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A Preliminary Quantification of the Impacts of Aspen to Conifer Succession on Water Yield Within the Colorado River Basin (A Process Aggravating the Salt Pollution Problem)

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A PRELIMINARY QUANTIFICATION OF THE IMPACTS OF ASPEN TO CONIFER SUCCESSION ON WATER YIELD WITHIN THE COLORADO RIVER BASIN (A PROCESS AGGRAVATING THE SALT POLLUTION PROBLEM)

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ABSTRACT

Heat pulse velocity techniques were developed for effectively monitoring water movement in aspen (*Populus ttremuloides*), subalpine fir (*Abies lasiocarpa*), and Englemann spruce (*Picea engelmannii*). Once the techniques were perfected, transpiration was monitored in replicated trees of each species for one year. This data was used to modify the plant activity index and the crop coefficient for each species within the model ASPCON, a deterministic, lumped-parameter model describing the hydrology of aspen to conifer succession. Results of the modeling indicate 18.5 cm (7.3 in) net loss of moisture available for streamflow when spruce replace aspen, and a loss of 7.1 cm (2.8 in) when fir forests cover the watershed. The aspen to conifer successional trend is therefore significantly reducing water yields within the Colorado River Basin, water that could be used to dilute salt downstream from the high water-yielding watersheds.

ACKNOWLEDGMENTS

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INTRODUCTION

General

Aspen forests are generally subclimax ecologic communities in the Rocky Mountain region. Mature aspen forests are replaced over time by evergreen conifers unless some form of catastrophic disturbance (i.e., fire, disease, clearcutting) occurs. When such disturbance destroys the overstory canopy of an aspen forest, aspen sprout from the roots and grow faster than the other vegetation, and the aspen stand is thus able to perpetuate itself.

As man has prevented natural fires and clearcutting, many areas once dominated by aspen have become coniferous forests. The impact of this shift in dominant forest cover on streamflow from subalpine mountain zones is poorly understood. Available literature and preliminary modeling efforts, however, strongly suggest that the aspen to conifer succession significantly reduces water yield (Jaynes 1978). The effect is already being felt since the aspen to conifer succession is presently well advanced on many former aspen acreages. Besides decreasing natural water yields, the increasing conifer acreage may also significantly reduce the gain in water yields achievable through snow augmentation by cloud seeding. Runoff volumes from aspen or conifer forest areas depend on the seasonal consumptive use pattern for the vegetation type and the influence of the respective canopies on incoming precipitation. Water yield reductions attributable to the aspen to conifer conversion can therefore be related to transpiration and canopy interception studies.

The ecological progression from aspen to conifer forest results in a reduction in runoff volumes and hence the water available to downstream users. The primary objective of this study was a preliminary quantification of the runoff reduction as an aspen watershed proceeds to conifer climax.

Managing Aspen Forests for Increased Water Yield

As pointed out by Hibbert (1979), quaking aspen (*Populus tremuloides* Michx.) is the most widely distributed tree in North America. This species occupies approximately 1.3 million hectares (3.3 million acres) in the Colorado River drainage area, almost all of it in the Upper Basin. About 75 percent is on National Forest land. Aspen is recognized for its multiple values; yet, in the West, it has received relatively little management or research attention (Mueggler 1976). About 1,106,000 hectares (2,765,000 acres) of aspen are classified as commercial.

Aspen is usually found between 2,188 m (7,000 ft) and 3,438 m (11,000 ft) elevation, in pure stands or interspersed among conifers in the subalpine, mixed conifer, and cooler portions of the ponderosa pine type. Aspen is so closely associated with these conifer types, especially Douglas-fir and Engelmann spruce, that it sometimes is included with them for inventory and management purposes, particularly in the Lower Basin, where aspen accounts for only about 46,000 hectares (115,000 acres) of commercial forest land (Hibbert 1979). Farther north, in central Colorado and eastern Utah, aspen is much more extensive, and often occurs in pure stands of up to several thousands of hectares. Aspen has generally been regarded as a fire-induced successional species able to dominate a site primarily by root sprouting until replaced by conifers in a single aspen generation upon curtailment of fire, while in other areas conifer invasion takes much longer (Mueggler 1976). In many areas, seral aspen eventually gives way to conifer climax if fire is excluded. Since uncontrolled wildfires lack social acceptability, harvesting and controlled burning are considered viable alternatives to prevent aspen from reverting to coniferous forest.

The climate where aspen grows is essentially the same as that found in forested areas of the closely associated lower subalpine and mixed conifer types. Mean annual precipitation ranges from about 50 to more than 100 centimeters (20 to 40 inches), half or more falling as snow. Water yield also varies greatly depending on precipitation, elevation, and latitude. In the Southwest, water yield averages from 7.6 to 12.7 centimeters (3 to 5 inches) on most sites, but yield increases with increasing precipitation and cooler climate; some of the wettest aspen sites probably produce upwards of 51 centimeters (20 inches) as streamflow, judging from data available in the subalpine type (Hibbert 1979).

The potential is good for increasing water yield by converting other forest types to aspen. However, the increase in yields declines rapidly after cutting or otherwise removing the other species if regrowth is not controlled.

The increases in water yield after clearing are attributed largely to reduction in summer evapotranspiration, although Swanson (1972a) working in southwestern Alberta, Canada, found one-third more snow in small openings in aspen stands than in the surrounding closed canopy. The ratio persisted throughout the melt season. Therefore, even though aspen is leafless during winter, redistribution of snow from surrounding forest to small openings may have significance in this type as well as in the subalpine conifer forests (Hibbert 1979).

Hibbert (1979) indicates that research started with the Wagon Wheel Gap study (Bates and Henry 1928). Average annual streamflow increased by an amount equal to a depth of 2.5 centimeters (1 inch) over the entire watershed during 7 years after clearcutting the predominantly aspen cover in 1919. Since that time, several plot studies (Croft and Monninger 1953, Brown and Thompson 1965, Tew 1967, Johnston 1970) have shown that cutting aspen overstory and leaving the herbaceous understory to protect the soil reduces soil moisture withdrawals by up to about 20 centimeters (8 inches), with the average about 11.5 centimeters (4.5 inches). The resulting increased soil moisture levels at the end of the growing season presumably translate to increased water yields during snowmelt, because less of the melting snow is used to recharge the soil profile, resulting in greater streamflow and seepage to groundwater.

Both plot and watershed studies have shown that water yield can be substantially increased by managing aspen in the Colorado River Basin. DeByle (1976) places streamflow increases at 10 to 15 centimeters (4 to 6 inches) annually for a year or so after clearcutting. Tew (personal communication, cited by Hibbert 1979) suggests that 13 centimeters (5 inches) increase is the maximum that can be expected by converting aspen to a grass-forb cover under conditions found in Utah. Investigators agree that if aspen clearcuts are allowed to revegetate naturally, the increase in streamflow will begin to diminish within a couple of years and may disappear within 10 to 15 years. Thus it appears that an initial increase of about 13 centimeters (5 inches) is the most that can be expected from aspen removal, and if the increase is to be maintained, sprouts must be controlled. Type conversion in the aspen probably would result in a long-term increase of less than 13 centimeters (5 inches) because replacement cover, once established, is likely to use more water than the herbaceous cover remaining immediately following reduction of the aspen stand. Since there is little information to go on, an arbitrary 8 to 10 centimeters (3 to 4 inches) per year is suggested as the increase that might be maintained from elimination of aspen on average sites (Hibbert 1979).

Although the future of aspen remains uncertain, the demand for aspen wood products could expand significantly over the next 25 years (Wengert 1976). Increase in demand for other values of aspen forest such as wildlife habitat and scenic beauty, can be expected as well. Clearcutting and perhaps controlled burning or other techniques can be used to halt deterioration of aspen stands (Mathison 1976) and thus perpetuate a forest type that is prized for its multiple values (Hronek 1976). Hibbert (1979) states that if aspen stands are allowed to regenerate naturally after cutting or other methods of stand reduction, the total water increase expected over the 10- and 15-year recovery period would be about 66 centimeters (2.2 acre-feet per acre treated). Therefore, if clearcutting for wood products is repeated every 80 years, for example, the long-term average increase in water yield for the 80-year period would be about 0.85 centimeter (0.3 inch) annually on the areas actually treated.

Hibbert (1979) states that in other forest types, the total water yield potential depends on the methods of treatment and the extent of application. If all 1.3 million hectares (3.3 million acres) of aspen within the Colorado River Basin were type converted at one time, the increase in water yield could reach 1,233 million cubic meters (1 million acre-feet) per year (assuming an average increase of 7 to 13 centimeters) (3 to 5 inches); almost all of it would be in the Upper Basin. However, the trade-offs would be great. Realistically, treatable hectares would be much fewer, and acceptable treatment methods would be less water productive than those that produce the greatest increase.

NOTE: Literature describing the impact of successional trends on water yields within the aspen-conifer complex is not yet available. The above literature review pertains only to management implications within existing aspen forests.

THERMOELECTRIC MEASUREMENTS OF TRANSPIRATION

Both thermocouples and thermistors possess a unique property which can be applied in thermoelectric monitoring of a flowing medium. If an electrical circuit includes a matched pair of thermistor beads or a pair of thermocouple junctions, such as copper-constant junctions, no current will flow as long as the beads or junctions are at the same temperature. If, however, temperatures are different, current will flow.

If a thermistor or thermocouple pair is inserted into a flowing medium, one downstream of the other, and a source of heat is added to the flow stream, the measured time of current flow is an indicator of the time necessary for the flowing medium to carry the heated portion out of the sensor range. Therefore, it is an indicator of flow velocity.

Thermoelectric techniques for measuring velocities were first developed by Rein in 1928 for the study of blood flow in humans. Huber (1932) and Huber and Schmidt (1937) adapted this method for use in plants. In Huber's studies, heat was applied somewhere in the transpiration stream of a plant. A thermocouple attached to a galvanometer was installed downstream from the heat source. Huber assumed the maximum deflection occurred on the galvanometer when the heated region of the sap reached the thermocouple. Using the distance from the heat source to the thermocouple and the time from heat injection to maximum deflection, Huber determined a velocity which he assumed to be sap velocity. Bloodworth et al. (1956) used a similar method to study the effect of humidity, soil moisture, and temperature changes on the relative rate of sap ascent in cotton plants.

Swanson's Analysis of Heat Flow in Trees

Swanson (1962) used equations developed by Marshall (1958) to further theoretical development of the heat pulse method. Marshall's equations were based on the physical theory behind thermoelectric methods, and will not be reviewed here.

By taking care to measure heat flow only in that vertical path to which heat is released, the point at which heat change is to be measured can be defined to have the value "y = 0" (i.e., measurement is only of heat flow in the vertical direction). Figure 1 delineates a point "C" on the axis of heat such that "C" = (0,0,0) and a point "B" where temperature change is be be measured such that "B" = (x1,0,0). This distance can be defined as "CB", and based on Marshall's previous work, the following equation results:

$$T_B = \frac{Q}{4kt} \exp-\left[\frac{(CB-Vt)^2}{4kt}\right] \qquad (1)$$

where:

V = heat pulse velocity
t = time
T = temperature change
k = diffusivity
Q = heat input

Since heat will be conducted downward as well as upward, a similar equation can be written for a second probe upstream from the heat source, at a point designated as "A", where "A" = (x2,0,0). In this case, convection is carrying the heat pulse away from point "A", lengthening the distance over which conduction must occur. The length is increased by a distance of "Vt".

$$T_A = \frac{Q}{4\pi kt} \exp - \left[\frac{(CA+Vt)^2}{4kt}\right] \qquad (2)$$

If "A" is carefully selected so that it is closer to "C" than is "B", there will be some point in time (designated "t_o")

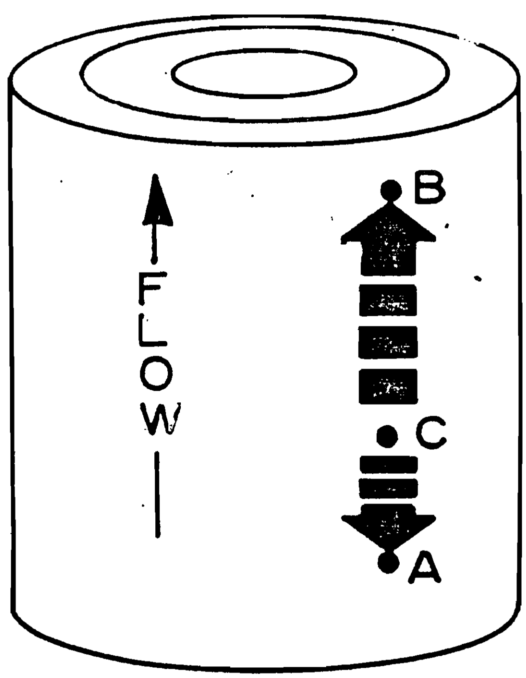

Figure 1. Flow of heat from a point of origin to two other p.

when "T_A" = "T_B". Under such conditions, Equations 1 and 2 can be solved simultaneously:

$$\frac{Q}{4\pi kt} \exp - \left[\frac{(CA+Vt)^2}{4kt}\right] = \frac{Q}{4\pi kt} \exp - \left[\frac{(CB-Vt)^2}{4kt}\right] \qquad (3)$$

Solving for V:

$$V = \frac{CB-CA}{2t} \qquad (4)$$

With Equation 4, sap velocities can be estimated with only information on the distance of the two thermocouple probes from a heat source in the xylem system, and the time from heat initiation until the temperatures at the two probes are equal.

There are several advantages to Swanson's technique:

Time can be accurately measured.

Heat pulse velocity (HPV) is largely determined by sap velocity, an indicator of transpiration.

HPV measurements are sensitive to relatively small changes in water flow.

Several researchers have recognized that in practice, HPV measurements underestimate sap velocities (Marshall 1958, Ladefoged 1960, Skau and Swanson 1963, Swanson 1971a). Swanson attributes at least part of the underestimation to disruption of flow by the insertion of heat and thermocouple probes.

Heat Pulse Velocity Measurements

Measurement of HPV has been used for two different purposes in plant-water relationship studies. Several researchers have used the method to study the effect of variability of climatic factors which control transpiration on water flow in plant stems. Gifford (1968) and Shaw and Gifford (1975) regressed HPV measurements in juniper (*Juniperus osteosperma* (Torr.) Little) and big sagebrush (*Artemisia tridentata*) against select environmental factors to determine their significance in controlling sap velocities. Balek and Pavliko (1977) used the technique with spruce (*Picea abies*) to correlate radiation, rainfall duration, air temperature, total rainfall and wind velocity with sap velocity. They also used the method to illustrate time lags between changes in those factors and changes in sap velocity. Hinckley and Scott (1971) found good relationships between solar radiation and HPV measured in Douglas fir (*Pseudotsuga menziesii*) when low moisture stress and evaporative demand were present. Lassoie et al. (1977) were successful in contrasting the water relations of various size Douglas fir trees using the heat pulse technique. They also studied rehydration of tissues following termination of water loss. However, poor relationships occurred when moisture stress and evaporative demand were high. Swanson (1975) used the absence or presence of measurable HPV to determine diurnal cycles of water use.

A second use of HPV measurements is that from correlation with measured transpiration losses. The HPV measurements can be used to predict transpirative loss. According to Swanson (1970):

> With an individual tree, heat pulse velocity is a linear function of transpiration. Comparisons of HPV at a point will indicate relative magnitudes of transpiration change. If one can relate it with some measure of actual transpiration for a calibration, the method can later be used to predict transpiration from that tree.
>
> This does not allow comparisons between trees, however, because it cannot be assumed two probes in different trees represent the same relationship to overall sap velocity and flow.

Swanson also states that the problems associated with HPV measurements as an indicator of transpiration are no greater than those using aerodynamics or energy budget techniques, and, therefore, he commends HPV measurements as potentially useful in this manner.

Studies using HPV measurements to estimate transpiration losses have had varying results. Ladefoged (1960) calibrated a modified version of the thermoelectric technique with whole-tree potometers and was successful in predicting transpirational losses in unnamed species of apple and pine. Swanson (1962) used pressure to force water through willow (Salix spp.) stems and measured the flow of that water thermoelectrically. He found high repeatability in sap velocity measurements at a constant pressure. Ladefoged (1963) found sap velocity to be a very sensitive indicator of transpiration rate changes due to variance in light intensity, wind and temperature. Skau and Swanson (1963) compared HPV rates and water flow rates forced through juniper (Juniperus osteosperma and Juniperus dipeana) stems and found good linear correlation. As shown in Figure 2, the slope of the correlation line varied with the proximity of the thermocouple probe to the sapwood-cambium and the sapwood-heartwood interfaces. For a given input flow, sap velocities were highest in the center of the sapwood and decreased near the heartwood and cambium. In a set of field experiments conducted

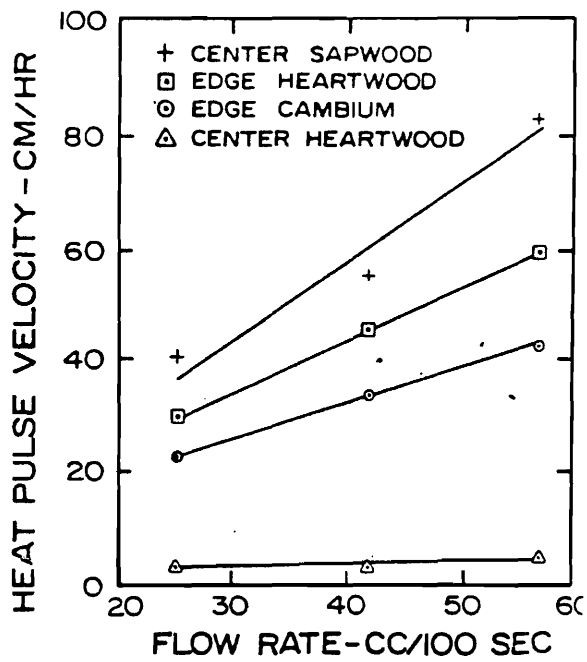

Figure 2. Heat pulse velocity versus flow rates in juniper stems (Skau and Swanson 1963).

during the same study, HPV was compared with transpirational loss as measured by an evaporation tent and found to be a reliable indicator of both magnitude and direction of gradual changes in vapor loss. HPV did lag slightly in amplitude with abrupt changes caused by artifical shading. This lag probably reflected the time needed to overcome various resistances to change in stress along the water conducting column.

Decker and Skau (1964) found similar good relationships between vapor loss measured by an evaporation tent and HPV in aleppo pine (Pinus halepensis) and alligator juniper (Juniperus osteosperma). Artificial shading of aleppo pine produced a time lag in HPV response similar to that found in the Skau and Swanson study.

Gale and Poljakov-Mayber (1964) compared HPV measurements with transpirational losses measured by the evaporation tent and lysimeter methods in pine (Pinus halepensis) and sour orange (Citrus aurantus). Transpiration measurements from both methods were in close agreement. At low water stresses, a highly significant regression line was obtained relating hourly transpiration losses and hourly HPV measurements. Points deviating from that developed regression line were determined to be periods of lag behind changes in transpiration. At high water stress, there was little correlation between hourly values.

During both lag and stress periods, correlation on a daily basis was acceptable. The study concluded:

> If a single thermocouple probe is used, a correlation between transpiration and HPV must be obtained immediately before or after actual measurements to obtain similar moisture and weather conditions. (p. 213)

Hinckley (1970) developed a physical model of sap flow to test HPV measurements. He collected HPV measurements on water flowing through a plastic tube at 5-minute intervals. Relating these HPV measurements to the known flows in the tube provided an excellent correlation ($r = 0.97$). Hinckley then applied the technique to three young Douglas fir trees in a controlled environment chamber. Actual transpiration was monitored by measuring the amount of water required to keep the weight of the seedling and container constant. Simple regression and correlation analysis indicated that HPV measurements provided an excellent estimate of transpiration under all conditions ($r = 0.91$).

Swanson (1972b) compared simultaneous HPV and lysimeter measurements in aleppo pine (*Pinus halepensis*) under extremely uniform environmental conditions. The sampling days were clear with uniform insolation and the trees were under high internal water stress. These conditions created constant HPV values over a given day. Daily transpiration amounts were closely correlated to 1,4,6 and 14-hour averages of HPV ($r = 0.98$ in all cases). Correlation of hourly transpiration with hourly HPV was low. From this study, Swanson concluded that HPV is a valid indicator of transpiration if one has six or more continuous hours of data. He attributed the good correlation at one and four hours to unusually uniform conditions.

Despite the good correlation between transpiration and HPV, there are rigid limitations to their application. The good correlations were generally obtained on small trees. Based on the work of Wendt et al. (1967) and Swanson (1967), one would expect decreasing correlation coefficients as the tree diameter is increased, due to the inability of one HPV sample to be representative. Also, the calibrations are only acceptable under the specific conditions for which they are developed. A developed calibration curve cannot be applied to a different tree or to the same tree over time. One reason for this is the change in conducting area from tree to tree and in the same tree seasonally or diurnally (Ladefoged 1960, Gale and Poljakov-Mayber 1964, Swanson and Lee 1966, Doley 1967, Swanson 1967). Swanson found the width of conductance in a cross-section of spruce (*Picea engelmannii*) to be 10 mm in the fall, but the width increased in the same cross-section to more than 30 mm in June.

In another study, Swanson (1971b) found a parabolic pattern of HPV rates across the sapwood. This supports results of a study by Skau and Swanson (1963) which found the highest flow rates to occur in the center of the sapwood and the lowest rates at the sapwood-heartwood and sapwood-cambium interfaces. Since it is impossible to assure that a probe will represent the same portion of the parabola in different trees, or the same trees over time, a correlation between a single probe set and transpiration cannot be universally applied for a species. Because of this variability in conducting areas and flow rates, many researchers prefer use of sap flux, a volumetric flow rate and more closely related to plant water use, to HPV, a point velocity measurement, for correlation with transpiration (Marshall 1958, Swanson 1962, Decker and Skau 1964, Swanson 1967, Hinckley 1970). Marshall states:

> ...it appears that values of sap speed may be used for two purposes, either to compare rates of sap flow (HPV) at different times and places (in the same or different trees) or to relate sap flow (HPV) to other numerical quantities such as the rate of evaporation from the leaves or the moisture intake at the roots. For the first purpose, sap flux is just as useful a measure as sap speed, and for the second it is more useful... (p. 385)

Recognizing this, Marshall continued his theoretical study of thermoelectric methods to cover sap flux measurements. The following equation resulted:

$$au = V\rho_b(m_c + 0.33) \tag{5}$$

where:

- au = sap flux (sap speed x area of conductance)
- ρ = bulk density
- m_c = moisture content
- V = heat pulse velocity

Both ρ_b and m_c can be determined by the destructive sampling of the tree. Marshall verified Equation 4 by using a vacuum pump to pull water through several 2.8-cm (1.1 inch)-long pine dowels, each containing part of three annual growth rings. The sides of the dowels were lacquered to prevent air leaks. Equation 5 was found to hold within an experimental error of "a few percent".

Several studies have applied Marshall's equation. Skau and Swanson (1963) compared sap flux measurements on eight juniper (Juniperus osteosperma) with vapor loss measurements determined with evaporation tents. An HPV value averaged from six sets of probe readings was used as the required sap velocity value in the Marshall equation and a very acceptable correlation coefficient was obtained (r = 0.965). In another study, Doley (1967) found a near linear relationship (r = 0.928) in jarrah (Eucalyptus marginata) between sap flux measurements and daily transpiration measured by the cut shoot method.

Although sap flux measurements are a better basis for predicting transpiration than are point HPV measurements, there are several problems with using sap flux as an indicator of transpiration. The sap flux method depends on HPV measurements to determine the velocity and, therefore, is subject to all of the limitations of that method. In addition, the destructive sampling necessary to acquire data on bulk density and moisture content prevents repeated sampling of the same tree. Also, bulk density and moisture content change over time and would require determination each time a tree is sampled (Swanson 1971b).

Swanson (1972b) also tried estimating volumetric flow by assuming that flow through a cross-section of a tree can be modeled as is by pipeflow.

$$Q = VA$$

where: Q = rate of flow
V = average velocity (estimated by average HPV)
A = cross-sectional conducting area of the tree

Swanson compared this method and the sap flux method to measured flow in trees of an unidentified species. Bulk densities varied from 0.46 to 0.52 and moisture content varied from 1.01 to 0.75. As Figure 3 illustrates, HPV relationships remained linear even with the above variances. This indicates that HPV measurements somehow integrate changes in bulk density and moisture content. Since bulk density and moisture content affect the conductive transport of heat in the tree, which in turn affects heat pulse

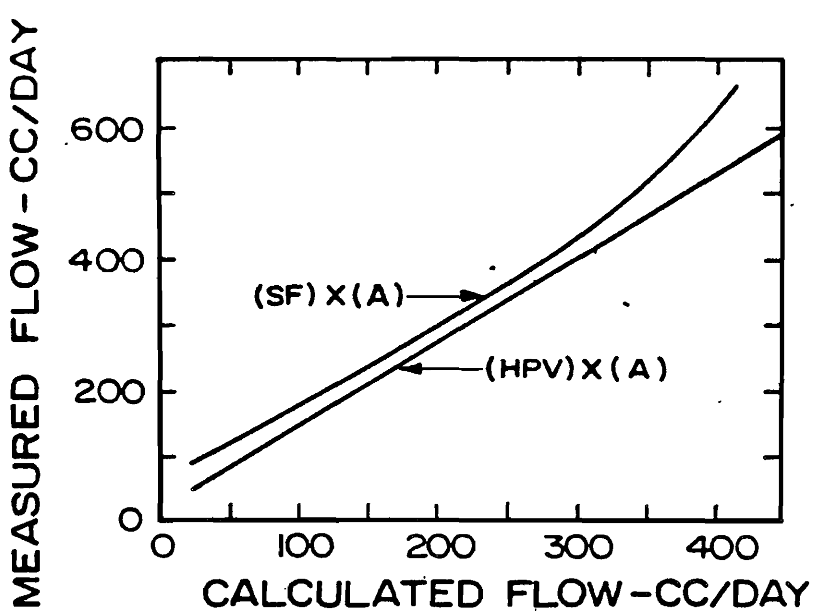

Figure 3. Measured flow versus calculated flow using sap flux and heat pulse velocity methods (Swanson 1971b).

velocities, such integration should be expected. The reintroduction of these terms into the sap flow equation is thus unnecessary and distorts the relationship of sap flux and measured flow to one of curve linearity.

Therefore, once conducting area is defined, sap flux measurements are not any better as an indicator of transpiration than are HPV measurements. If moisture content and bulk density varies, HPV measurements will be a more accurate indicator than sap flux. Therefore, HPV measurements, adjusted to a volumetric flow, are preferable to sap flux measurements as an indicator of transpiration.

To accurately apply Swanson's pipeflow model, the average HPV values must be accurate. Single measurements are not sufficient for large trees because sap velocity is not constant throughout the tree. Skau and Swanson (1963) compared HPV measurements with water forced through the stems of aleppo pine (Pinus halepensis) and found that velocities varied with their proximity to the sapwood-cambium and sapwood-heartwood interfaces (see Figure 2). Swanson (1971b) examined the velocity distribution with dye studies, tracheid diameter measurements, and mathematical calculations and found a parabolic pattern across the sapwood. Although he stated that the evidence for a parabolic velocity distribution was inconclusive, Swanson felt justified in developing a method of predicting a sap velocity profile across the sapwood using two HPV measurements at specified depths and a parabolic formula (Swanson 1971a, Swanson 1971b). This formula has the added advantage of determining the width of flow by finding the zero points of the parabola. By rotating this width 360° around the center of the tree, a conducting area (uncorrected for porosity) can be generated.

The above research suggests that transpiration can be predicted by correlation with volumetric flow rates determined from a series of HPV measurements and information on the conducting area of the tree at the time of sampling. If such a correlation gives good results when developed using values from various trees under various conditions, it can be widely applied to intact trees.

ADAPTATIONS OF THE HEAT PULSE TECHNIQUE FOR MONITORING TRANSPIRATION IN ASPEN AND ASSOCIATED CONIFERS

Materials and Methods

Studies using heat pulse velocity techniques to measure transpiration were conducted on three tree species in the Utah State University forest in the Wasatch Mountains between July 15 and November 1, 1979. The forest is situated in Cache and Rich Counties, about 15 km south of the Utah-Idaho border at an elevation of about 2600 m (8300 ft). The site is atop an undissected plateau-like ridge of gently sloping topography. Soils throughout the site are derived from the Knight formation of the Wasatch group, a Tertiary red conglomerate of quartzite, sandstone, and shale (Veatch 1907). This parent material occurs extensively south of the study site (Stokes 1963). The site contains no lakes or permanent streams. Photo periods (daylight hours) range from 15 h, 2 min on June 1, to 13 h, 9 min on September 1. Daily solar radiation totals (horizontal surface) as high as 768 cal cm^{-2} have been measured (Eaton 1971). Annual precipitation has been estimated at about 95 cm (37 inches), most of which comes as snow during the period November through April (Schimpf et al. 1980). The vegetation is characterized by aspen (*Populus tremuloides*), subalpine fir (*Abies lasiocarpa*), and Englemann spruce (*Picea engelmannii*) stands interspersed with open meadows.

There were 26 aspen, 20 Engelmann spruce, and 20 subalpine fir selected for this study. This was the largest number of trees that could be sampled in the period that the site was accessible by road. There were four trees of one species selected at one time for sampling. On the day before sampling the trees were suspended by ropes, a reservoir was placed around each tree and filled with water, and each tree was severed under water at the base. Each tree was then placed in a permanently sealed reservoir so that all water consumption from the reservoir would be from uptake by the tree. Trees were then fitted with thermocouples at a series of depths for HPV measurements of the sap velocity profile. This profile was used to estimate volumetric water flow through the trees. After all trees for each species were sampled, regressions were developed for each species to correlate transpiration (as measured by water uptake from the reservoir) and HPV measurements of water use as determined by Swanson's model (Equation 4).

Selection of Sample Trees

Sample trees were selected according to the following criteria:

1. A full range of tree sizes was desired to cover any variations in the sap velocity profile due to variances in tree diameter.

2. A full range of site characteristics, such as slope and aspect, was desired for each species to develop correlations with the widest possible applications.

3. The sampled trees had to be accessible enough to roads to allow water to be pumped to them from a truck.

It should be noted that sampling limited to trees near roads is biased by an edge effect. Specifically, one side of the sampled tree would receive more radiation at the surface of the leaves, that the xylem conducting water to those leaves would have higher average sap velocities than xylem conducting water to more shaded leaves. Therefore, the selection of the aspect of the tree for probe placement might affect the regression between HPV and measured consumptive water use. Nevertheless, sampling procedures necessitated the proximity of sample trees to roads.

Cutting Sample Trees

A temporary reservoir was placed around each tree once it was secured to nearby adjacent trees and before it was cut. The temporary reservoir was a modified oval stock watering tank in which a circular 36 cm (14 inch) diameter hole had been cut in the bottom but slightly offset from the center along the short axis. The tank had then been cut in half along the short axis so that the hole was divided. An angle iron had been welded along the cut except at the hole on the outside of each tank half. Holes for bolts had been drilled into the angle iron so that the tank halves could be bolted around the tree with the tree base in the cut hole. After the temporary reservoir was placed around a tree and bolted together, plastic was taped around the tree and the interior of the tank to minimize leaking. Once the plastic was in place, the temporary reservoir was filled with water. A modified bow saw was then used to sever the base of the tree below the reservoir water surface.

After cutting, a permanent, leakproof reservoir was maneuvered inside the temporary one so that it contained the base of the cut tree below the water line. At no time was the cut surface exposed to air. The temporary reservoir was then removed, red food coloring dye and copper sulfate bacteriacide were added to the permanent reservoir. The reservoir top was then sealed by taping a piece of plastic to the reservoir rim and the tree trunk, making the reservoir airtight.

Probe Depth Selection

Each exposed tree stump was examined to determine the general sap conducting region after removal of the temporary reservoir. In aspen, sapwood was visually distinguishable from heartwood due to color differences. In the conifers, oozing sap indicated the region of sap flow. This determination of sap flow area was crude and used only to select probe depths. Conducting area was determined more accurately at a later step in the sampling procedure. The top of each stump was measured for the width of sap conductance along a line from the bark to the center of the tree. There were three probe depths selected to adequately represent intervals along this length.

Probe Placement

Two criteria were used in selecting the location on the tree for probe placement:

1. A surface large enough for the placement of all probes in vertical sequence, without any knots, scars, or surface blemishes occurring on the bark within 1 cm of any probe was required. No blemishes were allowed between probes.

2. Probe placement surfaces were required to be approximately 1 meter above the ground surface.

Once the area of probe location had been determined, holes for the probes were drilled using a cordless electric drill and high speed carbon bit. A jig with three parallel holes, one 0.5 cm and one 1.0 cm from the center hole was used as a guide for drilling. Metal cleats on the back of the jib held it in place against the tree. Holes were drilled large enough to accommodate the 16 guage thermocouple probes. The matched thermocouple probes were then gently inserted into the upper and lower holes. Once the probes were inserted, the trees were allowed to stand overnight before sampling commenced.

Sampling

Beginning generally at daylight (although access and equipment problems occasionally necessitated a later starting time) on the day after cutting, the permanent reservoirs were filled to the marked maximum level. Sampling then began.

Each tree was generally sampled hourly with the conducting time for each probe measured with a Hewlett

Packard 419A Portable DC Null Voltmeter and stopwatch. Copper wiring with attached insulation copper clips facilitated connection to the exposed ends of copper wiring from the thermocouple probes. A 12 V battery was used to create a two-second heat input in the heat probe. Each tree was sampled generally until darkness or until HPV values fell below measurable levels, but in no case for less than 6 hours. Periodically during and at the end of the sampling period the amount of water necessary to fill the permanent reservoir at each tree to the original water level was measured and recorded. All water loss was assumed to be from water uptake by the tree.

Conducting Area Determination

At the completion of daily sampling the circumferences of the sampled trees were measured at the height of the center probe. By assuming that the trees were circular, the diameter and total area of the horizontal cross-section of each tree at the sampling height were estimated from the circumference data. A section of each tree at the center probe height was then removed. Red stain from the food coloring added to the reservoir indicated the area of the tree that had been conducting water at any time since the food coloring had been added. That area was assumed to be the sapwood for the tree at that height. The unstained non-bark area was assumed to be the heart wood. These definitions were used for HPV rate computations only, and do not necessarily agree with physiological definitions. Observations of the red stained areas on the sampled tree cross-sections indicated that it was not valid to assume heartwood and the combined heartwood-sapwood areas were circular. Instead, the observed stain patterns indicated that they were elliptically shaped. Therefore, the long axis (a) and the short axis (b) of the heartwood and the combined heartwood-sapwood regions were measured for each tree and areas for each region were computed using the formula for the area of an ellipse:

$$A = \pi ab$$

The heartwood area was subtracted from the combined heartwood-sapwood area for each tree to determine the area conducting water.

Volumetric Flow Computation

By measuring the length of the red stain on a line from the bark to the tree center at the height of the center probe, a determination of the sap flow width was obtained. By using the cambium-sapwood interface, the sapwood-heartwood interface and points located midway between the probe depths, a series of intervals was created for each tree along the sap flow profile.

Each interval was represented by the probe depth located in that interval. By dividing the length of each interval by the total width of the sap flow profile, the fraction of the profile represented by each interval was determined.

For each probe of each tree at each sampling time, Equation 4 was used to determine an HPV value. That value was multiplied by the fraction of the total profile represented by that interval. All of these values were then summed to get an average HPV for that sap velocity profile. It was assumed that this average HPV was valid for the entire conducting area in the tree. The product of this average HPV and the conducting area was then used to estimate the volumetric flow rate of the water in the tree at that time.

By collecting a series of such measurements over time, using an interval weighted averaging method similar to the one discussed above to find an average volumetric flow rate, and multiplying that average rate by the time length of sampling, an estimate of volumetric flow through each tree was determined.

Correlation of Flows and Water Use

The sampling compiled a body of data on estimated and actual water use (as determined by HPV measurements and consumption of water from the permanent reservoirs respectively). Linear, geometric and logrithmic regressions were developed from the data for each species.

Correlation of Areas

Regressions was also used to correlate cross-sectional areas of water conductance and total cross-sectional areas based on all the trees of each species. Linear, geometric, and logrithmic regressions were again used.

Results

Correlation of Actual and Computed Transpiration Volumes

Actual (as measured by water loss from the permanent reservoirs) and computed (from HPV measurements) transpirational loss volumes, for each tree of all the species studied, are presented in Table 1. The mean ratio of computed to actual transpiration losses is very nearly 1.0 for each species studied (0.992 for aspen, 1.029 for Engelmann spruce, and 0.980 for subalpine fir). This indicates that at least when averaged over large numbers of data points, actual transpiration losses from a reservoir match the losses measured by the HPV method.

A better method of expressing the relationship between actual transpiration losses and transpiration losses measured by the HPV method is to correlate the two data sets for each

Table 1. Measured and computed transpirational loss data for aspen, Engelmann spruce, and subalpine fir in Northern Utah.

Species	Tree Number	Date	Sampling Interval (hours)	Measured Loss (CC)	Computed Loss (CC)	Computed Loss / Measured Loss
Aspen	5	7/27/79	1410-2380	1265	1476	1.167
	6		1390-2380	3500	3713	1.060
	7		1420-2400	3640	5691	1.563
	8		1400-2425	16000	9275	0.580
	9	8/14/79	730-1670	1760	2733	1.553
	10		730-1680	1885	1554	0.824
	11		730-1680	3165	3279	1.036
	12		730-1680	6350	7663	1.207
	13	8/23/79	800-1770	11955	8156	0.682
	14		800-1780	5955	5047	0.845
	15		800-1780	8970	7218	0.805
	17	9/05/79	950-1790	8420	4591	0.545
	19		960-1830	13820	15700	1.136
	20		960-1830	5920	5724	0.967
	21	9/08/79	800-2070	5180	6628	1,087
	22		830-2808	11890	12698	1,068
	23		830-2200	4580	4299	0.939
	24		830-2220	12660	12144	0.959
	25	9/12/79	900-1800	3650	2807	0.769
	26		900-1820	6755	4884	0.723
	27		910-1830	5645	7071	1.253
	28		920-1850	13300	11774	0.885
	29	9/18/79	750-1880	2675	4128	1.543
	30		770-1890	4270	3910	0.916
	31		800-1900	1735	1423	0.822
	32		860-1910	8475	7421	0.854
Engelmann Spruce	5	8/08/79	780-1775	16400	16392	0.999
	6		850-1775	1760	3059	1.738
	7		880-1775	3670	4895	1.330
	8		890-1785	6370	10633	1.669
	9	8/29-79	775-1725	8260	7088	0.858
	10		800-1750	3220	3888	1.171
	11		800-1760	9250	9822	1.061
	13	9/21/79	1025-2140	2640	3354	1.270
	14		1025-2150	2470	2831	1.146
	15		1025-2160	14850	17252	1.162
	16		1030-2170	13720	13790	1.005
	17	8/28/79	875-2135	8275	8186	0.989
	18		860-2050	1880	2527	1.344
	19		875-2140	6810	4184	0.614
	20		875-2140	6500	5443	0.837
	21	10/01/79	1000-2030	7315	4985	0.681
	22		1010-2050	13055	8023	0.615
	23	10/01/79	1010-26060	4500	2861	0.636

Table 1. Continued.

Species	Tree Number	Date	Sampling Interval (Hours)	Measured Loss (CC)	Computed Loss (CC)	Computed Loss / Measured Loss
Engelmann	24		850-2040	8750	6776	0.774
Spruce	25		870-2050	5900	4028	0.683
Subalpine	5	8/01/79	680-1780	5235	6694	1.279
Fir	6		680-1790	11475	9215	0.803
	7		690-1790	2045	1971	0.964
	8		690-1800	9570	10573	1.105
	9	8/19/79	960-1700	2385	1817	0.762
	10		960-1700	100	61	0.608
	11		960-1710	465	650	1.399
	12	10/01/79	960-1720	2740	1721	0.628
	13		1000-2040	5030	3282	0.653
	14	10/08/79	840-1860	6040	3324	0.550
	15		840-1980	6050	3794	1.627
	16		850-1890	2105	2309	1.097
	17		850-1900	4190	2698	0.644
	18	10/12/79	1030-2050	2890	2748	0.951
	19		1040-2060	5190	3677	0.709
	20		1040-2060	2320	2825	1.218
	21		1040-2060	6845	4365	0.638
	22	10/16/79	980-1860	1095	3318	3.030
	23		990-1870	1055	1083	1.018
	24		1000-1900	1435	1324	0.923

species. Such a correlation allows presentation of the changes in the relationship over the measured range of values, determination of the statistical reliability and significance of the relationship, and the use of the relationship as a future predictive tool (Table 2). Linear, geometric, and logarithmic correlations of these data sets for each species are presented graphically in Figures 4 through 12. As these figures illustrate, the correlations were generally good. All correlations are significant at the 99 percent level. These levels of correlation are large enough to indicate that the above equations adequately estimate transpirational losses under conditions similar to those under which the study was conducted.

Correlation of Total Tree Cross-Section Area and Maximum Tree Water Conducting Cross-Sectional Area at the HPV Measurement Height

The total cross-sectional area and the water conducting cross-sectional area of all trees at the height at which the HPV

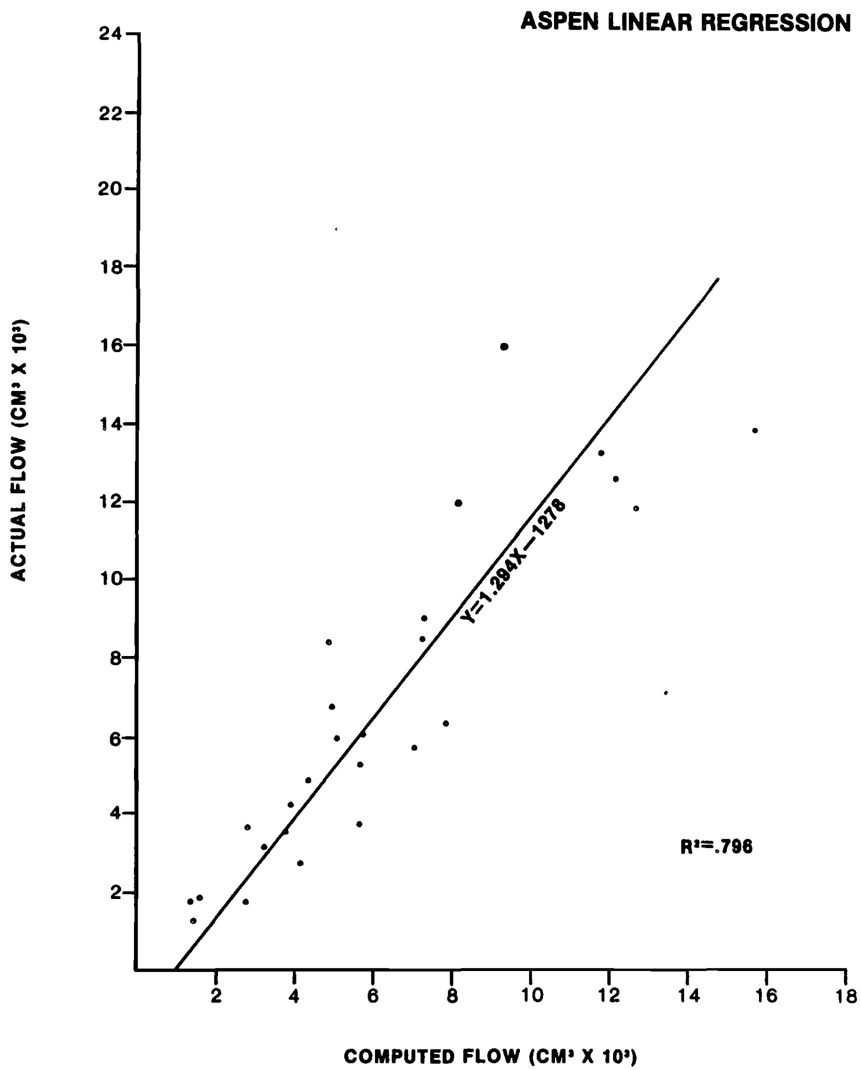

Figure 4. Actual flow (based on reservoir measurements) versus HPV method computed flow in aspen (linear regression).

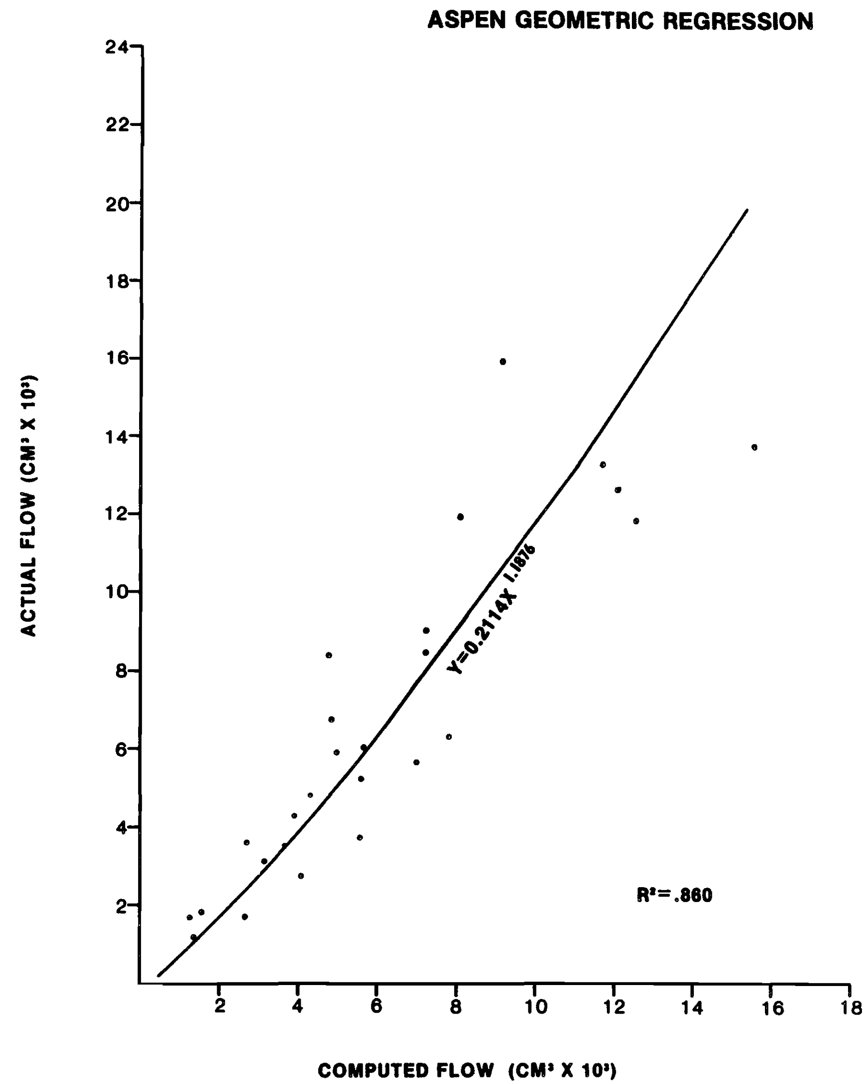

Figure 5. Actual flow (based on reservoir measurements) versus HPV method computed flow in aspen (geometric regression).

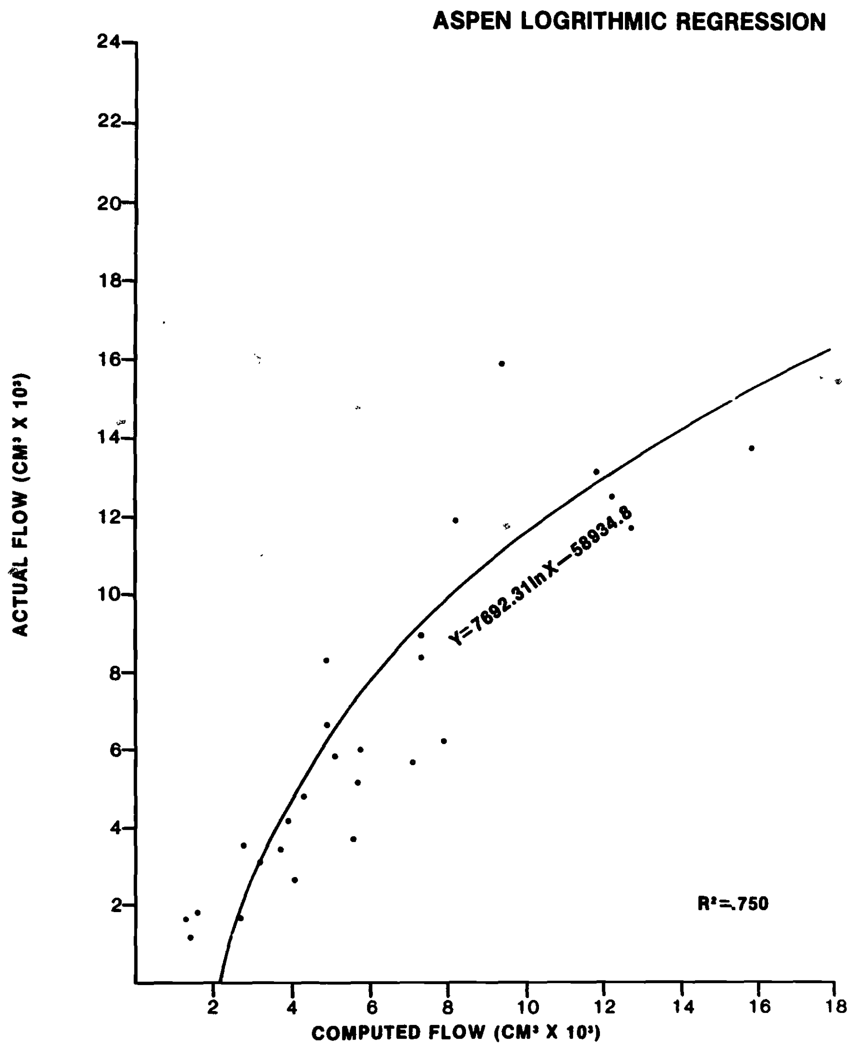

Figure 6. Actual flow (based on reservoir measurements) versus HPV method computed flow in aspen (logrithmic regression).

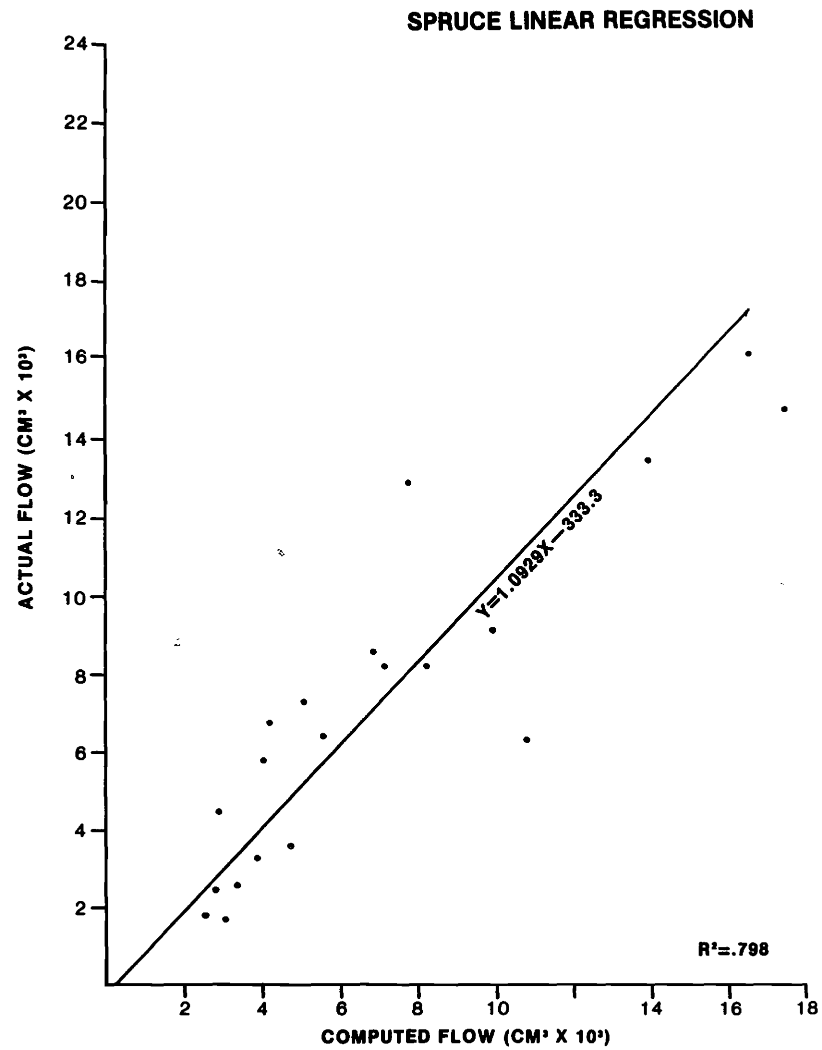

Figure 7. Actual flow (based on reservoir measurements) versus HPV method computed flow in Engelmann spruce (linear regression).

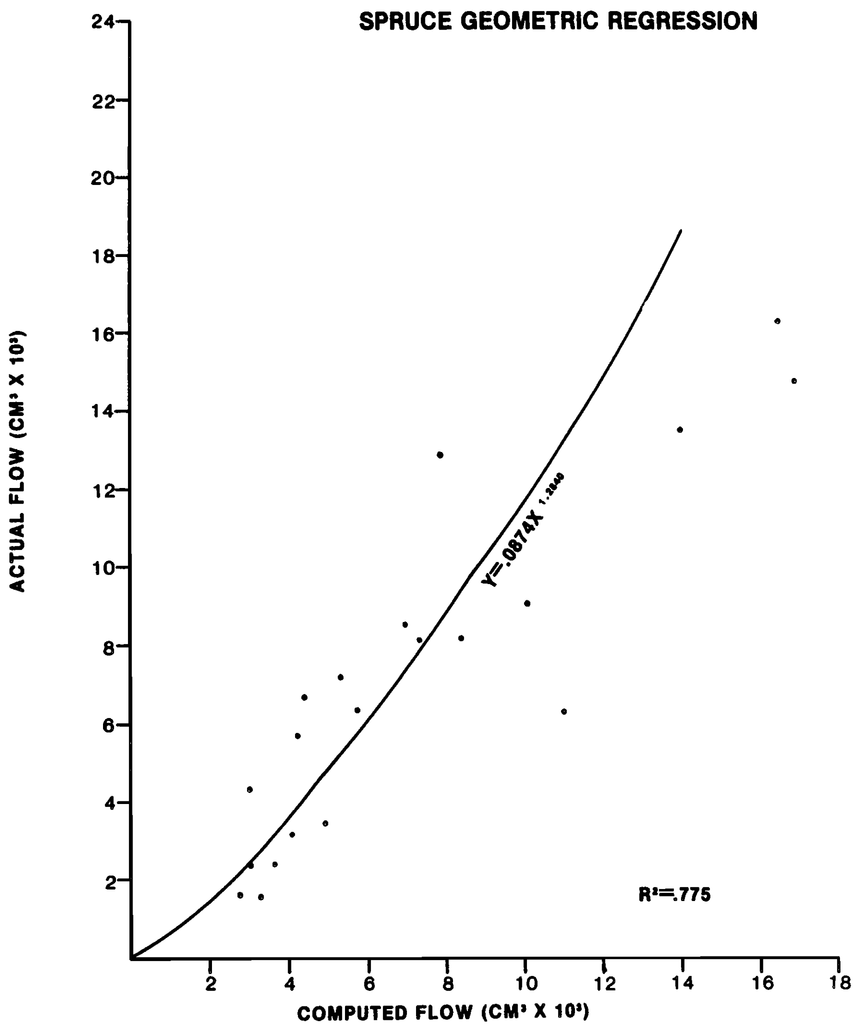

Figure 8. Actual flow (based on reservoir measurements) versus HPV method computed flow in Engelmann spruce (geometric regression).

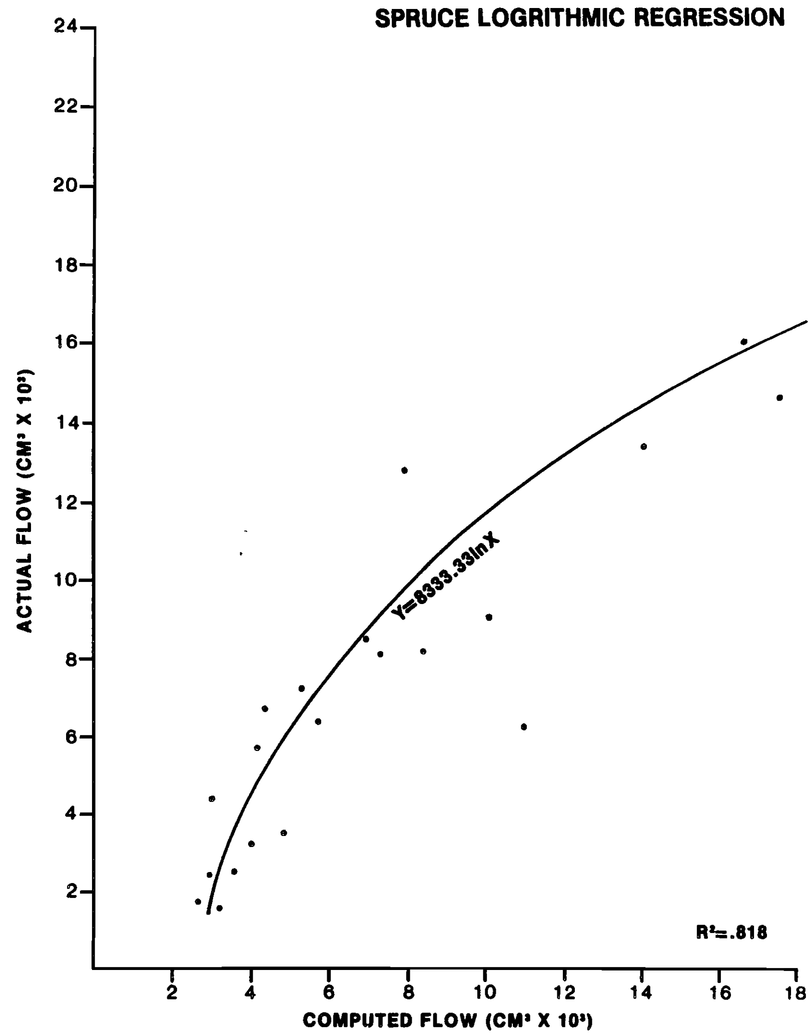

Figure 9. Actual flow (based on reservoir measurements) versus HPV method computed flow in Engelmann spruce (logrithmic regression.)

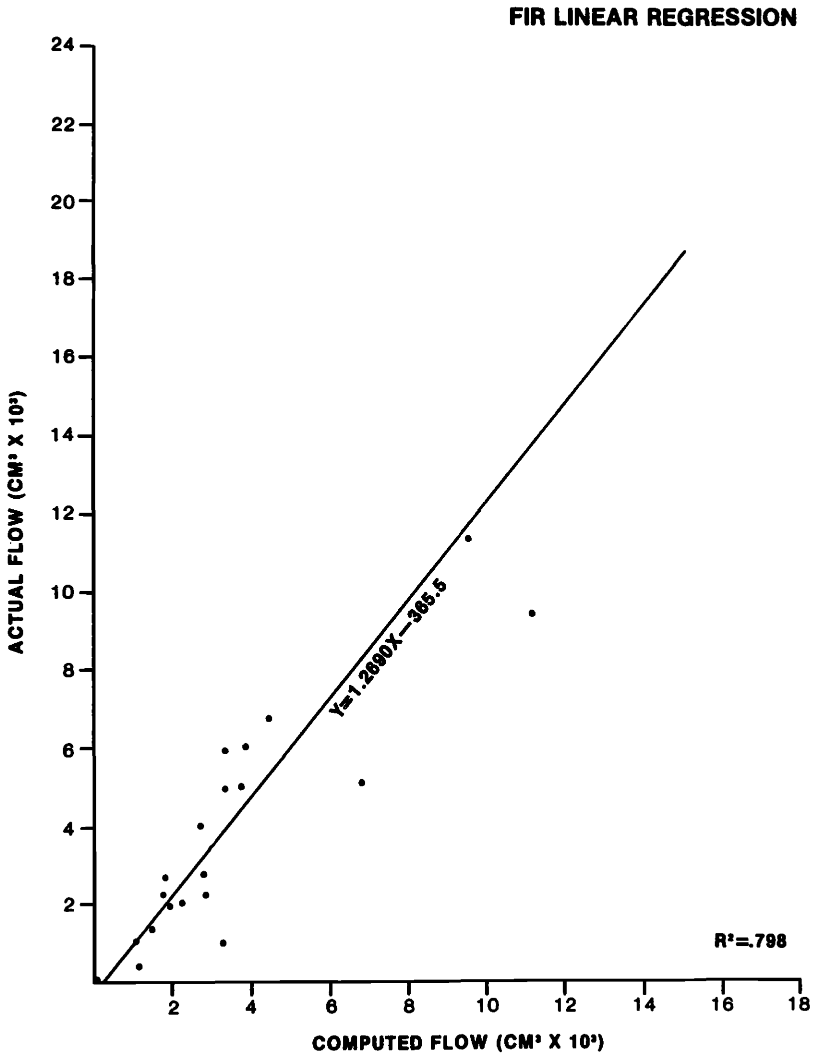

Figure 10. Actual flow (based on reservoir measurements) versus HPV method computed flow in subalpine fir (linear regression).

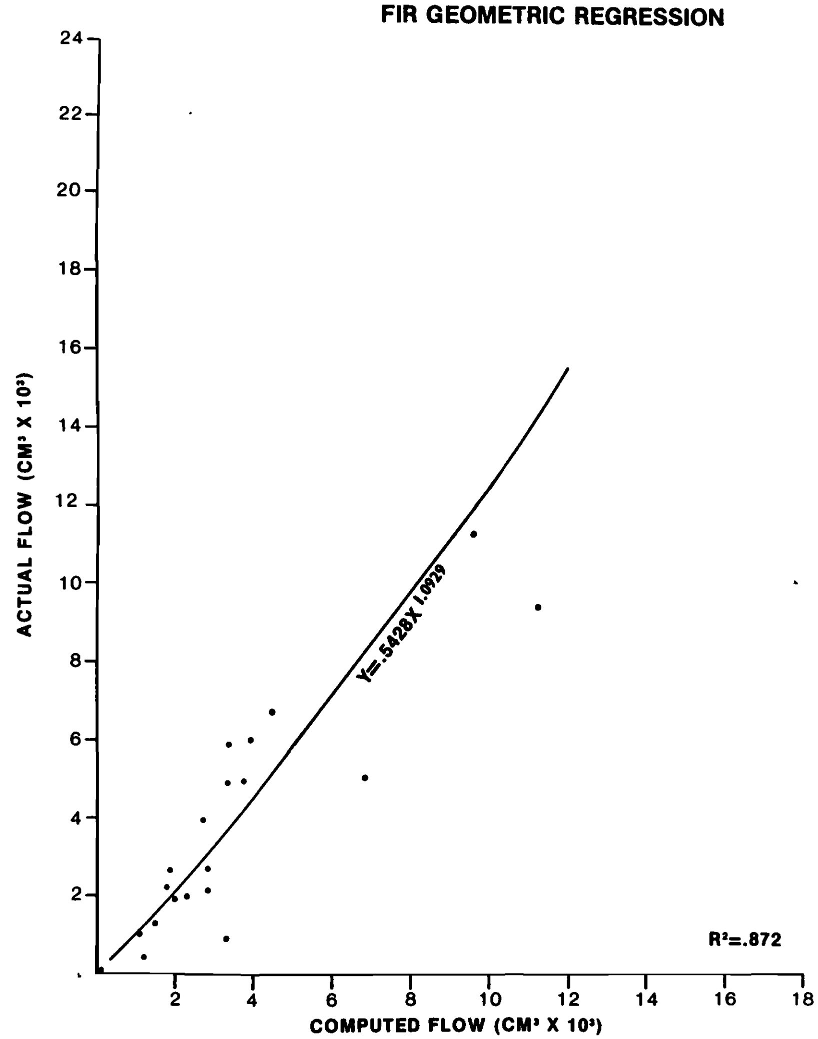

Figure 11. Actual flow (based on reservoir measurements) versus HPV method computed flow in subalpine fir (geometric regression).

Table 3. Tree total and water conducting cross-sectional areas at HPV measurement height for aspen, Engelmann spruce and subalpine fir in Northern Utah.

Species	Tree Number	Total Cross-Sectional Area (CM^2)	Water Conducting Area (CM^2)	Conducting Fraction of Total Area
Aspen	5	39.0	27.0	0.71
	6	67.0	38.0	0.57
	7	232.0	144.0	0.62
	8	161.0	63.0	0.39
	9	60.0	39.0	0.64
	10	39.0	22.0	0.56
	11	115.0	72.0	0.62
	12	144.0	66.0	0.46
	13	208.0	118.0	0.57
	14	67.0	40.0	0.60
	15	98.0	58.0	0.60
	17	84.0	58.0	0.69
	19	134.0	80.0	0.59
	20	77.0	36.0	0.47
	21	77.0	40.0	0.52
	22	182.0	100.0	0.55
	23	72.0	44.0	0.61
	24	147.0	85.0	0.58
	25	52.0	32.0	0.62
	26	118.0	56.0	0.48
	27	92.0	52.0	0.57
	28	211.0	124.0	0.59
	29	137.0	124.0	0.59
	30	140.0	71.0	0.51
	31	54.0	22.0	0.41
	32	147.0	84.0	0.57
Engelmann Spruce	5	266.0	171.0	0.64
	6	58.0	35.0	0.60
	7	74.0	44.0	0.63
	8	207.0	142.0	0.68
	9	115.0	74.0	0.64
	10	232.0	100.0	0.43
	11	183.0	104.0	0.57
	13	54.0	35.0	0.65
	14	140.0	55.0	0.39
	15	277.0	188.0	0.68
	16	241.0	195.0	0.81
	17	183.0	108.0	0.59
	18	154.0	62.0	0.40
	19	131.0	86.0	0.66
	20	144.0	103.0	0.71
	21	168.0	120.0	0.71
	22	151.6	90.0	0.59

Table 3. Continued.

Species	Tree Number	Total Cross-Sectional Area (CM^2)	Water Conducting Area (CM^2)	Conducting Fraction of Total Area
Engelmann Spruce	23	106.0	75.0	0.71
	24	183.0	108.0	0.59
	25	131.0	86.0	0.66
Subalpine Fir	5	77.0	32.0	0.41
	6	103.0	55.0	0.53
	7	147.0	50.0	0.34
	8	277.0	78.0	0.28
	9	224.0	68.0	0.30
	10	50.0	25.0	0.51
	11	158.0	47.0	0.30
	12	103.0	46.0	0.44
	13	127.3	43.0	0.34
	14	147.0	52.1	0.35
	15	134.0	41.0	0.31
	16	79.0	33.0	0.42
	17	115.0	46.0	0.40
	18	87.0	32.0	0.36
	19	124.0	47.0	0.38
	20	98.0	39.0	0.40
	21	131.0	42.0	0.32
	22	140.0	53.0	0.38
	23	124.0	40.0	0.32
	24	103.0	43.0	0.42

Table 4. Regression providing the best correlation of total and maximum water conducting cross-sectional areas at HPV measurement height for aspen, Engelmann spruce and subalpine fir in Northern Utah.

Species	Regression Type	Regression Equation	Coefficient of Correlation
Aspen	Linear	$Y = 0.589X - 2.04$	0.945
Engelmann Spruce	Exponential	$Y = 27.08e^{0.0072X}$	0.869
Subalpine Fir	Linear	$Y = 0.220X + 17.6$	0.838

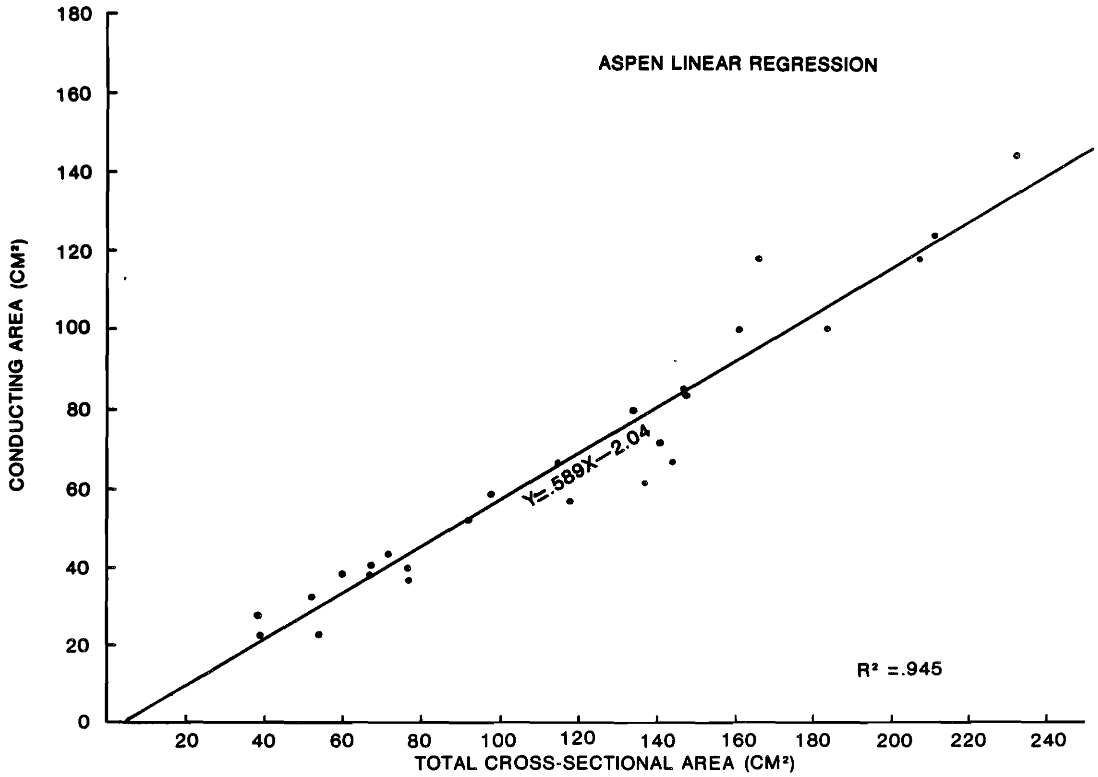

Figure 13. Maximum water conducting area versus total cross-sectional area in aspen.

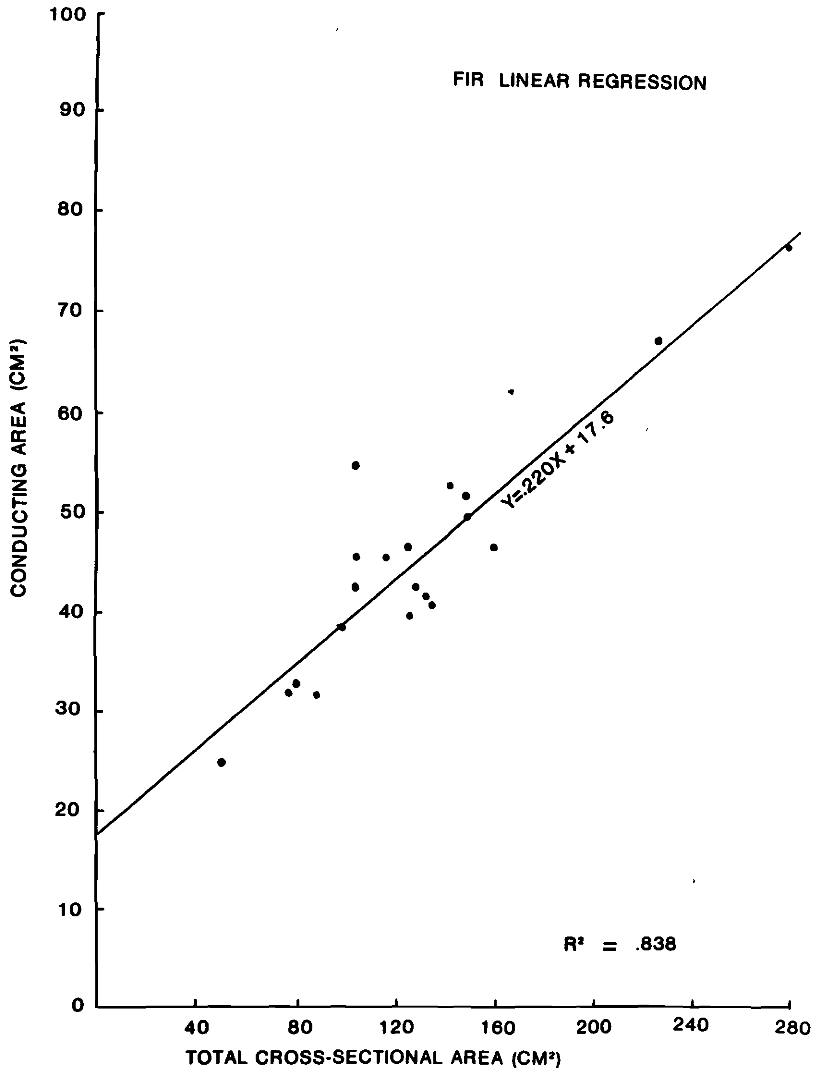

Figure 14. Maximum water conducting area versus total cross-sectional area in subalpine fir.

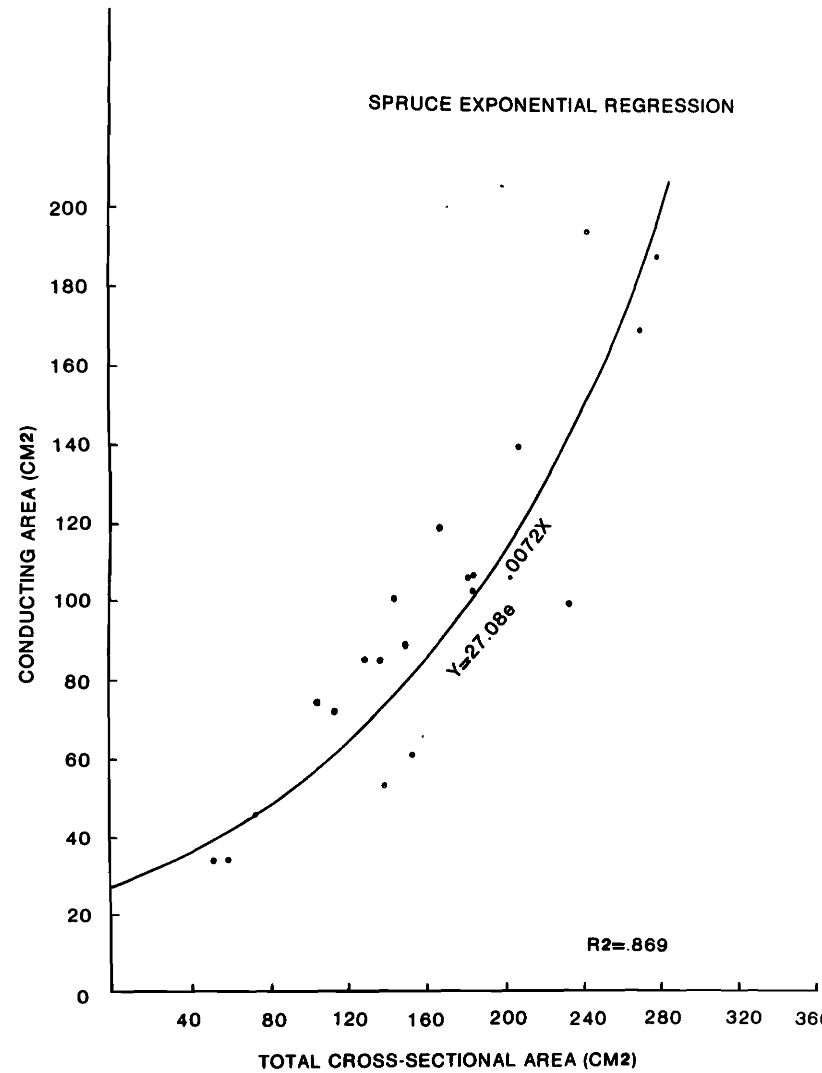

Figure 15. Maximum water conducting area versus total cross-sectional area in Engelmann spruce.

FIELD MEASURES OF INDICATED TRANSPIRATION

Procedures as recommended in Appendix I were utilized to instrument an aspen stand and a nearby spruce-fir stand. The aspen stand has approximately 1,090 trees per hectare (436 trees/acre) with a dbh range from 8.6 to 43.2 centimeters (3 to 17 inches). The spruce-fir stand has approximately 2,125 trees per hectare (850 trees/acre) with a dbh range from 5.0 to 40.4 centimeters (2 to 16 inches). Both stands are located on gentle slopes of perhaps 2 to 4 percent. Canopy coverage averaged 80 percent for the aspen stand and 74 percent for the spruce-fir stand (Figures 16 and 17).

Within each stand 12 trees, four of each species of dbh approximately 10.2 cm (4 inches), were selected for monitoring sap velocities. Each tree was instrumented with three sets of thermocouples and heater probes. Three trees of each species were monitored from near dawn to dusk at approximately 90-minute intervals on selected days during the period from June 30, 1980, to June 30, 1981. Indicated transpiration for each species on each sampling date is shown in Table 5. The indicated water losses are not intended to represent actual water loss but rather are an approximation and the values are utilized in adjusting the plant activity index utilized as part of the ASPCON model described later. Typical average heat pulse velocities (sap velocities) are shown for four dates in Figure 18 and computed flow rates are given in Figure 19. Actual water loss data (given in Table 5) are derived through application of appropriate formulae as previously described.

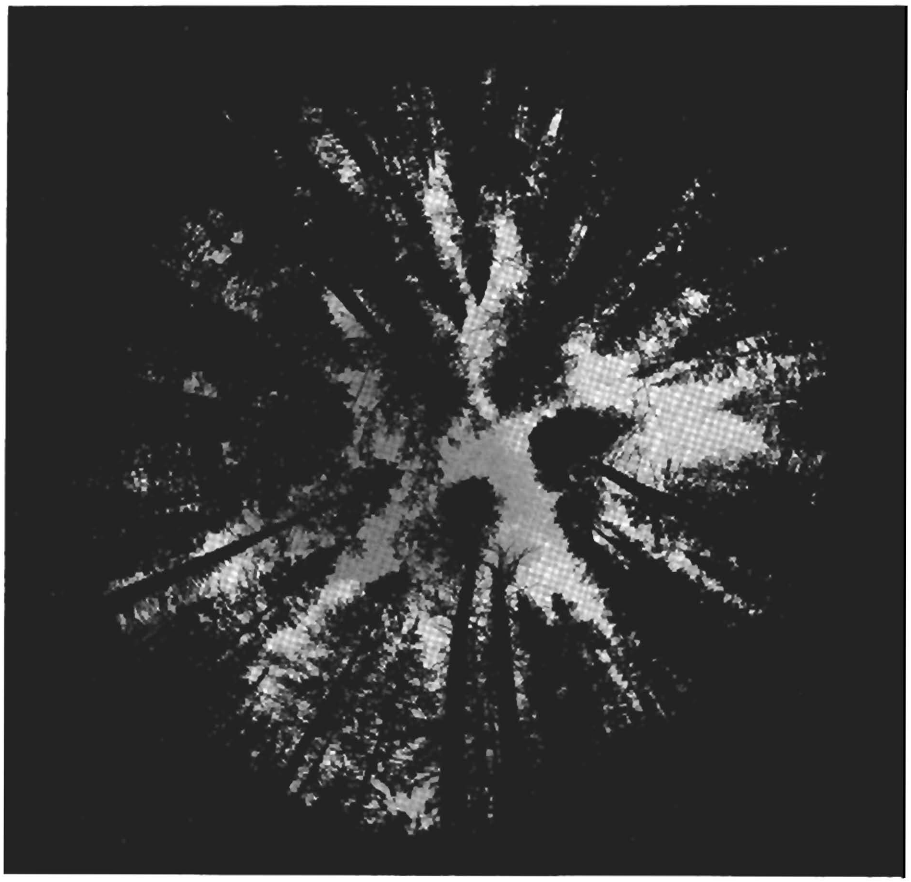

Figure 16. View of spruce-fir canopy from within the stand. Canopy coverage is about 70 percent.

Figure 17. View of aspen canopy from within the stand. Canopy coverage is about 82 percent.

Table 5. Indicated water loss from aspen, Engelmann spruce, and subalpine fir on various sampling dates. Indicated water losses are not absolute but rather are approximations and they are utilized in a relative sense to adjust the plant activity index portion of the ASPCON model.

Date	Indicated Water Loss (cm^3)[1/]		
	Aspen	Engelmann Spruce	Subalpine Fir
6-30-80	3,859	3,631	3,185
7-02-80	2,392	4,864	1,942
7-09-80	8,389	11,643	4,957
7-10-80	10,091	9,673	5,179
7-16-80	9,583	9,320	4,620
7-17-80	7,231	10,317	4,318
7-18-80	9,609	10,375	4,338
7-21-80	9,673	10,539	4,494
7-22-80	11,322	12,626	4,820
7-23-80	10,909	10,476	4,733
7-30-80	5,944	6,283	3,105
7-31-80	6,570	5,168	3,216
8-01-80	6,234	5,417	3,194
8-05-80	7,214	7,138	3,249
8-06-80	8,101	10,796	3,192
8-07-80	6,513	8,368	3,461
8-11-80	5,573	7,049	2,614
8-20-80	3,176	4,337	1,349
8-21-80	4,449	5,777	2,222
8-26-80	2,977	4,925	1,628
8-27-80	2,739	5,455	2,435
8-28-80	3,253	4,756	2,282
9-01-80	2,074	3,517	1,834
9-02-80	2,377	4,446	2,010
9-03-80	2,198	4,506	1,992
9-10-80	967	1,025	608
9-12-80	619	590	197
9-16-80	2,356	3,550	1,556
9-17-80	2,890	5,028	2,236
9-18-80	2,477	4,764	1,904
10-04-80	-0-	2,992	1,499
10-11-80	-0-	1,859	1,405
10-18-80	-0-	-0-	-0-
11-01-80	-0-	220	38
11-08-80	-0-	79	15
11-15-80	-0-	156	62
4-25-81	-0-	1,772	433
4-28-81	-0-	1,534	576
5-01-81	-0-	4,206	1,342
5-05-81	-0-	2,707	506
5-09-81	-0-	189	87

[1/] Each value represents the average of three trees.

Table 5. Continued.

Date	Indicated Water Loss (cm^3)[1/]		
	Aspen	Engelmann Spruce	Subalpine Fir
5-12-81	-0-	2	75
5-19-81	-0-	3,636	1,101
5-23-81	-0-	635	126
5-30-81	-0-	5,640	1,747
6-02-81	-0-	2,060	635
6-09-81	13	4,786	1,306
6-10-81	-0-	8,028	2,489
6-11-81	-0-	9,332	2,037
6-17-81	-0-	7,818	1,463
6-18-81	-0-	9,313	1,764
6-19-81	-0-	7,928	1,644
6-22-81	1,184	9,414	1,704
6-23-81	1,425	8,724	1,716
6-24-81	2,264	12,379	1,747
6-29-81	3,066	7,998	1,660
6-30-81	2,565	5,825	1,074

[1/] Each value represents the average of three trees.

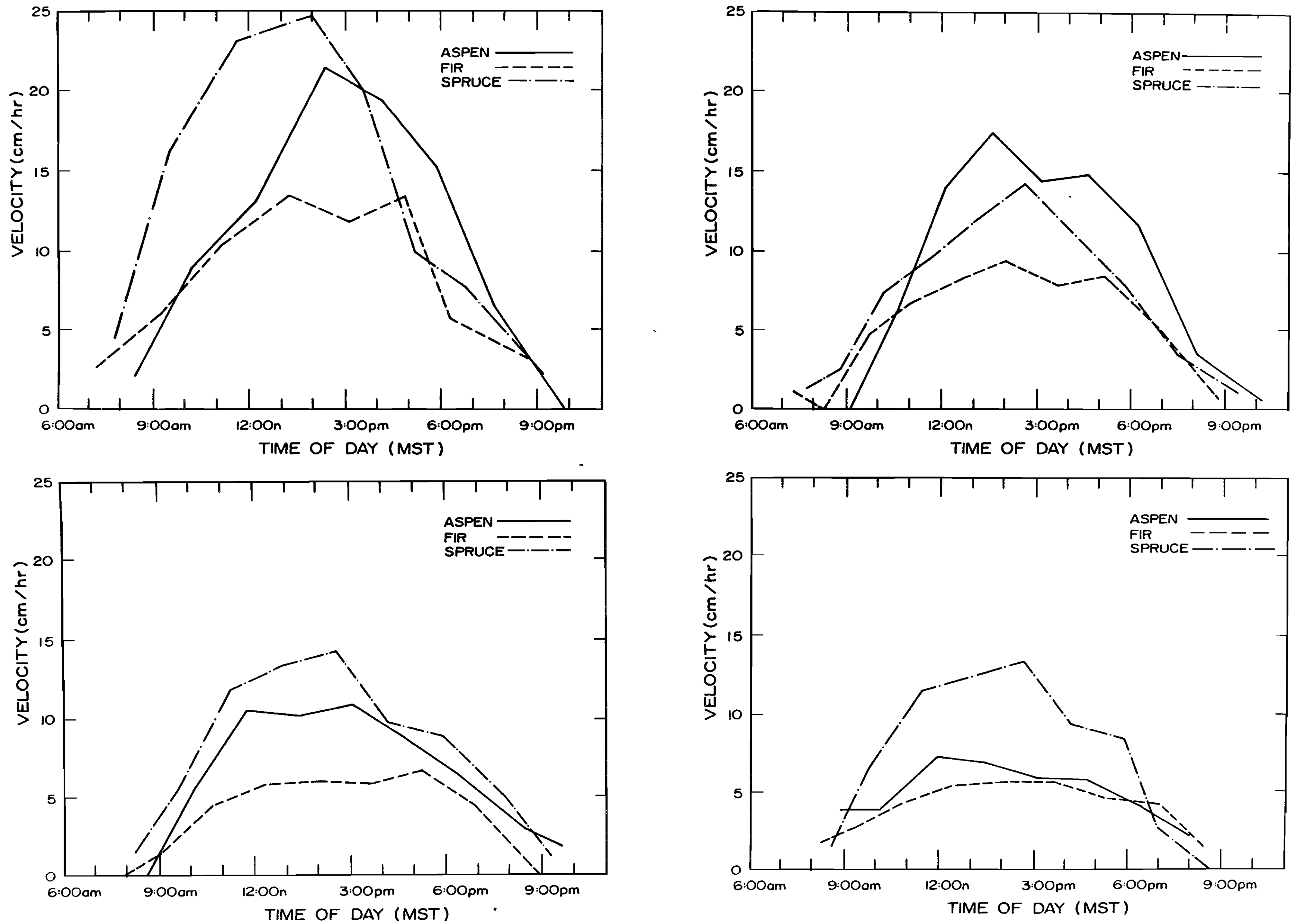

Figure 18. Average sap velocities of the three tree species on four select dates: A is July 9, 1980, B is July 30, 1980, C is August 21, 1980, and D is September 17, 1980.

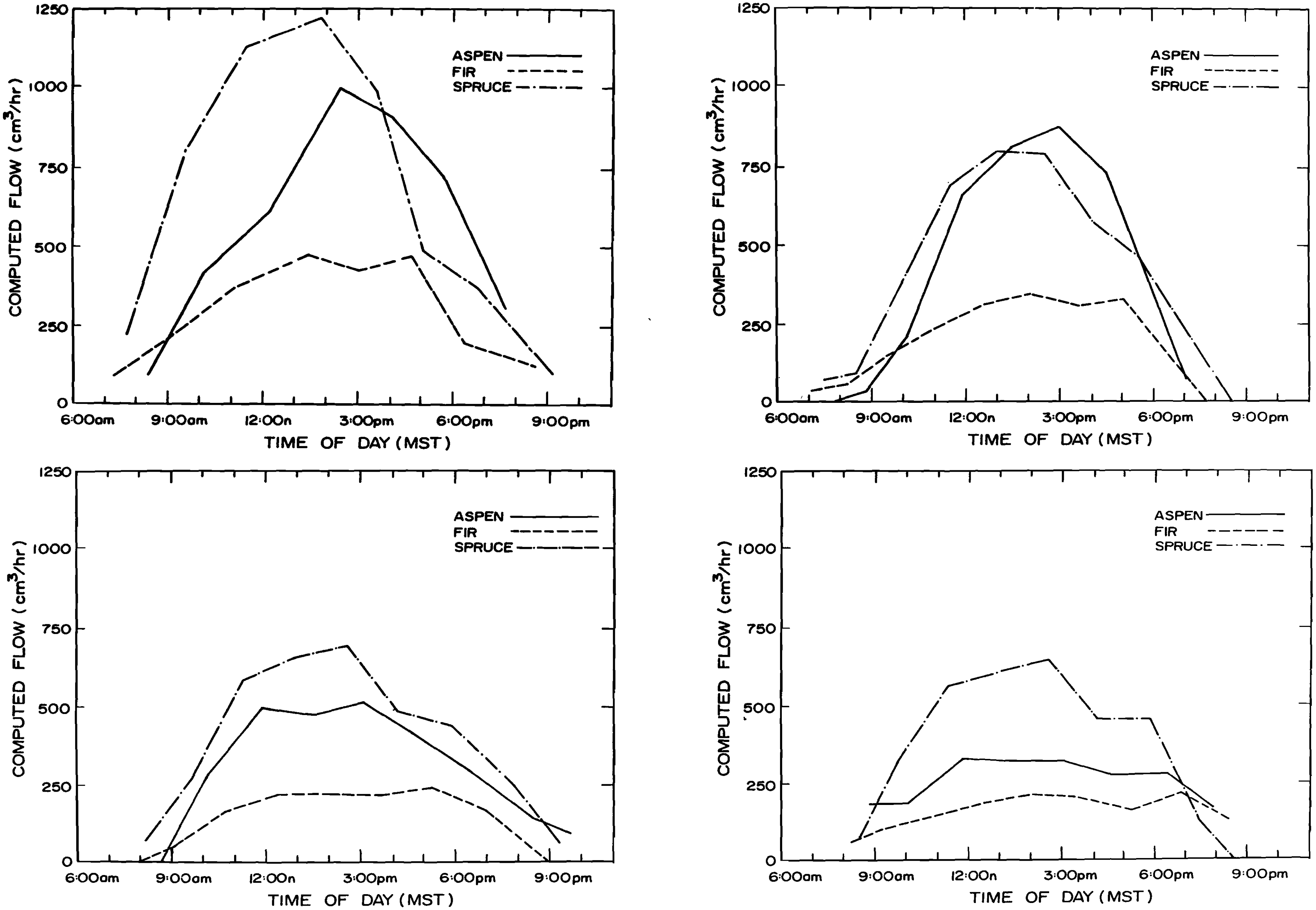

Figure 19. Average computed flow rates of the three tree species on four select dates: Ais July 9, 1980, B is July 30, 1980, C is August 21, 1980, and D is September 17, 1980.

ASPCON MODEL CALIBRATION AND MODIFICATION

The model (Jaynes 1978) describing the hydrology of aspen to conifer succession (ASPCON) consists of a series of moisture storage compartments connected by transfer equations that systematically deal with each set of input data (Appendix II). As moisture enters and interacts with a watershed, a certain amount is lost to the atmosphere via evapotranspiration, while the remainder may become streamflow or percolate deep into the soil.

ASPCON is a deterministic, lumped-parameter model. The watershed is treated as a single series moisture storage "tank". Model coefficients related to watershed characteristics represent averaged values. The model calculates weekly water budgets throughout one water-year (October 1 to September 30). System input includes only precipitation and average weekly air temperature. The transfer functions for moisture routing within the watershed are described in Appendix II.

The model was calibrated on the West Branch Chicken Creek Watershed (CCW), Davis County Experimental Watershed in Utah (Jaynes 1978). The vegetation on the 86.8-ha (217 acre) CCW is approximately 20 percent grass-forb, 78 percent aspen, and 2 percent conifer (Johnston and Doty 1972). A total of 119.4 cm (47 inches) of precipitation fell during the modeled year, of which 29.5 cm (11.6 inches) were rain and 89.9 cm (35.4 inches) were snow. Average soil profile depths to limiting horizons were assumed to be 150 cm (5 feet). A series of recorded annual hydrographs was analyzed and the model coefficients were adjusted until a predicted hydrograph agreed closely with past watershed behavior. During the calibration process, the only coefficients to be adjusted were those coefficients not easily estimated from a knowledge of watershed characteristics but to which the model is sensitive. The purpose of this calibration procedure is not to model CCW, but to develop a reasonable point of reference against which hydrologic changes attributable to vegetation changes may be estimated.

Perhaps the most important area needing further definition is the amount and time pattern of transpiration of different forest communities. ASPCON's plant activity index (PAI) forest crop coefficients need to be defined more precisely. The PAI is used in ASPCON to reflect the variation in the capability of a plant community to transpire water over the year. The index is defined as "that fraction of peak activity that a plant community may reach when water is not limiting growth". The PAI thus represents the week-to-week influence of day length and soil temperature on a plant's ability to transpire. It is important to recognize that weekly air temperature and available soil moisture are not included in the PAI definition; these factors are taken into account in the calculation of potential evapotranspiration by the Blaney-Criddle model, and an adjustment is made if soil moisture becomes limiting. Regardless of what the potential evapotranspiration is for a given week, the PAI determines the extent to which a community is phenologically able to transpire water. Of course, the PAI exerts the greatest influence on estimated transpiration in the Spring, when conifers are able to transpire water while aspen are leafless.

The objective of this portion of the study has been to modify ASPCON to reflect the recently-obtained information about seasonal plant activity patterns and consumptive use rates. To accomplish this, ASPCON has been modified to predict streamflow for watersheds which may contain spruce, aspen, or fir watershed cover; this slightly-modified version of ASPCON will be referred to as SAFMOD.

Plant Activity Index Adjustments

The data acquired in this study on seasonal transpiration rates of spruce, aspen, and fir were used to redefine the PAI. Since the PAI is a relative measure of a plant's ability to transpire water, all daily use rates were divided by the highest daily rate sampled for the respective species. The results are presented in Table 6. It should be noted that an index value of zero was assumed for all three species between late November and mid-April of the year of sampling.

Before the data in Table 6 could be used in SAFMOD, average weekly index values had to be determined. The figures in Table 6 were plotted as a function of the date of sampling and a smooth envelope curve was drawn through the uppermost points of the graph. Since the PAI is defined to be independent of day-to-day variations in temperature, humidity, wind, etc., this approach was considered the best means of extracting index values from the data. It was assumed, from past information available for the study area, that soil moisture was not a limiting factor, but that activity patterns in the fall are associated with plant phenological changes attributable to other environmental factors.

The average weekly PAI values are presented in Figure 20. The PAI of Figure 20 exhibits some remarkable differences from the index constructed previously for ASPCON. Aspen begin transpiring water much later in the season than was previously thought; conifers begin actively transpiring water at about the same time as that assumed in ASPCON. A major change in the index is the total area under the curves: the index curves developed from data in this study have only 40 percent and 50 percent of the area under the curves previously used for aspen and conifers, respectively (see Jaynes 1978 for original curves).

Table 6. Plant activity index values for spruce ("S"), aspen ("A"), and fir ("F") for the sampling dates indicated.

	Plant Activity Index		
Date	S	A	F
6-30-80	.29	.34	.61
7-02-80	.39	.21	.37
7-09-80	.92	.74	.96
7-10-80	.77	.89	1.00
7-16-80	.74	.85	.89
7-17-80	.82	.64	.83
7-18-80	.82	.85	.84
7-21-80	.83	.85	.87
7-22-80	1.00	1.00	.93
7-23-80	.83	.96	.91
7-30-80	.58	.52	.60
7-31-80	.41	.58	.62
8-01-80	.43	.55	.62
8-05-80	.57	.64	.63
8-06-80	.86	.72	.62
8-07-80	.66	.58	.67
8-11-80	.56	.49	.50
8-20-80	.34	.28	.26
8-21-80	.46	.39	.43
8-26-80	.39	.26	.31
8-27-80	.43	.24	.47
8-28-80	.38	.29	.44
9-01-80	.28	.18	.35
9-02-80	.35	.21	.39
9-03-80	.36	.19	.38
9-10-80	.08	.09	.12
9-12-80	.05	.05	.04
9-16-80	.28	.21	.30
9-17-80	.40	.26	.43
9-18-80	.38	.22	.37
10-04-80	.24	-0-	.29
10-11-80	.15	-0-	.27
10-18-80	-0-	-0-	-0-
11-01-80	.02	-0-	.01
11-08-80	.01	-0-	.01
11-15-80	.01	-0-	.01
4-25-81	.15	-0-	.01
4-28-81	.15	-0-	.25
5-01-81	.24	-0-	.29
5-05-81	.20	-0-	.28
5-09-81	.02	-0-	.01
5-12-81	.01	-0-	.01
5-19-81	.20	-0-	.27
5-23-81	.05	-0-	.02
5-30-81	.38	-0-	.38
6-02-81	.15	-0-	.27
6-09-81	.38	-0-	.36

Table 6. Continued.

	Plant Activity Index		
Date	S	A	F
6-10-81	.38	-0-	.37
6-11-81	.38	-0-	.34
6-17-81	.38	-0-	.43
6-18-81	.42	-0-	.46
6-19-81	.39	-0-	.45
6-22-81	.56	-0-	.51
6-24-81	.46	.19	.43
6-29-81	.46	.24	.49

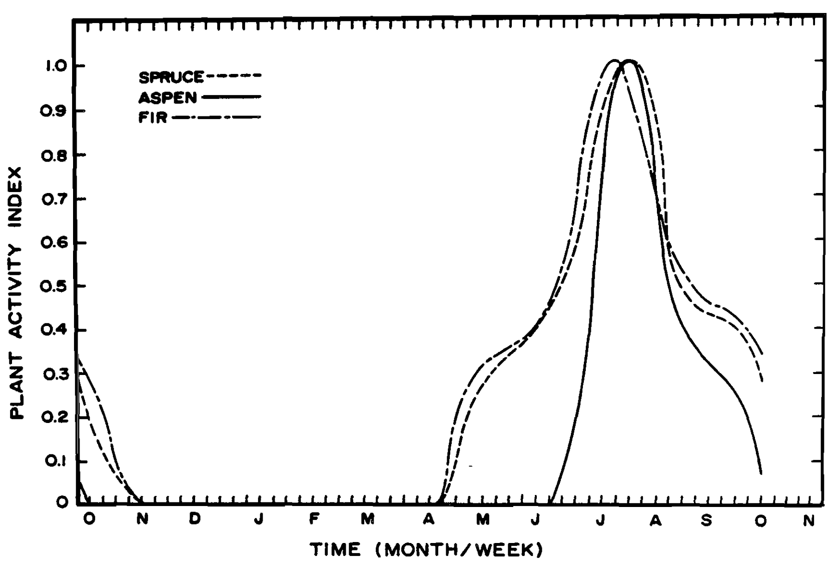

Figure 20. Plant activity index for spruce, aspen, and fir community types.

It should be noted that the PAI developed in this study reflects the general conditions of the study area, and may be expected to require modifications if applied to other areas. That is, areas with significantly different seasonal temperatures would justify an expansion of the PAI for warmer areas and a contraction for cooler areas.

Crop Coefficient Adjustments

The data from the present study on transpiration rates suggest that certain changes, some of which are rather startling, be made in the crop coefficients used for spruce, aspen, and fir communities. The actual amount of water consumed by the sampled trees for any given day when all three species are "active" (PAI defines seasonal activity pattern) is greatest for spruce, intermediate for aspen, and lowest for fir. In ASPCON, conifers were assumed to have similar consumptive use rates, but recent results consistently demonstrate a large difference between spruce and fir. Consequently, it was clear that new crop coefficients were needed for aspen and fir. The data suggested that, if the crop coefficient for spruce were kept at 1.25 (the value used for conifers in ASPCON), then values of 0.95 for aspen and 0.65 for fir would reflect the relative difference between the trees.

The selection of the foregoing crop coefficients was made without regard to differences in the forest understories. Aspen may be expected to have a more productive understory than spruce or fir forests. Therefore, it seems reasonable to adjust the aspen crop coefficient upward to reflect this condition. The midpoint between 0.95 and 1.25, or 1.10, was selected as the crop coefficient for aspen.

MODELING RESULTS

SAFMOD had the same structure as the ASPCON model. Since it was desired to compare the watershed hydrology of spruce, aspen, and fir forests, the coefficients for the grass-forb community in ASPCON were changed to reflect spruce forest conditions. The conifer community coefficients in ASPCON for PAI and crop coefficient were altered to reflect the coefficients for fir. Likewise, for aspen only the PAI and crop coefficient were adjusted. The rooting depth coefficient for all three types was set at 1.0 to allow a better assessment of transpiration differences resulting from the changes mentioned above. All coefficients which were manipulated during the initial calibration of ASPCON and which are independent of watershed cover were not altered.

SAFMOD was initially applied to determine the sensitivity of the model to the aspen crop coefficient. Values of 0.95, 1.10, and 1.25 were selected, and the model was exercised under a variety of spruce/aspen and fir/aspen combinations. The results of these tests are presented in Table 7. It is clear that the crop coefficient has little impact on annual streamflow, if other factors are not considered. Changes in the crop coefficient have the greatest effect on annual transpiration and net annual change in soil moisture. Such differences are greater between crop coefficients of 0.95 and 1.10 than they are between crop coefficients of 1.10 and 1.25. These results suggest that possible errors in estimating the aspen crop coefficient would not have a major effect on the runoff modeled by SAFMOD.

The precipitation and active moisture input patterns in SAFMOD are similar to the patterns in ASPCON. As one would expect the seasonal transpiration patterns for SAFMOD, shown in Figure 21, reflect the patterns of the new PAI.

The manner in which seasonal transpirational patterns interact with Spring snowmelt is evident in Figure 22. Under aspen forest conditions, the snowpack melts slightly earlier and transpiration begins much later than when conifers dominate the watershed. The result is that significantly greater amounts of runoff occur under aspen forest conditions. The hydrographs for the three forest types are similar for the portions of the year not shown in Figure 22.

The predicted annual water budgets for a year, in which 119.4 cm (47 in.) of precipitation was received, are given in Table 8 for different combinations of forest communities. First, succession from aspen to spruce forests was examined. Second,

Table 7. Sensitivity of SAFMOD to changes in the aspen crop coefficient (CCA). Multiply by 2.54 to obtain centimeters.

CCA	Plant Community	Annual Streamflow (in.)	ΔSM* (in.)	TRAN[2/] (in.)	CCA	Plant Community	Annual Streamflow (in.)	ΔSM* (in.)	TRAN[2/] (in.)
	Spruce/Aspen					Fir/Aspen			
0.95	0/100	23.4	0.5	8.8	0.95	20/80	22.1	0.6	9.2
1.10	0/100	23.3	-0.4	9.7	1.10	20/80	22.1	-0.1	9.9
1.25	0/100	23.3	-1.0	10.3	1.25	20/80	22.0	-0.7	10.5
0.95	20/80	21.8	-0.3	10.4	0.95	40/60	21.0	0.6	9.5
1.10	20/80	21.8	-0.8	11.0	1.10	40/60	21.0	0.1	10.1
1.25	20/80	21.8	-1.2	11.5	1.25	40/60	21.0	-0.4	10.6
0.95	40/60	20.4	-0.9	11.8	0.95	60/40	20.2	0.6	9.8
1.10	40/60	20.4	-1.2	12.2	1.10	60/40	20.2	0.2	10.2
1.25	40/60	20.4	-1.5	12.5	1.25	60/40	20.2	-0.1	10.5
0.95	60/40	19.4	-1.5	13.0	0.95	80/20	19.5	0.5	10.5
1.10	60/40	19.4	-1.6	13.2	1.10	80/20	19.4	0.3	10.2
1.25	60/40	19.4	-1.8	13.3	1.25	80/20	19.4	0.1	10.4
0.95	80/20	18.4	-1.9	14.0					
1.10	80/20	18.4	-2.0	14.0					
1.25	80/20	18.4	-2.0	14.1					

*ΔSM represents the net annual change in soil moisture.

[2/] TRAN represents annual transpiration.

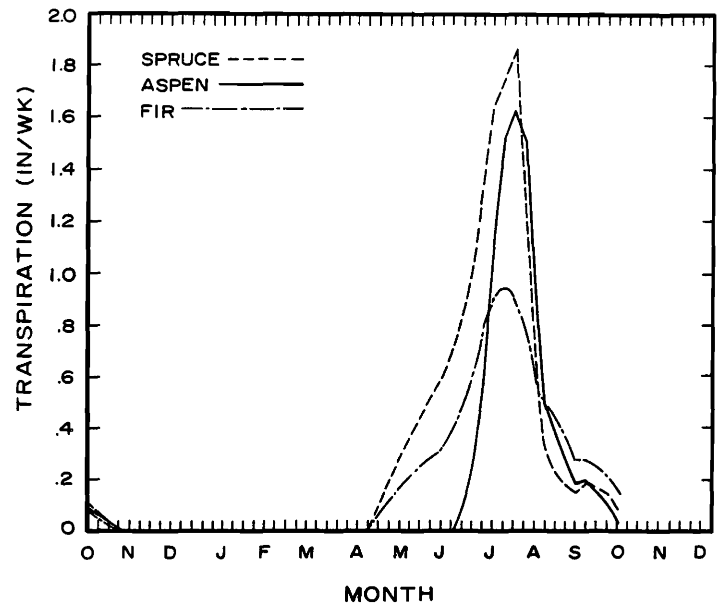

Figure 21. Weekly transpiration patterns for the Chicken Creek Watershed when dominated by spruce, aspen, and fir forests.

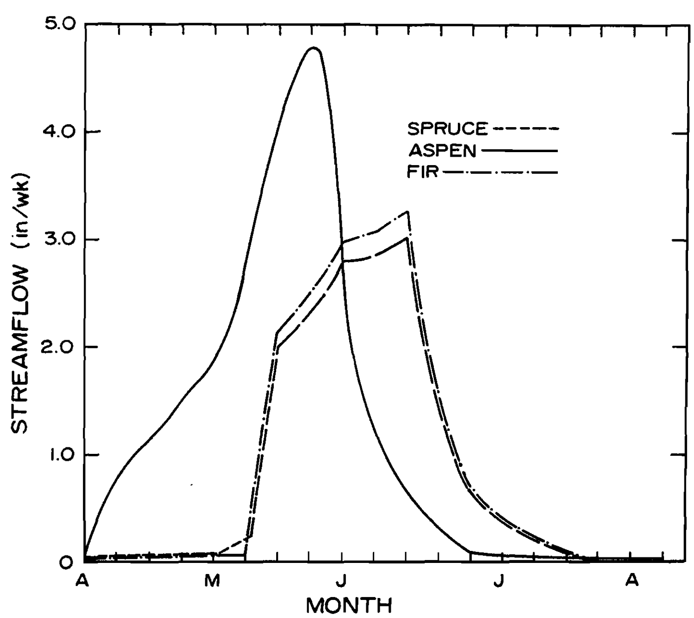

Figure 22. Spring runoff hydrographs for the Chicken Creek Watershed when dominated by spruce, aspen, and fir forests.

Table 8. Water budget components for an average water year on Chicken Creek Watershed at different stages of succession. All units are inches, except runoff, which is a percentage. (Multiply times 2.54 to obtain centimeters.)

Vegetation Status[1]	Streamflow	Streamflow[2] +ΔSM	Runoff[3]	QOF[4]	QF	ΔSM[2]	ΔGWL[2]	SEEP	TRAN	RINT	SINT	SVAP
0-100-0	23.3	22.9	48.7	5.2	15.8	-0.4	1.8	6.9	9.7	1.4	0.4	1.2
20-80-0	21.8	21.0	44.7	3.6	15.9	-0.8	1.8	6.9	11.0	1.6	0.8	1.1
40-60-0	20.4	19.2	40.9	2.2	15.9	-1.2	2.1	6.7	12.2	1.7	1.2	1.1
60-40-0	19.4	17.8	37.9	1.4	15.7	-1.6	2.3	6.4	13.2	1.9	1.6	1.0
80-20-0	18.4	16.4	34.9	0.5	15.6	-2.0	2.3	6.3	14.0	2.1	2.0	0.9
99-1-0	17.4	15.6	33.2	1.7	13.4	-1.8	1.7	5.5	15.5	2.3	2.4	0.9
0-80-20	22.1	22.0	46.8	3.7	16.1	-0.1	1.9	6.9	9.9	1.6	0.8	1.1
0-60-40	21.0	21.1	44.9	2.5	16.2	0.1	2.3	6.7	10.1	1.7	1.2	1.1
0-40-60	20.2	20.4	43.4	1.7	16.2	0.2	2.6	6.4	10.2	1.9	1.6	1.0
0-20-80	19.4	19.7	41.9	0.9	16.3	0.3	2.6	6.4	10.2	2.1	2.0	0.9
0-1-99	18.8	20.1	42.8	2.3	14.1	1.3	1.7	5.9	10.7	2.3	2.4	0.9
10-80-10	21.9	21.4	45.5	3.6	16.0	-0.5	1.9	6.9	10.5	1.6	0.8	1.1
20-60-80	20.7	20.1	42.8	2.4	16.1	-0.6	2.2	6.7	11.2	1.7	1.2	1.1
30-40-30	19.8	18.9	40.2	1.5	15.9	-0.9	2.4	6.4	11.8	1.9	1.6	1.0
40-20-40	18.9	17.8	37.9	0.6	16.0	-1.1	2.5	6.4	12.4	2.1	2.0	0.9
50-1-49	18.0	17.3	36.8	1.9	13.8	-0.7	1.9	5.6	13.6	2.3	2.4	0.9

1/ Percent watershed area cover composed of spruce, aspen, and fir communities, respectively.
2/ ΔSM and ΔGWL represent the net annual change in soil moisture and groundwater level, respectively.
3/ Runoff percent is equal to (streamflow + ΔSM)/precipitation) X 100.
4/ Alphabetic codes for annual hydrologic components (see appendix for detailed explanation).

QOF - overland flow when soil is saturated
QF - soil profile interflow
SEEP - deep seepage
TRAN - transpiration
RINT - rainfall interception
SINT - snowfall interception
SVAP - snowpack evaporation

aspen to fir succession was studied. Finally, aspen to both spruce and fir succession was tested.

The value for streamflow plus soil moisture change is presented since net change from the initial soil moisture at the end of the year will affect the following year's runoff (the soil moisture must be recharged prior to the runoff season).

The amount of streamflow reduction expected as aspen is replaced by either spruce or fir is shown in Figure 23. Spruce forests are predicted to reduce streamflow by 15.0 cm (5.9 in) over aspen-dominated conditions. Fir forests are expected to reduce streamflow by 11.4 cm (4.5 in.). If streamflow plus change in soil moisture are examined, then spruce produces a difference of 18.5 cm (7.3 in.), and fir a difference of 7.1 cm (2.8 in.).

Summary and Conclusions from Modeling Study

A preview hydrologic model of aspen to conifer succession previously developed has been modified to reflect data acquired from this study concerning plant activity patterns and community crop coefficients for spruce, aspen, and fir forests. Applying these new coefficients to describe the timing and rates of transpiration, the model predicts 18.5 cm (7.3 in.) net loss of moisture available for streamflow when spruce replace aspen, and a loss of 7.1 cm (2.8 in.) when fir forests cover the watershed. Considering all 1.3 million hectares (3.3 million acres) of aspen within the Colorado River system (obviously a bit optimistic), this translates into 2,500 million and 900 million cubic meters (2.0 and 0.8 million acre-feet) of water, respectively, that could be used to dilute salt downstream from the high water-yielding watersheds. Actual management opportunities would significantly lower these potential water yield increases. If aspen were managed to enhance runoff by methods such as those described in the literature review, even more water (perhaps 33.8 million cubic meters or .274 million acre feet) could be made available for salt dilution.

There are several limitations to this preliminary study, and they are as follows:

1. The predicted hydrology of the aspen-conifer environment is only as good as the algorithmic logic of the modified ASPCON model. The same logic may not be applicable to all parts of the aspen type within the Colorado River Basin.

2. Extrapolation of modeling results on the Chicken Creek Watershed near Farmington, Utah, may not be justified in every instance. This is especially true in the case of the entire Colorado River Basin.

3. It was assumed that entire stands of a particular species behave as did the 10 cm (4 inch) DBH trees whose measurements were used to adjust the plant activity indexes and also for determining crop coefficients. Deviations from defined behavior patterns as a function of tree size were not determined.

4. The actual number of hectares of aspen forest that could be managed to control successional patterns is not known. Therefore, sound estimates of potential water-yield impacts related to such management activities cannot be given.

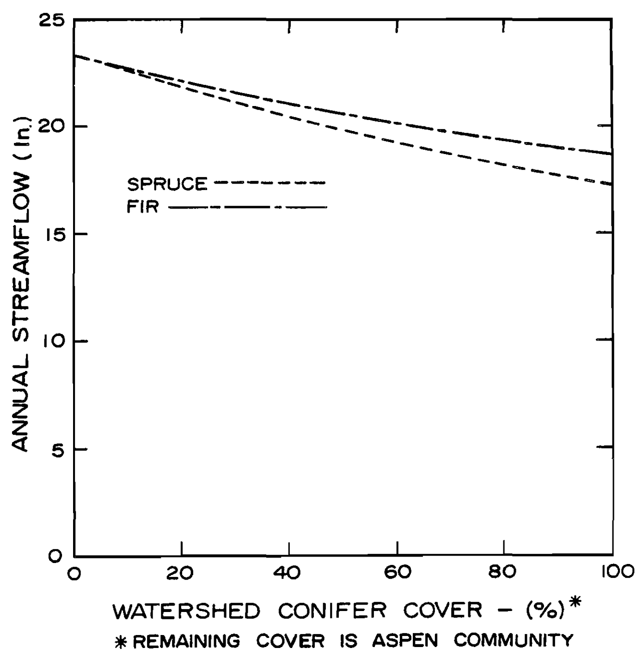

Figure 23. Streamflow reduction for the Chicken Creek Watershed as a function of replacement of aspen forests by spruce and fir.

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APPENDIX I

HPV Methodology for Live Trees

The following procedure is recommended for using HPV methods to measure transpiration in live aspen, Engelmann spruce and subalpine fir:

Sampling probes should be located in a defect-free portion of the lower trunk.

The tree circumference should be measured at the height selected for sampling, and the total cross-sectional area should be computed assuming a circular geometry for the tree. Using the regression equation developed for the species by this study, the water conducting area should be determined.

Three sets of thermocouples and heat injection probes should be placed in the tree in a vertical pattern, with the centers of the probe sets approximately 3 cm apart. The depth of the probes into the tree should be selected so that each one is centered in a different third of the expected sap flow region. It should be assumed that this region will extend from the bark toward the center of the tree a distance equal to the radius of the water conducting area, or 2/3 the radius of the total tree cross-sectional area, whichever is longer.

HPV measurements should be collected from each probe at least hourly for the entire time period for which transpiration is to be estimated. In no case should this time period be less than 6 hours.

For each sampling time, Equation 4 should be used to convert sampling measurements to HPV values.

For each sampling time, an average HPV for the maximum water conducting area should be determined by applying weighted averaging techniques to the values obtained in the previous step.

For each sampling time, the average HPV value should be multiplied by the maximum water-conducting cross-sectional area determined as above to obtain an instantaneous volumetric flow rate.

A total computed flow for the entire sampling period should be obtained by summing all the volumes computed for each timer interval in the previous step.

The proper regression equation or graph should be used to convert from computed to actual flow.

HPV Methodology Limitations

The HPV method developed in this study is subject to various assumptions and limitations. If this method is to be applied to intact trees, these considerations must be fully recognized and understood for accurate interpretation of the results. These limitations are:

The developed correlations of actual and computed flows, as well as total and water conducting cross-sectional areas, are regionally specific. Although a conscious effort was made during the study to sample under diverse a set of conditions as possible, there was little actual variance in ecotype, soils, and climate on the site.

The quantity of water lost from the permanent reservoir actually measures consumptive water use by the tree, and not transpiration. A certain amount of the water is stored temporarily in the tree, used in conducting photosynthesized sugars downward through the phloem or biologically captured in new cell production. This method assumes such amounts to be negligible when compared to transpirational losses for a 6-hour or longer period.

Research has indicated that there is a time lag between actual transpirational losses and the effect of those losses on HPV measurements. Therefore, the HPV method is not indicative of transpirational losses at the time of measurement. A long time period (greater than 6, and preferably 24 hours) must be used for HPV volumes to represent transpirational volumes.

Thermocouple probes are very fragile because of the fine wire used. Insertion of the probes, or even the weight of the wire from the voltage meter, can occasionally damage the probes, causing inaccurate readings. Damaged probes may not be detected.

As nichrome wire is used several times for heating, its resistance to current changes. With repeated use, it eventually burns in half. Therefore, the exact heat input varies from sample to sample.

Because the probe wire is so thin, it is easily blown about by the wind. This causes zeroing problems with the meter, as well as problems determining the return of zero. If windy conditions are likely to be encountered, some sort of wind screen should be utilized in the area where wires are exposed.

When holes are drilled into the trees, the drill encounters less resistance in the vertical direction than in the horizonal direction because of the growth ring structure. There is an increasing chance that the drill bit will drift in the vertical direction with increasing depth, creating undesired distances between the tips of the probes. As an example, with properly set probes and a time of 60 seconds for the current to return to zero, an HPV measurement of 15 cm/hr is obtained. If a drift of 1 mm had actually occurred, the actual rate would be 18 cm/hr, or an error of 17 percent.

The HPV technique assumes that flow through intact trees will follow the same correlation as flow through the severed trees. Intact trees have a different resistance to water flow than do the severed trees, such as soil and root resistance.

Very large trees presented problems in terms of being lifted into permanent reservoirs or being suspended. Therefore, the largest sampled trees were approximately 9 inches in diameter. If this technique is to be applied to estimate stand transpirational losses, much larger trees must be considered. In such cases, the assumption must be made that the developed correlations are also accurate for the larger trees.

The HPV technique assumes that the average HPV velocity will essentially be the same for any sap velocity profile sampled around the circumference of the tree at the sampling height.

The HPV method assumes a relatively uniform flow system in the vertical interval that the series of probe occupies. This is the reason that probe placement criteria requires no surface blemishes in the probe region which would indicate internal tissue disturbance. However, the cutting studies in this experiment revealed tissue disruption in the tree interior which was not indicated on the bark. Such disruptions distort flow and cause errors in measurements.

In very slow flows, enough heat is dispersed into the surrounding material that the temperature changes in the heat flow region are beneath the sensitivity of the thermocouple probes. Therefore, no measurements should be made when the time of electrical conductance exceeds an arbitrary time limit of 5 minutes. If current is still being conducted after that time, flow must be assumed to be zero.

All of the above limitations must be recognized when applying the HPV method developed in this study. Nevertheless, the good correlations achieved indicate that this method is a viable technique for measuring transpiration. This is especially true when one considers the low levels of accuracy and the limitations associated with other methods of transpiration measurement.

APPENDIX II

Transfer Fuctions for the Model ASPCON (from Jaynes 1978).

1. Calculation of initial groundwater level (GWL, in or cm) from baseflow. At the beginning of the water-year (October 1) average streamflow for the last rainless week of September is used to define the initial GWL. Initial GWL is the quotient of stream baseflow (in or cm) divided by a groundwater recession coefficient (AGW in/in or cm/cm).

2. Channel interception (QCHP, in or cm). The amount of moisture falling directly into the stream channel is defined as the fraction of the total watershed area consisting of surface water or saturated streambanks multiplied by the precipitation input.

3. Precipitation type. Form of precipitation is determined by using a routine similar to the model developed by the Army Corps of Engineers (1956).

4. Rainfall interception loss (RINT, in or cm). The amount of rainfall greatly influences the amount of net moisture (moisture entering the soil) for individual storms; estimates of yearly interception losses are as follows: grass-forb, 9 percent; aspen, 12 percent; and conifer, 20 percent (Helvey 1971, Johnston 1971, and Verry 1976). The fraction of moisture received as rainfall that may be considered interception loss is assumed to be an average, weighted by areal cover of each vegetation type.

5. Snowfall interception loss (SINT, in or cm). Researchers have many different opinions about moisture loss from intercepted snow in coniferous canopies (Satterlund and Haupt 1970, Miller 1962). Estimates of the magnitude of such losses generally range between 6 and 10 percent of total snowfall (Anderson 1969). The amount of snowfall interception loss from leafless aspen is assumed to be relatively minor. The fraction of snowfall that becomes interception loss is defined in ASPCON simply as the weighted average of two interception loss coefficients, SNA (aspen) and SNG (conifer), with respective values of 0.01 and 0.07 in/in.

6. Snowpack evaporation (SVAP, in or cm). Johnston et al. (1969) found evaporative losses from snowpacks in winter as follows: open ground, 0.05 in/in; under aspen, 0.034 in/in; and under conifers 0.026 in/in. A weighed average of three snowpack evaporative loss coefficients is assumed to be the fraction of snowfall that is evaporated during the year.

7. Snowpack accumulation. Research suggests that vegetative canopies influence snowpack in western watersheds (Gary and Coltharp 1967, Thies 1972, Dunford and Niederhof 1944, and Meiman 1970). Accordingly, snowpacks in the model are accumulated differently for each vegetative type. Snowpack accumulation is assumed to be a fraction of total net snowfall for each community type (99 percent of grass-forb areas, 106 percent in aspen areas, and 95 percent in conifer areas).

8. Snowpack melt. Snowmelt rates should be about the same for open and aspen areas but significantly slower for coniferous types (Thies 1972, Federer et al. 1972). Snowmelt in ASPCON is indexed by mean weekly air temperature in a manner similar to the Army Corps of Engineers (1960) model. Figure 24 shows that, for each vegetative type, the amount of snowmelt is a function of a melt rate coefficient as well as mean weekly temperature (F).

9. Channel inflow from snowmelt (QMCH, in or cm). Part of each increment of snowmelt may be expected to occur on saturated soil adjacent to stream channels and, therefore, to readily enter the stream channel. The fraction of snowmelt thus contributing to streamflow is equivalent to the product of the amount of snowmelt and a melt inflow coefficient.

10. Active moisture input. The term "active moisture" is defined as the sum of net weekly rainfall and snowmelt. Active moisture is capable of entry into the soil system (depicted as the large "tank" in Figure 24) for subsequent evapotranspiration, deep percolation, or direct contribution to streamflow.

11. Overland flow when infiltration rate is exceeded (QXS, QOF, in or cm). The model provides for calculating overland runoff when active moisture input exceeds infiltration capacity (FI, in or cm/wk). Because the model is incremented on weekly intervals, QXS cannot be estimated accurately. Consequently, the infiltration capacity is set at a sufficiently large value to preclude any QXS.

12. Transpiration (TRAN, in or cm). The model treats evaporation of water via plant stomates (transpiration) and evaporation of moisture from the surface soil as two distinct processes. To reflect the differences between aspen and conifer communities that are suspected to influence TRAN, the following relationship is assumed.

Transpiration = f (potential evapotranspiration, seasonal plant activity, plant rooting depth, community crop coefficient).

a. Potential evapotranspiration (PET, in or cm) is calculated according to the model described by Blaney and Criddle (1962).

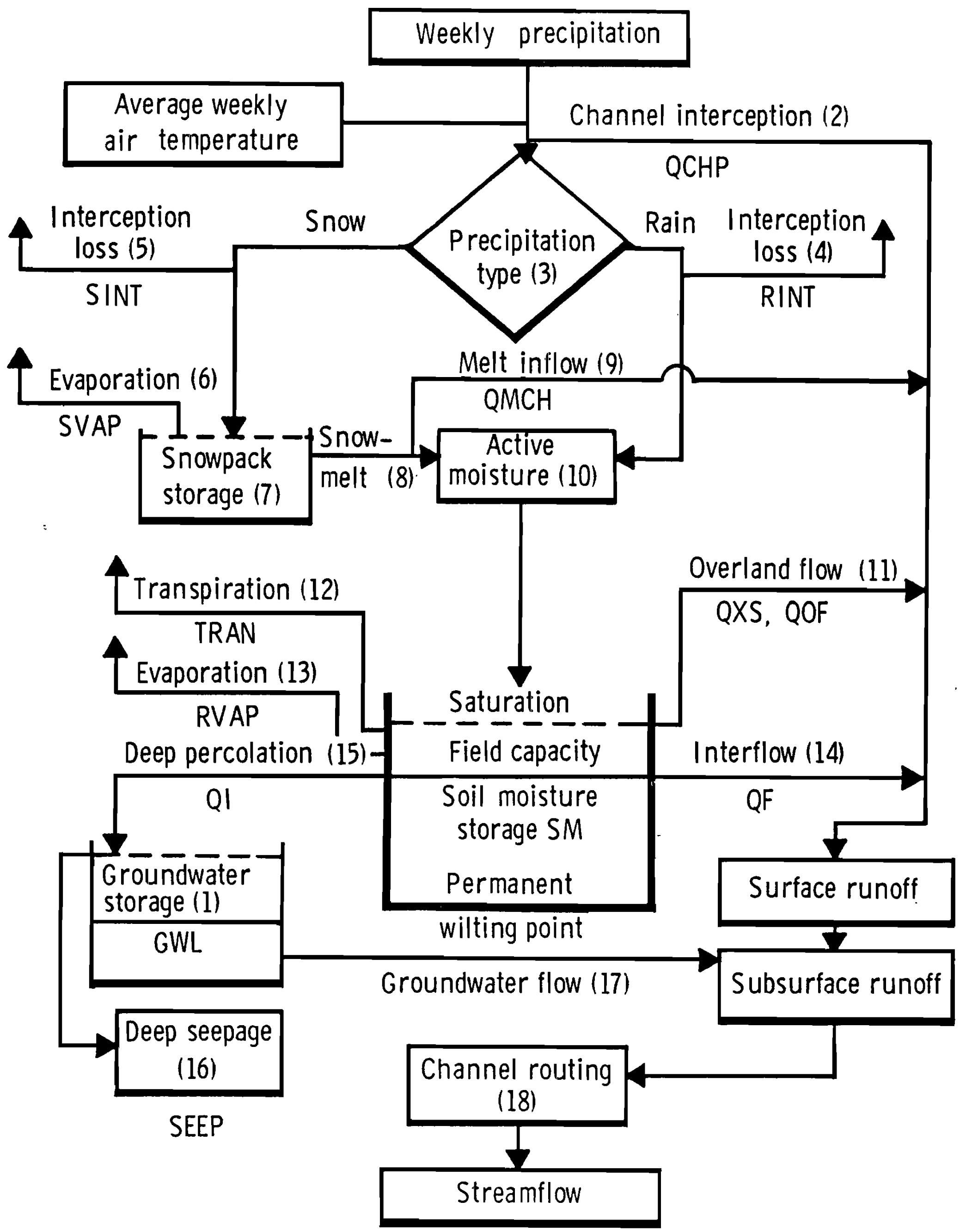

Figure 24. Flowchart for the succession hydrology model (ASPCON). Numbers in parenthesis refer to definition given in text (from Jaynes 1978).

b. Plant activity index (PAI). Although aspen and conifers have been shown to be comparable in terms of end-of-season soil profile moisture content (Brown and Thompson 1965), there is little direct research that describes relative year-round-consumption patterns. Several researchers have found that conifers may actively transpire water at times of the year when deciduous tree species are dormant (Swanson 1967, Owston et al. 1972, Smith 1975, and Urie 1959). Accordingly, a plant activity index (PAI) is defined as that fraction of peak activity that a plant community may reach when water is not limiting growth. The PAI is thus defined to reflect the week-to-week influence of day length and soil temperature on a plant's ability to transpire water.

A correction is applied to PET to account for the effects of limiting soil moisture on transpiration. The adjustment of PET for limiting soil moisture is made according to a model by Hanks (1976), which is similar to the approach taken by Leaf and Brink (1975).

c. Plant rooting depth (RDP). The RDP is defined as that fraction of the total available rooting zone in the soil profile that contains 90 percent of all live plant roots.

d. Community crop coefficient (CC). The crop coefficient is included in the model to reflect differences in consumptive use rates of water by different vegetation types when all other factors are held constant.

Watershed transpiration loss is weighted according to areal vegetation composition and is calculated as the product of PET, PAI, RDP, and CC values.

13. Evaporation of rainfall from surface soil (RVAP, in or cm). The model allows for a portion of rainfall to be evaporated from the surface soil. Generally in these forests, rain that falls during the growing season readily evaporates after each storm and seldom contributes to soil moisture recharge. As a consequence of defining RVAP as a function of rainfall amount as well as PET, significant amounts of rain are evaporated from the soil only during the growing season.

14. Soil profile interflow (QF, in or cm). Soil moisture in excess of field capacity is multiplied by an interflow coefficient to define interflow.

15. Deep percolation (QI, in or cm). The quantity of water that percolates through the soil profile and enters the groundwater reservoir is calculated similar to QF except that a deep percolation coefficient is applied instead of an interflow coefficient.

16. Deep seepage (SEEP, in or cm). A portion of the water entering the watershed may leave the area without contributing to local streamflow. The deep seepage storage compartment receives moisture when the groundwater level is multiplied by a deep seepage coefficient to calculate the amount of water added to SEEP.

17. Subsurface flow from groundwater storage (QGW, in or cm). The amount of water entering the stream channel from the groundwater reservoir is defined as the product of the ground water level and a groundwater recession coefficient.

18. Channel routing of flow. Moisture for streamflow that is generated by the model may be expected to experience a timelag before passing through the gaging station at the mouth of the watershed. Therefore, the model provides for fractions of generated runoff to be delayed up to 5 weeks.

ASPCON computes weekly and yearly water budgets by summing all components of streamflow, evapotranspiration, and changes in soil moisture and groundwater storage.