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Water use in a riparian cottonwood ecosystem: Eddy covariance measurements and scaling along a river corridor

Lawrence B. Flanagan[a,*], Trina E. Orchard[a], Gordon S.J. Logie[b], Craig A. Coburn[b], Stewart B. Rood[a]

[a] Department of Biological Sciences, University of Lethbridge, Water & Environmental Science Building 4401 University Drive, Lethbridge, Alberta, T1K 3M4, Canada

[b] Department of Geography, University of Lethbridge, Water & Environmental Science Building 4401 University Drive, Lethbridge, Alberta, T1K 3M4, Canada

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ABSTRACT

The survival of riparian forests depends on water input from their adjacent rivers. There are multiple, additional demands on river water that threatens to reduce the water supply, prompting the question, how much water must be left flowing within a river to sustain the native riparian ecosystems? To address this, we made eddy covariance measurements of riparian cottonwood forest evapotranspiration (ET) in a representative site and used remote sensing and the Penman-Monteith equation to up-scale ET along the 171 km river corridor from the Oldman River Dam to Lethbridge, Alberta. Our study was conducted in two growing seasons with contrasting weather conditions, including one with over-bank flooding (2014). Measured cumulative forest ET from May-September (2014: 451 ± 90 mm; 2015: 411 ± 18 mm) was very similar in the two years despite contrasting May-September cumulative precipitation input (2014: 362 mm; 2015: 181 mm). Integrated over the 56 km^2 area of riparian forest along the Oldman River corridor, the cumulative forest ET during May-September was 19.1 million m^3 (339 mm/season), about 0.9% of the average cumulative Oldman River discharge during 2008–2013. Cottonwood forest ET during May-June was less than 1% of average river flow rates during 2008–2013, but the ratio of ET to average river flow rate increased markedly to peak values of 4–5% in late July and early August. Our analysis indicated that the water-use rates of riparian cottonwood forests were high, even for a broad-leaf deciduous forest functional type, particularly given the modest leaf area index (1.4 m^2 m^{-2}) we measured for riparian forests along the Oldman River corridor. The high ET rates were possible because of tree access to alluvial groundwater to support transpiration. Our ET measurements and calculations provided perspective on riparian forest water use in relation to precipitation inputs and total river discharge, knowledge that is important for successfully managing the multiple demands on river water use.

1. Introduction

In most regions world-wide, rivers provide the primary surface water supplies for human uses including agricultural irrigation, and domestic, municipal and industrial consumption (Oki and Hanae, 2006; Vörösmarty et al., 2010). Rivers also support rich and bio-diverse aquatic (instream) and riparian (streamside) ecosystems that contribute many valued environmental services (Naiman et al., 2005). These riverine ecosystems are dependent upon sufficient instream flows and this prompts the fundamental questions, how much water must be left flowing within a river to sustain the native ecosystems and conversely, how much water can be withdrawn for human use (Richter and Richter, 2000; Stromberg, 2001)?

To answer these questions and optimize river resource management, it is essential to understand the water supplies and demands within a watershed. Mass balance river basin models are developed and these characterize the water supply as provided by the natural, seasonal river inflows, and then consider the multiple human withdrawals, along with considerations for

* Corresponding author at: Department of Biological Sciences, University of Lethbridge 4401 University Drive Lethbridge, T1K 3M4 Alberta, Canada.
E-mail address: larry.flanagan@uleth.ca (L.B. Flanagan).

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flow trapping and storage with dams and reservoirs (Sauchyn et al., 2016). A fundamental weakness in these models is the incomplete understanding of water use by the natural ecosystems along the river corridor. This information gap is especially problematic for semi-arid ecoregions, including the prairies, shrub-steppe and semi-desert zones, since in these areas, the rivers are 'losing streams' where water infiltrates from the river into the adjacent alluvial groundwater. The deep-rooted phreatophytic trees subsequently uptake and transpire substantial water volumes from this floodplain groundwater, but the magnitude and seasonality of floodplain forest water use and the proportional contributions from river water versus local precipitation are poorly understood (Scott et al., 2000, 2003, 2004; Wang and Dickinson, 2012).

Most of the rivers of the South Saskatchewan River Basin in southern Alberta are dammed and have regulated river flows (Schindler and Donahue, 2006; Rood et al., 2005, 2008). In the past, alterations of the river flow patterns associated with dams have caused considerable damage to riparian forests for two reasons (Rood et al., 1995, 2003a, 2005; Williams and Cooper, 2005). First, the dams reduce the magnitude of peak spring river flows and floods that create newly exposed sediments along the meandering river courses, which in turn, provide habitats for cottonwood seedling establishment without competition from other tall vegetation (Scott et al., 1997, 1999). Without the high spring flows, the cottonwood trees are unable to regenerate, because their seedlings cannot survive and develop in the shaded understory of mature forests or with other competing vegetation. Second, the dammed rivers normally only release very low water flows in the later portions of the summer (late June through September) after the natural peak in river flow that occurs in early June. The low stream flow in late summer occurs during the time of warmest air temperatures and high solar radiation input that can lead to drought stress and death of mature cottonwood trees in these riparian forest ecosystems (Rood et al., 2003a, 2005, 2008, 2013).

While it is clear that riparian forest ecosystems are reliant on the natural river flow regime they evolved with (Poff et al., 1997), it is impractical and even impossible to completely restore natural flow patterns on dammed and regulated rivers. As a practical alternative, however, it should be possible to develop procedures for a regulated river flow pattern (a functional flow pattern) that could still sustain healthy river ecosystems, but also allow for significant water withdrawal for important human uses (Rood et al., 2005). Recent examples of the implementation of the functional flows concept on the Bridge River (British Columbia, Canada) and Truckee River (Nevada, USA) have demonstrated that carefully managed river flows can restore severely degraded floodplain riparian forests (Rood et al., 2003b, 2005; Hall et al., 2009). Despite the significant success of these implementations of the functional flows concept, the new river flow patterns were applied without knowledge of the magnitude of the actual water requirements of the associated riparian forest ecosystems. This limits the water manager's ability to fine-tune the approach and to plan for altered river flow patterns and riparian forest water use in the future under climate change.

This study was undertaken to characterize the water use by a typical riparian forest in a northern prairie zone, and undertake spatial up-scaling to estimate the subsequent influence on river flows in a heavily allocated river system, the Oldman River. Our analyses involved eddy covariance flux measurements and upscaling based on remote sensing estimates of ecosystem leaf area index. The findings will contribute to the understanding of the eco-physiological function of riparian forests, and work towards resolving the largest current information gap for river basin water balance models (Nagler et al., 2005; Doody et al., 2015; Sauchyn et al., 2016).

2. Materials and methods

2.1. Study site description

Our main study site was in the Helen Schuler Nature Reserve (HSNR), a natural riparian cottonwood forest within the Oldman River valley at Lethbridge, Alberta, Canada (49.702°N, 112.863°W, elevation 928 m; Fig. 1). This riparian forest consists of the following tree species: prairie cottonwood (*Populus deltoides*), narrow-leaf cottonwood (*Populus angustifolia*), balsam poplar (*P. balsamifera*); or the closely related and almost indistinguishable black cottonwood, (*P. trichocarpa*); and their interspecific hybrids (Gom and Rood, 1999; Rood et al., 2014). Average (±SD, n = 60) tree height was 18 ± 5 m and tree diameter at breast height (1.35 m) was 37 ± 15 cm. The average (±SD; n = 33, 10 m × 10 m plots) tree density was 276 ± 300 trees per hectare. The understory of the forest consisted of grasses and other herbaceous plants plus a range of small shrubs, such as wolf willow (*Elaeagnus commutata*), silver buffaloberry (*Shepherdia argentea*), and wild rose (*Rosa acicularis*). The mean annual (1981–2010) temperature for Lethbridge was 5.9 °C and average annual precipitation was 380.2 mm (Canadian Climate Normals, Environment Canada; climate.weather.gc.ca/climate_normals/).

2.2. Leaf area index measurements at the HSNR

Leaf area index (LAI) was measured for the HSNR cottonwood canopy using the LAI-2000 (LI-COR Lincoln, NE, USA) and the Tracing Radiation and Architecture in Canopies (TRAC) (Leblanc et al., 2002) instruments. Two LAI-2000 instruments were employed to measure the LAI of the canopy. One LAI-2000 was placed on a tripod in a large open area of the cottonwood forest. It was used to collect measurements of incoming radiation with no interference from the cottonwood tree canopy. This was set to automatically measure unobstructed diffuse radiation at 30 s intervals. The second LAI-2000 was carried through the woodland along pre-determined transects to measure incoming radiation below the tree canopy. The 90° view caps were affixed to each instrument. At the start of each set of transect measurements, several measurements were taken simultaneously with the two LAI-2000 instruments side by side. These measurements were used to check the inter-calibration of the instruments while post-processing the data. The LAI-2000 measurements were conducted in the evening near sunset under diffuse illumination conditions.

The Tracing Radiation and Architecture in Canopies (TRAC) instrument was used to measure the canopy clumping index throughout the cottonwood forest along pre-determined transects. TRAC measurements were conducted in the mid-afternoon under clear, sunny skies by walking the instrument along each transect at a continuous, slow pace. The transect orientation and timing of the measurements were planned to result in a solar zenith angle between 30° and 60°, and with the Sun approximately perpendicular to the instrument path, following recommended practices (Leblanc and Chen, 2001; Leblanc et al., 2002). The clumping index was used to correct the results obtained from the LAI-2000, which does not account for within branch clumping (Leblanc and Chen, 2001; Chen et al., 2006). Tree LAI measurements were made every two weeks throughout the 2014 growing season (May-October).

Eq. (1) was used to calculate tree LAI from measurements of the LAI-2000, (Chen et al., 2006):

$$LAI = \frac{(1-\alpha_w)\cdot L_e \cdot \gamma_E}{\Omega_E} \tag{1}$$