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SEASONAL ESTIMATES OF RIPARIAN EVAPOTRANSPIRATION (CONSUMPTIVE WATER USE) USING REMOTE AND *IN-SITU* MEASUREMENTS

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1. INTRODUCTION

In many semi-arid basins, groundwater resources constitute the primary water source that sustains human habitation, agriculture and riparian systems. To utilize regional groundwater models to aid in management of these water resources requires accurate estimates of the basin boundary conditions. A critical groundwater boundary condition that is closely coupled to atmospheric processes and is rarely known is seasonal riparian evapotranspiration (ET). This quantity can often be a significant factor in the basin water balance in semi-arid regions, yet is very difficult to estimate over a large area (Maddock et al., this issue). Better understanding and quantification of annual, large-area riparian ET is one of the primary 1997 objectives of the *SALSA* Program (see overview by Goodrich et al., this issue). A number of multidiscipilinary experimental field campaigns were conducted in the U.S. portion of the Upper San Pedro Basin (USPB) riparian system to address this objective during the 1997 growing season. Current riparian ET estimates are not a trivial quantity . The Arizona Department of Water Resources Hydrologic Survey Report (1991) estimated them as one of the largest components of the water budget in the USPB.

The vibrant San Pedro riparian system is primarily made up of three vegetation types: mesquite, grasses and a cottonwood/willow forest gallery. Portions of the river contain some of the healthiest desert riparian ecosystems remaining in the southwestern United States (Grantham, 1996; Stromberg, 1994). However, serious concern exists that nearby groundwater pumping may affect the quantity and timing of groundwater reaching the San Pedro River (Richter and Richter, 1992).

Improved estimates of riparian consumptive water use and its seasonal distribution are necessary to improve regional groundwater models so they can be used as near-term management tools instead of their current use for long-range planning. Inflow and outflow quantities in most groundwater models ignore seasonal variations in recharge quantities and discharge by evapotranspiration (Maddock et al., this issue). Further understanding of the partitioning of this water use among dominant vegetation types will also improve the accuracy of the groundwater model. More importantly, with a better understanding of the riparian consumptive use processes we hope to develop better methods of simulating ET based on potential functions that can be directly coupled to similar potential-based flux functions for aquifer and stream flow. This will solve the problems noted in Maddock et al. (this issue) of the non-coupled treatment of evapotranspiration processes related to precipitation and runoff versus those originating from groundwater.

The goal of the discussion herein is to present some preliminary data and possible simple approaches to temporally extend the “snapshot” riparian-corridor ET estimates based on remote sensing data to obtain seasonal and annual estimates of consumptive riparian water use. Qi et al. (this issue) present a methodology to spatially extend *in-situ* measurements of ET taken at the intensively monitored Lewis Springs site to the entire San Pedro National Riparian Conservation Area (SPNRCA) riparian corridor using aircraft-based remotely sensed data. The approach by Qi et al. (this issue) will be briefly reviewed as well as the relevant data.

2. METHODS

Standard micrometeorological flux measurement techniques were used to estimate ET from the mesquite and grasses over the Lewis Springs intensive measurement area within the San Pedro riparian corridor (Scott et al., this issue). These measurements have been taken continuously since early 1997 and it was assumed that they are representative of mesquite, grasses throughout the corridor. The techniques used to estimate ET over these vegetation types cannot be utilized to estimate ET from the cottonwood/willow forest-gallery

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due to the height (20-30 m) and non-uniform linear nature of the forest gallery along the stream corridor (Hipps et al., this issue). To estimate forest gallery transpiration, short-term (2-5 days) sap flux measurements were made on a small sample of trees at the Lewis Springs site (Schaeffer and Williams, this issue) over four periods in 1997 (April, July, August and October) of the riparian growing season. Using these methods on a sample of 13 trees, Schaeffer and Williams (this issue) estimated total daily water use values per tree ranging from 20 to 703 kg/day on Aug. 11, 1997. With this data collection methodology we were not able to measure evaporation from the free stream water surface or ET from the understory of the cottonwood/ willow forest gallery.

During each intensive measurement period, aircraft overflights over the entire riparian corridor were made with a thermal imaging system to obtain remotely sensed estimates of surface temperature. In addition, a high resolution (5 m) map of vegetation types for the entire corridor was created from several spectral bands acquired from an airborne Daedalus sensor in May 1996. The map was created from an unsupervised classification and was validated with extensive ground reconnaissance (Moran et al., this issue). Total areas of the respective vegetation types were derived from this map.

In a preliminary set of analyses, Qi et al. (this issue) developed a relationship between the difference of remotely sensed surface temperature and air temperature (T_s - T_a) and hourly averaged ET. This relationship was developed using the ground data at Lewis Springs and low-level thermal flights over that site. Using this relationship and assuming that the water loss rates at Lewis Springs are representative of the whole corridor, the vegetation map was used to scale-up these values to obtain a value of total daily water loss from the corridor. The value obtained for the region from Lewis Springs to 6 km north of Fairbank for the August overflight was 48,270,000 kg (48,270 m^3 or 39.1 ac-ft) of water per day (Qi et al., this issue). Using the very simple assumption that the ET estimates from the August campaign are representative of the entire growing season and an average growing season of roughly 180 days a very crude estimate of approximately 8,689,000 m^3 (7,040 ac-ft) for the annual riparian ET for this reach of the San Pedro was obtained. The riparian region for this estimate represent roughly 60% of the area for which remotely sensed data was acquired and approximately 50% of the SPNRCA.

This first step in the analysis assumes water availability and atmospheric conditions were uniform over the corridor. The next step in the analysis will relax this assumption and use the thermal aircraft data to map differential ET via differences in remotely sensed surface temperature. This is an essential next step as it was known that for the July and August overflights the San Pedro dried up in the vicinity of Boquillas and remained flowing from Lewis Spring to at least the Charleston USGS gage. A drop in the water table and drying of the stream will lead to additional tree stress and decreased tree transpiration as confirmed by sapflow measurements in the ephemeral Escapule wash area adjacent to the main riparian corridor.

The above analysis will treat spatial variations in ET for a given remote sensing snapshot. The next step in the analysis is to estimate the temporal variations in riparian ET throughout the growing season and from remote sensing snapshot to snapshot. As noted above, significant temporal variations in the hydrologic regimes were observed as virtually the entire corridor had surface stream flow during the April synoptic run but large portions of the river dried up by July. If personnel and budgetary constraints were not an issue, greater frequency of synoptic and remote sensing measurements would be the best way to estimate the noted spatial and temporal ET variations. Given the realities posed by these constraints, more economical continuous sets of measurements and simple models must be employed to estimate ET between and outside the intensive measurement periods.

Two candidate continuous observations to aid in the estimation of riparian ET are air temperature and stream discharge. Air temperature is attractive as it is relatively uniform over large areas. Stream discharge is a large-area integrative measure and is arguably one of the most accurate hydrologic measurements that can be made. In Figure 1 stream discharge from the USGS Charleston

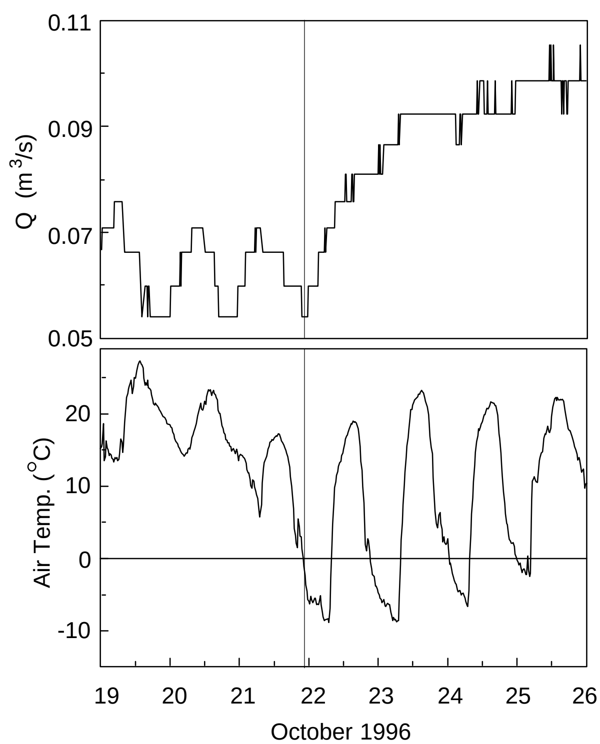

Figure 1. San Pedro River discharge at Charleston, AZ (top); Air temperature at Lewis Springs, AZ (bottom)

gage and air temperature at Lewis Springs are illustrated for portions of October 1996. A remarkable correlation between these two variables is apparent. Although ET is not directly measured in this case it would be logical to assume that the abstractions from runoff are directly attributable to riparian ET and the ET is directly proportional to air temperature. It is interesting to note that when the first hard freeze occurs on Oct. 21, 1996 the diurnal pattern in streamflow immediately breaks up and the discharge increases, indicating the frost had put a halt to riparian ET.

Assuming that baseflow in the stream results solely from groundwater inflow and that this inflow is steady, the abstractions from pre-greenup baseflow through the growing season can be used to estimate seasonal riparian ET. This concept is illustrated in Figure 2 which plots the 1997 San Pedro discharge measured at the Charleston Gage for the 1996 water year. The shaded portion of the figure is an estimate of the riparian ET that abstracts water from all baseflow stream inputs. For this example it was assumed that steady-state baseflow unaffected by riparian ET was equal to be the average winter discharge. During monsoon storm flows the

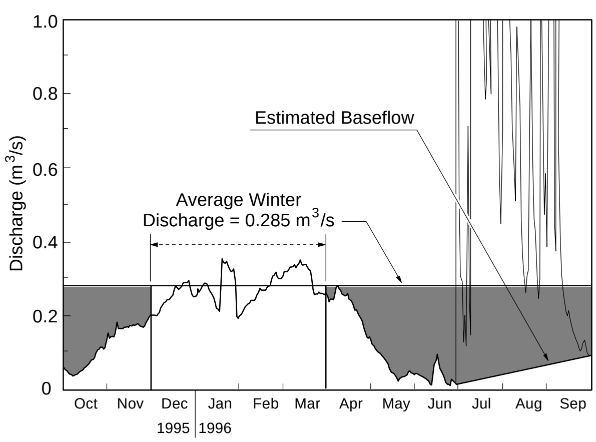

Figure 2. San Pedro River discharge at Charleston, AZ for the 1996 water year.

baseflow was linearly interpolated between June 28 and Oct. 1. Using these assumption the riparian ET is 9,928,800 m^3 (8,049 ac-ft). Although this method is straightforward it invokes several strong assumptions. First that groundwater inflow is steady throughout the river reach of interest. In the San Pedro this assumption is tenuous at best given the significant pumping taking place in the basin. Secondly it assumes baseflows can be easily separated from storm runoff. As noted by Maddock et al. (this issue), this is not a simple task. Finally, this method is only applicable in perennial stream reaches. If a reach becomes intermittent, as occurred on the San Pedro in 1997 downstream of the Charleston gage, this type of analysis cannot be carried out. This also points to another problem in this analysis. A related problem is that there is uncertainty in the length of river reach over which riparian ET losses are reflected in the downstream discharge measurements.

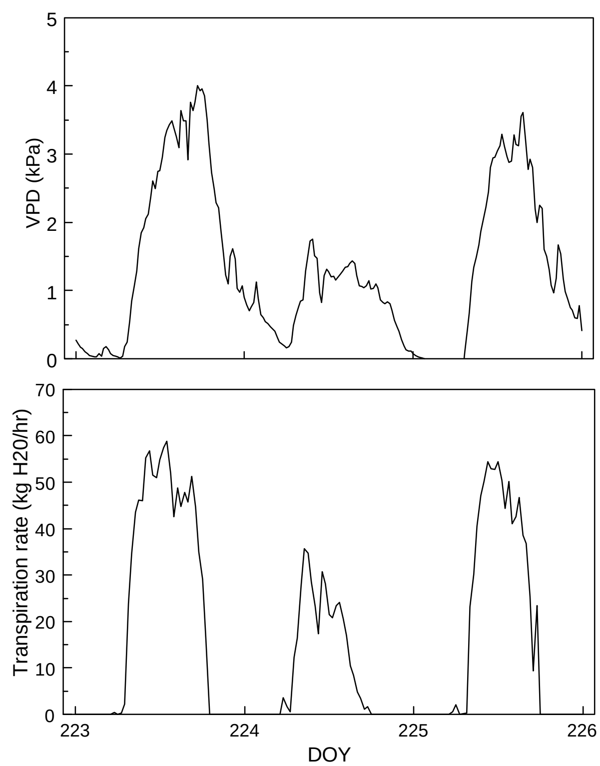

Figure 3. Vapor Pressure Deficit (VPD) and transpiration from a large cottonwood for julian days 223-225 (August 11-13).

Other atmospheric controls are also important for estimation of riparian ET. Air temperature, as noted above, is highly correlated to radiation or the available energy for driving ET. However, temperature-based ET-estimation methods are not recommended unless this is the only available data source (Shuttleworth, 1992). Shuttleworth (1992) also notes that preferred methods for estimating ET require a value of the difference between the saturated vapor pressure (e_s) and the ambient vapor pressure (e), or vapor pressure deficit (VPD = e_s - e). VPD and whole-tree transpiration (tree #203) are plotted for several days of the August campaign in Figure 3. A reasonable correlation exists between these quantities indicating a simple model that incorporates VPD could be utilized to estimate the temporal variations in ET between intensive measurement campaigns where remote sensing data was acquired. Variable cloudiness can complicate the sap flow versus VPD relationship. It can be improved if it is constrained to only well lit (high radiation: > 75 W/m^2) conditions.

Williams et al. (this issue) and Schaeffer and Williams (this issue) noted the strong influence of photosynthetically active radiation (PAR) on the diurnal variations in whole tree transpiration. Their plots of PAR versus whole tree transpiration for a portion of the same time shown in Figure 3 are even more clearly correlated than the VPD plot. Note that air temperature and VPD form the basis for the calculation of potential evapotranspiration which will also be considered in future analysis.

3. CONCLUSIONS - FUTURE DIRECTIONS

Additional variables will be examined to better estimate the temporal variation in riparian ET between intensive measurement periods as well as future work with models. Various space-time interpolation treatments for seasonal changes of the inferred differential riparian stress in space obtained from the multi-temporal remotely sensed data will also be examined. With this information it is expected that reasonable estimates of the seasonal variation in riparian ET as well as the total consumptive water use can be obtained in the near future.

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