Opportunities for forest hydrology applications to ecosystem management

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Abstract

Emerging environmental issues offer new opportunities for linking forest hydrology research to other sciences and applying principles to meet management needs. We discuss two such topical areas where hydrologic understanding is essential for addressing issues. In the first one, a lumped parameter model (PnetII-S) is used and validated for forest hydrology and productivity predictions for loblolly pine (Pinus taeda) at forest stand and regional scales. Utility of the model is then illustrated by applying the model to a potential global warming scenario predicted by a general circulation model and examination of the consequences for changes in regional evapotranspiration. Ecosystem management (EM), currently the operating philosophy of the USDA Forest Service, is the second topical area. We describe our approach to research and management planning and implementation of EM for Wine Spring Creek, a basin in the Southern Appalachian Mountains. The importance of applying forest hydrologic process information to obtain desired future conditions for resources is illustrated through a modeling approach for estimating soil erosion and stream sediment loading.

Introduction

Principles and an understanding of processes derived from forest hydrology research have traditionally provided the foundation for watershed management. Indeed, the influence of forests on storm runoff and concern about erosion frequently provided the stimulus to develop forest hydrology research programs in many countries (Swank and Johnson 1994). Small experimental watersheds have been particularly effective in predicting and interpreting the effects of management practices on the quantity, quality, and timing of streamflow from forested catchments. More recently, the utility of catchments as a basic unit for examining broader forest ecosystem concerns has emerged. The application of hydrology in an ecosystem context is natural since water is the primary mechanism for transporting materials within and from forested landscapes.

The literature is replete with traditional perspectives of forest management effects on hydrologic processes for many regions of the world; for example, in the eastern U.S. (Swank & Crossley 1988; Swank & Johnson 1994; Likens et al. 1977; Hornbeck & Swank 1992). Thus, our objective in this paper is to illustrate the role of hydrology in a broader forest environment perspective through specific examples of applications to ecosystem management and climate change analyses. The analyses are specific for forests in the southern United States, but the principles apply to most forest ecosystems.
The Regional Setting

The topics and findings discussed in this paper are primarily derived from the research program at the Coweeta Hydrologic Laboratory. The 2185-ha laboratory is a research facility of the USDA Forest Service that is located in the Southern Appalachian Mountains of western North Carolina (Figure 1). Established in 1934, the long-term research effort at Coweeta has focused on forest hydrology which has also served as a template for interdisciplinary ecosystem research (Swank and Crossley, 1988). The research approach melds theory development, experimental testing, modeling, and application of findings to resource management. Studies are conducted at the landscape-scale using the watershed as the unit of both hydrologic and ecosystem investigation.

Topography in the region is steep with side slopes that average about 50%; first-order watersheds typically have about 400m of relief. Bedrock in the area is comprised of gneiss, metasandstone, and schist; overlying soils are classified into two orders of immature Inceptisols and older developed Ultisols (Swank and Crossley, 1988). The regolith averages about 7 m in depth. The vegetation is classified as mixed oak-hickory forest with numerous associated species. Climate of the region is Marine, Humid Temperature because of high precipitation and mild temperatures (Swift et al., 1988). Annual average precipitation at Coweeta ranges from 180 cm at low elevations to 250 cm on the upper slopes and mean monthly temperatures vary from 3.6°C in January to 20.2°C in July. Snow typically comprises less than 5% of the precipitation. Long-term analyses of hydrologic response for first through third order streams at Coweeta show that less than 10% of the annual runoff on low elevation watersheds occurs as quickflow while on high elevation watersheds, the proportion of quickflow increases to 30%.

Climate Change and Forest Hydrology

A primary objective of the International Geosphere-Biosphere Programme (IGBP) is to understand the coupling of physical climate systems and biological systems at regional to global scales (Mooney and Koch 1994). Climate change and alteration of hydrologic fluxes are closely linked, and it is critical that we understand and predict cause and effect in order to evaluate impacts on water supplies, vegetation productivity and distribution, water quality, and biogeochemical cycles (Walker 1994).

The implications of climate change from a forest hydrology perspective are especially important in the southern United States. Forests occupy about 55% of the southern U.S. and over 40% of the softwood timber harvested annually in the U.S. comes from southern pine in the region. The region is also one of the most rapidly growing areas in the U.S. Thus,
climate change effects on tree growth and water supplies for humans are of paramount interest in the south. In response to a need for evaluating the magnitude and threat of global change to southern forests, the USDA Forest Service chartered a research initiative in 1990 called the Southern Global Change Program (Southeastern Forest Experiment Station). A major research project in this program is being conducted by Coweeta scientists that links climate, hydrology, and tree growth at stand, ecosystem, and regional scales for southern pine species. Models at different temporal and spatial scales of resolution are being validated using historic climatic, hydrologic, and tree growth data from across the region. Following validation, the models are then used to assess the influence of potential climate changes, as predicted by general circulation models (GCM's), on forest hydrology and productivity.

At the ecosystem and regional scales, an ecosystem model called PnET-IIS is used for hydrology and productivity predictions. This physiologically based model is a revision (McNulty et al., in press) of previous versions of PnET originally developed by Aber and Federer (1992). PnET-IIS is a lumped parameter model which predicts net primary production (NPP), evapotranspiration (Et), and drainage on a monthly time-step. The model requires site specific climate and soils information, and generalized vegetation data. The Et component of the model includes transpiration which is calculated from maximum potential transpiration. The potential is modified by plant water demand which is a function of gross photosynthesis, water use efficiency and leaf area index. Interception loss is based on an empirical relationship with precipitation that is set for the particular forest type of interest. Details of model structure, input data, and model outputs and validation are given in papers cited above.

We used a Geographic Information System to develop and link a data base to the PnET-IIS model to predict NPP, Et, drainage, and soil water deficit for loblolly pine (Pinus taedas) in the southern U.S. (McNulty et al., in prep.). Model-predicted outputs were compared to measured values in 12 stands located across the region. Predicted average annual site NPP was strongly correlated with the measured average annual (8 to 28 years) basal area growth of the trees on each site (Figure 2). The analysis also showed the importance of water in regulating and predicting growth as evidenced by the significant correlation ($r = 0.54$) between growing season Et and measured annual basal area growth.

In one of the first attempts of regional scale hydrologic model validation, PnET-IIS predictions of average annual drainage were significantly correlated ($R^2 = 0.66, P < 0.0001$) with over 2000 USGS stream gauging station measurements of annual run-off. We have also applied the PnET-IIS model to potential global warming scenarios produced by a variety of general circulation models (GCM's) at 0.5° x 0.5° (approximately 3600 km$^2$) cell.
resolution across the southern U.S. For example, annual Et was simulated using the Goddard Institute of Space Studies (GISS) GCM climate data as a PnET-IIS input. The GISS GCM predicts an average monthly trans-regional air temperature increase of 3.5°C and a 5% increase in precipitation (McNulty et al., in prep.). The difference in predicted annual Et using the GISS climate compared to predicted Et using historic (1951-1984) climate data shows that Et generally increased over the region using this GCM (Figure 3). Et increased despite a slight reduction in LAI across much of the region which was due to higher respiration rates with elevated air temperature. The remaining leaves utilized the elevated energy load and thus total Et generally increased. PnET-IIS also predicted that certain cells were no longer able to support loblolly pine (Figure 3). Tree death was predicted when respiration exceeded gross photosynthesis and LAI was reduced to zero. However, in cooler mountainous regions of the southeast, LAI, Et and NPP increased in response to elevated temperatures.

Figure 3 Difference in evapotranspiration using PnET-IIS with historic and GISS GCM climate data from 1951 to 1980 for loblolly pine across the southern U.S.
In this example, it is clear that understanding and modeling of hydrologic processes is critical in assessing potential effects of climate change on forests.

**Ecosystem Management and Forest Hydrology**

The USDA Forest Service has taken a new direction in its research and management programs in response to changing views of land and natural resources (Kessler et al., 1992). Ecosystem management is currently the operating philosophy of the Forest Service with the objective of using an ecological approach to achieve broader multiple use objectives.

There is no blueprint for implementing ecosystem management; in fact, a variety of approaches will be required to meet the needs of the varied forested regions in the U.S. We have developed and implemented an ecosystem management project on Wine Spring Creek, a 1820 ha basin on National Forest land in western North Carolina. The objective of the project is to use and/or develop ecologically based concepts, principles, and technology to achieve desired resource conditions. The ecosystem project encompasses an interdisciplinary partnership of aquatic and terrestrial ecologists, social scientists, resource managers, conservation and environmental groups, and the public. Our approach to research and management planning and implementation in an ecosystem context utilizes the basic framework of existing land and resource management plans but is innovative in devising desired conditions and specifying prescriptions to achieve conditions (Figure 4).

Based on the current process of forest planning, resource managers have previously identified eight management areas in the Wine Spring Creek basin, each with a different management emphasis (Table 1).

![Figure 4](image-url)
Table 1.
Management areas, resource emphasis, and area for the Wine Spring Creek basin designated by the forest planning process.

<table>
<thead>
<tr>
<th>Management Areas</th>
<th>Management Emphasis</th>
<th>Size (ha)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1B</td>
<td>Sustainable timber supply &amp; other traditional forest uses</td>
<td>755</td>
</tr>
<tr>
<td>2A &amp; 2C</td>
<td>Pleasant scenery for visitors and habitat of older forests for selected animals</td>
<td>65</td>
</tr>
<tr>
<td>4B &amp; 4C</td>
<td>Nonmotorized recreational use mature forests for bear and animals requiring similar habitat, pleasant scenery</td>
<td>942</td>
</tr>
<tr>
<td>14</td>
<td>Protection of National Scenic Trail</td>
<td>24</td>
</tr>
<tr>
<td>17</td>
<td>Mountain bald maintenance</td>
<td>5</td>
</tr>
<tr>
<td>18</td>
<td>Riparian areas and associated plant and interspersed animal communities</td>
<td></td>
</tr>
</tbody>
</table>

About 40% of the total area is designated as suitable for timber supply and other traditional forest uses. The management emphases on the remaining area are for a variety of resources including recreational uses, animal habitat, scenery, and special ecosystems such as riparian areas and high elevation mountain "balds" (open grass-shrub communities).

Table 2.
Major research and management themes derived from enumeration of desired future conditions for resources on the Wine Spring Creek basin.

Ecological Classification

Riparian Zone Management

Aquatic Productivity/Water Quality/Habitat Alteration

Sustainable Productivity (Regeneration, Biodiversity, and Biogeochemical Cycles)

Social and Amenity Value Assessment

Mammal and Bird Population Dynamics

Special Ecosystems ("Balds")

Desired resource conditions were developed over an 18 month period through workshops involving invited participants. Representatives from a variety of organizations participated, including terrestrial and aquatic scientists from five research units in the Southeastern Forest Experiment Station and fire universities; federal and state land managers, Trout Unlimited,
Bartram Trail Society, The National Wild Turkey Federation, Western North Carolina Alliance, and The Ruffed Grouse Society. From this consensus building process, 35 desired resource conditions were initially identified for the project area. Grouping of the desired conditions with research and technology transfer opportunities generated several themes for the project area (Table 2). A number of these themes depend upon an understanding of forest hydrologic processes; i.e., riparian zone management, water quality, and biogeochemical cycles.

An example of the linkage between a desired resource future condition and the process for implementation is illustrated by the following example as outlined in Table 3.

Table 3.
An example of the linkages between a desired future condition and the steps for implementation on Wine Spring Creek.

Desired Future Condition: Populations of native fish in Wine Spring Creek and tributaries which equal or exceed current levels.

1. Existing Data
   Historical estimate of fish population

2. Exploratory/Inventory
   a. Characterize stream sediment
   b. Quantify current fish population
   c. Determine genetic character of native brook trout
   d. Characterize large woody debris (LWD)
   e. Characterize macroinvertebrates, stream solutes, algae

3. Alternative Manipulations and Monitoring
   a. Develop and validate sediment model(s)
   b. Manipulate sources of organic matter
   c. Augment solutes
   d. Habitat improvement (LWD)
   e. Supplemental stocking, exclusion of non-native spp.
   f. Enhancement of riparian area stem growth

It is apparent that an understanding of forest hydrologic processes, particularly soil erosion and sediment production, is critical to achieving the objective related to fish populations. First, it is necessary to characterize the stream sediment load associated with existing fish and macroinvertebrate populations. Next, we must develop and validate models for predicting the effects of alternative management practices on sediment production and transport. Finally, we need to link concurrent research on changes in sediment with benthic and fish production to determine cause and effect relationships; if necessary, implement adaptive management to alter management prescriptions if desired conditions are not met (Figure 5).

Modeling watershed scale soil erosion, terrestrial and stream transport

Numerous soil erosion models have been developed to predict forest management impacts. However, estimates are usually site specific and, when applied across watersheds, yield invalid overestimates of total soil loss. Inadequate predictions are partly due to the fact that soil disturbance associated with forestry activities usually occurs in non-uniform,
discontiguous patches. Current best management practices attempt to isolate these patches of disturbance from the stream system. A more valid soil erosion model for forested watersheds should also determine if eroded soil moves off the source site, how far it moves before entrapment on the undisturbed forest floor, and what portion (if any) reaches the stream system. In a cumulative effects context, a watershed soil loss model should also determine the downstream fate of sediment added to the channel system.

Our soil erosion research is developing a user-friendly, modular based, Geographic Information System (GIS) for predicting soil erosion and the transport of terrestrial and stream sediment which will provide a tool for land managers to analyze the impacts of alternative forest management practices on soil loss and stream water quality. This tool predicts soil erosion and transport across watersheds for a variety of management practices including forest road construction, timber harvesting, prescribed burning, and creation of wildlife food plots, given a range of storm intensities for each season (i.e., spring, summer, fall, winter). The data necessary to develop and validate the model are derived from a combination of pre-existing digitized maps (e.g., soil series, forest compartment boundaries, road, stream) and field collected measurements (e.g., terrestrial soil transport rates and stream sedimentation).

Site parameters for Wine Spring Creek include topography, stand cover, stream bank slope angle, soil texture, stream speed, and stream bend angle; all are entered directly into the model through the GIS.

The model currently uses the revised Universal Soil Loss Equation (RUSLE) to predict sediment loss from 30 x 30 m grid cells across the management area for current or baseline land and cover conditions (Figure 6). After establishing baseline soil erosion losses, the model is re-run using various forest management practices, during different seasons and storm intensity years, as represented by R, the rainfall erosion index of RUSLE. The set of climate scenarios provide "most likely" and "worst case" scenarios for soil loss and movement.

Although the absolute amount of sediment loss as predicted from the USLE may not be accurate, a comparison of soil loss under two different R factors is informative. These results highlight those areas which are most susceptible to soil erosion and suggest relatively how much more soil loss could be expected if an extreme rainfall year were to occur. Additionally, the modular approach to model development allows for components to be easily exchanged. For example, when the Water Erosion Prediction Project (WEPP) soil erosion model becomes available, the grid version of the WEPP model can be exchanged for the RUSLE model as a predictor of soil erosion and downslope transport.

Our terrestrial transport model is based on land slope and forest floor resistance to soil movement. Structures such as brush barriers and natural sediment traps restrict soil movement. The amount of sediment that can be absorbed by a cell is dependent on ground
Figure 6 Estimated soil loss for a three month spring period based on a typical precipitation pattern on Wine Spring Creek.

cover type (e.g., forest floor, landings, or road). The estimate of total distance that eroded soil can move and the downslope distribution of sediment deposits are based on results from field studies at Coweeta, Wine Spring, and elsewhere. If a stream cell is encountered during terrestrial sediment transport, the amount of sediment moving into the stream will be determined and the stream sediment transport program will be invoked.

Stream sediment transport is a function of the rate of water flow, channel substrate, and sediment inputs. The rate of water flow is in turn a function of topography, baseline water flow and precipitation. Base flow and channel substrate are measured on each watershed before the model is run or default values could be applied. Special concern is given to predicting areas of high sediment production which adjoin streams and which are dominated with a high proportion of fine sediment.

Model validation is an important component of soil erosion modeling. At each step of model development, model predictions of soil erosion and terrestrial and stream sediment transport are being validated on the Wine Spring Ecosystem Management area through on-site measurements.

These three models, when combined with an easy to use model interface, will provide a tool for land managers to examine impacts of alternative management practices on soil erosion and transport. The outputs of these models will be useful to land managers in predicting potentially sensitive areas of soil loss, and in estimating changes in stream water quality associated with alternative management practices. More importantly, stream sediment measurements are concurrently linked with research on benthic insects and fish production to assess the effects of sediment levels on stream biology (Figure 5).
Additional examples could be cited for the strong linkage between hydrologic processes and other topical areas of ecosystem management such as other parameters of water quality, biogeochemical cycling, and riparian zone definition and management.

Summary

Traditional hydrologic process research will continue to provide basic principles useful in developing guidelines for watershed management. However, broad environmental problems have emerged which require an interdisciplinary research approach in order to develop solutions. Forest hydrology research provides the foundation for many of these forest environment assessments from a holistic perspective; thus, offering new opportunities for integration with other sciences. In one example, evaluation and prediction of climate change impacts on forest and water resources requires the scaling of hydrologic processes to larger spatial and longer temporal scales. In another case, ecosystem management, an understanding of water movement and associated regulatory function in the forest is closely linked with ecological processes to obtain desired future conditions of resources.

References


PROCEEDINGS OF
THE INTERNATIONAL
SYMPOSIUM ON
FOREST HYDROLOGY