

A RIPARIAN VEGETATION ECOPHYSIOLOGICAL RESPONSE MODEL¹

Jeffrey P. Leighton and Roland J. Risser²

Abstract: A mathematical model is described that relates mature riparian vegetation ecophysiological response to changes in stream level. This model was developed to estimate the physiological response of riparian vegetation to reductions in streamflow. Field data from two sites on the North Fork of the Kings River were used in the model development. The physiological response of three adult white alders and one juvenile red willow were simulated as a function of the meteorological and streamflow conditions. Estimates of predawn leaf water potential, leaf temperature and transpiration rate were comparable to measured values, indicating our model can be used for predictive purposes.

Limited water availability in many montane streams has resulted in recent concerns to maintain adequate flows for fisheries, power production, human consumption, irrigation, recreation, and maintenance of riparian communities. Few studies have been undertaken to assess the streamflow necessary to maintain existing riparian vegetation. A quantitative study evaluating various low streamflows and the response of associated vegetation is extremely expensive, politically sensitive, and could impact an established riparian community. Modeling can be used for predicting these effects. Utilizing data from a study site, a model was developed which allows scientists to predict how changes in streamflow may affect existing riparian vegetation.

We developed a model that defines riparian vegetation physiological response to variations in streamflow, through a number of intermediate relationships (Leighton and others 1988). Stream level and streamflow are related by a stage-discharge curve, or rating curve. Variation in stream height and meteorological conditions are used as a determinant of the variation in predawn leaf water potential. Stomatal conductance is compared to leaf water potential, photosynthetically active radiation, and time of day. An energy balance formulation is used to compute transpiration rate and leaf temperature in response to meteorological factors, canopy geometry conditions and stomatal conductance. This formulation considers the available energy (incoming radiation) and its utilization in latent and sensible heat exchange. As a result of evaluating these interrelationships, the physiological response of the plant to incoming radiation and water availability is given by its leaf water potential, leaf temperature and transpiration rate.

Site Description and Study Design

Soil, plant and atmospheric conditions were monitored during the growing season (from April to October) in 1986 along the North Fork of the Kings River at elevation 1200 ft. Additional data were obtained during 1987. The North Fork of the Kings River has large, spatially intermittent stands of riparian vegetation. Two sites were selected: a small stand of vegetation on a sand bar (referred to as One Mile Bar), and a streamside area of plants rooted in sand within a boulder field (near Balch Camp).

Bi-weekly monitoring of plants of five species was made during 1986 (Smith and Nachlinger 1987). In 1987, data were obtained once each in July, August and September. Leaf temperature, leaf water potential, stomatal conductance, relative humidity, and photosynthetically active radiation, were measured. Moisture levels in soil columns were also measured once every two weeks in 1986, and once in 1987.

The stand of riparian vegetation at One Mile Bar is drawn in plan in figure 1. Thirteen individuals were monitored. Two plants at One Mile Bar were used throughout the model development (plants 111 and 221). Plant 111 is an adult white alder (*Alnus rhombifolia*), with a leaf area index of 3, a height of 9 meters and horizontal area of 7 square meters. Plant 221 is a juvenile red willow (*Salix laevigata*), with a leaf area index of less than one, height of 2 meters and horizontal area of 3.8 square meters. Two adult white alders from the site near Balch Camp were also modeled, but will not be presented here.

Stream Height Versus Streamflow

In a stream where water flows from the stream to the ground, the stream condition considered most likely to predict soil moisture is the stream height. Within the riparian zone, we found saturation water levels within 0.5 ft (0.15 m) of the height of the stream (unpublished data). Stream height was measured during part of 1986 and 1987.

A gage site 2.4 kilometers south of Balch Camp on the North Fork Kings River measures streamflow. Mean minimum monthly summer flows averaged 50 cfs (1.4 cms) from 1975 to 1987. The average peak spring flow

¹ Presented at the California Riparian Systems Conference; September 22-24, 1988; Davis, California.

² Civil Engineer and Biologist, respectively, Pacific Gas and Electric Company, San Ramon, California.

for the same period exceeded 1000 cfs (28 cms). This is not a stream that goes dry, but often shows persistent low flows in late summer.

A succession of hydraulic controls along the stream reach create pockets of ponded water. The channel bottom or accumulated rocks create what is effectively a weir, which determines the stream height as a function of streamflow. We recorded changes in stream height for flows from 25 to 3000 cfs (.71 to 84.3 cms). Based on the observed data, we established a rating curve (figure 2). To complete the rating curve at flows below 25 cfs (.71 cms), it is hypothesized that openings in the rocks act as an equivalent V-notch weir.

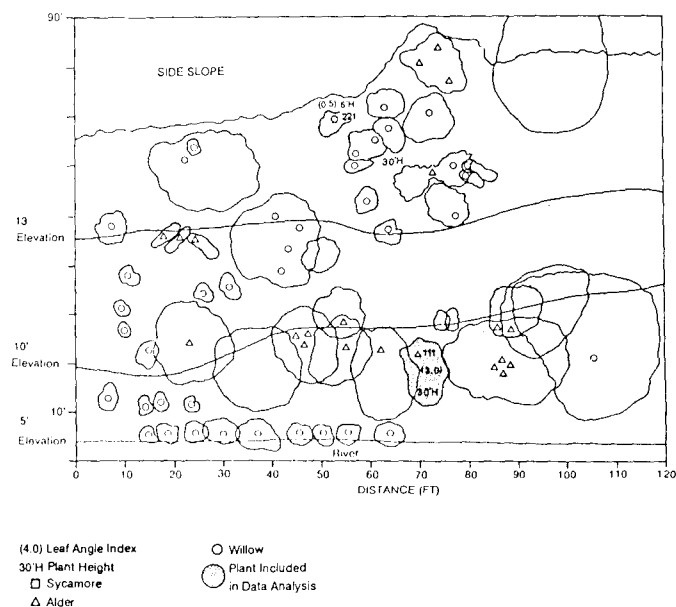


Figure 1- Site Map, One Mile Bar, Plan View.

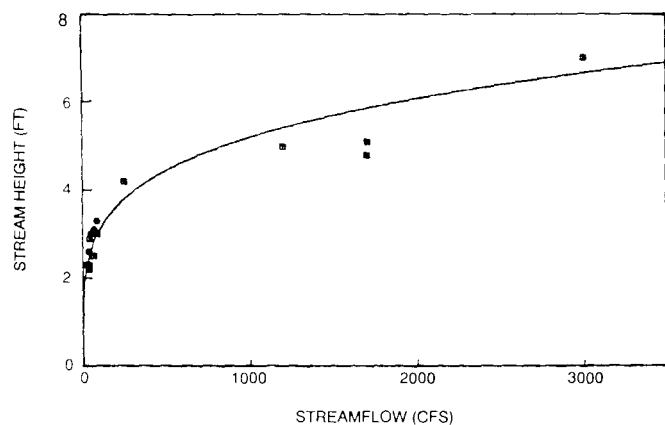


Figure 2- A Rating Curve.

Predawn Leaf Water Potential Versus Stream Height

As a plant transpires, it releases moisture and its leaf water potential (LWP) decreases. Leaf water potential reflects the water availability of a plant; the higher the value, the more water available. The leaf water potential recovered from midday values to reach maximum values by midnight. The predawn leaf water potential was found equal to values the previous midnight. The predawn leaf water potential was plotted in time and compared against stream height (an indicator of soil moisture) and the atmospheric demand for water (potential evapotranspiration, PET) during the leaf water potential recovery period; i.e., from 1300 to 2400 hours. We do not explicitly consider the effect of soil type on the capillary fringe, but we expect site-specific characteristics to be accounted for by the data comparison.

The predawn LWP was most negative when stream height was lowest and PET was highest. The recovery of the LWP appears to depend on the availability of soil moisture, and the demand of the atmosphere to continue to draw water from the plant following midday. This pattern is clearly indicated in late 1986 with Plant 221 at One Mile Bar (figure 3). In four successive test periods, the stream height remained low and constant; the predawn leaf water potential and the PET showed the same pattern of alternating high and low values.

The location of root mass in relation to soil moisture is important. The precise distribution of roots is not known, but we can compare the measured values of predawn LWP and stream height to develop what we will call a water availability factor. As the stream height remains relatively high, we expect that soil moisture will not be limiting (the water availability factor would equal one). At some point, as the water level decreases, the percent of root mass with access to extractable soil moisture reduces to a critical point. The amount of withdrawal is less, and the LWP remains more negative. The water availability factor was represented by a ratio of maximum rooting area (the elevation at which sufficient moisture is available and not limiting) to the amount of rooting area saturated by the present stream height conditions.

A preliminary analysis showed a less than linear decrease in LWP with rising PET. It also appeared that the predawn LWP was independent of PET for large values of PET (>3 mm). In physical terms, the atmospheric demand for water reaches a level where the moisture availability controls, and greater demand cannot be met. By using values of PET and the water availability factor, we obtain estimates of the predawn LWP versus streamflow (figure 4). Agreement is excellent.

Modeling Stomatal Conductance

We will use the estimate of predawn leaf water potential as one factor to predict stomatal conductance. Stomatal conductance represents the ease with which water is released from leaf stomates or openings. Measured stomatal conductance was compared to several variables: predawn leaf water potential, vapor pressure deficit, PAR, time of day and time of year. These variables were considered in the analysis because of their use in previous quantitative studies (Jarvis 1976; Simpson and others 1984). We included measured conductance values only for leaves with PAR values exceeding 300 watts per meter², to avoid stomate response to limiting light, although the leaf may have been shaded just prior to measurement. Predawn leaf water potential and time of day were the best predictors of stomatal conductance. A comparison of predicted versus measured stomatal conductance for a juvenile red willow is summarized in figure 5.

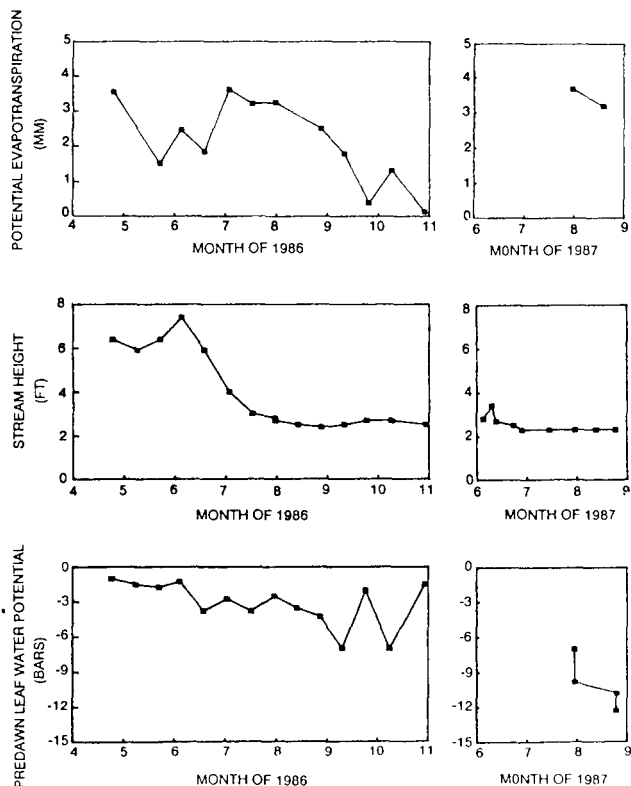


Figure 3— Variation in Predawn Leaf Water Potential, Stream Height and Potential Evaporation, Plant 221 at One Mile Bar.

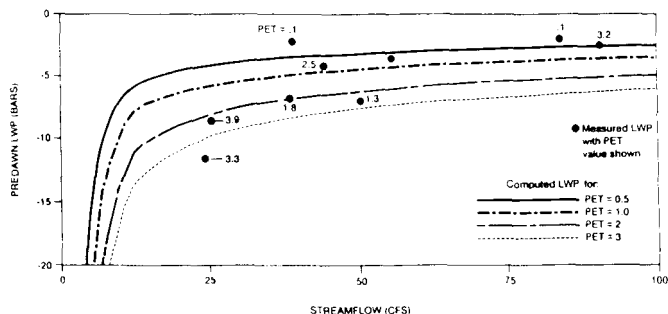


Figure 4— Measured versus computed predawn leaf water potential, plant 221 at One Mile Bar.

Of critical concern is the persistence of low flows (low water availability) accompanied by high PET. In late summer, a prolonged period exists where PET exceeds 3 mm. The model predicts that predawn leaf water potential will remain below -10 bars for plant 221 if streamflows remain less than 25 cfs (.71 cms).

The Energy Balance Model

We use the concept that there is a balance of energy within a control volume the size of a tree. The incoming energy minus outgoing energy (net incoming radiation) equals energy used (the latent heat transfer and sensible heat transfer).

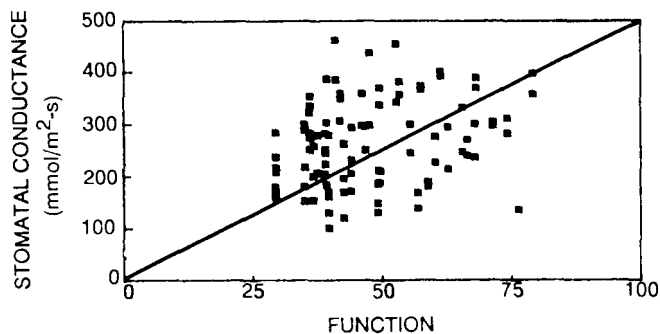


Figure 5— Relationship between measured stomatal conductance and the stomatal function, plant 221 at One Mile Bar.

Leaf surfaces may be exposed to direct and/or reflected short-wave radiation. The fraction of incident radiation available to the plant depends on the density and size of the surrounding canopy, the interference of leaves within the plant, the surrounding topography, and the sun altitude and azimuth. In a multiple layer tree, we assume the equivalent of one leaf layer to be directly exposed to incoming short wave radiation during sunlit hours. Other leaves may receive short wave radiation as a result of reflection from leaves or from the adjacent canopy or ground.

Long wave radiation exchange depends on emissivity, and surface temperature. We assume that long wave radiation losses occur in proportion to the leaf temperature and long wave radiation gains occur in proportion to the air temperature and adjacent leaf temperatures (Ross 1975).

The relative humidity within the stomatal cavity of the leaf is close to one (Tan and others 1978). Ambient air surrounding the leaf has less water vapor and the vapor density gradient between the air and the leaf is a driving force for plant water loss. Energy is needed to convert the liquid water leaving the plant to vapor. Latent heat transfer occurs in proportion to the vapor density deficit and inversely with the resistance to water vapor transfer. Two resistances in series comprise the transfer resistance: the internal resistance to transfer of water out of the leaf into the leaf boundary layer, and the aerodynamic resistance from the leaf boundary layer to outside the tree canopy, which accounts for the effects of wind speed (Campbell 1977). The cuticle or leaf surface resistance is very large, so internal transfer only occurs out of the stomatal cavity through the stomates (stomatal conductance).

Radiant energy impinging on a leaf surface will increase the leaf surface temperature. The sensible heat transfer is a function of the difference in leaf and air temperatures, the leaf area, and the leaf boundary layer resistance to sensible heat transfer.

We solve the energy balance model to determine plant transpiration and leaf temperature. The stomatal conductance relates back to streamflow.

Energy Balance Model Calibration

When the energy balance model is applied, with a shading factor of 0% (no shading), we overestimate the transpiration rate and leaf temperatures. The plants exist under varying degrees of shading. To calibrate the shading factor, we compare the measured leaf temperature excess and transpiration rates to computed values, as a function of stomatal conductance. Data and simulation results encompass sunlit hours from April to October.

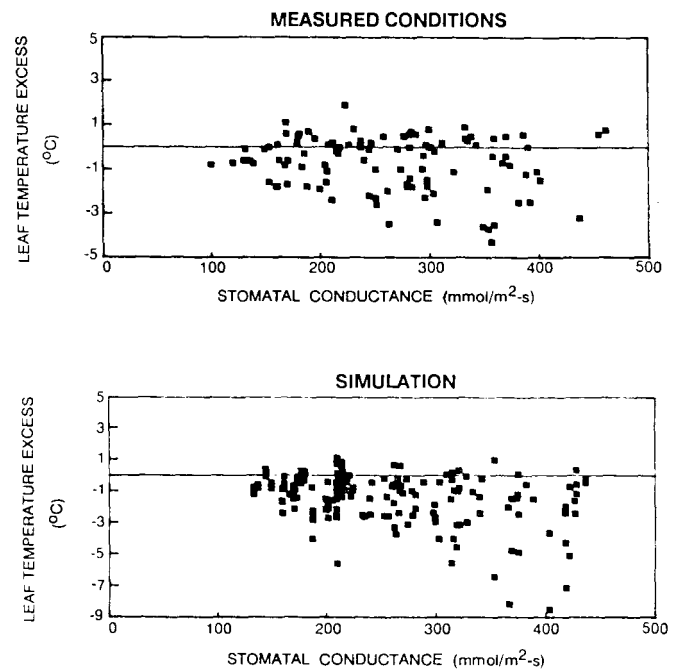


Figure 6— Measured versus predicted leaf temperature excess, plant 221 at One Mile Bar.

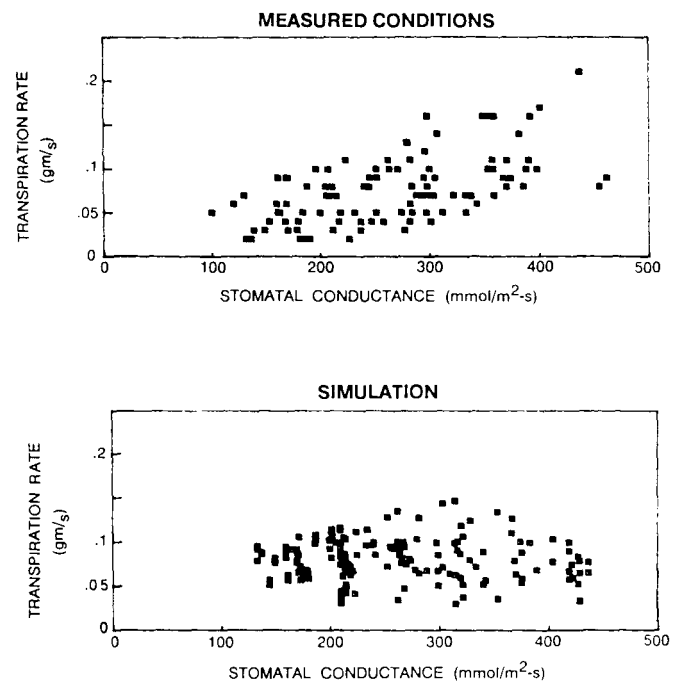


Figure 7— Measured versus predicted transpiration rate, plant 221 at One Mile Bar.

Transpiration rates and leaf temperatures were measured in the field on selected sunfleck leaves. Measured and computed leaf temperatures and transpiration rates are presented for plant 221 at One Mile Bar (figures 6 and 7). The energy balance model estimates of leaf temperature excess and transpiration rate are in excellent agreement with measured values, especially at low stomatal conductance, even though we assume a constant shading factor.

Model Predictions

The riparian vegetation response model has been developed to estimate physiological response in terms of predawn leaf water potential, leaf temperature excess on sunfleck leaves, and transpiration rates for each of four plants. Model simulations were made for various meteorological and time conditions, with streamflow variation from 5 to 100 cfs (1.4 to 2.8 cms). Figure 8 shows one set of results for Plant 221.

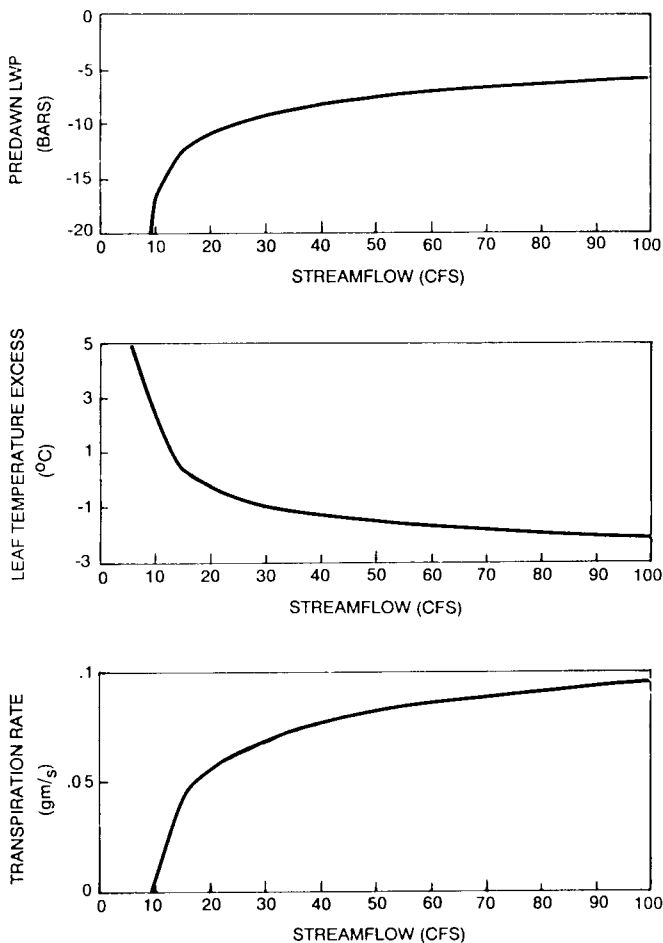


Figure 8— Predicted physiological response versus streamflow, plant 221 at One Mile Bar.

In general, the mature vegetation shows minimum stress except at very low flows. Cumulative indices of plant stress (based on reductions in transpiration from a potential rate) have been used in crop studies (Hiler and Clark 1971). The model allows us to consider streamflows leading to severe plant stress which we could identify by assuming a physiological threshold; e.g., the wilting point.

Conclusions

A mathematical model, based on field data from two sites on the North Fork Kings River, was developed to relate the physiological response of mature riparian vegetation to changes in stream height. The physiological response of white alder and red willow as a function of changes in stream height and meteorological conditions were simulated. Model simulation results were similar to measured values for predawn leaf water potential, leaf temperature, and transpiration rate. Our results indicate that there is little physiological plant "stress" relative to all but significant reductions in streamflow. This model may be used for these species at other locations to predict the physiological effect at reduced streamflow provided that site-specific data on stream height, predawn leaf water potential and meteorology are obtained.

References

- Campbell, G.S., 1977. *An Introduction to Environmental Biophysics*. Heidelberg Science Library. 159 p.
- Hiler, E.A; Clark, R.N., 1971. Stress Day Index to Characterize Effects of Water Stress on Crop Yields. *Transactions of the ASAE*: 757-761.
- Jarvis, P.G., 1976. The interpretation of the variations in leaf water potential and stomatal conductance found in canopies in the field, *Phil. Trans. R. Soc. London*. 273: 593-610.
- Leighton, J.P., Hsu, C.C., Risser, R.J., 1988. *Modeling of Mature Riparian Vegetation Ecophysiological Response to Instream Flows*. R&D Report No. 009.4-88.1. Pacific Gas and Electric Company, San Ramon, California. 80 p.
- Ross, J., 1975. *Radiative Transfer in Plant Communities*. In: *Vegetation and the Atmosphere*: 13-55. Academic Press.
- Simpson, J.R.; Fritschen, L.J.; Walker R.B., 1984. Estimating stomatal diffusion resistance for Douglas fir, lodgepole pine and white oak under light saturated conditions, *Agricultural and Forest Meteorology* 30: 299-313.
- Smith, S.D; Nachlinger, J.L., 1987. *Water Relations of Riparian Vegetation Along Bishop Creek and North Fork Kings River, Sierra Nevada, California*. Final Report Desert Research Institute, University of Nevada. Reno, Nevada. 69 p.
- Tan, C.S.; Black, T.A.; Nnyamah, J.U., 1974. A Simple Diffusion Model of Transpiration Applied to a Thinned Douglas Fir Stand. *Ecology* 59(6): 1221-1229.