THE EFFECTS OF SOUTHERN PINE BEETLE
(Dendroctonus frontalis Zimm.)
EPIDEMICS ON FOREST WATERSHED DYNAMICS:
WILL BENEFITS JUSTIFY CONTROL?

by

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INTRODUCTION

The southern pine beetle (*Dendroctonus frontalis* Zimm.) (SPB) is the most destructive of the eastern bark beetles and its range covers the southeastern United States. The beetle primarily attacks southern pines (*Pinus taeda*, *P. virginiana*, *P. echinata*, *P. palustris*, and *P. elliottii*) and kills them by burrowing under the bark and consuming the phloem (Coulson et al., 1972; Dixon and Osgood, 1961). There is presently no concrete knowledge of the combination of stand, edaphic, and climatic conditions that must exist for a SPB outbreak to occur; however, the conditions are currently the subject of intensive research. The determination of such conditions is not within the scope of this paper. This paper is concerned with determining the extent of any physical watershed impacts that SPB infestations and resultant pine mortality might cause and the economic implications associated with these impacts.

From 1948 to 1966 the southern pine beetle is estimated to have destroyed a billion board feet of timber. According to the USDA (1975) 12 of the 13 southeastern states experienced beetle infestations between 1971 and June 30, 1975. Oklahoma was the only state not reporting attacks. Forty percent of all counties, 360 of 898, containing host species experienced SPB attacks as of June 30, 1975.

Controlling SPB involves salvaging the infested trees and clearing a buffer strip around the infested spot to reduce the possibility of further outbreak (Texas Forest Service, 1975). When the trees cannot be economically salvaged, the U. S. Forest Service recommends the following control practices: (1) fell, pile, and burn infested trees, or (2) fell and spray infested trees with lindane (BHC) in No. 2 fuel oil (USDA, 1974). A buffer strip is also used with these controls.

The SPB can have an immense impact on both public and private forestry operations. Management schemes may be altered in the event of a SPB attack and costly harvesting measures must often be instituted to utilize salvageable timber and, at the same time, hopefully limit beetle damage. The economic impacts of SPB-caused pine mortality and salvage logging accruing to private and public forestry have underscored the need for establishing SPB control decision guidelines (Weitzman, 1975). Control decision guidelines would enable decision-makers to make economically feasible control strategy selections.

Leuschner and Newton (1974) have suggested benefit-cost (B/C) analysis to determine the economic feasibility of implementing a given control program. Program benefits must be estimated and compared with program costs by using present values. The basic economic criterion of B/C analysis is that benefits must exceed costs for program implementation. The program with the greatest net benefit (benefits minus costs) would be the most feasible if the programs under consideration are mutally exclusive. The main benefits of SPB control result from preventing tree mortality.

The ease of computing the various control program costs and benefits depends on the forest product under consideration. Timber is probably the most important forest product affected by SPB and the program benefits are relatively easy to compute. The forest not only produces timber but also recreation, water, and wildlife and these benefits must also be estimated to get a given program's total benefits. This study examines the physical and economic impacts on the watershed. SPB control costs are beyond the scope of this study.

The dynamics of a forested watershed under normal conditions should be known to set the stage for the SPB's effects on a watershed. Normally, the closed forest canopy acts as an obstacle to precipitation and this can change the two most important characteristics of precipitation reaching the soil surface, quantity and water delivery rate. These characteristics are affected by the amount of precipitation intercepted by the canopy and the amount of water held in the bark of the trunk and branches. The relative amount of precipitation reaching the ground increases as the duration and/or intensity of the precipitation increases. Precipitation usually ends up as streamflow (water yield), deep seepage, evaporation, or transpiration. The main impact of SPB attack and subsequent tree mortality will be from the loss of transpiring surface area.

The amount of annual water yield is unique to a watershed because species composition, stand density, and the amount of annual precipitation are unique. There is also a minimum erosion rate that will occur naturally. Any natural or man-made phenomenon that changes stand composition or density or disturbs the soil will have some effect on the water yield and/or erosion rates. The effects of stand composition changes should not be compared to soil disturbance effects because composition changes will usually only affect water yield while soil disturbances could affect nutrient leaching and erosion in addition to water yield.

A beetle infestation causes holes in the canopy. The fraction of total basal area in host stems, SPB infestation size, and the location of the nearest stream must be known to predict hydrologic changes which might occur. There is general agreement among eastern hydrologists that at least 20 percent of a watershed's total basal area must be removed or destroyed before there is any statistically significant change in annual water yield (Douglass, 1967). The 20 percent figure is an approximation because existing methods for detecting water yield changes are not very sensitive. Massive litter layer and organic matter layer disturbance must occur before noticeable changes in the erosion rate occur. A beetle infestation may also affect dissolved nutrient loss and stream water temperatures.

The duration of adverse effects on the watershed will largely depend upon stand, soil, topographic, climatic, management, and beetle attack variables (Table 1). The stand variables are most important because the stand determines the importance of the other hydrologic variables. For example, an infestation in a mixed pine-hardwood stand would not be as alarming as an attack in a pure pine stand because a massive spread in a mixed stand is not nearly as imminent as one in a pure stand. In addition, the hardwoods may compensate for the transpiring pine surface lost by transpiring more, therefore, reducing the expected impact.

Soil type and depth, in association with stand type and density, determine total annual water yield and the timing of water yield for individual precipitation events. It will be seen later how soil type

Table 1. Independent variables used to establish functional relationships between attacks and water production.

A. Stand Variables

1. Percent pine host material
2. Clustered or even mix
3. Percent of attackable stand infested

B. Soil Variables

1. Soil type
2. Soil depth

C. Topographic Variables

1. Position on slope and percent slope
2. Aspect (azimuth)

D. Climatic Variables

1. Average annual precipitation
2. Annual distribution of precipitation
3. Annual evapotranspiration rate

E. Management Practice Variables

1. Practices before attack
2. Practices in conjunction with attack
    (a) Salvage logging
    (b) Cut and burn infested trees

F. Attack Variables

1. Spot size
2. Time of year

affects the movement of water through the soil mantle. Soil depth is important because it is directly related to water-storage capacity and, also, because it can affect the duration of annual water yield changes.

SPB attack effects will also depend on the watershed's topography. Water yield changes can be affected by the beetle spot's slope position and also by slope steepness. Aspect also can affect water yield. A southwest aspect tends to yield less water than one facing north or east due mainly to the amount of solar radiation striking the vegetation and ground. Temperatures and transpiration rates will increase as more solar radiation is received.

Climate, including precipitation, average daily temperature, potential evapotranspiration (PET), and average absolute humidity, greatly affect the water yield process. Water yield could not occur without precipitation, therefore, the amount and timing of the precipitation, coupled with the physical and atmospheric conditions, will determine a watershed's water yield. PET can particularly pinpoint when water yield changes might occur because water yield will increase more if a SBP infestation occurs in the spring than the winter because tree mortality peaks when PET is highest. A decrease in evapotranspiration results in more water available for water yield.

The management practices applied to a given tract before a beetle outbreak may also affect water yield. For example, a commercial thinning prior to an attack may increase the water yield changes recorded after the attack. Similarly, the practices applied after an attack may cause changes in hydrologic components that would have otherwise not occurred.

Finally, SPB spot size and the time of year the attack occurs must be known. A spot's size and location within the watershed are perhaps the primary data needed in a SPB-watershed study. The time of year an attack occurs is also important because this, in conjunction with climatic data, will also give an estimate of how water yields might change. The implications of spot size and location and the timing of the SPB attack will be discussed at greater length in a later section of this paper.

A waterhsed's value can be changed if water yield, water quality in general, or any water quality determinant, including erosion, dissolved nutrient loss, or water temperature, are abnormally altered. It is here that the problems of watershed valuation become apparent. Unlike timber which has a stumpage value, the watershed and its primary product, water, cannot be given a market value. The problem of water valuation will be discussed in some detail in the next section of this paper.

This study's objectives are: (1) develop a methodology, using existing hydrologic simulation models, to estimate the physical impacts of the SPB on a forested watershed and (2) develop a methodology to place a value on (1) above. (1) and (2) can be combined to provide information to help decision makers determine optimal levels of SPB control with respect to watersheds.

LITERATURE REVIEW

A literature review was focused on forest hydrology, hydrologic simulation models, and water economics. Forest hydrology research is conducted in every region of the United States, however, this review has been purposefully limited to the eastern United States because the SPB is native only to this region. A number of hydrologic simulation models were reviewed but only three were considered applicable for use in this study.

Forest Hydrology

Several hydrologic components must be considered in assessing SPB's physical impact. Water yield is the most heavily studied component. Water yield is the water volume produced by a watershed as streamflow. It is generally expressed on a monthly or annual basis. Major studies have been conducted from New Hampshire (Hornbeck and Federer, 1975) to Mississippi (Ursic and Duffy, 1972). Water yield studies have been completed at the Fernow Experimental Forest in West Virginia (Kochenderfer and Aubertin, 1975) and the Coweeta Hydrologic Laboratory in North Carolina (Douglass and Swank, 1975). These studies found that water yield is a function of the basal area cut or destroyed and the location in the watershed of the removed timber. Douglass (1967) said that significant water yield increases occur only after at least a 20 percent reduction in basal area.

Water yields tend to increase in amount and duration as greater amounts of vegetation are removed from a watershed. Swank and Helvey (1970) found that streamflow will decrease to precutting levels in one to ten years depending on the intensity of the harvest cut and site productivity. However, Kovner (1957) states that clearcut studies at Coweeta have shown that water yield increases may last as long as 35 years if regeneration plantings are not made. A light selection cut causes the smallest water yield increase while a clearcut causes the most. Water yield increase durations decreased with progressively more productive sites.

Research on treatment locations has been studied mostly in relation with snowpack melting (Hornbeck and Federer, 1975) but specific studies relating treatment location to hydrologic effects, especially water yield, are nearly nonexistent. However, it is reasonable to assume that the closer a treatment is to the stream the greater the likelihood that a detectable impact on a hydrologic component will occur.

Water quality, in general, and erosion rates, in particular, are affected by management practices in much the same way as water yield. The more intense the management practice the greater the likelihood of a change in water quality due to a change in the erosion rate. However, this is not to say that changes will inevitably occur. Aubertin and Patric (1974) reported that clearcutting experiments on the Fernow Experimental Forest produced virtually no increase in dissolved solids, unless a precipitation event (storm event) took place that would wash dissolved solids into the stream system. The amount of dissolved solids in water is one determinant of water quality, while nutrient content and temperature are others. Precipitation would cause the stream to become turbid indicating dissolved solids had entered the water. Turbidity would only last a few hours and then return to prestorm levels. Packer's (1967) water quality research review concludes that timber cutting has no deleterious effects on water quality except during extremely high storm peaks. A storm peak is that period of time within a storm that produces the greatest (highest amount per unit of time) precipitation.

Erosion is generally the major source of dissolved solids in streamflow and, hence, the primary cause of reduced water quality. Therefore, causes of erosion are generally studied. Almost without exception researchers throughout the country agree that the major cause of erosion on a forested watershed is the logging road system (Hornbeck and Reinhart, 1964; Hornbeck, 1967; Dickerson, 1975; Kochenderfer, 1970). Natural erosion rates for various soil-vegetation complexes are known so it would not be very difficult to measure changes brought about by human or natural disturbances. However, abnormal soil erosion would be a secondary SPB infestation effect that would probably only result from salvage logging.

Nutrient loss is another important component of watershed research. The nutrients lost and the loss rate will depend largely on soil properties, climate, treatment intensity, and the revegetation rate following a treatment (Lull and Reinhart, 1972; Ursic and Duffy, 1972). Nutrient studies are necessarily site specific, therefore, only generalities can be covered in the SPB-watershed framework. A number of site specific studies contain detailed nutrient discussions (U. S. Forest Service, 1971; Pierce et al., 1970; Swank and Douglass, 1975;

Aubertin et al., 1973). However, one specific fact about nutrient loss is that nitrate-nitrogen is the nutrient most affected by management treatments and substantial loss could cause a site quality depletion (Sopper, 1971).

Water temperature is the final hydrologic component considered. Researchers have found that water temperatures are only affected when harvesting operations remove stems from along stream banks or in large areas above streams. This allows a formerly shaded stream to receive more direct sunlight which causes a rise in average stream temperature. In turn, this temperature rise could possibly have adverse effects on aquatic life (Douglass and Swank, 1975; Kochenderfer and Aubertin, 1975; Sopper, 1971). Higher average temperatures can be fatal to some species of fish, particularly trout in the mountainous northerly reaches of the SPB range, or higher temperatures can cause sharp increases in the number of freshwater plants which would clog streams and effectively compete with the larger aquatic animals for living space.

The study of watershed dynamics and their response to insect epidemics began in earnest only ten or fifteen years ago. Most research was in the west with the western (*D. brevicomis* Lec.) and mountain (*D. ponderosae* Hopk.) bark beetles and the Engelmann spruce beetle (*D. engelmanni* Hopk.). The most extensive work deals with the Engelmann spruce beetle and the disastrous outbreak that occurred in Colorado in the late 1940's (Bethlahmy, 1975). The epidemic covered hundreds of square miles in the Yampa and White River watersheds. About 30 percent of the two watersheds were infested and approximately 80 percent of all host trees, Engelmann spruce (Picea engelmannii) and subalpine fir (Abies lasciocarpa) were killed. Bethlahmy's research revealed that water yields were still slightly above normal after 25 years. This outbreak is probably the largest bark beetle epidemic to be studied.

Conclusions are difficult to draw from Bethlahmy's study beyond the basic vegetation-water yield relationship. However, it is reasonable to conclude that water yield increases could have been significantly reduced within ten years and possibly terminated after 15 years if a control strategy had been instituted and/or the land promptly reforested.

Work has been done in the east with the gypsy moth (Porthetria dispar L.) and the severely defoliated Newark, NJ Municipal Watershed (Corbett and Heilman, 1975). It was a 42 acre watershed which was 75 percent defoliated. An increase of just over five inches in water yield was measured the first year and 80 percent of the increase was in the growing season. The increase during the growing season is expected because transpiration is greatest during this time of year and massive defoliation decreases transpiration.

Hydrologic Simulation Models

The search for a hydrologic simulation model produced six models of which three were considered applicable for this study. A brief discussion of each model reviewed, along with its advantages and disadvantages, follows:

(1) Stanford Watershed Model - this model simulates a continuous hydrograph and has the Opset addition which is actually a self-calibrat-

ing model (James, 1972). Opset allows the user to develop functional relationships for parameters that are difficult to measure directly. The Stanford model is capable of simulating flow sequences over both long and short time intervals. The main advantages are that this model can be used with a forested watershed and it gives accurate results. The main disadvantage is the substantial data requirements for each site studied.

(2) Betters Simulation Model - this is a timber-water simulation model developed in Colorado for the Rocky Mountain Front Range region (Betters, 1975). Initial development centered around lodgepole pine stands growing on a 120 year rotation. The primary model advantage is that it is a dynamic joint timber-water simulation model while disadvantages include an involved set of submodels and calibration for a precipitation regime that has much snowfall.

(3) Douglass and Swank Model - this model was developed using data from New Hampshire, Pennsylvania, West Virginia, and North Carolina (Douglass and Swank, 1975). Its central feature is an equation that predicts annual increases in water yield by applying two independent variables, percent basal cut and the watershed's theoretical extraterrestial load (solar irradiation) measured in langleys. While this model is very easy to use, its major disadvantages are that it was developed from hardwood data and does not incorporate any soil parameters.

The first three models reviewed were not chosen for this study because (1) data were unavailable and/or (2) their applicability in the southeastern United States is very questionable. The next three models discussed were chosen for use in this study and consequently will be described in more detail. Particular attention will be given to the model characteristics that make them more usable than those that were rejected. The variables in each will be discussed also.

(4) Rogerson Model - this is a simple hydrologic simulation model developed in the Ouachita Mountains of central Arkansas to predict water balances and hydrologic changes on small pine-hardwood drainages where thinnings took place (Rogerson, 1976). Data from model development were obtained from three small drainages that ranged in size from 1.28- to 1.63-acres. The model can be used in two modes. Mode 1 uses actual precipitation in the simulation while mode 2 uses an empirically developed precipitation function to simulate storm events indigenous to central Arkansas. With mode 1 only one year of precipitation may be used for simulation while mode 2 allows the simulation of any number of years of hydrologic activity. The time unit for simulation is one day under the assumption that water yield will begin within 24 hours of a storm event on small drainages.

Table 2 is a list of variables used in simulating hydrologic events. Data unavailability for areas outside central Arkansas is the main drawback to using this model. Precipitation and potential evapotranspiration (PET) data for non-Arkansas areas were acquired but the remainder were not. The basal area function, variable C, was derived empirically and is the product of the combined effects of surface evaporation and plant transpiration at varying basal area levels. This

Table 2. Input variables for the Rogerson hydrologic model.

Variable	Unit
A. Daily precipitation	inches
B. Maximum transpiration-surface evaporation[a]	inches/day
C. Basal area	sq. ft./acre
D. Soil water deficit in the surface foot[b]	inches
E. Soil water deficit in the profile[b]	inches
F. Maximum soil water deficit in the surface foot	inches
G. Maximum soil water deficit in the profile	inches
H. Seepage rate in the surface foot	inches/day
I. Seepage rate in the profile	inches/day

[a] Analogous to potential evapotranspiration.

[b] These variables characterize initial drainage conditions in the model.

function has basal areas ranging from 0 to 200 sq. ft./acre for simulation purposes.

The majority of the input variables are soil water parameters. Variables D and E, soil water deficits in the surface foot and profile respectively, represent initial soil water conditions in the watershed. A soil water deficit is the difference between maximum recorded soil water content and the actual content at a point in time. Variables F and G are the maximum soil water deficits in the surface foot and profile that were recorded during the calibration of the experimental drainages in central Arkansas. Finally, variables H and I, seepage rates in the surface foot and profile, were developed from empirically derived soil water functions during periods of no precipitation and low transpiration. In the simulation process the model uses the seepage losses from the surface foot and profile to recalculate the soil water deficits of the surface foot and profile.

Despite gross soil water data unavailability, the Rogerson model is the most applicable to this study because it is the only model that directly relates basal area to water yield. This proven relationship is the vital ingredient in this assessment of the effects of SPB attack on water yield. An example of the Rogerson output is in Appendix A.

(5) Haan Model - this hydrologic simulation model was a cooperative effort by six Southern state agricultural experiment stations (Haan, 1975a; 1975b). A model was desired that would accurately simulate monthly water yields from small watersheds with a minimum of input data. The model operates on an October through September water

year and can be used for a calendar year with modification. The basic assumption underlying the simulation process is that rainfall and resultant water yield will occur on the same day.

The main input variables for this model are found in Table 3. Variables A and B, daily precipitation and potential daily evapotranspiration, are self-explanatory but the soil water parameters need clarification. Variables C and D, initial readily and initial less readily available moisture content, are roughly analogous to the Rogerson model's soil water deficits in the surface foot and profile (variables D and E in Table 2) because they represent initial soil water conditions in the watershed. Maximum possible infiltration rate and maximum seepage rate from the soil profile, variables E and F in Table 3, correspond well with variables H and I in Table 2, seepage rates in the surface foot and profile, because they are all water flow rates.

Variable G, the maximum storage capacity of less available water, refers to the water storage that is not readily available for evaporation or plant uptake. Finally, variable H, the fraction of seepage that becomes water yield, is the fraction of water that seeps through the soil profile and enters the stream system as return flow. The seepage that does not enter the stream system is assumed either to be used by plants or to leave the water yield cycle in the form of deep seepage.

The hourly distribution of precipitation within a day must also be input. This breaks daily precipitation into hourly precipitation which distorts the actual precipitation patterns, but minimizes input

Table 3. Input variables for the Haan hydrologic model.

Variable	Unit
A. Daily precipitation	inches
B. Potential daily evapotranspiration	inches
C. Initial readily available moisture content	inches of water/inch of soil[a]
D. Initial less readily available moisture content	b
E. Maximum possible infiltration rate	inches/hour
F. Maximum seepage rate from soil profile	inches/day
G. Maximum storage capacity of less readily available soil water storage	inches
H. Fraction of seepage that becomes runoff	percent

[a] Maximum is one inch.

[b] Some value 'C', a model parameter.

data by eliminating the need for the individual distribution of every precipitation event.

Three types of simulation runs can be made with this model. The first is a parameter optimization run that uses observed water yield data and will optimize the parameters to minimize the summed squares of the differences between simulated and observed water yield. The second type is made with known parameters and observed monthly water yield and plots one against the other. The final type simulates water yield using actual precipitation data and known soil parameters. Observed water yield is not used in this run.

The output of this model is very simple and easy to read (Appendix B). The first page lists the daily precipitation on a monthly basis for every day of a given year. The second and final page contains the values of variables E through H, Table 3. In addition, a month by month list is given of the precipitation in each month and the amount of simulated water yield. Annual totals for each are given also.

This model was chosen for five reasons: ease of use, data availability, gross similarities between the soil water parameters of this model and Rogerson model, the assumption that all precipitation input is rainfall, and the general accuracy of results. The major disadvantage of this model is that it was developed under the assumption that conditions within the watershed are stable over time. There is no vegetation function to account for the growth or death of herbaceous material. This eliminates the model from any simulation of hydrologic responses to SPB infestations but due to the nature of the model and general availability of data it will be used as a general indicator of the range of water yield that a study site might yield with varying levels of annual precipitation.

(6) PROSPER - this is a simulation model that predicts daily water exchange between the atmosphere, vegetation, and the soil (Swift et al., 1975). PROSPER uses either mean or total daily environmental conditions for simulation while the soil is divided into several layers to more accurately assess actual soil conditions. PROSPER's original version simulated water stress on forest vegetation with closed canopies, but more recently it has been adapted to simulate evapotranspiration (ET) and drainage (water yield) from a mature hardwood watershed in southwestern North Carolina.

Input data is read into the model through three subroutines, PARAM, SOIL, and ENDATA, which contain 34 variables in all. A total of 11 subroutines accompany the main program (Table 4). The high number of input variables for PROSPER makes it impractical to discuss each individually but a listing can be found in Appendix C. These variables can be investigated further by referring to Goldstein et al. (1973) and Luxmoore (1973).

PROSPER simulates daily ET and water yield by using an involved set of subroutines. These subroutines require a large number of input variables ranging from daily air pressure, in bars, to the albedo of the vegetation. The nature and number of these input variables makes field collection impossible for this project and in addition there is an acute shortage of available data sets.

Table 4. PROSPER simulation model subroutines.

Subroutine	Function
A. ENDATA	Inputs meteorological data.
B. PROSPR	Calculates water fluxes.
C. EVAP	Determines evapotranspiration demand from environmental parameters.
D. EVAL	Defines resistance parameters for electrical analog and estimates evapotranspiration.
E. DOUBLE PRECISION FUNCTION GROUND	Energy function that calculates net radiation at the ground surface.
F. SATVP	Computes saturation vapor pressure and derivatives with respect to temperature.
G. SUBEV	Calculates evapotranspiration.
H. SOLVO1	Solves for roots of a nonlinear equation using linear fractional iteration.
I. PARAM	Inputs model parameters.

Table 4. PROSPER simulation model subroutines. (Continued)

Subroutine	Function
J. SOIL	Calculates hydraulic conductivity.
K. TABLOK	Method of table look-up for matric water potential and conductivity from soil water content.

PROSPER's output is monthly and annual water budgets. The monthly budget gives a daily account of a dozen soil and atmospheric variables and how they change with each day. These variables range from ET and infiltration to soil evaporation and water yield. The monthly water budget contains 17 variables ranging from precipitation to soil water storage. Finally, an annual budget is given for each of the 17 variables in the monthly listing. An example of PROSPER's output can be found in Appendix D.

Large data requirements, data scarcity, and model complexity are the main disadvantages inherent to the use of PROSPER. Only one data set could be obtained, therefore, results from PROSPER will have to be examined within the strict limits of the data set. In spite of the large data requirement disadvantage PROSPER can be used to simulate vegetation changes. One example of such use involved Coweeta Watershed 18 where researchers simulated annual water yield for clearcut experiments and hardwood to pine conversion (Swift et al., 1975).

Vegetation changes are basically simulated by manipulating four input variables in the PARAM subroutine, maximum interception storage during summer and winter and leaf area index (LAI) during summer and winter. Manipulation of these four variables, particularly LAI, can be cumbersome because of a general lack of specific research. The basic difficulty with using LAI is that little research has been done concerning the relationship of stand density of LAI, especially for pine species (Knoerr, 1978). The lack of research on this topic may prove to be another disadvantage but it will not be so limiting as to exclude PROSPER'S results from the final assessment of SPB effects.

Water Economics

The economic valuation of water and the utilization of these values in the benefit-cost (B/C) analysis is an area of continuing inquiry. For centuries water was, barring droughts, an inexhaustible resource and, therefore, never had economic value. Unlimited supplies versus relatively limited demand made water a valueless commodity despite its essentiality for life. An economic value for water must be determined in this study for water flowing off a watershed.

Water is not easily given a market value. Water is usually valued by a number of indirect methods because of the difficulty of measuring an individual's true willingness to pay although supply and demand interaction can be studied by examining price and quantity trends within individual municipalities that supply metered water. These indirect methods establish what is sometimes referred to as a "shadow price" for water. A shadow price is a value that is artificially estimated to represent a nonexistent market price (Gregory, 1972).

Young and Gray (1972) propose four basic methods of water valuation. Brief summaries of each follow:

(1) Market Price Utilization -

A. Free Market Transaction - this is a rare form of water valuation peculiar to the arid West that stems from the ownership and sale of water rights. One must correctly interpret a number of items including type and extent of fixed costs, water quality, location and time considerations, and the accounting stance if this method is to accurately reflect value. Accounting stance refers to the geographic area under study, for example, national, regional, or local.

B. "Administered" Price - this is the price of water charged by a public utility or agency using a metered system.

(2) Residual Imputation - this method values an unpriced resource as the residual from the total production value of a commodity after the sum of the costs of all other inputs are deducted. This is the most commonly used method for withdrawal use valuation, particularly irrigation. It is a good method if all but one input price can be assigned, but problems can arise concerning the exact depletion of the total product, overlooked variables, and the handling of price supports and other exogenous variables.

(3) Alternative Cost - this procedure involves valuing a non-priced good by assuming that the value of this good, generally publicly supplied, "is no greater than the cost of an economically feasible private alternative source of supply" (Young and Gray, 1972). This method can set an upper limit on the consumer's willingness to pay without actual estimation of demand functions if there is difficulty obtaining a value at the margin. Alternative cost is especially applicable to water project evaluation, but it is not a good technique for water valuation at the watershed.

(4) Values From Demand Functions - this method proposes estimating the demand for a commodity, in this case, water. This procedure is generally only workable when water is the final consumption good. When this is the case, a demand curve may be derived from price-

quantity observations of public utilities and agencies that use metered rates. Difficulties arise with this method because of supply control and direct government subsidies. Subsidies understate the observed willingness to pay.

There are other water valuation methods that are closely related to the alternative cost method. Stober and Falk (1967), in a local water supply B/C analysis, derived a value for water by equating the discounted costs of a water supply project to the volume of additional water that would be supplied by the project. This will give a minimum per unit value for water that would just cover project expenses. Such a method is used when water sales will finance the project. It will not give a water value at the watershed.

Another water valuation technique is described by Worley and Patric (1971) in their analysis of timber cutting and streamflow relationships in the Fernow Experimental Forest, West Virginia. This method involves valuing the amount of timber growth foregone in a given management scheme and equating this value to the additional water released to streamflow as a result of the scheme. The technique values water on a per thousand gallon basis. The main problem with this technique is that the water value is an opportunity cost obtained with respect to supply. No accounting is made of the demand for this water.

There is no generally accepted technique for valuing water at the source. However, the most frequently used method for obtaining intake point water value is a type of residual imputation which involves taking the retail cost charged by a public utility or agency and subtracting treatment, storage, and distribution costs. The value derived by this method is conceptually equivalent to the values for other uses. Evidence shows that intake point water values for in-house municipal use are fairly stable throughout the country. They averaged about $101/acre-foot in 1972 (Young and Gray, 1972).

There are many proponents of a zero raw water value. Gregory (1972) supports this valuation explaining that the application of derived demand theory to gain a raw water value will usually always yield a zero value. Young and Gray (1972) concur stating that water, in and of itself, is not a valueless good but merely "free" in an economic sense. They conclude that the marketplace cannot adequately value water in the watershed due to its varied exogenous uses. They also cite eight basic uses for water: crop irrigation, municipal, industrial, waste assimilation, navigation, recreation, fisheries and wildlife habitat, and hydroelectric power generation. A zero raw water value has been chosen for use in this study. The reasons for this selection are found in the Methods section.

Benefit-cost analysis of water projects is extensively covered in the literature. It compares costs and benefits of alternative projects at a common point in time by discounting benefits and costs. A formal analysis can be an involved process as evidenced by Howe (1971) and Peskin and Seskin (1975). Benefits and costs must be identified and assigned economic values. Costs are generally easy to identify and value but the same is not always so with benefits. Benefits are often difficult to identify and even more difficult to value. Water is a case in point as shown earlier. For example, water valuation for a large-scale multiple-use project will have to be synthesized from its various uses.

Benefit-cost analysis is usually based on the objective of economic efficiency which is the maximization of the net value (benefits) whether on a local, regional, or national accounting stance. Other objectives could include a redistribution of income, minimization of the disruptive influence of a project on the human population, or minimization of project impact on the physical environment. Benefits will necessarily depend on the goals or objectives of a given project.

The accounting stance of a benefit-cost analysis is probably its most important characteristic. Benefits and costs will differ by whether the accounting stance is national, regional, or local. Finally, a project's time span and applied interest rate will also have dominant roles in the process.

METHODS

Introduction

The watershed components which SPB can possibly affect are water yield, water quality, and its traditional determinants, erosion, nutrient loss, and water temperature. This study attempts to estimate any SPB-caused physical impacts, to give these impacts an economic value, and to determine if there are water-related benefits or costs. Annual water yield changes will be estimated with simulation models and changes in other components will be qualitatively estimated using published relationships. They will not be quantified because it is difficult to simulate their responses at various SPB attack levels.

The water yield simulation will use three sites found within the SPB range. The sites were chosen from nine initial sites using results from the Rogerson model. Three years of precipitation data, above average, near average, and below average, were chosen for each site. The final study sites were those having the extremes and average water yield years with Rogerson simulation. The study sites and their particular precipitation, water yield, and potential evapotranspiration regimes are the standards used in analyzing the possible watershed effects of SPB infestations.

Water yield impacts will be estimated using three hydrologic simulation models. The models were developed in the Southeast and they include the Rogerson model (Rogerson, 1976), PROSPER (Swift et al., 1975; Goldstein et al., 1973; Luxmoore, 1973), and the Haan model (Haan, 1975a; 1975b). A range of parameter values for each model was desired but was infeasible for the Rogerson and PROSPER models due to data limitations. Parameter ranges would specifically set the ranges for SPB-water yield changes and would allow use of the results in a general assessment of actual infestations. The nonsimulatable hydrologic components will be assessed independently of the water yield simulation results.

The estimated water yield impacts will be given an economic value and will be assessed as benefits or costs depending on the climatic and locational circumstances involved. The other hydrologic components will be assessed in noneconomic terms because they are complex to measure and are site specific. This would make the assignment of economic values extremely difficult under the financial limitations of this study.

Study Sites

Nine sites in the SPB's range were selected for initial study (Figure 1). These sites met two criteria: first, each had to have rolling to mountainous terrain similar to the terrain where the hydrologic simulation models were developed and second, all sites had to have a fairly even precipitation distribution throughout the year. Three years of precipitation data, above average, near average, and below average, were selected for each of the nine sites and 27 trial runs were made with the Rogerson model. It was felt that this study could adequately characterize SPB impacts on forest hydrology by using the three sites that displayed the extremes and mean in annual water yield. The three sites were selected according to the following

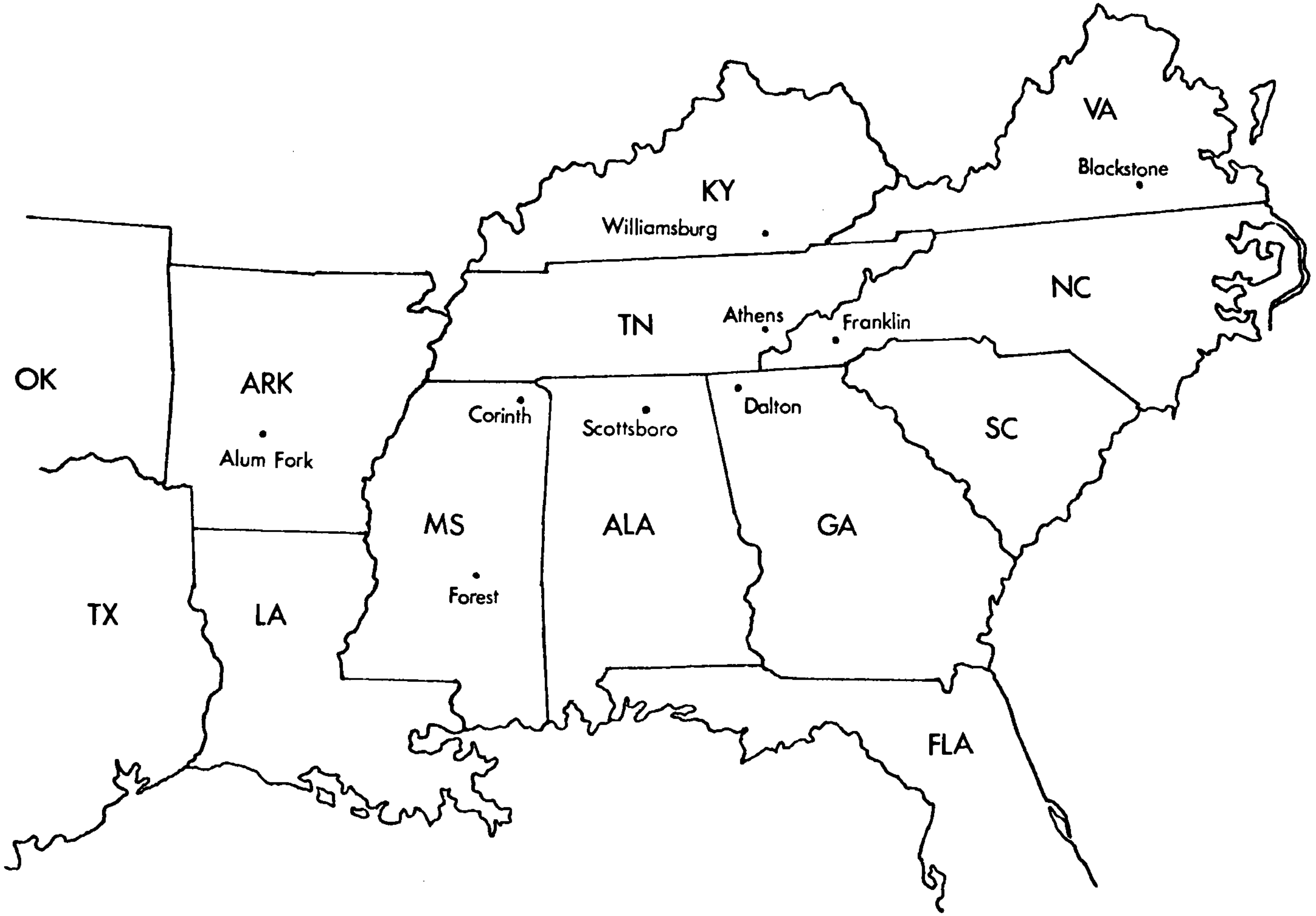

Figure 1. Study sites in the SPB range of the 13 Southeastern states.

criteria: (1) the site with the highest annual water yield at 0 sq. ft./acre basal area for any of its three precipitation years, (2) the site having the lowest annual water yield at 200 sq. ft./acre basal area for any of its three precipitation years, and (3) the site having the average annual water yield at 100 sq. ft./acre basal area for a near average precipitation year. Sites (1) and (2) were eliminated from determining (3) to rule out the possibility of a site being selected twice. The site meeting criterion (1), the highest annual water yield, was Corinth, MS. Blackstone, VA had the lowest annual water yield, criterion (2), and Dalton, GA had the average annual water yield, criterion (3). The annual precipitation data for the three final study sites is found in Appendix E.

An overview of each final study sites' major physical and climatic characteristics can be found in Table 5. An average annual precipitation range of 8.55 inches adequately accounts for most sites in the 13 southeastern states except for the coasts of Louisiana and Mississippi, where significantly more precipitation occurs, and central Texas and Oklahoma where significantly less occurs. Annual water yields in these areas can be estimated using the above and below average annual precipitation data of the three study sites.

There are also two noteable physical characteristics. First, soil depths for the three sites vary from the shallow soils of Dalton, GA to the deep soils of Blackstone, VA. Such variation allows for a broad range of effects that may occur with the hydrologic components being analyzed. Soil depth can have a significant effect on soil water

Table 5. General climatic and physical characteristics of the SPB-watershed study sites.

Site	Mean Annual Precipitation (inches)^c	Mean Annual Potential Evapotranspiration (inches)^b	Native SPB Hosts^c	Mean Annual Water Deficit (inches)^c
Corinth, MS (Alcorn Co.)	52.15	35	*P. echinata*	2-4
Dalton, GA (Whitfield Co.)	51.78	29	*P. echinata* *P. taeda*	0-1
Blackstone, VA (Nottaway Co.)	43.60	33	*P. taeda* *P. echinata*	0-2

Site	Annual Runoff (acre-inches)^c	Type of Productive Aquifer^c	Average Soil Depth for Pine Sites (inches)^d	Average Slope of Pine Sites (percent)^d
Corinth, MS (Alcorn Co.)	20-30	Unconsolidated Coastal Plain sand and gravel	60	7-15

Table 5. General climatic and physical characteristics of the SPB-watershed study sites. (Continued)

Site	Annual Runoff (acre-inches)[c]	Type of Productive Aquifer[c]	Average Soil Depth for Pine Sites (inches)[d]	Average Slope of Pine Sites (percent)[d]
Dalton, GA (Whitfield Co.)	20-30	Consolidated sandstone and carbonate rocks	12-40	+30
Blackstone, VA (Nottaway Co.)	10-15	Consolidated crystalline rocks (igneous and metamorphic)	24	2-7

[a] From U. S. Weather Service and NOAA publications.

[b] Estimated from Haan (1975b).

[c] From a Forest Atlas of the South (1969).

[d] From respective U. S. Soil Surveys.

storage and, therefore, on the amount and timing of water yield. Second, site slopes also show wide variation which will enable a broad analysis of the possible hydrologic changes caused by SPB attack. For example, a watershed with steep slopes and shallow soils will have a greater likelihood of rapid water yield response to a precipitation event.

In conclusion, it is felt that the three study sites give an adequate climatic and physical characteristic range that is needed to thoroughly analyze the hydrologic and economic impacts a SPB attack may have on a forested watershed. It is also felt that some kind of ordinal scale can be developed, using the range of climatic and physical characteristics, to show which combination would yield the largest and smallest hydrologic responses. This idea will be discussed in the Summary.

SPB Attack Data

SPB attacks cannot be simulated without using actual field data. This study will rely heavily on Leuschner et al. (1976). They conducted a SPB study on the Trinity District of the Davy Crockett National Forest in east Texas between July 1974 and June 1975 in which such data as basal area, spot size, number of trees per spot, diameter at breast height and height distribution, soil type, stand type, and other data were collected.

Their study does not characterize SPB activity throughout its range but it is one of the most complete published analyses and will be used within its limitations. Table 6 presents some of the SPB activity

Table 6. SPB activity in east Texas (Trinity District - Davy Crockett National Forest).[a]

1. 80867 of 83602 acres contain SPB host species.
2. 477 SPB spots were found on the 80867 acres; (< 6 spots/ 1000 acres).
3. Largest spot was 2.17 acres.
4. 75 percent of all spots had 5 trees or less.
5. 67 percent of all spots were $\leq$ .05 acres.
6. Stands $\geq$ 90 sq. ft./acre were especially prone to SPB infection. These stands contained:

   a. 65 percent of all SPB spots,
   b. 76 percent of all attacked trees,
   c. 63 percent of all attacked acreage, and
   d. 74 percent of all attacked stem volume.

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[a] Drawn from Leuschner et al. (1976).

data collected in east Texas. Annual water yield simulation will concentrate on the initial basal areas of 90 and 150 sq. ft./acre and it will be assumed that attacked stands are at least 50 percent pine because about 97 percent of all observed spots were that pure. Physical impact estimates will be made first, assuming the Texas data is representative of most SPB activity and second, assuming that most SPB activity is either more or less intense than the Texas data.

Physical Impact Measurement Simulation

Annual water yield changes caused by SPB attack will be estimated using three hydrologic simulation models. They are, the Rogerson model, PROSPER, and the Haan model. These modelsand their inputs have been discussed briefly in the Literature Review. The Rogerson model will be relied on most heavily for estimating annual water yield changes and the other two will be used to supplement it.

The Rogerson model will be emphasized for two reasons. First, its dynamic vegetation function allows for initial stand conditions control. This means that any basal area from 0 to 200 sq. ft./acre can be used to simulate a stand's water yield before a SPB attack and a reduction in this basal area can be used to simulate the water yield changes resulting from a SPB attack. PROSPER also has a dynamic vegetation function that can simulate annual water yield responses to various vegetation levels but it uses leaf area index (LAI) for this purpose and very little research has been done with conifers to relate LAI to stand density. This lack of research makes heavy reliance on PROSPER's results less desirable. The Haan model is static and, therefore, cannot simulate the water yields caused by vegetation reductions. Finally, the Rogerson model's vegetation function is more typical of stands that the SPB might infest than PROSPER despite the fact that one part of PROSPER's vegetation function represents a 16 year old white pine plantation. No reference could be found regarding stand density or volume for this stand.

Rogerson Model

The only data available for the nine initial sites other than that originally collected by Rogerson in central Arkansas were potential evapotranspiration (PET) and precipitation. The original data are from three small drainages, 1.28- to 1.63-acres in size, that have a northeast aspect and a 15 percent slope. The soils are stony loams and two and one-half to three feet deep. They are moderately permeable and have low water storage capacities. Average annual precipitation is about 55.0 inches and is fairly evenly distributed throughout the years. Annual water yield averages about six acre-inches per acre. The vegetative canopy is shortleaf pine and the understory is mixed hardwood (Rogerson, 1976). The Rogerson model annual water yield estimates will approximate the combined effects presented by the original data and can be used within reasonable limits to estimate water yields on similar sites.

PET varies with geographic location and climate but sensitivity analysis of PET with this model, using an approximate Southeastern range of 29 to 39 inches per year, showed evapotranspiration and deep seepage were effected more than water yield. An annual precipitation range of 43.47 to 75.06 inches was used over the PET range while all other inputs were held constant. High annual precipitation, greater than 70 inches, was the only cause of significant annual water yield increases and this was because of soil saturation. This, however, was not felt to be significant because such high annual precipitation is rare in most of the Southeast. PET data will be held constant for all study sites for this reason and because PET data is difficult to input into the Rogerson model. The annual PET used is 39.66 inches.

The soil water deficits and seepage rates were impossible to obtain except for the original test drainages. They would have to be measured at each study site, a task that is financially infeasible. Dr. Rogerson stated in personal communication that the original soil water data will suffice for this study since gross approximations of effects are required and not exact responses. A computer printout of the data inputs is found in Appendix F.

Precipitation data for the three study sites were gathered from U. S. Weather Service and NOAA publications. Three years of precipitation data were selected for each of the nine initial study sites; one year above average; one year below average; and one year near average. The above and below average years had to be at least 10 inches off the historical average to insure an adequate annual water yield range that could be subjected to simulated SPB attacks.

Final simulation runs were made for each year of precipitation data at each of the final three study sites. Runs were made at 0, 60, 120, and 200 sq. ft./acre basal area and curves were fitted to each precipitation year. An example is shown in Figure 2. SPB-caused annual per acre water yield changes, in acre-inches per acre, can then be estimated by starting at a given stand's initial basal area and sliding to the left on the horizontal axis to the after-attack basal area. The difference in the water yields at each point is the estimate of changes caused by the SPB. Water yield analysis will focus on 90 and 150 sq. ft./acre with uniform 10 percent basal area reductions rising to 100 percent in 10 percent increments. This data will be interpolated from the graphs and presented in tabular form.

The Rogerson model cannot account for SPB spot location or the probability of spot clustering so it must be assumed that SPB attacks occur uniformly over the entire watershed. This will permit the analysis of SPB attacks on mixed stands by observing the 10-50 percent reductions in total basal area, but any proportion of pine-hardwood mixture could be examined.

PROSPER

PROSPER's role is limited but its results are meaningful. Only one input data set could be found consequently only one study site could be analyzed. This means that only one physical and climatic data set will be used with three distinct precipitation data sets.

The data are from Watershed 18 at the Coweeta Hydrologic Laboratory, Franklin, NC. The watershed is 30.9 acres, and has a northwest aspect, a 22 degree slope, deep loamy soils underlain by granitic bedrock, and 77.16 inches of precipitation during the mean water year (May-April) (Swift et al., 1975).

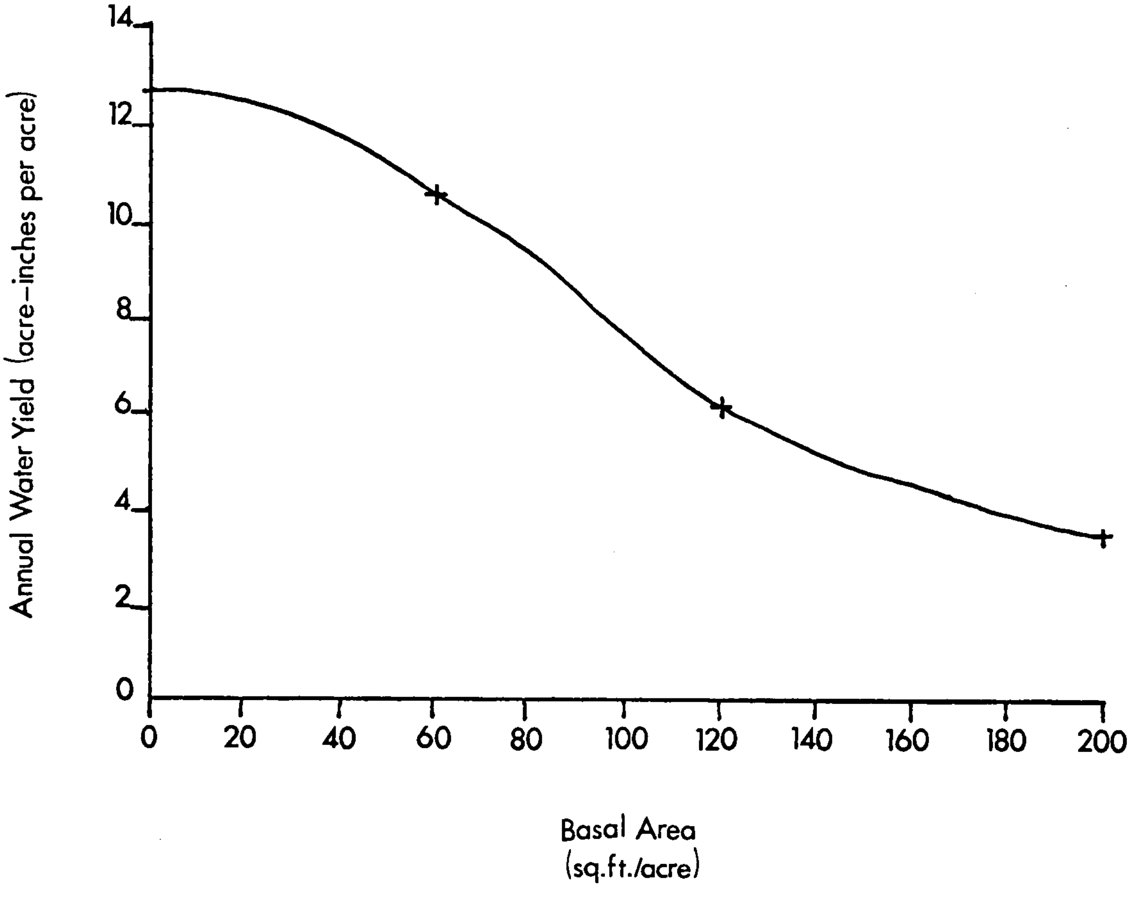

Figure 2. Hypothetical example of basal area - annual water yield relationships based on annual precipitation.

The same annual precipitation data will be used as with the Rogerson model. Simulated SPB attacks will use leaf area index (LAI). LAI is the ratio of foliage surface area to land surface area. Very little is known of LAI-stand density relationships, especially for conifers, so this study will use LAI data gathered by Swift et al. (1975). They are from a regrowing clearcut of unknown age and a 16 year old white pine (P. strobus) plantation. This will give a gross indication of the annual water yield range that would exist between a regrowing clearcut and a young white pine plantation. The LAI data are: (a) regrowing clearcut: LAI (summer) = 0.75, LAI (winter) = 0.50 and (b) 16 year old white pine plantation: LAI (summer) = 12.00, LAI (winter) = 6.00.

Haan Model

Data are readily available for the Haan model but matching the physical characteristics of the study sites with those sites used by Haan (1975b) is difficult. The study site's geography, geology, soils, and climate were noted and each Haan model run was fitted with the best approximation of study site conditions available (Appendix G). This matching process was done because collecting field data was precluded financially.

Annual precipitation data were the same as for the other models and evapotranspiration data were calculated by Haan using the Thornwaite (1948) method. Trial runs showed the model is sensitive to PET changes, therefore, PET data were collected for each study site. The soil water variables sensitivity were tested by exceeding Haan's extremes (1975b, p. 16) for them while all other variables were held constant. Large changes in water yield occurred when (a) the maximum infiltration rates were low (less than 0.27 inches/hour), (b) when maximum less readily available moisture fell below 1.0 inch, and (c) when there was an exceedingly high fraction of seepage becoming water yield. (Values above 72 percent inflated water yield predictions). The data selected for the final three study sites are well within Haan's extremes so no extraordinary results are expected.

This model will be used primarily to establish annual water yield ranges for each final study sites and not SPB attack effects because the Haan model does not have a vegetation function and, therefore, cannot simulate vegetation changes that might occur with SPB attacks. The soil water data will also be assessed to check their effects an annual water yield. A priori reasoning leads one to believe that definitive relationships will not be drawn from comparisons with the Rogerson or PROSPER results, but even so, the Haan results will be reviewed within the context of each site's data set.

In summary, the quantification of annual water yield changes will use three models. The Rogerson model will estimate annual water yield changes on the three study sites using site specific precipitation data and a basal area function that ranges from 0 to 200 sq. ft./acre. PROSPER, the most intricate of the three models, will use LAI to simulate annual water yield changes caused by vegetation reduction. Finally, the Haan model, because it has no vegetation function, will be used to determine annual water yield ranges for the study sites as they are characterized by specific PET, precipitation, and soil water data. The major analytical emphasis will be placed on the Rogerson estimates because of the basal area function and its ability to cover a wider range of forest conditions. Site characteristics, as expressed in the soil water and geographic data of each model, will be analyzed to check their effects on annual water yield.

Qualitative Analysis

The hydrologic components that cannot be dealt with through simulation are water quality and its determinants, erosion, nutrient loss, and water temperature. These components must be qualitatively analyzed by applying the accumulated knowledge of watershed research. The citations in the Literature Review are the foundation of the qualitative analysis which will deal mainly with direction (+, 0, -) and possible magnitude of effects that SPB attacks may have on a watershed with a given set of characteristics. This mean generalizations will be used that fit infestations occurring with the study sites' vegetative, climatic, edaphic, and topographic conditions. Generalizations will tell other investigators in a simple fashion whether SPB attacks will cause changes in a given hydrologic component and this may preclude some unnecessary fieldwork. The qualitative analysis will be made independently of the model's annual water yield estimates because of the nature of these components and the inability of this study to directly measure the changes that would be associated with a given SPB attack level.

Economic Valuation

It is difficult to select and defend a value for water at the edge of a watershed (raw water) because there has been little research or discussion directed at raw water valuation although much has been done for water that has been transported, treated, and made readily available for human use. Raw water valuation will be discussed in terms of shadow pricing and residual imputation.

Raw water values have been derived by applying a shadow pricing technique. Timber and timber growth foregone are usually the surrogates for the shadow prices (Worley and Patric, 1971; Brown et al., 1974; Calish et al., 1978). The values derived by shadow pricing are site and time specific. For example, Calish et al. (1978) show that water has a higher unit value for Douglas-fir rotations of less than 10 years due to timber growth foregone. Worley and Patric (1971) came to analogous conclusions in West Virginia experiments. They stated that water produced by intensive, high percentage timber removal operations gave raw water its maximum values and low percentage removals gave the least. A zero percent removal had a zero water value because no timber growth was foregone.

Such a valuation technique is infeasible for a number of reasons. First, it involves the construction of value schedules for each site, a knowledge of forest management schemes, and the SPB attack level. This is infeasible due to the magnitude of site characteristics found in the SPB range, the diversified management schemes, and the heterogeneous forest product markets that may be well represented in one area and not in another.

Even if such a valuation technique was workable there are several factual and theoretical questions that must be addressed. First, this shadow pricing technique only values raw water from the supply side of the market. True economic market values can only be assigned through the interaction of supply and demand forces in the marketplace. Second, it is illogical to assume that a commodity becomes more valuable the more expensive the production process as the Worley and Patric (1971) method holds. For example, in a competitive market the high cost producer will be forced out of business by those who can produce the same commodity at lower cost.

There is, however, a small thread of logic that exists in the Worley and Patric (1971) method. Demand may be introduced by decision makers. This, essentially, is one man's valuation decision based on trade-offs between timber and water production. It is a managerial decision based on a given set of objectives. However, SPB attack is a random occurrence and is not a managerial decision to produce water. Therefore, timber growth foregone does not reflect managerial decision makers' demand. The shadow pricing method will, therefore, not be used for all the preceding reasons.

The second valuation method, residual imputation, could conceivably be used to value raw water but research with this has only valued water as close to the watershed as municipal intake pipes (Young and Gray, 1972). Such values are derived by taking the municipal retail water price and subtracting storage, treatment, and transportation costs associated with getting the water from the intake pipe to the household. No accounting is made for getting water from the watershed to the intake pipe. This valuation procedure will conceptually give a water value at the intake pipe that would be the same for all uses. Still, such a value is not derived at the watershed. It is logical to assume that if time and opportunity costs were subtracted from the intake pipe value that a raw water value would be derived but no work could be found to substantiate this.

Residual imputation values have one major fault in common with shadow pricing, values are only derived from the supply side. Therefore, as with the shadow pricing method, values derived by residual imputation are invalid.

The preceeding discussion produces a preponderence of evidence declaring the raw water valuation techniques to be invalid and unacceptable measures of value. Since these techniques are invalid and no competitive human uses conceptually exist for raw water a zero value must be valid. Gregory (1972) and Young and Gray (1972) are also proponents of zero raw water values. Young and Gray state in summary: "So long as resources are available in unlimited supply they may be considered "free" in an economic sense. However, as soon as scarcity becomes a problem, resources begin to take on a positive economic value because of competition for their use." And Gregory (1972) similarly states: "It is not true that the water at the intake value is valueless; it simply has no regular <u>market price</u> and is viewed, essentially, as a free good."

Economic values will not be given to water quality (erosion, nutrient loss, or water temperature) because there has not been sufficient research in these areas to develop valid economic values and also because their changes will not be quantified in this study.

In conclusion, raw water has been accorded a zero economic value for annual water yield change evaluation and the remaining components have no assigned economic value. SPB control benefits and costs in the watershed framework will, therefore, be nonexistent. However, special cases will be reviewed under the assumption of a nonzero raw water value.

RESULTS AND CONCLUSIONS

Rogerson Model

The Rogerson model annual water yield estimates are graphically presented in Figures 3, 4, and 5 for Corinth, MS, Dalton, GA, and Blackstone, VA, respectively. The data points used to construct these curves are found in Appendix G. Each graph displays the basal area-annual water yield relationships for the three years of precipitation data used for each study site and are drawn from simulation runs at 0, 60, 120, and 200 sq. ft./acre basal area.

The graphs, in general, show that annual per acre water yields are highest when no timber is present on the watershed, 0 sq. ft./acre basal area, and gradually decrease to a low at 200 sq. ft./acre basal area, the model's maximum. Also, annual per acre water yields begin leveling out around 120 sq. ft./acre basal area.

Annual per acre water yield changes were drawn from Figures 3, 4, and 5 by taking 10 percent total basal area reductions from initial basal areas of 90 and 150 sq. ft./acre (Tables 7 and 8).

The tabular data will be used to do two things: (a) estimate annual per acre water yield changes that may be caused by SPB attacks representative of the east Texas data and (b) estimate annual per acre water yield changes for attack levels outside the east Texas data range.

Water yield changes can be estimated for SPB spots in 90 and 150 sq. ft./acre basal stands by reading the annual change from Table 7 or 8 and multiplying by the spot size. SPB spots in the east Texas study averaged less than six per 1000 acres and about 0.05 acres in size.

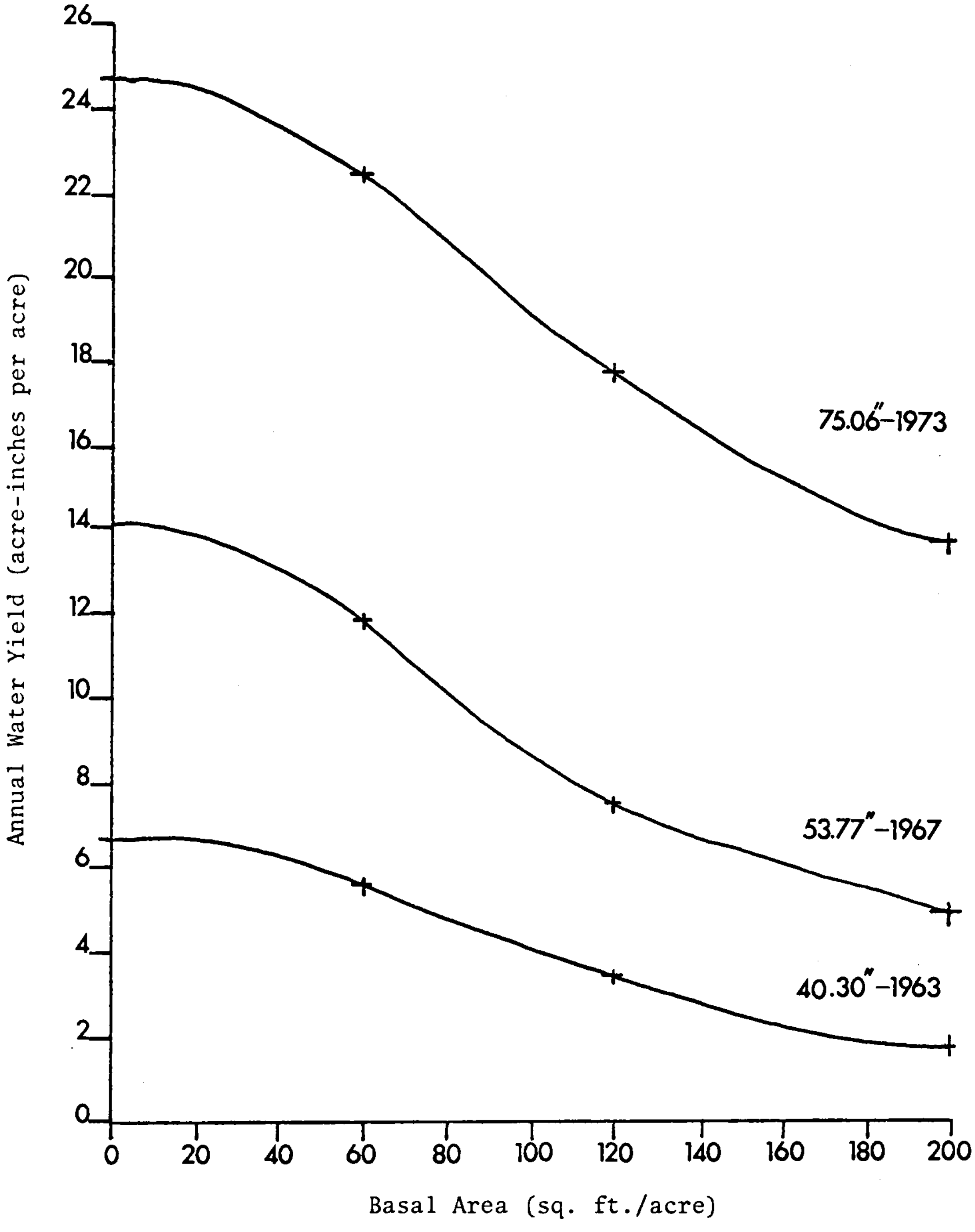

Figure 3. Basal area - annual water yield relationships for an above average site (Corinth, MS).

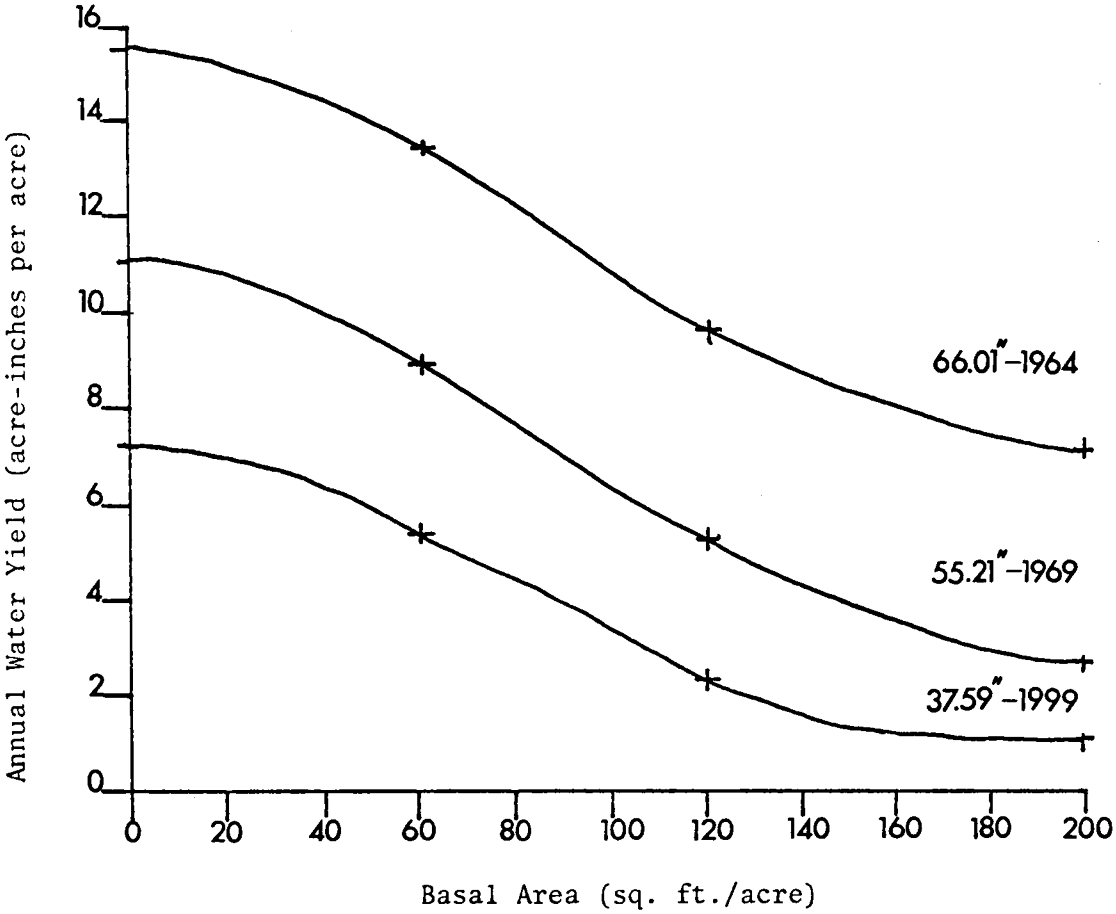

Figure 4. Basal area - annual water yield relationships for an average site (Dalton, GA).

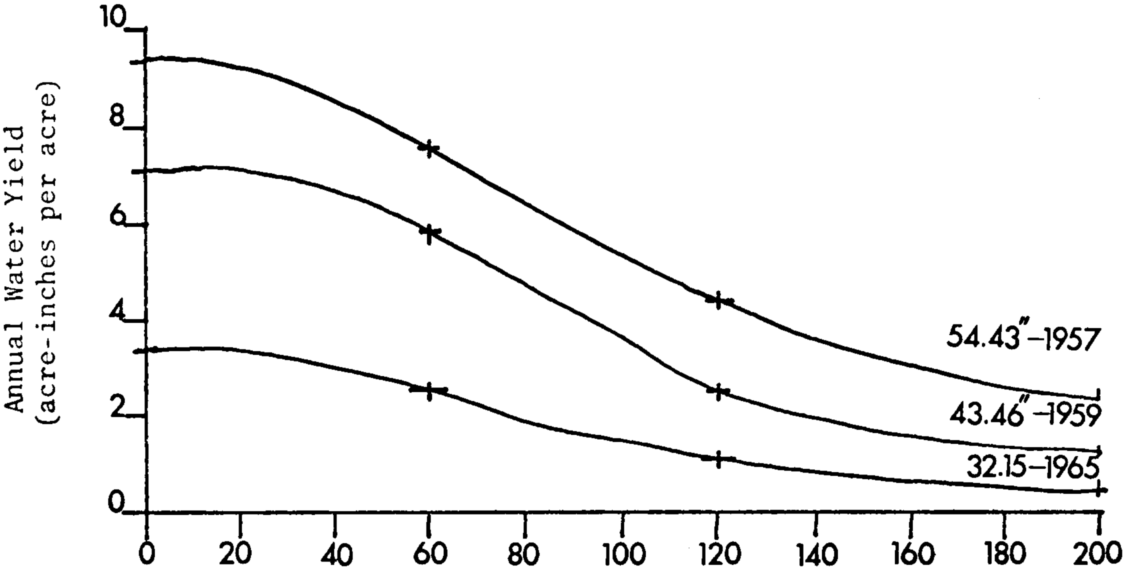

Figure 5. Basal area - annual water yield relationships for a below average site (Blackstone, VA).

Table 7. Rogerson model annual water yield change estimates: 90 sq. ft./acre initial basal area.

Percent Reduction of Total Basal Area	Annual Water Yield Changes (acre-inches/acre)								
	High Site (Corinth, MS) Annual Precipitation			Average Site (Dalton, GA) Annual Precipitation			Low Site (Blackstone, VA) Annual Precipitation		
	Below Average	Near Average	Above Average	Below Average	Near Average	Above Average	Below Average	Near Average	Above Average
10	0.4	0.6	0.6	0.5	0.5	0.6	0.2	0.4	0.5
20	0.5	1.2	1.2	1.0	1.1	1.2	0.4	0.9	1.0
30	0.9	2.0	1.9	1.4	1.7	1.7	0.6	1.3	1.5
40	1.2	2.7	2.8	1.9	2.2	2.4	0.9	1.8	2.0
50	1.6	3.4	3.6	2.4	2.8	2.8	1.2	2.2	2.5
60	1.8	3.8	3.8	2.7	3.1	3.2	1.4	2.5	2.9
70	2.0	4.2	4.1	3.0	3.5	3.5	1.5	2.8	3.1
80	2.2	4.5	4.5	3.2	3.9	3.8	1.7	3.0	3.4
90	2.4	4.7	4.7	3.4	4.1	4.1	1.8	3.1	3.7
100	2.4	4.9	4.9	3.6	4.2	4.4	1.9	3.2	3.8

Table 8. Rogerson model annual water yield change estimates: 150 sq. ft./acre initial basal area.

Percent Reduction of Total Basal Area	Annual Water Yield Changes (acre-inches/acre)								
	High Site (Corinth, MS) Annual Precipitation			Average Site (Dalton, GA) Annual Precipitation			Low Site (Blackstone, VA) Annual Precipitation		
	Below Average	Near Average	Above Average	Below Average	Near Average	Above Average	Below Average	Near Average	Above Average
10	0.4	0.5	0.9	0.3	0.5	0.4	0.1	0.3	0.4
20	0.9	1.0	1.9	0.8	1.3	1.2	0.3	0.8	1.1
30	1.4	1.7	2.8	1.6	2.0	1.8	0.5	1.5	1.6
40	1.9	2.8	4.0	2.3	3.1	2.8	0.8	2.3	2.4
50	2.4	3.8	5.2	3.2	4.2	3.8	1.1	3.0	3.2
60	3.0	4.2	6.4	4.0	5.2	5.0	1.7	3.9	4.2
70	3.5	6.1	7.4	4.7	5.8	5.7	2.0	4.5	4.9
80	4.0	6.9	8.0	5.2	6.5	6.2	2.3	5.0	5.5
90	4.3	7.3	8.6	5.6	7.0	6.7	2.5	5.3	5.9
100	4.8	7.7	9.0	5.9	7.3	7.2	2.7	5.5	6.3

The gross maximum annual water yield changes, assuming 100 percent pine and mortality (100 percent basal area reduction) are 0.245 acre-inches per spot (4.9 x 0.05) in a 90 sq. ft. basal area stand and 0.45 acre-inches in a 150 sq. ft. basal area stand. The respective figures for 1,000 acres are 1.47 and 2.70 acre-inches per year.

An acre-inch of water is approximately 27,154 gallons so the respective volumes for the two initial basal areas are 39,917 and 73,316 gallons per 1000 acres. These values are insignificant based on present watershed knowledge. The gross changes may be positive in a per spot or watershed assessment but the net changes could be zero because surviving trees and understory vegetation may use the additional water made available by SPB pine damage. Due to the insignificance of these changes calculations will not be presented for smaller total basal area reductions on an average spot because they will be even more insignificant.

The largest spot identified in the east Texas study was 2.17 acres in size. The gross maximum annual water yield increase for such a spot is 10.63 acre-inches for a 90 sq. ft./acre basal area stand and 18.53 acre-inches for a 150 sq. ft./acre basal area stand. The impact for such changes is difficult to assess for two reasons: (a) there is a low probability of finding such a spot size according to the east Texas date (5 or 477 total spots were greater than one acre), and (b) the significance of such a spot size will depend on the watershed's size and the spot's location within the watershed. The water volumes that may be produced by each spot are significant in themselves but the amount reaching the stream will depend on (b) above. For example, the net water yield changes at the stream would probably be zero for a spot this size if it occurred in the middle of the watershed because of the buffering capacity of the soil and surviving vegetation. On the other hand most of the additional water would reach the stream if the spot occurred at streamside but its significance due to this would probably be quite limited because of the amount of water given to streamflow by the rest of the watershed.

The water yield changes associated with the east Texas SPB activity can be generally regarded as insignificant and, at times, possibly unmeasureable. However, this data may not characterize SPB activity throughout its range. For example, SPB activity could move from the endemic stage to massive epidemic proportions virtually instantaneously. If this occurred large acreages of pine timber could be killed or damaged before control strategies could be implemented.

As an illustration suppose a 500 acre watershed with 90 percent pine basal area averaging 150 sq. ft./acre was attacked by the SPB with 100 percent pine mortality. This means a 90 percent reduction in total basal area. Hence the maximum and minimum annual water yield increase range for this infestation would be 4300 to 1250 acre-inches (116,762,200 and 33,942,500 gallons). The addition of this much water to streamflow over a year has some interesting implications, both positive and negative. Such an infestation during an above average precipitation year could possibly contribute to local flooding and during a below average year provide enough additional water to ease any existing drought conditions. Therefore, water yield changes resulting from large infestations can be large enough to produce significant positive or negative effects depending on the circumstances.

In summary, the east Texas SPB activity will cause insignificant or unmeasureable annual water yield changes based on the Rogerson model estimates. However, as the absolute SPB spot size increases the changes begin to take on greater significance based on the amount of pine killed, the total number of spots, and the watershed's size. The Rogerson model estimates could be used as a general guide to estimate the annual water yield changes resulting from a given SPB activity level. These results may also be used to estimate the water yield impacts occurring from SPB activity in mixed pine-hardwood watersheds.

PROSPER

The PROSPER annual water yield estimates compare a regrowing clearcut and a 16 year old white pine plantation of unknown density or volume for the three study sites (Table 9). The annual water yields over the study sites' precipitation range is unusually high for the regrowing clearcut in all years except the below average year of Blackstone, VA and for the 16 year old white pine plantation in the above average year for Corinth, MS. The large regrowing clearcut responses were unexpected because: (a) the deep loamy soils on the watershed should store more water and, therefore, release it to streamflow at a moderately staggered rate and (b) a regrowing clearcut should have reestablished sufficient vegetation to transpire and intercept enough water to moderately reduce streamflow. The white pine plantation's high yield in Corinth, MS's above average precipitation

Table 9. PROSPER annual water yield estimates.

		Annual Water Yield (acre inches/acre)	
Study Site	Annual Precipitation (inches)	Regrowing Clearcut	16 Year Old White Pine Plantation
High Site	75.06	51.65	25.55
(Corinth, MS)	53.77[a]	31.87	6.30
	40.30	16.97	0.36
Average Site	66.01	41.63	13.58
(Dalton, GA)	55.21[a]	31.10	5.17
	37.59	14.98	0.05
Low Site	54.43	30.01	5.24
(Blackstone, VA)	43.46[a]	19.99	0.10
	32.15	7.97	0.04

[a] Near average precipitation.

year is partially explained by unusually heavy precipitation in March and November when transpiration rates are generally lowest.

The regrowing clearcut estimates are explained to a certain degree by site characteristics. First, the soils are very permeable, deep, and steep (22°), thus, allowing rapid infiltration and entry into the stream system. Second, the site has a northwest aspect which means less solar radiation and, therefore, less evapotranspiration (Douglass and Swank, 1975). Aspect and solar radiation are not considered in the other models and may partially explain the unusually high regrowing clearcut annual water yields.

The unusually low 16 year old white pine plantation annual water yields apparently result from the pines intercepting and/or using most of the annual precipitation. First, studies have shown that pines intercept more precipitation year round than hardwoods and leaf interception is specifically considered in this model. Specific inclusion of these may account for the low 16 year old white pine plantation annual water yields.

PROSPER's estimates allow only one broad conclusion: watersheds with permeable soils, northern aspects, and steep slopes are likely to have greater water yield responses than watersheds with less permeable soils and western or southern aspects. This conclusion, however broad, can be made based on the site specificity of the input data and holds regardless of whether the SPB attacks.

Haan Model

The Haan model estimates will be analyzed solely on the basis of the input data found in Appendix H and each sites' PET (Table 10). This is necessitated by the lack of a vegetation function in this model. These data show several relationships between the fraction of seepage becoming runoff (water yield), soil water storage capacities, and PET. These relationships were expected and the simulations bore them out.

First, soils with higher seepage fractions becoming water yield generally had higher water yields. This is true by definition but was not readily apparent due to different data combinations. Second, higher soil water storage capacities will allow more water to be stored in the soil preventing rapid passage through the soil if it is not saturated and, hence, less rapid water yield responses to precipitation events. Also, water yields will possibly be lower because of the increased chances for vegetation and solar radiation to draw moisture from the soil. Finally, water yield varies inversely with PET. Specifically, the site with the highest PET will, on the average, have the lowest water yields. These relationships are further evidence of the importance of soil parameters and their relation to water yields.

Implications of Combined Estimates

The Rogerson model estimates will be examined as they relate to the east Texas SPB activity data and the PROSPER and Haan model estimates will be examined as they relate to the physical and climatic conditions.

The Rogerson model simulations show that SPB activity as characterized by the east Texas data causes insignificant and often unmeasureable water yield changes and that the significance of water yield changes caused by activity beyond the bounds of the Texas data

Table 10. Haan model annual water yield estimates.

Study Site	Annual Precipitation (inches)	Annual Water Yield (acre inches/acre)
High Site	75.06	37.48
(Corinth, MS)	53.77[a]	16.79
	40.30	7.95
Average Site	66.01	21.15
(Dalton, GA)	55.21[a]	16.16
	37.59	8.43
Low Site	54.43	18.29
(Blackstone, VA)	43.46[a]	12.61
	32.15	6.79

[a] Near average precipitation.

would rely on five things: (a) number of spots, (b) size of spots, (c) location of spots in the watershed, (d) size of the watershed, and (e) annual climatic conditions. Further, streamside SPB activity has the highest probability of causing significant water yield changes.

The PROSPER estimates emphasize that aspect, slope steepness, and soil permeability affect water yield response. Water yield response to SPB attacks will be greatest with northern or eastern aspects, relatively steep slopes (greater than 20°), and very permeable soils. The northern and eastern aspects will yield more water because there is less solar radiation to cause evaporation. Steep slopes will allow for more rapid lateral water flow due to gravity and permeable soils offer less resistance to water flow unless they are near saturation. Therefore, water flows through the soil profile more rapidly. So, an SPB attack on this type of site may produce a greater annual water yield change that will be recorded sooner than under other conditions.

The Haan results provide further evidence that soil characteristics, specifically seepage rates and soil water capacities, affect water yield. They also show how PET and water yield are related. The Haan model's seepage function shows that soils with higher seepage rates will have higher water yields if all other inputs are equal. Also, higher water storage capacities will slow down water yield responses provided the soil is not already saturated. Finally, high annual PET's will decrease water yield and vice versa. In general, PET varies seasonally and must be examined as such. PET is highest in the summer months and generally the cause of low flows during this period. PET will usually be a major factor in regulating streamflow when vegetation is dense, therefore, reductions in vegetation will allow more water to be available for the surviving vegetation and streamflow.

In conclusion, the three sets of estimates produce a number of facts concerning water yield increases and how possible SPB impacts may be affected by them. Water yield increases will be maximized when there is: (a) streamside SPB activity, (b) shallow, permeable soils, (c) steep slopes, (d) northern or eastern aspect, (e) average or above average precipitation, and (f) pine mortality during months when PET rates are highest (generally the summer).

Qualitative Assessment

Water quality and several quality measurement parameters will be reviewed independently of the simulations. Water quality, in general, and erosion rates, in particular, are not adversely affected by management practices as severe as clearcutting but rather only by the soil disturbance caused by the human activity (Aubertin and Patric, 1974; Hornbeck, 1967; Dickerson, 1975). Erosion, generally considered to be the major contributor to reduced water quality because of the addition of dissolved solids and nutrients to streamflow, is usually always attributed to the road systems that traverse the forest. Therefore, increased erosion rates are not likely to be caused by the SPB but by human activity such as salvaging SPB damaged timber.

Natural nutrient loss rates are generally dependent on the vegetative cover and the soil parent material. Although nutrient budgets are site specific it is generally agreed that various management practices, including clearcuts, will not increase nutrient loss rates sufficiently to affect municipal use patterns or wildlife habitat (Swank and Douglass, 1977; Pierce et al., 1970). Nitrate-nitrogen is the nutrient most sensitive to human or natural disturbances and significant losses may result in long-term site quality reductions (Sopper, 1971; Swank and Douglass, 1977). These losses may occur from massive soil disturbances and a lack of vegetative cover. Therefore, the single most likely method of significantly increasing nutrient loss and reducing water quality is through the complete denudation of a watershed (U. S. Forest Service, 1971; Swank and Douglass, 1975). However, since the SPB is incapable of watershed denudation, it is concluded that it will not affect nutrient loss rates in a significant fashion, except possibly in the case of nitrate-nitrogen where short-term site quality reductions might occur if understory vegetation does not quickly occupy spots destroyed by the SPB.

Water temperature is the final hydrologic component examined. Conclusive research shows that water temperatures are only affected by the removal of streamside vegetation. Streamside vegetation removal may raise the average stream temperature which could cause at least two adverse effects. First, some species of fish, particularly trout, can be abnormally affected and even killed by sustained temperatures that may only be a few degrees above their upper threshold. Second, increased temperatures may induce increased aquatic plant growth which may clog small streams. Higher temperatures will also increase decomposition rates which will reduce the amount of available oxygen for aquatic animal life (Douglass and Swank, 1975; Anderson et al., 1976). Therefore, SPB can affect water temperatures but only when it destroys enough streamside timber to sustain an average temperature rise. This seems a low probability event given the Texas spot size distribution. The primary impacts will affect decomposition rates and aquatic plant and animal life.

In conclusion, it is the opinion of this author that the SPB will not cause any significant impacts on hydrologic components other than water yield except in isolated streamside cases. This conclusion has been reached because hydrologic impacts tend to be magnified or quickened when streamside changes take place. Streamside changes, whether vegetative or soil disturbance, bear immediate effects because there is no buffering of the impacts before they reach the stream. Therefore, this is where the SPB has the greatest potential for causing changes in the hydrologic components reviewed.

Economic Valuation

The zero value assigned to raw water precludes including SPB control program benefits to the watershed. However, water yield changes from SPB activity may cause benefits or costs to accrue away from the watershed in special cases. Brief illustrations are given of two cases.

The first case involves flooding where water is given a nonzero shadow price because it is equated with the value of flood damages prevented. The volume of flood water attributable to local SPB activity during nonepidemic periods would ordinarily be very small when compared to the volume of water flowing off watersheds with no SPB activity. Therefore, flood damages prevented by SPB control would be an insignificant fraction of the whole and the program would produce insignificant benefits.

The second case involves drought conditions. Water supply increases during such times will accrue benefits to municipal users, wildlife, hydroelectric plants, waste disposal units, and farmers dependent on irrigation. SPB control may produce costs for any one of these by withholding water from streamflow that could help dissipate some of the drought effects. Water will have positive values for all of the uses but the limiting factor for a significant price times quantity (P x Q) end product is quantity. As with the flood damage example, the water volume attributable to SPB activity will normally be so small as to be an insignificant fraction of total water volume. Therefore, the costs of SPB control during drought would normally be so insignificant that their measurement would be impractical.

Finally, the water quality components, erosion, nutrient loss, and water temperature, were not given economic values and, therefore, will not factor in any SPB control program benefit-cost accounting.

SUMMARY

Water yield impact estimates were made for southern pine beetle (SPB) pine mortality using three hydrologic simulation models: the Rogerson model, PROSPER, and the Haan model. East Texas SPB activity data were analyzed, specifically the average and largest spot sizes. A spot is an area of land considered to be entirely infested by the SPB. For the average spot size, 0.05 acres, and a 100 percent total basal area reduction, gross annual water yields increased 0.245 and 0.45 acre-inches for stands with 90 and 150 sq. ft./acre basal area, respectively. The largest spot was 2.17 acres and produced increases of 10.63 and 19.53 acre-inches under the same stand and mortality parameters. These water yield increases are likely to be insignificant because they would be absorbed by the buffering capacity of surrounding vegetation and, therefore, would not become streamflow. They could be significant for larger spots if located at streamside. A 90 percent total basal area reduction was applied to a 500 acre watershed for illustrative purposes to estimate gross annual water yield changes. This reduction caused large annual increases from 90 and 150 sq. ft./acre stands which could have significant economic implications under the proper conditions.

The Rogerson estimates and their implications allow the development of a check list to determine the direction and possible magnitude of water yield changes caused by a given SPB activity level. They are: (a) number of spots, (b) size of spots, (c) location of spots in the watershed, (d) size of the watershed, and (e) annual climatic conditions.

The PROSPER and Haan model estimates show the importance of topographic, edaphic, and climatic characteristics that can be used in association with the forementioned list. SPB attacks have the greatest probability of causing significant water yield increases when: (a) the watershed has a northern or eastern aspect, (b) slopes are greater than 20 degrees, (c) soils are very permeable and have low water storage capacities, (d) pine mortality peaks during the months with the highest PET, and (e) annual precipitation is above or near average.

Published research was surveyed to determine the possible impacts of SPB attack on water quality and three quality parameters - erosion, nutrient loss, and water temperature. It was determined that only streamside SPB activity has potential impacts on any of these components. The potential impacts may take the form of increased dissolved solids and nutrients entering the stream and in higher average water temperatures. Such impacts may reduce overall water quality and may even be harmful to such aquatic life as trout.

Therefore, it is concluded that SPB activity, as characterized by the east Texas data, will cause insignificant water yield increases. The greatest potential for significant changes is in streamside SPB activity. The significance of SPB activity of greater magnitudes will depend largely on the set of attack, topographic, edaphic, and climatic characteristics previously mentioned. The findings of this study parallel those of a similar study involving the Douglas-fir tussock moth (Hemerocampa pseudotsugata McD.) (USDA, 1977).

Water at the edge of a watershed (raw water) was given a zero economic value, thus, precluding the accrual of SPB control benefits in the watershed framework. However, special cases were examined where raw water could be given a nonzero value and it was determined that SPB control would accrue insignificant benefits because water produced by average SPB activity would be a small fraction of the total water volume flowing from a watershed.

Further study is needed to develop hydrologic simulation models that give accurate results with easily accessed data, for example, data from soil surveys and U. S. Weather Service and NOAA publications. These models should also feature nonuniform vegetation change input parameters. This would make the assessment of vegetation changes in various parts of a watershed a simpler task that would rely on empirical data and not speculation.

Finally, this report can only give a general idea of the magnitude and direction of SPB-caused hydrologic impacts, therefore, this author believes that the only way to actually assess such impacts would be through fieldwork on gauged watersheds under SPB attack.

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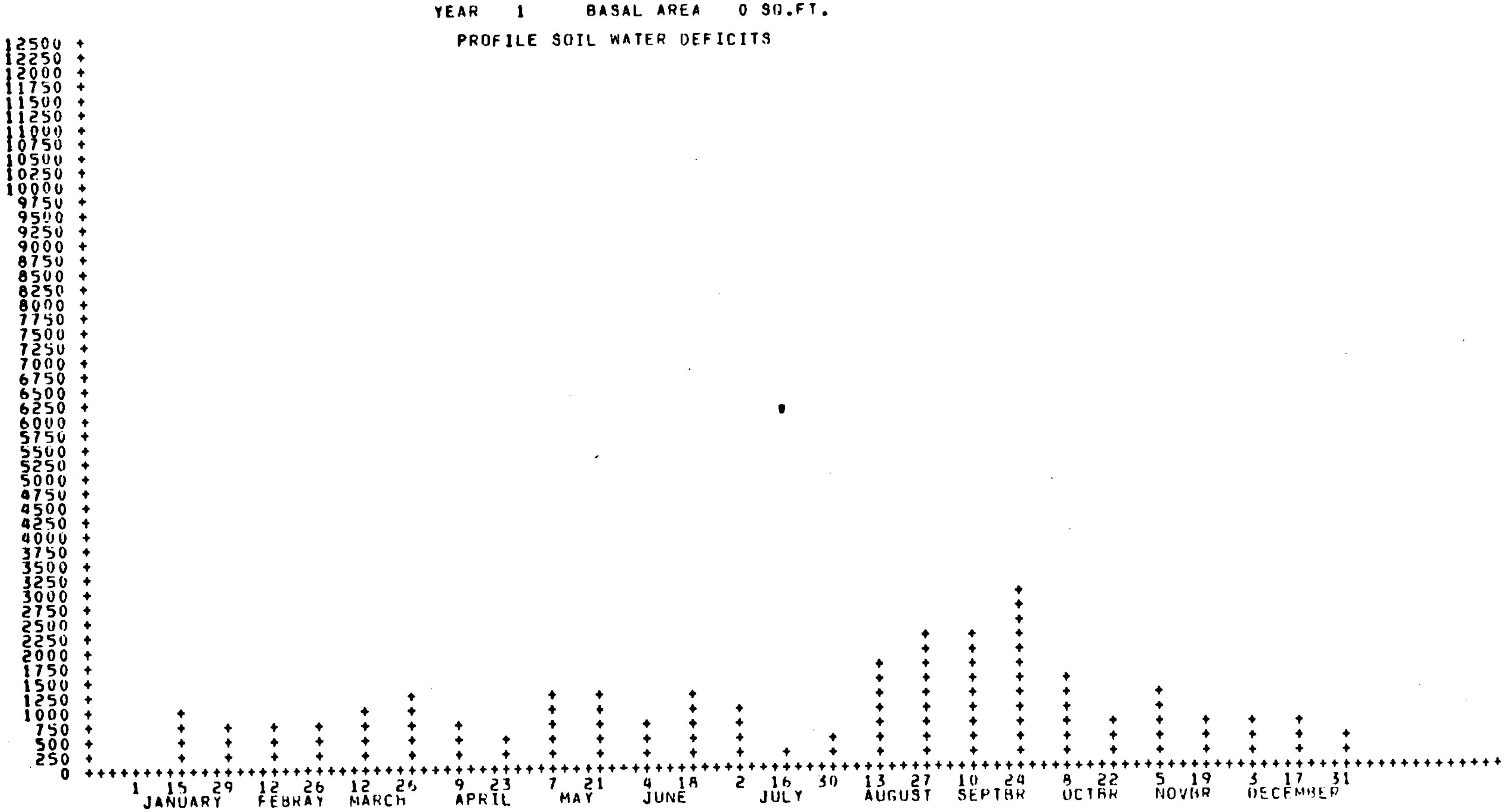
APPENDICES

Appendix A. Rogerson model sample computer output.



Appendix A. Rogerson model sample computer output. (Continued)

```
***** TOTAL RUN TIME (INCLUDING ASSEMBLY) = .13 MINUTES *****
                                  YEAR   1

              PRECIPITATION AND RUNOFF SUMMARY DATA

      DAY NUMBER      PRECIP      THRUFAL      RUNOFF      SWD PROFIL
           1           0.78        0.78         0.10         0.30
           2           0.01       -0.01         0.0          0.02
           8           0.20        0.19         0.0          0.65
          15           0.02        0.00         0.0          0.84
          16           0.48        0.47         0.0          0.88
          21           0.01       -0.01         0.0          0.72
          22           0.45        0.44         0.0          0.78
          34           0.18        0.16         0.0          0.99
          35           0.74        0.74         0.0          0.86
          36           0.01       -0.01         0.0          0.28
          40           0.04        0.02         0.0          0.63
          43           0.04        0.02         0.0          0.77
          44           0.57        0.57         0.0          0.80
          45           0.14        0.12         0.0          0.36
          46           0.14        0.12         0.0          0.37
          49           0.08        0.06         0.0          0.55
          54           0.16        0.14         0.0          0.79
          62           0.17        0.15         0.0          1.03
          64           0.08        0.06         0.0          0.97
          65           0.52        0.51         0.0          0.95
          69           0.01       -0.01         0.0          0.72
          70           0.01       -0.01         0.0          0.79
          71           0.02        0.00         0.0          0.85
          85           0.19        0.18         0.0          1.42
          86           1.20        1.20         0.16         1.28
          88           0.02        0.00         0.0          0.49
          89           0.75        0.75         0.04         0.57
          92           1.14        1.14         0.28         0.43
          93           0.04        0.02         0.0          0.02
          94           0.01       -0.01         0.0          0.21
```

Appendix A. Rogerson model sample computer output. (Continued)

```
100        0.01    -0.01     0.0      0.70
101        0.28     0.27     0.0      0.85
102        1.37     1.37     0.39     0.66
103        0.05     0.03     0.0      0.05
104        0.11     0.09     0.0      0.23
108        0.05     0.03     0.0      0.62
109        0.73     0.70     0.01     0.67
110        0.04     0.02     0.0      0.20
111        0.30     0.27     0.0      0.34
112        0.19     0.17     0.0      0.26
113        0.01    -0.01     0.0      0.28
118        0.03     0.01     0.0      0.77
121        0.01    -0.01     0.0      0.96
131        0.03     0.01     0.0      1.51
133        0.13     0.11     0.0      1.59
136        0.01    -0.01     0.0      1.63
138        0.59     0.56     0.0      1.73
141        0.15     0.13     0.0      1.35
143        0.11     0.09     0.0      1.34
151        0.67     0.64     0.0      1.70
153        0.94     0.90     0.04     1.20
164        0.41     0.38     0.0      1.32
167        0.10     0.08     0.0      1.18
182        1.01     0.97     0.0      2.18
183        0.41     0.38     0.0      1.29
184        1.33     1.28     0.28     1.01
190        0.03     0.01     0.0      0.88
191        1.31     1.26     0.25     0.97
192        0.05     0.03     0.0      0.22
193        0.03     0.01     0.0      0.38
194        0.62     0.59     0.00     0.51
195        3.37     3.28     2.15     0.20
196        0.20     0.18     0.0     -0.35
197        0.03     0.01     0.0      0.01
```

Appendix A. Rogerson model sample computer output. (Continued)

```
200        0.01      -0.01      0.0       0.13
201        1.18       1.14      0.30      0.34
202        0.36       0.33      0.0       0.02
203        0.05       0.03      0.0       0.06
206        0.35       0.32      0.0       0.57
207        0.20       0.18      0.0       0.42
208        0.21       0.19      0.0       0.42
210        0.44       0.41      0.0       0.55
211        0.10       0.08      0.0       0.34
212        0.02       0.00      0.0       0.43
213        0.01      -0.01      0.0       0.57
216        0.11       0.09      0.0       0.91
217        0.05       0.03      0.0       0.92
234        0.29       0.26      0.0       2.25
236        0.01      -0.01      0.0       2.13
239        0.27       0.25      0.0       2.34
242        0.24       0.22      0.0       2.30
243        0.35       0.32      0.0       2.15
244        0.08       0.06      0.0       1.89
248        0.12       0.10      0.0       2.10
249        0.09       0.07      0.0       2.07
272        0.42       0.39      0.0       3.26
273        2.10       2.04      0.25      2.91
281        0.10       0.08      0.0       1.60
283        0.97       0.93      0.00      1.62
287        1.41       1.36      0.32      0.99
295        0.15       0.13      0.0       0.89
296        0.26       0.24      0.0       0.83
297        0.14       0.12      0.0       0.68
298        0.01      -0.01      0.0       0.64
300        0.09       0.07      0.0       0.80
304        0.07       0.05      0.0       0.98
310        1.55       1.50      0.34      1.22
311        0.97       0.93      0.19      0.25
321        0.27       0.26      0.0       0.86
325        0.23       0.22      0.0       0.83
327        0.05       0.03      0.0       0.73
328        3.17       3.17      1.73      0.75
331        0.08       0.06      0.0       0.27
332        0.02       0.00      0.0       0.35
340        0.21       0.20      0.0       0.85
341        0.01      -0.01      0.0       0.71
346        1.01       1.01      0.11      0.93
352        0.65       0.65      0.0       0.65
353        0.94       0.94      0.20      0.20
362        0.48       0.47      0.0       0.73
```

Appendix A. Rogerson model sample computer output. (Continued)

```
                                                  *****WATER BUDGET SUMMARY*****
               PRECIPITATION     RUNOFF     EVAPOTRANSPIRATION    DEEP SEEPAGE     CHANGE IN SOIL WATER
JANUARY            1.95          0.10             0.33                2.13               -0.61
FEBRUARY           2.10          0.0              0.50                1.64               -0.04
MARCH              2.97          0.20             0.78                1.34                0.65
APRIL              4.36          0.68             1.20                3.14               -0.66
MAY                1.70          0.0              1.50                0.37               -0.17
JUNE               1.45          0.04             1.89                0.57               -1.05
JULY              11.96          3.01             2.94                4.40                1.62
AUGUST             1.33          0.0              2.34                0.31               -1.33
SEPTEMBR           2.81          0.25             1.78                0.08                0.70
OCTOBER            3.20          0.32             1.48                1.19                0.20
NOVEMBER           6.34          2.26             0.75                2.93                0.59
DECEMBER           3.30          0.31             0.30                2.69               -0.01
ANNUAL            43.47          7.18            15.80               20.79               -0.31
```

Appendix B. Haan model sample computer output.

```
          HAAN MODEL  WATERSHED RUNOFF TRIAL RUN 1    MAY 27, 1975
           1967-1968 WATER YEAR            DAILY PRECIPITATION
     OCTOBER   NOVEMBER  DECEMBER  JANUARY   FEBRUARY  MARCH     APRIL     MAY       JUNE      JULY      AUGUST    SEPTEMBER
 1   0.0       0.0       0.0       0.0       0.0       0.0       0.16      0.0       0.0       0.0       0.0       1.68
 2   0.33      0.21      0.0       0.0       0.0       0.0       0.0       0.0       0.0       0.0       0.0       0.0
 3   0.0       0.0       0.0       0.26      0.0       0.0       0.98      0.0       0.0       0.0       0.0       0.37
 4   1.06      0.0       0.0       0.0       0.05      0.0       0.0       0.0       0.60      0.0       0.25      0.0
 5   0.0       0.0       0.0       1.48      0.0       0.0       0.0       0.0       0.31      0.0       0.0       0.0
 6   0.0       0.0       0.0       0.0       0.0       0.0       0.0       0.0       0.0       0.0       0.30      0.0
 7   1.00      0.0       0.0       0.0       0.0       0.0       0.0       0.37      0.0       0.27      0.25      0.0
 8   0.0       0.0       0.0       0.0       0.0       0.0       1.00      0.24      0.0       0.0       0.0       0.0
 9   0.70      0.0       0.0       0.87      0.11      0.0       0.0       0.28      0.0       0.0       0.87      0.0
10   1.18      0.0       0.15      0.32      0.03      0.0       0.0       0.0       0.0       0.71      0.0       0.0
11   0.0       0.0       0.0       0.0       1.20      0.0       0.0       0.0       0.0       0.0       0.28      0.0
12   0.0       0.0       2.62      0.0       0.66      0.0       0.0       0.05      0.0       0.0       0.05      0.0
13   0.10      0.0       0.0       0.0       0.92      3.45      0.0       0.0       0.0       0.0       0.0       1.38
14   0.0       0.0       0.0       0.22      0.25      0.0       0.24      0.12      0.0       0.0       0.0       0.0
15   0.0       0.82      0.0       0.25      0.0       0.0       0.0       0.0       0.0       0.0       0.0       0.0
16   0.0       0.0       0.0       0.0       0.0       0.0       0.0       1.08      1.20      0.0       0.38      0.0
17   0.0       0.0       0.0       0.0       0.0       0.0       0.0       1.91      0.0       0.0       0.95      0.0
18   0.0       0.0       0.0       0.0       1.82      0.0       0.0       0.0       0.54      0.25      0.72      0.0
19   0.0       0.0       0.0       0.0       0.0       0.0       0.0       0.0       0.0       0.0       0.0       0.0
20   0.0       0.0       0.0       0.0       0.0       0.06      0.20      1.56      0.0       0.0       0.0       0.0
21   0.0       0.0       0.0       0.0       0.0       0.0       0.0       0.0       0.0       0.0       0.0       0.0
22   0.0       0.22      2.85      0.0       0.0       0.12      0.0       0.0       0.0       0.0       0.0       5.85
23   1.05      0.18      0.60      0.0       0.0       0.0       0.72      0.0       0.0       0.0       0.0       0.0
24   0.38      0.0       0.0       0.20      0.0       0.0       0.0       0.0       0.0       0.0       0.0       0.0
25   0.0       0.0       0.0       0.0       0.0       0.0       0.0       1.03      0.0       0.0       0.42      0.0
26   0.0       0.0       0.0       0.0       1.25      0.27      0.0       0.0       0.0       0.0       0.0       0.0
27   0.0       0.0       0.0       0.0       0.0       0.0       0.0       0.0       0.0       0.0       0.0       0.0
28   0.0       1.12      0.0       0.82      0.0       0.0       0.0       0.0       0.0       0.0       0.68      0.0
29   0.0       0.0       0.0       0.58      0.0       0.0       0.0       0.0       0.0       0.0       0.0       0.0
30   0.0       0.0       0.0       0.0       0.0       0.0       1.02      0.0       0.0       0.0       0.0       0.0
31   0.0       0.0       0.23      0.0       0.0       0.0       0.0       0.0       0.0       0.0       0.0       0.0


           HAAN MODEL  WATERSHED RUNOFF TRIAL RUN 1    MAY 27, 1975

           RUNOFF PREDICTIONS--NO STREAMFLOW RECORDS AVAILABLE FOR COMPARISON


  MAXIMUM INFILTRATION RATE            0.433
  MAXIMUM SEEPAGE RATE            0.08800
  SOIL STORAGE CAPACITY              7.750
  FRACTION OF SEEPAGE THAT BECOMES RETURN FLOW         0.323
                                         MONTHLY DATA
YEAR            OCTOBER  NOVEMBER DECEMBER JANUARY FEBRUARY   MARCH     APRIL      MAY       JUNE      JULY    AUGUST SEPTEMBER   ANNUAL
1974 PREC        5.80     2.55     6.45     5.00     6.29      3.90      4.32      6.64      2.65      1.23      5.15     9.28     59.26
1975 SIM RO      0.40     0.63     2.15     1.34     1.43      1.68      0.36      0.84      0.31      0.20      0.27     4.12     13.73
```

Appendix C. PROSPER input variables for the subroutines PARAM, ENDATA, and SOIL.

Symbol	Parameter	Unit of Measure
I. <u>PARAM subroutine</u>		
DL	Five soil layer thicknesses	cm
THETA	Initial moisture contents of the five soil layers	cm
FC	Field capacities of the five soil layers	fraction of total volume/ layer
PAIR	Air pressure	bars
CPO	Specific heat	cal/g°K
XL	Average leaf length	cm
V	Wind velocity	cm/sec
AT	Root cross-sectional area/unit area of soil for the two soil layers containing roots	
ARAT	Fraction of roots in each of the two soil layers	percent

Appendix C. PROSPER input variables for the subroutines PARAM, ENDATA, and SOIL. (Continued)

Symbol	Parameter	Unit of Measure
GM	Mean energy flow from ground to surface	langleys/day
GV	Mean peak variation in energy flow from ground to surface	langleys/day
ALBVEG	Vegetation albedo	percent
CANON	Day from Jan. 1 at which canopy vegetation has emerged 50 percent	Julian date
CANOFF	Day from Jan. 1 at which 50 percent of the canopy vegetation has died	Julian date
SIMIN	Maximum interception storage in winter	cm
SIMAX	Maximum interception storage in summer	cm
ALMIN	Leaf area index in winter	
ALMAX	Leaf area index in summer	

Appendix C. PROSPER input variables for the subroutines PARAM, ENDATA, and SOIL. (Continued)

Symbol	Parameter	Unit of Measure
II. <u>ENDATA subroutine</u>		
LASTDY	Number of days/month	1-31
MOBEG	Month in which simulation should begin	1-12
IMO	Numeric value of each month	1-12
RP (cards 3-38)	Daily precipitation	inches
RP (cards 39-74)	Total daily solar radiation	langleys/day
RP (cards 75-110)	Average vapor pressure ± 4 hours from solar noon	millibars
RP (cards 111-146)	Average air temperature ± 4 hours from solar noon	°F
III. <u>SOIL subroutine</u>		
THETA	Water content for each input point	(cm**3/cm**3)

Appendix C. PROSPER input variables for the subroutines PARAM, ENDATA, and SOIL. (Continued)

Symbol	Parameter	Unit of Measure
N	Number of input data points	≤ 20
NC	Number of incremented pore classes chosen for calculating data	≤ 50
TMAX	Maximum water content	(cm**3/cm**3)
SCON	Experimentally obtained saturated conductivity	cm/day
UNCON	Experimental unsaturated conductivity	cm/day
UNWAT	Water content at "UNCON" measurement	
DP	Desorption pressure	cm of water
RESWAT	Residual (immobile) water estimate	
EXPON	Exponent chosen for porosity term	

Appendix D. PROSPER sample computer output.

```
PROSPER.   A MODEL OF ATMOSPHERE-SOIL-PLANT WATER FLOW.

COWEETA WATERSHED 18   OAK FOREST   MAY 71 - APRIL 72                                  MONTH   4  LAI(MAX) =   4.50  LAI(MIN) =   0.50

DAY  INFILT      ET      RX(DAYS)  PSI(BAR)        ROOT FL1  ROOT FL2 SOIL FL1-2    SW FL2-3  SOIL EVAP  DRAINAGE    SOIL WAT1 SOIL WAT2
  1  0.0       7.109D-02 6.556D 00-1.472D 01      4.508D-02 2.602D-02-2.510D-02  -2.179D-02 3.530D-02 2.215D-02    8.771D 00 1.823D 01
  2  0.0       6.966D-02 6.263D 00-1.398D 01      4.385D-02 2.581D-02-2.558D-02  -2.274D-02 3.465D-02 2.017D-02    8.718D 00 1.820D 01
  3  0.0       7.490D-02 7.052D 00-1.504D 01      4.695D-02 2.795D-02-2.598D-02  -2.357D-02 3.732D-02 1.817D-02    8.660D 00 1.817D 01
  4  0.0       6.755D-02 5.907D 00-1.363D 01      4.223D-02 2.531D-02-2.626D-02  -2.418D-02 3.370D-02 1.629D-02    8.610D 00 1.814D 01
  5  0.0       7.662D-02 8.745D 00-1.546D 01      4.777D-02 2.885D-02-2.645D-02  -2.477D-02 3.831D-02 1.446D-02    8.551D 00 1.811D 01
  6  0.0       8.008D-02 1.140D 01-1.635D 01      5.020D-02 3.068D-02-2.673D-02  -2.560D-02 4.054D-02 1.310D-02    8.487D 00 1.808D 01
  7  0.0       7.304D-02 7.790D 00-1.571D 01      4.561D-02 2.823D-02-2.685D-02  -2.610D-02 3.709D-02 1.268D-02    8.431D 00 1.805D 01
  8  0.0       7.791D-02 9.818D 00-1.596D 01      4.794D-02 2.997D-02-2.683D-02  -2.634D-02 3.923D-02 1.231D-02    8.371D 00 1.802D 01
  9  0.0       7.518D-02 8.540D 00-1.537D 01      4.588D-02 2.931D-02-2.700D-02  -2.693D-02 3.793D-02 1.196D-02    8.314D 00 1.799D 01
 10  0.0       9.956D-02 6.874D 00-1.523D 01      5.944D-02 3.912D-02-2.709D-02  -2.815D-02 3.754D-02 1.162D-02    8.244D 00 1.795D 01
 11  0.0       8.216D-02 2.848D 00-1.017D 01      4.900D-02 3.315D-02-2.680D-02  -2.927D-02 2.460D-02 1.128D-02    8.197D 00 1.792D 01
 12  0.0       1.443D-01 5.334D 00-1.436D 01      8.485D-02 5.945D-02-2.630D-02  -3.135D-02 3.523D-02 1.094D-02    8.103D 00 1.787D 01
 13  0.0       1.866D-01 7.579D 00-1.553D 01      1.076D-01 7.896D-02-2.575D-02  -3.549D-02 3.814D-02 1.059D-02    7.983D 00 1.760D 01
 14  1.7888    2.097D-01 5.610D 00-1.455D 01      1.503D-01 5.939D-02 2.491D-01  -3.032D-02 3.625D-02 1.023D-02    9.336D 00 1.802D 01
 15  0.0       2.462D-01 5.896D 00-1.472D 01      1.805D-01 6.581D-02 1.638D-01   4.539D-03 3.676D-02 9.877D-03    8.955D 00 1.811D 01
 16  0.0       2.549D-01 4.405D 00-1.357D 01      1.781D-01 7.676D-02-4.226D-03  -1.213D-03 3.365D-02 9.548D-03    8.748D 00 1.803D 01
 17  0.0       2.873D-01 4.596D 00-1.376D 01      1.945D-01 9.275D-02-9.282D-03  -1.230D-02 3.400D-02 9.266D-03    8.529D 00 1.794D 01
 18  0.0       3.192D-01 4.767D 00-1.397D 01      2.069D-01 1.123D-01-1.287D-02  -2.328D-02 3.426D-02 9.017D-03    8.300D 00 1.784D 01
 19  0.0       3.286D-01 4.089D 00-1.320D 01      2.041D-01 1.245D-01-1.511D-02  -3.273D-02 3.229D-02 8.778D-03    8.079D 00 1.773D 01
 20  0.0       3.607D-01 4.292D 00-1.345D 01      2.152D-01 1.454D-01-1.603D-02  -4.101D-02 3.275D-02 8.523D-03    7.847D 00 1.761D 01
 21  0.0       2.447D-01 2.670D 00-8.737D 00      1.410D-01 1.037D-01-1.619D-02  -4.539D-02 2.064D-02 8.233D-03    7.702D 00 1.754D 01
 22  0.0       2.782D-01 2.726D 00-9.307D 00      1.546D-01 1.237D-01-1.627D-02  -4.737D-02 2.198D-02 7.907D-03    7.541D 00 1.745D 01
 23  6.2466    4.061D-01 3.266D 00-1.174D 01      3.327D-01 7.343D-02 2.536D 00   1.617D-01 2.971D-02 7.542D-03    1.089D 01 1.975D 01
 24  0.0       4.110D-01 3.079D 00-1.119D 01      1.286D-01 2.832D-01 8.239D-01   6.353D-01 2.828D-02 7.358D-03    9.909D 00 1.965D 01
 25  1.8496    2.987D-01 2.602D 00-7.723D 00      1.139D-01 1.848D-01 1.159D 00   3.898D-01 1.952D-02 6.501D-03    1.047D 01 2.024D 01
 26  4.3882    3.671D-01 2.697D 00-9.030D 00      1.070D-01 2.601D-01 3.748D 00   1.878D 00 2.289D-02 1.390D-02    1.098D 01 2.185D 01
 27  0.0       4.315D-01 2.849D 00-1.017D 01      4.375D-02 3.878D-01 8.783D-01   1.762D 00 2.573D-02 3.882D-01    1.003D 01 2.058D 01
 28  0.0       3.975D-01 2.697D 00-9.027D 00      5.795D-02 3.395D-01 6.544D-02   4.745D-01 2.274D-02 1.023D 00    9.882D 00 1.983D 01
 29  0.0       3.633D-01 2.617D 00-7.984D 00      1.006D-01 7.627D-01-2.920D-02   1.643D-01 2.003D-02 7.790D-01    9.791D 00 1.937D 01
 30  0.0       3.117D-01 2.560D 00-6.663D 00      1.253D-01 1.864D-01-3.389D-02   6.271D-02 1.661D-02 5.220D-01    9.683D 00 1.909D 01
MONTHLY WATER BUDGET (CM)

  PRECIPITATION  INFILTRATION   INTERCEPT-ET  INTERCEP-STORE     TRANSPIRATION NET RZ DRAIN
    15.11300       14.27320      0.0397999     0.0              6.696505        4.952637

  ROOT UPTAKE 1  ROOT UPTAKE 2  FLUX BETWEEN    SOIL EVAP        ET PLANT        TOTAL ET
    3.351386       3.345119       9.127890     0.9376603        6.696505        8.473966

     RUNOFF         DRAINAGE     OUTFLOW
   0.0             3.016915       3.016915

 SOIL STORAGE      BALANCE
    3.672119      0.3984868D-11
```

Appendix D. PROSPER sample computer output. (Continued)

```
 ANNUAL WATER BUDGET (CM)
  PRECIPITATION  INFILTRATION   INTERCEPT-ET  INTERCEP-STORE     TRANSPIRATION NET RZ DRAIN
    136.6012       125.2098       11.39139     0.0               75.52758        41.97285

  ROOT UPTAKE 1  ROOT UPTAKE 2  FLUX BETWEEN     SOIL EVAP       ET PLANT        TOTAL ET
    35.93757       39.59001       81.52129       7.772135        75.52758        94.69111

    RUNOFF          DRAINAGE     OUTFLOW
  0.0             42.01668        42.01668

 SOIL STORAGE       BALANCE
  -0.1065967      0.3385164D-10
```

Appendix E. Precipitation data for Corinth, MS, Dalton, GA, and Blackstone, VA (inches)[a]

Precipitation Regime	Study Site		
	Corinth, MS	Dalton, GA	Blackstone, VA
Historical average	52.15	51.78	43.60
Near average year	53.77 (1967)	55.21 (1969)	43.46 (1959)
Above average year	75.06 (1973)	66.01 (1964)	54.43 (1957)
Below average year	40.30 (1963)	37.59 (1999)[b]	32.15 (1965)

---

[a] Drawn from U. S. Weather Service and NOAA publications.

[b] A sufficiently below average year could not be found for Dalton, GA so the Rogerson model's mode 2 was used to artificially generate such a year.

Appendix F. Rogerson model computer printout of input data.

```
BLOCK                                                                                   STATEMENT
NUMBER  *LOC    OPERATION  A,B,C,D,E,F,G,H,I          COMMENTS                           NUMBER
                SIMULATE                                                                   1
        ***********************************************************                       2
        *   RUNOFF MODEL FOR ALUM CREEK EXERIMENTAL FOREST    *                          3
        *         **OUTPUT IN .000 INCHES TIMES 1000**        *                          4
        ***********************************************************                       5
        *                                                                                  6
        * THIS FUNCTION IS A DUMMY UNLESS MODE 1 IS USED                                   7
        * THEN PRECIPITATION VALUES ARE PUT IN THIS FUNCTION                               8
          PREC FUNCTION     C1,L365                                                        9
        ,780/,10/,0/,0/,0/,0/,0/,200/,0/,0/,0/,0/,0/,0/,20                                 10
        ,480/,0/,0/,0/,0/,10/,450/,0/,0/,0/,0/,0/,0/,0/,0/,0                               11
        ,0/,0/,180/,740/,10/,0/,0/,0/,40/,0/,0/,40/,570/,140/,140                          12
        ,0/,0/,80/,0/,0/,0/,0/,160/,0/,0/,0/,0/,0                                          13
        ,0/,0/,170/,0/,80/,520/,0/,0/,0/,10/,10/,20/,0/,0/,0                               14
        ,0/,0/,0/,0/,0/,0/,0/,0/,0/,0/,190/,1200/,0/,20/,750/,0                            15
        ,0/,1140/,40/,10/,0/,0/,0/,0/,0/,10/,260/,1370/,50/,110/,0                         16
        ,0/,0/,50/,730/,40/,300/,190/,10/,0/,0/,0/,0/,30/,0/,0                             17
        ,10/,0/,0/,0/,0/,0/,0/,0/,0/,0/,30/,0/,130/,0/,0                                   18
        ,10/,0/,590/,0/,0/,150/,0/,110/,0/,0/,0/,0/,0/,0/,0/,670                           19
        ,0/,940/,0/,0/,0/,0/,0/,0/,0/,0/,0/,0/,410/,0/,0                                   20
        ,100/,0/,0/,0/,0/,0/,0/,0/,0/,0/,0/,0/,0/,0/,0                                     21
        ,1010/,410/,1330/,0/,0/,0/,0/,0/,30/,1310/,50/,30/,620/,3370/,200                  22
        ,30/,0/,650/,10/,1180/,360/,50/,0/,0/,350/,200/,210/,0/,440/,100/,20               23
        ,10/,0/,0/,110/,50/,0/,0/,0/,0/,0/,0/,0/,0/,0/,0                                   24
        ,0/,0/,0/,0/,0/,0/,290/,0/,10/,0/,0/,270/,0/,0/,240/,350                           25
        ,80/,0/,0/,0/,120/,90/,0/,0/,0/,0/,0/,0/,0/,0/,0                                   26
        ,0/,0/,0/,0/,0/,0/,0/,0/,0/,0/,0/,0/,0/,420/,2100                                  27
        ,0/,0/,0/,0/,0/,0/,0/,100/,0/,970/,0/,0/,0/,1410/,0                                28
        ,0/,0/,0/,0/,0/,0/,150/,260/,140/,10/,0/,90/,0/,0/,0/,70                           29
        ,0/,0/,0/,0/,0/,1550/,970/,0/,0/,0/,0/,0/,0/,0/,0                                  30
        ,0/,270/,0/,0/,0/,230/,0/,50/,3170/,0/,0/,80/,20/,0/,0                             31
        ,0/,0/,0/,0/,0/,210/,10/,0/,0/,0/,0/,1010/,0/,0/,0                                 32
        ,0/,0/,650/,940/,0/,0/,0/,0/,0/,0/,0/,0/,480/,0/,0/,0                              33
        *                                                                                  34
        ** THE FOLLOWING FOUR FUNCTIONS SIMULATE PRECIPITATION IN MODE 2 **               35
        * AVERAGE NUMBER OF DAYS BETWEEN STORMS BY MONTHS FUNCTION                         36
         ADBSM FUNCTION     C1,D12                                                         37
        31,5.676/59,4.893/90,4.429/120,4.062/151,4.429/181,4.535/212,4.112                 38
        243,4.528/273,5.200/304,6.106/334,5.652/365,5.167                                  39
        *                                                                                  40
        * DAYS BETWEEN STORMS DISTRIBUTION FUNCTION                                        41
          DBSD FUNCTION     RN2,C31                                                        42
        0,.1232/.2802,.3110/.4213,.5184/.5188,.7259/.6234,.9333/.6995,1.1408               43
        .7492,1.3482/.7970,1.5557/.8345,1.7632/.8579,1.9706/.8893,2.1781                   44
        .9036,2.3855/.9228,2.5930/.9360,2.8004/.9452,3.0079/.9543,3.2154                   45
        .9665,3.4228/.9746,3.6303/.9807,3.8377/.9858,4.0452/.9888,4.2526                   46
        .9909,4.4601/.9919,4.6676/.9929,4.8750/.9939,5.0825/.9949,5.2899                   47
        .9960,5.4974/.9970,5.7048/.9980,5.9123/.9990,6.1197/1.00,6.3272                    48
        *                                                                                  49
        * AVERAGE STORM SIZE BY MONTHS FUNCTION                                            50
          ASSM FUNCTION     C1,D12                                                         51
        31,639/59,610/90,814/120,692/151,749/181,623/212,650/243,694/273,829               52
        304,802/334,865/365,795                                                            53
        *                                                                                  54
        * PRECIPITATION EVENT SIZE CLASS DISTRIBUTION                                      55
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Appendix F. Rogerson model computer printout of input data. (Continued)

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  RAIN FUNCTION    RN3,C48
0,.0138/.1706,.1377/.3036,.2755/.4142,.4132/.4964,.5510/.5685,.6887
.6284,.8264/.6711,.9642/.7107,1.102/.7421,1.240/.7695,1.377/.7970,1.515
.8213,1.653/.8447,1.791/.8619,1.928/.8792,2.066/.8843,2.204/.8964,2.342
.9015,2.479/.9147,2.617/.9228,2.755/.9299,2.893/.9350,3.030/.9421,3.168
.9482,3.306/.9553,3.444/.9584,3.581/.9624,3.719/.9645,3.857/.9665,3.994
.9685,4.132/.9736,4.270/.9787,4.821/.9807,5.096/.9817,5.234/.9838,5.372
.9888,5.510/.9898,5.647/.9909,6.061/.9929,6.336/.9939,6.612/.9949,6.887
.9959,7.025/.9970,8.540/.9980,8.815/.9990,9.901/.9998,11.433/1.0,13.499
*
* SOIL WATER DEFICIT FUNCTION (SURFACE FOOT)
  ETP1 FUNCTION    VSETP1V,C12
0,.727/156,.710/312,.676/469,.636/625,.580/703,.540/781,.489/859,.403
898,.352/938,.273/984,.091/1000,.010
*
* SOIL WATER DEFICIT FUNCTION (PROFILE)
   ETP FUNCTION    V$ETPV,C14
0,1.00/172,.982/259,.973/349,.955/431,.927/474,.909/517,.891/560,.864
603,.823/690,.714/776,.550/862,.355/948,.136/1000,.010
*
* VEGETATION FUNCTION (BASAL AREA SQ. FT./ACRE)
   ETV FUNCTION    X13,C16
0,.358/20,.375/40,.400/50,.425/60,.450/70,.487/80,.533/90,.592/100,.654
120,.787/130,.850/140,.904/150,.933/160,.967/170,.979/200,1.000
*
* DATE-MAXIMUM TRANSPIRATION-SURFACE EVAPORATION FUNCTION
   ETM FUNCTION    C1,C26
0,22/15,24/30,26/45,37/60,48/75,61/90,74/105,88/120,106/135,121/150,143
165,172/180,198/195,211/210,211/225,209/240,196/255,172/270,148
285,124/300,95/315,64/330,37/345,26/360,22/366,22
*
* SEEPAGE FUNCTION (SURFACE FOOT)
 SEEP1 FUNCTION    X4,C13
-1000,1000/-600,640/-275,400/-67,240/0,200/90,160/205,120/360,80
500,52/630,32/770,16/900,6/1100,1
*
* SEEPAGE FUNCTION (PROFILE)
  SEEP FUNCTION    X5,C13
-500,500/-375,400/-265,320/-100,235/100,160/300,106/500,60/
700,40/900,30/1100,20/1500,9/1900,4/2200,2
*
* DORMANT-GROWING SEASON FUNCTION
   DGR FUNCTION    C1,D3
105,1.05/319,1.0/365,1.05
*
* SOIL WATER DEFICIT GRAPH DATES
  SMRD FUNCTION    C1,D26
1,15/15,29/29,43/43,57/57,71/71,85/85,99/99,113/113,127/127,141/141,155
155,169/169,183/183,197/197,211/211,225/225,239/239,253/253,267/267,281
281,295/295,309/309,323/323,337/337,351/351,365
*
* DATE-MONTH ENDS FUNCTION
  MOED FUNCTION    X17,D11
31,59/59,90/90,120/120,151/151,181/181,212/212,243
243,273/273,304/304,334/334,365
*
* EQUATIONS
```

Appendix G. Rogerson model simulated annual water yields for graphical relationships.

Study Site/Precipitation Year	Annual Water Yield (acre-inches per acre) Basal Area (sq. ft./acre) 0	60	120	200
Corinth, MS				
1973 (75.06 inches)	24.76	22.15	17.65	13.87
1967 (53.77 inches)	14.22	11.69	7.51	4.94
1963 (40.30 inches)	6.79	5.38	3.28	1.75
Dalton GA				
1963 (66.01 inches)	15.46	13.25	9.52	6.99
1969 (55.21 inches)	11.14	8.99	5.12	2.79
1999 (37.59 inches)	7.29	5.42	2.18	1.13
Blackstone, VA				
1957 (54.43 inches)	9.52	7.54	4.42	2.53
1959 (43.46 inches)	7.18	5.58	2.54	1.20
1965 (32.15 inches)	3.54	2.45	1.07	0.70

Appendix H. Haan model soil water input data.

Variable	Corinth, MS	Dalton, GA	Blackstone, VA
Initial readily available moisture content[a]	.5 inches/inch	.5 inches/inch	.5 inches/inch
Initial less readily available moisture content[a]	1.5 inches	1.5 inches	1.5 inches
Maximum possible infiltration rate	0.433 inches/hour	0.493 inches/hour	0.750 inches/hour
Maximum seepage rate from soil profile	0.088 inches/day	0.102 inches/day	0.118 inches/day
Maximum storage capacity of less readily available soil water storage	7.75 inches	4.26 inches	5.85 inches
Fraction of seepage that becomes runoff	0.323	0.463	0.390

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[a] These values were not readily obtainable so the same values were used for each study site. The values listed are unique to a northeastern North Carolina soil unknown to the author.

THE EFFECTS OF SOUTHERN PINE BEETLE
(Dendroctonus frontalis Zimm.)
EPIDEMICS ON FOREST WATERSHED DYNAMICS:
WILL BENEFITS JUSTIFY CONTROL?

by

David Glenn Shore

(ABSTRACT)

Southern pine beetle (SPB) attacks may reduce the value of such forest products as timber recreation, aesthetics, water, wildlife, and grazing. SPB control programs may prevent pine mortality and simultaneously sustain the value of all forest products. Total program benefits include potential benefits accruing to the watershed. SPB impacts on water yield were estimated with hydrologic simulation models and water quality components, erosion, nutrient loss, and water temperature, were assessed for impacts with a literature survey. East Texas SPB activity data were used to extrapolate water yield changes to larger forested areas. SPB water yield and water quality impacts were insignificant based on this data. The significance and magnitude of larger infestations are related to certain attack, topographic, edaphic, and climatic characteristics.

SPB control program benefits usually will not accrue at the watershed because water is generally a free good and has no market price. However, special cases may occur away from the watershed where control benefits exist.