AN ECOHYDROLOGICAL FRAMEWORK FOR THE FUNCTIONAL ASSESSMENT OF SOUTHERN APPALACHIAN WETLANDS

A Thesis
by
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ABSTRACT

AN ECOHYDROLOGICAL FRAMEWORK FOR THE FUNCTIONAL ASSESSMENT OF SOUTHERN APPALACHIAN WETLANDS (NOVEMBER 2008)

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Southern Appalachian wetlands are a unique and rapidly disappearing ecosystem. In addition to the value of their biological components, wetlands are functional units of the watershed network. The global water resource crisis makes long-term management and permitting policies based on the best available information and information management tools an immediate priority. This study integrates various data sources, considers the need for time and resource efficient assessment methodologies and the multiple geographic scales involved in the maintenance of watershed functions like water storage and water quality in a GIS platform called the Southern Appalachian Wetlands Model (SAWeM). SAWeM is a prototypical SDSS (Spatial Decision Support System) for the New River watershed in Ashe and Watauga Counties, N.C. The Tater Hill wetland in Howard Creek basin was used as a reference functional wetland.

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Thanks to Dr. Eric Marland for introducing me to the fascinating world of non-linear dynamics and a completely new prism for looking at the complex systems that surround us. To Alex Martin and Tony Greco, for spending time in the field and for the hours of productive conversation on the many topics of common interest.

To the graduate school for their financial and administrative support. To the entire Geography Department for use of computers, equipment, and collective knowledge.

Special gratitude to my mother, Maria Elena Pearse, for her eternal support. To my father, Jorge Mario Molina, for a lifetime of advice. And to my daughter, Elena Camilla Molina, for the inspiration to value the planets' ecosystem as our greatest legacy to future generations.

DEDICATION

For my daughter, Elena Camilla Molina, surround yourself always with the riches of millennia.

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INTRODUCTION

Managing the 33,000,000 km^3 of freshwater available in the hydrologic cycle is the central challenge for humanity in the 21st century. This challenge has been recognized by the United Nations Educational Scientific and Cultural Organization (UNESCO) as the “implicit priority goal for science” (Janauer 2000). The importance of wetlands as systems of water storage and water quality improvement is well documented in the scientific literature (Pearson 1994, Whigman 1999, Sun et al. 2002). In the United States, wetlands are protected under sections 401 and 404 of the Clean Water Act. However, in order for an individual wetland to be protected under the Clean Water Act, a strong argument must exist for the importance of the specific wetland to the biological, physical, and/or chemical integrity of the nation’s waters.

In North Carolina, wetland classification has been based on the biological structure of the wetland community. The Natural Heritage Program (NHP) uses a classification system to evaluate wetlands based on their biological community structure (Schafale 1998). The North Carolina Division of Water Quality (NCDWQ) has adopted this system to assess the biological value of wetlands under their jurisdiction. Although the NCDWQ evaluates the biological component of wetlands prior to permitting development for 401 mitigation, it does not currently consider the relative functional value of these wetlands.

Wetland 401 permitting is of special concern in the Southern Appalachian Mountain region, where an estimated 95% of wetland area has been lost to agriculture and development since the 1780’s (Dahl 1990). Southern Appalachian wetlands are characteristically small (often less than 0.5 ha) and very few remain in a condition close enough to pristine to receive a high biological structure value according to the NHP classification system. These remaining mountain wetlands are of special concern because various studies have shown that disturbances to first-order basins have non-linear, cascading effects downstream (Leibowitz 2003, Sun et al. 2002).

On April 2, 2003 the Unique Wetlands Technical Advisory Committee (UWTAC) met to discuss the criteria for definition and identification of 'unique wetlands' proposed by the North Carolina Wetlands/401 Unit (DWQ) and the NHP. Presently, unique wetlands are defined by the North Carolina Surface Water and Wetland Standards as: "*wetlands of exceptional state or national ecological significance which require special protection to maintain existing uses. These wetlands may include wetlands which have been documented to the satisfaction of the Commission, as habitat essential for the conservation of state or federally listed threatened or endangered species*" (15A NCAC 2B. 0101 (e)(7)).

As explained by John Dorney (personal communication), manager of North Carolina's Department of Environment and Natural Resources (NCDENR) 401/ Wetlands Division, the unique wetland designation carries with it more stringent regulatory requirements; the UWTAC recommended that impacts only be permitted for water dependent projects demonstrated to be of public need and that mitigation for their loss be required regardless of the area of impact requested. Once agreed upon, the criteria used to interpret the codes' definition will have an impact on the total acreage protected and will be subject to review by the stakeholders.

During the April 2, 2003 meeting, the UWTAC agreed that wetland functions should be defined and quantitative measures of their functional significance developed. In May 2003, the DWQ organized the Wetlands Functional Assessment Team (WFAT) with the purpose of developing a wetland functional assessment methodology for the State of North Carolina. The WFAT's mission statement is "to adopt rapid and accurate GIS- based and field- based methodologies that will identify general wetland types and the functions of each" (John Dorney personal communication). The methodology that the WFAT adopts will be used by the DWQ and the North Carolina Department of Transportation (NCDOT) for 401 permit evaluation.

On March 18, 2004 the DWQ sponsored a symposium to discuss the WFAT's mission and different functional assessment methodologies. Attendees to the symposium agreed that in the mountainous regions of N.C. the National Wetlands Inventory (NWI) is a poor dataset for assessment. In the Southern Appalachians the NWI often mislabels wetlands as agricultural land or misses them completely due to thick forest cover that obscures aerial photography. A better dataset or a methodology that relies on a combination of acceptably accurate datasets is needed for assessment.

Geographic Information Systems (GIS) provide a platform for the integration of datasets relevant to wetland structure and function. Ecohydrological theory suggests that:

"*the application of GIS-based ecohydrological approaches to subsystems catchments and elementary patches, makes hydrological and ecological* *information gained in the microscale systems aggregable into higher levels of abstraction. The integration of this information into hydrological concepts will lead towards a more profound interpretation of the hydrological regime of catchments*" (Zalewski 2000).

Ecohydrology recognizes that the long-term structural integrity and survival of wetland communities is not independent of the ecosystems in which they exist and these systems are directly influenced by large scale geomorphic characteristics and hydrological processes of the landscape in which they are imbedded (Pearson 1994, Whigman 1999, Cedfeldt et al. 2000, Hayashi and van der Kamp 2000, Sun et al. 2002).

While water storage and quality improvement can be quantitatively assessed at a point scale, the resulting data must be integrated into larger scales to be useful for management and policy. Traditionally, information gained from water quality sampling programs and stream ecology studies generates large datasets that can be difficult for decision makers to relate to landscape hydrologic processes. Indices for freshwater management and planning should be based on assessments of both point/ local data and large-scale hydrologic processes (Zandbergen 1998).

Hydrologic process responses for a basin are likely to be apparent before community structure composition changes occur within a wetland embedded in the basin. For example, indications of consistently lower streamflow and/ or water tables within a basin can be used to develop management strategies to reduce evapotranspiration (ET) (i.e. by woody vegetation removal) before shifts in

community structure occur. The term *ecological significance* must include the importance of the system functions that sustain the biological community.

Changes in water quality and water storage are accepted wetland functions that can be quantitatively assessed and affect biological structure and water resource availability (Hayashi and van der Kamp 2000). The processes that determine storage, discharge and water quality improvement are regionally variable as determined by climate, physiographic region, and topography, and locally influenced by anthropogenic disturbances (Mitchell et al. 2004).

Minimizing disturbances near hydrologically unique wetlands, such as sites of groundwater discharge, is of paramount importance, especially near first-order streams, toward maintaining water quality and flow. Disturbance of these sites will affect organisms and processes downstream. Decision makers need tools that allow for rapid (less than 20 minutes in the field) assessments of regulatory wetlands (John Dorney, personal communication). Developing screening tools and functional assessment methodologies for selected functions at appropriate scales is a complex undertaking but one of urgent importance from a biological as well as a resource management perspective. Functional ecosystem importance can also be a selling point for conservation to stakeholders who do not have a biological background but understand the importance of appropriate resource management.

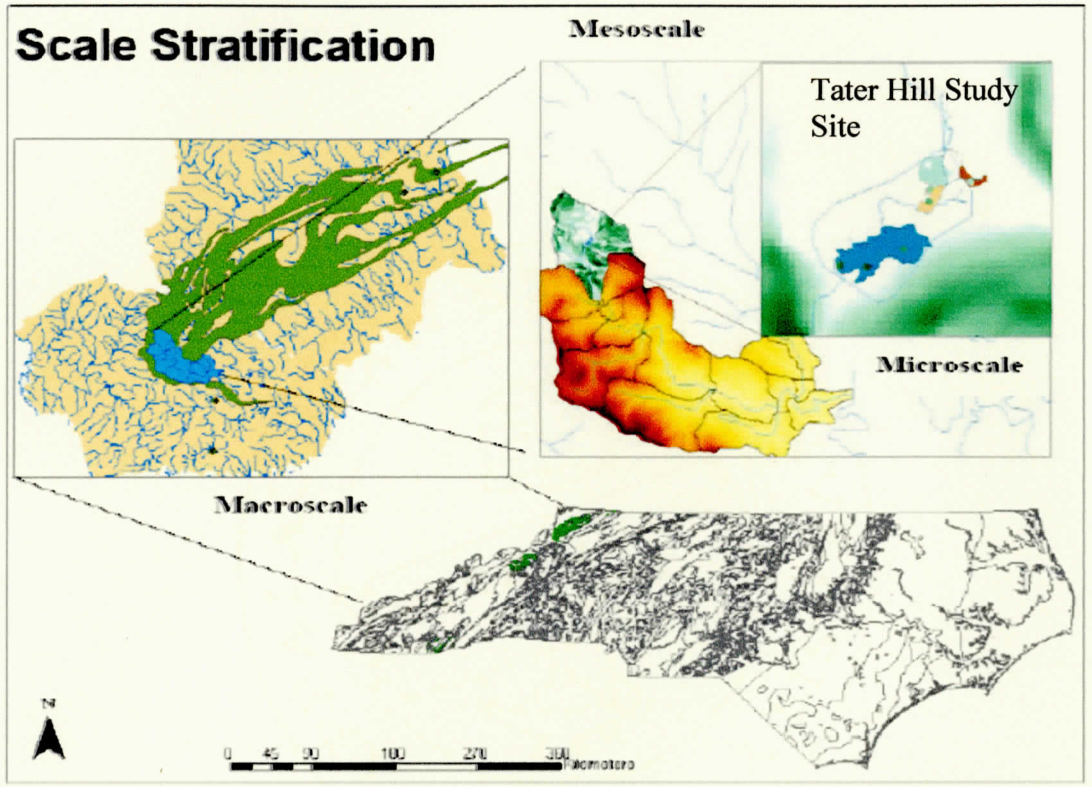
This study presents a conceptual model for Southern Appalachian wetlands (SAWeM) developed using GIS as the integrative platform for wetland inventories and functional assessments in the form of a geodatabase. A geodatabase is "a physical store of geographic information inside a database management system. The geodatabase architecture allows for the creation of common or essential data models for specific industries and applications. ArcGIS data models provide ready-to-use nonproprietary frameworks for modeling and capturing the behavior of real-world objects in a geodatabase" (ESRI 2008).

SAWeM is a descriptive model built on layers of geographic information and current knowledge of the direct spatial relationships between the data associated with those layers. In a descriptive model the relationships between datasets can be manipulated and information stored in its database can be used to query data for predictive analysis (Franklin 1995, Cedfeldt et al. 2000).

The model can be used as a tool in policy-making and management of natural water resources at various scales. By integrating data at various scales the model presents a holistic approach to wetlands within the watershed system as an alternative to traditional single-unit approaches, SAWeM integrates ecological structure and hydrologic process datasets within the framework of the spatially defined hierarchical environmental controls acting on them. The postulate that natural systems self-organize into levels of hierarchical control is central to ecohydrology, ecotechnology, and ecological engineering (Day et al. 2003). Within SAWeM, climate and physiography are the highest hierarchical levels of environmental control (Mitchell et al. 2004). Physical systems embedded in a physiographic region are implicitly subject to environmental changes at this scale.

In the research presented here, the North and South Forks of the New River, both headwaters of the New River watershed within the Blue Ridge physiographic region, are considered the macroscale components of the model. Catchments (and their basins) in the North and South Fork watersheds are mesoscale components whose land-use directly affects water-quality (Zandbergen 1998, Leibowitz 2000, Buck et al. 2004). Sub-basins and adjoint catchments (further subdivisions of the sub-basin) are the units associated with data gathered in the field and the microscale components of the model. Functions are defined as the interactions between model components and are not constrained within a hierarchical level. Model components built of units at lower hierarchical levels are considered information aggregates that transfer information about and from the lower level units to higher levels of abstraction (Figure 1).

Figure 1. Map showing the hierarchical relationship and spatial scale of the physical system and subsystems modeled in SAWeM.



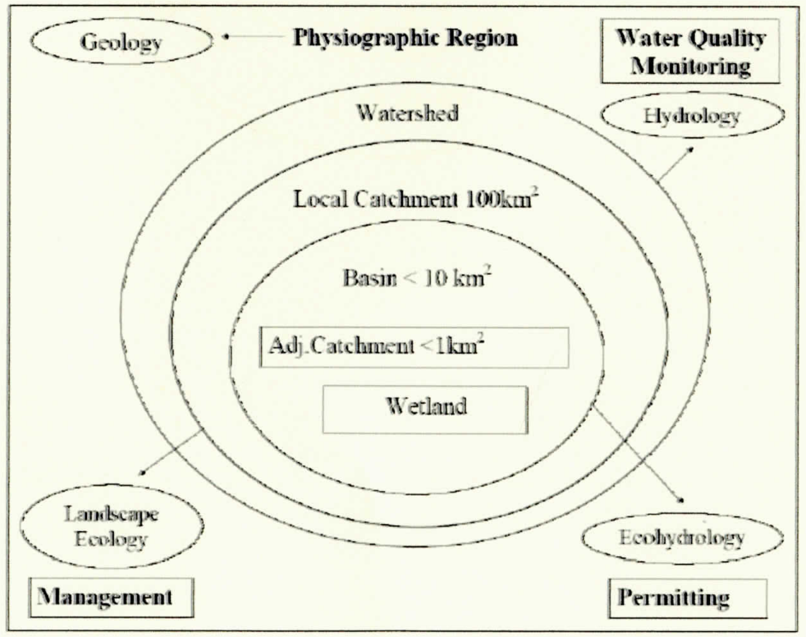
The objective of this study was to design a GIS platform for the integration of data on physical structure and hydrologic processes into aggregable subunits of watershed systems. The resulting model should provide a practical, easy-to-use assessment tool for decision makers and stakeholders.

MATERIALS AND METHODS

Modeling

Conceptual Model. The aggregation of information into higher levels of abstraction within spatially defined control hierarchies is frequently used in modeling studies of environmental systems (Seppelt and Voinov 2002). Through spatially defined classification the components of a large physical system, such as the New River watershed, can be grouped together based on their size. Climate, geology, and topography provide overriding controls that make aggregation within the spatial extent of their influence appropriate (Mitchell et al. 2004). The conceptual model behind SAWeM (Figure 2) incorporates microscale data on local ecohydrology to the scale of the sub-basin.

Figure 2. The conceptual structure of SAWeM. The scales of the physical system are represented as ovals with arrows pointing to respective study disciplines and boxes describing scales of human involvement.



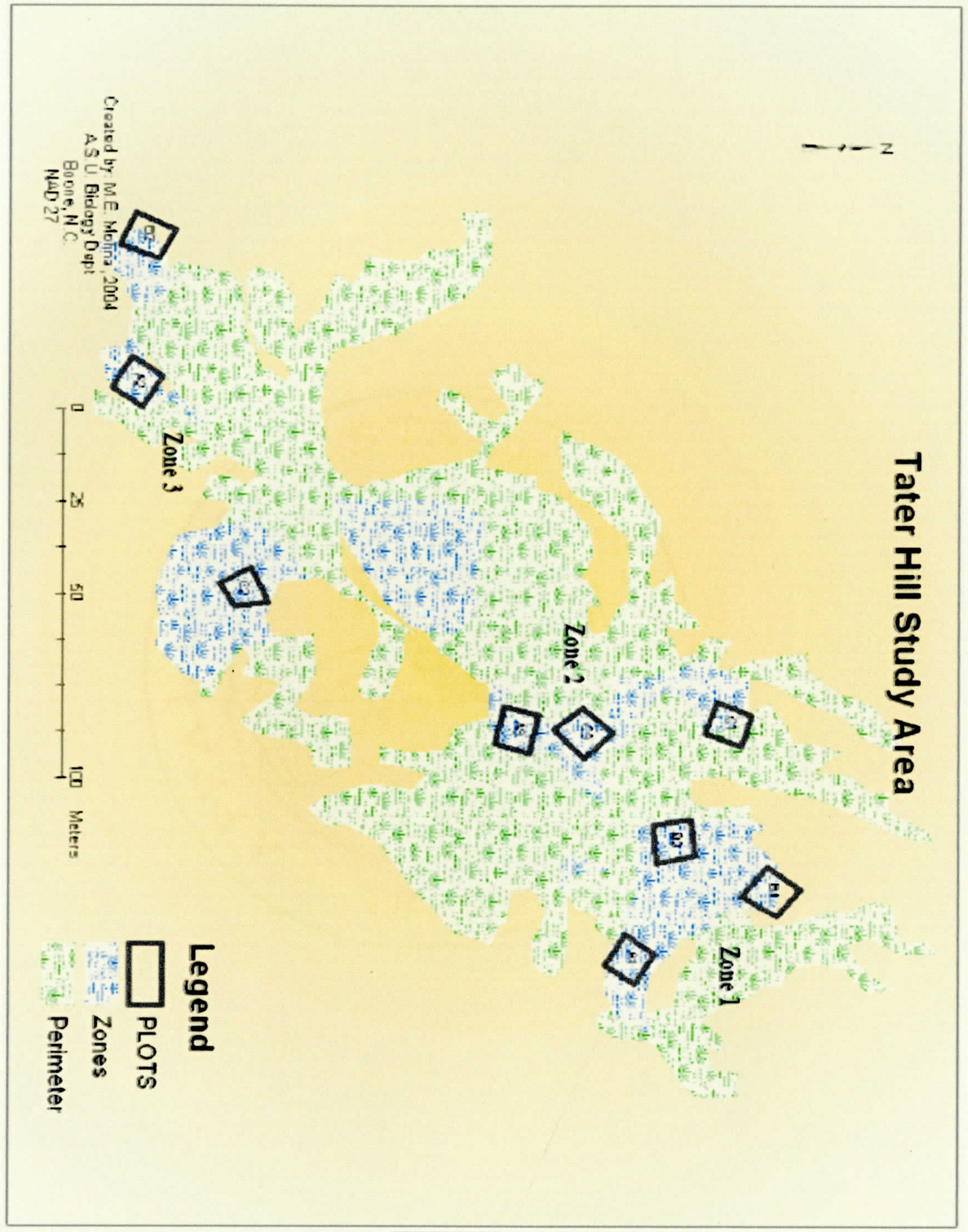
Information for the microscale components (zones, adjoint catchments, and sub-basins covering an area of 0-1 km^2) was derived from hydrologic, vegetation, and soil data gathered at the Tater Hill study site between September 2001 and March 2004. Descriptive data was gathered in the summer and fall of 2003 for 34 wetlands in the headwaters of the New River. Microscale units are considered the appropriate scale for site studies and 401 permitting (Zandbergen 1998).

The next level in the model incorporates mesoscale components (basins covering an area of 1-10 km^2 and catchments covering an area up to 100 km^2) as monitoring units. Data for monitoring units were derived by combining descriptive field data with datasets derived from digital sources. Mesoscale units are considered the appropriate scale for management (Janauer 2000, Buck et al. 2004). The macroscale components of the model and ultimate units of hydrologic concern are the North and South Fork watersheds of the New River. Macroscale data was derived from available digital datasets. Climate and physiography were considered implicit controls at all scales. All datasets were stored and processed in ArcInfo 8.0 (ESRI, Redlands, CA).

Study Area

Study site. The Tater Hill basin encompasses a surface area of 38.5 km^2 and is located at the headwaters of the Howard Creek catchment in Watauga County, NC. The Howard Creek Catchment is a listed NHP area that feeds a High Quality Water Source (HQW) listed. The Tater Hill site is a bog-fen complex with at least three, and possibly four, separate water tables, each with an associated zone of discharge (Figure 3).

Figure 3. Map showing the areal features (plots, zones, and perimeter) of the Tater Hill site.



Tater Hill is listed by the Natural Heritage Program of North Carolina as a unique example of a southern Appalachian bog (Schafale 1998). There are also a number of rare and threatened plant species at the site including *Lilium grayi*, *Ilex collina*, *Saxifraga pensylvanica*, and *Gentiana crinita,* making it a site with recognized biological value.

At the northeastern end of the site the water table intersects the surface creating an area (Zone 1) that remains wet throughout the year. Zone 1 is best characterized as a fen because the soil remains wet as the result of groundwater discharge. This area is 1,280 m^2 in extent and is dominated by hydrophytic vegetation. A crowbar was used to dig holes to refusal and the thickness of each horizon was then measured. Upslope peat accumulation is about 80 cm deep and is the only soil overlaying a colluvium layer that was probably deposited by a debris flow. Closer to the discharge zone the colluvium is overlain with about 40 cm of mineral soil. The O horizon is less than 10 cm deep.

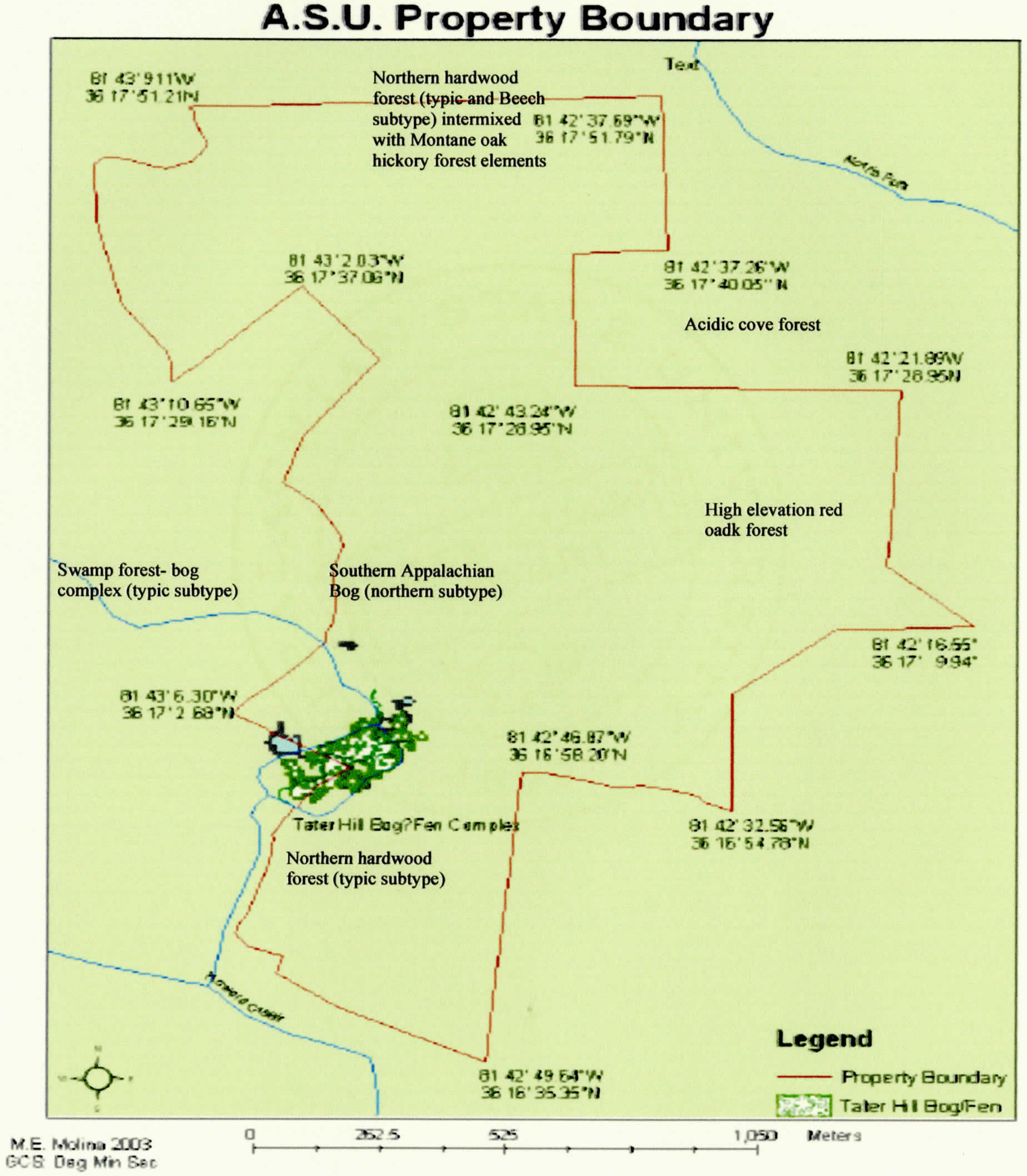
The presence of colluvium makes it impossible to determine the depth of the water table, but its density suggests that the volume of water stored in the space between colluvium must be less than that of the soil layer above it. Water rises to the surface as the result of throughflow from the relatively high slopes surrounding the area before intersecting the surface at Zone 1. Surface water has incised a small stream that also drains towards the main channel. This stream is ephemeral and its discharge is below measurable flow levels.

On the western side of the site an area of 420 m^2 (Zone 2) appears to have a common discharge zone. Close to the zone of discharge the water table intersects the surface throughout the year and depth to refusal is over 90 cm. The O, A, and B horizons are present and distinguishable. Further upslope the depth to refusal is between 50 and 60 cm and the water table is usually no more than 20 cm above refusal. Intersection with the surface is limited to an area of 245 m^2 adjacent to the zone of discharge. Surface water flow is minimal.

At the southern end of the site the water table intersects the surface in two areas (collectively called Zone 3) that are also connected by surface flow. The lower area encompasses 243 m^2 and is adjacent to the discharge zone for the whole basin. The elevation of the water table in Zone 3 usually remains higher than the elevation of the main channels stream, suggesting a perched groundwater table fed by through-flow.

Surrounding the wetland areas are 3,800 acres of protected land owned by the North Carolina Department of Plant Conservation Program and the North Carolina Department of Agriculture (NCDA) which at the time of the study had been entrusted to the Department of Biology at Appalachian State University (ASU) for management, so that land use surrounding the site does not, at this time, include activities that may lead to the deterioration of water quality (Figure 4).

Fig.4. Map showing the areal extent of the property under management by Appalachian State University. Labels denote dominant communities.



The New River Watershed. The New River watershed encompasses 11,112 km^2 in North Carolina, Virginia, and West Virginia. The New River's main stem flows northeastward for 513 km and has thousands of kilometers of tributaries, 146 km of which are designated as a Federal Wild and Scenic River. It was the nation's first American Heritage River. The headwaters of the New River watershed are located in the Blue Ridge Mountains of northwestern North Carolina (National Committee for the New River 2008).

The Blue Ridge Mountains Province can be divided into two sections with two different structural histories: the northern section which begins north of the Roanoke River and extends into Pennsylvania and the southern section which begins south of the Roanoke River and extends into Georgia. The northern section is composed mainly of igneous and metamorphic rocks of Precambrian origin and overlain by metasedimentary rocks of Cambrian age. The southern section exhibits complex structural relations as the result of the long distance tectonic transport of thrust sheets containing deformed rocks of low to high metamorphic grades (Clark et al. 1989).

The southern section widens westward, reaching a width of 113 km along the NC–TN border in the southern Appalachians. To the southeast it is bordered by the Blue Ridge escarpment and to the northwest by foothills. The landscape is one of irregular ranges separated by irregularly-shaped basins and criss-crossed by debris flows. South of the Wisconsian glacial border, the geomorphology of the Blue Ridge Province has resulted from weathering and erosion (Spotila et al. 2004), the rates of which have likely increased since the retreat of the last ice sheet and concomitant increases in precipitation.

Common landforms of the Blue Ridge Province include fluvial terraces, blockfields and boulders, talus and tors, and debris fans and flows. Fluvial terraces in the central Blue Ridge Mountains of Virginia indicate stream incision since the early Pleistocene and are characterized by a thin layer of weathered alluvium overlaying a deep saprolite (Clark et al. 1989). Blockfields and boulders are the result of mechanical weathering during the Pleistocene, when reduced vegetation cover and low temperatures facilitated mechanical weathering and debris flows. Unmodified blockfields and boulder streams suggest that most of the present Appalachian landscape was shaped during the periglacial climate of the late Pleistocene (Eaton et al. 2003). Debris fans in the Blue Ridge Province are responsible for carving much of the landscape and excavating colluvium that is then deposited in debris fans. With the loss of gradient, multiple debris fans may coalesce at the base of mountain slopes and form thick layers of colluvium (Eaton et al. 2003).

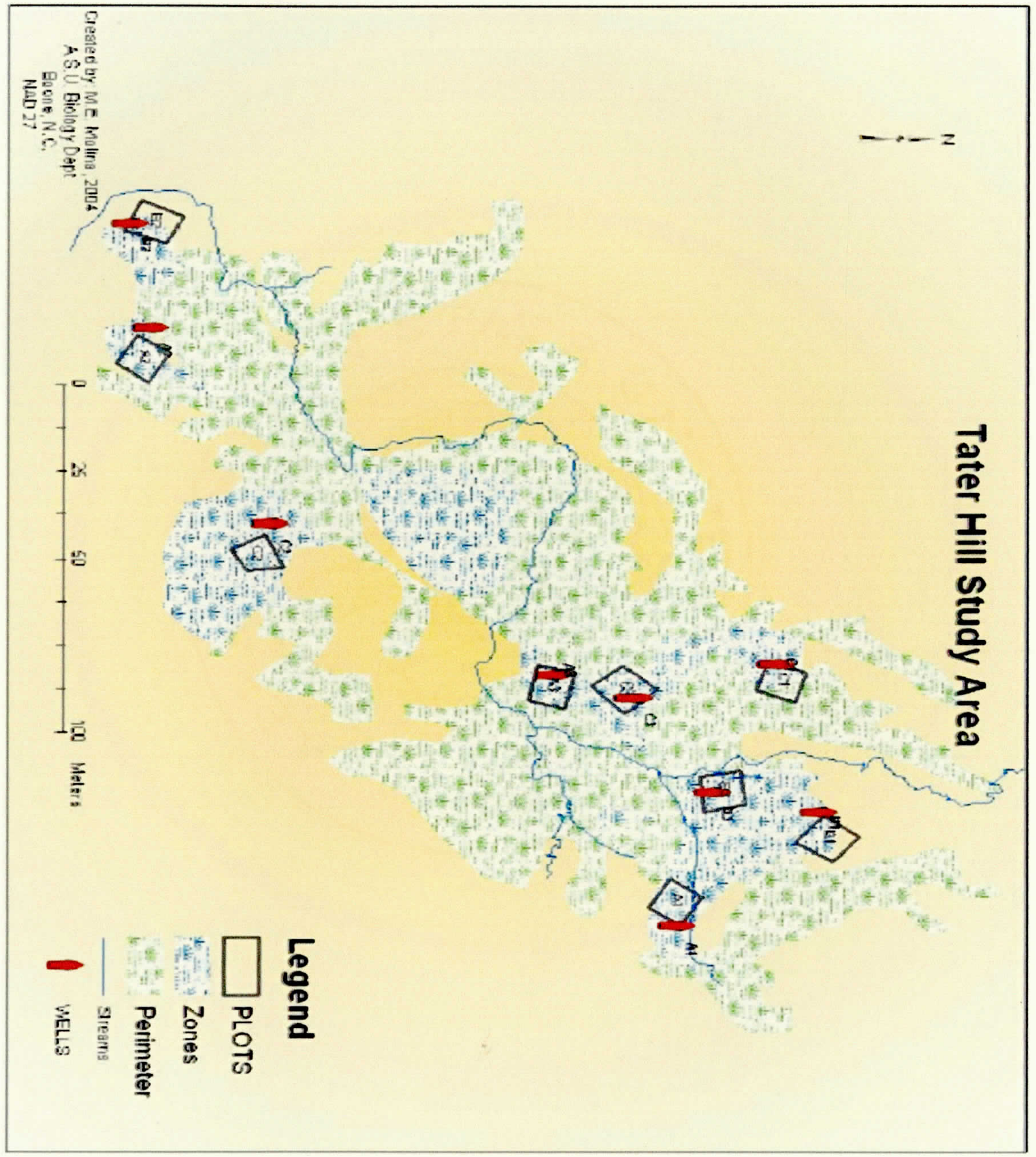
In the Blue Ridge Province colluvium resulting from mudflows or debris flows can be very thick (up to 100 m). The amount of soil formed by the weathering of colluvium decreases with increasing distance from the Wisconsin glacial border, but increases with increasing elevation. The most common soil types in the southern Blue Ridge region are Inceptisols on the steeper slopes, Haplumbrepts and Spodosols at high elevations and on gentler slopes, and Paleudults and Hapludults on alluvial and colluvial bedrock – floored coves. Paleudolts and Hapludults are both fine- loamy soils (Clark et al. 1989). Loam soils have hydraulic conductivities higher than 10^{-6} cm/s that makes them permeable to groundwater flow. Wetlands will form in loam soils in gentle (<25) slopes or flat terrain, if they coincide with areas of groundwater discharge (Fetter 1994).

The differential weathering resistance of Appalachian rock layers facilitates the movement of water through fractures and joints in the bedrock. Springs are likely to occur on steep slopes with shallow soils that become saturated when groundwater flowing through a fracture intersects the surface and cannot be diverted by throughflow (Fetter 1994). Topographic low spots such as the coves that form between debris flows in the southern Blue Ridge Mountains are likely settings for natural springs where the parent material of the cove's soil is siltstone or shale resulting in loamy soils whose topography intersects the water table. Large areas of infiltration with steep slopes and convergent throughflow contributing to a groundwater basin composed of unconsolidated subsurface materials with high hydraulic conductivities are the most likely to have depression springs. In areas with thick soils these springs will form wetlands, especially where throughflow water moving by gravity at the heads of drainages with short slopes end in flats with deep soils.

Data acquisition and aggregation

Mapping. In September 2001, the perimeter of the wetland complex was delineated based on microtopography and vegetation. Within the perimeter, Zones 1, 2, and 3 were delineated based on shared vegetation, microtopography, and hydrology. Streams, creeks, vehicle tracks within the site, and inflow and outflow stations for measuring discharge were also mapped (Figure 5).

Figure 5. Map showing stream features and the location of the groundwater wells associated with the three plots in each zone.



In October 2001, three 10 m^2 plots were established within each zone and categorized as A (top soil layer is obviously saturated), B (top soil layer is moist-wet), or C (top soil layer is dry). In December 2002, groundwater wells were installed within each plot based on the procedure outlined by Kerfoot (1998). All features (flow stations, perimeter, zones, plots, and wells) were mapped using a Trimble XPRO GPS unit (Sunnyvale, CA) and stored in an ArcInfo geodatabase. In the GIS the delineated perimeter file was laid over a georeferenced aerial photograph of the site and the correspondence of features found satisfactory for the scale of this study.

Vegetation Surveys. Seasonal surveys were conducted at each zone between the fall of 2001 and the spring of 2004. For this study the vegetation index VI= %C x WS was used (Zandbergen 1998). In this equation %C represents percent cover, and WS is the wetland indicator status value (Martin 2007) of every species within each 10 m^2 plot. The VI was chosen as a simple, quantitative metric to evaluate the vegetational wetland character of each plot. The cumulative value of this metric for all plots within a zone was used as the VI value for that zone (Martin 2007).

Stream Discharge. Between September 16, 2002 and March 16, 2004 stream discharge was calculated bi-monthly at all major inflows and outflows by measuring depth and velocity at 60% depth with a FlowStream (Flowatch, Aquamerik, St-Nicolas, CA) digital flowmeter. Flow measurements were taken at the junctions of streams with the main channel stream. Channel width at each station was measured once every six months to account for streambank erosion. All inflow measurements were combined into a single value called Inflow.

Soil Sampling and Groundwater Monitoring

In the fall of 2002, soil samples were taken from each plot using a standard soil corer. Soil horizons of each soil sample were classified using the USDA's soil triangle (Schoeneberger et al 1998). The physical properties and thickness of each soil horizon were recorded in the field in accordance to the USDA's soil sampling manual (Schoeneberger et al. 1998). Soil samples from each horizon were taken into the lab for particle size distribution analysis. The soil samples were dried in a standard herbarium drier over a period of 72 hours at temperature of 100° C. Dry organic matter was removed by placing each sample in a beaker over a hot plate, hydrating it into a paste and then adding 30% HCl until no reaction was observed. After the organic matter was removed, samples were allowed to dry. Once dry, each sample was sifted through a 2 mm sieve to separate sand from fine particulates. Sand samples were weighed and recorded as percentages of the total weight of the original sample.

In December 2002, nine groundwater wells were installed, one within each plot, and grouped by zone. Each well consisted of a PVC pipe 150 cm long and 5.1 cm in diameter with ten narrow slits (3mm) cut at 2 cm intervals from its base to minimize sediment infiltration. Wells were placed in holes dug to refusal depth using a soil auger (AMS one-piece, Carlsbad, CA). In this study refusal was defined as the depth at which bedrock or colluvium made it impossible to dig deeper despite three or more attempts. After the wells were placed in the holes, sand was used to fill up the first 40 cm, and the remainder was filled with the original soil. A benthonite seal around the PVC pipes and plastic caps on the open end were used to avoid surface and rain water infiltrating the wells. The relative elevation of all wells was surveyed in the spring of 2003. Groundwater levels at each well were monitored and recorded on a bi-monthly basis between March 2003 and March 2004 using a weighted string stained with colored chalk. Well data was grouped by zone and aggregated as a property of the respective adjoint catchments.

A Prototype Functional Unit at Tater Hill. To define the concept of a functional ecosystem unit within the Tater Hill sub-basin, Zone 1 was used as a prototype for the water storage function within its adjoint catchment. All calculations were performed using Maple 9 software (Maplesoft, Waterloo, Ontario), and the complete program used to model Zone 1 is attached as Appendix 1. To model the water storage function of Zone 1, the coordinates of each well within Zone 1 were used as the points of a Euclidean triangle and a scaling factor was used to make its area (502 m^2) equivalent with the area of Zone 1 (1,280 m^2). The new triangle was then projected onto the plane:

$$Z = (-1.54x + .823\ y + 441.23)$$

The empty volume under Z was calculated using the known maximum relative elevation of the water table at each well (A1: 368.3 cm, B1: 444.81 cm, B3: 433.25 cm) to generate a second plane representing the depth to refusal. The plane crossed a centerpoint generated using inverse distance weighting. Integration yielded an empty volume value for the shape. Water stored below colluvium refusal is not accounted for in this model.

The procedure outlined by Fernandez-Illescas et al. (2000) used soil texture to calculate porosity, *n*, and saturated hydraulic conductivity. The specific yield of the Zone 1 three-dimensional model was calculated as follows:

$$SY_{Z1} = SY_{A1} + SY_{B1a} + SY_{B3a} + SY_{B3b}$$

where SY_{Z1} = thickness of the horizon for an area equal to that of Zone 1 (j) at well (i) times the effective porosity for the texture class of (j), n. The specific yield was then added to the model as a percentage of the total empty volume of the shape. Within the model data on vegetation, soil type, and relative elevation of the groundwater table, becomes a characteristic of the zone where it was gathered and a property of the adjoint catchment in which a zone is imbedded. Adjoint catchments within a basin were derived from a digital elevation model (DEM's) using the ArcHydro extension for ArcInfo 8.0. These subdivisions of the basin are appropriate for aggregation of point data such as groundwater levels, stream flow, and vegetation to the scale of the basin.

Wetland Field Searches. Within catchments, basins are reasonable units for vegetation surveys and aggregation of microscale data (Janauer 2000). Point scale impacts however, are not necessarily associated with land cover change at the catchment scale. As a methodology for basin scale assessment and dataset integration, a sample of 34 wetlands in the North and South Forks of the New River was also incorporated into the GIS as an independent dataset of functional units. The wetland dataset was combined with land use/ land cover data (LULC) for the mesoscale assessment of catchments.

After a preliminary survey confirmed that the National Wetlands Inventory is not a precise or accurate inventory for the Appalachian Mountains region, wetland locations were obtained from oral reports and systematic field searches. Oral reports from local landowners and staff from the Watauga County Soil and Water Conservation Service were verified during field searches. Field search methodology had to adhere to the following criteria: they had to be rapid (less than 20 minutes per site), they had to require a minimum amount of training (one day), and there be at least one wetland indicator species at each wetland event (x, y coordinates) recorded. The following data was collected for each wetland record: 1) coordinates; 2) estimated area; 3) distance of wetland to closest channel (0-10 m, 10-20 m, 20-30 m, 30 m); 4) indicator species; 5) alteration of surface hydrology (drained vs. undrained); 6) catchment land cover; and 7) wetland land use (see Appendix 2: Southern Appalachian Wetlands Project Data Entry Form).

In Ashe County, an optimized route for field searches was derived from the following GIS layers: 1) Ashe County slope; 2) Ashe County hydrography; 3) Ashe County roads; and 4) Ashe County soil polygons, all of which were obtained from the NCNR GIS office. The map was created by selecting and reclassifying soil-type polygons and the raster slope dataset into values derived from characteristics of wetland areas (Table 1).

Table 1. Suitability values based on soil type and slope. Hydric soil type A are map units that are all hydric soils or have hydric soils as a major component. Hydric soil type B are map units with inclusions of hydric soils or that have wet spots.

Soil Type	**Hydric**	**Slope**	**Description**	**Suitability Value**
BrB		2-8	Braddock gravelly loam	2
BrD		8-15	Braddock gravelly loam	2
Co			Colvart Fine Sandy loam	2
CfE		15-25	Clifton loam	2
To	A		Toxaway loam/hydric	5
To			Toxaway loam	4
TsD		8-15	Tusquitee loam	4
TsD	B	8-15	Tusquitee loam	5
TUE		15-25	Tusquitee and Spivey	2
WaF		25-45	Watauga loam	3

The wetland set was combined with the land use/land cover (LULC) dataset to derive assessment values.

Catchment Delineation and Classification. Because the properties of a large, complex system such as a watershed cannot be predicted from the properties of its functional units, adaptive management and assessment approaches at the macroscale require complex strategies that can be evaluated and revised at each stage of implementation and adjusted to improve the efficiency of further steps (Zalewski 2000). In this study feature properties common to both scales were used to relate ecological information gathered at the site scale with digital datasets at the landscape mesoscale.

Sixteen local catchments within the New River Watershed: Beaver Creek, Deep Gap Creek, Dog Creek, East Fork, Elk Creek, Howard Creek, Laurel Fork, Lazon Creek, Meadow Creek, Meat Camp Creek, Mutton Creek, Naked Creek, Obids Creek, Pine Swamp Creek, Three Top Creek, and Winkler Creek, were delineated from a 10 m resolution DEM using the ArcHydro extension for ArcInfo 8.1. Individuals or sets were used as prototypes in the different stages of implementation of the model.

Relationships between land-use change and stream health have been documented for catchments on the order of 100 km^2 (Zandbergen 1998), making local catchments appropriate classification and water quality monitoring units. Janauer (2000) also suggests that an element area of this order should have biological landscape elements compatible with this scale. In the GIS the LULC dataset was reclassified into three functional land-cover types: urban, agricultural, and natural. A conservative estimate for an urbanized watershed is 10% total impervious surface area. Total impervious area is considered the best indicator of urbanization by watershed professionals and 10% the threshold between "good" and "fair" associated stream health. The imperviousness indicator is appropriate for basins between 5 and 150 km^2 (Zandbergen 1998). High-intensity developed and low-intensity developed land-cover types were grouped into the functional class 'urban'.

Land covers that could reasonably be expected to be under fertilizer or pesticide treatment, or used for animal farming were reclassified as agricultural and included

cultivated and managed herbaceous cover. Catchments were classified as 'agricultural' if 30% or more of their cover was cultivated or managed herbaceous.

Catchments were classified as 'natural' if their reclassified land cover did not exceed 30% agricultural or 5% urban. The 'natural' functional class included: unmanaged herbaceous cover, evergreen shrubland, deciduous shrubland, mixed shrubland, mixed upland hardwoods, bottomland forest/hardwood swamp, other broadleaf deciduous forest, needleleaf deciduous, mountain conifers, southern yellow pine, other needleleaf evergreen forest, broadleaf evergreen forest, mixed hardwoods/ conifers, oak/gum/cypress, water bodies, water bodies, unconsolidated sediment, and exposed rock.

Catchments within a functional class are macroscale aggregates that serve as monitoring units for the hydrologic processes within the watershed. A dimensionless number indicating the cumulative value of water quality parameters specific to the catchment's functional class is used as an assessment metric for the 'health' of that catchment.

The Water Quality Index (WQX). In Ashe and Watauga Counties, NC the NCNR has organized a local community effort to monitor water quality on the North Fork and on tributaries to the South Fork of the New River. The British Columbia Ministry of Environment Water Quality Index developed in 1994 (Zandbergen 1998) was adapted for use with the NCNR dataset. The index is based on water quality objectives for each catchment and is expressed as:

$$\frac{100- \sqrt{(F1)^2 + (F2)^2 + (F3/3)^2}}{1.453}$$

where F1is the number of objectives not met as a % of all objectives checked, F2 is the frequency with which objectives were not met as a % of all instances of objectives being checked, and F3 is the amount by which objectives were not met as the maximum deviation for any one objective.

Seven objectives were established for the catchments in the model: Ammonia-nitrogen concentrations under 10 ppb, nitrate concentrations under 5 ppb, orthophosphate concentrations under 16 ppb, turbidity values under 6 NTU (nephelometric turbidity units), suspended solid concentrations under 47 ppb, conductivity values under 63.1 umhos/cm, and pH values of 7.1.

The WQX for each catchment is calculated in a spreadsheet outside of the GIS environment. The spreadsheet is then exported in database format (.dbf) into the GIS and related to its catchment through a unique identifier. WQX values for catchments are reclassified into four classes: 0-25 being very poor, 25-50 being poor, 50-70 being average, 70-90 being good, and 90> being very good. The results can then be compared to assess the relative health of each catchment within its class and the relative health of all the catchments in one class with that of catchments in another class.

The Laurel Fork Creek and Three Top Creek catchments were used as prototypes for the WQX within the model. Howard Creek is assumed to be either good or very good and Winkler Creek, a highly developed catchment, to be very poor. More data from sampling programs is needed to refine the WQX and apply the assessment to a large enough sample of catchments to make statistical comparisons.

Model Structure. Predictive models must rely on statistically proven relationships to be applicable. In a dynamic system, such as a watershed, there are complex interactions between the macroscale system and its subsystems. The non-linear properties of such interactions make statistical modeling extremely difficult to develop (Leibowitz et al. 2000). Physical

systems however, also have structural components that possess distinguishing attributes. As a representation of a physical system, SAWeM is a descriptive model meant to organize information on the spatial relationships between the watershed system's components relevant to its overall functionality. The model incorporates information gained from the extensive literature available on watershed properties and wetlands and the functions they perform (Pearson 1994, Whigman 1999, Janauer 2000, Zalewski 2000, and Sun et al. 2002), to derive importance values for each wetland event for one of two wetland functions: water quality improvement and water storage. The functional assessment value is a quantitative representation of a wetlands function within the system. In a sense, it is a descriptive symbol for the aggregate of relationships that result in the selected assessment functions. Thus, the model is built on two premises:

1) The functions of mountain wetlands are the aggregate result of their structural components and their interactions with other agents in the hydrologic network.

2) Agents and their interactions are subject to spatially defined control hierarchies. Thus changes in a lower hierarchical level will only affect an aggregate in a higher hierarchy through a synergistic effect, while changes in a higher hierarchical level will affect the functionality of every agent beneath it (Pearson 1994, Holland 1996, Whigman 1999, Janauer 2000, Leibowitz et al. 2000, Zalewski 2000, Mitchell et al. 2004).

Development of Metrics. While it is conceptually useful to identify and scale the environmental parameters within which biological and geophysical processes occur, the functionality of any unit within the system, regardless of scale, is the result of the interactions between that unit and other system components. These interactions may occur within the same hierarchical level or across hierarchical levels. There is little doubt that the functions of wetland ecosystems are affected by the surrounding land cover and other landscape properties (Pearson 1994). The functionality of the basin is itself affected by the wetland network within it (Leibowitz et al. 2000). The wetland network is connected by subsurface flow and/or the stream network (Zalewski 2000). By necessity, metrics in SAWeM are unidirectional. The values representing a relationship assess the functionality of a single-model component. The alternative would result in information loops within the model and complex non-linear relationships.

Wetland events received an assessment score from field metrics and GIS metrics. Field metrics included: 1) land- use of the wetland; 2) distance of the wetland edge to the channel; and 3) hydrological alteration to the wetland (Table 2).

Table 2. Field Metrics. Shows classes and associated values assigned to measurements and observations of field checked wetlands.

	Land use of wetland (LuW)	Distance of the wetland to the channel (m)	Hydrologic alteration to the wetland (Hy)	Maximum value
Cal-culated	According to classified values	According to distance categories	According to drainage condition	(LuW) x ((m) + (HY))
Value	Developed= 0 Cultivated= 1 Pasture= 2 Unmanaged= 3 Conservation= 4	0-10 = 5 10-20=4 20-30=3 30-40=2 40-50=1	Drained= 1 Not drained= 2	
Max Value	4	5	5	40

Field metrics are converted to values between 1 and 4 or 1 and 5. The land-use metric is based on the observed land use at the site when last checked. The land- use value is assigned based on the relative impact of each land- use to a wetland's structure and function. The proximity-to-stream metric is derived from the distance in meters of the wetland to its associated channel. The proximity value is an assessment of the connectivity of the wetland

to the hydrologic network. The hydrologic alteration metric is based on drainage within the site. The value reflects a decrease in function if the wetland has been drained or ditched. GIS metrics included: 1) The ratio of wetland area to catchment area; 2) the position of the wetland within the watershed; 3) the proximity of the wetland to the stream; and 4) the functional load of the wetland. Metric values are derived from simple mathematical relationships between two agents (Table 3).

Table 3. GIS Metrics. Shows values assigned to mathematical relationships between feature properties.

GIS Metrics	Wetland area to catchment area ratio	Watershed position	Proximity to stream (m)	Functional load	Maximum value possible
Cal-culated	WtA/ WsA	Inverse of Stream Order	Distance from edge of wetland to stream (mts)	Log of the number of known wetlands	
Value	0-.25 = 5 .25-.40 = 4 .40-.60 = 3 .60-.80 = 2 .80- 1.0 =1	1=5 2=4 3=3 4=2 5=1	0-10 = 5 10-20=4 20-30=3 30-40=2 40-50=1	0 = 5 0-0.7 = 4 0.7-1 = 3 1-1.25 = 2 1.25-1.5 = 1	
Max Value	5	5	5	5	20

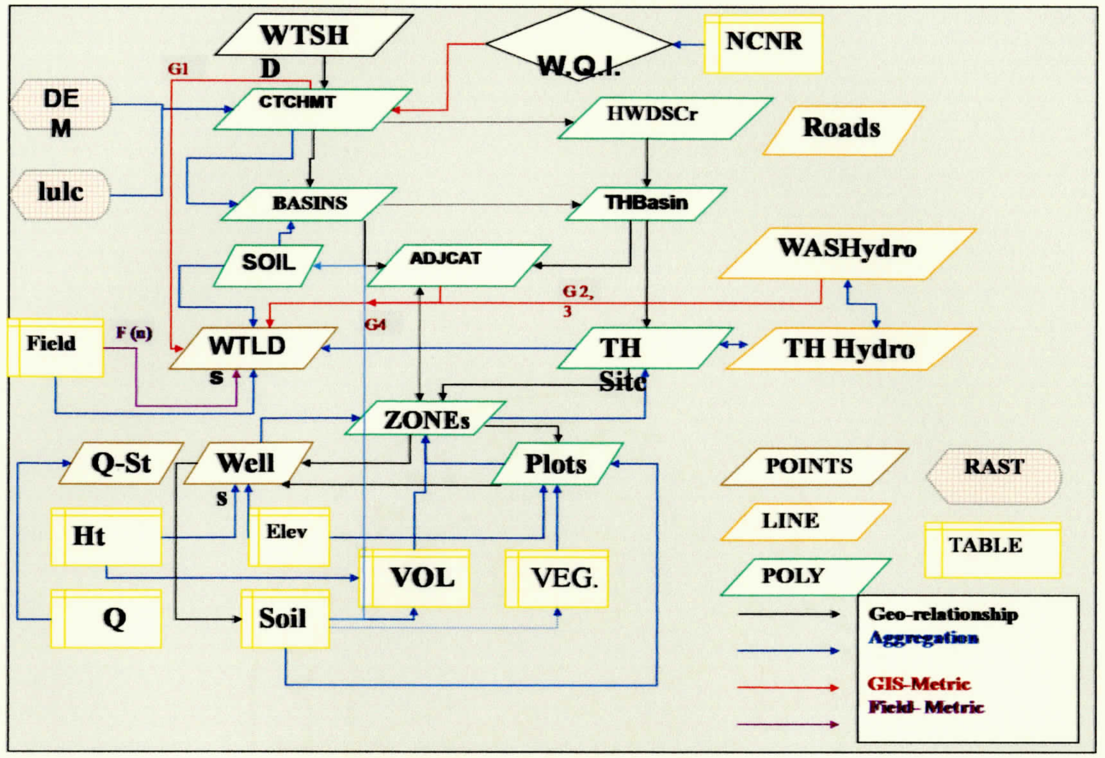
All GIS metrics are converted to a value between 1 and 5. The wetland-area to catchment-area ratio is derived by dividing the area of the wetland by the area of its basin. The WtA/WsA value is an assessment of the wetlands 'uniqueness' within its watershed. The position within the watershed metric is derived as the inverse of the associated stream order. This value is an assessment based on the functional importance of headwater wetlands. The proximity-to-stream metric is derived from the distance in meters of the wetland to its associated channel. The proximity value is an assessment of the connectivity of the wetland to the hydrologic network. The functional-load metric is derived by taking the log of the number of known wetlands in the catchment. The functional load value is an assessment of the relative importance of a wetland to the entire catchment.

Metrics are calculated outside of the GIS environment. Physical features are stored as shapefiles or geodatabase files. DEM's and land use/land cover are stored as raster datasets, and time series data is stored in tables which are then related to one or many shapefiles.

RESULTS

GIS Model Structure. All of the data is aggregated in a GIS model structure by linking and relating files containing geographic information of point, line, polygon features and associated tables of data collected in the field or from RSD sources. Relationships between files can be geographical (containment or adjacency) or of aggregation. The aggregation data consists of multiple datasets combined to generate information on a feature such as stream discharge, estimated storage volume, or relationship to larger features. These relationships are illustrated in Figure 6 by black and blue arrows, respectively.

Figure 6. Schema of the SAWeM model structure, relationships, and file types.



Metrics derived from the relationship of the GIS features within the model are illustrated by red arrows (the metric derived labeled). Metrics derived from field data added to a feature in the GIS is illustrated with a purple arrow.

SAWeM aggregates information at the microscale level by linking tables which contain information on flow discharge at each input/output station (Q), as well as soil characteristics (Soil) and groundwater levels at each well point location (Ht) with the associated point GIS files 'Well.shp' and 'Q.shp'. The polygon file 'Plots' contains information on the surface area of each plot, is linked to the table 'Elev' which contains information on the relative elevation of each plots surface (which is necessary to calculate the changes in groundwater levels), the table 'Soil', and can contain additional tables such as a 'VEG' table with a value index based on floristic data.

The file 'ZONE's' is a polygon delineating each of the three distinct study areas within the Tater Hill site and is linked by OID to the file 'Plots' and the point file 'Well' so it contains all their information. Additionally, 'ZONE's' also contains the table 'VOL' which is used to calculate the potential water-storage volume based on each zones area, soil properties, and groundwater levels. The ZONE's polygons represent the first level of data aggregation and the microscale units of study in SAWeM.

The 'TH' polygon delineates the perimeter of the Tater Hill study site and contains ZONE's (linked by ID), 'TH' is also related to the line file,'TH Hydro', all streams with measurable flow at the Tater Hill site. The 'TH' feature is included in the 'WTLD' point file, which contains all field confirmed wetland sites from the NWI and field checked wetlands. The 'WTLD' file is related to the 'Field' table, which contains land use/land cover (LULC), shape, approximate acreage, and surrounding landscape data for 26 wetland sites. Field metrics derived from these data are illustrated by a purple arrow. The TH, TH Hydro, and WTLD features represent the second level of data aggregation, but are still considered local microscale features within the SAWeM framework. Information related to microscale features is derived from GPS, measurement, or observation in the field.

Mesoscale features include the GIS files: 'Roads' (used as visual geographical reference only but not related or linked to other datasets in the model); 'WASHydro'polygon, contains all stream features in Watauga and Ashe counties; the 'SOIL.shp' polygon contains information on soil type derived from the Watauga and Ashe county soil GIS datasets; 'ADJCAT' is a polygon file that contains all the adjoint catchments adjoining the Tater Hill Basin. The 'HWDSCR' polygon file contains 'TH Basin' polygon features file (which delineates the extent and area of the Tater Hill site basin) and the 'ADJCAT 'polygon features file (which delineates the extent and area of catchments adjoining the Tater Hill basin). 'HWDRCR.shp' is itself a feature derived from the polygon file 'CTCHMT' which delineates all basins ('BASINS.shp' file) within Watauga and Ashe Counties. The relationship between the number of features from the 'WTLD' amongst features in the 'CTCHMT' file is the crucial metric relating macro and mesoscale information derived from RSD to field checked data within SAWeM.

The Howard Creek basin feature, 'HWDSCr', the 13 Basin polygons (listed in the Methods section) in 'BASINS.shp', and the 'CTCHMT' file within which they are contained represent the third level of aggregation within the SAWeM framework. Information at this level of aggregation is derived from RSD datasets: DEM's and LULC.

The WQX is calculated at the macroscale by establishing mathematical relationships named 'metrics' which assign a simple numerical value to the relationships between geographical features at the various levels of aggregation. At the fourth and highest level of aggregation is the 'WTSHD.shp' polygon, which delineates the entire South Fork of the New River Watershed.

Vegetational Survey at Tater Hill

According to the floristic index used by Martin (2007) Zone 1 of the Tater Hill site contains the highest Quality value 10 m x 10 m plots (Figure 7) and the highest number of species per plot (Figure 8). Martin (2007) presents a thorough review of the floristics of Tater Hill.

Figure 7. Vegetational quality value of plots at the Tater Hill site according to Martin (2007). A1, B1, and B3 are plots within Zone 1; A2, B2, and C1, C2, and A3 are plots within Zone 2; A2, B2, and C3 are plots within Zone 3.

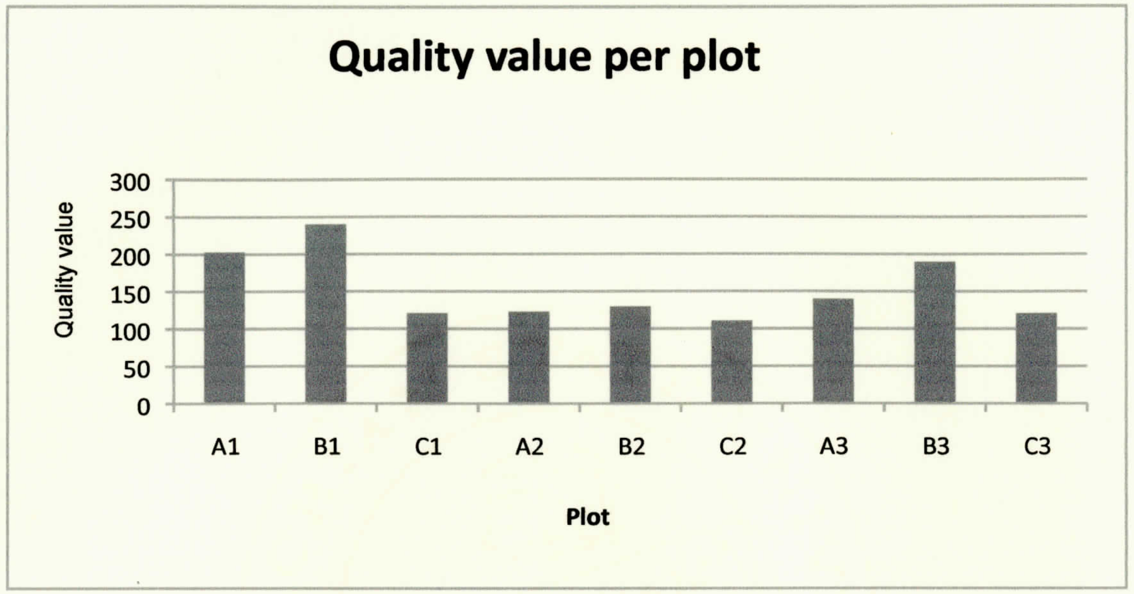
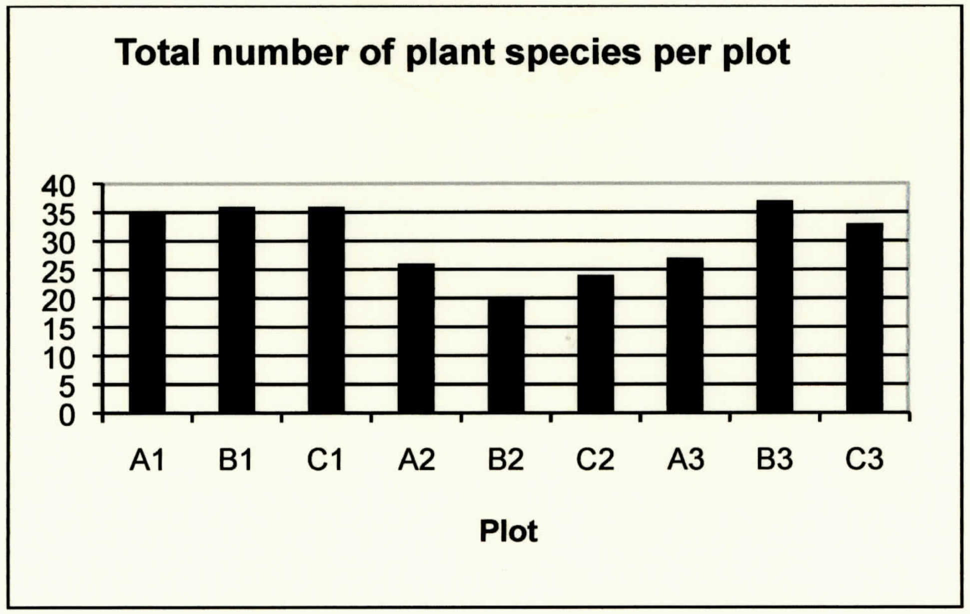
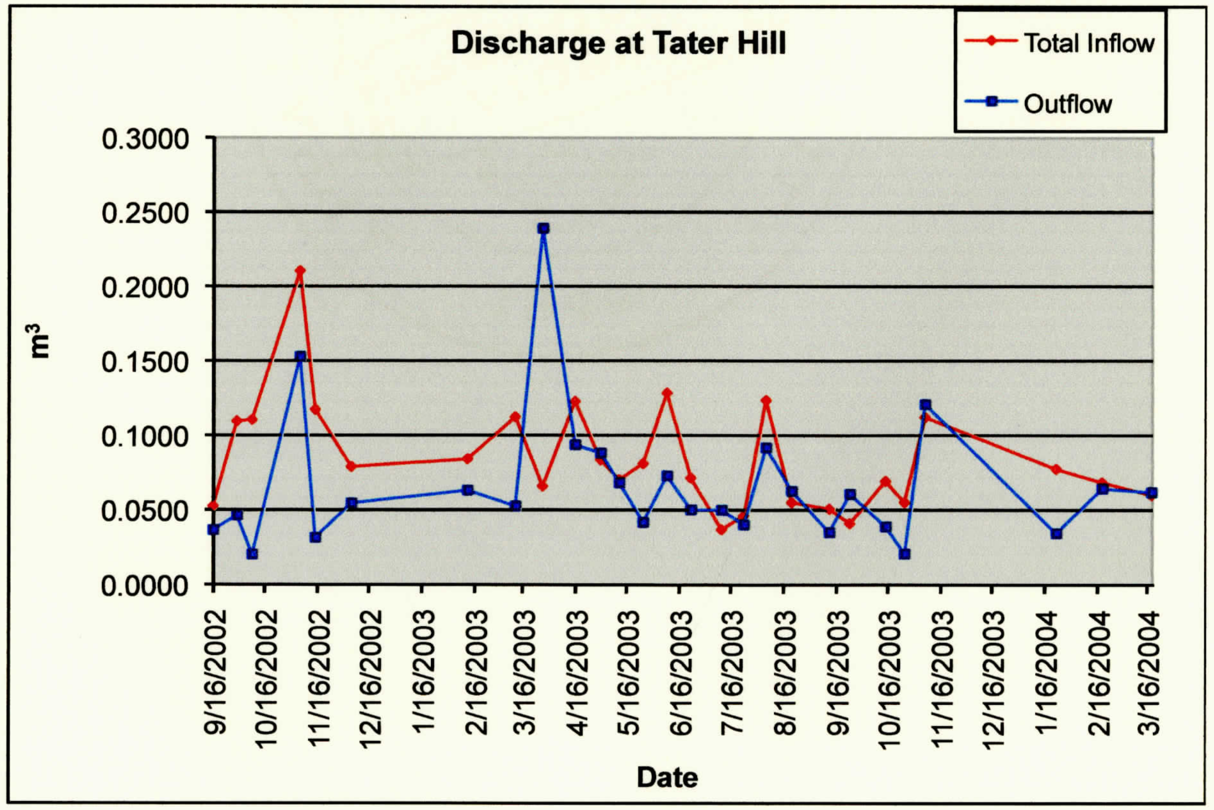


Figure 8. Total number of species per plot at the Tater Hill site according to Martin (2007). A1, B1, and B3 are plots within Zone 1; A2, B2, and C1, C2, and A3 are plots within Zone 2; A2, B2, and C3 are plots within Zone 3.



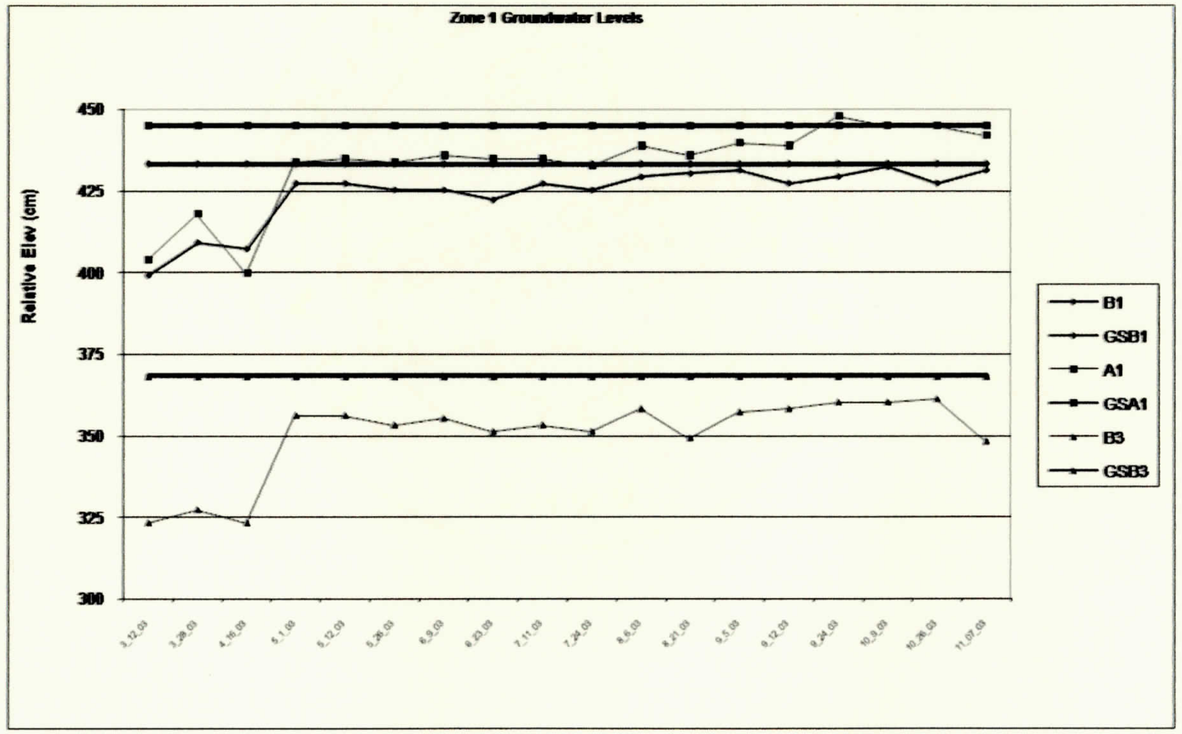
Stream Discharge. The main inflow channel and the channel flowing from the eastern boundary of the property through WS3 had the highest average discharge (Q), averaging Q = 0.44 m^3 and Q=0.33 m^3 respectively. The stream flowing out of Zone 1 and through WS 1 had a consistent, but low flow, averaging 0.06 m^3. The streams at WS2 and WS4 had values that were regularly below measurable flow and occasionally dry, so they are not considered significant sources of inflow. The sum of the inflow at all stations for all measurements was 2.23 m^3. The total outflow for the outflow station for all measurements was 1.74 m^3. The net difference for all measurements taken was 0.49 m^3 greater inflow than outflow (Figure 9).

Figure 9. Discharge at the inflow and outflow stations at Tater Hill site.



Soil Sampling and Groundwater Monitoring. Of the three distinct ecohydrological zones within the Tater Hill study site, Zone 1 is suitable as a model for a functional water storage unit due to its shape, the observation that it remains at saturation throughout the year (as evidenced by its plant cover), and the observation that its outflow is very low for most of the year. This last observation suggests that there should not be any major fluctuations in water discharge that should affect the model (Figure 10).

Figure 10. Ground surface (GS) relative elevation at each well in Zone 1 and associated elevation of the water table.



The core sample from well A1 consisted entirely of peat moss up to refusal at 0.44 m. The core sample from well B1 contained a distinct 'A' horizon 0.60 m thick that consisted of silty-clay-loam down to refusal. The core sample from well B3 contained two distinct soil horizons: an 'A' horizon of silt-loam with a thickness of 0.48 m and a 'B' horizon of clay

with a thickness of 0.47 m (Table 3). The soil type, thickness, and effective porosity of each soil horizon sampled at each well location in Zone 1 are shown in Figure 11.

Figure 11. Thickness and effective porosity of soil samples from the Tater Hill site.

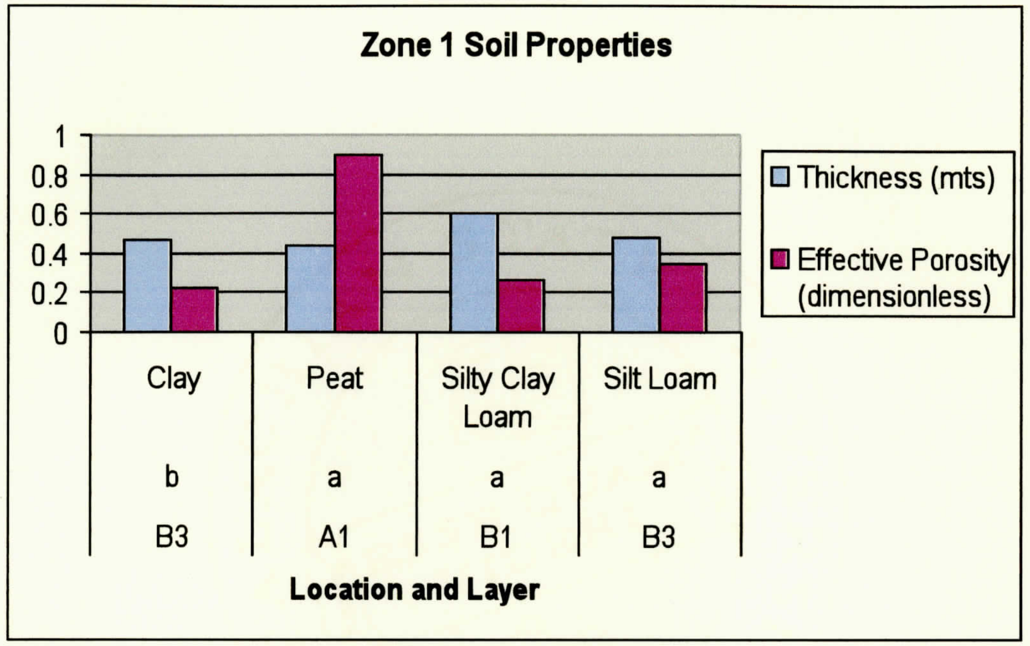


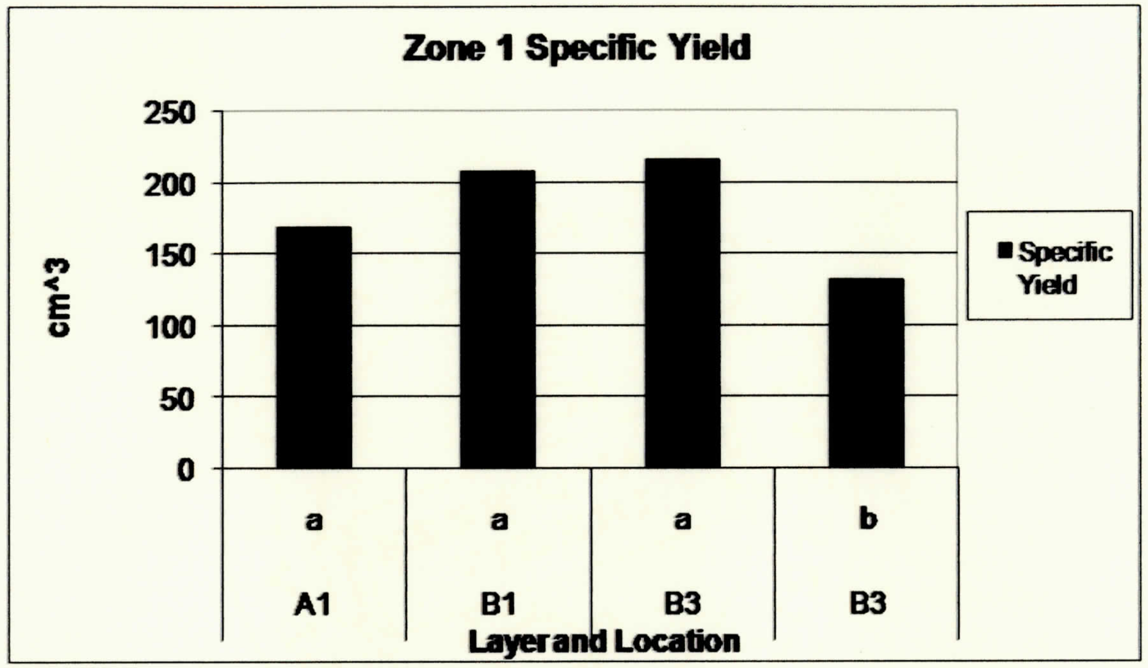
Table 4. Soil properties of the horizons sampled at each well location with associated effective porosity values.

Sample ID	Layer	Class	Thickness (m)	Effective Porosity (dimensionless)
B3	b	Clay	0.47	0.22
A1	a	Peat	0.44	0.9
B1	a	Silty Clay Loam	0.6	0.27
B3	a	Silt Loam	0.48	0.35

Appendix 3 provides the complete results of the soil properties of samples at the Tater Hill site. Layer thickness and effective porosity values were used to estimate the specific yield for each soil layer at all three well locations. Specific yield for the 'A' soil horizon at

A1 was 132 cm^3, 207 cm^3 for the 'A' soil horizon at B1, 215 cm^3 for the 'A' soil horizon at B3, and 132 cm^3 for the 'B' horizon at B3 (Figure12).

Figure 12. Specific yield (measured as the area of Zone 1 multiplied times the effective porosity and the layers thickness).

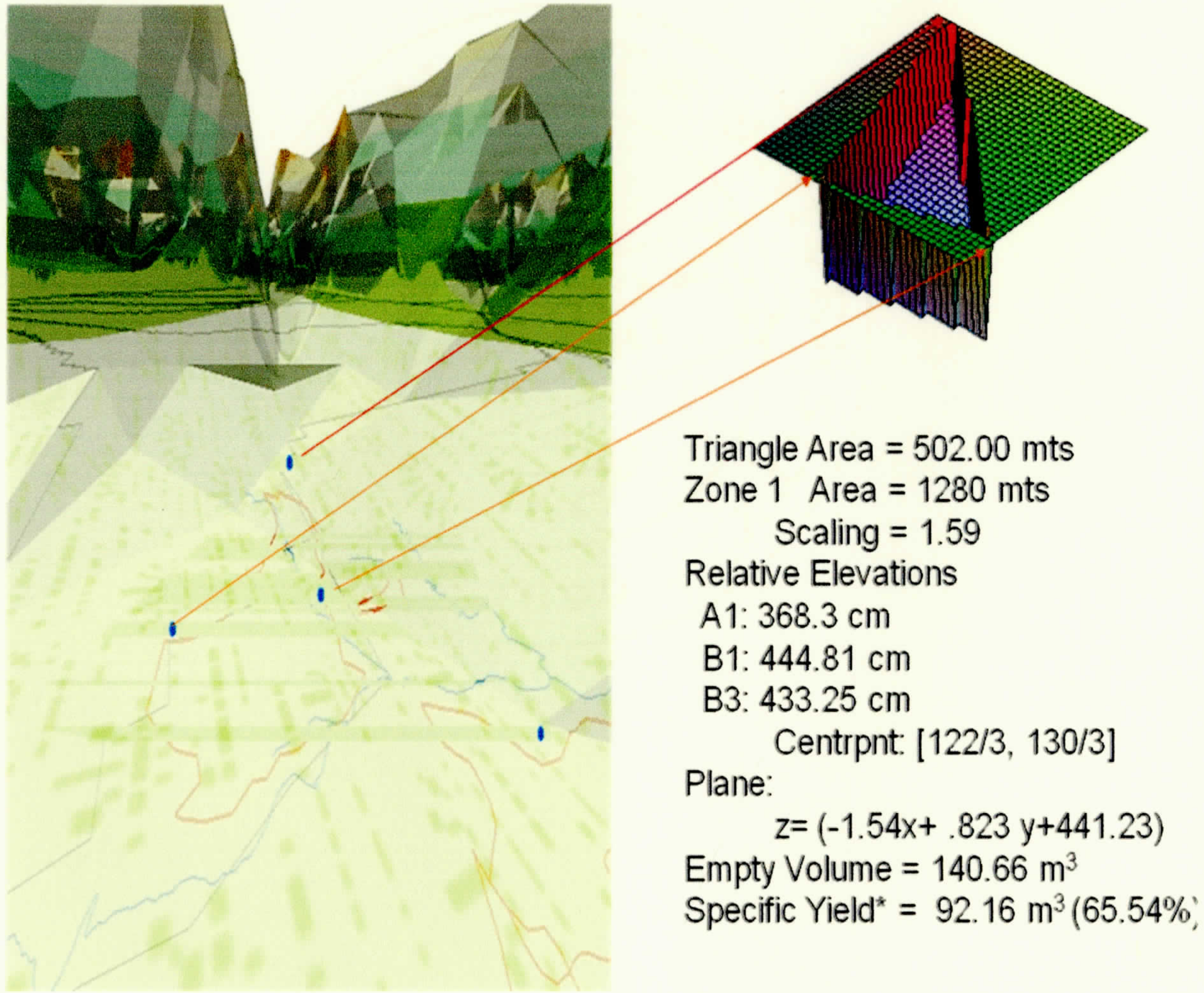


A prototype functional unit at Tater Hill. The empty volume of the model of Zone 1 was calculated as 140.62 m^3 by using the formula

$$SC= SY/EV *100$$

where SC is the estimated storage capacity, SY is the weighted average of each soil horizon's specific yield (SYi) and EV is the empty volume of the three dimensional object representing Zone 1 in SAWeM, an estimated storage capacity for Zone 1 at saturation is 92.16 m^3, or 65.54% (Figure 13).

Figure 13. Zone 1 functional model. The geographic coordinates and well depths are used to generate a model object with the same area as Zone 1, soil texture data are then used to estimate specific yield for the functional unit within the model.



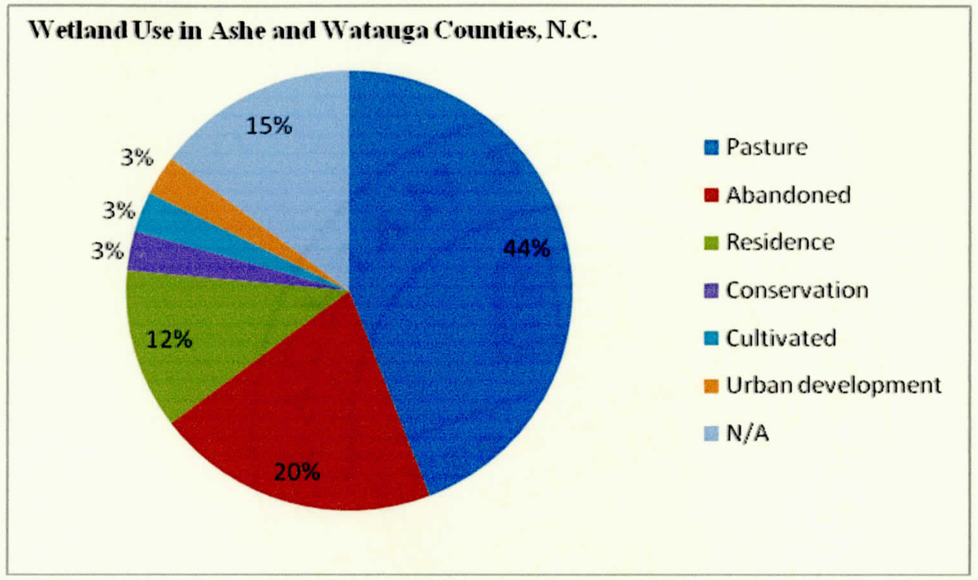
Wetlands Field Search. An initial attempt to locate wetlands in the North Fork of the New River watershed using the NWI as a reference map showed that the NWI dataset is inaccurate for the region. The dataset regularly mislabeled ponds and open bodies of water as wetlands. In addition, known wetlands (i.e. The Tater Hill site) were regularly missed by the NWI (Table 5).

Table 5. Sample dataset of 14 wetlands that were field checked. Only one matched NWI.

Site ID – Quad	Land Cover	Wetland	Match NWI
1- Todd	Managed herbaceous	Riverine	No
2- Todd	Water	Riverine	No
3- Todd	Water	Riverine	No
4- Todd	Mixed hardwoods	Riverine	No
5- Todd	Needleleaf, deciduous	Riverine	No
6- Boone	Needleleaf, deciduous	Riverine	No
7- Boone	Needleleaf, deciduous	Riverine	No
8- Laurel Spr.	Mixed hardwoods	Riverine	No
9 – Jefferson	Managed herbaceous	Riverine	No
10 - Jefferson	Deciduous	Riverine	No
11- Jefferson	Managed herbaceous	Riverine	No
12 – Jefferson	Managed herbaceous	Palustrine	No
13 – Jefferson	Managed herbaceous	N/A	Yes
14 – Jefferson	Managed herbaceous	N/A	No

Of the 34 wetlands in the dataset, 11 were drained. Pastures accounted for 15 of the wetland sites, seven of the sites were abandoned, four of the sites were residential, one site was paved, one site was under cultivation, and one site was under protection. Specific land use was not available for the five remaining sites (Figure 14).

Figure. 14. Percent use of the 34 wetland sites sampled in Ashe and Watauga Counties, NC.



The methodology described for wetland field searches was the result of an effort to create a more adequate wetland inventory for this study. The combination of field searches, collaborative information sharing with the NCNR, and follow up on oral reports, yielded 34 confirmed wetland sites in Ashe and Watauga Counties (Table 6).

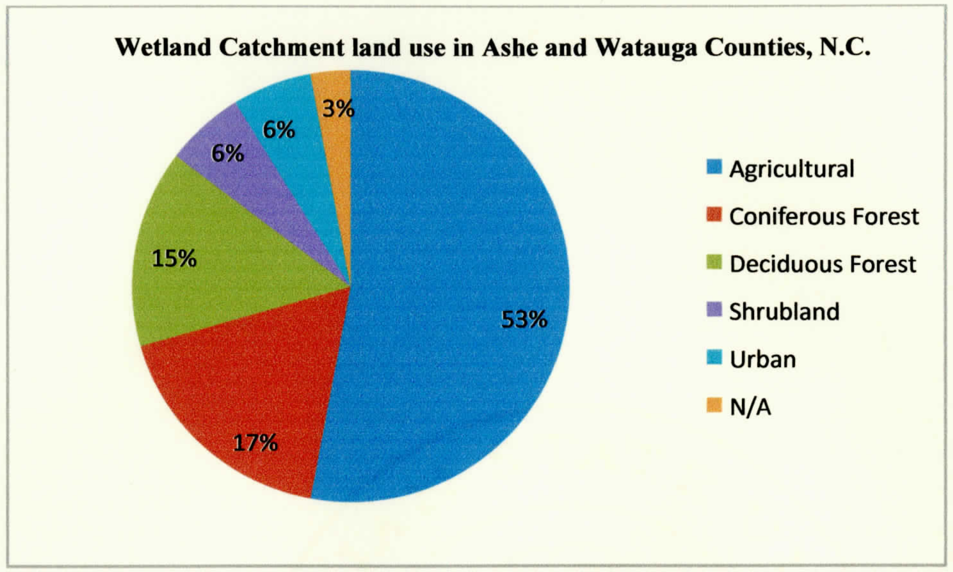
Table 6. Wetland site dataset collected from field searches and NCNR records.

ID	Associated Stream Order	# of known wetlands in WTSH	Proximity to stream (m)	Adjoint Catchment LULC	Bio-Indicator	Wetland use	Drained
1	4	1	70	Conifer	Skunk Cbg.	None	No
2	1	1	n/a	Na	*Juncus sp.*	N/A	na
3	2	4	10	Conifer	*Juncus sp.*	Pasture	na
4	1	2	30	Conifer	*Juncus sp.*	Pasture	Yes
5	1	4	50	Agricultural	*Juncus sp.*	Pasture	No
6	3	5	30	Shrub	*Juncus sp.*	None	No
7	2	1	10	Shrub	*Juncus sp.*	None	No
8	1	3	n/a	Agricultural	*Juncus sp.*	Pasture	No
9	1	3	10	Agricultural	*Juncus sp.*	Pasture	No
10	2	2	30	Agricultural	*Juncus sp.*	Pasture	Yes
11	1	2	30	Conifer	*Juncus sp.*	Pasture	No
12	1	2	70	Conifer	*Juncus sp.*	Pasture	Yes
13	1	2	90	Conifer	*Juncus sp.*	Pasture	Yes
14	1	1	30	Agricultural	*Juncus sp.*	None	No
15	3	1	30	Agricultural	*Juncus sp.*	Resid.	Yes
16	1	1	50	Agricultural	*Juncus sp.*	Pasture	No
17	1	3	n/a	Agricultural	*Juncus sp.*	N/A	n/a
18	1	2	n/a	Agricultural	*Juncus sp.*	Pasture	No
19	1	2	30	Agricultural	*Juncus sp.*	N/A	n/a
20	1	1	50	Agricultural	*Juncus sp.*	N/A	No
21	1	2	50	Agricultural	*Sphagnum spp.*	Cons.	No
22	1	2	10	Deciduous	*Juncus sp.*	None	Yes
23	1	1	10	Agricultural	*Juncus sp.*	Pasture	No
24	1	5	10	Agricultural	*Juncus sp.*	Pasture	No
25	3	5	70	Agricultural	*Juncus sp.*	Res.	Yes
26	2	5	90	Urban	*Juncus sp.*	Cultivated	No
27	3	2	70	Deciduous	*Juncus sp.*	Developed	Yes
28	4	1	70	Deciduous	*Juncus sp.*	N/A	Yes
29	4	1	30	Agricultural	*Juncus sp.*	Pasture	No
30	1	2	50	Deciduous	*Juncus sp.*	Res.	Yes
31	1	2	30	Deciduous	*Juncus sp.*	Res.	Yes
32	1	1	70	Urban	*Juncus sp.*	None	No
33	1	1	n/a	Agricultural	*Juncus sp.*	None	No
34	3	5	n/a	Agricultural	*Symplocarpus foetidus*	Pasture	No

Table 6 (continued). Wetland site dataset collected from field searches and NCNR records.

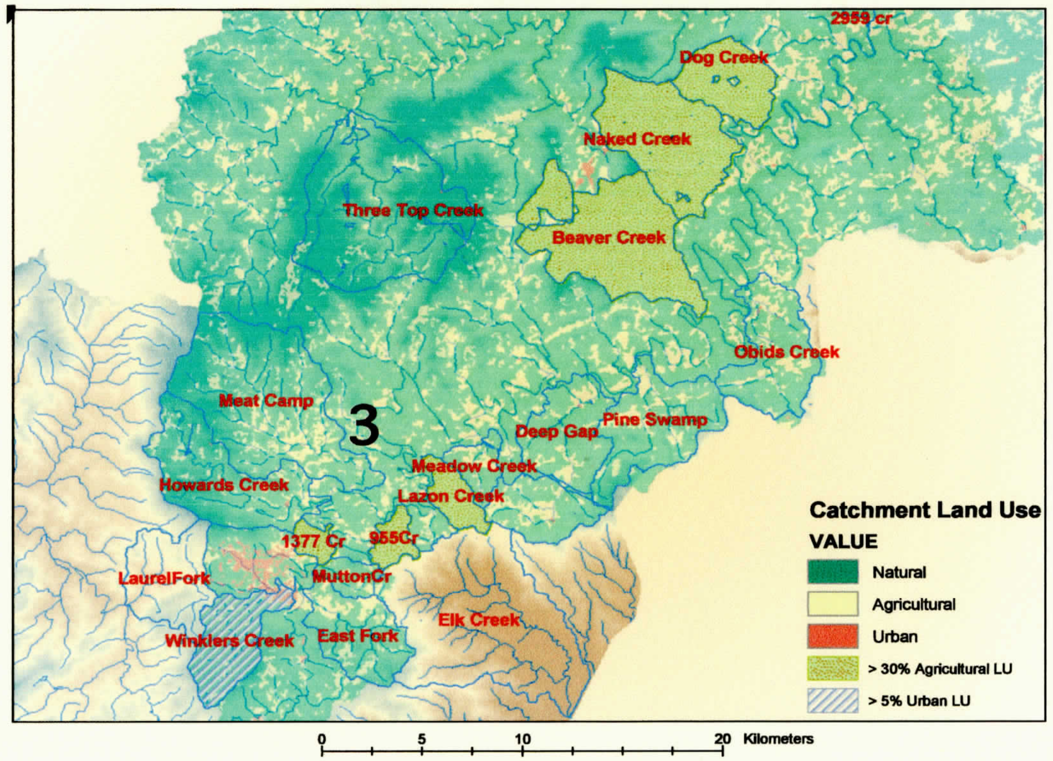
Catchment classification. The land cover of the catchment in which a wetland occurs has an effect on its functionality (Pearson 1994). Wetlands occurred in five adjoint catchment land use classes. Agricultural (mostly Christmas tree farms) catchments contained 18 sites, coniferous forest catchments contained six, deciduous forest catchments contained five, shrubland catchments contained two, urban developed catchments contained two, and data is not available for one location. Figure 15 shows the percentage of land use types for catchments containing wetlands.

Figure 15. Percentage of land use types in catchments surrounding wetlands.



In SAWeM the 16 catchments within the South Fork of the New River are shown in Figure16.

Figure 16. Catchment classification into functional land cover types.



These were re-classified according to their land cover into three major classes: natural (non-agricultural), agricultural, and urban (Table 7).

Table 7. SAWeM catchment classification into functional land cover types. >10% impervious surface = Urban, >30% agricultural cover = Agricultural,<10%, Impervious and <30% Agricultural = Natural.

Watershed Name	Land Cover	Watershed Name	Land Cover
Beaver Creek	Agricultural	Mutton Creek	Natural
Deep Gap Creek	Natural	Naked Creek	Natural
Dog Creek	Agricultural	Obids Creek	Natural
East Fork	Natural	Pine Swamp Creek	Natural
Howard Creek	Natural	Three Top Creek	Natural
Lazon Creek	Agricultural	Winkler Creek	Urban
Meadow Creek	Natural	Creek 1377	Agricultural
Meat Camp Creek	Natural	Creek 955	Agricultural

Water Quality Index

The WQX results for the two prototype catchments, Laurel Fork and Three Top Creek were 'poor' and 'very poor' respectively. Laurel Fork had an F1 of 46.4%, an F2 of 100%, and an F3 value of 2.5 for a WQX score of 24.1 or 'very poor'. Three Top Creek had an F1 of 47.6%, an F2 of 80%, and an F3 value of 2.36 for a WQX score of 35.9 or 'poor' (Table 8). Measurement values can be found in Appendix 4.

Table 8. WQX results for the Laurel Fork and Three Top Creek catchments. DMax is the cumulative WQX point deviation from the seven objectives: 0.1 mg/L Ammonia-Nitrogen, 0.5 mg/L Nitrate, 0.16 mg/L Orthophosphate, 6.0 NTU turbidity, 4.7 mg/L suspended solids, 63.1 (umhos/cm) conductivity, 7.1 ph. AVG#Obj not met is the average number of objectives not met.

SITEID	Laurel Fork	Three Top Creek
Objectives	7	7
DMAX	18.90	29.50
(Scaled)	7.50	7.10
AVG#Obj Not Met	3.25	3.33
Total Samples	5.00	5.00
F1	46.43	47.62
F2	100.00	80.00
F3	2.50	2.37
WQX	24.10	35.91
SCALED	Very Poor	Poor

Wetland Metrics

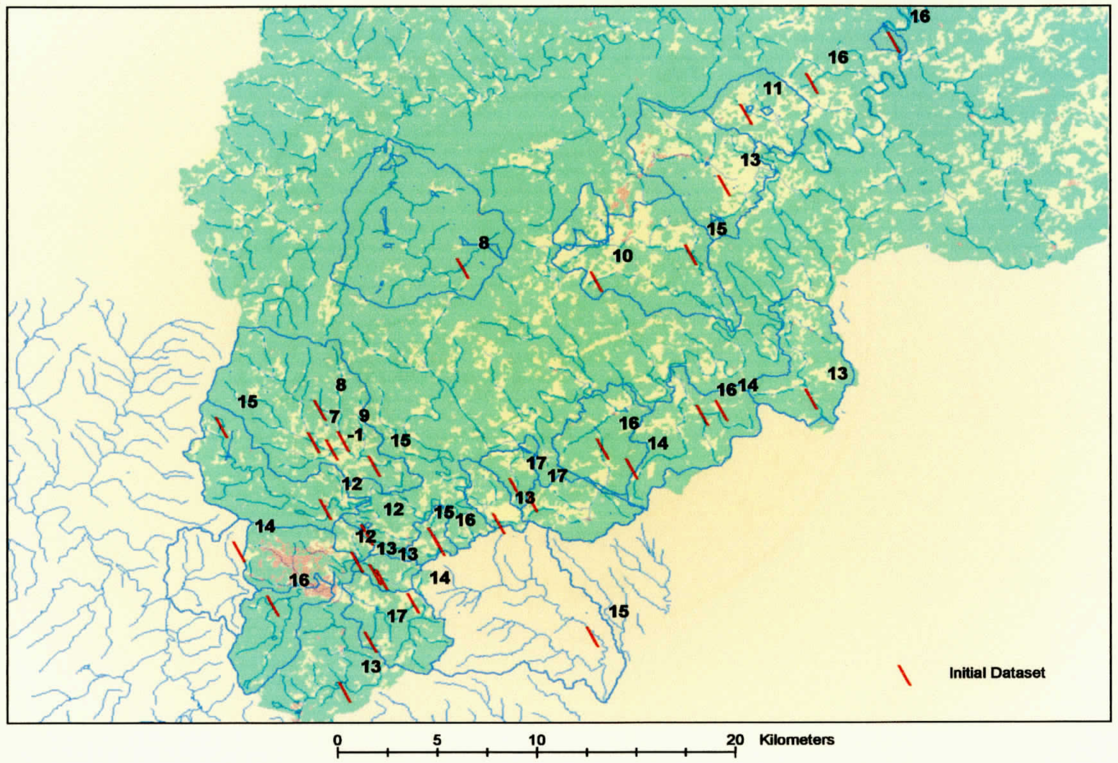
SAWeM metrics. Results for the metrics from both field data and GIS analysis are listed in Table 9.

Table 9. Results from the GIS and Field Metrics for the 34 wetlands sampled.

ID	LuW	Distance	Hy	Field Metric	Area Ratio	Watershed Position	Proximity	Functional Load	GIS Metric	Total Score
1	3	1	2	5	5	2	1	5	13	18
2	0	0		0	5	5	0	5	15	15
3	2	5		10	5	4	5	4	18	28
4	2	3	1	7	5	5	3	4	17	24
5	2	1	2	4	5	5	1	4	15	19
6	3	3	2	11	5	3	3	3	14	25
7	3	5	2	17	5	4	5	5	19	36
8	2	0	2	2	5	5	0	4	14	16
9	2	5	2	12	5	5	5	4	19	31
10	2	3	1	7	5	4	3	4	16	23
11	2	3	2	8	5	5	3	4	17	25
12	2	1	1	3	5	5	1	4	15	18
13	2	1	1	3	5	5	1	4	15	18
14	3	3	2	11	5	5	3	5	18	29
15	0	3	1	1	5	3	3	5	16	17
16	2	1	2	4	5	5	1	5	16	20
17	1	0		0	5	5	0	4	14	14
18	2	0	2	2	5	5	0	5	15	17
19	3	2		6	5	5	2	5	17	23
20	1	1	2	3	5	5	1	5	16	19
21	4	5	2	11	5	1	4	5	15	26
22	3	5	1	16	5	5	5	5	20	36
23	2	5	2	12	5	5	5	5	20	32
24	2	5	2	12	5	5	5	3	18	30
25	0	1	1	1	5	3	1	3	12	13
26	1	0	2	2	5	4	0	3	12	14
27	0	1	1	1	5	3	1	5	14	15
28	3	1	1	4	5	2	1	5	13	17
29	2	3	2	8	5	2	3	5	15	23
30	0	1	1	1	5	5	1	4	15	16
31	0	3	1	1	5	5	3	4	17	18
32	3	1	2	5	5	5	1	5	16	21
33	3	0	2	2	5	5	0	5	15	17
34	2	0	2	2	5	3	0	3	11	13

The total score adds both the Field and GIS metrics into a single value. The total score is a value that reflects an assessment of the wetland based on all available information. The Tater Hill site (ID 21) had a Field Metrics score of 11, a GIS Metrics score of 15 for a total score of 26. SAWeM assigned the site a low score on its Watershed position value (1). Figure 17 shows the distribution of GIS metric scores at the 34 wetland sites.

Figure 17. GIS score for each of the 34 wetlands sampled in SAWeM.



DISCUSSION

The term *wetlands of ecological significance* is very broad and its application to policy and management decisions requires a multidisciplinary approach that combines as much of the available information on affected wetlands as possible, but is also time efficient and practical. The SAWeM model, as developed in this study, can be used as the first step toward the development of an assessment tool that can integrate multiple datasets of various scales and obtained from unrelated sources, into a single operational environment with an easy to understand output, such as maps. The objective of this study, to use GIS as a platform for the integration for multiple sources of data, is met in SAWeM. The model uses remote sensing data and field data from multiple sources at multiple scales and can be used to store, analyze, and display information related to the functional assessment of southern Appalachian wetlands.

The application of the model has limitations and interpretation of its output should take place with these in mind. Models, by definition, are representations of reality (Tiner 2003) and determining which components of a 'real' object are represented in a model is a qualitative judgment. Within SAWeM, and especially at the third and fourth levels of aggregation, information derived from low resolution datasets, such as soil and LULC, should be considered appropriate for watershed- scale assessments, but not for point-scale assessments. On the other hand, the ability to access point scale information from the same platform and relate it to a single assessment tool is very powerful and, as shown in this study, its applications at the basin and watershed levels can be much improved if more detailed studies on individual wetland sites are added. Detailed studies on individual sites should incorporate biological, ecological, and hydrological components. It is well documented that wetland ecosystems, especially small ones like those found in the Appalachian Mountains, are interconnected with both surface and groundwater flow and are dependent on the condition of the ecosystem in which they are embedded (Pearson 1994, Whigman 1999).

As the groundwater variations and stream discharge values at the Tater Hill site show, detailed wetland studies, and especially those conducted for mitigation purposes, should identify whether the site is a homogenous unit or whether there exist multiple functional units within the same site. At the Tater Hill site, Zones 1, 2, and 3 show different groundwater table and surface flow values while discharging into the same outflow stream. For example, if ASU planned to build a permanent structure within the site, it would be better to do so in Zone 2 instead of the more functionally and biologically valuable Zone 1. It is not surprising that Zone 1 is not only a functional unit of importance, due to the fact that it contains an estimated 65% of storage capacity (Figure 13), but also the most biologically valuable zone within the site (Figures 7 and 8) (Martin 2007). Small, saturated wetland areas will implicitly host more obligate wetland species per square meter than larger areas with mixed soils that may host facultative species as well (Pearson 1994). The importance of reliable data on wetland soil properties cannot be overemphasized. Mesoscale datasets do not have the resolution for appropriate assessment of soil types at the individual wetland scale. Soil type and texture affect wetland functions such as water storage capacity and surface flow (Fernandez-Illescas et al. 2001) as well as plant communities. Reference data at this scale on wetland field functions that contains reasonable information on the multiple variables affecting a particular function is then useful to target other sites from a larger- scale dataset for further study prior to making management decisions at both the point and local scales that

may affect such sites. Such targeting could be used to identify high, medium, and low priority management sites or basins.

A better understanding of wetland function indicators, such as groundwater levels and net outflow, can help stakeholders propose and validate other (perhaps simpler) indicators such as the presence of *Sphagnum* sp. or *Symplocarpus foetidus.* While *Juncus* sp. was found in both drained and undrained wetlands, *Sphagnum* and *Symplocarpus* were only found on wetlands that had not been drained (Table 6). The SAWeM model of Zone 1 shows that it is possible to integrate these point scale indicators as part of a larger dataset and create both mathematical and visual representations.

Larger wetland datasets are much needed for the southern Appalachian region. As shown in Table 5, there is little doubt that the NWI and drained NWI datasets contain too many site errors to be reliable sources of information for a GIS model. The 34 sites used in SAWeM are not meant to represent the range of site quality, potential functionality, or types of wetlands within the South Fork of the New River. They are, however, sites distributed throughout the watershed where confirmed wetlands exist (or existed) that fill the criteria for evaluation through field or GIS metrics, or both.

As mentioned in the introduction, the value of wetlands for water storage and quality improvements is well documented and recognized by scientists and legislatures. Pastures accounted for most wetland site land use (44%) and 53% of wetland catchments land use was agricultural, underlining both the importance and the potential of these small ecosystems in the region. Agriculture depends on water availability for irrigation of crops, but it is also a source of non-point pollution. Wetlands in agricultural catchments can be of great importance in reducing nutrient loads resulting from the activities of surrounding land use

(Cedfeldt et al. 2000). At the same time, wetlands that are not managed or are managed for pasture have a greater potential for successful restoration efforts than wetlands that have been paved to create parking lots. SAWeM metrics that address the relationship between individual wetlands and their catchments in combination with the WQX for those catchments can be used as an aid in prioritizing the allocation of restoration resources.

GIS metrics within SAWeM that address wetland-landscape relationships are wetland area to catchment area ratio, watershed position, proximity to stream, and functional load. These provide valuable information that does not require extensive field-work. The wetland area to catchment area ratio gives an indication of the individual value of a single wetland within the catchment, or its ‘functional uniqueness’. A wetland with a low ratio is more likely to be ‘functioning’ at capacity than a wetland with a high ratio. The position of a wetland within a watershed metric evaluates the potential for any given site to perform wetland functions for the entire catchment. The Tater Hill site, for example, scores low (1) on this metric because it is located at the headwaters of Howard Creek. A wetland located next to a first order stream is not as likely to be inundated with pollutants as a wetland on a third or fourth order stream. A wetland adjacent to a fourth order stream may also be more valuable in dispersing discharge surges after extreme rain events than one adjacent to a first order stream where discharge has not accumulated momentum. The proximity to stream metric accounts for the value of the wetland in connection to the surface water system. While the interconnectedness of the groundwater system should not be ignored, it is impossible to assess its functional importance from RSD. The functional load metric seeks to account for the relative value of any given wetland based on the number of wetlands present in the watershed. The value of any given wetland within a watershed decreases with the number of other wetlands in the same watershed that may also perform the same functions.

It is thus important that SAWeM metrics be interpreted within the context of the decision for which the information is to be used. A site in question may have a low functional load score because there is another wetland in the catchment, but it may be adjacent to a higher order stream and have a high watershed position score. A high watershed position score may be more important for catchments classified as agricultural where water quality improvement is a priority, but it may not be as important for a catchment classified as natural. Metrics derived from rapid field visits can further refine understanding of the value of a given site, in addition to validating (or not) the reliability of the RSD used to generate the GIS score. For example, it is not difficult to determine whether a wetland has been drained or not, but a drained wetland will be harder to restore and is likely not performing the same functions as one that has not been drained. Likewise, a decision maker looking for likely wetland restoration sites in an effort to improve the overall quality of water within a catchment may prioritize a site based on its location within the watershed, but realize that the site has been drained and restoration would not be cost effective.

The WQX is a large-scale approach to quantifying the overall health of a basin. By combining information on multiple water quality objectives (that can be determined by the stakeholders) into a single, easy to understand value, the WQX provides a useful screening tool at the mesoscale level for identifying management priorities as they relate to water resources. This has the added benefit of being useful also at the level of local government decision-making. The WQX provides a value that reflects specific objectives for the general condition of the watershed. This value is derived from data that can be collected by community initiatives at relatively low cost, such as basic water sampling for key indicators at selected locations within the watershed. The sampling sites can be identified using similar GIS criteria as those used for the development of metrics. Results from a WQX can then be used to develop a wetland management plan aimed at meeting objectives such as conservation and/or restoration. Water quality is also a flagship concept for landscape-level management and policy. Thus, an ecohydrological approach to water resource management will also encompass wetland ecosystem conservation/restoration efforts.

All datasets within SAWeM can be updated and/or replaced and new datasets (such as vegetation) can be added at any level of aggregation without affecting the integrity of the model's framework. WQX objectives and catchment classifications can be modified based on the needs of the stakeholders. It is this ability to provide stakeholders, particularly decision makers, with a tool to store, manage, analyze, and display the vast amount of information at multiple scales that effects the complex interactions of wetland functionality in a time efficient manner that makes SDSS such as SAWeM a practical tool (Crossland et a. 1995).

Further research at the point-scale, however, is necessary if models that can be applied to multiple sites are to be developed. Specific research projects for each wetland function are needed. Depth-area-volume relationship studies could eventually provide models applicable to multiple wetlands for the water- storage function. More advanced models should look at the effect of vegetation cover classes on stream discharge and soil storage.

At the macroscale, better RSD sources for vegetation and soil type would greatly increase the capacity of the model to evaluate the function of individual wetlands and reduce the time required in the field to obtain such data. The GIS datasets used in the SAWeM do not have the data resolution for application at the microscale.

It is the author's opinion that wetland mitigation policy will always trail scientific knowledge on the geomorphology, hydrology, and landscape relationships important to wetland functions. These components and relationships are too complex to be written into legislation and accepted as guidelines for policy in a timely manner. It is thus necessary to further develop SDSS's that can be used as tools that can help enforce existing policies more effectively and thoroughly. SAWeM provides a glimpse of the potential for information management that arises from combining field data with RSD and GIS technology.

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APPENDICES

Appendix A

Maple program used to generate empty volume of Tater Hill Zone 1

```
> restart;
> with(linalg);
# x-values add 435700, y-values add 4015400
> x1:=[26,38]:x2:=[32,63]:x3:=[64,29]:
#
> plot([x1,x2,x3,(x1+x2+x3)/3],style=point);
Warning, unable to evaluate the functions to numeric values in the
region; see the plotting command's help page to ensure the calling
sequence is correct
> v1:=x1-x2; v2:=x1-x3;

                         v1 := [-6, -25]
                          v2 := [-38, 9]
> d1:=sqrt(v1[1]^2+v1[2]^2);d2:=sqrt(v2[1]^2+v2[2]^2);
                                  1/2
                          d1 := 661
                                  1/2
                          d2 := 5 61
> theta:=evalf(arccos((v1[1]*v2[1]+v1[2]*v2[2])/(d1*d2)));
                       theta := 1.567808288
> Area:=evalf(1/2*d1*d2*sin(theta));
                       Area := 502.0000001
> Areadesired:=1280
                       Areadesired := 1280
> scaling:=sqrt(Areadesired/Area);
                      scaling := 1.596809568
> centerpt:=(x1+x2+x3)/3;
                    centerpt := [122/3, 130/3]
> p1:= x1-scaling*(centerpt-x1);
#
                p1 := [2.58012634, 29.48368230]
> p2:= x2-scaling*(centerpt-x2);
                p2 := [18.16098374, 94.40392150]
> p3:= x3-scaling*(centerpt-x3);
                p3 := [101.2588899, 6.11239619]
> plot([p1,p2,p3,x1,x2,x3]);
> plane:=z=a*x+b*y+c;
                    plane := z = a x + b y + c
> depth1:=433.25:depth2:=444.81:depth3:=368.3:
```

```
> e1:=subs({x=x1[1],y=x1[2],z=depth1},plane);
               e1 := 433.25 = 26 a + 38 b + c
> e2:=subs({x=x2[1],y=x2[2],z=depth2},plane);
               e2 := 444.81 = 32 a + 63 b + c
> e3:=subs({x=x3[1],y=x3[2],z=depth3},plane);
               e3 := 368.3 = 64 a + 29 b + c
> solve({e1,e2,e3},{a,b,c});
         {c = 441.2293028, b = 0.8256772908, a = -1.513655378}
> assign(%);
> plane;
          z = -1.513655378 x + 0.8256772908 y + 441.2293028
> subs({x=x3[1],y=x3[2]},plane);
                        z = 368.3000000
> line1:=(p2[2]-p1[2])/(p2[1]-p1[1])*(x-p1[1])+p1[2];
              line1 := 4.166666669 x + 18.73315588
> line2:=(p3[2]-p2[2])/(p3[1]-p2[1])*(x-p2[1])+p2[2];
             line2 := -1.062500000 x + 113.6999667
> line3:=(p1[2]-p3[2])/(p1[1]-p3[1])*(x-p3[1])+p3[2];
             line3 := -0.2368421053 x + 30.09476485
> plot({line1,line2,line3},x=0..100,y=0..100);
> surf:=rhs(plane)*Heaviside(-y+line1)*Heaviside(line2-y)*Heaviside(-lin
> e3+y);
  surf := (-1.513655378 x + 0.8256772908 y + 441.2293028)
      Heaviside(-y + 4.166666669 x + 18.73315588)
      Heaviside(-1.062500000 x + 113.6999667 - y)
      Heaviside(0.2368421053 x - 30.09476485 + y)
> plot3d(surf,x=0..100,y=0..100,numpoints=1000);
> int(int(surf,x=0..100),y=0..100);
     100   100
     /     /
    |     |
    |     |    (-1.513655378 x + 0.8256772908 y + 441.2293028)
    |     |
   /     /
    0     0
      Heaviside(-y + 4.166666669 x + 18.73315588)
      Heaviside(-1.062500000 x + 113.6999667 - y)
      Heaviside(0.2368421053 x - 30.09476485 + y) dx dy
> evalf(%);
                                  7
                     0.1406198471 10
```

Appendix B

Southern Appalachian Wetlands Project

Data Entry Form

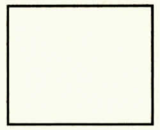
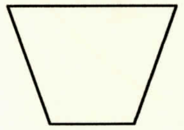
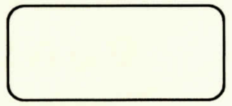
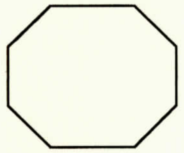
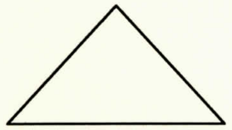
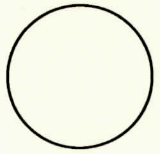
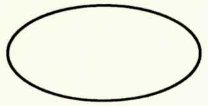
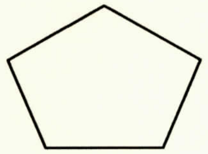
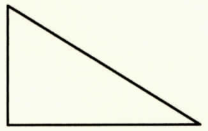
The characteristics of a wetland and the landscape surrounding it help us determine their relative importance and function within the landscape. It is important that you observe carefully before making any entries. Please take a few minutes to really look at the site and its surroundings before you make any entries.

1) **Write down the coordinates that appear on the G.P.S. unit.** _______________

____

(Please be very careful, a single misplaced digit changes the location completely)

2) **Which of these shapes most closely resembles the site (circle one)**

Use the meter tape to measure (the best you can) the sides of the appropriate shape and write them down on the sides.

3) How far is the wetland from the water channel? 0-30m 30-60m 60-90m >90

4) Read through the NCGIA's Land Cover Land Use description. Which of these classes best describes the area surrounding the site if there are two list both.

(Please take the time to read this classification system and look at the landscape since this data is crucial for verifying these classifications in the area.)

Class 1______ Percent Cover _____ Class 2________ Percent Cover__________

5) Are there any boulders within the site? How big? How many?

Large (the size of a car) __, medium (size of a trash can) ____,

small (size of a basketball) ____.

6) How wide is the main channel? 0-1 mtr 1-3 mts 3>9 mts >10 mts

7) How far below the wetland surface is the water running?

8) Is the ground wet? How wet?

Water pools Very wet Wet Somewhat wet Moist Dry

(If you see standing water please estimate the percentage of the site it covers).

9) Please estimate the percent herbaceous, shrubby, and tree cover within the site.

Herbaceous_____Shrubby______ Tree Cover________

10) Write down any other species in the site that you recognize.

11) Please write a short description you believe will help me get a better idea of what this site is like. Is it a cow pasture, an agricultural field, are there signs of recent disturbance

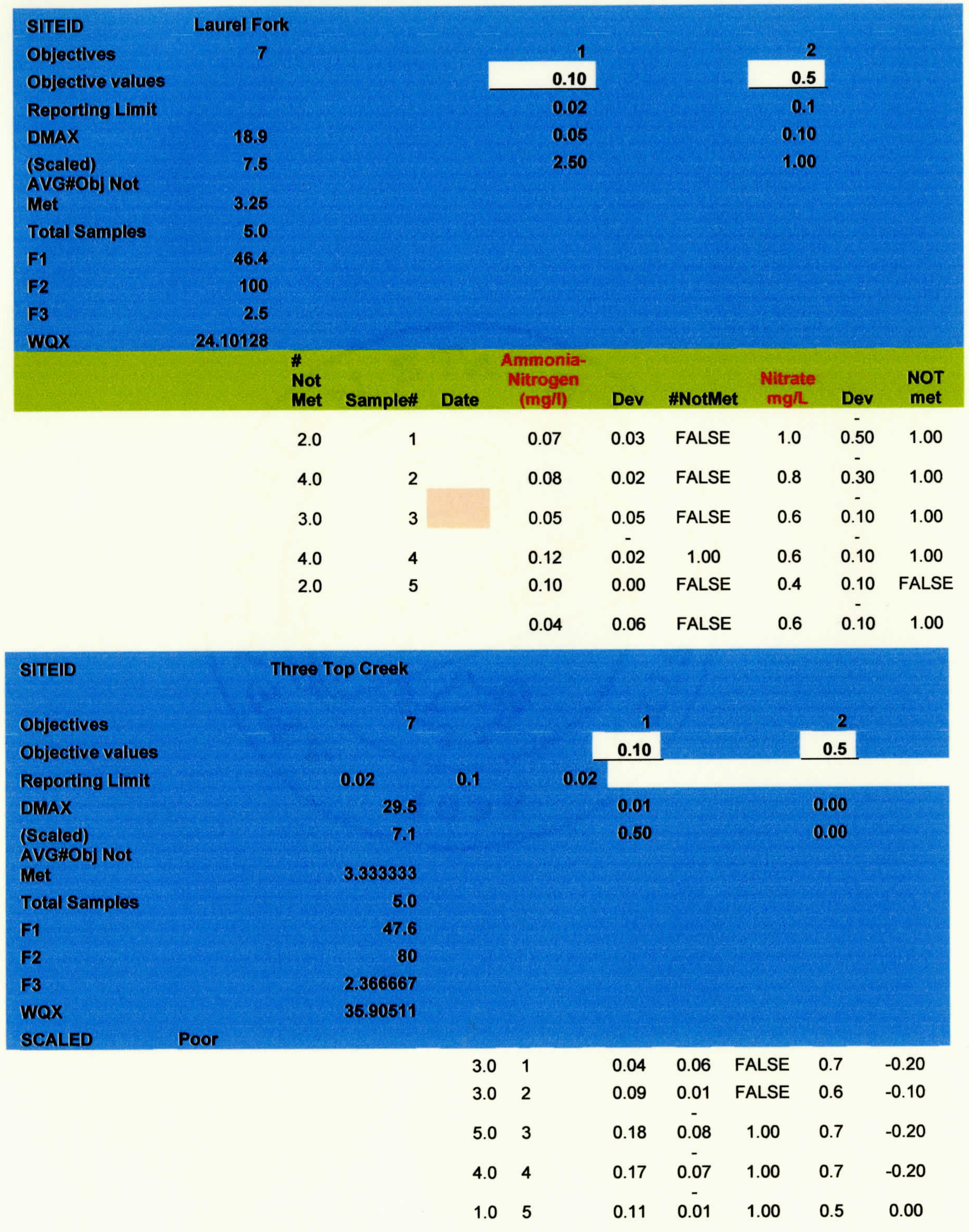
---

Appendix C

Soil Properties of Tater Hill Core Samples

Sample ID	Layer	SandWt	Class	K (cm/s)	Thickness	Effective Porosity	Intrinsic Permeability	Specific Yield (cm^3)
B3	b	27.83	Clay	10^-6	0.47	0.22	12	132.352
A1	a	1.73	Sand (peat moss)	10^-3	0.44	0.9	n/a	168.96
B1	a	9.04	Silty Clay Loam	10^-5	0.6	0.27	10	207.36
B3	a	0.84	Silt Loam	10^-4	0.48	0.35	5.5	215.04
Z1								
A2	a	1.17	Silty Clay Loam	10^-4	0.3	0.27	10	
A3	b	4.21	Clay Loam	10^-4	0.68	0.3	7.5	
A3	a	5.47	Silty Clay Loam	10^-5	0.68	0.27	10	
A3	c	14.4	Clay	10^-6	n/a	0.22	12	
B2	a	9.81	Silty Clay Loam	10^-5	0.53	0.27	10	
B2	b	16.66	Clay Loam	10^-5	0.8	0.3	7.5	
C1	b	10.01	Silty Clay Loam	10^-4	0.21	0.27	5.5	
C1	a	13	Clay	10^-6	0.54	0.22	12	
C2	b	8.92	Clay	10^-6	0.12	0.22	12	
C2	a	7.15	Silty Clay Loam	10^-5	0.34	0.27	10	
C2	c	28.7	Clay	10^-6	n/a	0.22	12	
C3	a	6.1	Silt Loam	10^-4	0.15	0.35	5.5	
C3	b	10.5	Clay Loam	10^-5	0.4	0.3	7.5	

Appendix D: WQX matrix for Three Top and Laurel Creek



SITEID	Laurel Fork									
Objectives	7				1			2		
Objective values					0.10			0.5		
Reporting Limit					0.02			0.1		
DMAX	18.9				0.05			0.10		
(Scaled)	7.5				2.50			1.00		
AVG#Obj Not Met	3.25									
Total Samples	5.0									
F1	46.4									
F2	100									
F3	2.5									
WQX	24.10128									
		# Not Met	Sample#	Date	Ammonia-Nitrogen (mg/l)	Dev	#NotMet	Nitrate mg/L	Dev	NOT met
		2.0	1		0.07	0.03	FALSE	1.0	-0.50	1.00
		4.0	2		0.08	0.02	FALSE	0.8	-0.30	1.00
		3.0	3		0.05	0.05	FALSE	0.6	-0.10	1.00
		4.0	4		0.12	-0.02	1.00	0.6	-0.10	1.00
		2.0	5		0.10	0.00	FALSE	0.4	0.10	FALSE
					0.04	0.06	FALSE	0.6	-0.10	1.00

SITEID	Three Top Creek										
Objectives		7					1			2	
Objective values							0.10			0.5	
Reporting Limit		0.02	0.1			0.02					
DMAX		29.5					0.01			0.00	
(Scaled)		7.1					0.50			0.00	
AVG#Obj Not Met		3.333333									
Total Samples		5.0									
F1		47.6									
F2		80									
F3		2.366667									
WQX		35.90511									
SCALED	Poor										
				3.0	1		0.04	0.06	FALSE	0.7	-0.20
				3.0	2		0.09	0.01	FALSE	0.6	-0.10
				5.0	3		0.18	-0.08	1.00	0.7	-0.20
				4.0	4		0.17	-0.07	1.00	0.7	-0.20
				1.0	5		0.11	-0.01	1.00	0.5	0.00

VITA

Mario Eduardo Molina was born in Guatemala City, Guatemala, on February 24th, 1976. He attended the Guatemalan Austrian Institute in Guatemala City from Kindergarten through graduation from high school. From August 1994 to December 1998 he attended the University of the Ozarks in Clarksville, AR on a Walton International Scholarship. He graduated cum laude with a Bachelor of Arts in Biology. In the Fall of 1998 he attended Colorado Outward Bound Fall Leadership Semester. In the Fall of 2000, he accepted a teaching assistantship in the Biology Department at Appalachian State University. After five years working for an international non-profit organization, Mr. Molina returned to Appalachian where he graduated with a Master of Science degree in December 2008.

Mr. Molina is the Ecuador Country Director for a non-profit organization in Quito, Ecuador. His home address is Edificio Leo, Apto. 2A, Calle La Cumbre 201, Quito, Ecuador. His parents are Jorge Mario Molina and Maria Elena Pearse.