ENVIRONMENTAL EFFECTS OF FOREST LAND USES:
A MULTI-RESOURCE SIMULATION-BASED APPROACH*

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ABSTRACT

Describes a computer simulation model for examining the physical, economic and environmental consequences of alternative land-use decisions and manipulations of a forest ecosystem. The model consists of a set of subsystems which include forest production, recreation, fish, wildlife, atmospheric and hydrologic processes. Model outputs are assessed in relation to their impacts on land, water and air resources as well as the production of utilizable goods and services. The significance of space-time model resolution in assessing the environmental consequences of alternative land-use plans and manipulations is discussed. The model is applied to a portion of the Snohomish River Basin in Western Washington through the use of four alternative management strategies. Projected impacts for the period 1974-2000 are reported in graphical form. With the exception of projected suspended sediment loads, results suggest that the forest management manipulations included in the four alternative strategies and the activities associated with developed camping will not significantly alter the pre-manipulation levels of selected environmental indices.

Today, society is confronted with the responsibility of making many significant decisions relating to the future use of the nation's renewable natural resources. In recent years, increased public attention has focused on critical issues affecting the use of many of these resources including the nation's forest and wildlands. In part, many of today's pressures are the result of increasing demands for the multitude of goods and services produced from a static or shrinking forestland base. Coupled with these increasing pressures are signs of a developing

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environmental ethic which has aroused man's concern for protecting the environment in which he lives, works, and recreates. Recent task force reports, legislative activities, judicial rulings, activities of state and federal land management agencies and rules promulgated by federal and state environmental regulatory agencies provide ample evidence that resolution of problems affecting the use of the nation's forest and wildlands is one of the most pressing problems currently facing society.

In analyzing the issues involved, it is instructive to identify two distinctly different, yet related problems. One issue concerns the allocation of the nation's forest and wildlands to a set of selected land-uses. Typically, solutions to specific allocation problems are the primary goal of forest land-use planning studies. Although disguised by a variety of labels, this process inevitably results in a broad stratification of the nation's wildlands into a set of relatively homogenous strata used primarily for the production of a similar or compatible set of goods and services. In essence, forest land-use planning is an allocation of available land resources to satisfy current and expected needs of society.

Closely related to this land allocation process are issues concerned with the environmental, social, and economic consequences resulting from land-use allocation decisions. Typically, these issues arise at various times during the planning process. Results of anticipated impacts are reported in a variety of documents including environmental impact statements, economic feasibility studies, etc.

Both aspects of the land-use allocation process must be considered in any comprehensive analysis. However, in practice, the two are commonly treated independently. Often this is inevitable in order to satisfy the intent of various state and federal laws. Nevertheless, the effects of resulting decisions and actions must be viewed in their totality and not as isolated events.

The central objective of the research reported below is the development of a general methodology for evaluating the physical, economic, and environmental consequences of alternative land-use decisions and resultant manipulations of the forest ecosystem. Because of the scope and complexity of this task, as well as the necessity to assume a holistic rather than an elemental approach, the methodology of systems analysis and operations research has been adopted.

Funded by a National Science Foundation grant under the auspices of the Research Applied to National Needs program, the specific objectives of the project revolve around the development of a multi-resource system model that interfaces with an automated information storage and retrieval system. The system model is composed of a series of subsystem models which include forest production processes, recreation supply processes, fish and wildlife supply processes, and atmospheric and hydrologic processes. Manipulations of the ecosystem are assessed in relation to their impacts on land, water, and air resources, as well as the production of utilizable goods and services. Since many of the manipulations generate nonpoint sources of pollution, a large portion of

the program is directed at modeling these processes. A detailed description and discussion of the entire project may be found in [1, 2, 3, 4].

The area selected for calibration and testing of the models developed by the project is the Snohomish River Basin located on the west slope of the Cascade Mountains in Western Washington. This basin of approximately 1.2 million acres drains into Puget Sound at Everett, Washington. With the exception of agricultural activities along the flood plains and the land devoted to urban development in the Seattle-Everett metropolitan area, the basin is covered by forests. These forest lands are used for a multiplicity of purposes including timber production, outdoor recreation, water, fish, wildlife, and the generation of outstanding scenic amenities.

Study Objectives

The objective of this paper is to present the results of a computer simulation study undertaken as part of this large research project. Specifically, a computer simulation model developed for the Middle Fork of the Snoqualmie River watershed will be presented. This watershed of 109,903 acres (approximately 172 square miles) is one of the largest of the twenty watersheds which in total make up the Snohomish River Basin (Figure 1). Following a presentation of the model, empirical results generated by the simulator will be presented to illustrate the environmental effects of alternative forest-land use allocation decisions and attendant manipulations of the forest ecosystem.

The primary objective for developing the computer simulation model used in this study was to evaluate selected environmental impacts associated with alternative forestland use decisions and man-induced manipulations. The model is composed of a timber production section, a timber harvesting section, a hydrology section, and a recreation section. This latter section is external to the computer version of the model but still allows the estimation of environmental impacts.

The choice of temporal resolution is an important decision when designing a multi-resource model for a forest ecosystem such as the Middle Fork of the Snoqualmie. Not only does temporal resolution affect model efficiency, it also significantly affects the estimation of the severity of environmental impacts associated with man-induced manipulations. For this study a yearly resolution was adopted. However, the hydrology model operates at a monthly level with monthly figures aggregated to provide annual measurements.

Spatial resolution is a second important modeling decision. Many site specific impacts are in effect masked out when aggregated over an entire watershed. Theoretically, this problem can be circumvented by considering the impact of decisions on an acre by acre basis. However, this is a computational impossibility for large forested areas. For this study the Middle Fork watershed was subdivided into nine subwatersheds (Figure 2). Forest management decisions
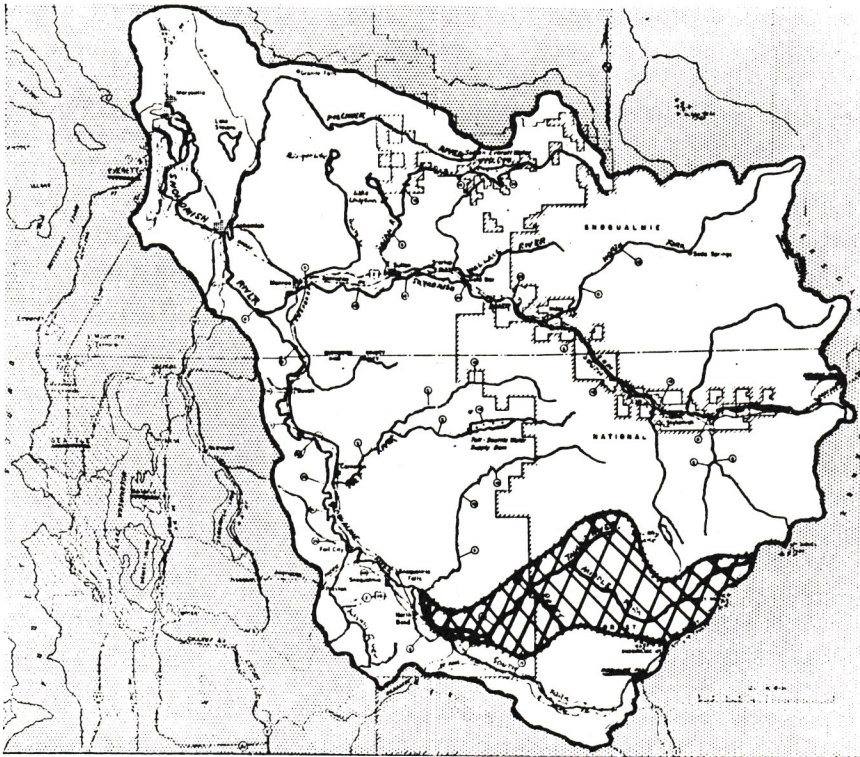
Figure 1. Location map of Middle Fork of Snoqualmie Watershed.

were subsequently implemented on a subwatershed basis. Water quality parameters were measured at the outflow of each of these nine subwatersheds thus permitting a realistic prediction of selected environmental impacts for a large land area as it is manipulated over time. This also provides some capability for determining the sensitivity of spatial resolution in assessing environmental impacts.

Hydrology Section

GENERATION OF STREAMFLOWS

The Middle Fork of the Snoqualmie River watershed is typical of mountain drainages of the Western Cascades. Narrow valleys are bordered by steep side slopes reaching average gradients of over 50 per cent in the upper tributaries. Elevation ranges from approximately 400 feet at the watershed mouth to 7000 feet at the crest of the Cascades. Soils on the upper slopes were formed from the Snoqualmie Batholith and have thin, poorly developed profiles. Gravel, stone,
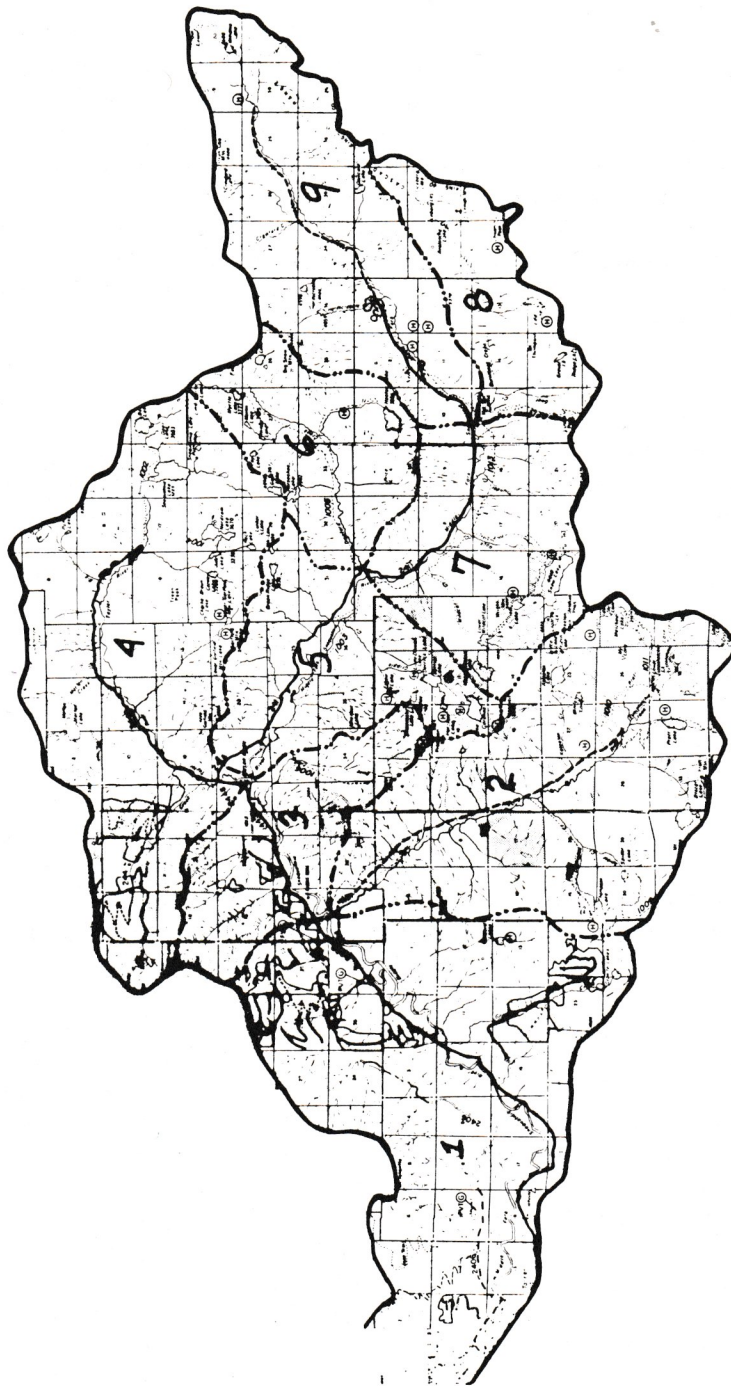
Figure 2. Location map of Subwatersheds within Middle Fork Watershed.

and boulders are common. At the higher elevations, the soil surface is broken by outcrops of bedrock. Rapid runoff and drainage from these soils results from the steep gradients. In the valley bottoms, deeper soils have formed from glacial till. These soils are coarse with high percentages of coarse sand and gravel causing them to be highly porous with low soil moisture holding capacities.

Mean annual runoff from the Middle Fork of the Snoqualmie River watershed and its nine subwatersheds was determined by generating precipitation and temperature inputs and transforming them by the following hydrologic model into surface runoff:

$$R = P - ET - I \pm \Delta S \qquad (1)$$

where R = monthly runoff; P = precipitation; ET = evapotranspiration loss; I = interception loss and ΔS = changes in monthly watershed storage.

Evapotranspiration losses were estimated using Thornthwaite's [5] model because only mean monthly temperature and an estimate of day length were required as inputs. Less empirical methods which require other meteorological parameters were found to be inappropriate due to the lack of necessary data.

Storage processes considered significant over a monthly time period included snowpack accumulation, soil moisture storage, and subsurface watershed storage. The snowpack was incremented when precipitation occurred as snow. This was assumed to occur when mean air temperature reached or dropped below a threshold value of 28°F. Snowpack depletion by snowmelt was estimated using the U.S. Army Corps of Engineers [6] degree-day equations. Soil moisture storage was increased to a maximum waterholding capacity by addition of rainfall and snowmelt and was depleted by the ET term in equation (1). Once soil moisture storage reached maximum waterholding capacity, further rainfall and snowmelt were assumed to increase subsurface watershed storage. Subsurface storage was defined as water stored below the soil rooting zone and was depleted by surface streamflow which was simulated by a linear depletion model.

Water balance was evaluated monthly for each hydrologic unit[1] within the watershed. Subwatershed streamflows were calculated by weighting the yield from each unit by the ratio of the unit area within the subwatershed to the total watershed area and summing to obtain mean area-inch runoffs. These results were subsequently converted to cubic feet per second. Monthly runoff values were averaged giving a mean annual instantaneous discharge rate. Four of the subwatersheds within the study area are more accurately defined as interwatershed areas since a fraction of their total outflow consists of flows from other subwatersheds. Outflow from these areas was calculated by summing the runoff from the interwatersheds with the flows from the contributing subwatersheds. Figure 3 illustrates the mixing of the nine subwatersheds in schematic form.

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[1] Hydrologic units were based on 1000 foot elevation zones since definite hydrologic regimes with distinct streamflow patterns are associated with elevation.
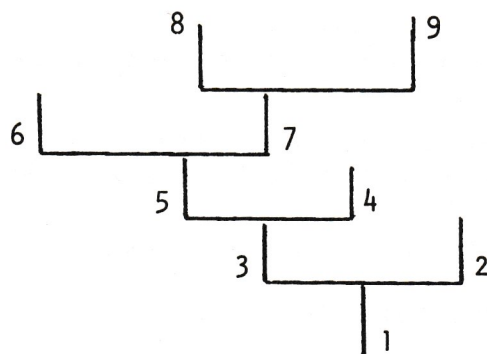
Figure 3. Schematic flow diagram of runoff from the nine subwatersheds of the Middle Fork Watershed.

SUSPENDED SEDIMENT

Suspended sediment in streams of forested watersheds results from natural erosion processes such as sheet erosion, channel cutting and mass soil movements. Concentration of suspended sediment is a function of hydrology, meteorology, topography, and soil conditions. Land-use activities can also affect concentrations by accelerating erosion processes. Anderson [7] related watershed conditions and land-use activities on 29 Oregon watersheds with annual suspended sediment production using multivariate analysis. He concluded that the most significant forest land-use affecting sediment concentrations was timber harvesting and that 80 per cent of the increase caused by this activity could be attributed to road development.

The method used to predict suspended sediment concentrations for the nine subwatersheds of the Middle Fork of the Snoqualmie River watershed was based on Anderson's work. However, not all of the independent variables used in his analysis were available for the Snohomish Basin. Values for dependent and the available independent variables from Anderson's data were used in a multivariate analysis yielding the following equation:

$$\text{Log}_{10}\text{SS} = -1.979 + 1.143\ \text{Log}_{10}\text{A} + 1.053\ \text{Log}_{10}\text{MA} - .0077\text{SC} + .7976\ \text{R} + .0483\ \text{Log}_{10}\ \text{S} \tag{2}$$

where

  SS = average annual suspended sediment in thousands of tons per year

  A = subwatershed area in square miles

MA = mean annual runoff in cfs per square mile

SC = mean percentage of silt and clay in top 6 inches of soil (equal to 35% for all subwatersheds)

R = per cent of subwatershed area in roads

S = mean slope of streams in feet per mile (equal to 1900 feet for all subwatersheds).

Average concentration of suspended sediment in mg/l was calculated for each of the nine subwatersheds by converting the antilog of the results from equation (2) using the expression:

$$MGL = 1017 * SS/(MA*A). \qquad (3)$$

IMPACT OF FERTILIZATION ON WATER QUALITY

Most of the literature concerning the effect of fertilization on water quality describes the processes under agricultural conditions. However, several monitoring studies of forested watersheds have been conducted in the Pacific Northwest. In all studies, the loss of applied fertilizer was small. Moore [8] found the total loss over a 12-month period following application to be only .2 per cent of 200 lbs/acre applied to small watersheds in Southwestern Oregon. Similarly, Anderson [9] estimated between .3 and .4 per cent of the 442 lbs/acre applied to the Tahjya River watershed in Western Washington reached surface waters. In both studies the fertilizer was in the form of urea pellets and was applied by helicopter.

The above studies and measurements taken by Malueg, Powers, and Krawcayk [10] in Western Oregon and McCall [11] in Western Washington show similar response patterns. Initially a brief rise in nitrogen primarily in the form of urea N was detected for a few days and then concentrations returned to near base levels. All authors concluded that this was the result of direct application to the stream. During the high rainfall months of fall and winter nitrate concentrations increased and then declined to base levels over a period of about 3 months. This response was attributed to soil leaching. In all the above studies concentrations never exceeded 1 ppm.

The movement of nitrogen fertilizer through the soil profile was examined by Cole and Gessel [12] using lysimeters. Their data indicate that over a 12-month period .3 per cent of a 200 lb/acre urea-N application moved below 36 inches and out of the assumed rooting zone. Using the lysimeter data, a plot of the per cent of total nitrate loss remaining in the soil versus accumulated rainfall suggests that a strong linear relationship exists with nitrate concentrations remaining constant throughout the leaching process.

Due to the time resolution of the Middle Fork simulation model, estimating the initial urea response was deemed impractical. Therefore peak monthly nitrate concentration occurring during the 12-month period following fertilization was estimated.

The model operates in two steps. First, the concentration of the leachate from fertilized areas is estimated. Secondly, the leachate is mixed with the added potential runoff from the remaining watershed area and existing watershed

storage. Total loss in lbs/acre is assumed to be a constant percentage of the application rate. This seems to be a reasonable assumption since in the above listed studies the per cent loss was similar for a range of over 200 lbs/acre. The concentration in lbs/acre-ft of leachate is calculated using the relationship based on the lysimeter data. While the slope of the line could be expected to vary with soil conditions, it was not possible to do this because comparisons over a range of forest soil characteristics have not been undertaken. Since the study of Cole and Gessel [12] was conducted on a watershed adjacent to the Middle Fork the extrapolation of their results seems reasonable. The above concentration is then converted to mg/l by the expression:

$$ADDNO3 = (lbs/acre-ft) \times 10^3/43560 * .0624).\qquad(4)$$

Measurements of nitrate concentrations in the Snohomish Basin indicate near constant levels under normal conditions. Therefore it is assumed that runoff from non-fertilized areas has a constant nitrate concentration, BASNO3 (equal to .1 ppm for all subwatersheds). The average concentration of incoming excess soil moisture is calculated on a subwatershed basis by the expression:

$$SUBCON = BASNO3 + FRAC * (ADDNO3 - BASNO3)\qquad(5)$$

where SUBCON is the concentration for the subwatershed in mg/l and FRAC is the fraction of the watershed fertilized. The contribution of each elevation zone is mixed with the watershed storage, STOR, using the equation:

$$WSNO3(MO) = (WSNO3(MO - 1) * STOR +$$
$$SUBCON * ADDSTOR)/(STOR + ADDSTOR),\qquad(6)$$

where ADDSTOR is total water added to watershed storage in month MO. Concentration of surface flows is represented by WSNO3 in mg/l. This process is iterated each month until the total potential nitrate loss is exhausted and concentrations return to BASNO3.

As discussed above, the peak concentration occurring during the 12-month period following fertilization was estimated using the above model. This concentration occurs when

$$WSNO3 = SUBCON$$

Therefore, peak nitrate concentration is described by equation 5 and is a function of leachate concentration and the proportion of the watershed fertilized.

STREAM TEMPERATURE

Stream temperature increases caused by exposure from removal of stream bank vegetation were estimated by a relationship proposed by Brown [13] and Brown and Krygier [14] which relates change in stream temperature to the

stream surface area exposed, net heat input, and stream discharge by the following expression:

$$\Delta T = \frac{A \times H}{Q} \times .000267 \qquad (7)$$

where

ΔT = change in stream temperature in °F;

A = area of exposed stream surface in ft^2;

H = net heat input in BTU/ft^2-min;

Q = stream discharge in cfs.

Net heat input was based on a function of solar angle proposed by Brown [15]. Stream discharge was generated by the water yield section of the model.

Temperature responses are very site specific. The measured response at the outlet of a watershed is as dependent on the location within the watershed as the extent of vegetation removal. In order to predict temperature responses on a watershed basis, the effects of spacially varying stream hydraulics were approximated by stratifying streams in terms of stream order. The length of streams in each order affected by a harvest operation was estimated by

$$L_i = DD \times ACUT \times PS_i \qquad (8)$$

where

L_i = length of exposed stream in order i, ft;

DD = watershed drainage density in ft/acre;

ACUT = acres harvested;

PS_i = proportion of total length of streams classified in order i.

Stream width varies with discharge and was approximated for each order by the expression

$$W_i = aQ_i{}^b \qquad (9)$$

where W_i is the average width for order i, Q_i is the average discharge for order i, and a and b are constants empirically derived from measurements within the Middle Fork watershed. The exposed area for each stream order is the product of L_i and W_i.

Equation (8) was solved for each stream order within a subwatershed. Water temperature, T_s, at the outlet of each subwatershed was then determined by the equation

$$T_s = \sum_{i=1}^{n} Q_i \Delta T_i / Q_s + BT \qquad (10)$$