

HILLSLOPE NUTRIENT FLUX
DURING NEAR-STREAM VEGETATION REMOVAL
L A MULTI-SCALED MODELING DESIGN.

J.A. YEAKLEY^{1,3}, J.L. MEYER¹ AND W.T. SWANK²

¹*Institute of Ecology, University of Georgia, Athens, Georgia, 30602, USA.* ²*Coweeta Hydrologic Laboratory, Southeastern Forest Experiment Station, USDA-Forest Service, Otto, North Carolina, 28763, USA.* ³*Current address: Department of Environmental Sciences and Resources, Portland State University, Portland, Oregon, 97207, USA.*

Abstract. At the **Coweeta** Hydrologic Laboratory in the southern Appalachians of western North Carolina, a near-stream vegetation manipulation experiment is being conducted to determine the effect of removal of streamside *Rhododendron maximum* L. on the export of hillslope nutrients (K, Na, Ca, Mg, N, P, S) and organic matter. Experimental hillslope transects that span topographical **flowpaths** from a local highpoint to the stream have been instrumented with **lysimeters** and TDR rods at two depths, as well as with **streambed** and **streambank** piezometers. We present a review of studies of nutrient flux in the riparian zone of forested watersheds. In the southern Appalachians, we hypothesize that *R. maximum* is a keystone species at the interface between terrestrial and aquatic systems, with extensive near-stream thickets having a possible impact on carbon and nutrient transport into streams. We present the conceptual basis and initial implementation of a model-based experimental design to test the effect of *R. maximum* removal on hillslope nutrient and organic matter export in upland watersheds. The model is terrain-based and will be used to extrapolate elemental flux measurements both spatially from the hillslope to watershed scale and temporally for various climate regimes. The model consists of three modules: (1) objective terrain analysis (**TAPES-C**); (2) a dynamic interception canopy module; (3) a hillslope hydrology module (**IHDM4**) with a 2-D Richard's equation of subsurface moisture dynamics. Calibration and validation of the model **will** occur at two scales: at the hillslope scale, using well, **lysimeter**, and TDR data; at the watershed scale, using **streamflow** measurements across a variety of storm types. We show watershed terrain analysis for the experimental watershed (**WS56**) and discuss use of the model for understanding effects of watershed management of riparian zone processes.

1. Introduction

One of three major thrusts of the Coweeta Long Term Ecological Research (**LTER**) project is to investigate the role of riparian zone linkage between terrestrial and stream ecosystems in the southern Appalachian mountains (Franklin *et al.*, 1990; Van Cleve and Martin, 1991). Central to **this** investigation, a manipulation experiment is underway that seeks to determine the effect of removal of streamside *Rhododendron maximum* L. on the export of coarse **particulate** organic matter, of dissolved organic carbon (DOC) and of nutrients (Na, K, Ca, Mg, **NO₃-N**, **NH₄-N**, **SO₄**, **PO₄-P**). Information gained from the experiment will assist the U.S. Forest Service in understanding stream water quality effects of proposed management strategies to remove streamside *R. maximum* in the southern Appalachian mountains.

We review studies of nutrient flux in the riparian zone of forested watersheds. In the southern Appalachians, we hypothesize that *R. maximum* is a keystone species at the interface between terrestrial and aquatic systems, with extensive near-stream thickets having a possible impact on carbon and nutrient transport into streams. We present the conceptual basis and initial implementation of a model-based experimental design to test the effect of *R. maximum* removal on **hillslope** nutrient and organic matter export in upland watersheds. Our model has the capability to extrapolate elemental flux from ongoing plot-scale measurements to larger scales both spatially at the level of the watershed and temporally for various climate regimes, providing a tool for regional analysis and management. We show results from the first stage of model implementation, watershed terrain analysis, for an experimental watershed in the riparian component of the **Coweeta** LTER.

2. Literature Review

2.1. RIPARIAN ZONES AS NUTRIENT FILTERS

Riparian zones in forested watersheds have been defined as locations of direct interaction between aquatic and terrestrial ecosystems, with boundaries extending outward to the limits of flooding or near-surface saturation and upward into the canopy of **streamside** vegetation (Gregory *et al.*, 1991). In agricultural watersheds, forested riparian zones have been depicted as sinks for nutrients transported from upland sources **that** thereby buffer nutrient discharge from surrounding **agro-ecosystems** (Lowrance *et al.*, 1984a). For some time, it has been emphasized that riparian vegetation was important in improving water quality in agricultural watersheds (Schlosser and Karr, 1981). In a contrasting view, Omernik *et al.* (1981) hypothesized that mature riparian forests are not nutrient filters, because no net annual uptake would occur. They speculated that forest buffer strips can reach nutrient saturation and lose their nutrient filter capacity as they reach maturity, as has also been proposed in general for **successional** "climax" vegetation by Vitousek and Reiners (1975). It has been **suggested**, moreover, that ecosystem management be directed toward keeping riparian vegetation below mature stages by periodic selective harvesting (Lowrance *et al.*, 1983). Yet another view comes from research on the impact of afforestation in acid moorlands in the United Kingdom, where studies have shown streams draining forested **areas** are more acidic and contain larger aluminum concentrations compared with adjacent moorland catchments (Ormerod *et al.*, 1989; Waters and Jenkins, 1992; Reynolds *et al.*, 1992). A likely reason for these findings is increased scavenging of acid deposition by coniferous canopies (Anonymous, 1991); one modeling study showed afforestation in western Britain increasing total sulfur deposition by one third and total nitrogen deposition by a factor of two (Fowler *et al.*, 1989). Streams draining such clearfelled forests have shown proximal increases in nitrate and decreases in sulfate and chloride (Reynolds *et al.*, 1992).

Most empirical studies, however, have found that riparian forests generally act as nutrient sinks. For coastal agricultural watersheds, it has been shown that forested riparian zones removed **total-N** predominantly by subsurface uptake, whereas **total-P** removal in the riparian zone was equally divided between surface and subsurface losses

(Peterjohn and Correll, 1984). They later found that the riparian forest acted as an important sink for $\text{NO}_3\text{-N}$ and significantly reduced the acidity of **groundwater** and precipitation that entered it (Peterjohn and Correll, 1986). In an agricultural watershed in the Georgia Coastal Plain, a riparian forest was found to act as a sink for $\text{NO}_3\text{-N}$, **Ca**, **Mg**, **K** and $\text{SO}_4\text{-S}$ (Lowrance *et al.*, 1984b). It was projected that conversion of riparian forest to cropland would increase $\text{NO}_3\text{-N}$ and $\text{NH}_4\text{-N}$ loads by as much as 800% (Lowrance *et al.*, 1983). A study of riparian **peatlands** of a forested watershed in Minnesota found that **36-60%** of all annual nutrient inputs were retained in the **streamside zone** (Verry and Timmons, 1982).

In coastal plain riparian forests with shallow underlying aquicludes, areas of near-surface saturation may remove much of the nitrate load through **denitrification** rather than uptake by vegetation (Jacobs and Gilliam, 1985; Jordan *et al.* 1993). Studies of riparian nutrient dynamics in other watersheds, however, have indicated either that significant nitrate removal occurs both through vegetation uptake and denitrification (Correll and Weller, 1989) or that vegetation processes were the primary form of removal (Lowrance, 1992). Additionally, nitrate retention by riparian zones has been shown to occur during winter months under either grass or poplar cover (Haycock and Pinay, 1993). They found that nitrate retention was greater under poplar and suggested that, although **aboveground** vegetation has no active role in retaining nitrate in the winter, poplar root systems contributed more carbon to denitrifying soil bacteria. In a northern hardwood forest in Turkey Lakes Watershed in Ontario, nitrate concentrations were highest in soil and stream water during the dormant season, peaking at the start of snowmelt. During the growing season, $\text{NO}_3\text{-N}$ and $\text{NH}_4\text{-N}$ increases were greatest in the **Oe** horizon, decreasing with depth (Foster *et al.*, 1989). It was recently shown at the **Coweeta** Hydrologic Laboratory in western North Carolina that biological and **geochemical** processes in the upper soil horizons in oak-hickory forests at Coweeta retained N and P, thus reducing inputs to streams (Quails *et al.*, 1991). In the Walker Branch Watershed in eastern Tennessee, partitioning between biological uptake and leaching during a 12 year period was site specific and depended significantly on slope position in the watershed (Johnson and Todd, 1990).

Dynamics of nutrient export from forested watersheds are dependent on several factors. The geological setting largely determines both the supply of inorganic nutrients available to forest biota and the general character of streamwater chemistry (Velbel, 1988; Gilvear *et al.*, 1993; Mulholland, 1993; O'Brien *et al.*, 1993). Biological controls on nutrient export include type, maturity and extent of vegetation cover (Swank, 1988), as well as biological processes in soils (Swank, 1986; Correll and Weller, 1989). **Geomorphic** and climatic controls include **channel** morphology (Pinay *et al.*, 1992; Harvey and Bencala, 1993), distribution and depth of near-stream soil saturation (Gaskin *et al.*, 1989; Geyer *et al.*, 1992) as well as frequency and duration of precipitation events (Mulholland *et al.*, 1990; Schnabel *et al.*, 1993). The subsurface riparian zone has been depicted as an **ecotone** between two interfaces. Inland is a terrestrial boundary where transport of water and dissolved solutes is toward the channel and controlled by watershed hydrology. Streamside is an aquatic boundary, where exchange of surface water and dissolved solutes is **bi-directional** and flux is strongly influenced by channel hydraulics (Triska *et al.*, 1993a). Several recent studies have explored solute dynamics **across** this ecotone (Triska *et al.*, 1989, 1993a,b; Mulholland, 1992; Harvey and Bencala, 1993). Terrestrial water is often low in

dissolved oxygen (DO) and therefore chemically reducing. In contrast, hyporheic zone, or stream subsurface, water may entrain DO laterally into near-stream hillslope areas causing a chemically oxidizing environment (Triska *et al.*, 1993b). Dynamics of hyporheic exchange have been shown to be a function of streambed topography (Harvey and Bencala, 1993) as well as channel roughness, gradient, sediment size and permeability, and pool-riffle sequence (Triska *et al.*, 1993b). For example, a study at Walker Branch indicated that the riparian zone was a potential source of NH_4^+ and P to the stream when dissolved oxygen concentrations in riparian groundwater were low, but a sink for P when dissolved oxygen concentrations were high (Mulholland, 1992). Such a fluctuating and reversible nutrient pathway in the riparian zone, where the direction is related to the redox state of the soil, indicates the need to understand the timing, duration and extent of saturated and unsaturated states of riparian zone soils.

2.2. NUTRIENT UPTAKE BY FOREST BIOMASS

Forest biomass accumulation of nutrients has been verified in a variety of forests, with studies indicating that understory species play a significant role in aboveground nutrient accumulation (Day and Monk, 1977b; Grove and Malajczuk, 1985; Kellman *et al.*, 1987; Turner *et al.*, 1992). On a whole watershed basis in second growth forests, extensive study in the Coweeta Basin (e.g., Day and Monk, 1974, 1977a,b; Yount, 1975; McGinty, 1976) has yielded nutrient cycling budgets for Ca, K, Mg, N, P for aggrading mixed oak-hickory forests (Monk and Day, 1988). They showed that elemental content of net annual biomass accretion, in $\text{kg ha}^{-1} \text{yr}^{-1}$, was Ca: 4.5, K: 4.9, Mg: 0.9, P: 3.0, and N: 6.7. As a percentage of standing soil-litter pools, to a depth of 60 cm, annual net nutrient assimilation by forest biomass was Ca: 0.7%, K: 1.1%, Mg: 0.2%, P: 8.0%, N: 0.1%. The effect of nutrient accumulation over an extended time period in an aggrading forest at Coweeta was shown recently by comparing soil-litter pools (0-20cm depth) in 1970 vs. 1990 (Knoepp and Swank, 1994). In all nutrients studied (Ca, K, Mg), there were large decreases in soil-litter concentration over the 20 year period due both to losses to the stream and to accumulation in forest biomass.

In a lowland riparian forest adjacent to an agricultural field, approximately 25% of nitrogen retained annually in the riparian zone was assimilated by trees (predominantly *Liquidambar styraciflua* and *Acer rubrum*; Correll and Weller, 1989). Detailed analysis of biomass uptake of nutrient within riparian zones in forested southern Appalachian uplands, however, is yet lacking.

2.3. NUTRIENT RESPONSES TO VEGETATION REMOVAL

Removal of forest vegetation generally causes transient increases in nutrient exports to streams (Johnson *et al.*, 1982; Hopmans *et al.*, 1987; Swank, 1988; Blackburn and Wood, 1990; Hornbeck *et al.*, 1990). Elevated nutrient export resulting from vegetation removal has been found to depend greatly on the method and extent of removal (Pye and Vitousek, 1985; Swank, 1988; Blackburn and Wood, 1990). In three northeastern forests and an eastern Tennessee forest, clearcutting and stem removal

caused total ecosystem **Ca** depletion to a much greater extent than other elements (Johnson *et al.*, 1982; Hornbeck *et al.*, 1990), although Ca loss was primarily via removal of woody tissues rather than to leaching through the soil to the stream. A study in the root zone of four northern hardwood species at Hubbard Brook in New Hampshire following **clearcutting** showed that K and Mg were released while Ca was retained by decaying roots (Fahey *et al.*, 1988). They also found that N and P release from decaying roots was an important nutrient flux pathway to both stream outflow and vegetation **regrowth** for two years following harvest. A variety of vegetation removal experiments conducted at the **Coweeta** Hydrologic Laboratory showed only marginal increases in nutrient concentrations in streamwater after vegetation removal. The constituent most sensitive to vegetation disturbance was found to be **NO₃-N**, with elevated levels in streams draining **clearcuts** persisting as long as 20 years after cutting (Swank, 1988).

2.4. RHODODENDRON MAXIMUM AS A KEYSTONE RIPARIAN SPECIES

In southern Appalachian upland watersheds, near-stream **understory** vegetation is frequently dominated by the evergreen **sclerophyllous ericaceous** shrub *Rhododendron maximum* L. In many cases, this **mesic** shrub acts to completely close the understory canopy in pure stands over upland streams. We hypothesize that *R. maximum* is a keystone species on this landscape at the interface between terrestrial and aquatic systems, with near-stream thickets acting as **hillslope** debris dams and having an impact on organic matter processing in the riparian zone, on element transport into streams, and on stream ecosystem structure and function.

It was reported that *R. maximum* establishment at Bent Creek Experimental Forest in western North Carolina primarily occurred in the early 1900's, during a period that coincided with the cessation of fire and grazing disturbance in the region (McGee and Smith, 1967). It has been suggested that the long history of burning of forests in the southern Appalachians (Sharitz *et al.*, 1992) until the turn of this century prevented substantial establishment of *R. maximum* thickets in the area (Phillips and Murdy, 1985). Logging operations in the early twentieth century dramatically opened the canopy and stimulated the establishment and growth of understory species. Subsequent opening of the forest canopy in the 1930's by blight-induced decline of the American chestnut (*Castanea dentata*) has also been suggested as a means of *R. maximum* establishment at the Coweeta Hydrologic Laboratory (McGinty, 1972).

Vegetation analyses at Coweeta, both over long periods as well as following severe drought, indicate that *R. maximum* canopies can have significant impact on hardwood regeneration (Clinton, 1989). Significant hardwood suppression may have been occurring since the 1930's. A long-term study found that regeneration of *Quercus prinus* and *Q. alba* was significantly reduced in plots with high *R. maximum* densities, although other hardwood species (*Q. coccinea*, *Q. velutina*, *Acer rubrum*) were not affected (Phillips and Murdy, 1985).

In comparison with three common species (*Q. prinus*, *Tsuga canadensis*, *Cornus florida*), Day and McGinty (1975) found that *R. maximum* had the largest leaf **biomass** for WS 18 at Coweeta. *R. maximum* leaf turnover time ranges from 4 to 7 years (Nilsen, 1986). Although nutrient concentrations in *R. maximum* leaves are generally

lower than that in deciduous leaves, such long-lived and abundant leaf mass creates a significant nutrient storage reservoir in the riparian zone (Monk *et al.*, 1985).

2.5. RIPARIAN ZONE HYDROLOGY

In the deep-soiled forested watersheds of the southern Appalachian mountains, the variable extent of the saturated source areas, or near-stream areas, primarily determine the timing and volume of **streamflow**. This variable source area mechanism of **streamflow** generation, described by **hydrologists** at the **Coweeta** Hydrologic Laboratory (Hewlett and **Hibbert**, 1963; Hewlett and Nutter, 1970), begins as precipitation infiltrates undisturbed forest soils and migrates **downslope**, accumulating at lower slope positions. These saturated or near-saturated areas maintain **baseflow** and readily contribute subsurface flow to storm flow as the zone of saturated soil surface expands during a storm event. The degree to which saturation and subsequent expansion would occur for a given **hillslope** varies as a function of antecedent soil moisture conditions, precipitation volume and duration of input (Hibbert and Troendle, 1988). The **hydrological** extent of riparian zones in the southern Appalachians vary temporally, then, in response to the frequency and amount of precipitation.

Spatially, the hydrological extent of riparian zones are constrained by watershed topography as well as distribution and depths of soils (Hewlett and Hibbert, 1966; Dunne *et al.*, 1975; Anderson and **Burt**, 1978; Beven *et al.*, 1988). Upland watersheds in the southern Appalachians generally have steep **hillslopes** that constrain riparian zones to relatively small near-stream areas. Relatively deep soils in these watersheds, however, provide drainage to near-stream areas that allow riparian zones to persist even during short-term drought periods. Within a watershed, extent of near-stream saturated zones varies with hillslope type (Anderson and **Burt**, 1978). Persistence of saturated areas varies with hillslope **planform**, with convergent hillslope **planform** resulting in riparian zones of greater width (Crabtree and **Burt**, 1983) and of greater variation in response to climate variation (**Yeakley**, 1993). **Geomorphic** differences in the structure of stream channels and **floodplains** can cause differences in whether riparian zones are effective sources or sinks of carbon, nitrogen and phosphorus (**Pinay et al.**, 1992). They suggest explicit analysis of **geomorphic** characteristics to determine the retention ability of a given reach.

Important processes of nutrient retention and cycling, however, occur at several hierarchical levels within valley floor **landforms** (Gregory *et al.*, 1991), from stream unit scales on the order of a meter to reaches or sections on the order of 10^2 - 10^7 meters. Mechanistic investigation should begin at lower space and time scales compatible with generative processes (Allen *et al.*, 1984; **Luxmoore et al.**, 1991; Yeakley and **Cale**, 1991), to understand patterns produced at higher levels. To characterize the extent and dynamics of variable riparian zones in mountain watersheds over climatic time periods, we present a multi-scaled modeling approach that incorporates both topographic spatial variation at the plot scale and temporal variation at the scale of a storm event.

3. A Multi-scaled Modeling Approach

The remainder of this paper describes our experimental design featuring a terrain-based watershed hydrology model. We will use this model to extend elemental flux estimates from ongoing plot-scale measurements spatially to **hillslope** and watershed scales and temporally both for short-term storm responses and for long-term climate regimes. We present results from watershed terrain analysis, the first stage of model implementation, for the experimental watershed of the riparian component of the **Coweeta LTER** and describe potential use of the model for watershed management of riparian zone processes.

A terrain-based hillslope hydrology model has been developed from several existing models to characterize climate scale distributions of hillslope soil moisture in the southern Appalachians (Yeakley, 1993). The model consists of a dynamic canopy interception module (Rutter *et al.*, 1971, 1975) and a **two-dimensional** hillslope hydrology module (IHDM4: Institute of Hydrology Distributed Model, version 4; Beven *et al.*, 1987) having hillslope planes objectively delineated using contour-based terrain analysis (TAPES-C: Topographic Analysis Programs for the Environmental Sciences-Contour; Moore and Grayson, 1991). Calibration is performed at two scales: watershed and hillslope. Results are validated at both scales, using information from plot measurement studies of soil moisture and downstream measurement of watershed stream discharge over storm and **baseflow** periods (Yeakley, 1993).

3.1. CANOPY MODULE

The subsurface model (IHDM4) receives inputs from an **aboveground** module that accounts for canopy and litter fluxes. The aboveground model was specified by Rutter *et al.* (1971, 1975). The Rutter model follows a dynamic canopy storage (C) with input of a constant fraction of rainfall determined by leaf area index and vegetation type, and output as evaporation and drainage. The equations of the model are:

$$\frac{dC}{dt} = Q - K_C[\exp(b_C C) - 1] \quad (1a)$$

$$Q = (1-p)R - E_p \cdot f(C) \quad (1b)$$

where K_C and b_C are drainage parameters, R is the total rainfall, E_p is potential evaporation (determined by a **Penman-Monteith** equation with **stomatal** resistance set to zero), p is the canopy **throughfall** fraction. If $C > S$, $f(C)$ equals 1. Otherwise, if $C < S$, then $f(C)$ equals C/S , where S is interception storage and corresponds to a completely wet canopy. The model allows for simultaneous evaporation and transpiration from a partially wet canopy ($C < S$).

The model is regulated by a water balance given as:

$$R = T + E + AC \quad (2)$$

where T is **throughfall** and E is evaporative loss. Transpiration demand is calculated as E_p for that fraction of the canopy that is dry. An effective precipitation is then calculated that is the throughfall amount (which includes direct throughfall as well as drainage) minus the transpiration demand. In the absence of **throughfall**, effective precipitation at the soil surface is negative, which is input to the **hillslope** hydrology model (**IHDM4**) as a sink term at the surface. The sink is regulated by soil moisture availability times the fractional root distribution in a given layer in the hydrology model as given by Feddes *et al.* (1976). If positive, i.e. if rainfall is occurring, then input to the surface becomes a source term.

3.2. HILLSLOPE HYDROLOGY MODULE

For a given hillslope plane in **IHDM4**, cells are bounded by two vertically-layered sets of finite element nodes. The top surface of the soil (*i.e.*, highest set of nodes) is treated as a flux boundary with fluxes controlled by applied input rates of effective precipitation unless the surface becomes saturated and overland flow develops. The surface boundary then changes to a fixed head boundary while saturation persists, with potentials fixed at atmospheric pressure. Change of boundary conditions at the soil surface can occur locally on the slope to enable simulation of a time-varying near-stream saturated area. Subsurface elements may be extended to beneath the mid-point of the channel, which is assumed to be a no-flow boundary. Other no-flow boundaries in the model are the upslope divide, the base of the soil/rock profile, hillslope plane sides (*i.e.* “**streamtube**” boundaries, see discussion below) and the **unsaturated** part of the seepage face (Beven *et al.*, 1987).

For a given hillslope plane, subsurface flow is given by a Richards equation expressed as

$$BC(\psi) \frac{\partial \phi}{\partial t} - \frac{\partial}{\partial x} [BK_x(\psi) \frac{\partial \phi}{\partial x}] - \frac{\partial}{\partial z} [BK_z(\psi) \frac{\partial \phi}{\partial z}] = Q_s \quad (3)$$

where B is a streamtube width; ψ is capillary potential; x is horizontal distance downslope; z is gravity potential (measured vertically from some arbitrary datum); $\phi (= \psi + z)$ is total hydraulic potential; $C(\psi)$ is the specific moisture capacity of the soil (slope of relation between θ and ψ); θ is soil moisture content by volume; K_x , K_z are saturated hydraulic conductivities in the x , z directions; Q_s is a source/sink term (Q from equation (1b)); and t is time. Implementation of (3) requires several assumptions, including: (a) water is of constant viscosity and unit density; (b) flow occurs in an isothermal medium; (c) Darcy's law applies with time-invariant parameters; (d) only single phase water flow in response to hydraulic gradients is considered; (e) the relationship between θ and ψ is locally differentiable (Beven *et al.*, 1987; Calver, 1988).

If either the infiltration capacity of the soil surface is exceeded by input rates or the soil becomes fully saturated resulting in return flow, then overland flow occurs and is given by

$$B \frac{\partial Q}{\partial t} - c \frac{\partial [BQ]}{\partial y} - Bic = 0 \quad (4)$$

where Q is discharge, i is net lateral inflow rate per unit **downslope** length, y is distance **downslope**, c is kinematic wave velocity defined by dQ/dA where A is the cross-sectional area of flow (Calver, 1988). Solution of (4) requires a specification between discharge and cross-sectional area, which in IHDM4 is given as a power law function of the form

$$Q = f s^{0.5} A^b \quad (5)$$

where s is local slope angle, f is an effective roughness parameter (Chezy), such that the kinematic wave velocity is given by $c = Qb/(Q/fs^{0.5})^{1/b}$ (Beven *et al.*, 1987).

Soil moisture characteristics are determined using modified Campbell (1974) relationships with parameters based on soil **textural** differences (Clapp and Hornberger, 1978). Actual **evapotranspiration** (E_A) is given as a function of E_P and soil moisture based on Feddes *et al.* (1976):

$$E_A = W_R \cdot \alpha(\psi) \cdot E_P \quad (6)$$

where W_R is a weighting of proportion of root mass for a depth and $\alpha(\psi)$ is a linear scaling function: when $\psi_i < \psi < \psi_a$, $\alpha(\psi)$ equals 1; otherwise when $\psi_w < \psi < \psi_i$, then $\alpha(\psi)$ equals $(\psi - \psi_w)/(\psi_i - \psi_w)$; otherwise when $\psi < \psi_w$ or when $\psi_a < \psi$, then $\alpha(\psi)$ equals 0. Note here that ψ_a is **anaerobiosis** point (-0.05 bars), ψ_i is vegetation stress initiation point (-0.3 bars, Hewlett, 1962), and ψ_w is wilting point (-15.0 bars).

At the end of each subsurface **timestep**, inputs from each **hillslope** section to both overland flow and the channel are calculated. To compute channel flow, IHDM4 uses the same kinematic wave equation and power law flow relationship (4-5) as the overland flow solution on hillslope planes, except that each channel is assumed to be of uniform width. Four levels of timestep occur in IHDM4. The highest level is the input climate data timestep, which here is at one-hour intervals. The next level involves flux exchange between hillslope and channel at a timestep equal to or smaller than the climate step. Subsurface and channel flow is calculated at a finer time resolution; following (Calver and Wood, 1989), a one-half hour step is used. Finally, overland flow if it occurs is calculated a fixed number times in each subsurface flow timestep (Beven *et al.*, 1987).

3.3. TERRAIN ANALYSIS

There are three primary ways of structuring a network of topographic data: (1) triangulated irregular networks (**TINs**); (2) raster or grid networks; (3) vector or contour line based networks (Moore and Grayson, 1991). Of the three, contour-based networks provide more physical realism than grid based networks that restrict water flow from a given node to only one of eight possible directions. TINs provide physical realism, but require interpretive alignment of the elements, many times based on vector

digital elevation maps (**DEMs**). Moore and **Grayson** (1991) provide an automated contour-based method (**TAPES-C**) for partitioning watersheds into natural units bounded by irregularly shaped polygons. These polygons are bounded by equipotential (or contour) lines on two sides and by streamlines, orthogonal to the contours, on the other two sides. Streamlines are assumed to be no-flow boundaries; thus **groundwater** flow is constrained to flow through a series of elements positioned along a natural gradient. Such a series of cells is termed a "**streamtube**." By orienting the flow equations of a distributed parameter model along streamtubes, spatial complexity in the equations may be reduced from three dimensions to two, while accomplishing a terrain-based model structure.

Contour-based terrain analysis as developed by Moore *et al.* (1988) and Moore and Grayson (1991) required three general steps. First, a contour map of the watershed was digitized, creating a vector DEM. Here the **Arc/INFO** geographic information system (**GIS**) was used to accomplish this task for watershed 56 (**WS 56**) at **Coweeta**, which is the primary experimental watershed for the riparian component of the Coweeta LTER (Figure 1, left). A preprocessing program (**PREPROC**) was used to transform the vector DEM for input to the program TAPES-C, which partitioned the watershed into streamtube, or **hillslope**, units using a constant offset between trajectory (i.e., stream tube boundary) starting points. Figure 1, center, shows results from a TAPES-C computation for WS 56 using a 30 meter offset, selected to correspond to the width of the experimental cut.

Further processing is then required to transform the streamtube output of TAPES-C into a structure suitable for IHDM4. Each hillslope plane in IHDM4 is represented by a two-dimensional vertical cross-section of **finite-element** nodes running longitudinally from watershed divide (or interior high point) to stream. At each vertical set of nodes in the cross-section, a constant width is assumed. From map view, a hillslope plane in IHDM4 is constrained to a series of adjacent **trapezoids** beginning at the stream and continuing to the divide (**Yeakley**, 1993). To fit TAPES-C output to IHDM4, the no-flow boundaries shown in Figure 1 (center) were extended to permanent stream locations using Arc/INFO to derive 21 hillslope planes (Figure 1, right).

3.4. INSTRUMENTATION AND DATA COLLECTION

The experimental transects for the planned *R. maximum* removal are shown in Figure 1 (right, planes #18 and #19). The lower 15 meters of each transect have been instrumented with tension **lysimeters** for the BA and B soil horizons for solute measurement (3 locations x 2 depths x 4 replicates per transect). The entire span of each transect, as well as upper slope positions continuing to the **highpoint** (HP1), has been instrumented with TDR measurement points for soil moisture measurement for the BA and B soil horizons (18 locations x 2 depths x 3 replicates). Installation of **streambed** and near-stream piezometers is in process to determine depth and slope of **phreatic** surfaces in the **hillslopes** (2 locations x 3 replicates per transect). These experimental transects correspond to streamtubes determined from the terrain analysis (Figure 1, right).

Sample collection frequency is weekly (composited to monthly) for lysimeters and bi-weekly for TDR and piezometer measurements. Storm samples for solute

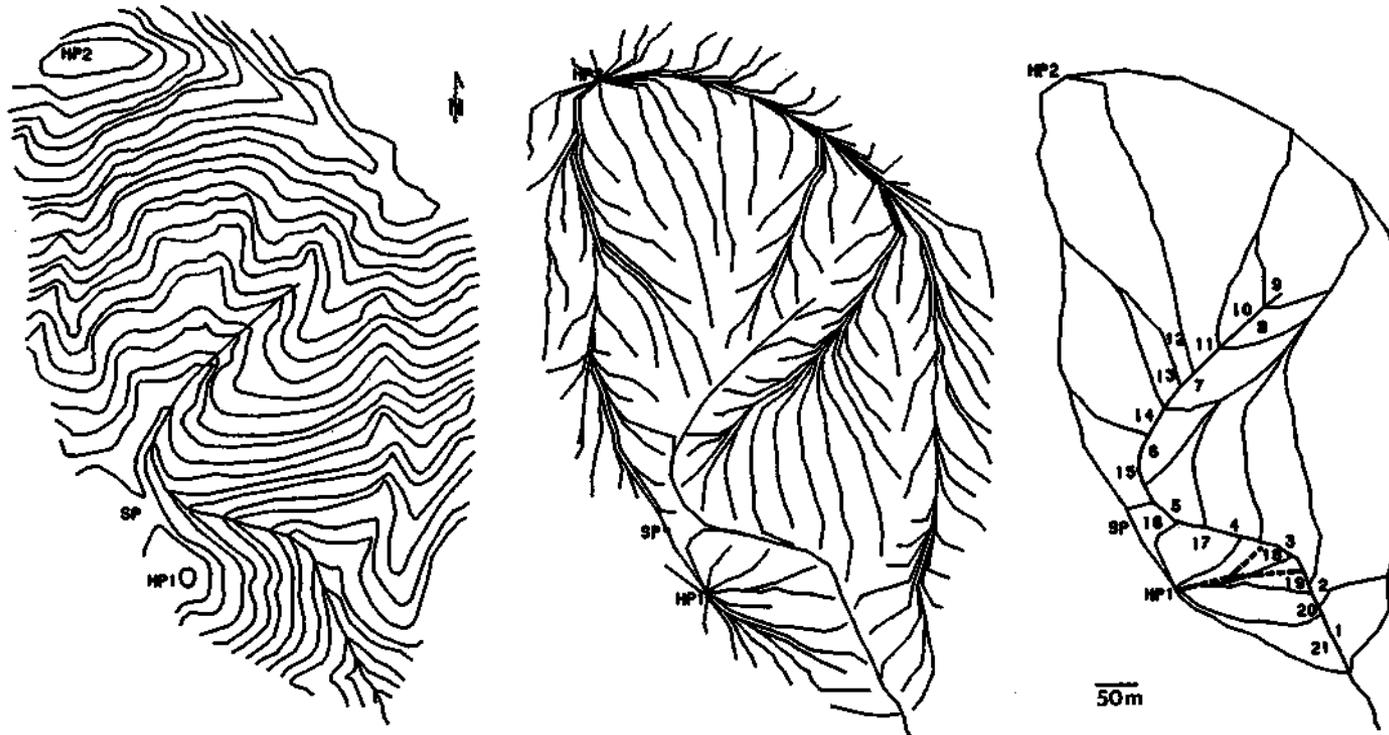


Figure 1. Terrain analysis of Watershed 56 at the Coweeta Hydrologic Laboratory. Shown at left is the original contour map with stream, two high points (HP1, HP2) and a saddle point (SP). Contours are from 725.4 m to 981.5 m M.S.L. (interval alternates between 6.10 m and 9.14 m). Shown center is "streamtube" delineation using TAPES-C (Moore and Grayson, 1991). Stream tube width interval was set at 30 meters. Shown at right are IHDM4 (Beven *et al.*, 1987) hillslope planes selected from TAPES-C analysis. Streamtube boundaries are specified as no flow boundaries. Shown are one headwater plane (#9) and twenty side planes. Also shown are control (in plane #18) and treatment (in plane #19) transects for the near-stream (< 15 m) vegetation removal experiment. Each transect (dotted lines from HP1 to stream) is the centerline of TDR, lysimeter and piezometer instrumentation.

concentrations, water content and flow are being taken for various storm types in **throughfall** collectors, flow-weighted stream samplers, **lysimeters**, **TDR** stations and piezometers throughout WS 56, with one spring storm collected **thusfar** (Webster and Yeakley, unpublished data). Estimates of depth to saturation from piezometers will provide further information for calibration, following suggestion from Wood and Calver (1992). Estimates of **litterfall** and **detrital** flux are being conducted with traps every 5 meters through the first 20 meters on both experimental transects. Soil moisture measurements over storm and seasonal response ranges will be used, along with WS 56 discharge measurements, to calibrate **hillslope** model parameters as was performed for nearby WS 2 in Yeakley (1993). Validation will be performed using both measured **streamflow** and hillslope soil moisture distribution on time periods successive to calibration periods. Water fluxes resulting from the validated hillslope model will be coupled with solute concentration measurements to compute hillslope elemental exports for the experimental transects.

4. Prospectus

The *R. maximum* manipulation experiment is currently (mid 1994) in the pretreatment phase, with removal planned for mid 1995. A preliminary *R. maximum* cut has been conducted, with **allometric** relations relating stem and branch diameters to **biomass** and leaf area in progress (Coleman and Haines, unpublished data). The pretreatment period will provide approximately 2 years of soil moisture and solute data, giving a temporal control and calibration information for the model over seasonal and annual response ranges. Analysis for treatment effects between cut and uncut transects will be conducted using a **BACI** approach, such as randomized intervention analysis (Stewart-Oaten *et al.*, 1986; Carpenter *et al.*, 1989).

The model presented here allows for extrapolation of hillslope results to the watershed scale. Coupled with estimates of *R. maximum* extent in WS 56, hillslope results from this experiment can be extended using the physically-based framework of the model to the remainder of the watershed. Cut scenarios for selected **hillslopes** or for the entire watershed can then be evaluated for their effects on hillslope export of solutes. With completion of this work, the model will have been implemented for two watersheds at **Coweeta**, with several more in the initiation stages. Management strategies for areas as large as the Coweeta **Basin** could be implemented using the model.

In terms of response to climate variation, stochastic equations for input meteorological information could be developed and implemented in the current model framework, as has been done previously for other hydrology models (Wolock and Hornberger, 1991; Yeakley *et al.*, 1991) in Appalachian watersheds. This would extend understanding of possible management scenarios to span the range of storm types (March *et al.*, 1979) and sequences.

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