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1.13 ESTIMATION OF EVAPORTRANSPIRATION OVER THE SAN PEDRO RIPARIAN AREA WITH REMOTE AND IN SITU MEASUREMENTS

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1. INTRODUCTION

Water in the southwest US has been and remains an issue of paramount importance. Its quality and usages have been the source of political and legal activity for over 100 years(Carey Act, 1894). With increases in regional population and on going use of irrigation, the issue of water continues to become more important. With ever increasing water demands and decreasing ground water tables, it becomes apparent that knowledge of water recharge, its spatial distribution, and its partitioning into ground infiltration, surface runoff, and evaporative losses to the atmosphere, is critical for properly addressing water issues in semi-arid regions. Apart from these societal issues, water in arid and semi-arid regions is also an important component in the hydrological cycle. Its spatial and temporal variations are key inputs to hydrological models and determine rainfall patterns. Therefore, its spatial and temporal distribution, especially the evaporative losses, not only provides an input to the water budget equation, but also improves our understanding of the hydrological process in the semi-arid environment.

Aimed at addressing these issues, the SALSA (Semi-Arid Land Surface-Atmosphere) Program was initiated at the USDA-Agricultural Research Service, Southwest Watershed Research Center, to provide an infrastructure for long term monitoring of some of the key variables in understanding the hydrological processes and its environmental impacts in the riparian area along the San Pedro River (Goodrich et al(a), this issue). The objective of this study, as part of the integrated SALSA program objectives, is to develop practical algorithms to estimate seasonal/annual/inter-annual, and decadal variations in the evaporative water losses, using remotely sensed imagery and *in situ* measurements. This paper presents some preliminary results of evaporative water losses over a spatially heterogeneous portion of the San Pedro River basin with a focus on a portion of the riparian corridor from Lewis Spring to Fairbanks (See Figure 1 in Goodrich et al., in this issue).

2. FIELD EXPERIMENT

A total of six intensive field campaigns was conducted at this site, four with aircraft remote sensing measurements in April, July, August, and October 1997, at the Lewis Spring site(see Figures 1 and 2 in Goodrich et al(a)., this issue). This site is composed of riparian cottonwood along the corridor, sacaton grasses on either side of the bank, and mesquites further away from the banks(Figure 1). During the intensive field campaign in August, remote sensing images from satellite and multi-altitude aircraft sensors were acquired at spatial resolutions ranging from 0.63m to 30m and with different spectral bands ranging from optical to thermal infrared to microwave. These images were georegistered and calibrated to obtain surface reflectances and temperatures(Moran et al.,this issue). In particular, low altitude aircraft images of surface temperatures acquired by Agrometrics® were used in this analysis, together with *in situ* ground measurements, to map the spatial variations of water losses through the evaportranspiration process and temporal changes through the season over the four campaigns.

Ground *in situ* measurements of surface temperatures, evaporative water losses, sensible heat fluxes, and the available incoming solar radiation, along with other meteorological variables, were made at this site (Figure 1) to document the variations of these physical parameters. The evaporative water losses were measured with the following devices:

1) Bowen ratio: This is a long-term effort to record evaportranspiration (ET) to document both diurnal and seasonal changes of water loss through evaportranspiration. Two towers were placed on the site, one being located within the mesquite and another within the sacaton sites (Scott et al., this issue). Due to spatial heterogeneity, some mesquites were found to exist at the sacaton site within the fetch of the Bowen ratio devices and vice verser for the mesquite site.

2) Scintillometer: This device was first placed over the sacaton grass-dominated site (see Figure 1) from August 7 to 10 and moved to approximately 1.5 km west of the site to measure the sensible heat flux across the mixture of sacaton grasses and mesquite shrubs (Chehbouni et al., this issue). This device measured the sensible heat fluxes, from which evaporative water fluxes can be computed, using the available energy measurements by the Bowen ratio towers.

3) 3-D Sonic: This 3-dimensional sonic device simultaneously measures both sensible and latent heat fluxes of a representative area (Schieldge et al., this issue). The device was deployed at the site to measure the fluxes of sacaton grasses.

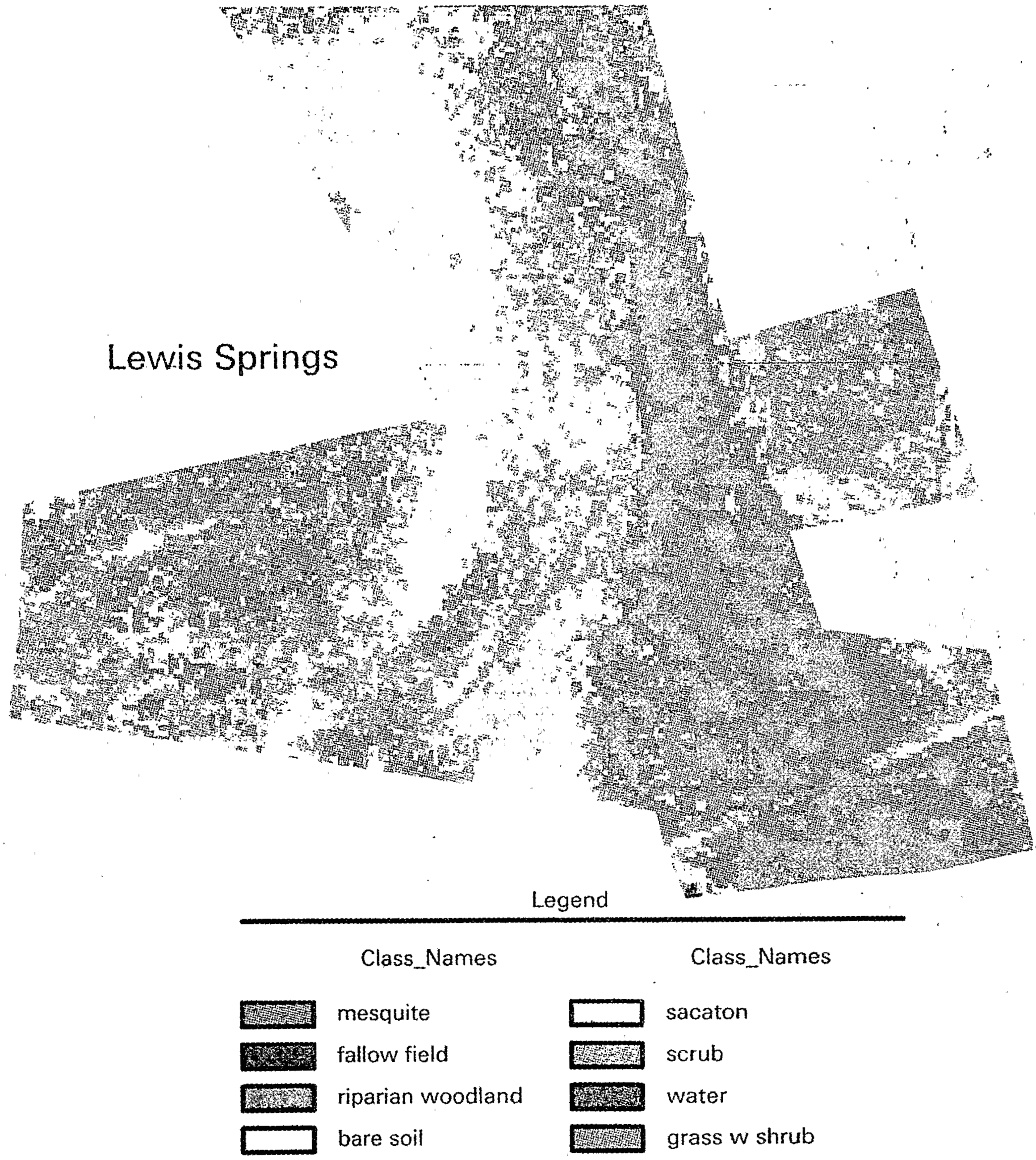

Figure 1. Vegetation classes and their spatial distribution at the Lewis Spring site, and locations of equipment used for evaportranspiration measurements.

4) Sapflow: The rate of water flowing across a sapwood section was measured(Schaeffer and Williams, this issue). The flow rate was later translated into evaportranspiration rates per canopy area, using information of sapwood area and sizes of the trees. This conversion was very empirical at the time of this study due to a lack of sophisticated measurements of the dimensions of the trees, distribution and densities of branches. In addition, a third tower was placed near one of the trees where sapflow was measured. On this tower were infrared thermometers to record both air temperature and the canopy surface temperature of the cottonwood trees.

All devices for ET measurements were cross-calibrated to ensure compatibility and were synchronized at a 30 minute time interval (except the Bowen ratio devices which were set at a 20 minute interval) so that comparison could be easily made.

3. METHODOLOGY

Water loss via evaportranspiration is primarily driven by the water vapor difference between the substomatal cavities in the leaf and the ambient air. As water evaporates, heat is extracted both from the canopy leaves and from the air that is near the canopy surface. This results in a lower canopy temperature than the ambient air temperature. It is therefore a reasonable assumption that the ET rate is a function of differential temperature dT=Ts - Ta, where Ts is the canopy surface temperature and Ta is air temperature. This can be theoretically derived from energy balance equation:

$$ET = Rn - G - H \quad (1)$$

where Rn is net radiation (w/m^2), G is soil heat flux, and H is sensible heat flux. Jackson et al(1977) suggested relating daily sensible heat to differential temperature dT:

$$ET = Rn - G - B\,(dT) \quad (2)$$

where B is a constant depending primarily on surface roughness and wind speed. This approach was used in various studies (Seguin and Itier, 1983; and Moran et al., 1994). The soil heat flux G was assumed to be zero when daily average was used. Using equation (2) with instantaneous remote sensing imagery requires further assumptions, because G can be relatively large and Rn may vary from location to location. As a first approximation, we rewrite equation (2) in the following format:

$$ET = A - B\,(dT) \quad (3)$$

where A = Rn - G, which is sometimes termed the "available energy". Parameters A and B can be determined empirically using ground data. Thus ET values can be estimated with the differential temperature dT which can be obtained from remote sensing images.

To investigate the feasibility of this approach, ET measurements with Bowen ratio devices over the sacaton and mesquite sites were averaged from 9:00am to 10:00am, corresponding to the time period of the Agrometrics overpasses. The differential temperature dT was also computed during this period to establish the ET - dT relationship. The sapflow rate of the cottonwood canopy was initially recorded in the unit of $cm^3H_2O/cm^2/hr$, where the cm^2 was the sapwood area. This unit was converted to ET per unit canopy area in order to use equation (3).

4. RESULTS AND DISCUSSION

The hourly averaged ET data were plotted against their corresponding differential temperatures, dT in Figure 2. A linear regression model was fit to the data, where A=184, B=36.8 and r^2=0.45. Note that the data were acquired from three types of vegetation: cottonwood, sacaton, and mesquite. Whether one can fit a single line through different vegetation types remains questionable. Since we did not have enough data points for each vegetation type, we assumed that parameters A and B were constant, or similar in magnitudes for the three vegetation types, thus allowing us to fit a single line for all data points.

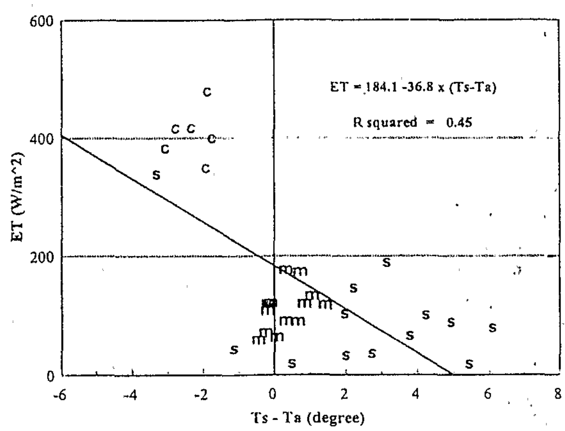

Figure 2. Scatter plot of ET (W/m^2) versus differential temperature dT for cottonwood (c), mesquite (m), and sacaton (s). The line is a linear fit based on ground data that was used in mapping spatial ET.

As can be seen, the regression line reaches zero at dT=5. This suggests that the differential temperature dT is not the only driving force for evaportranspiration. Other factors such as the water vapor and wind speed are also important environmental variables that affect evaportranspiration. For the sacaton grasses, the surface temperature was generally higher than the ambient air temperature, having lower ET values than mesquite and the cottonwood canopy. The cottonwood appeared much cooler than the ambient temperature. It should be pointed out here that the ambient temperature of the cottonwood was recorded at a short distance from the cottonwood tree. The water flux may well have affected the ambient temperature. The proper distance from the canopy surface for measurement of ambient temperature is still under investigation. In this study, the ambient temperatures at 2 meters above the sacaton and mesquite sites were used, whereas the ambient temperature at 2 feet adjacent to the cottonwood canopy was used for cottonwood site.

The ET values estimated with remotely sensed surface temperature were compared with *in situ* measurements using the Scintillometer, 3-D sonic and Bowen ratio techniques in Figures 3-5 for the three major vegetation types. For the sacaton site (Figure 3), the ET value estimated with remote sensing techniques was very close to the ET values measured with Bowen ratio device, but lower than those estimated with the other two devices. It should be pointed out here, the comparison between remote sensing and Bowen ratio estimated ET values does not serve as a validation, since the equation was derived based on the Bowen ratio data. Comparison of ET values with the other two devices indicated that the remote sensing technique underestimated the ET values of the sacaton canopy. It should be further noted that an average Ts value of all sacaton areas, including those that were covered by the other three devices, was used in the estimation of ET values with remote sensing techniques. Therefore, the remotely sensed ET values of sacaton represent a larger area than those covered by the other three devices. This may have resulted in some differences between remotely sensed ET and values from other devices.

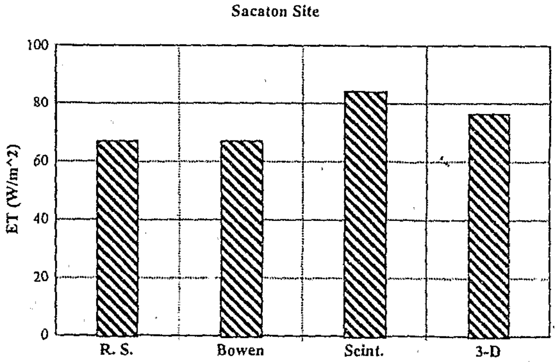

Figure 3. Comparison of ET values (W/m^2), at the sacaton site, estimated with remote sensing (R.S.) and Bowen ratio, Scintillometer, and 3-D sonic devices.

For the mesquite site, ET values estimated with all three techniques are presented in Figure 4. All techniques, including remote sensing techniques, resulted in a comparable estimate of ET. The remotely sensed ET value is lower than those ET values derived from Bowen ratio and Scintillometer devices. The differences among the ET values estimated with different techniques seemed to be within the measurement accuracy of the devices. It should be kept in mind that the remotely sensed ET values represent a much larger area than those covered by any of the devices used, because the entire mesquite area of the Lewis Spring site was used in the ET calculations.

Because other devices were not deployed to measure the ET values of the cottonwood canopy, the remote sensing ET estimates of the cottonwood were compared in Figure 5 for different trees with the values obtained with sapflow techniques. ET estimates from remotely sensed images generally agreed with the ET values from the sapflow measurements. For all trees where the sapflow measurements were made, surface

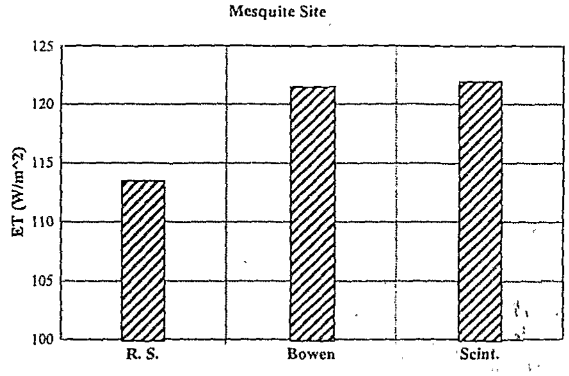

Figure 4. Comparison of ET values, at the mesquite site, estimated with remote sensing and other devices.

temperature Ts was obtained from remote sensing images. The ET values were estimated with these Ts and the ambient air temperature recorded at tree 203, assuming that the Ta was constant for all trees studied. It should also be noted that the tree sizes were empirical estimates based on the sapwood areas. Even if accurate measurements were made about these tree sizes, it is difficult to translate the sapflow rate to ET, because the effective canopy areas are almost impossible to be inferred from the physical sizes of the trees, and even more difficult from the sapwood area estimates. Scaling from individual tree estimates of ET to canopy level is another issue to be further studied. Nevertheless, an actual measurement of these tree sizes may improve the accuracy of the ET estimates. With these issues being considered, the ET values estimated from remotely sensed data are a reasonable approximation to the actual water loss from the cottonwood trees.

The spatial distribution of ET rates at the Lewis Spring site was mapped using the thermal images acquired with Agrometrics sensor (Figure 6) and equation (3). The cottonwood transpired water at a much higher rate than the sacaton grasses and mesquite shrubs. The lowest ET rate was found for the sacaton grasses. Field records indicate that most sacaton grasses were almost senesced during the August field campaign while the cottonwood and mesquites reached maximum greenness. Much of the senesced sacaton and litter covered new growth, preventing water evaporation and transpiration. It was also noted that the sacaton grasses were clumped and, therefore, there were exposed bare soil surfaces. This resulted in higher surface temperature, and the reduced ET rates.

The water loss rates at the Lewis Spring site can be estimated based on the ET map(Figure 6). The total water loss rate from the three major vegetation types (cottonwood, mesquite, and sacaton) was estimated to be 4125, 3465, and 1335 kilograms of water per hectare per hour (Table 1). Assuming that these numbers were typical values at 9:00am-10:00am period, and this rate lasts for 9.5 hours based on the

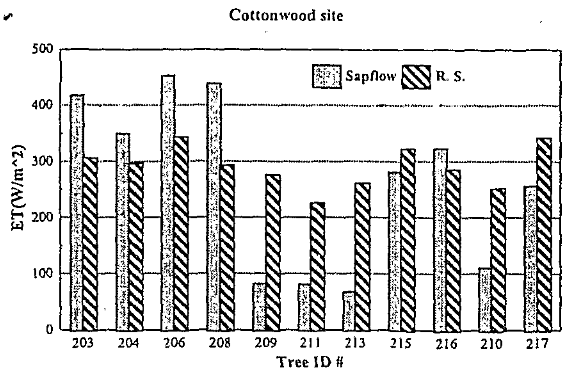

Figure 5. Comparison of ET values, at the cottonwood site, estimated with remote sensing and other devices.

sapflow data (Schaeffer and Williams, this issue), the total daily loss of water via evaportranspiration from these three classes were 39188, 32918, and 12683 kilograms of water per hectare. Using another remote sensing image (TIMS data acquired by JPL in May 1996) that covered the entire corridor, and assuming that these water loss rates are representatives of the whole corridor (range from Lewis Spring to Fairbanks; see Figure 1 in Goodrich et al., this issue), then the total estimates of water loss for the entire corridor were approximately 4336, 41637, and 2296 tons of water per day from cottonwood, mesquites, and sacaton grasses (these three classes account for up to 52% of all entire corridor). Water losses from other classes were expected to be much less than these three, because the remaining classes were primarily bare soils. The total of water loss from the corridor was summed to be about 48270 tons per day. These values are equivalent to 176 thousands gallons of water per day per hectare evaporated from these three major vegetation. The daily evaporative water loss for the entire riparian corridor was estimated to be about 1.0x 10^8 gallons.

Table 1. Water loss estimates on hourly and daily basis for the entire corridor (from Lewis Spring to 6 Km north of Fairbanks).

Veg. class	Hourly loss (Kg/Hect)	Daily loss (Kg/Hect)	Hourly loss of the corridor (Kg)	Daily loss of the corridor (Kg)
Cottonwood	4125	39188	456460	**4336371**
Mesquite	3465	32918	4382879	**41637346**
Sacaton	1335	12683	241712	**2296268**
Total	**8925**	**84788**	**5081051**	**48269985**

5. FUTURE WORK

It is expected that when multitemporal remote sensing images are processed, temporal interpolation and extrapolation with simple models (Goodrich et al(b), this issue) between and beyond remote sensing acquisition dates, can be accomplished to establish the seasonal variation of water loss at the corridor and total consumptive water use of the riparian vegetation in the near future.

6. ACKNOWLEDGMENT

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7. REFERENCES

Carey Act, 1894, Federal government ceded land to the state for irrigation.

Chehbouni, Hartogensis, Hipps, Brunel, Watts, Rodriguez, Boulet, Dedieu, Kerr, De Bruin, 1998, Sensible heat flux measurements using a large aperture scintillometer over heterogeneous surfaces.

Goodrich D. C., A. Chehbouni, B. Goff, et al., 1998(a), An overview of the 1997 activities of the semi-arid land-surface-atmosphere (Salsa) program.

Goodrich, G. D., M.S. Moran, R. Scott, J. Qi et al., 1998(b) Seasonal Estimates of Riparian Vegetation evaportranspiration (Consumptive Water Use) using Remote and In-Situ Measurements.

Jackson R. D. R. J. Reginato, S. B. idso, 1977, Wheat canopy temperature: A practical tool for evaluating water requirements, Water Resourc. Res., 13, 651-656.

Moran S. M., T. R. Clarke, W. P. Kustas, M. Weltz, and S. A. Amer, 1994, Water Resourc. Res. Vol. 30, no. 5, 287-1297.

Moran S. M., D. Williams, D. Goodrich, et al., 1998, Overvview of remote sensing of semi-arid ecosystem function in the upper San Pedro River Basin, Arizona. Schaeffer, S., and D. Williams, 1998, Transpiration of desert riparian forest canopies estimated from sap flux.

Schieldge, J., and A. Kahle, Use of remotely sensed and in situ data to investigate the effects of surface heterogeneity and terrain on the spatial and temporal distribution of sensible and latent heat fluxes in the semi-arid San Pedro basin.

Scott R. L., W. J. Shuttleworth, and D. C. Goodrich,1998, Water use of two dominant riparian vegetation communities in southeastern Arizona,

Seguin B., B. Itier, 1983, Using midday surface temperature to estimate daily evaporation from satellite thermal IR data, Int J., Remote Sens. 4, 371-383.

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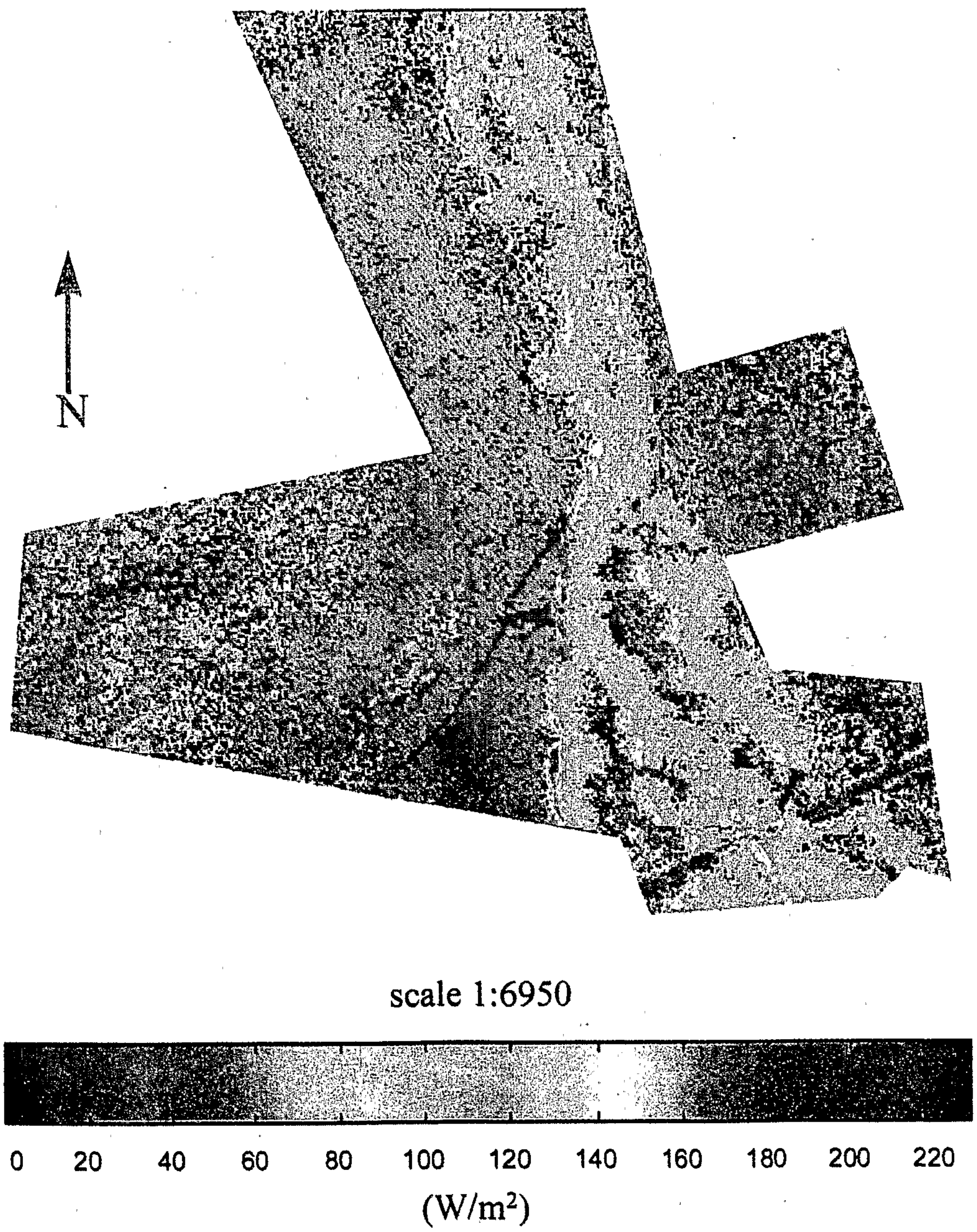

RIPARIAN ET FROM THE SALSA PROGRAM

AMERICAN METEOROLOGICAL SOCIETY