Simulation of Evapotranspiration and Drainage From Mature and Clear-Cut Deciduous Forests and Young Pine Plantation

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Prosper, a phenomenological model of water exchange between soil, plant, and atmosphere, was used to simulate evapotranspiration and annual drainage for 2 years from a mature oak-hickory forest in the southern Appalachians. The simulation was tested by comparing drainage to measured streamflow. In a year of unusually high precipitation the simulated annual drainage was within 1.5% of measured streamflow. Simulations were also performed by using the same 2 years of meteorologic data, but vegetation parameters were changed to represent a young white pine plantation and a regrowing hardwood forest 1 year after clear-cutting. The model estimated that drainage for an average rainfall year was reduced 20 cm by a 16-year-old white pine plantation and increased 36 cm by clear-cutting. These results were comparable to changes of −20 and +38 cm observed in watershed experiments at Coweeta Hydrologic Laboratory. Simulated evapotranspiration during the summer was nearly identical for hardwood and pine forests, while winter and early spring water loss was greater for pine. Simulation suggests that the greater evapotranspiration by pine was due to increased interception in all seasons and increased transpiration in the dormant season. For the clear-cut area, simulated evapotranspiration was considerably less than it was for the pine or hardwood forest and thus caused simulated soil moisture contents to be greater during the summer season.

A model that estimates evaporation and streamflow from forested lands may meet several needs. The researcher uses models to study and interpret the physical and biological processes that control water movement in the watershed. The forest hydrologist needs a technique for extending research results to watersheds with various kinds of vegetation, soil, climate, and physiography. The land manager wishes to predict how forest management alternatives change evapotranspiration (ET) and, more particularly, streamflow.

Watershed model development has usually emphasized the surface and subsurface water flows that generate streamflow. Because of the complexity of measuring or estimating ET these models usually contain simplified ET functions based on pan measurements or regional potential ET [*Crawford and Linsley,* 1966; *Holtan and Lopez,* 1971; *Leaf and Brink,* 1973; *Tennessee Valley Authority,* 1972]. Actual ET may exceed 50% of annual precipitation and thus is a significant part of the water balance. Since ET varies with vegetation size and density [*Hibbert,* 1967; *Douglass,* 1967], a model should be capable of simulating the effect of vegetation changes on the water balance in order to be of value to land managers. The research and modeling activities of the International Biological Program link processes such as plant growth, decay, and nutrient movement to water content and flux. The linkage requires a definitive and versatile submodel of evapotranspiration to be used with a watershed transport model.

Prosper is a phenomenological model of atmosphere-soil-plant water flow which was developed to estimate water stress on forest vegetation with a closed canopy [*Goldstein et al.,* 1974]. The original application was on Walker Branch watershed, an Eastern Deciduous Forest Biome experimental site at Oak Ridge, Tennessee [*Goldstein and Mankin,* 1972]. Further development was stimulated when Prosper was found inadequate to handle cases of drastic vegetation alteration such as forest clearing. This paper reports the application of the current version of Prosper to experimental watershed data from Coweeta Hydrologic Laboratory. A future step is the implementation of Prosper as the ET submodel for the watershed transport model described by *Huff* [1975]. The simulation procedure for Prosper is outlined in the appendix.

The three objectives for this paper are (1) to familiarize the reader with Prosper and describe current refinements of the model, (2) to use experimental data from the Coweeta Hydrologic Laboratory to test this model, and (3) to illustrate several uses for the simulation.

METHODS

The Coweeta Hydrologic Laboratory, a 2185-ha research installation of the USDA Forest Service, was established in western North Carolina in 1933 with the objective of studying the effects of forest land usage upon quantity and quality of streamflow. By using a network of 31 gaged watersheds a series of vegetation alteration treatments was initiated in 1939. The two treatments pertinent to this paper are (1) the complete cutting of all living vegetation (clear-cutting) for the experimental purpose of reducing transpiration and studying the effect on streamflow and (2) the clear-cutting of a deciduous forest and conversion to eastern white pine (*Pinus strobus* L.). Detailed descriptions of watershed characteristics, treatment histories, and streamflow responses to treatment have been presented for

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the clear-cut experiments [*Swank and Helvey*, 1970] and pine conversion [*Swank and Miner*, 1968].

Prosper was used to simulate the ET which might have taken place if each of the two treatments had been applied to watershed 18. The simulated treatment effects were compared to the real treatment effects found on other watersheds. Watershed 18 has a mature oak-hickory forest of 25.6 m^2 ha^{-1} basal area. No major changes in its forest vegetation have occurred during the last 40 years. This 12.5-ha watershed has deep loamy soils which are underlain by granitic bedrock. Its elevation ranges from 721 to 977 m, and its slope is 22°, facing northwest.

The data requirements for Prosper include daily values of precipitation, air temperature, relative humidity or dew point, solar radiation, and wind speed. Mean values of albedo, leaf area of vegetation, and interception storage for summer and winter seasons; mean slope and aspect of the land surface; and typical resistance values for water movement through soils, plants, and atmosphere are also needed. Much of this information and the hydrologic data used to compare and test the simulations is available at the Coweeta Hydrologic Laboratory. Soil hydraulic properties and root distribution data were obtained from studies summarized by *Luxmoore* [1972].

Meteorologic data from May 1971 through April 1973 were used in this application of Prosper. Because soils are consistently wet in May [*Helvey et al.*, 1972], the May–April water year minimizes differences in soil moisture storage between years and insures that the model starts with approximately the same initial conditions each year. Prosper simulates changes in soil water to a depth chosen by the user. In this case, soil moisture was calculated for two layers, the 0- to 30-cm and 30- to 90-cm depths. These layers correspond to the A and B horizons of the sandy loam soil on watershed 18, similar to the Porters series. The ET model did not simulate the movement of water between 90 cm and the stream. Therefore the drainage term of Prosper was equated to streamflow only for annual periods.

Except for precipitation, climatic variables were similar for the 2 years (Table 1). Precipitation for the mean water year is 196 cm. Snow comprises about 5% of the annual total and usually melts in a few days. Precipitation for 1971–1972 was 199 cm and for 1972–1973 was 234 cm. For both years precipitation in the growing season was about 12% above average, but in the second year, the wettest in 38 years of record, a large excess came during the dormant season (Figure 1). Table 1 also shows the climatic averages for the years immediately following each of three clear-cutting experiments at Coweeta.

Parameters were chosen to fit the simulation to annual streamflow for 1971–1972. Without further adjustments to these parameters a simulation was made for the mature oak-hickory by using climatic data for the second year. Other simulations used climatic data for both years but varied the parameters to describe the evaporative surfaces of a 1-year-old regeneration forest of sprouts and seedlings and a 16-year-old white pine plantation. Table 2 lists the parameters that were used to describe the three vegetation types. Leaf area index is the ratio of the foliage surface area to the land surface area. Values were based in part on measurements made at Coweeta [*Swank and Schreuder*, 1973]. Evergreen shrubs (kalmia and rhododendron) provide the winter leaf area for deciduous and clear-cut forests. The seasonal change in leaf area for white pine is due to the annual needle cast. Albedo values were taken from measurements at Coweeta [*Swift*, 1972] and by *Leonard* [1967]. Interception storage is the apparent depth of precipitation per unit land area that is held by foliage and litter and was calculated from data by *Helvey* [1967]. The minimum surface diffusion resistance shown in Table 2 is an estimate for the uniform single-layer surface described in the appendix. The resistance values were derived from data for individual leaf, needle, and litter layers.

RESULTS

Because the simulation for the oak-hickory forest was fitted to the 1971–1972 data, the difference between measured and simulated streamflow was small for that year. Without additional fitting the Prosper simulation for 1972–1973 matched the measured streamflow within 1.5% (Table 3), although precipitation was 18% greater. Because a direct measurement of watershed ET is not possible, all judgments of the fit of the simulations were based on comparisons between the annual

TABLE 1. Climatic Averages at Coweeta Hydrologic Laboratory

Year	At Laboratory Office, Elevation 686 m: Air Temperature, °C	Solar Radiation, Ly/d	Pan Evaporation, cm/6 month	Watershed 18 Precipitation: cm/6 month	Rank*
			May–October, Growing Season		
38-year mean	18.5	...	57	83	...
1940	17.6	...	55	83	20
1941	19.6	...	60	64	7
1963	17.4	...	59	63	6
1971	19.1	378	57	93	27
1972	18.1	399	60	94	29
			November–April, Dormant Season		
38-year mean	6.7	...	32	113	...
1940–1941	6.2	...	34	71	1
1941–1942	5.9	...	37	94	7
1963–1964	5.2	...	41	133	32
1971–1972	7.3	254	33	106	16
1972–1973	6.9	233	34	140	34

*One is driest; 38 is wettest.

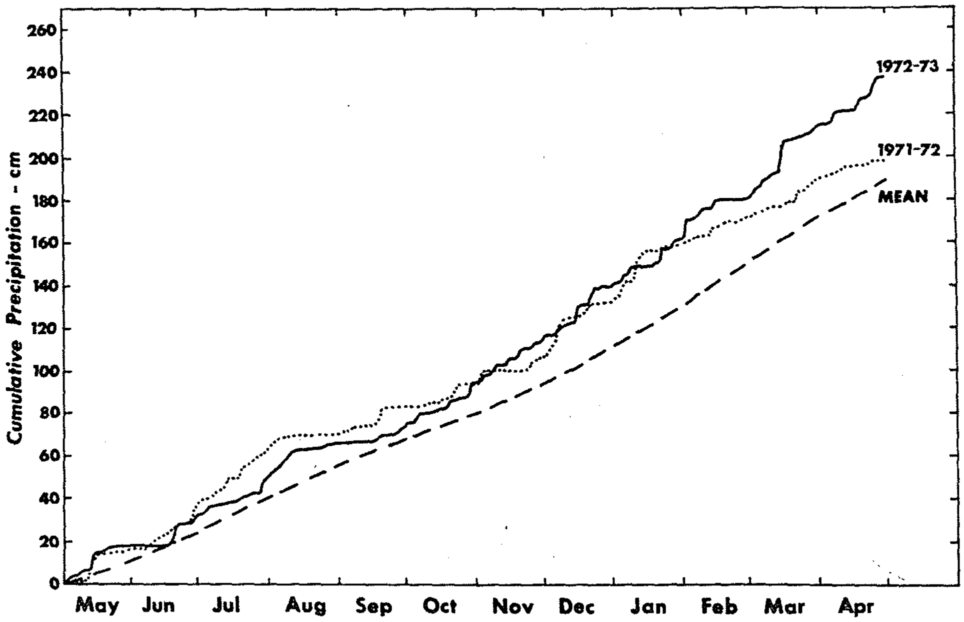

Fig. 1. Cumulative precipitation at watershed 18, Coweeta Hydrologic Laboratory, for the mean water year and the years used for simulation.

totals of measured streamflow and the drainage term from the simulation.

Table 4 lists the changes in streamflow and simulated drainage associated with conversion from oak-hickory to white pine and clear-cut forests. The white pine plantation is on a north-facing slope adjacent to watershed 18. For this comparison the measured and simulated results are for the 1971–1972 and 1972–1973 years. In both years the drainage change was within 1.5 cm of the measured streamflow change.

Three clear-cut treatments on north- or east-facing watersheds at Coweeta produced streamflow increases in the first years following cutting which ranged from 36.0 to 41.3 cm (Table 4). Increases determined by simulations for 1971–1972 and 1972–1973 were 36.5 and 42.2 cm. None of the watershed treatment years had the same climatic conditions as the years used in the simulation (Table 1), and the shape, aspect, and elevation of the clear-cut watersheds differ from those of watershed 18. Nevertheless, Table 4 shows that the simulations covered the range of the measured treatment effects.

The simulations were used to visualize monthly and seasonal fluctuations of ET, transpiration, interception, soil moisture, and plant water status and to infer how these may vary between the three types of plant cover. The graph of monthly totals of simulated ET over 2 years shows differences in timing and water use rates (Figure 2). In summer the simulated pine and deciduous forests had similar water use rates except that pine began using water a month earlier in the spring. In the winter the simulated ET for pine is significantly greater than that for either the clear-cut or the deciduous forest.

On the basis of data from interception and watershed studies, *Swank and Miner* [1968] suggested that greater winter ET from the pine plantation was due largely to interception loss. They also pointed out that greater transpiration from pine than from hardwoods probably contributed to observed streamflow reductions, although experimental transpiration data were not available. Simulation yields estimates of transpiration and interception for the two forest types. For both years, Table 5 shows interception by pine to be about 5 cm greater than interception by oak-hickory forest in each of the growing and dormant seasons. Simulated transpiration by the two forests is nearly equal during the growing period, but pine exceeds oak-hickory transpiration by 12–16 cm during the dormant season. Thus the simulation indicates that more than half of the greater annual ET from pine is due to dormant season transpiration.

Although the second year was the wettest on record, precipitation from June 1 through September 15 (full-leaf

TABLE 2. Values for Prosper Parameters for Three Vegetation Types

Vegetation Type and Canopy State	Leaf Area Index	Albedo	Interception Storage, cm/cm²	Minimum Surface Diffusion Resistance, s/cm
Mature oak-hickory				
Summer	5.00	0.22	0.24	2.5
Winter	0.50	0.16	0.16	4.0
Regrowing clear-cut				
Summer	0.75	0.20	0.10	2.5
Winter	0.50	0.16	0.09	4.0
White pine plantation				
Summer	12.00	0.12	0.35	3.5
Winter	6.00	0.10	0.24	4.5

TABLE 3. Measured and Simulated Annual Streamflow for Coweeta Watershed 18 With Mature Oak-Hickory Forest

Water Year May–April	Total Precipitation, cm	Streamflow Measured, cm	Streamflow Simulated,* cm	Streamflow Difference, %
1971–1972	198.9	104.3	103.6	−0.6
1972–1973	234.3	136.0	138.0	1.5

*Drainage from 90-cm soil layer.

period) was 9 cm less than that during the first year. In spite of this the ET patterns shown in Figure 2 are very similar for both years. Tables 6 and 7 show the minor effect of the precipitation differences upon the range of simulated water potentials for the evaporative surface and upper soil layer. Table 6 shows the number of days that the simulated water potential for the ET surface was within each of five ranges. The water potential of either forest was rarely less than −10 bars. The oak was under stress slightly more often than the pine. These two findings suggest that summer forest vegetation on the north slope was subjected to little or no water stress during the 2 years. This finding is supported by *Hewlett* [1962], who concluded that water stress in four forest species, as measured by diffusion pressure deficit, rarely exceeded 10 atm at Coweeta.

Simulation shows the number of days that the soil water potential of the 0- to 30-cm depth was within each of five ranges (Table 7). There was little difference between the simulations for pine and oak-hickory. A comparison of years shows that soil water potential was lower in 1972, possibly owing to lower precipitation, but soil moisture was still quite high. This tendency for high soil moisture agrees with 10 years of soil moisture measurements at Coweeta [*Helvey and Hewlett*, 1962; *Helvey et al.*, 1972], which showed that the moisture content of the surface soil rarely falls below 18–20% by volume or approximately −2.5 bars of water potential. Simulation also showed that about 50% of the annual evapotranspiration (excluding interception) came from the top 30 cm of soil.

The ET surface of the clear-cut is a heterogeneous mixture of exposed soil, leaf litter, dead woody material, and young vegetation. Unlike the living and dead material in the shade of the forest, the clear-cut surface is exposed and subjected to a high evaporative demand but has a limited number of roots to extract water from the soil. Therefore much of the clear-cut surface could be desiccated even though the soil moisture was high. The simulation for the clear-cut showed that the water potential of the mixed ET surface (Table 6) was below that for either forest, while the soils of the clear-cut (Table 7) remained substantially wetter than those under pine or hardwoods. Table 7 also shows little difference in the clear-cut soil water potential between years. The resistance of the ET surface, and not the soil moisture content, reduces the ET rate in the clear-cut and appears to have masked any effect upon soil moisture of the meteorological differences between the years.

DISCUSSION

We believe that a model such as Prosper, which represents the processes that control water movement through the soil-vegetation-atmosphere system, can simulate water use for a variety of climatic, plant, and soil combinations. An objective was to test the model by comparing simulations with data from experimental watersheds. Results were encouraging. The annual totals of simulated drainage agreed closely with measured streamflow and streamflow changes that were produced experimentally by clear-cutting hardwood forests and converting a hardwood forest to white pine. Moreover, simulated and measured values agreed closely for 2 years despite seasonal and annual differences in precipitation. The two leaf area functions described in the appendix were chosen to fit data from the clear-cutting and regrowth experiment described by *Swank and Helvey* [1970]. The functions appear to work well over a wide range of leaf area indices from 0.5 to 12.0.

Streamflow from a watershed is influenced by both events in past months and current ET and precipitation. Therefore streamflow cannot indicate day-to-day water use by vegetation. The Prosper simulation of evapotranspiration is helpful because it can model the effects of vegetation manipulation on water use rates. The model estimates possible day-to-day changes in moisture content and water potential for plants and soil, details which cannot be reasonably obtained by direct measurement. The model may also be used with other environmental data to estimate moisture stress of forest vegetation in dry years or on a drier site.

The simulations reveal research needs. For example, the model is sensitive to the leaf area and minimum stomatal resistance of the evaporating surface and to the water potential

TABLE 4. Change in Annual Streamflow Attributable to Conversion From Mature Oak-Hickory Forest

Water Year May–April	Annual Precipitation, cm	White Pine Measured Streamflow, cm	White Pine Simulated Drainage, cm	Clear-Cut Measured Streamflow, cm	Clear-Cut Simulated Drainage, cm
1940–1941	154.0	...	...	+36.0	...
1941–1942	158.5	...	...	+41.3	...
1963–1964	196.0	...	...	+38.1	...
1971–1972	198.9	−20.2	−20.2	...	+36.5
1972–1973	234.3	−18.3	−16.9	...	+42.2

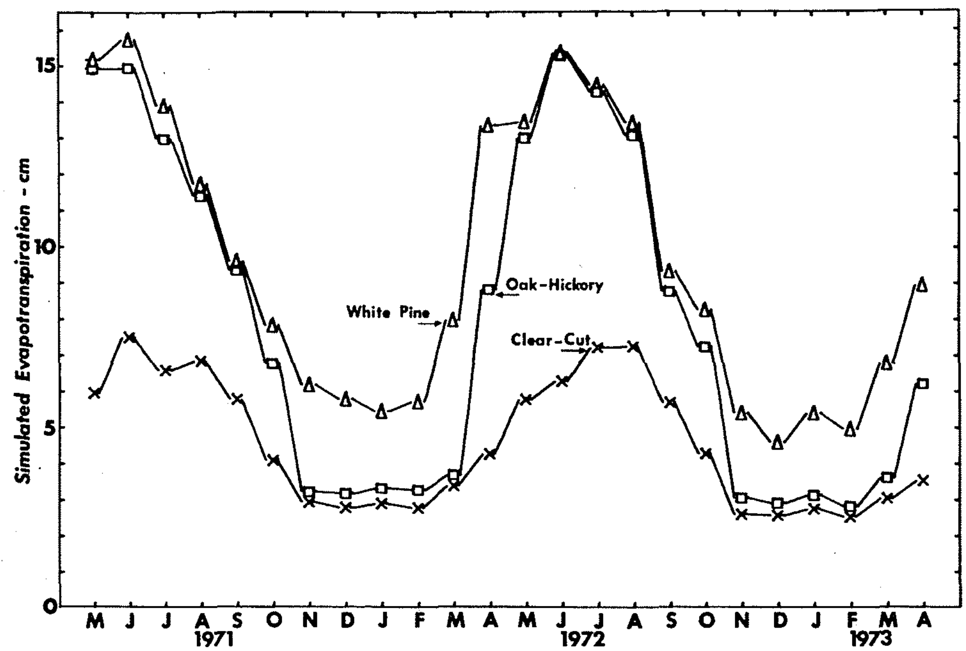

Fig. 2. Monthly totals of simulated evapotranspiration for a 16-year-old white pine plantation, a mature oak-hickory forest, and a clear-cut forest.

versus diffusion resistance relationship at the surface. These types of data are generally lacking for forest vegetation.

APPENDIX: THE PROSPER MODEL

This appendix is an outline of Prosper as implemented for this application. Further details are available in articles by *Goldstein and Mankin* [1972] and *Goldstein et al.* [1974].

Prosper applies a water balance to a stand of vegetation and several soil layers. A hypothetical ET surface which homogenizes the plant, soil surface, and litter characteristics is defined. This choice is based on the assumption that a model which simulates water dynamics on a day-to-day basis and uses daily means or totals for environmental inputs does not require a detailed description of canopy geometry. Evapotranspiration is conceptualized as taking place from a single surface (surface 1 in Figure 3) which is a combination of the ground and all canopy surfaces.

An equation for vapor flow from the evapotranspiration surface is derived by the combined energy balance–aerodynamic method [*Monteith*, 1965]. The equation for liquid flow to the ET surface is derived by applying the law of conservation of mass and Darcy's law [*Gardner*, 1960]. On the assumption that the system is in steady state, the liquid and vapor flows are equated, and this equation is solved for ET. *Cowan* [1965] developed a similar description and solved some cases with an approximate analytical solution. Prosper uses an approximate numerical solution.

Previously, the energy balance of the ET surface was solved in units of energy per unit ground area. The assumption of a single ET surface, equal to the ground area, ignores the greater surface area of the plant canopy. Leaf area varies dramatically with plant species, stage of plant maturity, and time of year. Total leaf area should not be used, since not all the canopy is equally active in the ET process. The energy balance equation was modified by inserting a function for effective leaf area $f(A)$, where A is total leaf area:

$$R_n = [f(A) + 1]L_v F_v + [\sigma f(A) + 1]H + G \qquad (1)$$

where all values are daily totals, R_n is the net radiation per unit ground area above the ET surface, L_v is the latent heat of vaporization for water, F_v is the vapor flow per unit area of evaporative surface, $L_v F_v$ is the energy of latent heat, H is the net heat energy per unit convective area transferred from the surface to the air, G is the net heat energy per unit ground area transferred from surface to soil, $[f(A) + 1]$ is the multiplier for the effective leaf area plus ground area, and σ is the ratio of convective area to evaporative area.

TABLE 5. Simulated Interception and Transpiration Totals for Oak-Hickory and White Pine Forests During the Growing and Dormant Seasons

Year and Vegetation Type	Interception		Transpiration	
	May–October, cm	November–April, cm	May–October, cm	November–April, cm
1971–1972				
Oak-hickory	15.09	9.38	53.54	13.02
White pine	20.07	14.16	52.64	29.53
1972–1973				
Oak-hickory	13.83	9.01	56.05	9.98
White pine	18.28	13.64	54.68	21.84

TABLE 6. Distribution by Days of Water Potential of Evaporating Surface From Simulations for June 1 Through September 15

Year and Vegetation Type	Growing Season Precipitation, cm	Range of Surface Water Potential, bars				
		0 to −2 days	−2 to −5 days	−5 to −10 days	−10 to −15 days	−15 to −20 days
1971	58					
Oak-hickory		1	56	48	2	0
White pine		1	65	41	0	0
Clear-cut		0	1	6	44	56
1972	49					
Oak-hickory		0	31	69	7	0
White pine		0	38	66	3	0
Clear-cut		0	0	4	31	72

Deriving the equation for vapor flow [*Goldstein et al.*, 1974] and using (1) give

$$F_v = \left\{\frac{[f(A)+1][R_n - G]\Delta}{[\sigma f(A)+1]C_p\rho} + [f(A)+1]\frac{\rho_2{}^* - \rho_2}{r_a}\right\} \cdot \left(\frac{r_a + r_x}{r_a} + \frac{[f(A)+1]L_v\Delta}{[\sigma f(A)+1]C_p\rho}\right)^{-1} \qquad (2)$$

where Δ is the derivative of saturated vapor pressure with respect to temperature, C_p is the specific heat of air at constant pressure, $\rho_2{}^*$ is the saturated vapor density, ρ_2 is the vapor density of surface 2 (Figure 3), r_a is the resistance to transfer of water vapor between surfaces 1 and 2, and r_x is the resistance of the ET surface to the release of water vapor.

The effective canopy area for ET is $f(A)$. Data from the experiment described by *Swank and Helvey* [1970] suggested the function

$$f(A) = A/[1 + (A/A_0)] \qquad (3)$$

where A is the leaf area index and A_0 is a canopy scale factor calculated from experimental data at Coweeta Hydrologic Laboratory to be 3.0.

The roots and the soil in each soil layer were interpreted as resistances in an electrical network (Figure 1), and network analysis techniques were used to derive an equation for the flow of liquid water to the ET surface as a function of surface water potential. This liquid flow was equated to the vapor flow equation (2), and ET and plant water potential were computed by using standard techniques for solving nonlinear equations. These steps are described by *Goldstein et al.* [1974].

As was stated previously, Prosper was developed for the closed canopy situation. But the regrowth of a newly cut forest is a significant deviation from a closed canopy, and one cannot assume a homogeneous distribution of active roots, stems, or leaves within any horizontal layer. Low plant densities, and thus small indices of leaf area, represent a reduction in the number of transpiration pathways for each unit of ground area. In terms of the model, decreasing leaf area index below some degree of canopy closure should increase the plant resistance to liquid flow. Therefore plant resistance terms are divided by a function $g(A)$ to account for the heterogeneity associated with small leaf area indices. The function chosen was

$$g(A) = kA^2/(A_1{}^2 + A^2) \qquad (4)$$

where A_1 is the scaling factor for canopy closure and k is an efficiency factor. The values of both factors, 1.95 and 0.422, respectively, were determined from experimental watershed data.

Among the climatic data needed to use Prosper, solar radiation measurements on a sloping watershed are the least likely to be available. For our application an algorithm was added which calculates the incident solar radiation on any sloping watershed on the basis of standard radiation measurements taken at a distant point [*Swift and Luxmoore*, 1973].

The computational steps by which Prosper simulates water dynamics for a single day are:

1. Precipitation for the day enters the system. If there is no precipitation, the simulation proceeds to step 2. The precipitation initially enters the interception storage compartment (Figure 3), which has a maximum storage capacity that is a function of leaf area index. When the interception compartment is full, any additional precipitation becomes throughfall.

2. If the interception storage compartment θ_0 does not contain any water, then the simulation proceeds to step 3. If $\theta_0 > 0$, then F_v is calculated from (2). Since r_a is the only resistance to evaporation of intercepted water, r_x is set to zero. If $\theta_0 \geq F_v$, then an amount of water equal to F_v is evaporated from the interception storage compartment, the liquid flow to the transpiration surface is set to zero, and the simulation proceeds to step 3. If $F_v > \theta_0$, then all of θ_0 is evaporated, and an amount of energy equal to $L_v\theta_0$ (where L_v is the latent heat of vaporization for water) is subtracted from the total net

TABLE 7. Distribution by Days of Water Potential of First Soil Layer From Simulations for June 1 Through September 15

Year and Vegetation Type	Growing Season Precipitation, cm	Range of Soil Water Potential, bars				
		0 to −2 days	−0.04 to −0.3 days	−0.3 to −0.8 days	−0.8 to −2 days	−2 to −3 days
1971	58					
Oak-hickory		0	47	27	33	0
White pine		0	47	21	39	0
Clear-cut		1	84	22	0	0
1972	49					
Oak-hickory		0	22	35	45	5
White pine		0	22	34	46	5
Clear-cut		1	85	21	0	0

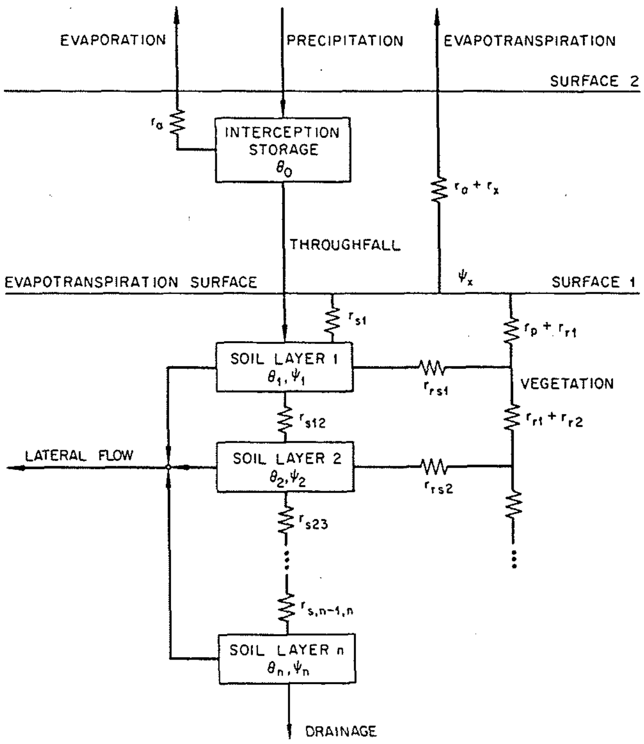

Fig. 3. Schematic diagram of the Prosper simulation.

radiation for the day R_n. The adjusted value of R_n will be used instead of the total net radiation in later steps.

3. At this point, the simulation enters a loop to calculate evapotranspiration from soil moisture storage and soil water redistribution and drainage. For high values of soil water conductivity, single daily calculations produce numerical instabilities. This necessitates the inclusion of a loop structure which makes N iterations in calculating the daily water movement. The number of passes through the loop N is dependent upon throughfall, layer thickness, maximum saturated soil water conductivity, and N for the previous day.

4. Upon entrance into the loop soil water potentials, conductivities, and resistances are calculated for the soil layers. One Nth of the daily throughfall and net radiation is used to calculate vapor flow unless liquid flow has been set to zero in step 2 in which case the depletion of soil water by evapotranspiration is zero. Also calculated are plant water potential and the change in soil water content for each soil layer. If the moisture in any layer exceeds saturation, the excess is removed by lateral flow. The amount of water in the bottom layer exceeding field capacity drains at a rate equal to the hydraulic conductivity.

5. When the simulation has gone through the loop N times, the daily totals of evapotranspiration, lateral flow from each soil layer, and drainage are calculated by summing the amounts calculated in each of the N passes through the loop.

6. The simulation proceeds to the next day and returns to step 1.

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