

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

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11
12 **Abstract**

13 Understanding seasonal partitioning of water in riparian areas is important for assessing how
14 vegetation affects water resources. A combined hydrological-isotopic field study was conducted
15 within a headwater catchment to explore the dynamics of stream discharge and the effect of riparian
16 evapotranspiration (ET) on summer low flow conditions. In addition to collection of meteorological
17 data and depth to unconfined groundwater, stream flows were measured at three locations along the
18 length of the river. Isotope ratios of local precipitation, stream water, groundwater, and willow
19 xylem water were used to estimate pathways and sources of water used by vegetation. Using
20 meteorological variables, leaf area index and stand area measurements, willow transpiration (T) was
21 estimated using the Penman-Monteith method. Combining the data from hydrometric, isotope, and
22 vegetation ET analysis revealed that water abstraction by stream-side willows peaked to 5.6
23 mm/day and had a distinct impact on summer low-flow conditions and patterns of stream discharge
24 at the daily time scale. Average annual willow transpiration was 270 mm, while average annual
25 precipitation during the study period was 1067 mm. However, willow transpiration reduced stream

26 flow and altered water budgets most strongly during critical summer low flow periods. Our analysis
27 of transit times, young water fraction, and depth to groundwater water data showed Waipara
28 headwater areas have limited water storage capacity, making them vulnerable to annual variations
29 in precipitation and any other changes in water usage. Removal of streamside willows could
30 potentially influence water balance during summer months when flows tend to be the lowest.

31

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

34

35 **1 Introduction**

36 Quantifying water transfer, surface and subsurface, across landscapes is a fundamental issue in
37 water resources management (Ward and Pulido-Velazquez, 2012). At the catchment scale, it is
38 hydrologically important to delineate different water sources, pathways of transfer from rainfall to
39 stream flow, and lag times when seeking to determine local storage and availability of water.
40 Prolonged drought periods are often a driving force for development of sustainable water
41 management regimes for different purposes (Aghakouchak *et al.*, 2014). In water limited regions,
42 the security of water supply for municipal, agriculture, and freshwater aquatic ecosystem needs is
43 highly important (Jackson *et al.*, 2001; Lake, 2011; Perez-Blanco and Comez, 2014).

44 The effect of vegetation on catchment water budgets, through transpiration and interception,
45 is widely acknowledged (Jasechko *et al.*, 2013), especially in riparian areas where plant
46 transpiration can even play a dominant role during low-flow conditions (Cleverly *et al.*, 2006;
47 Moore and Owens, 2012). Globally, transpiration accounts for more than 80% of total
48 evapotranspiration and the amount ranges from 100 to 1300 mm y⁻¹ (Jasechko *et al.*, 2013). Recent
49 studies provide strong evidence of large-scale eco-hydrological separation between water in the soil
50 matrix that roots take up for transpiration and water draining through the soil to groundwater and

51 streams (Evaristo *et al.*, 2015; Good *et al.*, 2015). Thus it is highly important to study not only flow
52 paths, but also the effects of vegetation on local hydrology from stream corridor to regional scales
53 (Jasechko *et al.*, 2013). Currently, there is no clear understanding of how transpiration by stream-
54 side trees affects stream flow and interception of subsurface flows to streams. Stream-side trees can
55 consume water from different sources, including soil water, stream water and groundwater (Dahm
56 *et al.*, 2002; Schilling 2007; Doody *et al.* 2009; Folch and Ferrer 2015; Doody *et al.*, 2015, Scott-
57 Shaw *et al.* 2017), and can thus play a significant role in catchment water budgets (Cadot *et al.*,
58 2012).

59 Infestation of headwater catchments by invasive vegetation is a major environmental problem
60 world-wide (Doody and Benyon, 2011). In New Zealand and Australia, invasive woody plant
61 species such as crack willow (*Salix fragilis*), are particularly problematic (Doody and Benyon,
62 2011; Doody *et al.*, 2014). Most willow species consume large quantities of water through
63 transpiration (Cermák *et al.*, 1984; Hall *et al.*, 1998; Schaeffer *et al.*, 2000), thus potentially
64 reducing stream flows. Estimated maximum daily evapotranspiration (ET) rates for willow ranges
65 from 5 to 12 mm (Persson and Lindroth, 1994; Hall *et al.*, 1998; Doody *et al.*, 2006; Amaravathi,
66 2010). Such high transpiration rates can cause significant losses to the local water budget (Doody
67 and Benyon, 2011), resulting in reduced water availability for in-stream and off-stream uses. An
68 Australian study estimated that ET from stream-side willows could be as much as 5.5 million L ha⁻¹
69 y⁻¹ (Doody and Benyon, 2011). However, more information is needed on the actual effects of
70 streamside willow trees on stream flows, particularly for New Zealand, where fewer such estimates
71 are available. This information is critical for local government, which in New Zealand sets
72 minimum limits on flows to support in-stream ecological function, and determines limits for water
73 abstraction. Willows often invade previously unvegetated streams and their removal could
74 potentially reduce ET, increasing stream flow, especially during low flow periods.

75 In this study, we utilized stable isotopic, hydrometric and meteorological approaches to
76 characterize processes and sources of streamflow generation in a water limited headwater catchment
77 of New Zealand, specifically addressing the following two questions: i) what are the water sources
78 for streamflow generation? and ii) do invasive stream-side willows influence seasonal low-flow
79 conditions in the stream by utilising water sources otherwise contributing to streamflow? The aims
80 were to assess the impact of transpiration by invasive willows on stream flow and to discuss
81 relevance to water resources management.

82

83 **2 Methods**

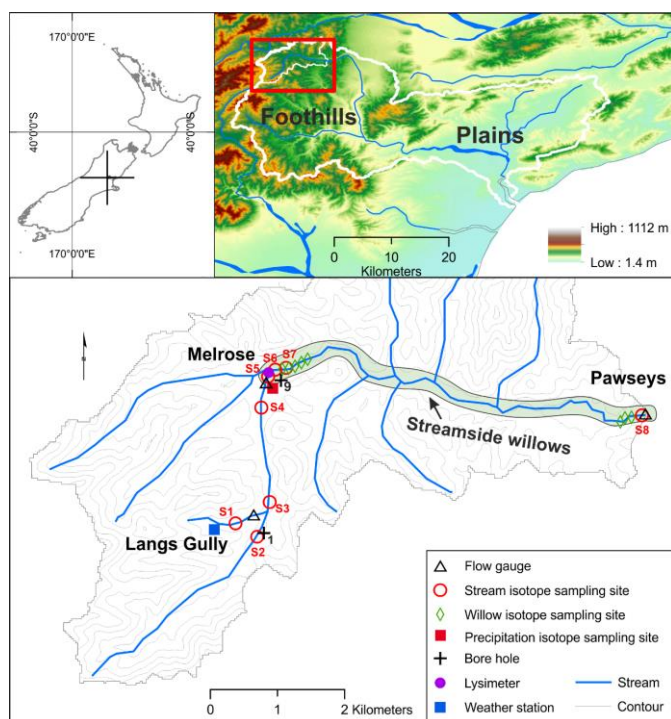
84 **2.1 Study area**

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

95 The present study area is located in the headwaters of the North Waipara River in Canterbury
96 (Figure 1). The riparian zone in the Waipara catchment is steep, typically resulting in a chain of
97 small flushes from surface soils or small aquifers to the bottom of the Waipara valley. The study
98 area consists of three nested catchments: Langs Gully (0.687 km², previously described in
99 McMillan and Srinivasan, 2015), Melrose (7.89 km²) and Pawseys (33.86 km²) (Figure 1). The

100 geology consists of greywacke, a hard sandstone with poorly sorted angular grains set in a rather
 101 compact matrix. The soil contains fractions of stones and sand that are typical of shallow gravelly
 102 silt loams within the Canterbury foothills landscape. Soil depth and clay fraction typically increase
 103 from hillslope to foot hill (McMillan and Srinivasan, 2015). Based on the virtual climate network
 104 data from 1972 to 2014 (Cliflo, 2016), the annual precipitation was found to vary from 500 to 1100
 105 mm yr⁻¹ (mean 943 mm) and annual potential evapotranspiration (PET based on the Penman
 106 method) from 432 to 958 mm. Summers are relatively warm and dry with the majority of the
 107 precipitation occurring in fall and winter with frequent frost and occasional snowfall. The land
 108 cover is primarily pasture for low intensity sheep and beef cattle grazing, with a partial cover of
 109 sparse matagouri (*Discaria toumatou*) shrubs. Some areas with the greater catchment are used for
 110 forestry (*Pinus radiata*, *Eucalyptus delegatensis* and *Pseudotsuga menziesii*), and stream sides
 111 within lower reaches are dominated by invasive willow trees (*Salix fragilis*) (Figure 1).
 112

112



113

114 Figure 1. Maps showing the location of the study catchments and river stage measurement and
 115 isotope sampling points. Light green represents areas with stream-side willows.



116

117 Figure 2. Typical stream-side willow stand at the stream section from Melrose to Pawseys.

118

119 2.2 Experimental set-up and data collection

120 We designed our experiment to measure temporal and spatial variability of stream water sources,
 121 pathways, and sinks within the catchment, with particular focus on water use by invasive willow
 122 trees. The study area provided a natural testing site for this purpose, as stream-side willows
 123 dominate the lower reaches of the North Waipara River (between the Melrose and Pawseys stage
 124 recorders; see Figure 1), but have been removed by landowners from upper reaches (Langs Gully to
 125 Melrose stretch of the river). Stream flow was monitored at three gauging stations (Langs Gully,
 126 Melrose, and Pawseys), representing headwaters and mid-stream points without and with willow
 127 trees, respectively (see Figure 1). Measurements were performed at 15-min intervals, with a 120
 128 degree V-notch weir and a bubbler at Langs Gully and with bubblers at Melrose and Pawseys. . The
 129 flow sites were periodically gauged at different flow conditions to develop a stage-discharge curve.
 130 Being a headwater stream, the North Waipara stream undergoes extreme flow conditions, hence a
 131 robust stage-discharge curve is essential to estimate flows. Hydrological data were collected from
 132 September 2014 to April 2016.

133

134 To reveal gaining or losing stream sections along the stream continuum, we conducted spot gauging
135 from Langs Gully to Pawseys during summer flow conditions. At all gauging sites we measured
136 cross-sectional wetted perimeter and water velocity using a Sontek® current meter. Spot gauging
137 was performed between 10am and 4pm on 25th of January, 2013, to give a representative estimation
138 of spatial changes in stream specific yield. Since the spot gauging was performed over a few hours,
139 it is unlikely to pick up the willow water use signal, however would have revealed GW seepage
140 patterns if these existed. Also there is no surface water abstraction between Melrose and Pawseys,
141 thus any major stream water losses are due to ET.

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

152

153 **2.3 Isotope analysis**

154 Stable isotope samples from precipitation were collected daily at Melrose using a standard
155 precipitation collector. These samples were collected each morning, to minimize evaporation
156 effects. Surface water, groundwater and spring samples were collected at monthly intervals from
157 seven locations throughout the stream corridor (Figure 1), by a syringe or as a grab sample from the
158 main stream flow by filling 10-mL bottles with no head space. Two boreholes and two natural

159 springs were sampled for local groundwater signal (Figure 1). The borehole samples were collected
160 with a suction pump (bore hole emptied before each sample was taken) and the spring sampled by
161 grab sampling. Suction lysimeters and flushes in willow tree areas were used to sample the near-
162 surface water component. In addition, soil isotope samples collected from Langs Gully during 2015
163 and 2016 were used in comparison analysis (see Dudley et al. 2017 for more details). All samples
164 were stored in darkness at +4 °C until analysis.

165 Dual isotope ratios from water samples, $^2\text{H}/^1\text{H}$ and $^{18}\text{O}/^{16}\text{O}$, were determined using cavity
166 ring-down spectroscopy with a Picarro L1102-i spectrometer at NIWA, Christchurch, and calibrated
167 using in-house standards calibrated to Vienna Standard Mean Ocean Water (VSMOW). All isotope
168 ratios are expressed in δ notation relative to VSMOW, with precision for $\delta^{18}\text{O}$ and $\delta^2\text{H}$ values of
169 $\pm 0.1\text{‰}$ and $\pm 1.0\text{‰}$, respectively. Furthermore, electrical conductivity (EC) of stream and
170 precipitation water samples were measured in the laboratory using a Mettler Toledo InLab 730
171 conductivity meter.

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

184 spectrometer (WS-CRDS) model L1102-i water analyzer (Picarro, Sunnyvale, California, USA).

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

186 To identify and delineate the pathways and sources of water in the stream during low-
187 flow periods, isotope samples were used to calculate proportions of GW and new water fractions,
188 following Kirchner 2016a, b. For the GW analysis, an end-member mixing model (EMM, *sensu*
189 hydrograph separation) was used to determine GW proportion in the catchments studied. EMM is
190 the conventional method applied to estimate different water sources from hydrographs using only
191 two mixing components (Klaus and McDonnell 2013). In this study, average $\delta^{18}\text{O}$ values from
192 boreholes and springs were used as the GW signal and the average volume-weighted monthly
193 precipitation isotope value for the month prior to sampling time as the precipitation signal. For
194 mean transit time (MTT) estimation, the sine curve method was used (McGuire and McDonnell,
195 2006), with isotopic values from monthly volume-weighted precipitation and monthly stream
196 samples. This method is based on approximation of isotope inputs (precipitation) and outputs
197 (discharge) using the sine curves. Transit time analysis has recently been criticized for not
198 accounting for heterogeneity in catchments (Kirchner, 2016a). In light of this shortcoming in the
199 method, transit time was used here only to obtain tentative estimates of water transit times and
200 pathways at the study sites. For further analysis, new water fractions (F_{yw}) and short-term aquifer
201 volume (STS, mm) values were calculated (Kirchner, 2016b).

202

203 **2.4 Evapotranspiration from stream-side willows and reference evapotranspiration**

204 Daily transpiration from willows (T) was calculated based on meteorological data from the Langs

205 Gully climate station, using the Penman-Monteith method (Allen *et al.*, 1998):

$$206 \quad \lambda T = \frac{\Delta(R_n e^{-kLAI} - G) + \rho_a C_p \frac{D}{r_a}}{\Delta + \gamma(1 + \frac{r_c}{r_a})} \quad (1)$$

207 Where λ is the latent heat of vaporization, Δ is the slope of the saturation vapor pressure curve, γ is
 208 the psychrometric constant, R_n is net radiation, G is the soil heat flux (assumed to be 0.1 of R_n), ρ_a is
 209 air density, C_p is the specific heat of air, D is the vapor pressure deficit, and r_a is the aerodynamic
 210 resistance (calculated for 10 m canopy height). Canopy resistance (r_c) was calculated as a function
 211 of D , incoming solar radiation, and estimated leaf area index (LAI) according to Doody *et al.*
 212 (2006). Estimates of LAI were based on an existing model of seasonal LAI for *Salix fragilis* (Doody
 213 *et al.*, 2013), restricted to the local period in which leaves were present on trees (September 30 –
 214 May 30). In order to isolate transpiration of willow from total ET, a light extinction coefficient, k ,
 215 was used with LAI to account for net radiation intercepted by plants. The value of k was set to a
 216 moderate estimate of 0.5 (Zhang *et al.* 2014). Surface area of stream-side willows between Melrose
 217 and Pawseys was calculated from aerial photos (Doody *et al.*, 2014) and was used to calculate T by
 218 willows for the stream reach from Melrose to Pawseys. As an estimate of potential ET, reference
 219 ET was calculated according to the FAO-56 method (Allen *et al.*, 1998).

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

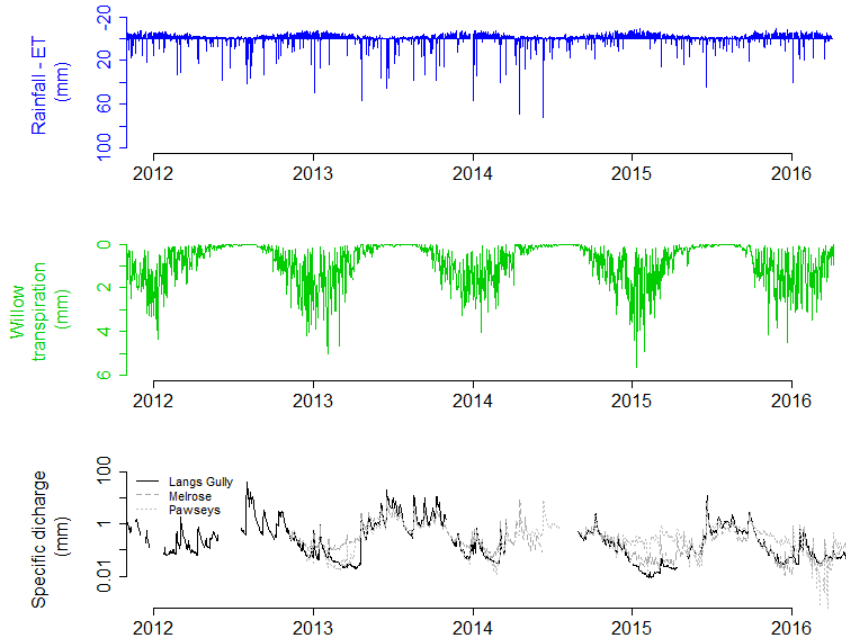
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232 **4 Results**

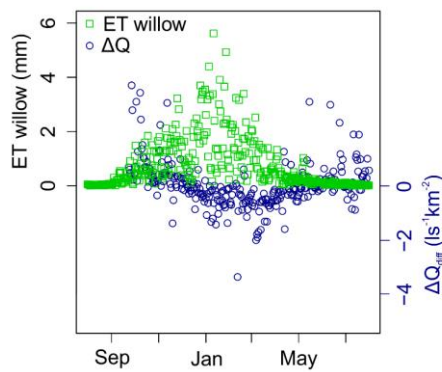
233 **4.1 Hydrological conditions in study area**

234 During the study period, the median annual Q was 2.8, 32, and 188 L s⁻¹ at Langs Gully, Melrose,
235 and Pawseys, respectively, which in terms of catchment area was equivalent to 0.35, 0.35, and 0.48
236 mm day⁻¹, respectively. The three sites showed a similar seasonal pattern, characterized by a strong
237 decline in flow during summer (Figure 3) due to lower precipitation and greater evapotranspiration.
238 Discharge is increasing from upstream to downstream when annual budgets are looked, but during
239 summer time this was observed to be opposite. Sub-daily variation, with a maximum flow in early
240 morning and a minimum in late afternoon at all sites, also showed a strong seasonal pattern. At the
241 Langs Gully and Melrose sites, the highest Q_{diff} values were observed during the winter period i.e.
242 wet season and the lowest in the summer period i.e. dry season. In contrast, Q_{diff} at Pawseys, which
243 is influenced by stream-side willow vegetation, was high even during the growing season (as shown
244 for the 2015 season in Figure 4). Local GW levels also showed a strong seasonal variation, with the
245 aquifer being filled by winter precipitation events and with a decline in GW level during summer
246 (Figure 5). No diurnal variations were observed in GW levels. The summer spot gauging at stream
247 continuum from Langs Gully to Pawseys revealed no major seepage from stream to GW in the area
248 (Figure 6). Specific yield remained circa 0.11 mm/day along the stream continuum, and all local
249 gains were due to flow from incoming tributaries.

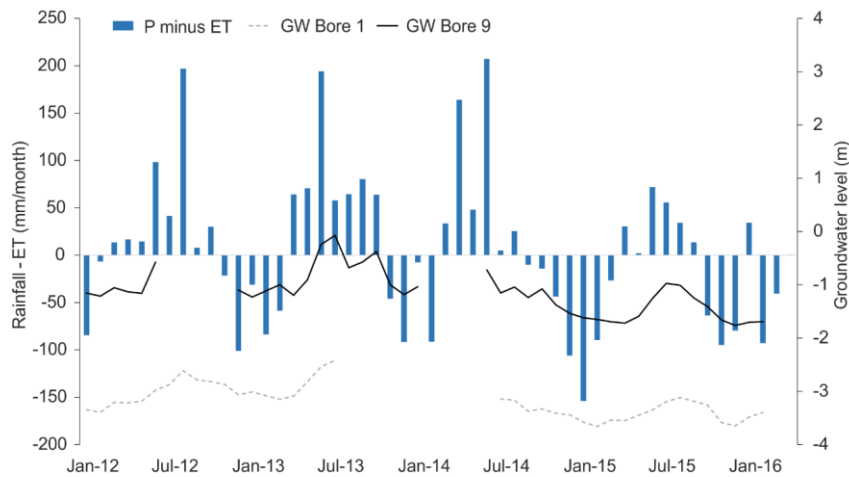
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251
 252 Figure 3. (Top diagram) Daily precipitation minus reference evapotranspiration (ET) in the Waipara
 253 catchment, (middle) daily estimated water use by stream-side willows (T) from Melrose to
 254 Pawseys, and (bottom) specific discharge at Langs Gully, Melrose, and Pawseys. January 2012-
 255 April 2016.

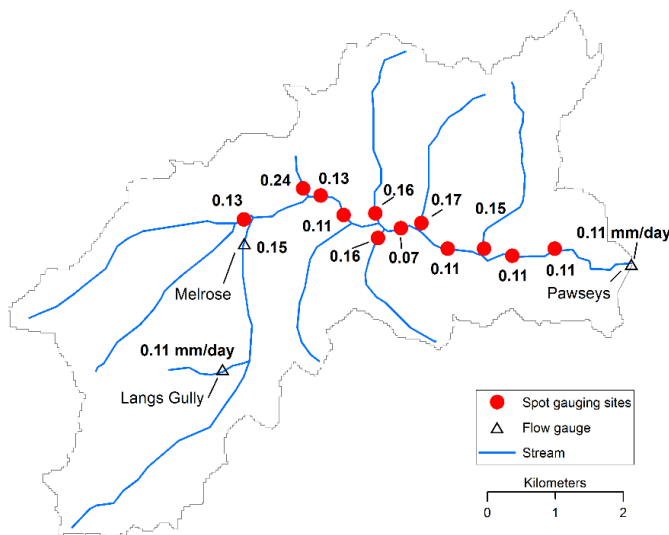


257
 258 Figure 4. Evapotranspiration (ET, mm) by stream-side willow trees and diurnal variation in stream
 259 discharge (ΔQ_{diff}) between Melrose and Pawseys, July 2014-August 2015.



262

263 Figure 5. Monthly precipitation minus potential evapotranspiration and monthly average
 264 groundwater level in boreholes 1 and 9 (see Figure 1 for location), January 2012-January 2016.



265

266 Figure 6. Spatial variation of specific yield at spot gauging campaign during summer low flow on
 267 25th of January, 2013.

268

269 4.2 Dual isotope composition and transit time

270 Local stable isotopes in precipitation (min for $\delta^2\text{H}$ and $\delta^{18}\text{O}$: -139.6 and -19.22; max for $\delta^2\text{H}$ and
 271 $\delta^{18}\text{O}$: 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 $\delta^2\text{H}$ and $\delta^{18}\text{O}$: -67.7 and -10.49; average max for $\delta^2\text{H}$ and $\delta^{18}\text{O}$: -50.2 and -7.3) but shifted towards summer rainfall values in site S8 during summer period (Figure 7c, min for $\delta^2\text{H}$ and $\delta^{18}\text{O}$: -64.7 and -9.9; max for $\delta^2\text{H}$ and $\delta^{18}\text{O}$: -45.1 and -5.9). Isotopic composition in groundwater bores showed some fluctuation (min for $\delta^2\text{H}$ and $\delta^{18}\text{O}$: -68.3 and -10.2; max for $\delta^2\text{H}$ and $\delta^{18}\text{O}$: -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 $\delta^2\text{H}$ and -66.2 and -56.2‰ for $\delta^{18}\text{O}$ 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

sources (Figure 8a). 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 (F_{yw} , %), and short-term aquifer volume (STS, mm) for stream sampling sites S1-S8 and groundwater (GW) wells

Site	Mean transit time, months	Young water fraction, %	Short-term aquifer volume, mm
S1	8.21	19	22.74
S2	9.29	17	20.21
S3	8.21	19	22.74
S4	7.34	21	25.26
S5	7.09	22	26.10
S6	6.02	25	30.32
S7	6.62	23	27.79
S8	3.75	38	45.47
GW wells	15.05	11	12.63

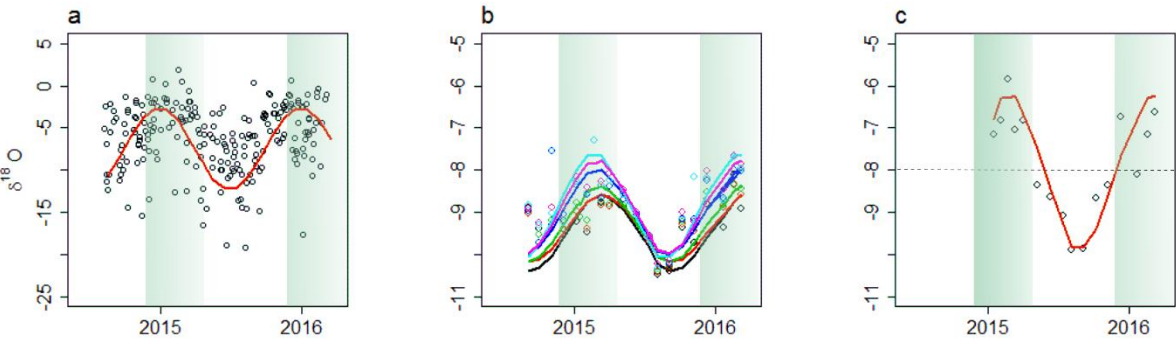


Figure 7. a) Daily precipitation stable oxygen isotope values ($\delta^{18}O$) and volume-weighted monthly precipitation (red line), b) isotope fluctuations in stream water at sites between Langs Gully and Melrose (color lines represent different sampling sites), and c) isotope fluctuations in stream water at Pawseys, with green bands representing the growing season, when stream-side willows have leaves.

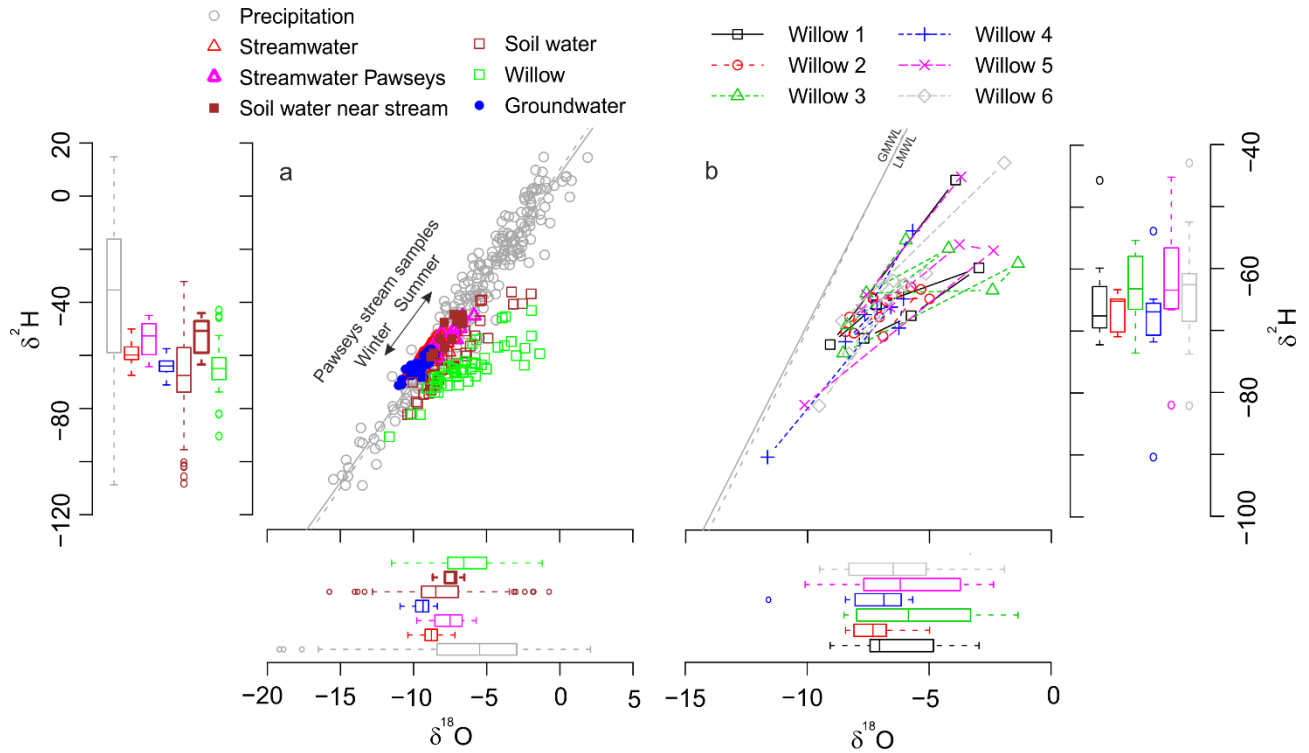


Figure 8. Dual isotope plots. a) Stable isotope ratio in precipitation water (N=225), stream water (N=152), groundwater (N=52), soil water near stream (N=10), and willow xylem (N=44). LMWL (local meteoric water line): $\delta\text{D}=7.73\delta^{18}\text{O}+8.15$. b) Seasonal and temporal variation in 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).

326 **5 Discussion**

327 **5.1 Limited storage in Waipara headwaters**

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

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

351 bank flushes were closer to summer precipitation values (Figure 8), indicating shallow subsurface
352 flow to streams from occasional summer precipitation events.

353

354 **5.2 Effects of transpiration by stream-side willows on water sources and stream discharge**

355 The results of isotopic analysis indicated variable water sources for stream-side willow trees. The
356 isotope signal from individual trees fluctuated widely during summer, indicating various water
357 sources even during dry periods. Site S8 (Pawseys), which is influenced by transpiration from
358 stream-side willows (estimated leaf area of willows 0.09 km²), had a clearly different isotope signal
359 during summer (Figure 7c). This was reflected in shorter transit time and young water fraction
360 (Table 1). Young water fraction increased from S7 (Melrose) to S8 (Pawseys), indicating a shift
361 from a groundwater-dominated to a more surface water-dominated system, especially during
362 summer low-flow periods. A similar change was observed in stream flow. Seasonally, there was a
363 clear deficit in stream flow at Pawseys during the summer of 2013, 2015, and 2016 (Figure 3).
364 During summers when precipitation minus evapotranspiration was lower, this was not observed.
365 The results thus strongly suggest that during summer when the dominant stream flow source is
366 groundwater (derived from rainfall-recharge from previous winter), the stream water from Melrose
367 (S6) does not reach Pawseys (S8). Instead, stream flow at Pawseys mainly originates from shallow
368 subsurface sources (not GW). Moreover, dual isotope values for stream water at Pawseys showed a
369 small evaporation signal. This means that water losses from Melrose to Pawseys were not greatly
370 added to by evaporation from open stream surfaces. It should be noted that there is surface storage
371 (e.g. ponds, wetlands, etc.) between Melrose and Pawseys that could potentially alter isotopic or
372 hydrometric signatures. Furthermore, in the Waipara catchment, the riparian zone is rather steep,
373 typically resulting in a chain of small flushes from surface soils or small aquifers to the bottom of
374 the valley. Isotope samples taken from these flushes directly matched isotope values measured in
375 stream water at Pawseys (Figure 8). This further supports the hypothesis of a shift from GW-

376 dominated to surface water-dominated flow as moved downstream from Melrose to Pawseys. The
377 summer spot gauging along the stream continuum revealed that there is no measurable seepage
378 from stream to GW, thus summer low flow differences between Melrose and Pawseys is not due to
379 loss to GW from stream channel. The main difference between the Melrose and Pawseys
380 catchments is presence of invasive willows, which dominate the riparian zone in lower reaches of
381 the North Waipara River (Melrose to Pawseys), whereas in upper reaches (upstream from Melrose,
382 S6) willows have been totally removed. This arrangement allowed us to study water use by the
383 willows, since climate, land use, soils, and geology in the two catchments are similar.

384 Recent findings suggest different water sources for stream flow generation and water use by
385 plants (Brooks *et al.*, 2010; Evaristo *et al.*, 2016). Those studies showed that trees can use tightly
386 bound soil water, especially during dry periods. At our study sites, analysis of stable dual isotopes
387 ($\delta^{18}\text{O}$, $\delta^2\text{H}$) in water indicated water usage by individual willows in many cases diverged from
388 stream, groundwater and springtime near-stream suction lysimeter samples for the stretch from
389 Melrose to Pawseys, and resembled dryer soil water values taken concurrently from a hillslope in
390 nearby Lang's Gully (Dudley *et al.* 2017). This is a striking result, since our working hypothesis
391 was that the main water source for stream-side willows is stream water, especially since willows are
392 partly situated in-stream. The isotope values for willows varied temporally even for individual trees
393 (see Figure 8b), and there was no dependence on whether willows were situated in-stream or near-
394 stream. When we traced the isotope composition of the precipitation from which willow xylem
395 water originated, we found that the intersection points of the local plant xylem evaporation line with
396 LMWL indicated a plant xylem δ source value (see Evaristo *et al.*, 2015 for an explanation of the
397 method). The willow xylem source water δ value ($-81 \delta^2\text{H}$, $-11.45 \delta^{18}\text{O}$) differed from the value for
398 mean stream flow at Melrose ($-60.0 \delta^2\text{H}$, $-8.9 \delta^{18}\text{O}$) and the value for groundwater ($-59.9 \delta^2\text{H}$, -8.93
399 $\delta^{18}\text{O}$). The results from isotopic analyses thus indicate that stream-side willows can utilize several
400 water sources and there was no difference between the seasons in willow water source. An

401 explanation provided by Goldsmith et al (2012) for a similar pattern - preferential use of water from
402 dryer shallow soils by both canopy and understory species - was that the nutrient distributions
403 across soil depths may dictate rooting patterns and water sources. It may be that nutrient
404 requirements of willows also dictate that a significant portion of transpired water is derived from
405 dryer streambank soils, where nutrient availability is greater, ahead of readily-available, but more
406 oligotrophic streamwater and groundwater. Nevertheless, a significant role of riparian vegetation in
407 taking up stream discharge has been reported previously (Cadot *et al.*, 2012; Gribovszki *et al.*,
408 2010; Lundquist and Cayan, 2002; Lupon *et al.*, 2016; Kellogg et al. 2008). Riparian water demand
409 ($0.5\text{-}5\text{ mm day}^{-1}$) can lower the GW level and thus significantly (30-100%) decrease the amount of
410 GW entering the stream (Schilling, 2007; Dahm *et al.*, 2002; Folch and Ferrer, 2015). Moreover,
411 actual ET often exceeds estimated potential ET due to enhanced aerodynamic conductance,
412 stomatal conductance, and leaf area compared with reference surfaces and open water (Grip *et al.*,
413 1989; Hall *et al.*, 1998; Doody and Benyon, 2011).

414 According to our results, ET by stream-side willows can significantly influence stream
415 discharge in small headwater streams under low flow conditions. Even though stream-side willows
416 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
417 the catchment. Estimated average ET rate by stream-side willows was around 1.41 mm/day during
418 summer but reached up to 5.6 mm/day on individual days, thus explaining the majority of the
419 diurnal variation in low flow discharge in the catchment. This is in agreement to previously reported
420 willow transpiration values in Australia (5-12 mm/day, Doody and Benyon, 2011) and in the
422 Moutere region of New Zealand (Amaravathi, 2010). On an annual basis, ET by willows at the
423 study site was 0.74 mm/day (or 270 mm/a), while rather low at daily scale, still affects summer
424 water budgets because the bulk of willow transpiration occurs during mid to late summer when
425 flows tend to be low. Since these transpiration numbers are volume per area, they can be also used

426 in other similar regions to estimate willow water usage. Willows in our study area were clustered
427 close to the stream, or within the stream, due to steep river banks. Doody et al (2006) identified in-
428 stream willows (rather than those on banks) as filling an otherwise unoccupied niche, which lead to
429 a potential to return water to the stream should they be removed. The current presence of grazing
430 cattle, and previous history of vegetation removal in these pastoral catchments mean that willows
431 also occupy a niche that would be vacant in their absence, suggesting water savings if they were
432 removed. While the removal of willows would reduce transpiration, streams would lose their
433 shading effect and direct evaporation from water surface would increase. Quantification of water
434 savings that recognize this tradeoff (e.g. Doody and Benyon, 2011, Doody et al. 2013) are possible
435 for these systems.

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

448 By linking vegetation water use in headwater catchments to the timing and magnitude of
449 flows from these catchments, a more realistic low-flow estimate can be produced. The data
450 presented here indicate that riparian land cover can influence water availability in downstream

451 areas. Our results showed the vulnerability of low flows to water uptake by invasive willow trees,
452 which dominate stream-side areas in many regions of New Zealand and Australia. Thus willow
453 removal could be a potential tool to manage low-flow conditions, especially during prolonged dry
454 spells. Although, this will depend strongly upon the water-use characteristics of replacement
455 vegetation.

456

457 **6 Conclusions**

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

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

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

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

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

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

474

475

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