

A groundwater recharge perspective on locating tree plantations within low rainfall catchments to limit water resource losses

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Abstract

Despite the many studies that consider the impacts of plantation forestry on groundwater recharge, and others that explore the spatial heterogeneity of recharge in low rainfall regions, there is little marriage of the two subjects in forestry management guidelines and legislation. Here we carry out an in-depth analysis of the impact of reforestation on groundwater recharge in a low-rainfall (>700 mm annually), high-evapotranspiration paired catchment characterised by ephemeral streams. Water table fluctuation (WTF) estimates of modern recharge indicate that little groundwater recharge occurs along the topographic highs of the catchments (average 18 mm/yr); instead the steeper slopes in these areas direct runoff downslope to the lowland areas, where most recharge occurs (average 78 mm/yr). Recharge estimates using the chloride mass balance (CMB) method were corrected by replacing the rainfall input Cl^- value with that for streamflow, because most recharge occurs from infiltration of runoff through the stream bed and adjacent low gradient slopes. The calculated CMB recharge values (average 10 mm/yr) are lower than the WTF recharge values (average 47 mm/yr), because they are representative of groundwater that was mostly recharged prior to European land clearance (>200 years BP). The tree plantation has caused a progressive drawdown in groundwater levels due to tree water use; the decline is less in the upland areas.

30 The results of this study show that spatial variations in recharge are important considerations
31 for locating tree plantations. To conserve water resources for downstream users in low
32 rainfall, high evapotranspiration regions, tree planting should be avoided in the dominant zone
33 of recharge, i.e. the topographically low areas and along the drainage lines, and should be
34 concentrated on the upper slopes, although this may negatively impact the economic viability
35 of the plantation.

36

37 **1 Introduction**

38 Tree plantations are known to have the potential to reduce groundwater recharge and surface
39 water flows (e.g. Bell et al., 1990; Benyon, 2002; Bosch and Hewlett, 1982; Jobbagy and
40 Jackson, 2004; Scanlon et al., 2007; van Dijk et al., 2007), particularly in low rainfall, high
41 evapotranspiration regions where the high transpiration demands of the trees make them a
42 significant user in the water balance (e.g. Benyon et al., 2006; Fekeima et al., 2010; Jackson
43 et al., 2005; Schofield, 1992). This is often regarded as a negative aspect of tree plantations,
44 but may be a positive outcome if the aim of a particular forestry project is to reduce
45 groundwater levels, e.g. to decrease groundwater salinization (discussed further below).
46 Groundwater recharge in low rainfall regions is also affected by a variety of other factors that
47 cause substantial spatial variability, in particular topography, soil characteristics and geology
48 (e.g. Delin et al., 2000; Scanlon et al., 2002; Schilling, 2009; Webb et al., 2008; Winter,
49 2001). However, the important conclusions made in the recharge studies have not been
50 brought together with the results of tree plantation studies and directly applied to water
51 resource management problems accompanying the establishment of tree plantations (Farley et
52 al., 2005).

53 Since the earliest work on defining groundwater systems, recharge has been shown to be
54 controlled predominantly by topography: the majority of groundwater recharge occurs at
55 topographic highs, and discharge is mostly in topographic lows where the upward hydraulic
56 gradient prevents recharge from occurring (Domenico and Schwartz, 1998; Schilling 2009).
57 However, in arid and semi-arid regions, recharge following rainfall events often occurs
58 predominantly in local depressions and along ephemeral streams (diverging from early
59 conceptual models), due to the focussing of overland flow in these areas. Water tables under
60 ephemeral streams are generally below the streambed (except during extended rainfall
61 events), and therefore upwards groundwater gradients do not occur most of the time.

62 Infiltration beneath these areas may also be encouraged by the presence of preferential
63 pathways, along which infiltrating water may more readily reach the water table (Delin et al.,
64 2000; Scanlon et al., 2002; Schilling, 2009; Winter, 2001). In south-eastern Australia in
65 particular, it has been observed that recharge can vary significantly within catchments due to
66 multiple modes of recharge (Cartwright et al., 2007).

67 Vegetation can significantly impact groundwater recharge due to transpiration and by
68 intercepting rainfall and overland flow (Scanlon et al., 2002; Winter, 2001); changing land-
69 use can therefore affect recharge patterns. For example, land salinisation has occurred in large
70 parts of south-eastern Australia due to the replacement of native forest by pasture and crops
71 that use less water; this has led to increased recharge which raised water tables, causing saline
72 groundwater to come to the land surface and discharge into surface water features (Allison et
73 al., 1990; Bennetts et al., 2006, 2007). In contrast, afforestation of cleared farmland is likely
74 to decrease recharge, due to the high rate of transpiration by the actively growing, closely
75 planted trees, as well as the interception of overland flow and evaporation from the canopy
76 (Benyon et al., 2006). In particular, the evergreen Eucalyptus tree plantations commonly
77 planted in south-eastern Australia take up and transpire significantly more water than pasture,
78 their canopy intercepts more rainfall and allows it to evaporate, and their roots reach greater
79 depths than grasses, meaning they can extract water over a larger volume of the soil column
80 (Bosch and Hewlett, 1982; Feikema et al., 2010; Hibbert, 1967). This recharge reduction is
81 the reason why some studies have suggested using targeted tree plantations to reduce recharge
82 in areas where there are high rates of saline groundwater discharge (e.g. Bennetts et al., 2007).
83 Tree plantations also sequester carbon dioxide, prompting ongoing debate over the trade-off
84 between increased water use by trees versus their increased carbon sequestration potential
85 (Farley et al., 2005). As such, efforts over the past few decades in south-eastern Australia to
86 reforest land that was cleared in the late 1800s by European settlers (Schofield, 1992) are now
87 causing difficulties for land managers trying to define sustainable action plans for surface
88 water and groundwater (Dalhaus et al., 2008; Jackson et al., 2005; Nicholson et al., 2006).

89 A whole catchment approach is key to managing groundwater recharge in the context of land
90 use change (Cartwright et al., 2007). However, despite the evidence that recharge is often
91 concentrated in topographic lows, groundwater management strategies in south-eastern
92 Australia typically operate on the assumption that recharge occurs primarily in the upper parts
93 of catchments, particularly along the ridgelines. Current regulations for tree plantations in

94 Australia focus on the percentage of a given catchment that can be forested, rather than what
95 areas should be planted to maintain or intercept groundwater recharge, depending on the
96 management application.

97 Here we present the findings from a paired catchment study in south-western Victoria,
98 Australia, where one catchment is planted with a tree plantation, and the adjacent catchment is
99 covered with pasture. This approach largely removes the variables of climate, topography,
100 soil and geology, with the only major difference between the two catchments being vegetation
101 cover. Previous paired catchment studies on the impact of tree plantations tended to focus on
102 surface water responses to afforestation, while groundwater has been somewhat neglected
103 (Brown et al., 2005). In this study conceptual models of groundwater flow (based on ^{14}C and
104 tritium groundwater dating) and groundwater recharge estimates (based on the water table
105 fluctuation and chloride mass balance methods) are used to assess the impact of a *Eucalyptus*
106 *globulus* plantation on the hydrologic and hydrogeologic regime. This contextualisation is
107 then used to discuss the best areas to site tree plantations within low rainfall catchments.

108

109 **2 Background**

110 This study is part of a multi-site, paired-catchment investigation into the impacts of land use
111 and climate change on the quality and quantity of groundwater and surface water resources in
112 western Victoria, Australia (Adelana et al., 2014; Camporese et al., 2013, 2014; Dean et al.,
113 2014; Dresel et al., 2012).

114 **2.1 Site description**

115 The study area consists of a pair of small, adjacent catchments at Mirranatwa in south-western
116 Victoria, one (referred to as the eucalypt catchment) covered predominantly in a recently
117 planted (July 2008) *Eucalyptus globulus* (Blue Gum) plantation (0.8 km²), the other (referred
118 to as the pasture catchment) is mostly pasture for grazing sheep (0.4 km²; Fig. 1).

119 **2.1.1 Geology**

120 Both catchments are underlain by the same weathered/fractured aquifer, the Devonian Dwyer
121 Granite (390-395 Ma; Hergt et al., 2007; VandenBerg 2009). The upper ~20 m of the granite
122 is well-weathered, porous and permeable saprolite; below this is relatively fresh, fractured
123 bedrock. The fractured granite aquifer extends no deeper than 150 m, as below this depth the

124 fracture conductivity is negligible due to the high lithostatic pressure (Boutt et al., 2010;
125 Cook, 2003; Dept. Sustainability and Environment, 2012). The granite saprolite is generally
126 thicker beneath the lower parts of the catchment than along the ridges, and is overlain by up to
127 7 m of alluvial/colluvial material along and adjacent to drainage lines. This
128 alluvium/colluvium is clay-rich and impermeable in places, causing temporally variable
129 artesian behavior in some of the bores along the drainage lines in both catchments. The
130 topography of the site (hills in the middle of a broad valley, Fig. 1) means both catchments
131 are local ground water systems, and there are no regional groundwater inputs. There is 50 m
132 of relief in the eucalypt catchment, and 30 m in the pasture catchment; both catchments
133 comprise reasonably steep hills separated by a marked break in slope from the more or less
134 flat topography along the drainage lines (Fig. 1).

135 2.1.2 Climate and Land use

136 The climate is Mediterranean, maritime/temperate (Cfb in the Köppen classification); the
137 average annual rainfall since records began in 1901 for the area is 672 mm ($\pm 125 \sigma$), while
138 pan evaporation is around 1350 mm annually, exceeding rainfall for the majority of the year,
139 excepting the winter months of May to September (Dean et al., 2014). Runoff ratios for the
140 pasture and eucalypt catchments are 3.0% and 3.3% respectively (based on the stream
141 hydrograph records from February 2011 to February 2014), and both streams are ephemeral.

142 Vegetation of the area prior to European settlement was mostly open eucalypt woodland
143 (Department of Sustainability and Environment, Victoria). Following European settlement
144 there was extensive land clearance, and the catchments were entirely converted to pasture by
145 1869 (White et al., 2003). 76% of the northern catchment was subsequently converted to an *E.*
146 *globulus* plantation in July 2008 (Fig. 1). Prior to the planting of the eucalypts, the eucalypt
147 plantation catchment (Euc – Table 1) was used for grazing, and was virtually identical to the
148 pasture grazing catchment (Pas – Table 1) immediately to the south. During the planting of
149 the trees the eucalypt catchment was ripped to an average depth of 800 mm and mounded to
150 an average height of 300 mm. The tree density is 1010 stems per ha (2.2 m between trees
151 along a row, and 4.5 m between rows), and fertilizer was applied following ripping and
152 mounding at 60 kg per ha (McEwens Contracting, pers. comm.). The tree rows run east-west
153 across the slope in the main north-eastern part of the catchment, and north-south (~down the
154 slope) to the west of H Addinsalls Road (Fig. 2).

155 2.1.3 Catchment instrumentation

156 The pasture catchment has 13 bores drilled to different depths, and the eucalypt catchment has
157 10 bores (the bores may be considered to be piezometers – they are screened towards the
158 bottom of the casing over a discrete two metre interval; Table 1). Seven bores in the eucalypt
159 catchment and two bores in the pasture catchment were drilled for this project in late 2009;
160 the other bores were installed in the late 1980s in the pasture catchment, and the mid-1990s in
161 the eucalypt catchment. A groundwater logger was installed in every bore in the eucalypt
162 catchment in August 2009, measuring at a minimum four hour time interval, and eight bores
163 in the pasture catchment have loggers measuring at the same frequency. There is a v-notch
164 weir at the end of each catchment on both streams, with one bore immediately adjacent to the
165 eucalypt catchment weir and two next to the pasture catchment weir (Fig. 1). The bores
166 adjacent to the weirs have Campbell CS450-L pressure transducers (accuracy ± 0.01 m)
167 measuring water level and electrical conductivity (EC) at 30-minute intervals, while the other
168 bores have Schlumberger Mini Diver loggers (accuracy ± 0.025 m) measuring only water
169 level. At the weirs the surface water level was measured using a standard V-notch
170 construction, and electrical conductivity (EC) was recorded using a logger in the weir pool
171 (Dresel et al., 2012). Prior to installation of groundwater loggers in the older bores,
172 groundwater levels were generally measured manually bi-monthly.

173 There are two small dams in each catchment, ranging in size from 10 m^2 to 50 m^2 ; they are
174 not large enough to significantly impact the hydrology of the site (Fig. 1). The roads at the
175 site are single lane and unsealed, and although they are less permeable than the normal ground
176 surface and therefore promote runoff, their very small area means that they have negligible
177 impact on the site hydrology.

178

179 **3 Methods**

180 Groundwater levels, surface water flow and rainfall data were collected from August 2009 to
181 February 2013 for this study, with some older long-term groundwater level data from manual
182 measurements going back as far as 1986 available from the Victorian Department of
183 Environment and Primary Industries archives. Groundwater and surface chemistry is available
184 from sampling campaigns between August 2010 to August 2011 (Dean et al., 2014).

185 **3.1 Rainfall and streamflow**

186 Daily rainfall measurements were available from a Bureau of Meteorology station (089019)
187 approximately two kilometres south of the study site; rainfall was also measured in the study
188 catchments and showed an excellent correlation with the Bureau of Meteorology station. Due
189 to significant gaps in the onsite data, the Bureau of Meteorology station data was used for
190 consistency throughout the study period. To determine rainfall patterns, cumulative deviation
191 from the monthly mean (CDM) values were calculated alongside daily values (section 4.1.1),
192 whereby the difference between a given monthly rainfall total and the average for that month
193 (calculated from the entire station's data record of 1901 to 2012), was cumulatively summed
194 from one month to the next (modified from Craddock, 1979). The CDM values represent the
195 longer term rainfall patterns, with a sustained negative trend for drought periods and positive
196 values indicating wetter than usual periods, and match well with the longer term hydrographs
197 (section 4.1).

198 Streamflow in both catchments is ephemeral, and was measured at 30-minute intervals at V-
199 notch weirs at both catchment outlets and summed to annual totals, and a total for the
200 complete study period, 2009-2013. To allow comparison between catchments, volumes were
201 converted to depth equivalents (mm) by dividing by the respective catchment area.
202 Streamflow is derived predominantly from direct runoff, as the proportion of groundwater
203 input into the stream is small (discussed further below).

204 **3.2 Grain size analysis**

205 The grain size of the saprolite was used to estimate the average specific yield value for this
206 aquifer over the whole study site, as the geology of the two catchments is very similar (see
207 section 3.6.1). During drilling of five bores on the eucalypt catchment, samples of the regolith
208 were taken at one metre intervals to a depth of 10 m, or until bedrock was encountered.
209 Samples were sieved using a two-millimetre sieve and the material that passed through was
210 then analysed using a Malvern Mastersizer 2000.

211 **3.3 Groundwater composition**

212 All 23 groundwater bores across the entire site were sampled once each over a period of a
213 year, from August 2010 to August 2011. Seasonal variability in groundwater composition is
214 considered negligible due to the age of the groundwater at the study site (mostly >200 years;

215 Table 1), and repeat sampling produced virtually identical field parameters (Dean et al.,
216 2014). Subsamples for Cl^- were filtered with 0.45 μm filter paper and analysed using Ion
217 Chromatography. Groundwater sampling, Cl^- analyses and calculations of volume-weighted,
218 average rainfall Cl^- concentrations are described in more detail in Dean et al. (2014).

219 **3.4 ^{14}C analysis and tritium analysis**

220 Dating of the groundwater was carried out to determine the time period over which recharge
221 has occurred. Groundwater samples from all the bores at the study site were ^{14}C dated and no
222 corrections were applied, as there is no indication that the radiocarbon ages have been
223 compromised by “dead” carbon in the regolith; standard error of groundwater ages is 25-100
224 years (Dean et al., 2014). In addition, seven bores in the eucalypt catchment and 11 bores in
225 the pasture catchment (including the shallowest and deepest bores and a range in between),
226 were dated using tritium (standard error in these measurements was 0.005-0.015 Bq kg^{-1} ;
227 Dean et al., 2014; Table 1). The methodologies for both are described in more detail in Dean
228 et al. (2014).

229 **3.5 Radon (^{222}Rn)**

230 Radon surveys were carried out on groundwater and surface water samples in both
231 catchments to ascertain whether there is a significant contribution of groundwater to surface
232 water flow. The ^{222}Rn content of surface water and groundwater was measured using the gas-
233 extraction for H_2O accessory of the Durridge RAD-7 radon detector. The RAD-7 is an alpha
234 particle detector that measures the decay of the radon daughters, ^{214}Po and ^{218}Po . Samples
235 from weirs, bores and dams (disconnected surface water bodies; Fig. 1) were collected in 250
236 ml vials and aerated for five minutes to degas the radon into the air circulation within the
237 instrument, which takes four measurements (five minutes each), and then gives the mean
238 ^{222}Rn concentration in Bq/L ; the average standard error for measurements using this
239 instrument is 10% (Durridge Co. Inc., 2010).

240 **3.6 Groundwater recharge**

241 To ensure robust estimates of groundwater recharge, two different, well established methods
242 were used, namely the water table fluctuation method and chloride mass balance method.

243 While both methods are in widespread use, they have known deficiencies that are discussed
244 below.

245 3.6.1 Water table fluctuations

246 The water table fluctuation (WTF) method for measuring groundwater recharge was first
247 applied in the 1920s (Healy and Cook, 2002; Meinzer, 1923) and has since been refined (e.g.
248 Jie et al., 2011; Scanlon et al., 2005; Sophocleus, 1991). The principle of this method is that
249 rises in the groundwater hydrograph of an unconfined aquifer provide an estimate of recharge
250 to the water table, calculated from:

$$251 \quad R = S_y \frac{\Delta h}{\Delta t} \quad (1)$$

252 where recharge (R) is the product of the specific yield of the aquifer (S_y) and the change in
253 hydrograph height (Δh) over a given time interval (Δt). This method assumes that recharge
254 occurs vertically from piston flow and that water discharges continuously from the aquifer,
255 causing a drop in the water table when recharge is not occurring. Therefore the change in
256 hydrograph height from which recharge is calculated is the sum of the rise in the hydrograph,
257 together with the decline in the hydrograph that would have occurred in the absence of
258 recharge over the same time period (Healy and Cook, 2002; Jie et al., 2011). Several
259 techniques have been developed to estimate the hydrograph decline: the graphical approach –
260 where the exponential decay curve of the hydrograph is manually extended to coincide with
261 the peak of the next recharge event (Delin et al., 2007), the master recession curve approach –
262 where regression functions are assigned to simulate the potential hydrograph decline for each
263 data time-step (Heppner et al., 2007), and the RISE approach – where the assumption is made
264 that in the absence of recharge, no decline in the water table occurs (Jie et al., 2011; Rutledge,
265 1998).

266 It proved difficult to apply the graphical and master recession curve methods in the present
267 study because these methods focus on the section of the hydrograph recession limb which
268 decays exponentially, whereas the recession limbs in the Mirranatwa hydrographs often had
269 significant sections which were steep and straight (Fig. 3); this can lead to the
270 underestimation of actual groundwater recharge, as has been highlighted elsewhere (Cuthbert,
271 2014). In addition, because the streams in both study catchments are ephemeral, groundwater
272 discharge as baseflow occurs only occasionally; the majority of groundwater discharge occurs
273 at the bottom of the catchments and downstream of the catchment boundaries. This

274 intermittent baseflow means that the recession curve in the hydrographs following a recharge
275 event may not be exponential (as observed in the hydrographs). Because the assumption of an
276 exponential recession curve is implicit in the graphical and master recession curve WTF
277 methods, the RISE approach was adopted, i.e. the decay curve of the hydrograph was ignored.
278 Applying the RISE approach means that the values calculated in this study potentially
279 underestimate actual recharge, but when compared with the graphical approach carried out for
280 sections of the hydrographs where exponential recession curves were evident, gave very
281 similar values.

282 Raw bore hydrograph data collected using data loggers at the site contain small fluctuations
283 due to the impact of barometric pressure on the water column in the bore (Fig. 3a; Rasmussen
284 and Crawford, 1997). The fluctuations in the water level and the barometric pressure are
285 normally inversely correlated (Butler et al., 2011), and can be readily corrected (Rasmussen
286 and Crawford, 1997; Toll and Rasmussen, 2007). At the study site these fluctuations are
287 clearly positively correlated with barometric fluctuations (Fig. 3a), and as a result normal
288 barometric compensation techniques could not be applied. Instead a 15-day moving average
289 was used to remove the small fluctuations but retain the overall response to rainfall (Fig. 3b).
290 The 15-day timestep is a narrow enough time period to incorporate recharge events and reflect
291 the general trend of the hydrograph, but removes the small barometrically forced fluctuations
292 that bear no relationship to rainfall (Fig. 3). Recharge was then calculated using equation [1],
293 where Δh was taken as the sum of the increases in groundwater level over the timestep, and
294 then summed for the entire length of the record. When there was a drop in groundwater level
295 from one timestep to the next, this was taken as zero recharge. The measurement uncertainty
296 of the loggers (± 0.025 m) was used as the threshold for recognition of recharge for each 15-
297 day timestep. The RISE method was also used to calculate recharge for the longer-term
298 hydrographs (generally bi-monthly measurements taken prior to logger installation).

299 A specific yield value of 0.095 ± 0.014 was calculated for the unconfined saprolite aquifer
300 from the average grain size (clay to coarse sand; Table 2) of all the bore samples analysed
301 (see Section 3.2), using the general relationship between specific yield and grain size in Healy
302 and Cook (2002, Tables 1 and 2). The estimation of specific yield is a potential source of
303 considerable error in recharge calculations as it can vary spatially, although it can be assumed
304 to be independent of time (Healy and Cook, 2002). The specific yield value calculated here is
305 comparable to other values from weathered granites in the region (0.043 – Hekmeijer and

306 Hocking, 2001; 0.075 – Edwards, 2006). When calculating recharge for the study site, this
307 specific yield was applied to bores that are screened within the saprolite, and is assumed to be
308 representative for the whole site because of the relatively uniform nature of the soils (Table
309 2).

310 3.6.2 Chloride mass balance

311 The chloride (Cl^-) mass balance (CMB) method for calculating recharge is based on the
312 relationship between Cl^- in groundwater and in precipitation, assuming that all Cl^- in the
313 groundwater is derived from rainfall and remains in solution within the groundwater system,
314 that direct recharge (R , in mm) occurs via piston flow, and that runoff is negligible:

$$315 \quad R = P \frac{C_p}{C_{gw}} \quad (2)$$

316 where P is the amount of rainfall (mm), C_p is the concentration of Cl^- in P , and C_{gw} is the
317 concentration of Cl^- in groundwater (Allison and Hughes, 1978; Scanlon et al., 2002). R was
318 calculated at all bores using the groundwater Cl^- content (Table 1), and rainfall Cl^- content
319 was the median value from three different sampling periods at nearby sites (Fig. 1): 1954-
320 1955 at Cavendish (Hutton and Leslie, 1958), 2003-2004 at Hamilton (Bormann, 2004), and
321 2007-2010 at Horsham (Nation, 2009); all Cl^- values were volume weighted based on rainfall
322 during the sampling periods in these studies. These three sampling periods include a wet
323 period (1954-1955) and two dry periods (2003-2004 and 2007-2009). The median rainfall Cl^-
324 from all of these studies is 4.3 ± 0.9 mg/L, and the annual rainfall is 672 ± 125 mm (1σ); the
325 uncertainties associated with each value were used to estimate the overall uncertainty in the
326 recharge values calculated. R is strongly governed by C_p in this equation, so it is important to
327 take into account the variability in C_p .

328

329 4 Results and discussion

330 4.1 Groundwater recharge estimates

331 Recharge estimates calculated using both the WTF and CMB methods range from 0.8 ± 0.3 to
332 161 ± 24 mm/yr (Table 3), a very wide range that matches recharge calculations from similar
333 climatic areas in Australia ($5 - 250$ mm/yr; Allison and Hughes, 1978; Cook et al., 1989), and
334 elsewhere from low rainfall regions around the world ($0.2 - 35$ mm/yr; Scanlon et al., 2006).

335 4.1.1 Water table fluctuation method

336 The groundwater hydrographs vary significantly across the study site (Fig. 4), indicating
337 substantial variation in groundwater recharge. Because hydrographs from the upper parts of
338 the catchment show a limited response to rainfall patterns, both in the detailed groundwater
339 logger data (Fig. 4) and the longer term monitoring data for the older bores (Fig. 5), recharge
340 values calculated using the WTF method are relatively low for these areas in both catchments
341 (average 18 mm/yr; 3% of rainfall).

342 In contrast, bores on or close to drainage lines show a much greater sensitivity to sustained
343 rainfall and streamflow events (e.g. for bore Pas96, rises in the hydrograph directly
344 correspond to flow in the ephemeral stream channel; Fig. 6). As a result, recharge values
345 calculated from logger data and longer-term hydrographs using the WTF method are
346 relatively high for low-lying areas in both catchments (average 78 mm/yr; 12% of rainfall;
347 Fig. 4; Table 3). These recharge trends have been consistent over the past 20-30 years (Fig.
348 5).

349 The greater recharge in the lower-lying areas is predominantly because the steeper slopes in
350 the upland areas direct runoff downslope to the lowland areas, which are consequently
351 saturated for longer with a greater volume of runoff. In addition, runoff velocities across the
352 lower areas decrease due to the reduction in slope, allowing more infiltration into the soil.
353 Runoff from the upland areas is aided by the low permeability, silty soils (Table 2), and
354 infiltration in the lower lying areas, particularly through the stream bed, is increased by the
355 greater depth of weathering (9 m depth to bedrock in the pasture catchment and 30 m in the
356 eucalypt catchment, except at the very bottom of this catchment).

357 Two of the lowland bores (Euc84 and Euc85) show very similar recharge patterns to upland
358 bores (e.g. Euc83), i.e. little recharge, due to the presence of a localised confining layer (both
359 bores frequently go artesian; Fig. 4).

360 Two of the upper slope bores show high recharge (Pas74 and Pas 78), due to preferential
361 recharge down fractures in the granite (Section 4.2; Fig. 5).

362 4.1.2 Chloride mass balance method

363 Recharge values calculated from the CMB method (equation 2) are much lower than the WTF
364 method values, often by an order of magnitude or more (Table 3), e.g. Pas96 has recharge

365 values of 1.1 ± 0.4 mm/yr (CMB) and 161 ± 24 mm/yr (WTF), and Pas82 has a CMB value of
366 8.8 ± 3.3 mm/yr and a WTF value of 26 ± 4 mm/yr. Furthermore, the bore hydrographs used
367 to calculate the WTF recharge values indicate that there is much more recharge occurring in
368 the lowland areas than is indicated by the CMB values.

369 The most likely explanation for the mismatch between the CMB and WTF results is that the
370 input Cl^- value used in the CMB method should be for runoff/streamflow rather than rainfall,
371 because most recharge occurs from infiltration of surface flow through the stream bed and
372 across the low gradient slopes adjacent to the streams, as previously discussed.

373 To account for this difference, the CMB values were recalculated using the volume and Cl^-
374 content of streamflow (assumed to be the same as runoff here) in place of rainfall in equation
375 2:

$$376 \quad R = RO \frac{C_{ro}}{C_{gw}} \quad (3)$$

377 where RO (mm) is the estimated amount of runoff that would reach a given bore, and C_{ro} is
378 the estimated Cl^- concentration of the runoff (volume weighted).

379 The volume of runoff at a particular bore (RO) is calculated using streamflow as a proxy for
380 runoff, by dividing the average streamflow per year by the amount of the catchment that could
381 theoretically provide runoff to the bore location (i.e. a bore in the middle of the catchment is
382 only going to receive approximately half the runoff that could potentially recharge a bore at
383 the bottom of the catchment). The Cl^- concentration of the runoff (C_{ro}) is calculated from the
384 average EC measured at each weir (May 2010 to February 2013), converted to Cl^- using the
385 EC: Cl^- ratio for the study site dataset (0.39 and 0.37 for the pasture and eucalypt catchments
386 respectively). Equation 3 was only applied to bores in the lowland parts of the landscape
387 where runoff is likely to recharge the groundwater. Because of the highly variable nature of
388 the streamflow Cl^- , the potential variation in recharge values calculated from equation 3 is
389 large, and this is seen in the error values (1σ – Table 3).

390 The recalculated recharge values generated from equation 3 are much closer to the WTF
391 recharge values, but are still generally a factor of five to 15 lower. This may reflect the fact
392 that the groundwater across the study site is mostly >200 years old, indicating that the CMB
393 values are generally representative of recharge rates under native vegetation prior to land
394 clearance during European settlement in the late 1800s, whereas the WTF values represent
395 recent recharge (August 2009 to February 2013). The older, pre-European settlement

396 vegetation caused lower recharge, as these trees transpire much more water from groundwater
397 and the soil zone than modern pasture. This disparity between modern and pre-European
398 recharge rates has been observed elsewhere in south-eastern Australia (e.g. Allison et al.,
399 1990; Bennetts et al., 2006, 2007; Cartwright et al., 2007).

400 The CMB method estimates of recharge do not vary significantly between the two
401 catchments, showing that both catchments behaved in a similar fashion before measurements
402 began, prior to the establishment of the plantation. This corrects for the lack of a calibration
403 period prior to the change in land use, a potential source of considerable error (Brown et al.,
404 2005).

405 **4.2 Topographic controls on recharge**

406 Recharge estimates using the WTF method (Table 3) show that within the local groundwater
407 systems of the study catchments, variations in recharge predominantly reflect differences in
408 topography. Dominant areas of recharge are not along the topographic highs of the
409 catchments, as in the traditional conceptual model of recharge, but are instead analogous with
410 more arid regions, where most recharge occurs in topographic depressions (Scanlon et al.,
411 2002).

412 Recharge rates increase as surface elevation decreases (Fig. 7). The steeper slopes of the
413 upland areas promote runoff rather than infiltration, aided by low permeability, silty soils
414 (Table 2). Overland flow is focused into topographic lows and along drainage lines. Here the
415 granite is most weathered, as indicated by the greater depth to bedrock here (9 m in the
416 pasture catchment, and 30 m in the eucalypt catchment except at the very bottom of this
417 catchment), encouraging recharge to occur, particularly through the stream bed.

418 **4.3 Influence of fractures on groundwater recharge**

419 The ^{14}C data (Table 1) shows that most of the groundwater at the study site is older than the
420 tree plantation, but the groundwater in some bores (Pas74, Pas81, Euc93 and Euc97) also
421 contains measurable tritium, indicating a component of younger groundwater (<50 years old).
422 Recharge in fractured rock aquifers like granite is controlled to some extent by the fracture
423 network (Cook, 2003), which forms multiple recharge pathways. In the study area this has
424 allowed mixing of young groundwater (containing tritium) with much older groundwater (as
425 shown by the ^{14}C dates; Table 1). The hydrograph for the upslope bore Pas74 (Fig. 4) shows

426 high recharge following rainfall events (in contrast to most of the other upslope bores), most
427 likely because it is located on a fracture in the granite that allows rapid recharge, as shown by
428 the dilute groundwater with low Cl⁻ concentrations (Dean et al., 2014) and the presence of
429 significant amounts of tritium (Table 1).

430 This dual porosity (matrix and fracture flow) influence on recharge has been observed
431 elsewhere in south-eastern Australia where there was disparity between the residence times of
432 groundwater samples (Cartwright et al., 2007). Nevertheless, the dominant recharge control
433 across both catchments is topography rather than fracture heterogeneity, as shown by the
434 relatively flat hydrographs for most of the upland bores, and strongly oscillating hydrographs
435 in the lowland bores (Fig. 4).

436 **4.4 The interplay between ephemeral stream flow and groundwater recharge** 437 **and discharge**

438 The streams at the study site are ephemeral, flowing on average only 40% of the time at the
439 catchment outlets. When they are dry, recharge can occur readily along and near the
440 streambeds as upwards groundwater gradients are not present, because the water table is
441 below the base of the stream. As a result, bores in the lower parts of the catchments (e.g.
442 Pas96 near the outlet of the pasture catchment; Fig. 6) show a clear, sometimes instantaneous
443 link between recharge and runoff.

444 Following extended periods of wet weather, the ephemeral stream at the bottom of the
445 eucalypt catchment is fed by groundwater discharge, as shown by the significant levels of
446 ²²²Rn measured at the weir (11 Bq/L; Fig. 8); groundwater at the bottom of this catchment is
447 forced upwards because granite bedrock lies less than two metres below the surface (Fig. 9).
448 In contrast, the bedrock at the bottom of the pasture catchment is nine metres deep, so the
449 water table lies more consistently below the base of the stream and there is less groundwater
450 discharge; as a result, the pasture catchment has fewer low flows than the eucalypt catchment
451 (Fig. 9) and lower ²²²Rn levels (1 Bq/L at the weir; Fig. 8).

452 In both catchments, during periods of little or no rainfall, the water table lies below the
453 surface, so recharge can occur along the length of the channel. When it begins to rain and the
454 system wets up, the water table rises at the downstream end of the catchment and groundwater
455 begins to discharge here (this occurs more frequently and to a greater extent in the eucalypt
456 catchment). Continued rain raises the water table so it connects to the stream further

457 upstream, increasing the length of the stream that receives groundwater discharge (Fig. 9;
458 Adelana et al., 2014). When rainfall ceases, the water table drops and progressively
459 disconnects from the stream, starting upstream, until it is completely disconnected throughout
460 the catchment. This means that during smaller rainfall events, when the water table remains
461 below the land surface and does not connect to the stream, recharge occurs along the length of
462 the stream. During larger rainfall events, as the water table comes to the surface along the
463 stream channel, the area of potential recharge decreases.

464 The groundwater hydrographs indicate that during the study period, recharge occurred readily
465 in the lowland areas of both catchments, particularly when there was enough rainfall to
466 generate consistent flow in the streams, while much less recharge is evident on the upper
467 slopes. There is relatively little groundwater discharge along the streams, as shown by the
468 ²²²Rn data (Fig. 8), and groundwater within the catchments is lost predominantly through
469 evapotranspiration, particularly when the water table is within two metres of the ground
470 surface (as commonly occurs in south-eastern Australia, e.g. Bennetts et al., 2006, 2007); a
471 small amount flows out at the bottom of the catchment.

472 **4.5 Vegetation controls on recharge**

473 The bore hydrographs in the eucalypt catchment show a clear overall declining trend of up to
474 3 m during the study period, evident even in artesian bores (Euc84 and Euc85), and regardless
475 of landscape position (Fig. 4). This decline is not evident in hydrographs from the pasture
476 catchment (Fig. 4), where the water table has increased by 0.5-1 m during the whole study
477 period as a result of consecutive wet summers of 2010/11 and 2011/12 (Fig. 7). The tree
478 plantation was a little over one year old when the main measurements of this study began, and
479 as the age of the plantation increased, a steeper decline in groundwater depth was observed
480 (Fig. 4).

481 The water level decrease in the eucalypt catchment, with no corresponding drop in the pasture
482 catchment, is attributed to greater water use by the trees, as has been demonstrated elsewhere
483 (e.g. Adelana et al., 2014; Bosch and Hewlett, 1982). The water table decline is less in the
484 upland areas (Fig. 9), probably because recharge rates here are lower, so that the decrease in
485 recharge due to tree water use has had relatively little impact. Furthermore, in the upland
486 areas the water table is too deep for the vegetation to access the groundwater directly; Benyon
487 et al. (2006), in a study in the same region of south-eastern Australia, found that deep-rooted

488 eucalypts can only access groundwater up to a depth of six to eight metres. In the lowland
489 areas the trees are able to reach the groundwater (Fig. 2), and this, combined with the
490 interception of potential recharge in the soil zone by the growing plantation, causes the
491 observed decline in groundwater level (Fig. 4). Although tree roots can provide preferential
492 pathways for infiltration of rainfall to the water table (Burgess et al., 2001), any effect of this
493 is masked by the overall impact of eucalypt water use. The increasing rate of decline in
494 groundwater depth over time can be attributed to the greater water usage by the trees as they
495 grow (Fig. 4).

496 The narrow areas immediately adjacent to the drainage lines in the eucalypt catchment are
497 covered in grass and therefore there is less direct interception of potential recharge, but in fact
498 these areas show the biggest decline in groundwater level (Fig. 7). The highest rates of
499 recharge occur along the drainage lines and the adjacent trees will therefore have a substantial
500 impact there, in particular because they are directly accessing the groundwater.

501 With groundwater levels in the eucalypt catchment still in decline at the end of the study
502 period, five years since the establishment of the eucalypt plantation, there is no sign that the
503 system is reaching equilibrium under the new land use. Brown et al. (2005) indicate that
504 equilibrium would not be expected until more than five years after the land-use change
505 occurred.

506 **4.6 Management of tree plantations and recharge**

507 Afforestation of farmland was widespread in south-eastern South Australia and south-western
508 Victoria (known as the Green Triangle) from the 1980s through to the 2000s, with the
509 plantation area expanding by 5-14% to 30,000 ha in Victoria alone (Adelana et al., in 2014;
510 Benyon et al., 2006; Ierodiconou et al., 2005). However, the subsequent development of tree
511 plantations in the region has been hindered by a poor timber market (HVP Plantations, pers.
512 comm.) and concerns that plantations use more groundwater and surface water than other land
513 uses like farming. As a result, tree plantations in the state of South Australia must now be
514 licenced as groundwater users (Govt. of South Australia, 2009), while it is hoped that the
515 potential reduction in water availability resulting from reforestation will be offset by the
516 beneficial gains of the carbon sequestration within the new trees (Schroback et al., 2011).

517 A reduction of groundwater recharge by plantations, as documented in this study, lowers the
518 water table and can reduce stream flow. If this is the object of the reforestation, for example to

519 reduce saline groundwater discharge, then this land-use change may well serve its purpose
520 (Bennetts et al., 2007). However, the recent drought in south-eastern Australia (1997-2010)
521 has exacerbated concerns that trees may be a significant user of local and regional water
522 resources, reducing groundwater recharge, discharge and surface water availability (Jackson
523 et al., 2005).

524 In order to reduce the impact on water availability, current regulation of tree plantations in
525 south-eastern Australia focuses on the percentage of a catchment that may be planted.
526 However, the present study shows that the location of the plantation within the catchment is
527 significant also, with a smaller water table decline seen in the upland areas of the eucalypt
528 catchment. Therefore to reduce the impact of plantations on groundwater recharge, tree
529 planting should be avoided in the dominant zone of recharge, i.e. the topographically low
530 areas and along the drainage lines, and should be concentrated on the upper slopes, where the
531 water tables are deeper and the trees are less likely to access the groundwater and transpire it
532 directly. At present, tree plantations in Victoria cannot be planted within 20 m of drainage
533 lines, to avoid erosion of creek banks when the trees are removed (Dept. of Environment and
534 Primary Industries, Victoria); we suggest that this currently restricted area along the drainage
535 lines be expanded to include as much of the low topography parts of the site as practicable.

536 The expansion of the drainage line exclusion zone in tree plantations will have an added
537 benefit in many regions of south-eastern Australia where the groundwater is saline. This is
538 because the parts of the catchments where the saline groundwater is within a few metres of
539 the land surface (generally the lowland areas) can have a negative effect on tree health; at the
540 study site, the trees closer to the drainage lines are shorter and thinner than those upslope.

541 However, excluding tree planting from low elevation areas reduces the number of trees that
542 can be planted within a catchment, and also means that trees are not planted in areas where
543 (good quality) groundwater is shallowest and can be most readily accessed for tree growth. As
544 the primary purpose of many tree plantations is the production of wood and pulp products for
545 economic gain, this restriction will slow economic returns. To overcome this, consideration
546 could be given to planting lower water use trees that can better cope with the upslope areas
547 where water supplies for tree growth may be limited.

548 This management strategy of balancing economic and hydrologic perspectives when locating
549 tree plantations within catchments will be applicable to other low-rainfall, high-evaporation
550 regions, and should be considered for tree plantations in similar climatic areas worldwide.

551

552 **5 Conclusions**

553 While the importance of topography and ephemeral streams to focused recharge in low
554 rainfall regions around the world has been known for some time, the implications of this
555 aspect of the groundwater resource literature have not been incorporated into plantation
556 management guidelines and legislation. In this study, it is shown that the majority of modern
557 recharge at the study site, calculated from the water table fluctuation method, occurs in the
558 lower parts of both study catchments (12% of rainfall versus 3% in the upland areas).
559 Overland flow is focused into topographic lows and along drainage lines where greater
560 infiltration can occur. Recharge calculations using a corrected chloride mass balance method
561 gave lower values than modern recharge estimates because the groundwater across the study
562 site is mostly >200 years old, representing recharge under native eucalypt forest prior to
563 European land clearance. Relatively little groundwater discharges into the streams or flows
564 out at the bottom of the catchment; groundwater within the catchments is lost predominantly
565 through evapotranspiration. Overall the tree plantation in this study caused a drawdown in
566 groundwater levels, increasing over time as the trees aged, compared to a slight rise in
567 groundwater levels in the pasture catchment.

568 The results of this study lead to the conclusion that both the hydrogeological and economic
569 frameworks for commercial forestry need to be considered. If conserving groundwater
570 recharge is a primary objective, tree planting should be avoided in the dominant zone of
571 recharge, and concentrated on the upper slopes, where recharge is low enough that any further
572 reduction will have minimal impact. We suggest expanding present regulations for tree
573 plantations which specify that trees cannot be planted within a certain distance of drainage
574 lines, including as much of the low topography parts of the site as practicable. Consideration
575 should be given to the potential negative impact on the financial viability of a tree plantation.
576 This management strategy is applicable to low-rainfall, high-evaporation regions worldwide.

577

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- 747
- 748

749 **Figure captions:**

750 Figure 1: Left - location of the study site in south-western Victoria, Australia. Right - location
751 of the streams, weirs and bores and their reference numbers. “L” denotes the presence of a
752 water level logger in a bore.

753 Figure 2: Orientation of the tree rows in the Eucalypt plantation and the area where tree roots
754 may be able to reach groundwater up to depths of six and eight metres below the surface.

755 Figure 3: (a) barometric pressure (in equivalent cm of H₂O), groundwater logger data, rainfall
756 and the 15 day moving average used for the water table fluctuation method estimates of
757 groundwater recharge. The black dots represent the average groundwater level for the
758 preceding 15 days. (b) Full record for the bore used in (a) – Euc90 – showing the complete
759 removal of the large amount of barometric noise, but keeping the overall trend of the 15 day
760 period.

761 Figure 4: bore hydrographs, rainfall and recharge estimates (in mm/yr from Table 3), for the
762 water table fluctuation and chloride mass balance methods. Hydrographs are sorted by
763 landscape position – lowland or upland.

764 Figure 5: Long-term hydrographs for bores with available data and cumulative deviation from
765 mean monthly rainfall to show the relationship between groundwater levels and long term
766 rainfall patterns.

767 Figure 6: pasture stream hydrographs (Dwyer’s Creek) and bores hydrographs from the
768 bottom of the catchment (Pas96) and midway up the catchment (Pas75).

769 Figure 7: Cross section from bore Euc91 across both catchments to bore Pas74 showing
770 recharge rates based on both methods used in this study, and the water table change over the
771 course of the study period (see Fig. 1 for bore locations).

772 Figure 8: ²²²Rn concentrations in the streams, measured at the weirs of both sites, and nearby
773 bores. Surface water from further up the catchments is represented by water from dams
774 located upslope in both catchments. The relatively high levels in the groundwater are a result
775 of the decay of uranium present in the allanite and zircon of the granite.

776 Figure 9: Long section from bores Euc97 to Euc92 showing the effect of the shallow granite
777 on the water table under different flow conditions shown in the flow duration curve below; (1)
778 where low flows in the eucalypt catchment stream are sustained for longer due to some

779 groundwater discharge compared to virtually no groundwater discharge in the pasture
780 catchment, (2) where the water table is at the surface and runoff is transported more quickly
781 out of the eucalypt than in the pasture catchment, and (3) where there are some rare, very high
782 flows, much higher than observed in the pasture catchment.

783

784

785 Table 1: Groundwater characteristics and bore construction.

Bore ID	Earliest data from bore	Screen depth (m below surface)	Surface elevation (m AHD)	Radiocarbon age (yr BP)	1 σ - error	Activity of ³ H (Bq/kg)	1 σ - error	Logger	Groundwater Cl ⁻ (mg/L)
Pasture Catchment									
Pas72 - Low	31/08/1986	9.4-11.6	259.55	1665	± 30	BD		N	3292
Pas73 - Low	31/08/1986	4-6.1	259.54	2055	± 30			N	3110
Pas75 - Low	31/08/1986	12-13.6	263.93	935	± 35			Y	2231
Pas76 - Low	31/08/1986	2.2-4.2	263.98	575	± 30	BD		Y	1595
Pas95 - Low	26/08/2009	22.8-24.8	254.13	3540	± 30	BD		Y (weir)	2732
Pas96 - Low	26/08/2009	5-7.55	254.18	345	± 25	0.133	±0.011	Y (weir)	2553
Pas74 - Up	31/08/1986	6.2-8.5	268.62	790	± 30	0.053	±0.005	Y	306
Pas77 - Up	31/08/1986	17.7-19.7*	271.11	Modern		0.339	±0.015	N	28
Pas78 - Up	31/08/1986	17.3-19.4	277.45	650	± 90	BD		Y	1185
Pas79 - Up	31/08/1986	23.65-25.65*	283.23	Modern		0.304	±0.014	N	38
Pas80 - Up	31/08/1986	23.3-24.4	288.23	115	± 30	0.148	±0.01	Y	2290
Pas81 - Up	31/08/1986	7.1-8.9	272.12	690	± 100	0.094	±0.007	N	668
Pas82 - Up	31/08/1986	23.2-24.8	283.54	430	± 30	0.072	±0.006	Y	329
Eucalypt catchment									
Euc84 - Low	12/11/1996	5.6-7.5	268.67	785	± 30			Y	3909
Euc85 - Low	12/11/1996	7.9-10	268.66	**		BD		Y	3537
Euc89 - Low	30/10/2009	26-28	261.80	7330	± 50			Y	2833
Euc90 - Low	30/10/2009	13-15	261.93	6980	± 45			Y	2788
Euc92 - Low	30/10/2009	26.2-29.2	255.43	20770	± 90	BD		Y (weir)	1490
Euc93 - Low	2/03/2010	11-14	263.31	725	± 30	0.087	±0.007	Y	1357
Euc83 - Up	12/11/1996	14.8-16.7	274.21	685	± 30	BD		Y	2064
Euc91 - Up	30/10/2009	33.9-35.9	280.02	415	± 30	0.047	±0.005	Y	1114
Euc94 - Up	30/10/2009	28-30	286.05	2060	± 30	BD		Y	2891
Euc97 - Up	30/10/2009	43.1-45.1; 57.6-59.6	291.74	5655	± 35	0.0354	±0.005	Y	3494

786 BD denotes below detectable; * assumed screen depths; ** CO₂ concentration too low for
 787 analysis.

788

789

790 Table 2: Median grain size compositions for sampled profiles used to estimate a range of
 791 values for S_y in equation 1.

Bore ID	Clay (%)	Silt (%)	Fine sand (%)	Coarse sand (%)
Euc89 – Low	3	39	38	19
Euc91 – Low	3	39	40	18
Euc93 – Low	3	36	43	18
Euc94 – Up	3	35	44	18
Euc97 – Up	3	34	43	20

792

793

794 Table 3: Recharge (R) values using different methods for all the bores across both
 795 catchments.

Bore ID	R (mm/yr) – groundwater Cl ⁻	R (mm/yr) – groundwater Cl- with stream input correction	R (mm/yr) – water table fluctuation method	R (mm/yr) – long- term hydrograph water table fluctuation method
Pasture catchment – lowland landscape position				
Pas72 – Low*	0.9 ± 0.3	6.8 ± 4.6	L	D
Pas73 – Low*	0.9 ± 0.3	7.2 ± 4.8	L	D
Pas75 – Low	1.3 ± 0.5	3.9 ± 2.6	58 ± 9	38 ± 6
Pas76 – Low	1.8 ± 0.7	5.5 ± 3.7	77 ± 11	D
Pas95 – Low*	1.1 ± 0.4	24 ± 16	C	D
Pas96 – Low	1.1 ± 0.4	26 ± 17	161 ± 24	D

Pasture catchment – upland landscape position				
Pas78 – Up	2.5 ± 0.9	C	36 ± 5	D
Pas80 – Up	1.0 ± 0.4	C	12 ± 2	30 ± 5
Pas82 – Up	8.8 ± 3.3	C	26 ± 4	28 ± 4
Pasture catchment – possible fracture flow				
Pas74 – Up	9.4 ± 3.5	C	65 ± 10	56 ± 8
Pas77 – Up	102 ± 38	C	L	D
Pas79 – Up	76 ± 29	C	L	D
Pas81 – Up	4.3 ± 1.6	C	L	D
Eucalypt catchment – lowland landscape position				
Euc84 – Low*	0.7 ± 0.3	1.7 ± 1.3	C	C
Euc85 – Low*	0.8 ± 0.3	1.9 ± 1.4	C	C
Euc89 – Low	1.0 ± 0.4	5.7 ± 4.3	59 ± 9	D
Euc90 – Low	1.0 ± 0.4	5.8 ± 4.4	74 ± 11	D
Euc93 – Low	2.1 ± 0.8	8.0 ± 6.1	40 ± 6	D
Eucalypt catchment – upland landscape position				
Euc83 – Up	1.4 ± 0.5	C	10 ± 2	19 ± 3
Euc91 – Up	2.6 ± 1.0	C	17 ± 3	D
Euc94 – Up	1.0 ± 0.4	C	1.7 ± 0.2	D
Euc97 – Up	0.8 ± 0.3	C	26 ± 4	D
Eucalypt catchment – possible fracture flow				
Euc92 – Low*	1.9 ± 0.7	C	C	D

796 * denotes confined bores; ^L no logger present; ^D no data; ^C indicates that this calculation was
797 not done for that bore as it did not meet the required conditions (see sections 3.6.1 and 3.6.2).

798