Does transpiration from invasive stream side willows dominate low flow conditions? An investigation using hydrometric and isotopic methods in a headwater catchment

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Abstract

Understanding seasonal partitioning of water in riparian areas is important for assessing how vegetation affects water resources. A combined hydrological-isotopic field study was conducted within a headwater catchment to explore the dynamics of stream discharge and the effect of riparian evapotranspiration (ET) on summer low flow conditions. In addition to collection of meteorological data and depth to unconfined groundwater, stream flows were measured at three locations along the length of the river. Isotope ratios of local precipitation, stream water, groundwater, and willow xylem water were used to estimate pathways and sources of water used by vegetation. Using meteorological variables, leaf area index and stand area measurements, willow transpiration (T) was estimated using the Penman-Monteith method. Combining the data from hydrometric, isotope, and vegetation ET analysis revealed that water abstraction by stream-side willows peaked to 5.6 mm/day and had a distinct impact on summer low-flow conditions and patterns of stream discharge at the daily time scale. Average annual willow transpiration was 270 mm, while average annual precipitation during the study period was 1067 mm. However, willow transpiration reduced stream
flow and altered water budgets most strongly during critical summer low flow periods. Our analysis of transit times, young water fraction, and depth to groundwater water data showed Waipara headwater areas have limited water storage capacity, making them vulnerable to annual variations in precipitation and any other changes in water usage. Removal of streamside willows could potentially influence water balance during summer months when flows tend to be the lowest.

**Keywords:** transpiration, stable isotopes, low flow, willow water use, headwater/first order catchment

1 Introduction

Quantifying water transfer, surface and subsurface, across landscapes is a fundamental issue in water resources management (Ward and Pulido-Velazquez, 2012). At the catchment scale, it is hydrologically important to delineate different water sources, pathways of transfer from rainfall to stream flow, and lag times when seeking to determine local storage and availability of water. Prolonged drought periods are often a driving force for development of sustainable water management regimes for different purposes (Aghakouchak *et al.*, 2014). In water limited regions, the security of water supply for municipal, agriculture, and freshwater aquatic ecosystem needs is highly important (Jackson *et al.*, 2001; Lake, 2011; Perez-Blanco and Comez, 2014). The effect of vegetation on catchment water budgets, through transpiration and interception, is widely acknowledged (Jasechko *et al.*, 2013), especially in riparian areas where plant transpiration can even play a dominant role during low-flow conditions (Cleverly *et al.*, 2006; Moore and Owens, 2012). Globally, transpiration accounts for more than 80% of total evapotranspiration and the amount ranges from 100 to 1300 mm y⁻¹ (Jasechko *et al.*, 2013). Recent studies provide strong evidence of large-scale eco-hydrological separation between water in the soil matrix that roots take up for transpiration and water draining through the soil to groundwater and
3 streams (Evaristo et al., 2015; Good et al., 2015). Thus it is highly important to study not only flow
paths, but also the effects of vegetation on local hydrology from stream corridor to regional scales
(Jasechko et al., 2013). Currently, there is no clear understanding of how transpiration by stream-
side trees affects stream flow and interception of subsurface flows to streams. Stream-side trees can
consume water from different sources, including soil water, stream water and groundwater (Dahm
et al., 2002; Schilling 2007; Doody et al. 2009; Folch and Ferrer 2015; Doody et al., 2015, Scott-
Shaw et al. 2017), and can thus play a significant role in catchment water budgets (Cadol et al.,
2012).

Infestation of headwater catchments by invasive vegetation is a major environmental problem
world-wide (Doody and Benyon, 2011). In New Zealand and Australia, invasive woody plant
species such as crack willow (Salix fragilis), are particularly problematic (Doody and Benyon,
2011; Doody et al., 2014). Most willow species consume large quantities of water through
transpiration (Cermák et al., 1984; Hall et al., 1998; Schaeffer et al., 2000), thus potentially
reducing stream flows. Estimated maximum daily evapotranspiration (ET) rates for willow ranges
from 5 to 12 mm (Persson and Lindroth, 1994; Hall et al., 1998; Doody et al., 2006; Amaravathi,
2010). Such high transpiration rates can cause significant losses to the local water budget (Doody
and Benyon, 2011), resulting in reduced water availability for in-stream and off-stream uses. An
Australian study estimated that ET from stream-side willows could be as much as 5.5 million L ha\(^{-1}\)
y\(^{-1}\) (Doody and Benyon, 2011). However, more information is needed on the actual effects of
streamside willow trees on stream flows, particularly for New Zealand, where fewer such estimates
are available. This information is critical for local government, which in New Zealand sets
minimum limits on flows to support in-stream ecological function, and determines limits for water
abstraction. Willows often invade previously unvegetated streams and their removal could
potentially reduce ET, increasing stream flow, especially during low flow periods.
In this study, we utilized stable isotopic, hydrometric and meteorological approaches to characterize processes and sources of streamflow generation in a water limited headwater catchment of New Zealand, specifically addressing the following two questions: i) what are the water sources for streamflow generation? and ii) do invasive stream-side willows influence seasonal low-flow conditions in the stream by utilising water sources otherwise contributing to streamflow? The aims were to assess the impact of transpiration by invasive willows on stream flow and to discuss relevance to water resources management.

2 Methods

2.1 Study area

The foothill, headwater catchments of the Canterbury region of South Island, NZ, are referred to as “water towers” (McMillan and Srinivasan, 2015), as they sustain in-stream and off-stream uses such as irrigation (Srinivasan and Duncan, 2011) within the lowland catchments, as well as recharge groundwater systems spread across the lowland plains (Larned et al. 2011). Regional groundwater (GW) resources across the Canterbury plains are dependent on recharge in foothill areas (Environment Canterbury, 2012), which are typically located in transition zones between plains and mountains. Thus any changes to water abstraction or land use and land cover within the foothill catchment will lead to changes in water availability to downstream plains. During recent years, the Canterbury region has suffered from significant droughts, leading to water shortages in agricultural areas, drops in flows in major rivers and declines in regional GW levels.

The present study area is located in the headwaters of the North Waipara River in Canterbury (Figure 1). The riparian zone in the Waipara catchment is steep, typically resulting in a chain of small flushes from surface soils or small aquifers to the bottom of the Waipara valley. The study area consists of three nested catchments: Langs Gully (0.687 km², previously described in McMillan and Srinivasan, 2015), Melrose (7.89 km²) and Pawseys (33.86 km²) (Figure 1). The
The geology consists of greywacke, a hard sandstone with poorly sorted angular grains set in a rather compact matrix. The soil contains fractions of stones and sand that are typical of shallow gravelly silt loams within the Canterbury foothills landscape. Soil depth and clay fraction typically increase from hillslope to foot hill (McMillan and Srinivasan, 2015). Based on the virtual climate network data from 1972 to 2014 (Cliflo, 2016), the annual precipitation was found to vary from 500 to 1100 mm yr\(^{-1}\) (mean 943 mm) and annual potential evapotranspiration (PET based on the Penman method) from 432 to 958 mm. Summers are relatively warm and dry with the majority of the precipitation occurring in fall and winter with frequent frost and occasional snowfall. The land cover is primarily pasture for low intensity sheep and beef cattle grazing, with a partial cover of sparse matagouri (*Discaria toumatou*) shrubs. Some areas with the greater catchment are used for forestry (*Pinus radiata, Eucalyptus delegatensis* and *Pseudotsuga menziesii*), and stream sides within lower reaches are dominated by invasive willow trees (*Salix fragilis*) (Figure 1).

**Figure 1.** Maps showing the location of the study catchments and river stage measurement and isotope sampling points. Light green represents areas with stream-side willows.
Figure 2. Typical stream-side willow stand at the stream section from Melrose to Pawseys.

2.2 Experimental set-up and data collection

We designed our experiment to measure temporal and spatial variability of stream water sources, pathways, and sinks within the catchment, with particular focus on water use by invasive willow trees. The study area provided a natural testing site for this purpose, as stream-side willows dominate the lower reaches of the North Waipara River (between the Melrose and Pawseys stage recorders; see Figure 1), but have been removed by landowners from upper reaches (Langs Gully to Melrose stretch of the river). Stream flow was monitored at three gauging stations (Langs Gully, Melrose, and Pawseys), representing headwaters and mid-stream points without and with willow trees, respectively (see Figure 1). Measurements were performed at 15-min intervals, with a 120 degree V-notch weir and a bubbler at Langs Gully and with bubblers at Melrose and Pawseys. The flow sites were periodically gauged at different flow conditions to develop a stage-discharge curve. Being a headwater stream, the North Waipara stream undergoes extreme flow conditions, hence a robust stage-discharge curve is essential to estimate flows. Hydrological data were collected from September 2014 to April 2016.
To reveal gaining or losing stream sections along the stream continuum, we conducted spot gauging from Langs Gully to Pawseys during summer flow conditions. At all gauging sites we measured cross-sectional wetted perimeter and water velocity using a Sontek® current meter. Spot gauging was performed between 10am and 4pm on 25th of January, 2013, to give a representative estimation of spatial changes in stream specific yield. Since the spot gauging was performed over a few hours, it is unlikely to pick up the willow water use signal, however would have revealed GW seepage patterns if these existed. Also there is no surface water abstraction between Melrose and Pawseys, thus any major stream water losses are due to ET.

Weather conditions were monitored using a compact weather station located in the Langs Gully catchment (see Figure 1). A Vaisala WXT520 weather transmitter was used to measure wind speed and direction, air temperature, barometric pressure, and relative humidity. A LiCOR LI200 pyranometer was used to measure solar radiation. Rainfall was measured using an OTA OSK15180T 0.2 mm resolution tipping bucket gauge at Langs Gully and Pawseys. All weather measurements were made at 5-min intervals. At Melrose, daily precipitation was measured by the land owner using a standard manual precipitation collector. Meteorological data have been collected since December 2011. The study area contains 11 bore holes with continuous water level loggers (Solinst levelogger) for monitoring local GW levels at 15 minutes intervals. Two of these boreholes (site 1 and 9) were selected for water isotope analysis to represent deeper GW.

2.3 Isotope analysis

Stable isotope samples from precipitation were collected daily at Melrose using a standard precipitation collector. These samples were collected each morning, to minimize evaporation effects. Surface water, groundwater and spring samples were collected at monthly intervals from seven locations throughout the stream corridor (Figure 1), by a syringe or as a grab sample from the main stream flow by filling 10-mL bottles with no head space. Two boreholes and two natural
springs were sampled for local groundwater signal (Figure 1). The borehole samples were collected with a suction pump (bore hole emptied before each sample was taken) and the spring sampled by grab sampling. Suction lysimeters and flushes in willow tree areas were used to sample the near-surface water component. In addition, soil isotope samples collected from Langs Gully during 2015 and 2016 were used in comparison analysis (see Dudley et al. 2017 for more details). All samples were stored in darkness at +4 °C until analysis.

Dual isotope ratios from water samples, δ2H/δ1H and δ18O/δ16O, were determined using cavity ring-down spectroscopy with a Picarro L1102-i spectrometer at NIWA, Christchurch, and calibrated using in-house standards calibrated to Vienna Standard Mean Ocean Water (VSMOW). All isotope ratios are expressed in δ notation relative to VSMOW, with precision for δ18O and δ2H values of ±0.1‰ and ±1.0‰, respectively. Furthermore, electrical conductivity (EC) of stream and precipitation water samples were measured in the laboratory using a Mettler Toledo InLab 730 conductivity meter.

To study water usage by stream-side willows (Figure 2), stem samples were collected from eight permanently marked plots between Melrose and Pawsey for stable isotope analysis of xylem water. One fully suberized stem segment, approximately 5 cm in length, was collected from 2-3 trees within plots (n = 8, samples composited from each sampling date) during monthly sampling from September 2014 to April 2015. A further six composite samples were collected on a single occasion at the Melrose site in February 2016. Stem segments were immediately placed in 50-mL vials with screw-top lids and sealed with Parafilm (Bemis Flexible Packaging, Neenah, Wisconsin, USA), kept on ice during transport, and refrigerated until analyzed. Xylem water extraction and isotope analysis of all water samples were performed at the Stable Isotope Ratio Facility for Environmental Research (SIRFER) at the University of Utah (Salt Lake City, Utah, USA). Xylem water extraction was performed following West et al. (2006). Xylem water isotope values were measured by isotope ratio infrared spectroscopy (IRIS) on a wavelength-scanned, cavity ring-down
spectrometer (WS-CRDS) model L1102-i water analyzer (Picarro, Sunnyvale, California, USA).

Samples were analyzed against three laboratory reference materials calibrated to VSMOW.

To identify and delineate the pathways and sources of water in the stream during low-flow periods, isotope samples were used to calculate proportions of GW and new water fractions, following Kirchner 2016a, b. For the GW analysis, an end-member mixing model (EMM, sensu hydrograph separation) was used to determine GW proportion in the catchments studied. EMM is the conventional method applied to estimate different water sources from hydrographs using only two mixing components (Klaus and McDonnell 2013). In this study, average $\delta^{18}$O values from boreholes and springs were used as the GW signal and the average volume-weighted monthly precipitation isotope value for the month prior to sampling time as the precipitation signal. For mean transit time (MTT) estimation, the sine curve method was used (McGuire and McDonnell, 2006), with isotopic values from monthly volume-weighted precipitation and monthly stream samples. This method is based on approximation of isotope inputs (precipitation) and outputs (discharge) using the sine curves. Transit time analysis has recently been criticized for not accounting for heterogeneity in catchments (Kirchner, 2016a). In light of this shortcoming in the method, transit time was used here only to obtain tentative estimates of water transit times and pathways at the study sites. For further analysis, new water fractions ($F_{yw}$) and short-term aquifer volume (STS, mm) values were calculated (Kirchner, 2016b).

2.4 Evapotranspiration from stream-side willows and reference evapotranspiration

Daily transpiration from willows ($T$) was calculated based on meteorological data from the Langs Gully climate station, using the Penman-Monteith method (Allen et al., 1998):

$$\lambda T = \frac{\Delta(R_n e^{-k_{LAI}G} + P_{a}C_{p}D)}{\Delta + \gamma(1 + \frac{e}{T_{a}})}$$  \hspace{1cm} (1)
Where $\lambda$ is the latent head of vaporization, $\Delta$ is the slope of the saturation vapor pressure curve, $\gamma$ is the psychrometric constant, $R_n$ is net radiation, $G$ is the soil heat flux (assumed to be 0.1 of $R_n$), $\rho_a$ is air density, $C_p$ is the specific heat of air, $D$ is the vapor pressure deficit, and $r_a$ is the aerodynamic resistance (calculated for 10 m canopy height). Canopy resistance ($r_c$) was calculated as a function of $D$, incoming solar radiation, and estimated leaf area index (LAI) according to Doody et al. (2006). Estimates of LAI were based on an existing model of seasonal LAI for Salix fragilis (Doody et al., 2013), restricted to the local period in which leaves were present on trees (September 30 – May 30). In order to isolate transpiration of willow from total ET, a light extinction coefficient, $k$, was used with LAI to account for net radiation intercepted by plants. The value of $k$ was set to a moderate estimate of 0.5 (Zhang et al. 2014). Surface area of stream-side willows between Melrose and Pawseys was calculated from aerial photos (Doody et al., 2014) and was used to calculate $T$ by willows for the stream reach from Melrose to Pawseys. As an estimate of potential ET, reference ET was calculated according to the FAO-56 method (Allen et al., 1998).

Diurnal variation in stream discharge at all three sites ($Q_{\text{diff}}, \text{L s}^{-1} \text{km}^{-2}$) was calculated by subtracting daily maximum discharge ($Q$) from daily minimum $Q$ for two consecutive days. In these calculations, only discharge values during base-flow conditions were used (all storm events were ignored). These values were used to estimate losses through ET by stream-side willows ($\Delta Q_{\text{diff}}, \text{mm}$) along each stream reach (Langs Gully to Melrose and Melrose to Pawseys) using the method described in Lupon et al. (2016), and assuming that values integrated the riparian ET upstream from the point. Many other factors such as drainage, aquifer recharge and soil moisture also affect diurnal variation in streamflow, but in our case, we could compare gauging stations with and without willows effects. We used this comparison to estimate the willow ET effect on diurnal variation. Furthermore, we examined the relationship between diurnal stream discharge cycle and stream-side willow ET (calculated using Eq. 1).
4 Results

4.1 Hydrological conditions in study area

During the study period, the median annual $Q$ was 2.8, 32, and 188 L s$^{-1}$ at Langs Gully, Melrose, and Pawseys, respectively, which in terms of catchment area was equivalent to 0.35, 0.35, and 0.48 mm day$^{-1}$, respectively. The three sites showed a similar seasonal pattern, characterized by a strong decline in flow during summer (Figure 3) due to lower precipitation and greater evapotranspiration. Discharge is increasing from upstream to downstream when annual budgets are looked, but during summer time this was observed to be opposite. Sub-daily variation, with a maximum flow in early morning and a minimum in late afternoon at all sites, also showed a strong seasonal pattern. At the Langs Gully and Melrose sites, the highest $Q_{\text{diff}}$ values were observed during the winter period i.e. wet season and the lowest in the summer period i.e. dry season. In contrast, $Q_{\text{diff}}$ at Pawseys, which is influenced by stream-side willow vegetation, was high even during the growing season (as shown for the 2015 season in Figure 4). Local GW levels also showed a strong seasonal variation, with the aquifer being filled by winter precipitation events and with a decline in GW level during summer (Figure 5). No diurnal variations were observed in GW levels. The summer spot gauging at stream continuum from Langs Gully to Pawseys revealed no major seepage from stream to GW in the area (Figure 6). Specific yield remained circa 0.11 mm/day along the stream continuum, and all local gains were due to flow from incoming tributaries.
Figure 3. (Top diagram) Daily precipitation minus reference evapotranspiration (ET) in the Waipara catchment, (middle) daily estimated water use by stream-side willows (T) from Melrose to Pawseys, and (bottom) specific discharge at Langs Gully, Melrose, and Pawseys. January 2012-April 2016.

Figure 4. Evapotranspiration (ET, mm) by stream-side willow trees and diurnal variation in stream discharge ($\Delta Q_{\text{diff}}$) between Melrose and Pawseys, July 2014-August 2015.
Figure 5. Monthly precipitation minus potential evapotranspiration and monthly average groundwater level in boreholes 1 and 9 (see Figure 1 for location), January 2012-January 2016.

Figure 6. Spatial variation of specific yield at spot gauging campaign during summer low flow on 25th of January, 2013.

4.2 Dual isotope composition and transit time

Local stable isotopes in precipitation (min for $\delta^2$H and $\delta^{18}$O: -139.6 and -19.22; max for $\delta^2$H and $\delta^{18}$O: 14.7 and 1.91) and stream water showed clear seasonal fluctuations, which allowed new water
fraction and transit times to be estimated (Figure 7). Isotopic values from stream samples were close
to each other in sites S1 to S7 (Figures 7 and 8, average min for $\delta^2$H and $\delta^{18}$O: -67.7 and -10.49;
average max for $\delta^2$H and $\delta^{18}$O: -50.2 and -7.3) but shifted towards summer rainfall values in site S8
during summer period (Figure 7c, min for $\delta^2$H and $\delta^{18}$O: -64.7 and -9.9; max for $\delta^2$H and $\delta^{18}$O: -
45.1 and -5.9). Isotopic composition in groundwater bores showed some fluctuation (min for $\delta^2$H
and $\delta^{18}$O: -68.3 and -10.2; max for $\delta^2$H and $\delta^{18}$O: -57.6 and -8.49). The results indicated rather
small storage and short transit times in Waipara headwater areas (Table 1). Average transit time,
young water fraction ($F_{yw}$), and short-term aquifer volume (STS) for upper reaches were 7.5
months, 21%, and 25 mm, respectively. Average transit time in GW boreholes was 15 months,
indicating an almost annual fluctuation cycle. In streams (except for location S8), GW was the
dominant flow source (contributing over 50%) during summer.

Plots of isotope ratios for stream water, groundwater, and average annual volume-weighted
precipitation against the local meteoric water line (LMWL, Figure 8) indicated that none of these
parameters was greatly altered by evaporation, but dual isotope values for stream water at Pawseys
showed a small evaporation signal. The lysimeters and water samples collected from these small
springs, i.e., flushes at stream banks, were closer to summer precipitation values (-8.3 and -8.0 for
$\delta^2$H and -66.2 and -56.2% for $\delta^{18}$O for lysimeters and flushes, respectively) and did not show a
substantial evaporation signal. These samples had a similar isotope signal to stream samples at
Pawseys (Figure 8). Suction lysimeter water samples taken during winter months near the stream
also showed minimal divergence from the meteoric water line.

Willow xylem water samples, however, mainly showed an evaporation signal by falling
below the LMWL. Because there was insufficient soil moisture in streamside soils to provide a
suction lysimeter sample during dry summer months, we have presented soil moisture data collected
from dry hillslopes in Lang’s Gully (Dudley et al. 2017.) in Figure 8, for comparison with xylem
samples. Stable water isotopes from willow xylem samples were used to distinguish different water
The isotope signal from individual trees fluctuated markedly during summer, indicating contributions from various water sources even during dry periods (Figure 8b).

Table 1. Estimated mean transit time (MTT, months), young water fraction (Fyw, %), and short-term aquifer volume (STS, mm) for stream sampling sites S1-S8 and groundwater (GW) wells

<table>
<thead>
<tr>
<th>Site</th>
<th>Mean transit time, months</th>
<th>Young water fraction, %</th>
<th>Short-term aquifer volume, mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>S1</td>
<td>8.21</td>
<td>19</td>
<td>22.74</td>
</tr>
<tr>
<td>S2</td>
<td>9.29</td>
<td>17</td>
<td>20.21</td>
</tr>
<tr>
<td>S3</td>
<td>8.21</td>
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<td>S4</td>
<td>7.34</td>
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<tr>
<td>GW wells</td>
<td>15.05</td>
<td>11</td>
<td>12.63</td>
</tr>
</tbody>
</table>

Figure 7. a) Daily precipitation stable oxygen isotope values (δ^{18}O) and volume-weighted monthly precipitation (red line), b) isotope fluctuations in stream water at sites between Langs Gully and Melrose (color lines represent different sampling sites), and c) isotope fluctuations in stream water at Pawseys, with green bands representing the growing season, when stream-side willows have leaves.
Figure 8. Dual isotope plots. a) Stable isotope ratio in precipitation water (N=225), stream water (N=152), groundwater (N=52), soil water near stream (N=10), and willow xylem (N=44). LMWL (local meteoric water line): δD=7.73δ18O+8.15. b) Seasonal and temporal variation in stable isotope ratio for six individual willow trees. Soil water data derived from hillslope samples taken in nearby Lang’s Gully (Dudley et al. 2017) is provided for comparison.

4.3 Transpiration by stream-side willows

Water use by stream-side willows - was the highest during summer (up to 5.6 mm day\(^{-1}\), Figure 3) for willows from Melrose to Pawseys. Average annual transpiration rate for willows was 0.74 mm day\(^{-1}\). Total average annual willow transpiration was 270 mm, while average annual precipitation during the study period was 1067 mm. Since the flow deficit between the Melrose and Pawseys sites was 0.94 mm day\(^{-1}\) during summer, willow transpiration explained the majority of diurnal flow variation during summer (Figure 4).
5 Discussion

5.1 Limited storage in Waipara headwaters

The results showed that the hydrological system in Waipara headwaters is strongly dependent on winter precipitation, which recharges local GW systems. These local aquifers support flows during summer, when ET exceeds precipitation and rainfall-runoff events are rare. Dual isotope analysis showed rather small catchment storage and short transit times in Waipara headwater areas. In addition, young water fraction ($F_{yw}$) and the short-term aquifer volume (STS) were relatively small. This confirms previous findings by McMillan and Srinivasan (2015) that surface soils are shallow and water storage is limited in this catchment. Those authors also reported winter and summer modes for GW formation, whereby water movement in soils in winter is dominated by GW movement and bypass, while in summer it is controlled by shallower processes (interaction between soils and vegetation) and summer precipitation does not usually result in runoff generation or groundwater recharge. This was partly supported by the isotope values for GW wells in the present study, which showed only small seasonal fluctuations and corresponded to winter precipitation values (Figure 8). White et al. (2003) and Duncan et al. (2016) have also shown in Canterbury catchments that the majority of rainfall-recharge occur during the winter months and the recharge is minimal to almost nil in summer.

The lack of an evaporation signal from both GW and stream water suggests that these water balance components have a water source that is transported quickly to deeper subsurface storage. This deeper subsurface storage, i.e., deep GW, thus acts as the main component for stream generation in the study areas, which agrees with observations on GW levels in wells (Figure 5) and isotope values in streams. GW levels showed clear seasonal variation, and released water to runoff during summer period as shown in declining GW levels early to late summer. Hence, our results are in general agreement with estimations made in nearby hillslope at Lang’s Gully (McMillan and Srinivasan, 2015, Dudley et al. 2017). However, isotope values for stream-side lysimeters and side
bank flushes were closer to summer precipitation values (Figure 8), indicating shallow subsurface flow to streams from occasional summer precipitation events.

5.2 Effects of transpiration by stream-side willows on water sources and stream discharge

The results of isotopic analysis indicated variable water sources for stream-side willow trees. The isotope signal from individual trees fluctuated widely during summer, indicating various water sources even during dry periods. Site S8 (Pawseys), which is influenced by transpiration from stream-side willows (estimated leaf area of willows 0.09 km²), had a clearly different isotope signal during summer (Figure 7c). This was reflected in shorter transit time and young water fraction (Table 1). Young water fraction increased from S7 (Melrose) to S8 (Pawseys), indicating a shift from a groundwater-dominated to a more surface water-dominated system, especially during summer low-flow periods. A similar change was observed in stream flow. Seasonally, there was a clear deficit in stream flow at Pawseys during the summer of 2013, 2015, and 2016 (Figure 3). During summers when precipitation minus evapotranspiration was lower, this was not observed. The results thus strongly suggest that during summer when the dominant stream flow source is groundwater (derived from rainfall-recharge from previous winter), the stream water from Melrose (S6) does not reach Pawseys (S8). Instead, stream flow at Pawseys mainly originates from shallow subsurface sources (not GW). Moreover, dual isotope values for stream water at Pawseys showed a small evaporation signal. This means that water losses from Melrose to Pawseys were not greatly added to by evaporation from open stream surfaces. It should be noted that there is surface storage (e.g. ponds, wetlands, etc.) between Melrose and Pawseys that could potentially alter isotopic or hydrometric signatures. Furthermore, in the Waipara catchment, the riparian zone is rather steep, typically resulting in a chain of small flushes from surface soils or small aquifers to the bottom of the valley. Isotope samples taken from these flushes directly matched isotope values measured in stream water at Pawseys (Figure 8). This further supports the hypothesis of a shift from GW-
dominated to surface water-dominated flow as moved downstream from Melrose to Pawseys. The 
summer spot gauging along the stream continuum revealed that there is no measurable seepage 
from stream to GW, thus summer low flow differences between Melrose and Pawseys is not due to 
loss to GW from stream channel. The main difference between the Melrose and Pawseys 
catchments is presence of invasive willows, which dominate the riparian zone in lower reaches of 
the North Waipara River (Melrose to Pawseys), whereas in upper reaches (upstream from Melrose, 
S6) willows have been totally removed. This arrangement allowed us to study water use by the 
willows, since climate, land use, soils, and geology in the two catchments are similar.

Recent findings suggest different water sources for stream flow generation and water use by 
plants (Brooks et al., 2010; Evaristo et al., 2016). Those studies showed that trees can use tightly 
bound soil water, especially during dry periods. At our study sites, analysis of stable dual isotopes 
($\delta^{18}$O, $\delta^2$H) in water indicated water usage by individual willows in many cases diverged from 
stream, groundwater and springtime near-stream suction lysimeter samples for the stretch from 
Melrose to Pawseys, and resembled dryer soil water values taken concurrently from a hillslope in 
附近 Lang’s Gully (Dudley et al. 2017). This is a striking result, since our working hypothesis 
was that the main water source for stream-side willows is stream water, especially since willows are 
partly situated in-stream. The isotope values for willows varied temporally even for individual trees 
(see Figure 8b), and there was no dependence on whether willows were situated in-stream or near-
stream. When we traced the isotope composition of the precipitation from which willow xylem 
water originated, we found that the intersection points of the local plant xylem evaporation line with 
LMWL indicated a plant xylem $\delta$ source value (see Evaristo et al., 2015 for an explanation of the 
method). The willow xylem source water $\delta$ value (-81 $\delta^2$H, -11.45 $\delta^{18}$O) differed from the value for 
mean stream flow at Melrose (-60.0 $\delta^2$H, -8.9 $\delta^{18}$O) and the value for groundwater (-59.9 $\delta^2$H, -8.93 
$\delta^{18}$O). The results from isotopic analyses thus indicate that stream-side willows can utilize several 
water sources and there was no difference between the seasons in willow water source. An
explanation provided by Goldsmith et al (2012) for a similar pattern - preferential use of water from dryer shallow soils by both canopy and understory species - was that the nutrient distributions across soil depths may dictate rooting patterns and water sources. It may be that nutrient requirements of willows also dictate that a significant portion of transpired water is derived from dryer streambank soils, where nutrient availability is greater, ahead of readily-available, but more oligotrophic streamwater and groundwater. Nevertheless, a significant role of riparian vegetation in taking up stream discharge has been reported previously (Cadol et al., 2012; Gribovszki et al., 2010; Lundquist and Cayan, 2002; Lupon et al., 2016; Kellogg et al. 2008). Riparian water demand (0.5-5 mm day$^{-1}$) can lower the GW level and thus significantly (30-100%) decrease the amount of GW entering the stream (Schilling, 2007; Dahm et al., 2002; Folch and Ferrer, 2015). Moreover, actual ET often exceeds estimated potential ET due to enhanced aerodynamic conductance, stomatal conductance, and leaf area compared with reference surfaces and open water (Grip et al., 1989; Hall et al., 1998; Doody and Benyon, 2011).

According to our results, ET by stream-side willows can significantly influence stream discharge in small headwater streams under low flow conditions. Even though stream-side willows occupied only a small proportion of the Waipara catchment (estimated leaf area of willows 0.09 km$^2$, 2.5‰ of Pawseys catchment area), they made a large contribution to summer water budget in the catchment. Estimated average ET rate by stream-side willows was around 1.41 mm/day during summer but reached up to 5.6 mm/day on individual days, thus explaining the majority of the diurnal variation in low flow discharge in the catchment. This is in agreement to previously reported willow transpiration values in Australia (5-12 mm/day, Doody and Benyon, 2011) and in the Moutere region of New Zealand (Amaravathi, 2010). On an annual basis, ET by willows at the study site was 0.74 mm/day (or 270 mm/a), while rather low at daily scale, still affects summer water budgets because the bulk of willow transpiration occurs during mid to late summer when flows tend to be low. Since these transpiration numbers are volume per area, they can be also used
in other similar regions to estimate willow water usage. Willows in our study area were clustered close to the stream, or within the stream, due to steep river banks. Doody et al (2006) identified in-stream willows (rather than those on banks) as filling an otherwise unoccupied niche, which lead to a potential to return water to the stream should they be removed. The current presence of grazing cattle, and previous history of vegetation removal in these pastoral catchments mean that willows also occupy a niche that would be vacant in their absence, suggesting water savings if they were removed. While the removal of willows would reduce transpiration, streams would lose their shading effect and direct evaporation from water surface would increase. Quantification of water savings that recognize this tradeoff (e.g. Doody and Benyon, 2011, Doody et al. 2013) are possible for these systems.

Sub-daily discharge analyses suggested that stream-side vegetation caused diurnal fluctuations in stream discharge (Figure 4). Dual isotope measurements supported this finding, indicating that willows take up water from the near-stream aquifer, but also from soil water. Stable isotope values in willow xylem water showed fluctuations between these two main water sources, GW and soil water, meaning that willows can influence the water budget by lowering local GW level or by reducing surface soil moisture. Previous studies have indicated that riparian trees can obtain 30 to 90 % of the water they need from surface soil (Brooks et al., 2009; Sanchez-Perez et al., 2008; Snyder and Williams, 2000). The potential of riparian forests to control stream hydrology has been shown to depend on water availability (Lupon et al., 2016). In regions experiencing water limitation, trees adapt to varying water sources. At Waipara, stream-side willows seem to take water from several sources (stream water, groundwater, and soil water), thus affecting the local water budget in more than one way.

By linking vegetation water use in headwater catchments to the timing and magnitude of flows from these catchments, a more realistic low-flow estimate can be produced. The data presented here indicate that riparian land cover can influence water availability in downstream
areas. Our results showed the vulnerability of low flows to water uptake by invasive willow trees, which dominate stream-side areas in many regions of New Zealand and Australia. Thus willow removal could be a potential tool to manage low-flow conditions, especially during prolonged dry spells. Although, this will depend strongly upon the water-use characteristics of replacement vegetation.

6 Conclusions

The present study in a headwater catchment of North Waipara River, Canterbury, New Zealand, indicated that invasive stream-side willow trees cause water losses from subsurface waters and stream flow to the atmosphere via transpiration. We found that:

1. Stable isotopic analysis of precipitation, ground- and stream water suggest that catchment streamflow generation is highly reliant on fast-turnover groundwater, maintained by seasonal precipitation, and is thus vulnerable to water-use by riparian vegetation during summer low-flow period.

2. Independent assessments of ET from meteorological methods and diurnal variations in streamflow indicate the quantity of water used by riparian transpiration (270 mm y⁻¹) and the relevance of this quantity to streamflow during summer low-flow periods.

3. Riparian willows had a marked effect on base flow during summer and reduced stream flow during critical low-flow periods.

4. Although riparian water-use is substantial, stem water isotopic analyses indicate that willows were not exclusive in their use of streamflow as a water source.

The evidence presented here suggests that willow removal may be a useful management tool for mitigating lows of streamflow to vegetation water-use during seasonal low flow periods.
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