokee Creek

Observed Data - Series 2		OTIS Modeled Data- Series 1	
Time (hrs)	Cl- (mg L^{-1})	Time (hrs)	Cl- (mg L^{-1})
1.00	7.36	0.50	7.36
1.22	7.42	0.60	7.36
1.40	7.45	0.70	7.38
1.43	7.53	0.80	7.36
1.48	8.07	0.90	7.36
1.50	8.32	1.00	7.36
1.53	8.98	1.10	7.36
1.57	9.57	1.20	7.36
1.62	10.37	1.30	7.39
1.68	11.16	1.40	7.70
1.73	11.79	1.50	8.61
1.77	12.13	1.60	9.97
1.83	12.67	1.70	11.36
1.87	12.86	1.80	12.52
1.92	13.21	1.90	13.36
1.97	13.49	2.00	13.94
2.00	13.69	2.10	14.32
2.10	14.11	2.20	14.58
2.20	14.43	2.30	14.77
2.33	14.74	2.40	14.90
2.47	14.96	2.50	15.01
2.65	14.99	2.60	15.10
2.77	15.11	2.70	15.18
2.87	15.25	2.80	15.26
3.03	15.39	2.90	15.29
3.23	13.77	3.00	15.05
3.27	13.32	3.10	14.19
3.30	12.81	3.20	12.89
3.35	12.04	3.30	11.54
3.37	11.87	3.40	10.44
3.43	11.05	3.50	9.64
3.50	10.48	3.60	9.10
3.55	10.17	3.70	8.76
3.63	9.77	3.80	8.53
3.72	9.52	3.90	8.38
3.80	9.18	4.00	8.28
3.88	8.75	4.10	8.20
3.97	8.55	4.20	8.14
4.08	8.13	4.30	8.08
		4.40	8.03
		4.50	7.99
		4.60	7.95
		4.70	7.91
		4.80	7.88
		4.90	7.85
		5.00	7.82
		5.10	7.79



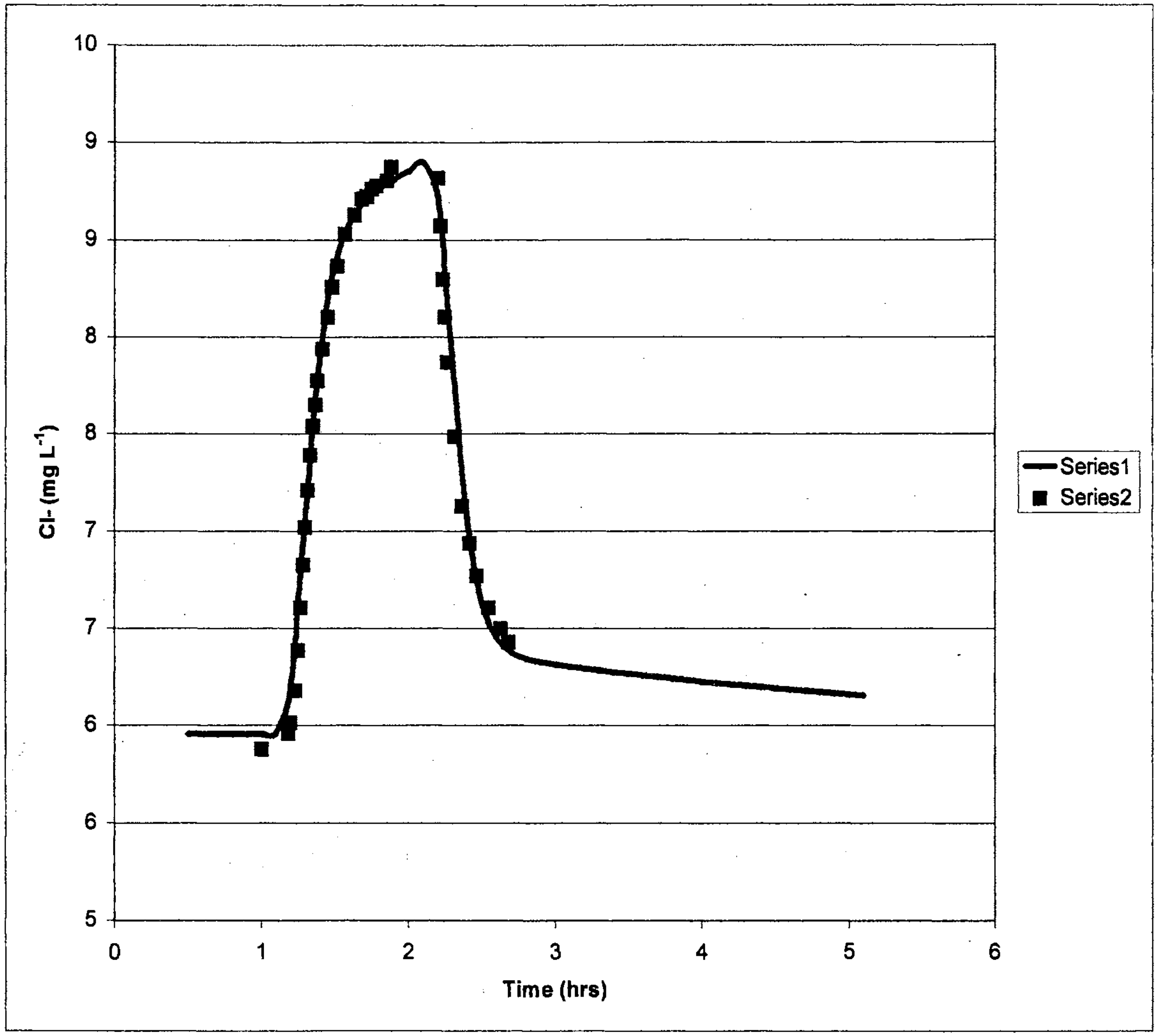
14-Jan-00 Cherokee Creek

Observed Data - Series 2		OTIS Modeled Data- Series 1	
Time (hrs)	Cl- (mg L^{-1})	Time (hrs)	Cl- (mg L^{-1})
1.00	9.40	0.50	9.40
1.15	9.38	0.60	9.40
1.20	9.34	0.70	9.40
1.27	9.36	0.80	9.40
1.28	9.48	0.90	9.40
1.30	9.70	1.00	9.40
1.33	10.97	1.10	9.40
1.35	12.02	1.20	9.40
1.37	12.93	1.30	10.00
1.38	14.46	1.40	14.01
1.40	15.44	1.50	18.36
1.43	17.50	1.60	20.58
1.48	18.91	1.70	21.68
1.52	19.80	1.80	22.32
1.57	21.09	1.90	22.72
1.82	21.89	2.00	22.97
1.68	22.21	2.10	23.13
1.75	22.40	2.20	23.23
1.78	22.60	2.30	23.29
1.90	22.82	2.40	23.28
2.38	23.00	2.50	21.17
2.47	22.94	2.60	16.32
2.50	22.68	2.70	13.10
2.53	21.49	2.80	11.57
2.58	19.29	2.90	10.75
2.63	16.35	3.00	10.25
2.67	15.04	3.10	9.93
2.70	14.20	3.20	9.73
2.77	12.70	3.30	9.60
2.85	11.82	3.40	9.53
2.88	11.41	3.50	9.48
2.98	10.77	3.60	9.45
3.10	10.39	3.70	9.43
3.13	10.27	3.80	9.42
3.20	10.13	3.90	9.41
3.32	9.76	4.00	9.41
		4.10	9.40
		4.20	9.40
		4.30	9.40
		4.40	9.40
		4.50	9.40
		4.60	9.40
		4.70	9.40
		4.80	9.40
		4.90	9.40
		5.00	9.40
		5.10	9.40



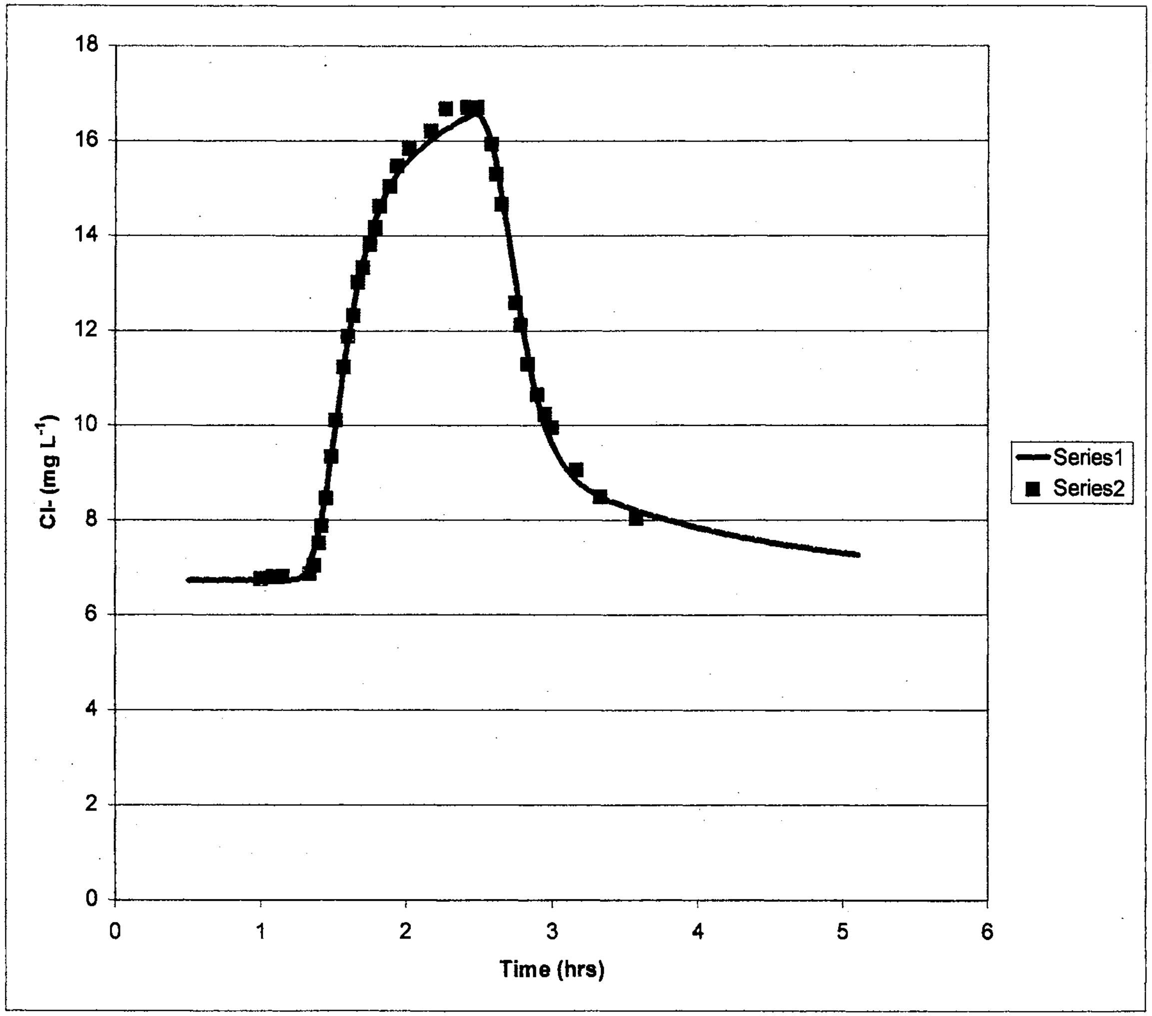
19-Jul-99 Cloud Creek

Observed Date - Series 2		OTIS Modeled Data - Series 1	
Time (hrs)	Cl- (mg L^{-1})	Time (hrs)	Cl- (mg L^{-1})
1.00	5.88	0.50	5.96
1.18	5.96	0.60	5.96
1.20	6.01	0.70	5.96
1.23	6.18	0.80	5.96
1.25	6.39	0.90	5.96
1.27	6.81	1.00	5.96
1.28	6.83	1.10	5.96
1.30	7.02	1.20	6.18
1.32	7.21	1.30	7.06
1.33	7.39	1.40	7.90
1.35	7.54	1.50	8.37
1.37	7.65	1.60	8.59
1.38	7.77	1.70	8.70
1.42	7.94	1.80	8.76
1.45	8.10	1.90	8.81
1.48	8.25	2.00	8.86
1.52	8.36	2.10	8.90
1.57	8.53	2.20	8.72
1.63	8.63	2.30	7.87
1.68	8.71	2.40	7.07
1.72	8.72	2.50	8.64
1.75	8.76	2.60	6.45
1.78	8.78	2.70	6.38
1.85	8.80	2.80	6.35
1.88	8.87	2.90	6.33
2.20	8.82	3.00	6.32
2.22	8.57	3.10	6.31
2.23	6.30	3.20	6.30
2.25	8.10	3.30	6.29
2.27	7.87	3.40	6.28
2.32	7.49	3.50	6.27
2.37	7.13	3.60	6.26
2.42	6.94	3.70	8.25
2.47	6.77	3.80	6.24
2.55	6.61	3.90	6.24
2.63	6.50	4.00	6.23
2.68	6.43	4.10	6.22
		4.20	6.21
		4.30	6.21
		4.40	6.20
		4.50	6.19
		4.60	6.19
		4.70	6.18
		4.80	6.18
		4.90	6.17
		5.00	6.16
		5.10	6.16



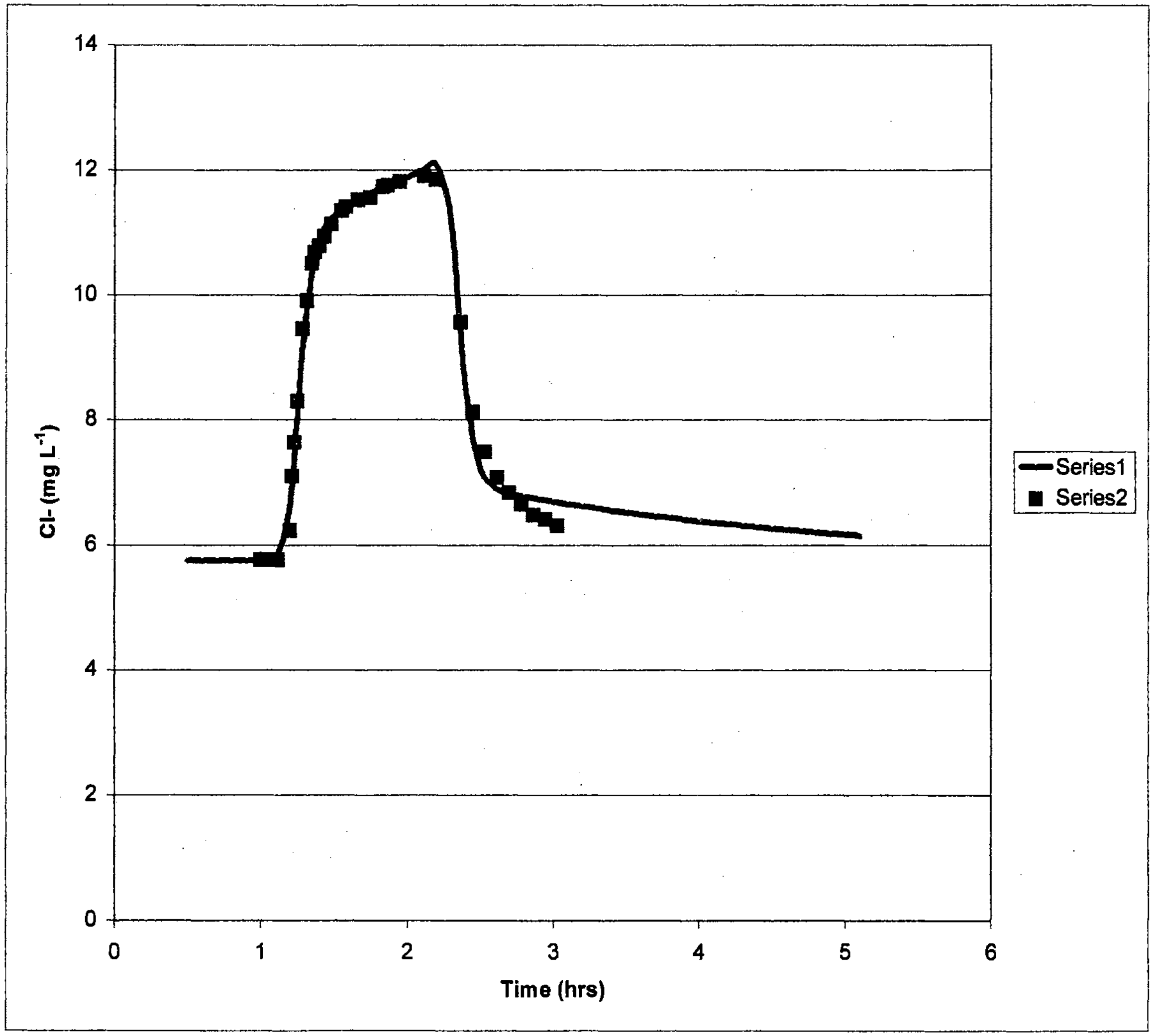
27-Jul-99 Cloud Creek

Observed Data - Series 2		OTIS Modeled Data - Series 1	
Time (hrs)	Cl- (mg L^{-1})	Time (hrs)	Cl- (mg L^{-1})
1.00	6.76	0.50	6.75
1.08	6.80	0.60	6.75
1.12	6.80	0.70	6.75
1.15	6.81	0.80	6.75
1.33	6.87	0.90	6.75
1.37	7.05	1.00	6.75
1.40	7.52	1.10	6.75
1.42	7.88	1.20	6.75
1.45	8.46	1.30	6.88
1.48	9.34	1.40	7.81
1.52	10.10	1.50	9.73
1.57	11.22	1.60	11.82
1.60	11.87	1.70	13.44
1.63	12.32	1.80	14.49
1.67	13.03	1.90	15.14
1.70	13.33	2.00	15.57
1.75	13.82	2.10	15.87
1.78	14.18	2.20	16.11
1.82	14.63	2.30	16.31
1.88	15.05	2.40	16.50
1.93	15.48	2.50	16.54
2.02	15.84	2.60	15.77
2.17	16.20	2.70	13.99
2.27	16.67	2.80	12.03
2.42	16.71	2.90	10.55
2.48	16.71	3.00	9.62
2.58	15.93	3.10	9.06
2.62	15.30	3.20	8.76
2.65	14.67	3.30	8.56
2.75	12.59	3.40	8.41
2.76	12.12	3.50	8.29
2.83	11.29	3.60	8.19
2.90	10.64	3.70	8.10
2.95	10.23	3.80	8.01
3.00	9.94	3.90	7.93
3.17	9.05	4.00	7.85
3.33	6.49	4.10	7.78
3.58	8.04	4.20	7.72
		4.30	7.66
		4.40	7.60
		4.50	7.54
		4.60	7.49
		4.70	7.45
		4.80	7.40
		4.90	7.36
		5.00	7.32
		5.10	7.28



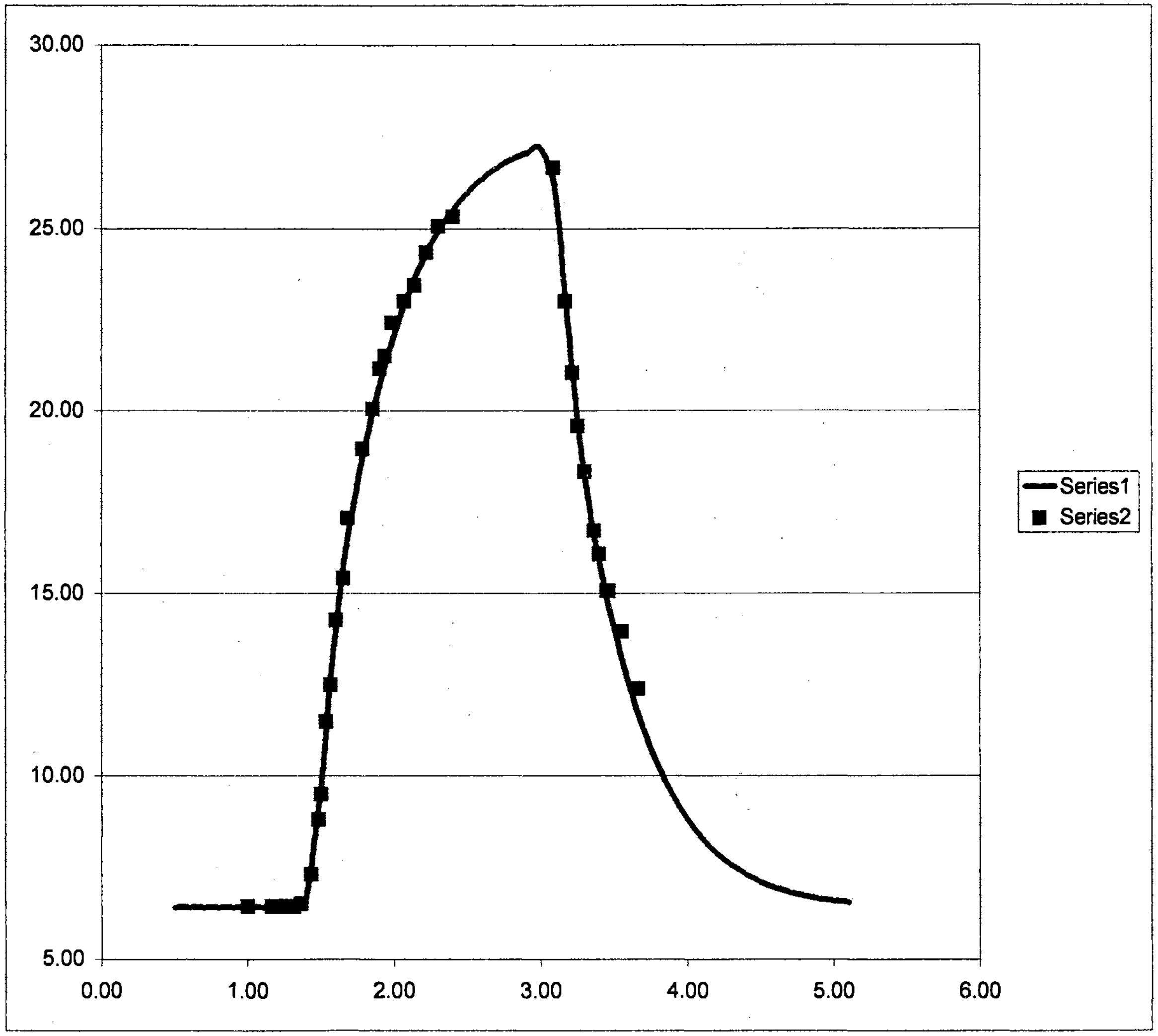
6-Jan-00 Cloud Creek

Observed Data - Series 2		OTIS Modeled Data- Series 1	
Time (hrs)	Cl- (mg L^{-1})	Time (hrs)	Cl- (mg L^{-1})
1.00	5.76	0.50	5.76
1.03	5.76	0.60	5.76
1.12	5.76	0.70	5.76
1.20	6.23	0.80	5.76
1.22	7.10	0.90	5.76
1.23	7.64	1.00	5.76
1.25	8.30	1.10	5.76
1.28	9.47	1.20	6.68
1.32	9.91	1.30	9.45
1.35	10.51	1.40	10.86
1.37	10.69	1.50	11.28
1.40	10.78	1.60	11.45
1.43	10.94	1.70	11.58
1.48	11.13	1.80	11.69
1.55	11.35	1.90	11.80
1.58	11.41	2.00	11.90
1.67	11.52	2.10	12.00
1.75	11.56	2.20	12.10
1.83	11.74	2.30	11.28
1.87	11.75	2.40	8.59
1.95	11.81	2.50	7.26
2.12	11.91	2.60	6.92
2.20	11.85	2.70	6.83
2.37	9.56	2.80	6.78
2.45	8.13	2.90	6.74
2.53	7.49	3.00	6.70
2.62	7.08	3.10	6.66
2.70	6.83	3.20	6.63
2.78	6.65	3.30	6.59
2.87	6.48	3.40	6.56
2.95	6.40	3.50	6.53
3.03	6.30	3.60	6.50
		3.70	6.47
		3.80	6.44
		3.90	6.41
		4.00	6.39
		4.10	6.36
		4.20	6.34
		4.30	6.32
		4.40	6.29
		4.50	6.27
		4.60	6.25
		4.70	6.23
		4.80	6.21
		4.90	6.19
		5.00	6.18
		5.10	6.16

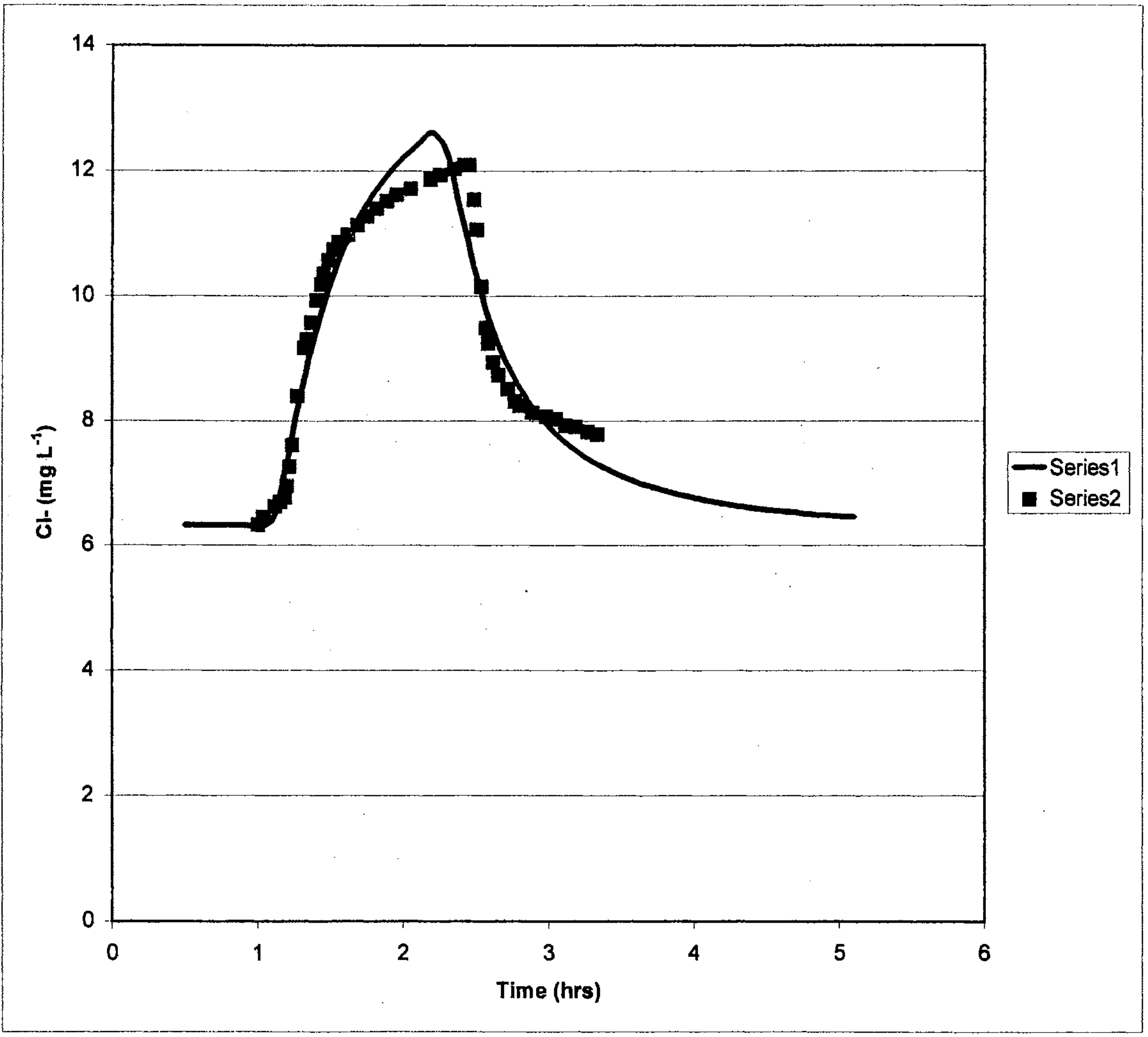


21-Jan-00 Cloud Creek

Observed Data - Series 2		OTIS Modeled Data - Series 1	
Time (hrs)	Cl- (mg L^{-1})	Time (hrs)	Cl- (mg L^{-1})
1.00	6.44	0.50	6.44
1.17	6.44	0.60	6.44
1.25	6.44	0.70	6.44
1.32	6.44	0.80	6.44
1.37	6.52	0.90	6.44
1.43	7.31	1.00	6.44
1.48	8.80	1.10	6.44
1.50	9.51	1.20	6.44
1.53	11.48	1.30	6.44
1.57	12.50	1.40	6.73
1.60	14.27	1.50	9.74
1.65	15.41	1.60	14.08
1.68	17.07	1.70	16.95
1.78	18.96	1.80	19.03
1.85	20.06	1.90	20.72
1.90	21.16	2.00	22.12
1.93	21.51	2.10	23.26
1.98	22.42	2.20	24.19
2.07	23.01	2.30	24.93
2.13	23.44	2.40	25.53
2.22	24.35	2.50	26.00
2.30	25.06	2.60	26.38
2.40	25.33	2.70	26.67
3.08	26.67	2.80	26.90
3.17	23.01	2.90	27.08
3.22	21.04	3.00	27.19
3.25	19.59	3.10	26.01
3.30	18.33	3.20	21.80
3.37	16.71	3.30	18.25
3.40	16.08	3.40	15.92
3.45	15.06	3.50	14.09
3.47	15.06	3.60	12.58
3.55	13.96	3.70	11.34
3.67	12.38	3.80	10.32
		3.90	9.51
		4.00	8.85
		4.10	8.33
		4.20	7.91
		4.30	7.58
		4.40	7.33
		4.50	7.12
		4.60	6.97
		4.70	6.84
		4.80	6.75
		4.90	6.68
		5.00	6.62
		5.10	6.58

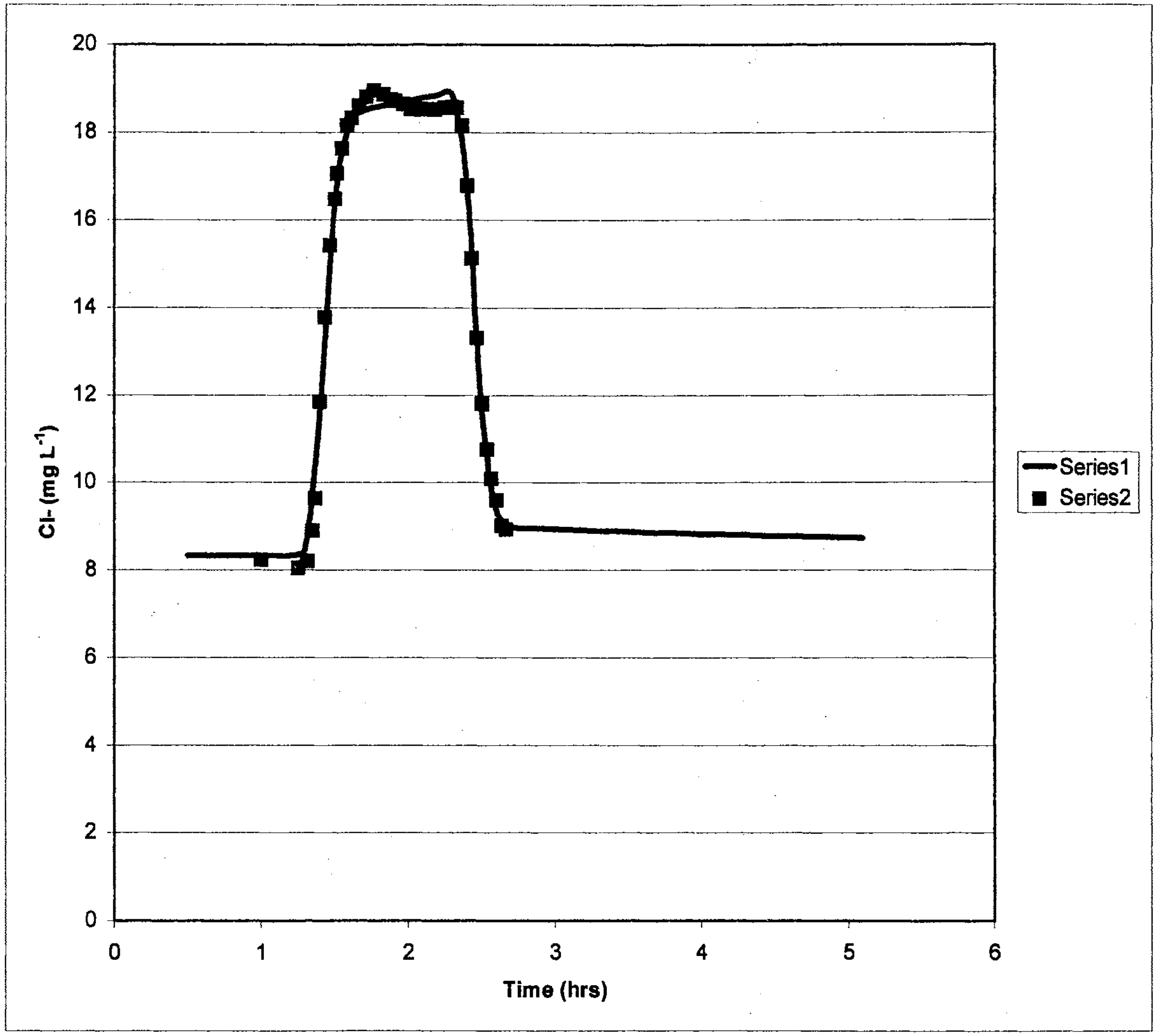


19-Jul-99	Dry Creek		
Observed Data - Series 2		OTIS Modeled Data - Series 1	
Time (hrs)	Cl- (mg L^{-1})	Time (hrs)	Cl- (mg L^{-1})
1.00	6.33	0.50	6.33E+00
1.03	6.45	0.60	6.33E+00
1.12	6.63	0.70	6.33E+00
1.15	6.70	0.80	6.33E+00
1.18	6.77	0.90	6.33E+00
1.20	6.96	1.00	6.33E+00
1.22	7.26	1.10	6.43E+00
1.23	7.61	1.20	7.34E+00
1.27	8.40	1.30	8.50E+00
1.32	9.17	1.40	9.47E+00
1.33	9.31	1.50	1.02E+01
1.37	9.57	1.60	1.08E+01
1.40	9.92	1.70	1.13E+01
1.43	10.18	1.80	1.17E+01
1.45	10.36	1.90	1.20E+01
1.48	10.57	2.00	1.22E+01
1.52	10.75	2.10	1.24E+01
1.55	10.85	2.20	1.26E+01
1.62	10.97	2.30	1.23E+01
1.68	11.13	2.40	1.13E+01
1.75	11.27	2.50	1.03E+01
1.82	11.39	2.60	9.56E+00
1.88	11.52	2.70	8.98E+00
1.95	11.62	2.80	8.53E+00
2.05	11.71	2.90	8.18E+00
2.18	11.87	3.00	7.90E+00
2.25	11.94	3.10	7.68E+00
2.35	12.02	3.20	7.50E+00
2.42	12.10	3.30	7.35E+00
2.45	12.10	3.40	7.23E+00
2.48	11.53	3.50	7.12E+00
2.50	11.06	3.60	7.03E+00
2.53	10.15	3.70	6.95E+00
2.57	9.48	3.80	8.88E+00
2.58	9.24	3.90	6.82E+00
2.62	8.94	4.00	6.77E+00
2.65	8.73	4.10	8.72E+00
2.72	8.50	4.20	6.68E+00
2.77	8.31	4.30	6.64E+00
2.80	8.24	4.40	6.61E+00
2.88	8.13	4.50	6.58E+00
2.98	8.06	4.60	6.55E+00
3.05	8.03	4.70	6.53E+00
3.12	7.92	4.80	6.51E+00
3.18	7.91	4.90	6.49E+00
3.27	7.82	5.00	6.47E+00
3.33	7.78	5.10	6.46E+00



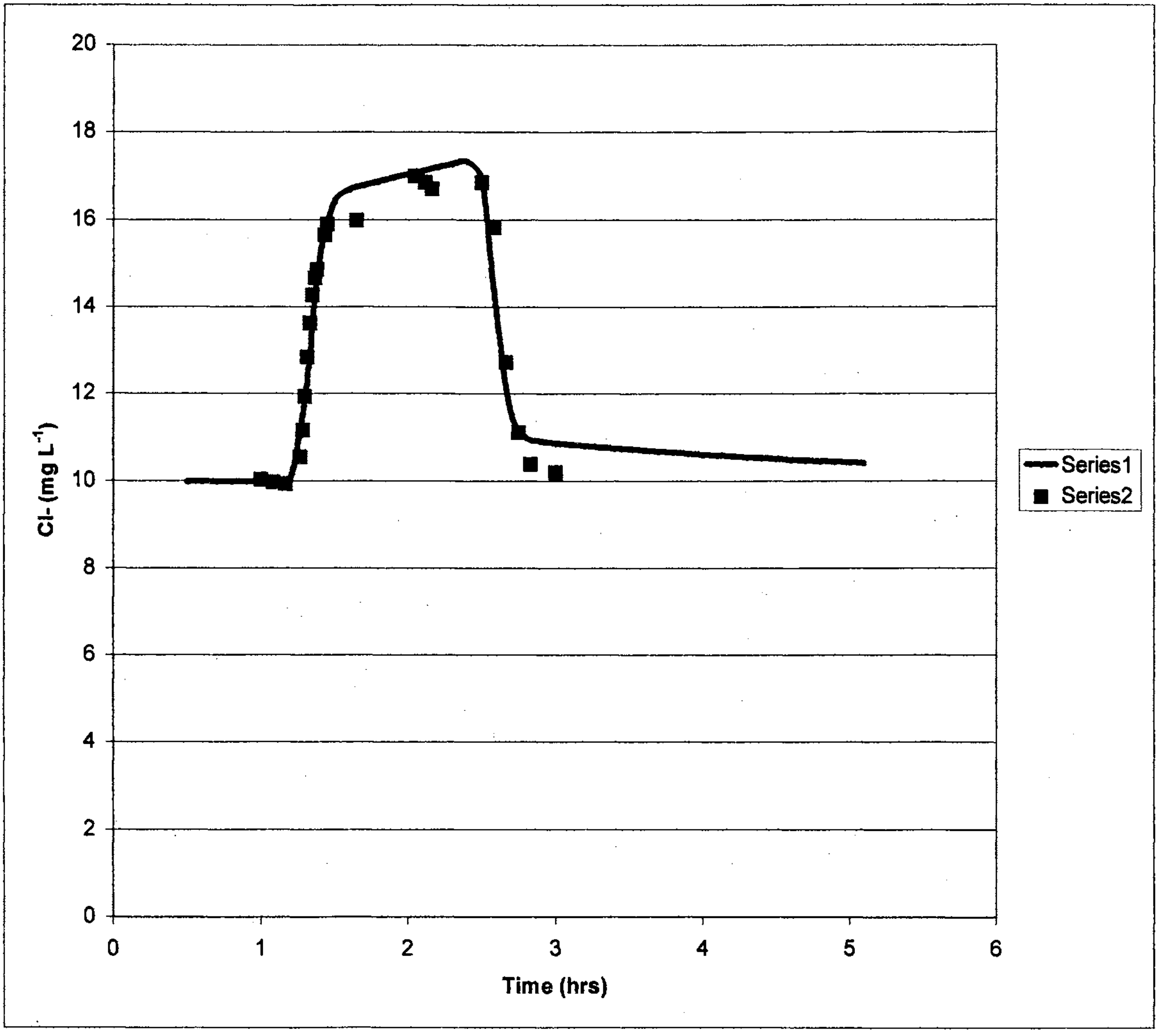
3-Aug-99 Dry Creek

Observed Data - Series 2		OTIS Modeled Data - Series 1	
Time (hrs)	Cl- (mg L^{-1})	Time (hrs)	Cl- (mg L^{-1})
1.00	8.23	0.50	8.33E+00
1.25	8.04	0.60	8.33E+00
1.32	8.21	0.70	8.33E+00
1.35	8.90	0.80	8.33E+00
1.37	9.65	0.90	8.33E+00
1.40	11.86	1.00	8.33E+00
1.43	13.79	1.10	8.33E+00
1.47	15.42	1.20	8.33E+00
1.50	16.49	1.30	8.48E+00
1.52	17.07	1.40	1.15E+01
1.55	17.63	1.50	1.65E+01
1.58	18.16	1.60	1.82E+01
1.62	18.33	1.70	1.85E+01
1.67	18.60	1.80	1.86E+01
1.72	18.81	1.90	1.87E+01
1.77	18.95	2.00	1.87E+01
1.83	18.86	2.10	1.88E+01
1.88	18.74	2.20	1.89E+01
1.92	18.72	2.30	1.89E+01
1.97	18.65	2.40	1.68E+01
2.02	18.53	2.50	1.17E+01
2.08	18.51	2.60	9.35E+00
2.13	18.53	2.70	9.01E+00
2.18	18.51	2.80	8.97E+00
2.25	18.56	2.90	8.96E+00
2.30	18.58	3.00	8.94E+00
2.33	18.56	3.10	8.93E+00
2.37	18.16	3.20	8.92E+00
2.40	16.79	3.30	8.91E+00
2.43	15.14	3.40	8.90E+00
2.47	13.32	3.50	8.89E+00
2.50	11.81	3.60	8.88E+00
2.53	10.77	3.70	8.87E+00
2.57	10.09	3.80	8.86E+00
2.60	9.60	3.90	8.85E+00
2.63	9.02	4.00	8.84E+00
2.67	8.93	4.10	8.83E+00
		4.20	8.82E+00
		4.30	8.81E+00
		4.40	8.80E+00
		4.50	8.79E+00
		4.60	8.78E+00
		4.70	8.77E+00
		4.80	8.77E+00
		4.90	8.76E+00
		5.00	8.75E+00
		5.10	8.74E+00



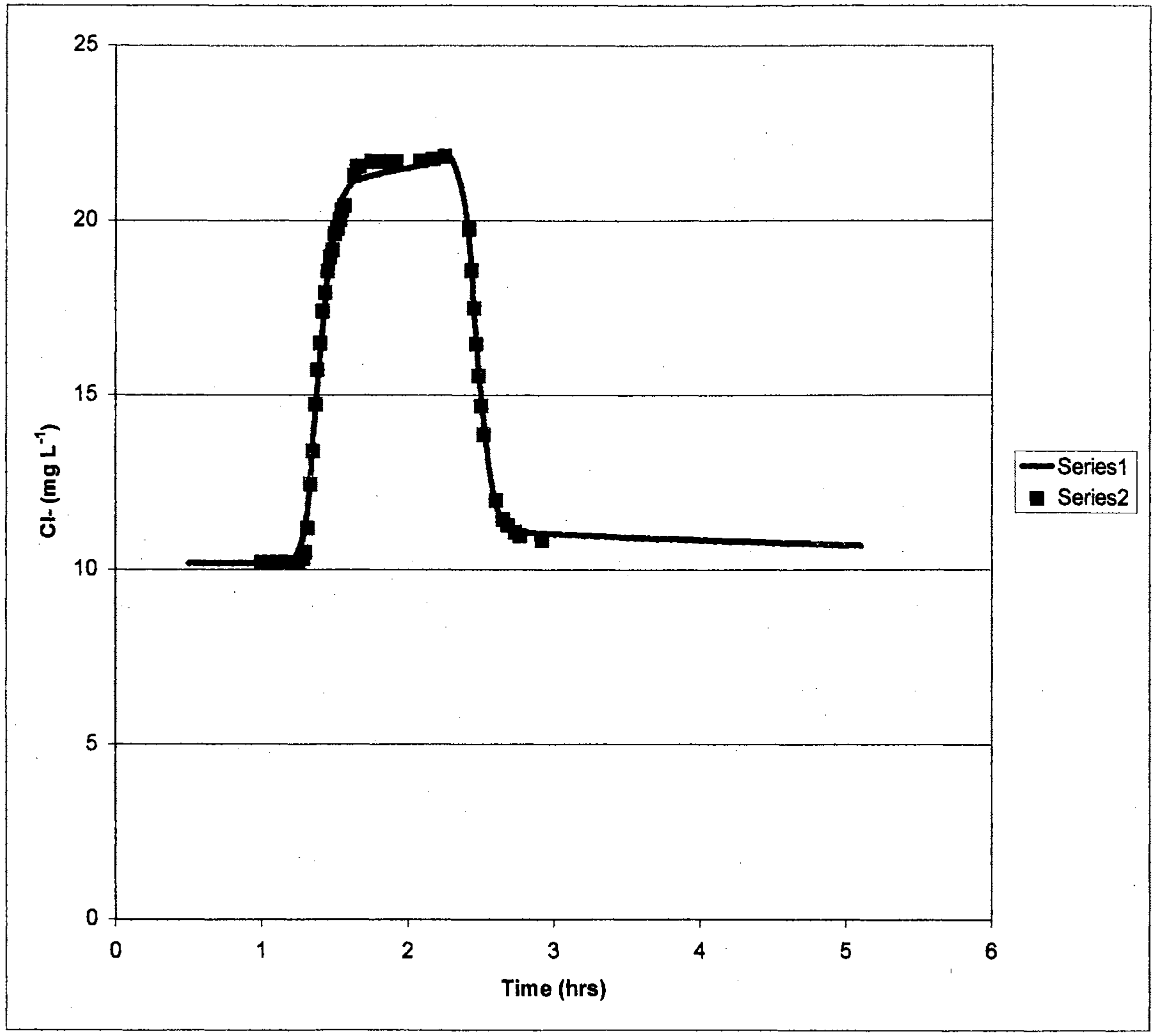
6-Jan-00 Dry Creek

Observed Data - Series 2		OTIS modeled Data - Series 1	
Time (hrs)	Cl- (mg L^{-1})	Time (hrs)	Cl- (mg L^{-1})
1.00	10.02	0.50	1.00E+01
1.08	9.96	0.60	1.00E+01
1.17	9.93	0.70	1.00E+01
1.27	10.54	0.80	1.00E+01
1.28	11.15	0.90	1.00E+01
1.30	11.93	1.00	1.00E+01
1.32	12.83	1.10	1.00E+01
1.33	13.61	1.20	1.00E+01
1.35	14.26	1.30	1.19E+01
1.37	14.67	1.40	1.52E+01
1.38	14.85	1.50	1.64E+01
1.43	15.65	1.60	1.87E+01
1.45	15.89	1.70	1.68E+01
1.65	15.98	1.80	1.69E+01
2.05	17.00	1.90	1.70E+01
2.12	16.85	2.00	1.71E+01
2.17	16.70	2.10	1.71E+01
2.50	16.85	2.20	1.72E+01
2.58	15.81	2.30	1.73E+01
2.67	12.72	2.40	1.73E+01
2.75	11.11	2.50	1.69E+01
2.83	10.37	2.60	1.38E+01
3.00	10.19	2.70	1.15E+01
		2.80	1.10E+01
		2.90	1.09E+01
		3.00	1.09E+01
		3.10	1.08E+01
		3.20	1.08E+01
		3.30	1.08E+01
		3.40	1.08E+01
		3.50	1.07E+01
		3.60	1.07E+01
		3.70	1.07E+01
		3.80	1.07E+01
		3.90	1.06E+01
		4.00	1.06E+01
		4.10	1.06E+01
		4.20	1.06E+01
		4.30	1.06E+01
		4.40	1.05E+01
		4.50	1.05E+01
		4.60	1.05E+01
		4.70	1.05E+01
		4.80	1.05E+01
		4.90	1.04E+01
		5.00	1.04E+01
		5.10	1.04E+01



14-Jan-00 Dry Creek

Observed Data - Series 2		OTIS Modeled Data - Series 1	
Time (hrs)	Cl- (mg L^{-1})	Time (hrs)	Cl- (mg L^{-1})
1.00	10.20	0.50	1.02E+01
1.08	10.20	0.60	1.02E+01
1.17	10.20	0.70	1.02E+01
1.25	10.20	0.80	1.02E+01
1.28	10.32	0.90	1.02E+01
1.30	10.50	1.00	1.02E+01
1.32	11.18	1.10	1.02E+01
1.33	12.43	1.20	1.02E+01
1.35	13.39	1.30	1.12E+01
1.37	14.72	1.40	1.62E+01
1.38	15.72	1.50	2.00E+01
1.40	16.48	1.60	2.10E+01
1.42	17.39	1.70	2.12E+01
1.43	17.93	1.80	2.14E+01
1.45	18.55	1.90	2.14E+01
1.47	18.95	2.00	2.15E+01
1.48	19.15	2.10	2.16E+01
1.50	19.61	2.20	2.17E+01
1.52	19.77	2.30	2.18E+01
1.53	20.03	2.40	2.01E+01
1.55	20.28	2.50	1.49E+01
1.57	20.42	2.60	1.19E+01
1.63	21.28	2.70	1.12E+01
1.65	21.54	2.80	1.11E+01
1.67	21.56	2.90	1.11E+01
1.75	21.68	3.00	1.10E+01
1.83	21.68	3.10	1.10E+01
1.92	21.68	3.20	1.10E+01
2.08	21.70	3.30	1.10E+01
2.17	21.76	3.40	1.10E+01
2.25	21.84	3.50	1.09E+01
2.42	19.75	3.60	1.09E+01
2.43	18.57	3.70	1.09E+01
2.45	17.49	3.80	1.09E+01
2.47	16.46	3.90	1.09E+01
2.48	15.54	4.00	1.09E+01
2.50	14.68	4.10	1.08E+01
2.52	13.87	4.20	1.08E+01
2.60	11.97	4.30	1.08E+01
2.65	11.44	4.40	1.08E+01
2.68	11.26	4.50	1.08E+01
2.73	11.06	4.60	1.08E+01
2.77	10.98	4.70	1.08E+01
2.92	10.84	4.80	1.07E+01
		4.90	1.07E+01
		5.00	1.07E+01
		5.10	1.07E+01



VITA

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Candidate for the Degree of

Doctor of Philosophy

Thesis: STREAM NUTRIENT RETENTION IN THE LAKE EUCHA-SPAVINAW BASIN

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Experience: Employed by University of Arkansas, Department of Agronomy as a graduate research assistant August 1994 to December 1996; employed by Oklahoma State University, Department of Biosytems and Agricultural Engineering as a graduate research assistant, January 1997 to December 1999; employed by the United States Geological Survey, Water Resource Division, Oklahoma District, Tulsa, Oklahoma, January 2000 to present.

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