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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

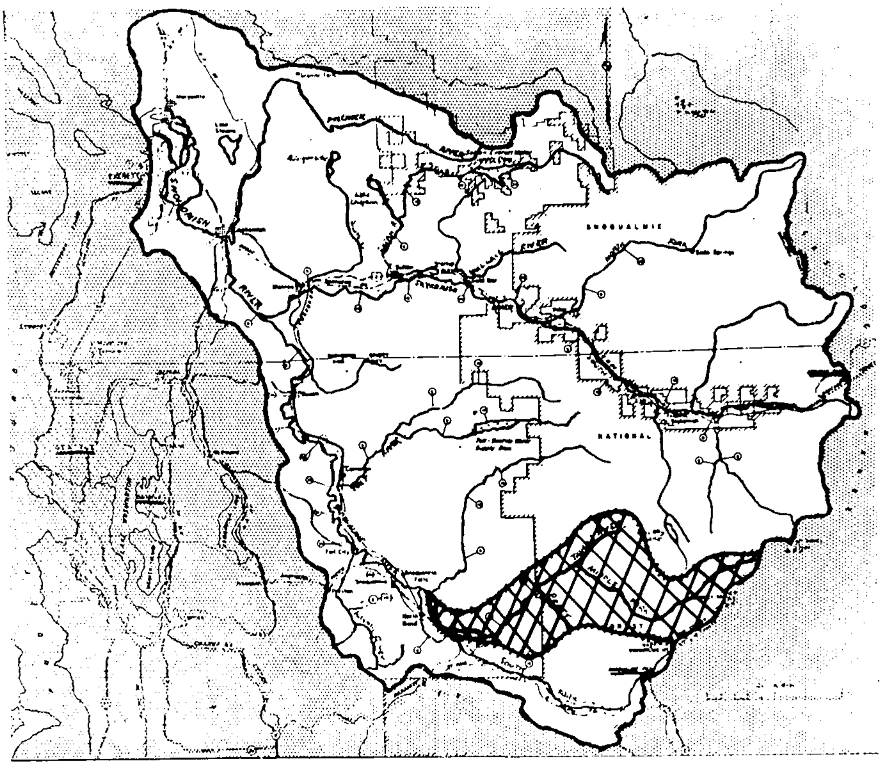

Figure 1. Location map of Middle Fork of Snoqualmie Watershed.

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,

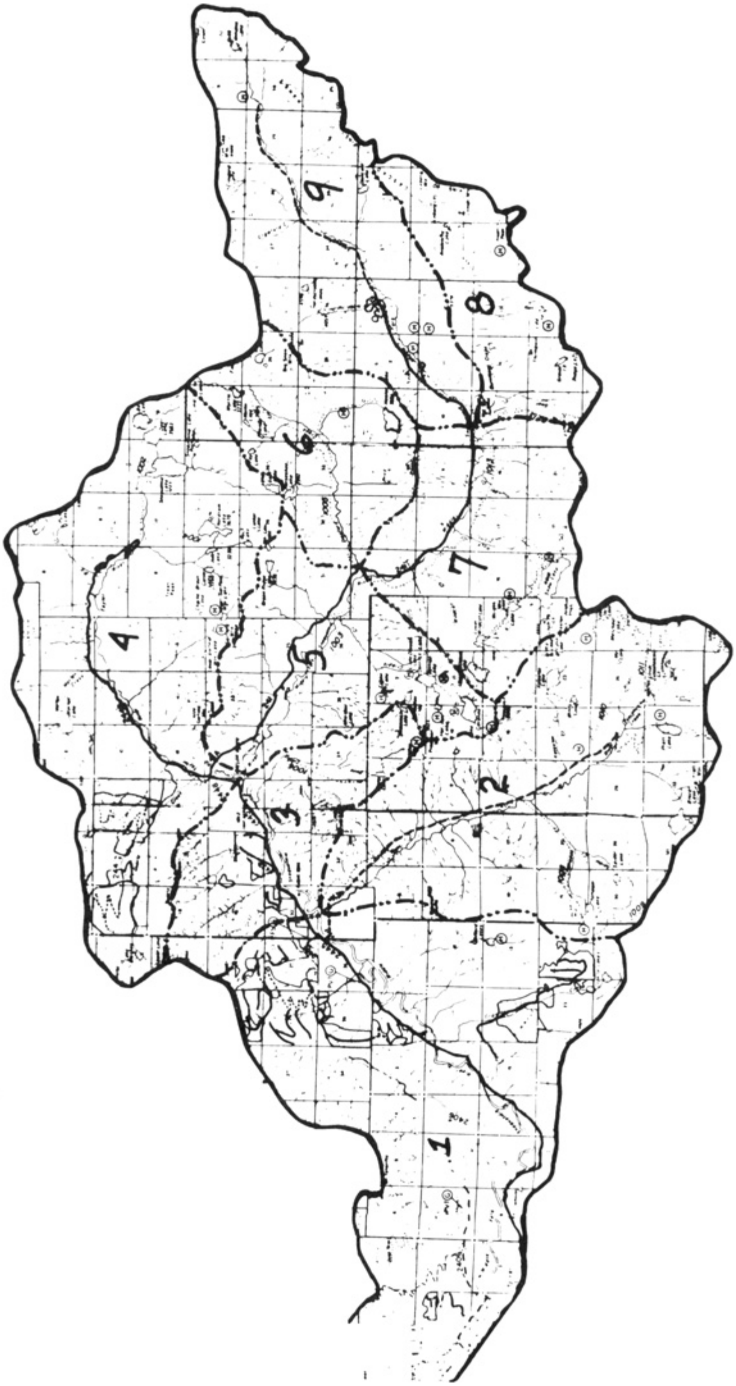

Figure 2. Location map of Subwatersheds within Middle Fork Watershed.

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:

$$R = P - ET - I \pm \Delta S \tag{1}$$

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.

[1] Hydrologic units were based on 1000 foot elevation zones since definite hydrologic regimes with distinct streamflow patterns are associated with elevation.

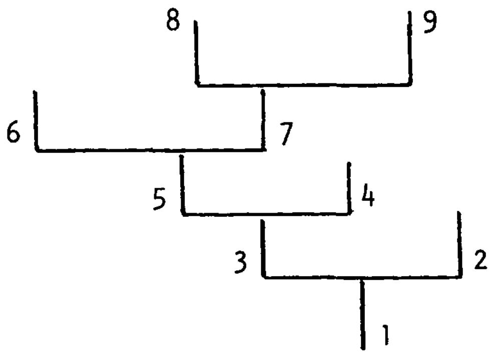

Figure 3. Schematic flow diagram of runoff from the nine subwatersheds of the Middle Fork Watershed.

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:

$$MGL = 1017 * SS/(MA*A). \tag{3}$$

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:

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

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:

$$\text{SUBCON} = \text{BASNO3} + \text{FRAC} * (\text{ADDNO3} - \text{BASNO3}) \tag{5}$$

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:

$$\begin{aligned}\text{WSNO3(MO)} = (\text{WSNO3(MO} - 1) * \text{STOR} + \\ \text{SUBCON} * \text{ADDSTOR})/(\text{STOR} + \text{ADDSTOR}),\end{aligned} \tag{6}$$

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

$$\text{WSNO3} = \text{SUBCON}$$

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:

$$\Delta T = \frac{A \times H}{Q} \times .000267 \tag{7}$$

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

$$L_i = DD \times ACUT \times PS_i \tag{8}$$

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

$$W_i = aQ_i^{\,b} \tag{9}$$

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

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

Conditions at the outlet of a subwatershed are indicated by the subscript s. The initial or base temperature, BT, was assumed to be equal to mean monthly air temperature.

Stream temperature was calculated for each subwatershed for the month of August. During August the most extreme increases in stream temperature usually occur since flows are low and energy inputs high. If buffer strips were left it was assumed that the strip width was sufficient to maintain shade conditions equal to the undisturbed state. In such cases stream temperature remained at BT.

DISSOLVED OXYGEN

Dissolved oxygen concentration varies with the solubility of oxygen in water and the relative differences between supply and depletion processes. Supply processes include natural aeration and photosynthesis by aquatic plants. Oxygen is depleted by bacterial oxidation of organic matter and respiration of plants and animals. In youthful drainages such as the Middle Fork, aeration aided by the turbulent flow is far greater than depletion unless high concentrations of oxygen demanding wastes are added to the streams. Consequently, oxygen levels tend to be near saturation. This is assumed to be the case for the subwatersheds of the Middle Fork since no concentrated source of organic pollution exists. Dissolved oxygen measurements from the area substantiate this assumption. Therefore, the most significant impacts of forest management practices are those which affect the conditions controlling oxygen solubility, namely stream temperature.

Oxygen solubility decreases as water temperature increases. From a table of saturated oxygen levels over a range of water temperatures [16] the expression

$$DO = 15.08 - 1.34\sqrt{t_w} \tag{11}$$

was derived to approximate the solubility-temperature relationship between 0 and 30°C. DO represents saturated dissolved oxygen concentration in mg/l at water temperature t_w. Equation (11) assumes a constant barometric pressure of 760 mm.

Oxygen solubility follows Henry's Law and therefore is directly proportional to changes in the partial pressure of oxygen. Assuming a constant proportion of oxygen in the atmosphere, solubility is also directly proportional to changes in barometric pressure. The ratio, BP, of the barometric pressure at a station above sea level to the pressure at sea level is approximated by the expression

$$BP = [((16{,}000 + 64t_a)/E) - 1] / [((16{,}000 + 64t_a)/E) + 1] \tag{12}$$

where t_a is the mean air temperature between sea level and the station in °C and E is the elevation of the station in meters [16]. Assuming an average barometric pressure at sea level of 760 mm, the saturated dissolved oxygen concentration, SDO, at a station above sea level is calculated by

$$SDO = DO \times BP \tag{13}$$

Using equations 11, 12, and 13, dissolved oxygen was calculated for each subwatershed in the Middle Fork for the month of August. August was chosen since concentrations are at the low extreme under conditions of low flow and high stream temperatures. The value of E was considered the average elevation of the subwatershed and t_a was determined by correcting the weather station temperature using the elevation lapse rate. The results of the stream temperature section of the model were used for t_w.

Timber Production Section

A timber yield function was developed for predicting the future volume of forest stands under differing levels of management intensity. Yield functions were generated to fit the data reported by the Washington State Department of Natural Resources [17]. These yield functions which assume full (100 per cent) stocking determine volume as a function of site quality and stand age. Figure 4 displays the yield functions used in this study. Yields for stands > 100 years of age were extrapolated from the given data. Timber volumes include all trees 7 inches and larger in diameter and include the cubic foot volume of the total stem.

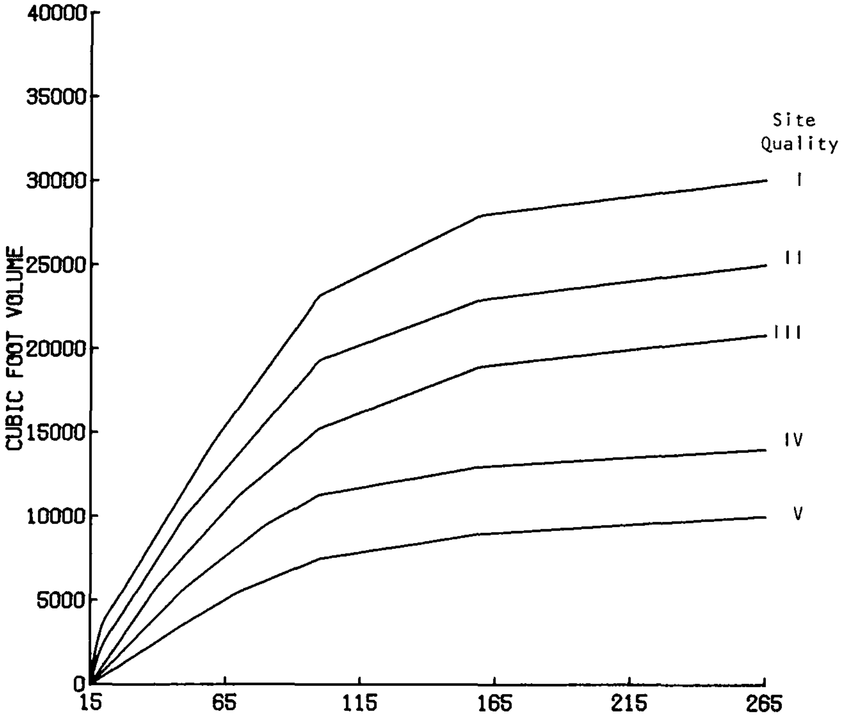

Figure 4. Stand volume as a function of age and site quality.

The timber volumes shown in Figure 4 were adjusted to reflect the impact of three levels of management intensity. Tables 1 and 2 contain the definitions and assumptions utilized in the timber production section. In Table 2 the timber volumes that are assumed removed via a commercial thinning operation are average figures extracted from DNR Harvest Regulation Report No. 4 [18]. Also shown in Table 2 are average increases in final harvest levels due to fertilization. These figures are based on preliminary results of a regional forest fertilization

Table 1. Levels of Management Intensity

Level of Management	*Definition*
No Management	Regeneration; protection against fire; clear-cutting at rotation age
Light Management	Regeneration; commercial thinning at ages 45, 55, 65, 75 and 85; protection against fire; clear-cutting at rotation age
Intensive Management	Regeneration; fertilization at ages 15, 25, 35; pre-commercial thinning at age 15; commercial thinning at ages 35, 45, 55, 65, 75 and 85; protection against fire; clear-cutting at rotation age

Table 2. Timber Yields Resulting From Intensive Management

Level of Management	*Assumption and Procedures*
No Management	Final harvest volume equals 75 per cent of volume shown in Figure 4. The assumption is that the average stand in the watershed is 75 per cent stocked.
Light Management	Final harvest volume equals 75 per cent of volume shown in Figure 4. Additionaltthinning volumes shown below.
Intensive Management	Final harvest equals 75 per cent of the sum of volume shown in Figure 4 plus increase due to fertilization. Additional thinning volumes shown below.

Average Volume Removed By Commercial Thinning		*Increase in Final Harvest Volume Due to Fertilization*	
Thinned at age	*Cubic foot volume/acre*	*Site quality*	*Cubic foot volume increment if fertilized at ages 15, 25 and 35*[a]
35	726	1	525
45	1419	2	495
55	1415	3	450
65	1214	4	405
75	1365	5	375
85	818		

[a] Stands fertilized only once or twice receive only 1/3 and 2/3 respectively, of above increment.

program and are assumed to reasonably reflect an average response to fertilization. An application rate of 250 lbs of N/acre was assumed for all acres fertilized.

Costs of the intensive management activities included in the study are shown in Table 3. These figures represent region-wide averages as of 1974. In the simulation results reported below, all costs are increased at a rate of 1 per cent per annum. The regeneration expenditure was assumed to be needed on each acre harvested.

A simplified harvest regulation system was built into the model by using area regulation. Each subwatershed was regulated as an independent unit. Based on the age class structure of each subwatershed, the specified rotation age and an arbitrary harvest schedule priority of harvesting the oldest timber first, the acreage and cubic foot volume harvested annually was computed. Using area regulation an equal number of acres are harvested annually with wide variations in harvested volume resulting. The previously discussed timber yield functions were used to generate the volume harvested each year as a function of site quality and the average age of the age class being harvested. As shown in Table 4, with the exception of subwatershed one, the major portion of the forested acres in the Middle Fork watershed are occupied by old-growth timber stands.

Table 3. Summary of Timber Management and Harvesting Costs

Item	*Initial values*	*Annual increase %*
Fertilization (250 lbs. N/Acre)	$30.00/Acre	1.0
Precommercial Thinning	$45.00/Acre	1.0
Regeneration	$50.00/Acre	1.0
Road Construction		
a. Mainline	$79,200/Mile	1.0
b. Secondary	$63,360/Mile	1.0
c) Spur	$39,600/Mile	1.0
Logging Costs (Felling, Bucking, Yarding, Loading)		
a. Highlead	$162/MCF[a]	1.0
b. Skyline	$210/MCF	1.0
c. Running Skyline-chokers	$186/MCF	1.0
d. Thinning	$225/MCF	1.0
Average Log Prices		
a. Final Harvest (Old-growth)	$1,212/MCF	2.0
b. Thinning	$700/MCF	2.0

[a] MCF = one thousand cubic feet

Table 4. Forested Acres by Age Class

Subwatershed number	Acres By Age Class 10	30	50	70	90	110	130	150	170	Old-growth 250+
1	1160	4400	8040	1040	720	160	40	280	520	3400
2	40	3000	40	0	0	0	0	0	0	9240
3	120	200	560	400	0	0	0	0	0	4480
4	160	1080	1160	160	0	0	0	0	0	7520
5	40	720	560	0	0	0	0	0	0	3920
6	0	0	0	0	0	0	0	0	0	4680
7	120	1040	0	0	0	0	0	0	0	3000
8	0	0	0	0	0	0	0	0	0	1880
9	0	0	0	0	0	0	0	0	0	1640

As shown in Table 2, timber yields were increased to reflect the level of management intensity specified for each age class within each subwatershed. Annual commercial thinning volumes, acres thinned, acres fertilized and acres pre-commercially thinned were computed by averaging the total volumes and acres, respectively, over the entire rotation established for each subwatershed. This was a simple and convenient procedure for handling the timing of these activities.

Timber stands aged 0-30 years were given the most intensive level of management, stands between 50 and 70 years of age were subjected to light management and stands 90+ years were given no management (see Table 1 for definition of these levels of management intensity).

Timber Harvesting Section

Three optional methods for harvesting timber stands were incorporated into the model. These were: a) highlead–the conventional system in the Pacific Northwest, b) skyline, and c) running skyline outfitted with chokers. One of the above logging methods was selected for each subwatershed to be harvested. The road requirements as well as the costs of logging varied as a function of each logging method.

Three classes of roads were recognized in this study. Mainline roads were defined as those log haul roads connecting a secondary road to either a paved road, a log dump or a log yard. All mainline roads are 24 feet in width and are unpaved. As seen in Figure 2 and Table 5 the current mileage of mainline roads in each subwatershed varied considerably. The future harvesting in certain subwatersheds also implied the construction of additional mainline roads. The fourth column in Table 5 contains the maximum mainline road mileage for a given planned road network. The rate of mainline road construction was dependent upon the rate of harvesting in the watershed. All mainline roads were retained as permanent additions to the road network.

Table 5. Summary of Road Mileages

	Current Miles of Road			
Watershed number	*Mainline (width = 24')*	*Secondary (width = 14')*	*Spur (width = 10')*	*Maximum miles of mainline required*
1	13.25	30.00	4.00	14.25
2	0.00	0.00	0.00	6.00
3	3.00	3.00	0.00	3.00
4	6.00	4.00	5.25	6.00
5	4.75	0.00	0.00	4.75
6	0.50	0.00	0.00	0.50
7	4.00	0.00	0.00	4.00
8	0.00	0.00	0.00	0.00
9	2.50	0.00	0.00	7.00

Secondary roads were defined as those log haul roads connecting a spur road to a mainline road. All secondary roads are 14 feet in width and are unpaved. The initial secondary road mileages are also shown in Table 5. It was assumed that all secondary roads constructed were maintained as permanent additions to the road network. The rate of new secondary road construction was determined as a function of the logging method selected for a subwatershed and a road difficulty factor associated with each subwatershed. Table 6 contains the miles of secondary roads required per acre harvested for each of three logging methods. Secondary roads were constructed until the entire subwatershed was cut over. The road difficulty factor located in column 9 of Table 7 is a composite index which represents the degree of difficulty involved in building roads and removing timber from each subwatershed. This factor was estimated by considering the topographic characteristics of each subwatershed. This factor was multiplied times the product of the acres harvested and the miles of road required per acre harvested to generate the mileage of secondary roads constructed each year.

Spur roads were defined as those log haul roads connecting a landing to a secondary road. All spur roads are 10 feet in width and are unpaved. The initial spur road mileages are shown in Table 5. It was assumed that the average spur road was utilized for approximately one year after which it was put to bed. The rate of new spur road construction was determined in the same manner as for secondary roads. The mileage of spur roads required per acre harvested is contained in Table 6. The road difficulty factor was also used when determining spur road mileage.

The area of each subwatershed devoted to landings and skid trails was also generated as a function of the selected logging method. Table 6 contains the coefficients used for this purpose. The sum of the acreage covered by roads, landings and skid trails was summed and expressed as a per cent of the total area for each subwatershed. As seen in equation (2) this figure significantly affects the suspended sediment concentration for any particular year.

Table 6. Road Requirements for Different Logging Methods

Logging method	*Miles of Road Required Per Acre Harvested*		*Acres in landings and skid trails per acre harvested*
	Secondary	*Spur*	
Highlead	.00750	.00375	.163
Skyline	.00375	.00094	.062
Running Skyline-choker	.00750	.00094	.046

The costs of felling, bucking, yarding, and loading for each of the three logging methods as well as the costs of road construction are shown in Table 3. These figures represent averages for both public and private organizations in the Pacific Northwest as of 1974. Also shown in Table 3 are average log prices for final harvest and commercial thinning operations. These log values represent average prices for logs delivered at Snoqualmie Falls, Washington. Hauling costs are shown in Table 7. Stumpage values were derived using the conversion surplus approach utilizing a profit ratio of 15 per cent. Log values were increased at an annual rate of 2 per cent.

Results of Model Experimentation

The above described models were applied to the Middle Fork of the Snoqualmie River watershed to determine selected economic and environmental impacts of four alternative forest management and harvesting regimes over a 27-year planning horizon. A summary of selected input values for these four experiments are contained in Table 8. One alternative was to manage subwatersheds 1-5 primarily for the production of timber while leaving the remaining subwatersheds in their current state. To test the effects of different logging methods this alternative was subdivided into three separate trial runs. The highlead, skyline and running skyline logging systems were evaluated on each of three successive runs. The results of these three trials were compared with the baseline data generated in experimental run four which assumed no timber management activities in any of the subwatersheds during the 27-year planning period. Thus, two alternative land-use plans with three optional logging methods were considered.

Figure 5 contains the predicted annual flow in cubic feet per second (cfs) at the outflow of the Middle Fork watershed for each of the next 27 years (i.e., 1974-2000). The predicted annual precipitation for the same duration is illustrated in Figure 6. As expected, the two graphs are highly correlated. The predicted total suspended sediment concentrations (mg/1) at the outflow of the Middle Fork resulting from road building and timber harvesting activities for each of the four simulation runs involving three logging systems are illustrated in

Table 7. Characteristics of Subwatersheds

Subwatershed number	*Total area*	*Forested acres*	*Average slope (%)*	*Average site quality*	*Per cent Ownership*			*Road difficulty factor*	*Hauling costs ($/MBF)*
					Federal	*State*	*Private*		
1	23042	19760	36	3	3	12	85	0.8	7.59
2	18763	12320	47	3	51	16	33	0.5	9.17
3	6364	5760	43	4	52	8	40	1.0	8.63
4	18983	10080	48	4	76	0	24	1.5	11.15
5	7900	5240	48	4	68	14	18	1.2	9.75
6	7200	4680	50	4	100	0	0	1.1	11.21
7	9217	4160	50	4	87	13	0	0.9	10.74
8	5925	1880	54	5	100	0	0	0.8	12.83
9	12509	1640	51	5	100	0	0	0.8	12.59

Table 8. Summary of Input Parameter Values for Different Simulation Runs

Subwatershed number	*Rotation age*	*Annual area to harvest (Acres)*	*Logging Method*				*Year management and harvesting initiated*	
			Run 1	*Run 2*	*Run 3*	*Run 4*	*Runs 1-3*	*Run 4*
1	45	439	Highlead	Skyline	Running Skyline	—	1974	—
2	50	246	Highlead	Skyline	Running Skyline	—	1983	—
3	65	89	Highlead	Skyline	Running Skyline	—	1974	—
4	70	144	Highlead	Skyline	Running Skyline	—	1978	—
5	80	65	Highlead	Skyline	Running Skyline	—	1983	—
6	100	47						
7	100	42						
8	100	19						
9	100	16						

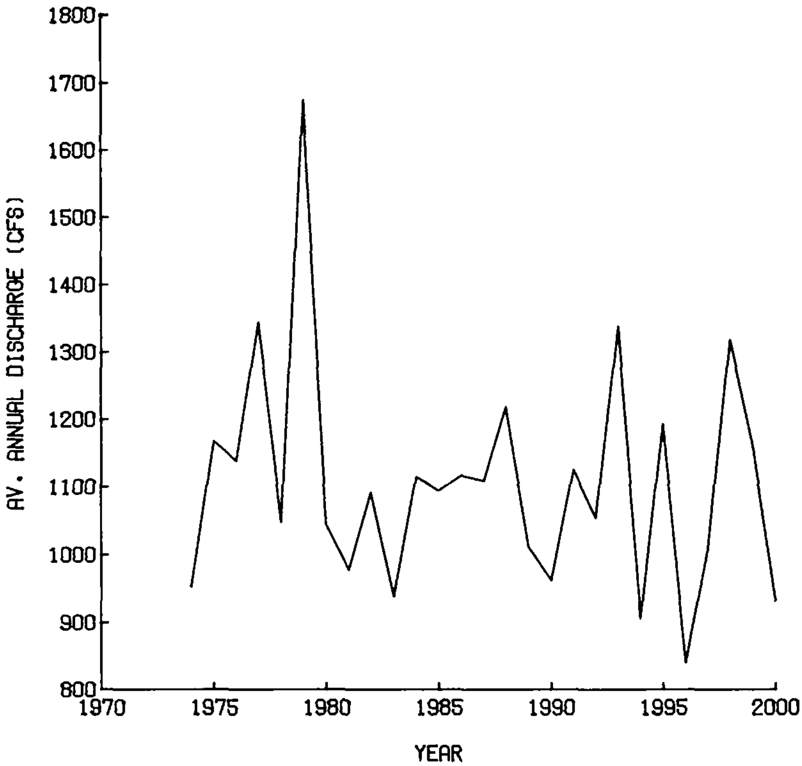

Figure 5. Average annual discharge at outflow of Middle Fork Watershed.

Figure 7. The logging system with the lowest logging costs (i.e., the highlead) produced the greatest amount of sediment primarily because of the higher road requirements of this system. As seen in equation (2) sediment concentrations are highly correlated with the per cent of the watershed devoted to roads, skid trails and landings.

The number of acres fertilized over the 27-year planning horizon are depicted in Figure 8. The peak nitrate concentration resulting from this activity was 0.1001 ppm. It is clear from this figure that fertilizing a maximum of 216 acres at the rate of 250 lbs of N/acre per year induces an infinitesimally small response in the peak nitrate concentration as measured at the outflow of the Middle Fork watershed.

The effects of timber harvesting—with and without buffer strips—on stream temperature and dissolved oxygen were also estimated over the 27-year planning horizon. As shown in Figure 9, leaving a buffer strip which maintains pre-logging shade conditions has a minor effect on stream temperature when measured at the outflow of the Middle Fork watershed. In fact, the greatest temperature

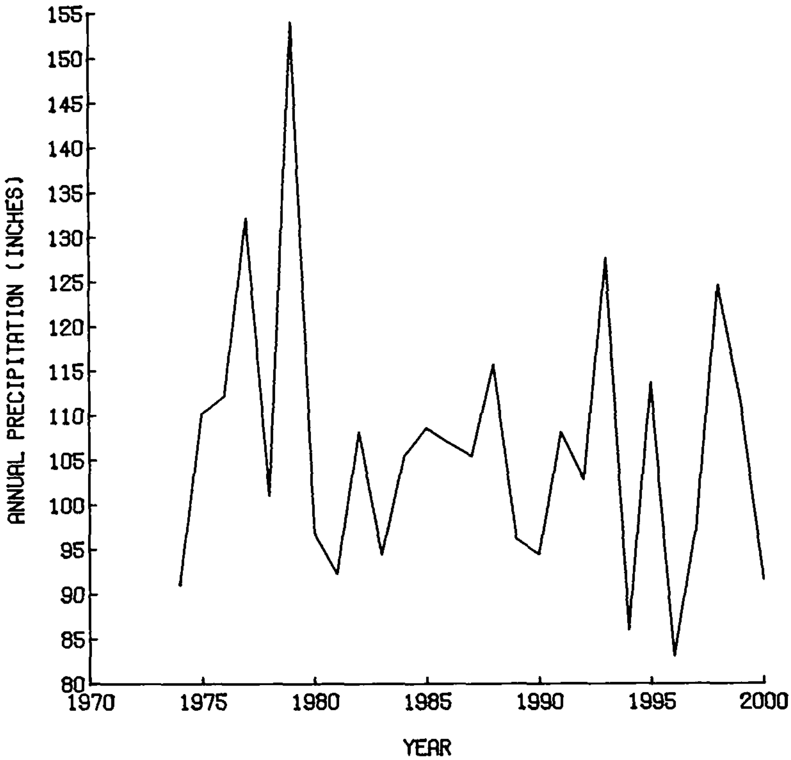

Figure 6. Annual precipitation in Middle Fork Watershed.

differential during the entire 27-year simulated time period was 0.16°F. As expected, the dissolved oxygen concentrations did not differ markedly with or without buffer strip protection. Concentrations ranged from 9.34-9.48 mg/l with buffer strips to 9.33-9.47 mg/l when no buffer strips were retained. This minimal impact was primarily the result of minor stream temperature variations which themselves were diluted because of the mixing of runoff from several subwatersheds.

Using the previously specified levels of management intensity and dates of entry into the subwatersheds a total of 23,184 acres were clear-cut during the 27 years. The volume of timber removed during each year is shown in Figure 10 and the stumpage value of this harvested volume is displayed in Figure 11. A total timber harvest volume of 278 million cubic feet with a stumpage value of 313; 296; and 304 million dollars for the highlead, skyline and running skyline systems, respectively, were removed. The total expenditure for secondary roads over the planning period was 11 million dollars for the highlead and running skyline systems and 6 million dollars for the skyline. Spur road expenditures

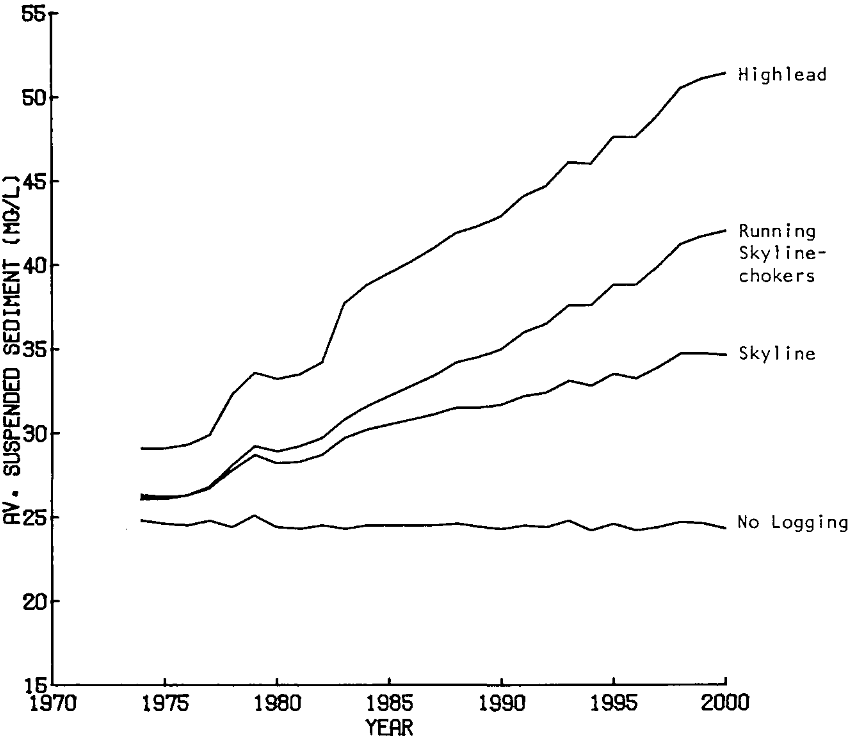

Figure 7. Average suspended sediment at outflow of Middle Fork Watershed by logging method.

totalled 7 million dollars for the highlead and 881 thousand dollars for the skyline and running skyline systems. These expenditures were in addition to the logging costs and stumpage returns reported earlier. In addition, commercial thinning occurred on a total of 10,732 acres removing 12 million cubic feet. Using tractor logging, this produced 5 million dollars of stumpage.

To evaluate the impact of forest management manipulations on a natural ecosystem it is instructive to monitor the responses generated for each subwatershed individually. Also, this reveals the spatial sensitivity involved in estimating selected environmental impacts. As an example, consider subwatershed number four. Management activities were initiated in this subwatershed in 1978. A history of the annual flows and suspended sediment are pictured in Figures 12 and 13, respectively. The results depicted in Figure 13 indicate that the highlead system produced the most sediment with concentrations ranging from 18.6-43.3 mg/l as compared with 18.3-19.0 mg/l under no logging. Thus, results for subwatershed number four are consistent with those reported earlier for the entire Middle Fork watershed.

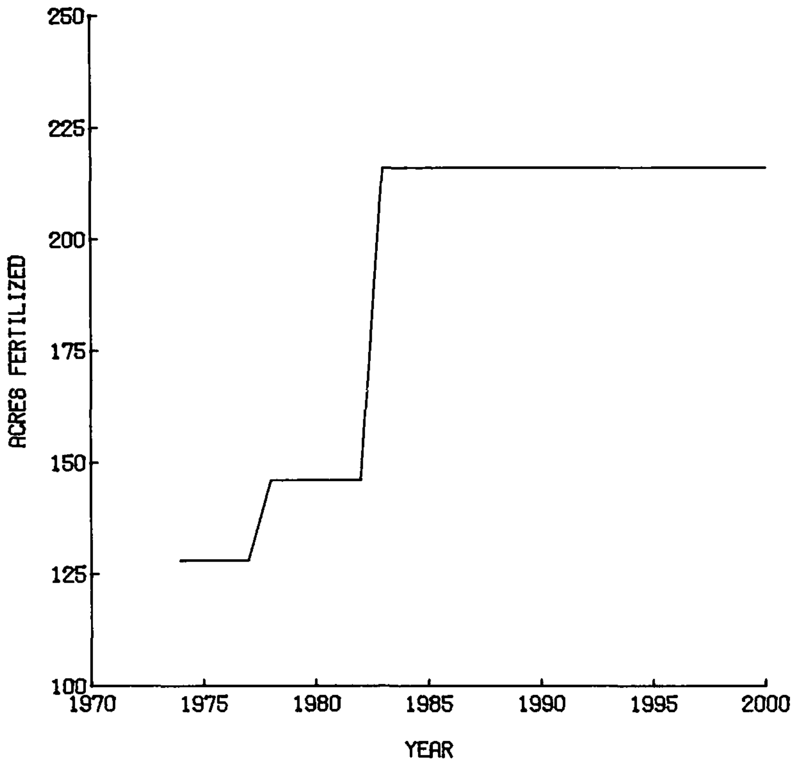

Figure 8. Acres fertilized in Middle Fork Watershed.

Due to the small number of acres [18] being fertilized annually in subwatershed number four, the peak nitrate concentration measured at the outflow of the subwatershed was not affected by fertilization. Because of the small number of acres being clear-cut annually (144), the effects of buffer strip protection had a minimal impact on stream temperature with a maximum differential of 0.13°F estimated during the entire 27-year planning period. Similarly, as reported earlier for the total Middle Fork watershed, dissolved oxygen concentrations as measured at the outflow of subwatershed four were not significantly affected by the presence or absence of buffer strips along the streams. Lastly, over the 27-year planning period 35 million cubic feet were harvested with a stumpage value of 40; 38; and 39 million dollars for the highlead, skyline and running skyline systems, respectively. In addition, a total of 907 thousand cubic feet with a stumpage value of 420 thousand dollars were removed via commercial thinning from the subwatershed during this same period.

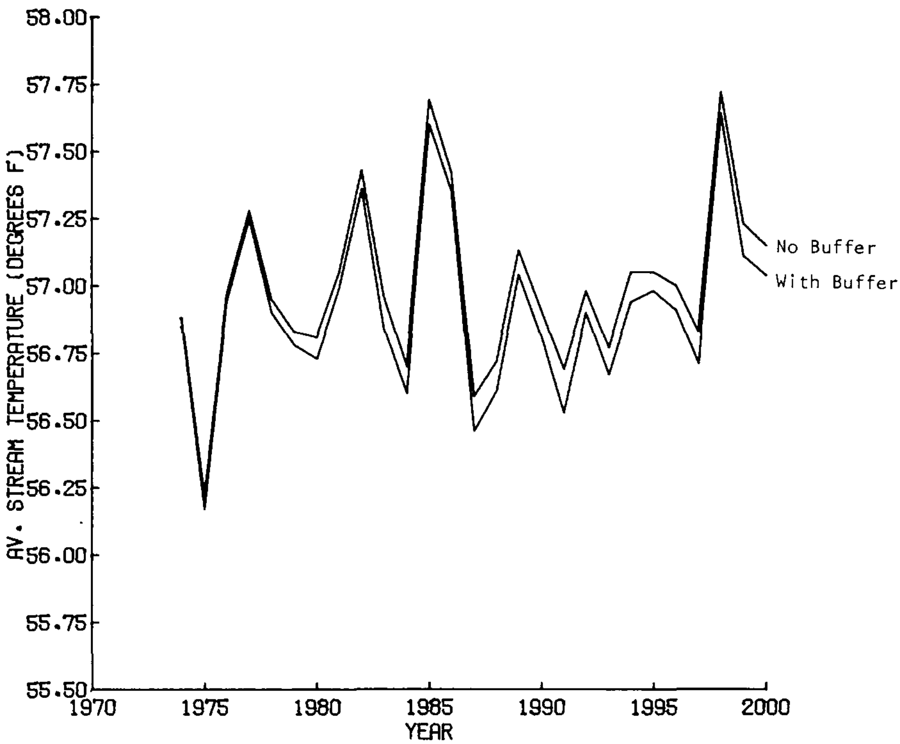

Figure 9. August stream temperature at outflow of Middle Fork Watershed with and without stream protection.

Recreational Impacts

The last section of this paper considers the impact of outdoor recreation activities which occur in lieu of, or simultaneously with, timber production. As an illustration, the environmental impacts associated with a single recreation activity–developed camping–are presented. Following a brief introduction to the methodology employed, environmental impacts associated with this activity within the Middle Fork watershed are estimated.

The primary objective of the recreation section of the model is to predict the demand for outdoor recreation activities as a function of: a) a number of exogenous variables, b) dominant land-use, and c) land management decisions. A second objective is to generate the resulting environmental impacts associated with these land uses. Recreation activities are part of the total human, physical and biological system that are currently and will continue to take place in the region. Consequently, these recreation activities along with the characteristics of the various recreation facilities affect other land-uses and are in turn influenced by them. Some of these interactions are direct while other times they occur indirectly through the environmental network.

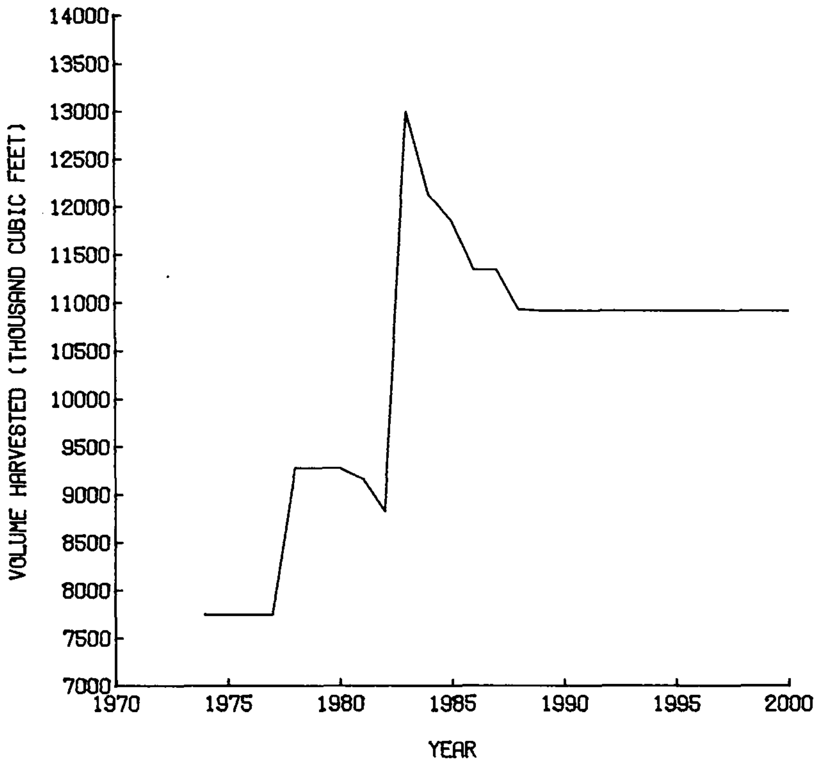

Figure 10. Volume of harvested timber in Middle Fork Watershed.

In the case of developed camping, direct impacts are those generated during a visit to a camping area (i.e., sewage, rubbish and garbage generated), or impacts associated in making the trip to the site (i.e., air pollution by motor vehicles and highway littering). Indirect impacts are soil compaction, sheet erosion, changes in rates of infiltration and effects on vegetative composition and vigor.

Prior to estimating environmental impacts, an estimate of demands for certain recreation activities must be completed. The procedure developed by Chicchetti, Davidson, and Seneca [19] was adopted for this purpose. The overall approach was to predict the level of various recreational activities for a population unit given its socio-economic characteristics and given the availability of various recreational resources. The procedure was designed to predict recreational activities which are either area or site specific. In addition, the approach can be used to project future activity levels for a changing population and changing recreational resources.

Briefly, the model works as follows. On the basis of some 75 independent variables, the total number of user days for each of 11 recreational activities was generated for people in King, Pierce and Snohomish counties. These 75 independent variables were divided into two sets. One set contained all variables

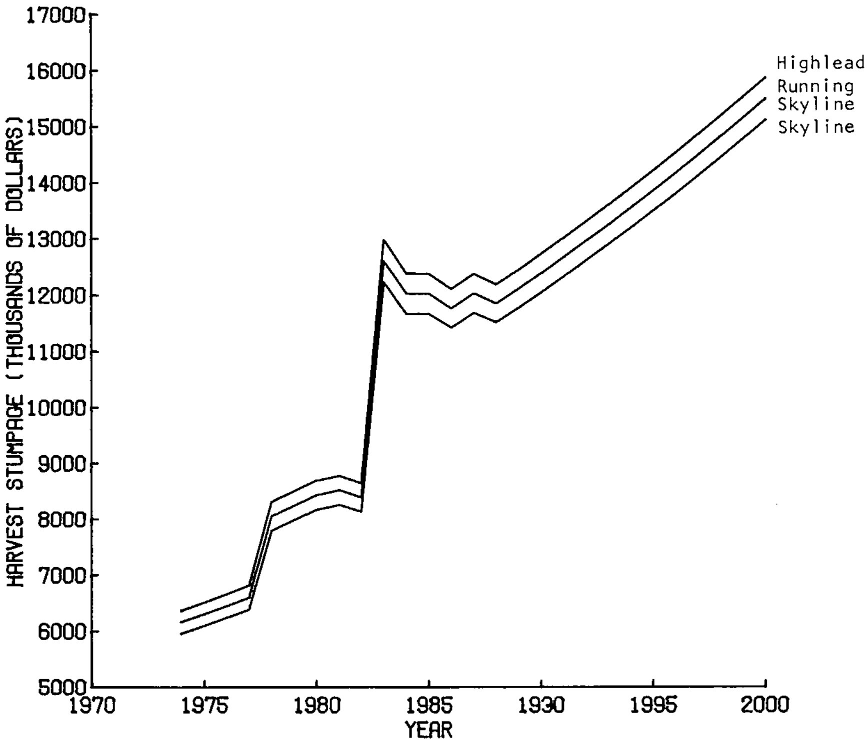

Figure 11. Stumpage value of harvested timber in Middle Fork Watershed by logging method.

creating demand for a recreational activity. This set included such variables as income, education, age, race, sex, etc. The other set included supply variables such as number of swimming pools in an area, number of wildland acres available for recreation, etc. Most of these 75 independent variables were assumed to be constant during any given simulation run. On the demand side only income and population numbers were variable and trends for these variables were included in the model. On the supply side variables were subject to land-use allocation decisions.

Data for the independent variables were collected from a wide variety of sources, collated, reconciled and projected out to the year 2000. These data were collected for three counties (i.e., King, Pierce and Snohomish), as well as for the State of Washington as a whole. The recreation activities included in the study were: Camping remote, camping developed, canoeing, other boating, driving for pleasure, fishing, hiking, hunting, sightseeing, snowskiing, and swimming. Results presented below are only concerned with developed camping.

Once the number of activity user days for developed camping were obtained a

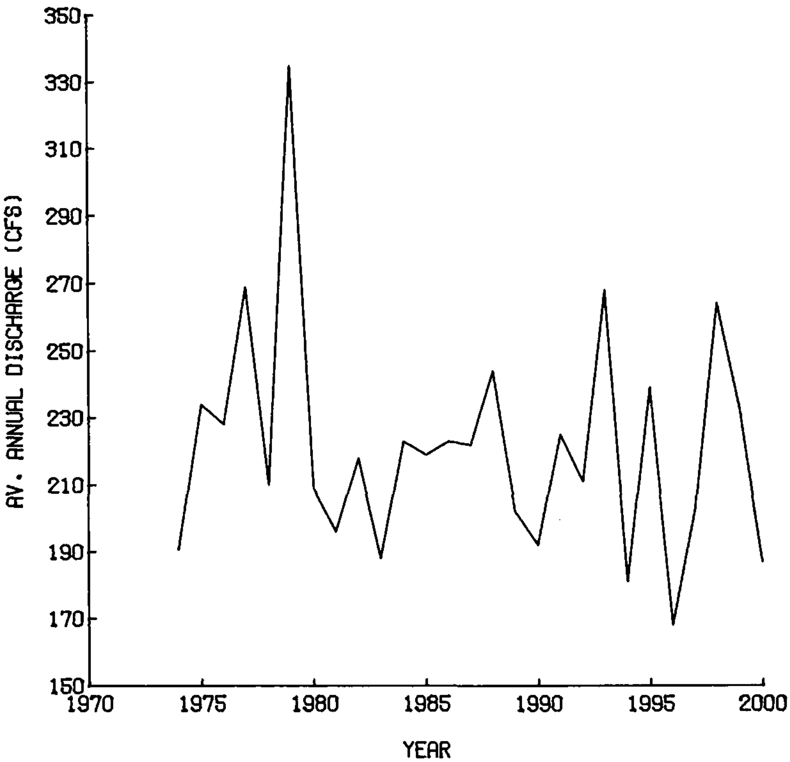

Figure 12. Average annual discharge at outflow of subwatershed four.

percentage of them were allocated to the Snohomish River Basin, and subsequently to the Middle Fork watershed. This allocation was based on developed camping capacity in the basin and in the Middle Fork watershed as compared to the capacity in the State of Washington (the State being defined as the potential recreational "radius" of the counties of interest). Approximately 1.88% of the developed camping capacity of the State of Washington lies in the Snohomish Basin, with the Middle Fork watershed accounting for 11.25% of the total.

The determination of total activity user days in the Middle Fork included two groups of recreationists. The first group consisted of King, Snohomish, and Pierce county residents who recreate in the watershed, and the second group was made up of those recreationists from outside the three-county area who recreated in the watershed. Approximately 25% of the developed camping recreationists were comprised of out-of-state visitors.[2] The total number of

[2] Unofficial estimate by U.S. Forest Service (USFS) administrator based on license plate counts at three USFS campgrounds in N.W. section of Washington.

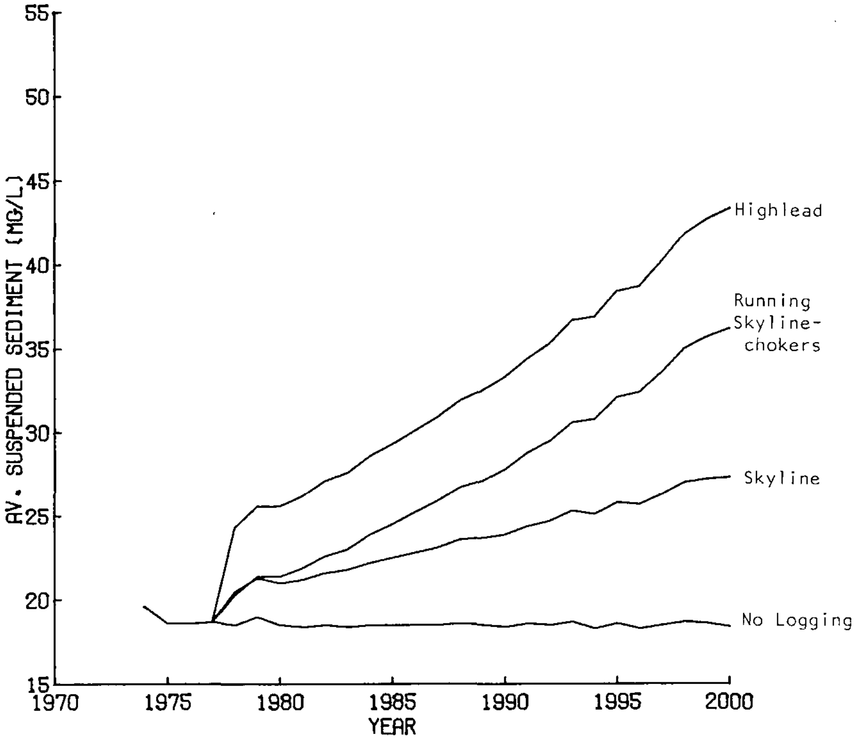

Figure 13. Average suspended sediment at outflow of subwatershed four by logging method.

developed camping user days in the Middle Fork for the year 1974 were estimated as:

King-Snohomish, Pierce user days allocated to the Middle Fork	184,492 user days
Out-of-state visitor user days	61,463
Total user days in Middle Fork	245,955

The amounts of various pollutants generated by the above number of users were estimated using procedures summarized below. Two types of pollutants generated by the developed camping activity are: a) solid waste, and b) air pollution. Estimates of the volume of these pollutants for the Middle Fork watershed are shown as follows:

Solid waste

1. Rubbish	1.4 lb/use day[3]	=	172 tons
2. Sewage	.15 gal/user day[4]	=	36,878 gallons

Air pollution[5-6]

1. Carbon monoxide–30.5 grams/mile	=	441,134 pounds
2. Exhaust hydrocarbons–3.8 grams/mile	=	54,961 pounds
3. Nitrogen oxides–1.8 grams/mile	=	26,034 pounds
4. Littering–.005 items/mile[7]	=	36,027 items

Since sewage is typically handled by either a pit or vault-type facility, no environmental impact occurs in the vicinity of the campground. Solid waste must be removed from the site and disposed of elsewhere. The environmental impacts resulting from the generation of air pollutants could have some adverse impact. However, no effort was made in this study to assess these impacts. Similarly, no attempt was made to estimate the indirect impacts resulting from developed camping.

Summary and Conclusions

The empirical results presented above for four experimental runs of the simulation model indicate the relative magnitudes of selected effects of man-induced manipulations in a forest ecosystem. With the exception of suspended sediment concentration the results indicate that the manipulations included in the four experimental trials would not significantly alter the pre-manipulation levels of the identified indices. However, because many impacts are spatially and temporally very site specific, adverse effects of manipulations may only be detectable at higher degrees of model resolution.

When interpreting the above reported results several qualifying comments must be considered. First, only selected environmental impacts and manipulations were included in the study. Perhaps the most notable of those omitted was

[3] U.S. Dept. of Health, Education and Welfare, 1966, Environmental Health Practices in Recreational Areas. p. 74.

[4] Unofficial estimate by USFS administrator for campgrounds with pit toilets.

[5] These figures are based on: 1) an average of three recreationists/vehicle; 2) an average distance of 48 miles from Seattle to the watershed and 60 miles from Tacoma; 3) a majority of vehicles used in 1974 will be 1973 and 1974 models.

[6] U.S. Environmental Protection Agency, April 1973, "Compilation of Air Pollutant Emission Factors," 2nd Edition, Table 2.1. 2-1.

[7] Washington Dept. of Ecology, 1974, "Preliminary Analysis State Highway Periodic Litter Survey.

the visual impact generated by forest management operations. However, this is an extremely difficult impact to consider. First, a model resolution much higher than that used in the study must be selected. Second, since visual impact, like beauty, rests in the eye of the beholder, it is extremely difficult to incorporate into a model at any degree of resolution. Third, the transient nature of visual impacts compounds an evaluation at any point in time.

Also omitted from the study were impacts of forest management operations on the fish and wildlife resources of the watershed.[8] Because of the occurrence of Snoqualmie Falls located downstream from the outflow of the Middle Fork watershed, no anadromous fishery exists in the watershed. However, a resident fishery does exist and provides many user days of pleasure for sports fishermen. Two important environmental determinants of fishery productivity are water temperature and suspended and inter-gravel sediment concentrations. The spatial and temporal resolution of the model precluded an assessment of manipulations on water temperature and hence on fish spawning and rearing productivity.

Assessing the impact of forest management operations on wildlife resources is a very difficult and complicated task all by itself. For example, it is generally acknowledged that certain wildlife species, such as black tail deer, benefit from forest harvesting operations. Hence, these animals would not fare as well in an ecosystem subject to land-use decisions which precluded timber harvesting or some other form of habitat manipulation. However, other wildlife species thrive in a more stable forest ecosystem. The problem of determining the response of wildlife populations to manipulations is just part of the larger problem of dealing with species diversity in forest ecosystems as influenced by manipulations. Much additional experimentation is necessary before it is feasible to incorporate these elements into a total forest ecosystem model.

The above discussion and conclusions illustrate one of the inherent difficulties involved in evaluating comprehensive plans for forest ecosystems. This difficulty arises because of the need to consider the interrelationships and interdependencies between land-use planning, forest management manipulations and the attendant environmental impacts during the planning process. The extreme differences in spatial and temporal resolution associated with wildland use planning and environmental impact assessment poses a very difficult challenge to land-use planners and environmental analysts. Only the development of a comprehensive and holistic approach to wildland use allocation and environmental impact analysis will produce satisfactory results for future generations.

[8] Although omitted from this study, both of these resources are incorporated into the framework of the larger project.

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