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Estimating evapotranspiration under warmer climates: Insights from a semi-arid riparian system

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SUMMARY

This paper presents an approach to quantify evapotranspiration under changing climates, using field observations, theoretical evaporation models and meteorological predictions from global climate models. We analyzed evaporation and meteorological data from three riparian sites located in a semi-arid watershed in southern Arizona USA and found that the surface resistance to water vapor transport was closely related to the vapor pressure deficit. From this, we developed a relatively simple daily conductance model and included a growing season index to accurately replicate the onset and the end of the growing season. After the model was calibrated with observations from January 2003 to December 2007, it was used to predict daily evapotranspiration rates from 2000 to 2100 using Penman–Monteith equation and meteorological projections from the IPCC fourth assessment report climate model runs. Results indicate that atmospheric demand will be greater and lead to increased reference crop evaporation, but evapotranspiration rates at the studied field sites will remain largely unchanged due to stomatal regulation. However, the length of the growing season will increase leading to a greater annual riparian water use. These findings of increased riparian water use and atmospheric demand, likely affecting recharge processes, will lead to greater groundwater deficits and decreased streamflow and have important implications for water management in semi-arid regions.

1. Introduction

The quantification of climate change impacts on hydrology has focused on how changes in precipitation and temperature can affect runoff, evapotranspiration (ET) and recharge (Scibek and Allen, 2006; Seager et al., 2007; Serrat-Capdevila et al., 2007; Milly et al., 2008; Barnett et al., 2008). Nevertheless, in most hydrologic modeling studies attempting to quantify the impacts of climate change, the inclusion of actual ET changes has usually been the least developed aspect of the research. This is mostly due to the complexities of measuring ET, the subsequent lack of data and the number of variables needed to accurately estimate future evaporation rates. The current paper focuses on estimating climate induced changes in the ET of a semi-arid riparian system.

In semi-arid and arid regions evaporation is mostly limited by precipitation in the basin. However, in riparian systems where there is a linkage between the river and the aquifer, transpiration by riparian ecosystems tapping groundwater is an important component of the water balance in such basins (Goodrich et al., 2000; Scott et al., 2000). Despite this, little effort has been directed to predict changes in evapotranspiration (ET) of riparian ecosystems and vegetation cover. For instance, Serrat-Capdevila et al. (2007) present an approach to link an ensemble of global climate model outputs with a hydrological model. Their work focuses on changes in a semi-arid basin's water budget due to changes in recharge, but they assume yearly ET rates to be constant through the century. Picking on this improbable assumption, the present paper explores the effects of climate change on ET and attempts to fill this void.

Climate change impacts on evapotranspiration can be seen as twofold: (1) changes in ET due to changes in the length of the growing season, and (2) changes in ET rates during the growing season. Most of the modeling studies on climate change impacts in hydrology predict an increase in annual ET due to an earlier start of the growing season, mostly due to earlier snowmelt and a reduction in snow cover (Dankers and Christensen, 2005). Similarly, the end of the growing season, often marked by the first frosts in temperate regions, may be delayed in a warmer climate. Kaszkurewicz

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and Fogg (1967) analyze growing season data for cottonwood and sycamore species from trees widely distributed throughout their natural ranges. Looking at a variety of factors that could potentially influence the beginning and end of the growing season, they study the joint effects of photoperiod and temperature, which would have opposite controls on the growing season. At higher latitudes, the onset of the growing season happens when photoperiods are longer even if temperatures are lower, and vice versa at lower latitudes. Both photoperiod and temperature seem to control growing season onset through a key interplay, allowing for onsets at different temperatures due to different photoperiods. Starr et al. (2000) artificially recreate a longer growing season in a species of forb, using snow cover removal and soil warming. The forbs became active earlier but senesced earlier too. Leaf size and number, photosynthetic assimilation and nutrient concentration remained the same as in the control site. Thus, some plants may not be able to adapt physiologically to an extended growing season and would be at a disadvantage with respect to more adaptive plants or to southern species spreading north due to global warming. However, Churkina et al. (2005) perform a spatial analysis of the relationship between net ecosystem exchange (NEE) and the length of the carbon uptake period (i.e. number of days where the ecosystem is a net carbon sink) and observations seem to show a linear correlation between uptake period and growing season length. Their findings imply that a longer growing season leads to greater carbon uptake and likely, ET. Shi et al. (2008) find tree growth to be strongly affected by temperature at the beginning and end of the growing season, while soil moisture is the main control in between. A percentage of growth limitation for each day of the year is presented as a probability of being growth-limited due to temperature and soil moisture. Menzel and Fabian (1999) analyze more than 30 years of phenological observations in Europe. They report that spring events – such as leaf unfolding – have advanced by 6 days, while fall events – such as leaf coloring – have delayed by 4.8 days, with an average growing season 10.4 days longer than in the early 1960s, attributable to warmer air temperatures. According to their model, more than 70% of the yearly variability in bud-break can be explained by daily temperatures. Similarly, the model predicted an onset advance of up to 6 days per 1 °C increase in winter temperatures.

On the other hand it has proven perhaps even more complex to predict changes in actual evapotranspiration rates during the growing season itself. Jacobs and De Bruin (1997) use a coupled planetary boundary layer and vegetation model to study the effects of doubled CO_2 concentrations on surface resistance and regional transpiration. Their model results show that an increase in surface resistance would be magnified through a positive feedback with the resulting dryer canopy air. Kruijt et al. (2008) provide a good review of the effects of increased CO_2 concentrations on the productivity and functioning of plants. By using partial corrections on crop factors to account for the effects of CO_2 concentrations in stomata conductance and other properties, they estimate future effects on ET in the Netherlands using climate scenarios. Results seem to indicate that reductions of stomatal conductance due to high CO_2 concentrations and higher ET due to warmer temperatures may even each other out. Gedney et al. (2006) present evidence that increasing CO_2 concentrations have in average contributed, through reduced transpiration, to a net increase in runoff. Their findings suggest that reduced stomatal openings have a significant influence in the global water cycle. Using a multi-model approach, Milly et al. (2005) present patterns of trends in streamflow in different continental regions, some are increasing and some are decreasing, as is the case for the semi-arid southwest US. Thus, it is probable that the relevance of findings by Gedney et al. (2006) varies regionally. Wang et al. (2008) quantify changes in Light-Use Efficiency (LUE) and Evaporative Fraction (EF) due to variations in the ratio of diffuse to total incident solar radiation, which is controlled by cloud and aerosol cover. Because of higher leaf area incidence by diffuse radiation, their findings indicate that LUE can be from 20% to 200% higher with aerosols and increasing cloud cover compared to clear skies. This results in 9% or 15–23% increase in evaporative fraction, the ratio of evapotranspiration to total latent and sensible heat fluxes. Few publications if any have assessed the effects of warmer temperatures and associated meteorological variables on evapotranspiration rates. A physically based approach to estimate future actual evapotranspiration rates is the main contribution of this publication, using insights from field observations, existing evaporation models and climate model projections.

1.1. The San Pedro Basin riparian system

The semi-arid San Pedro Basin constitutes one of the last perennial desert rivers in the Southwestern United States. Between its headwaters near Cananea, in Sonora (Mexico) to its confluence with the Gila River 240 km further north in Arizona (US), it hosts the *San Pedro Riparian Natural Conservation Area (SPRNCA)*, a riparian ecosystem and migratory corridor with a high biodiversity. In this semi-arid basin, annual temperature maximums and minimums average 26 °C and 7 °C respectively, and rainfall averages around 350 mm with high spatial and temporal variability. Winter rains from frontal storms provide ~30% of the mean annual precipitation (November to March) and the monsoons – high intensity, short-duration convective storms – along with latter residual moisture from tropical storms, provide ~60% (July to September). From April through June, days are typically very dry and hot. Because of the rainfall regime and the long dry periods between rains, evapotranspiration in the basin is mostly limited by precipitation. In other words, most of the rain that falls in the basin either (1) immediately evaporates back to the atmosphere or runs off as flash floods as is the case for monsoon storms, or (2) is mostly trapped in the soil and evaporates in the following dry period as is the case with winter rains. Only a small part of rainfall in the basin contributes to basin-floor recharge through focused recharge of storm runoff in ephemeral channels, estimated at about 10% or 15% of total basin recharge (Goodrich et al., 2004; Coes and Pool, 2005). However, in basin and range landscapes such as in Southern Arizona, most aquifer recharge originates from rainfall–runoff in the mountains separating the basins, which infiltrates into the sedimentary basin along a fringe at the mountain front. This process is estimated to contribute about 80% of the basin's groundwater recharge (Anderson et al., 1992; Phillips et al., 2004; Wilson and Guan, 2004). The high seasonal and interannual variability of this mountain front recharge is smoothed out by the long travel times of groundwater from the mountain front to the river. Thus, the aquifer, recharged at the mountain front, is able to perennially drain through the river, sustaining a lush riparian ecosystem year-round. Because of this linkage between the aquifer and surface water, riparian vegetation can easily tap ground water along the river, and ET is not limited by precipitation. Riparian transpiration along the river can be an important component of the water balance in such basins (Scott et al., 2008).

Due to the high climatic variability in the region, the vegetation in the area is adapted to cope with strong seasonal changes in the partitioning of surface energy and water fluxes, controlled by water availability, temperature and vapor pressure deficit. While water is thought to be the main limiting factor to evapotranspiration, temperature plays an important role defining the length of the growing season. Measurements in a setting with such a high seasonal variability allowed analysis under a broad range of meteorological conditions and surface controls, as shown in Shuttleworth et al. (2009).