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# Stemflow and soil water recharge during rainfall in a red pine chronosequence on the Oak Ridges Moraine, southern Ontario, Canada

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SUMMARY

Stemflow focusses water delivery to the forest floor in a relatively small area surrounding the tree bole, with the potential to enhance soil water contents and water recharge relative to more distal sites beneath the canopy. These stemflow fluxes may decrease as a given tree species ages due to changes in branch orientation and bark roughness, suggesting that the relative contribution of stemflow to water recharge near the bole will decline with time. The hypothesis that stemflow fluxes decline with tree age was tested in a chronosequence of red pine (*Pinus resinosa* Ait.) stands in a managed forest in southern Ontario, Canada, and stemflow contributions to soil water recharge below 1 m depth were quantified. Throughfall, stemflow and sub-canopy soil water contents (0.1 m and 1.5 m from the tree bole to 1 m depth) in stands ranging from 28 to 80 years in age were studied from late-Spring to Fall in 2012, supplemented by artificial irrigations of stemflow to examine short-term soil wetting at the two distances from the bole. The hypothesized decline in stemflow with increasing tree age was not supported, and canopy cover variations and forest management exerted a greater control on inter-stand differences in stemflow fluxes. Stemflow contributions generally resulted in greater soil water recharge below 1 m depth at 0.1 m from the tree bole compared to the 1.5 m distance. This enhanced recharge was greatest for the youngest stand and differences in recharge between the 0.1 m and 1.5 m distances from the bole were likely not significant for stands between 40 and 80 years of age. Nevertheless, the relative contribution of stemflow to soil water recharge may increase in this managed forest as red pine stands give way to a mixed hardwood-conifer forest, due to greater stemflow fluxes from hardwood species in this landscape.



## 1. Introduction

Forests partition above-canopy precipitation ($P_g$) between throughfall (*TF*), stemflow (*SF*) and canopy interception ($I_c$), the latter returned to the atmosphere via evaporation. Of these, *SF* is considered to be the smallest fraction of $P_g$ (Helvey and Patric, 1965; Levia and Frost, 2003), although its ability to concentrate water delivery to and beneath the soil surface at the tree bole has been widely recognized (Voigt, 1960; Ford and Deans, 1978; Durocher, 1990; Chang and Matzner, 2000). This focussing of incident rainfall by *SF* to soil around the bole and its subsequent transport belowground along tree roots and other preferential flow paths has been characterized as a double-funneling process (Johnson and Lehmann, 2006; Schwärzel et al., 2012).

Despite the potential of *SF* to make a disproportionate contribution to soil water and groundwater recharge (Johnson and Lehmann, 2006; Nàvar, 2011), its role in soil water dynamics in forest landscapes has often been ignored due to its generally small fraction of $P_g$ (Liang et al., 2009; Tanaka, 2011). Nevertheless, the influence of *SF* on soil water and groundwater recharge has received some attention. Empirical studies include Taniguchi et al.'s (1996) mass balance estimate that *SF* contributes up to 20% of total groundwater recharge in Japanese red pine, fluorescent dye tracing of *SF* channelization along root systems (Martinez-Meza and Whitford, 1996; Schwärzel et al., 2012), Liang et al.'s (2011) study of *SF*, soil water content and pore water dynamics around a tree on a steep slope, and Germer's (2013) investigation of perched water table development in response to *SF* from babassu palms. Modelling (e.g. Tanaka et al., 1996; Chang and Matzner, 2000; Liang et al., 2009) has also shown that *SF* can enhance soil and groundwater recharge significantly within a relatively small area surrounding the tree bole compared to more distal regions beneath the canopy.

Stemflow volumes vary as a function of tree species, largely due to differences in bark roughness and branching geometry (Levia

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**Nomenclature**

| | | | |
|---|---|---|---|
| *AET* | actual evapotranspiration (mm, mm $d^{-1}$) | *PET* | potential evapotranspiration (mm, mm $d^{-1}$) |
| *c* | canopy cover | $P_g$ | above-canopy precipitation (mm) |
| CV | coefficient of variation | $P_{net}$ | net precipitation (mm) |
| DBH | diameter at breast height (m) | RP | red pine |
| *E* | soil evaporation plus transpiration (mm) | SD | standard deviation |
| $F_g$ | gap fraction | SE | standard error |
| GF | Ganaraska Forest | *SF* | stemflow (L, mm) |
| $I_c$ | canopy interception (mm) | *SWR* | soil water recharge below 1 m depth (mm) |
| *LAI* | leaf area index ($m^2$ $m^{-2}$) | *SWC* | soil water content ($m^3$ $m^{-3}$) |
| *OM* | organic matter (%) | *TF* | throughfall (mm) |
| ORM | Oak Ridges Moraine | | |

et al., 2010). Lower branch angles increase the amount of water flow along the branch lost to *TF*, thus reducing contributions to *SF* (Herwitz, 1987). The relative importance of *SF* in partitioning net water delivery to the soil surface in forests may also change with stand age for a given species. Individual tree branch angles decrease as branches age, while branches slope away from the trunk for much of their length as a forest ages (Ford and Deans, 1978). Stemflow is greater in younger relative to older hardwood stands in the eastern US due to greater stem density, smoother bark and the tendency of branches to grow up rather than out in younger stands (Helvey and Patric, 1965). Increasing bark roughness for older trees of the same species leads to greater water storage capacity and decreased *SF* (Levia and Frost, 2003). Stemflow as a% of net precipitation (*TF* + *SF*) appeared to increase from age 0 to 14 years and then declined as trees continued to age in upland catchments in the UK (Johnson, 1990). Stemflow contributions to net precipitation reaching the forest floor in red pine (RP, *Pinus resinosa* Ait.) stands in the Ganaraska Forest on the Oak Ridges Moraine (ORM) in southern Ontario were hypothesized to decrease as stands age (Buttle and Farnsworth, 2012), due to increasing branch length and consequent change in branch orientation relative to the bole from near horizontal to sub-horizontal (Levia and Frost, 2003) combined with greater water sorption by RP's irregular and furrowed bark (Voigt and Zwolinski, 1964; Iida et al., 2005). Mature RP branches are fewer in number, much thicker, longer and flatter than for young RP and often curve downward towards the outer end (Voigt, 1960), reducing channelling of *SF* to the bole. This suggests that *SF* fluxes may decline, and by implication the influence of *SF* on soil water and groundwater recharge may lessen, as trees age. However, there is currently no evidence to support this assumption.

The objectives of this paper were to: (1) characterise *SF* fluxes at the scale of an individual tree during rainfall in a chronosequence of RP stands in the Ganaraska Forest; (2) test the hypothesis that *SF* decreases with tree age in this managed forest; (3) estimate the area surrounding the tree bole that infiltrates this *SF*; and (4) quantify the role of *SF* in soil water recharge across this chronosequence.

## 2. Study area

The study was conducted in the western portion of the Ganaraska Forest (GF, 44°5′N, 78°30′W) on the crest and flanks of the Oak Ridges Moraine (ORM, Fig. 1). The ORM is an interlobate kame moraine consisting of sand and gravel hills and high ridges comprised of interlayered gravels, sands, silts, clays and minor diamictons up to 150 m thick (Barnett et al., 1998). The upper several m of surficial deposits in the GF along the crest of the ORM are dominated by sand with low silt and clay content, and water well records indicate the water table is at least 30 m below the ground surface (Funk, 1977). Maximum elevation in the GF is 384 m asl, 309 m above Lake Ontario to the south. The region has a humid mid-latitude climate (Köppen DfB) and mean annual precipitation ranges from ~950 mm on the western edge of the GF to ~825 mm on its eastern edge (Ganaraska Region Conservation Authority, 2008) with no marked seasonality in precipitation (Buttle, 2011). About 20% of mean annual precipitation falls as snow. Mean daily air temperatures in January and July are −7.2 °C and 20.5 °C, respectively, while annual average regional evapotranspiration is ~530 mm (Buttle and Farnsworth, 2012). Soils are brunisolic gray brown luvisols (Soil Classification Working Group, 1998; FAO equivalent: arenosol) belonging to either the Pontypool sand or gravelly sand series. Typical profiles have a 0–5 cm LFH layer, a dark greyish-brown loamy sand Ah horizon (0–5 cm), a light gray sandy Ae horizon (5–10 cm), a reddish brown sand Bfh horizon (10–28 cm), a light reddish brown sandy Bm horizon (28–58 cm), a dark brown sandy loam Btj horizon (58–64 cm), and an underlying gray medium sand Ck horizon (Hoffman and Acton, 1974). Soils have occasional layers of coarse and fine sand or gravel, and single-grain structure with the exception of the Ah (weak, fine granular) and Btj (medium subangular blocky) horizons. Both the Bm and Btj horizons have lower boundaries with deep tongues that extend into the underlying horizon. Soils in the GF have large saturated hydraulic conductivities, with mean values to 1 m depth >266 mm $h^{-1}$ (Greenwood and Buttle, 2014).

The ORM was deforested in the 19th century through logging and agricultural development. Large-scale reforestation of marginal and sub-marginal land in the GF began after 1945, ending in 1985 (described in more detail in Buttle, 2011). Red pine and white pine (*Pinus strobus* L.) were generally planted in combination at densities of ~2100 trees $ha^{-1}$, with RP being the main species planted. A ridge-and-furrow system was not used during planting. Plantations serve as overstory for regenerating mixed hardwoods and conifers, and are selectively thinned and harvested to promote conversion to a mixed hardwood-conifer forest. Red pine plantations are thinned every 10–12 years with a basal area at the time of thinning of ~28–32 $m^2$ $ha^{-1}$. Thinning reduces the basal area to ~20–22 $m^2$ $ha^{-1}$ (R. Penwell, Ganaraska Region Conservation Authority, oral communication, 2010). Trees are also pruned (live and dead branches removed from standing trees) to within ~0.1–0.2 m of the bole up to 7.4 m from the ground to produce knot-free sawlogs.

## 3. Methods

### 3.1. Stand characterization

Six stands consisting of at least 50% RP at time of planting were selected to span the range in RP plantation ages in the GF, varying in age from 28 to 80 years (Fig. 1, Table 1). The maximum distance between stands was <6 km. Species, diameter at breast height