

1 **Groundwater-dependent ecosystems:**
2 **recent insights from satellite and field-based studies**

3
4 **D. Eamus^{1,2}, S. Zolfaghar^{1,2}, R. Villalobos-Vega^{1,2}, J. Cleverly², and A. Huete²**

5
6 ¹National Centre for Groundwater Research and Training, University of Technology Sydney,
7 P.O. Box 123, NSW 2007, Australia

8
9 ²School of Life Sciences, University of Technology Sydney, P.O. Box 123, NSW 2007,
10 Australia

11
12
13
14 Correspondence to: D. Eamus (derek.eamus@uts.edu.au)

15
16
17
18
19
20
21 **ABSTRACT**

22
23 Groundwater-dependent ecosystems (GDEs) are at risk globally due to unsustainable levels
24 of groundwater extraction, especially in arid and semi-arid regions. In this review, we
25 examine recent developments in the ecohydrology of GDEs with a focus on three knowledge
26 gaps: (1) how do we locate GDEs, (2) how much water is transpired from shallow aquifers
27 by GDEs and (3) what are the responses of GDEs to excessive groundwater extraction? The
28 answers to these questions will determine water allocations that are required to sustain
29 functioning of GDEs and to guide regulations on groundwater extraction to avoid negative
30 impacts on GDEs.

31 We discuss three methods for identifying GDEs: (1) techniques relying on remotely sensed
32 information; (2) fluctuations in depth-to-groundwater that are associated with diurnal
33 variations in transpiration; and (3) stable isotope analysis of water sources in the transpiration
34 stream.

35 We then discuss several methods for estimating rates of GW use, including direct
36 measurement using sapflux or eddy covariance technologies, estimation of a climate wetness
37 index within a Budyko framework, spatial distribution of ET using remote sensing,
38 groundwater modelling and stable isotopes. Remote sensing methods often rely on direct
39 measurements to calibrate the relationship between vegetation indices and ET. ET from
40 GDEs is also determined using hydrologic models of varying complexity, from the "White
41 method" to fully coupled, variable saturation models. Combinations of methods are typically

42 employed to obtain clearer insight into the components of groundwater discharge in GDEs,
43 such as the proportional importance of transpiration *versus* evaporation (e.g., using stable
44 isotopes) or from groundwater *versus* rainwater sources.

45 Groundwater extraction can have severe consequences on structure and function of GDEs. In
46 the most extreme cases, phreatophytes experience crown dieback and death following
47 groundwater drawdown. We provide a brief review of two case studies of the impacts of GW
48 extraction and then provide an ecosystem-scale, multiple trait, integrated metric of the impact
49 of differences in groundwater depth on the structure and function of eucalypt forests growing
50 along a natural gradient in depth to groundwater. We conclude with a discussion of a depth-
51 to-groundwater threshold in this mesic GDE. Beyond this threshold, significant changes
52 occur in ecosystem structure and function.

53

54 **1 Introduction**

55 Water stored belowground in the saturated zone (groundwater) is the largest global store of
56 liquid freshwater, accounting for about 96 % of all liquid freshwater (Shiklomanov 2008).
57 Whilst readily accessed by humans for millennia at naturally occurring springs/oases and as
58 baseflow discharge into rivers, it has only been during the past 100 years that exploitation of
59 groundwater resources has become of global concern (Gleick and Palaniappan 2010). The
60 rate of groundwater use of three (Pakistan, Iran and Saudi Arabia) of the seven largest users
61 of groundwater (India, the USA, Pakistan, China, Iran, Mexico and Saudi Arabia) use
62 groundwater at an annual rate that exceeds the renewable resource volume (Giordano 2009).
63 Only three of the top 10 users are OECD members, reflecting the large reliance on
64 groundwater of less developed nations, which are often located in arid and semi-arid climates
65 where surface water stores are generally low.

66 About two fifths of the world's terrestrial surface area is arid or semi-arid and more than 38
67 % of the world's population lives there. Managing groundwater resources sustainably is
68 therefore a major global social and economic priority (Glazer and Likens 2012). Whilst
69 about 40 % of global groundwater abstraction occurs in these regions, the scarcity of rain
70 means that only 2 % of groundwater recharge occurs there (Wada et al., 2010). Water is
71 increasingly becoming a geopolitical and strategic resource. Disputes between neighbouring
72 states are increasing as demands for groundwater increase. Because of the close relationship
73 between crop yield and water supply, diminishing availability of groundwater in arid and
74 semi-arid regions has immediate and severe impacts on food supplies, food prices and
75 concomitant social unrest. Recent estimates suggest that between 10 and 25 % of the food
76 produced in China and India (home to 2.5 billion people) is at risk because of groundwater
77 depletion (Seckler et al., 1999; Brown 2007).

78 Over extraction of groundwater stores can create several problems. These include: loss of
79 discharge from groundwater to wetlands, springs and streams/rivers, which results in loss of
80 ecosystem structure and function and the associated loss of ecosystem services (Eamus et al.,

81 2006a; Murray et al., 2006); increased depth of groundwater, thereby reducing its availability
82 within the root zone of terrestrial groundwater-dependent vegetation; reduced availability of
83 groundwater for direct human consumption; and reduced availability of groundwater for
84 commercial use, including irrigation, stock watering and other industrial applications.

85 In a recent wide-ranging review of GDEs, Orellana et al., (2012) identified quantification of
86 the water used by GDEs and an understanding of the physiology of GDEs as major
87 unresolved problems. Naumburg et al., (2005) provide a review of the impact of both
88 declining and increasing depth to the water table on phreatophytic vegetation in arid zones
89 and provide two conceptual models describing ecosystem responses to these changes in
90 depth. They note that information on root depth and the impact this may have on responses
91 to changes in depth-to-groundwater as a key knowledge gap. In this current review we
92 discuss application of remote sensing techniques to quantify rates of water use of GDEs. We
93 present ecophysiological responses of vegetation to differences in groundwater availability in
94 two case studies plus the results of a four year ecophysiological study of eucalypt woodlands
95 across a natural gradient in depth-to-groundwater in a mesic environment. From this last
96 study we produce an integrated response metric for the response of these woodlands to
97 differences in groundwater depth.

98 Whilst Hatton and Evans (1998) recognised five classes of ecosystem dependency on
99 groundwater, we use the simplified classification system proposed by Eamus et al., (2006b):

100

101 (Class I) *Aquifer and cave ecosystems where stygofauna reside*. This class also includes
102 the hyporheic zones of rivers and floodplains.

103 (Class II) *Ecosystems reliant on the surface expression of groundwater*. This includes
104 springs, estuarine seagrasses, and base-flow rivers, streams and wetlands.

105 (Class III) *Ecosystems reliant on sub-surface presence of groundwater within the rooting*
106 *depth of the ecosystem* (usually via the capillary fringe).

107 Application of this simple classification scheme assists managers in identifying the correct
108 techniques for assessing GDE structure, function and management regime (Eamus et al.,
109 2006b), and this classification scheme was recently adopted in the Australian National Atlas
110 of Groundwater-Dependent Ecosystems.

111

112 In this review, we focus on the ecohydrology of groundwater-dependent ecosystems rather
113 than on groundwater resources *per se*. This is because we feel that environmental allocations
114 of groundwater have generally received less attention than allocations to human demands and
115 because we identify three important knowledge gaps to the sustainable management of
116 groundwater for environmental allocations. These are:

- 117 1. How do we know where a groundwater-dependent ecosystem (GDE) is in the
118 landscape? If we don't know where they are, we can't manage them and allocate
119 groundwater resources appropriately.

- 120 2. How much groundwater is used by a GDE? If we don't know how much groundwater
121 is used, we cannot allocate an appropriate quantity of the resource.
122 3. What are the likely responses of GDEs to over extraction of groundwater? Without
123 knowing what to measure, we cannot regulate groundwater extraction in ways that do
124 not negatively impact on GDEs.
125

126 **2 Identifying groundwater dependent vegetation**

127 Identifying the location of GDEs is the first requisite step to managing them. However,
128 identifying their location across a landscape is difficult, time-consuming, expensive and
129 requires a high level of technical expertise. In this section, a range of new techniques that can
130 be used to assist in this are discussed.

131

132 **2.1 Methods to identify GDEs: indirect inference**

133 Early assessments of groundwater dependency generally relied on inference (Eamus et al.,
134 2006a; Clifton and Evans 2001). Recent applications of inferential techniques to springs,
135 wetland, rivers and lakes can be found in Brown et al., (2011) and to springs, wetlands and
136 streams reliant on baseflow in Howard and Merrifield (2010) and are not further discussed
137 here.

138

139 **2.2 Direct methods**

140 *2.2.1 Satellite based approaches*

141 In recent years remote sensing (RS) of land surfaces and vegetation structure (e.g. phenology,
142 LAI) and function (e.g. ET, gross primary productivity) has become increasingly
143 sophisticated (Glenn et al., 2010; Yuan et al., 2010; Jung et al., 2011; Rossini et al., 2012;
144 Kanniah et al., 2013; Ma et al., 2013; Nagler et al., 2013) and increasingly applied to real-
145 world applications of water resource management (Scott et al., 2008; Glenn et al., 2010;
146 Barron et al., 2014; Doody et al., 2014). Remote sensing (RS) provides a robust and spatially
147 explicit means to assess not only vegetation structure and function but also relationships
148 amongst these and climate variables.

149 A key concept in the development of RS applications for identifying the location of GDEs is
150 that of "green islands" (Everitt and DeLoach, 1990; Everitt et al., 1996; Neale, 1997;
151 Akasheh et al., 2008), which began with the airborne observations of desert oases and
152 riparian corridors. In this model the structure or function of one pixel in an RS image is
153 compared to that of another pixel located nearby. If one pixel contains a GDE but the other
154 does not, the hypothesis that the structure and function of vegetation in the two pixels will
155 diverge during extended dry periods can be tested. The underlying assumption is that
156 vegetation with access to groundwater will not be subject to the same degree of soil water

157 deficit as vegetation that does not have access to groundwater, thus the spectral signature of
158 the two pixels will diverge over time. By comparing vegetation structure or function across
159 contrasting periods (e.g., comparisons across “wet” and “dry” periods) or across landscapes
160 (e.g., comparisons from riverside to upland pixels), green islands within a sea of browning
161 vegetation can be identified (Contreras et al., 2011)

162 Munch and Conrad (2007) used Landsat imagery to identify the presence/absence of wetlands
163 across three catchments in South Africa. They combined this with GIS terrain modelling to
164 determine whether GDEs could be identified using a landscape “wetness potential” for class
165 II GDEs (those reliant on a surface expression of groundwater). They concluded that RS data
166 could be used to classify landscapes by comparing the attributes of potential GDEs to the
167 attributes of surrounding land covers during three periods: in July when rains started at the
168 end of a dry year; in August during the winter of a wet year; and at the end of a dry summer.
169 When this was combined with a GIS model using landscape characteristics, they were able to
170 produce a regional-scale map of the distributions of GDEs.

171 Plant density is often correlated with water availability, especially in arid and semi-arid
172 regions. Thus, plant density tends to be larger when groundwater is available than in nearby
173 vegetation that does not have access to groundwater. Lv et al., (2012) used a remotely sensed
174 vegetation index (normalised difference vegetation index; NDVI; 300 m resolution) to
175 examine changes in depth-to-groundwater within a small region in northern China. NDVI is a
176 reliable measure of the chlorophyll content (“greenness”) in leaves and vegetation cover
177 (Gamon et al., 1995; Carlson and Ripley, 1997; Huete et al., 2002). Using a 25 m resolution
178 digital elevation model and groundwater bore data, the resultant relationship between NDVI
179 and depth-to-groundwater was obtained (Fig. 1).

180

181 Fig 1 here

182

183 Similar in shape to the relationship between LAI and NDVI, the largest values of NDVI
184 occurred at sites with shallow groundwater and declined curvi-linearly as depth-to-
185 groundwater increased. In that study, a cut-off of approximately 10 m depth-to-groundwater
186 was identified below which vegetation cover was relatively insensitive to further increase in
187 groundwater depth. In contrast, the threshold was about 4.4 m depth-to-groundwater in the
188 Ejina area of NW China (Jin et al., 2011). In their study, which included part of the Gobi
189 desert where annual rainfall was about 40 mm, vegetation was absent in regions where
190 groundwater depth exceeded 5.5 m. They also used NDVI and 13 groundwater bores, from
191 which relationships between NDVI and groundwater depth for three vegetation classes
192 (grassland, woodland and scrubland) were established. Maximal values of NDVI occurred at
193 sites with intermediate (2.5 – 3.5 m) depth-to-groundwater rather than at sites with shallower
194 groundwater, a result often ascribed to the effect of anoxia arising from root flooding when
195 the water table is too shallow (Naumburg et al., 2005).

196 Geological, hydrological and ecological data can be used to define areas that have common
197 physical and climatic profiles. These regions are expected to have similar vegetation cover
198 (assuming no management has induced significant changes), thus such areas are expected to
199 have a similar RS signature. Dresel et al., (2010) applied this approach for individual regions
200 in South Australia by developing a correlation analysis using Landsat summer NDVI and
201 MODIS enhanced vegetation index (EVI) as surrogate measures of productivity. EVI is
202 effective for scaling productivity across the range of global ecosystem types (Campos et al.,
203 2013). MODIS EVI images were used to identify regions displaying a consistent
204 photosynthetic activity throughout the year. Landsat NDVI images were then used to locate
205 areas displaying large inter-annual variation in photosynthetic activity across wet and dry
206 years, which were identified by aridity thresholds that were calculated from the Thornthwaite
207 index. Finally, they used an unsupervised classification of Landsat spectral data to locate
208 pixels with similar spectral signatures of areas corresponding to known groundwater-
209 dependent ecosystems. Species-specific differences in spectral signatures have been
210 identified previously (Nagler et al., 2004). By combining all three sources of information
211 (geological, hydrological and ecological) within a GIS, Dresel et al., (2010) identified all
212 pixels across a catchment that had a very high probability of being a GDE. Critical for
213 providing assurance of accurate mapping, ground reconnaissance (“truthing”) was used to
214 validate these findings.

215 Mapping of groundwater discharge zones (that is, discharge through transpiration and to the
216 ground surface) provides an alternative approach to finding GDEs. Discharge of groundwater
217 has a large effect on local ecology. To define the spatial extent of discharge, information is
218 required about the geology, hydrology, ecology and climate of a site (Tweed et al., 2007). By
219 using thermal, Landsat optical and MODIS NDVI data coupled to digital elevation models
220 and depth-to-groundwater data, Leblanc et al., (2003a, b), located discharge areas in semi-
221 arid Lake Chad basin in Africa. Similarly Tweed et al., (2007) examined discharge (and
222 recharge) of the Glenelg-Hopkins catchment in SE Australia. Discharge occurred through
223 direct evaporation from the water table (i.e., groundwater evaporation); groundwater
224 transpiration; and discharge to the ground surface at landscape depressions, rivers, wetlands
225 and break-of-slope localities. Importantly, they observed low variability of vegetation
226 activity across wet and dry periods (seasons or years) using the NDVI as a measure of
227 vegetation. In this case, the variability in NDVI was correlated with locations where
228 groundwater was supporting vegetation activity. One possible limitation to this method is
229 that it tends to be most accurate in more xeric locations, where rainfall is more likely to limit
230 vegetation function, except during extended droughts.

231

232 2.2.2 *Fluctuations in groundwater depth*

233 When rooting depth is sufficient, vegetation can directly access the water table via the
234 capillary zone of shallow unconfined aquifers. In some circumstances groundwater uptake by
235 vegetation can be seen as a diel fluctuation in the depth-to-groundwater (Miller et al., 2010),
236 as first identified in groundwater hydrographs by Walter White (1932). These daily

237 fluctuations in depth-to-groundwater cease when the water table falls below the rooting zone
238 (Butler et al., 2007) or when vegetation is dormant (Lautz, 2008; Martinet et al., 2009; Miller
239 et al., 2010). However, changes in the density of water with temperature can cause expansion
240 and contraction of an aquifer (Post and von Asmuth, 2013), leading to the erroneous
241 conclusion that the vegetation is accessing groundwater. Additionally, when the water table
242 is very shallow direct evaporation from groundwater via bare soil can be substantial (1–10
243 mm d⁻¹) (Thorburn et al., 1992) and this may also be misinterpreted. Thus, groundwater
244 dependency generally requires supporting confirmation from multiple indicators and cannot
245 be identified definitively from the "White method" alone. Further elaboration of the White
246 method is given in section 3.5.1 and described in detail in Orellana et al., (2012).

247

248 2.2.3 *Stable isotope analysis*

249 Direct evidence that vegetation is using groundwater can be obtained by comparing the stable
250 isotope composition of groundwater, soil water, surface water (if relevant) and xylem water
251 (Thorburn et al., 1993; Zencich et al., 2002; Lamontagne et al. 2005; O'Grady et al., 2006a,
252 b; Kray et al., 2012; Busch et al., 1992; Ehleringer and Dawson, 1992; Smith et al., 1998).
253 This method is very effective in semi-arid regions where groundwater is derived from
254 snowmelt or winter precipitation (which is isotopically lighter than summer precipitation)
255 (Ehleringer and Dawson, 1992; Smith et al., 1998; Jobbagy et al., 2011). When sufficient
256 differences in isotopic composition exist among sources of water, the dominant source used
257 by different species at different times of year can be identified (Zencich et al., 2002).

258 An example of deuterium isotope analysis of water collected from xylem, soil, river and
259 groundwater is shown in Table one. Species growing close to groundwater (*Melaleuca*
260 *argentea*) have xylem isotope compositions close to that of groundwater but species growing
261 further upslope away from the river had xylem isotope compositions close to that of soil
262 water isotope. Further examples include: a) identification of soil and surface water use by
263 juvenile riparian plants, in contrast to groundwater use by mature trees (Dawson and
264 Ehleringer, 1991); and b) determination of the mountainous source of groundwater and
265 opportunistic use of that groundwater by riparian trees (Chimner and Cooper, 2004).

266 Mixed-member models (i.e., "Keeling plots") can be applied to allow estimation of the
267 relative contribution of multiple sources of water to the water absorbed by roots (Phillips and
268 Greg 2003). While it is possible for a linear mixing model to distinguish more than two
269 potential sources of water, such an application requires the fractionation of ²H or ¹⁸O to be
270 independent of each other, which is often not the case. At a minimum, the use of stable
271 isotopes can provide information about spatial and temporal variation in groundwater
272 dependency across species and ecosystems. Application of stable isotope analyses to quantify
273 the rate of water use is discussed later (Section 3.5.2).

274

275 Table 1 here

276 **3 Application of remote sensing to the study of GDEs**

277 **3.1 A primer on remote sensing derived values of rates of water flux**

278 Before discussing the application of RS techniques to estimate rates of groundwater use by
279 vegetation, we will provide a simple summary of the principles of using RS to estimate ET
280 more broadly. For a detailed and comprehensive evaluation of these methods, refer to Glenn
281 et al., (2007). Table 2 provides examples of recent studies that have used RS in the study of
282 GDEs.

283 The energy balance equation for land surfaces is:

284
$$LE + H = R_n - G \quad (1)$$

285 where LE is latent energy flux (ET), H is sensible heat flux. R_n is net radiation and G is soil
286 heat flux. Differences in temperature between air temperature and canopy temperature have
287 been used to estimate sensible heat flux (Glenn et al., 2010). Using the reasonable assumption
288 that G averages out to zero over any single 24-hour period and R_n is either measured or
289 derived from remote sensing data, then LE (that is, ET) can be calculated by difference.

290

291 Table 2 here

292

293 Li and Lyons (1999) compared three methods that use surface temperatures to estimate ET.
294 In two methods, differences in surface and air temperature were used to estimate ET,
295 although the two methods differed in the details of the aerodynamic resistance functions. The
296 third model combined NDVI, surface temperature and a soil-adjusted vegetation index that
297 required the four extreme values of surface temperature and NDVI to be located
298 simultaneously within the study area (i.e., patches of dry bare soils; wet bare soil; wet, fully
299 vegetated patches; and dry, water stressed, fully vegetated surfaces). This can make its
300 application problematic. Two methods used the energy balance equation to estimate ET,
301 whereas ET was estimated in a third by using RS data to estimate the Priestley-Taylor factor
302 that scales between ET and potential ET (ET_p). They concluded that the simplest first and
303 second models produced better estimates of ET and that inclusion of the soil index improved
304 the estimates of ET from native (i.e., non-agricultural) vegetation. Likewise, Nagler et al.,
305 (2005a) found that estimates of ET from riparian corridors using RS were improved with the
306 incorporation of a soil index.

307

308 **3.2 Estimating groundwater use by remote sensing**

309 Quantifying the water balance of arid and semi-arid landscapes and aquifers is important to
310 sustainably manage water resources. Accurate and spatially distributed estimates of discharge

311 through vegetation are difficult to obtain through field measurements. Recently, RS methods
 312 have been calibrated against Penman-Monteith estimates of ET (Glenn et al., 2010; Nagler et
 313 al., 2013; Doody et al., 2014), which requires only standard weather data (net radiation, wind
 314 speed and vapour pressure deficit) and thus increases the coverage of calibration sites.
 315 Because ET in GDEs is generally not limited by soil moisture when groundwater is of high
 316 quality (i.e. not saline), it is assumed that actual ET rates are equivalent to the ET of a
 317 reference grass crop (i.e., reference ET, ET_0), as computed following FAO-56 (Allen et al.,
 318 1998). Then, normalised VIs, either EVI^* or $NDVI^*$, can be used like crop coefficients to
 319 estimate the spatial distribution of ET_a from ET_0 on a per-pixel basis. Nagler et al., (2013)
 320 used an exponential scaling function of EVI^* to estimate ET_a :

321

$$322 \quad ET_a = ET_0 \left(a \left[1 - e^{-b EVI^*} \right] - c \right) \quad (4)$$

323 Similarly, Groeneveld and Baugh (2007) found that this methodology is particularly
 324 applicable to arid and semi-arid vegetation underlain by a shallow water table. In arid and
 325 semi-arid regions, annual rainfall is low and often erratic. Consequently, the presence of a
 326 shallow water table results in a relatively consistent supply of water to roots. $NDVI^*$ was
 327 calculated from summer peak season NDVI (Groeneveld and Baugh 2007):

328

$$329 \quad NDVI^* = \left(NDVI - NDVI_z \right) / \left(NDVI_m - NDVI_z \right) \quad (5)$$

330 where $NDVI_z$ and $NDVI_m$ are the NDVI values for zero vegetation cover and NDVI at
 331 saturation, respectively. Although selection of the values for $NDVI_z$ and $NDVI_m$ can
 332 introduce uncertainty, Groeneveld and Baugh (2007) found significant convergence in the
 333 NDVI by removal of non-systematic scatter in the data. Calibration of ET in the field is not
 334 required to apply this method but it is necessary to define $NDVI_m$. This requires highly
 335 verdant pixels in the RS images, arising either from irrigation or the presence of, for example,
 336 riparian vegetation that maintains a large LAI. At mesic sites, defining $NDVI_z$ may also be
 337 difficult. Despite these problems, Groeneveld and Baugh (2007) were able to disaggregate the
 338 influence of groundwater supply from that of recent rainfall.

339 Groeneveld et al., (2007) applied this $NDVI^*$ methodology to three arid sites in the US where
 340 annual ET_a values were available through the availability of Bowen ratio or eddy covariance
 341 measurements. A significant linear relationship ($R^2 = 0.94$) was found between measured
 342 annual ET_a and mid-summer $NDVI^*$, despite very different vegetation composition and
 343 structure across those sites. However, the regression of ET_a/ET_0 versus $NDVI^*$ did not pass
 344 through the origin and would introduce an offset error if $NDVI^*$ were used to estimate ET_a .
 345 To overcome this, Groeneveld et al., (2007) transformed ET_a to ET_a^* :

$$346 \quad ET_a^* = \left(ET_a - \text{rainfall} \right) / \left(ET_0 - \text{rainfall} \right) \quad (6)$$

347 The resulting regression of ET_a^* versus $NDVI^*$ yielded a slope of 0.97, an intercept of zero
 348 and an R^2 of 0.96. They concluded that $NDVI^*$ was a reliable indicator of ET_a^* . Re-
 349 arranging the equation above and substituting $NDVI^*$ for ET_a^* , they demonstrated that:

350

$$351 \quad ET_a \text{ (estimated)} = (ET_0 - \text{rainfall}) NDVI^* + \text{rainfall} \quad (7)$$

352

353 They estimated the amount of groundwater transpired (ET_g) by deducting annual rainfall
 354 from annual ET_a . That is, $ET_g = (ET_0 - \text{rainfall}) NDVI^*$. The average error in ET_g was
 355 estimated to be about 12 %, which in the absence of field measurements is a very valuable
 356 estimate of rates of groundwater use. Further application of the Groeneveld et al., (2007)
 357 method can be found in Groeneveld (2008).

358

359 3.2.1 Up-scaling from point to larger-scale estimates of ET

360 Riparian vegetation is often reliant on groundwater (either through bank recharge or direct
 361 access to the shallow water table), especially in arid and semi-arid regions. Rates of ET are
 362 enhanced by groundwater use in dry environments (Cleverly 2013), where riparian ET is a
 363 large component of the water balance (Dahm et al., 2002; Scott et al., 2008). However,
 364 measurement of the riparian ET component depends upon the physical characteristics of the
 365 riparian corridor. If a riparian corridor is sufficiently wide, eddy covariance can be used to
 366 directly measure ET (Cleverly 2013). Where the corridor is insufficiently wide, tree-scale
 367 sapflow techniques can be used (O'Grady et al., 2006)(Goodrich et al., 2000b). Combinations
 368 of both methods (Moore et al., 2008; Oishi et al., 2008) can be used to partition transpiration
 369 from evapotranspiration (Scott et al., 2006a), thereby estimating the proportion of ET due to
 370 transpiration from groundwater with the condition that groundwater evaporation is negligible.

371 RS methods are used to expand from measurements of ET at discrete locations to the large-
 372 scale that is required by resource managers. In two studies, (Nagler et al., 2005a; Nagler et
 373 al., 2005b) MODIS EVI and maximum daily air temperatures (from MODIS land surface
 374 temperature LST) were used to derive an empirical estimate of riparian ET for the San Pedro
 375 River and Middle Rio Grande of the USA (Nagler et al., 2005a; Nagler et al., 2005b). Their
 376 equations for daily ET were:

$$377 \quad ET = a \left(1 - e^{-b \text{EVI}^*}\right) \left(c \left/ \left[1 + e^{-\{T_a - d\}/e}\right] \right. \right) + f \quad (\text{Middle Rio Grande}) \text{ and} \quad (2)$$

$$378 \quad ET = a \left(1 - e^{-b \text{EVI}^*}\right) (LST - c) + d \quad (\text{both rivers}) \quad (3)$$

379 where a, b, c, d, e and f are regression constants derived by regression analysis, T_a is air
 380 temperature derived from MODIS LST retrievals, and EVI was normalised to obtain EVI^* .

381 Strong correlations between EVI*, T_a and ET were observed and used to provide scaled
382 estimates for larger areas of vegetation. Despite this being an empirically derived equation
383 from a single study, the form of the equation appears to be relatively robust across
384 catchments (Nagler et al., 2005b). Similarly, Scott et al., (2008) and Nagler et al., (2009)
385 applied these equations (Nagler et al., 2005a; Nagler et al., 2005b) in which they used
386 MODIS-derived nocturnal surface temperature and daily maximal air temperature,
387 respectively. In the regression between ET derived from RS and EC methods, the coefficient
388 of determination (R^2) was larger than 0.93 during all three years of study and across three
389 vegetation types (grassland, shrubland and woodland), thereby indicating the broad
390 applicability of this method. Thus, this method has the ability to (a) scale from point
391 measurements using individual EC towers to much larger areas; and (b) estimate the
392 difference between annual rainfall and ET and, where $ET > \text{rainfall}$, estimate vegetation
393 groundwater use.

394

395 **3.3 Gravity recovery and climate experiment (GRACE) for detecting changes in** 396 **total terrestrial water storage**

397 In addition to remote sensing measures of ET anomalies or NDVI green islands, there are
398 also new satellite sensors and techniques that provide estimates of groundwater fluctuations
399 and soil moisture storage changes that are of value to the study of GDE's (Brunner et al.,
400 2007). The twin satellites known as the Gravity Recovery and Climate Experiment (GRACE)
401 were launched in 2002 for the purpose of making detailed measurements of Earth's gravity
402 field (Tapley et al., 2004). Although Earth's gravity variations tend to be relatively constant
403 over long time intervals, more dynamic, time-variable gravity fields can be detected and these
404 have been related to land surface moisture, ground water fluctuations, sea ice, sea level rise,
405 and deep ocean currents. GRACE's ability to monitor changes in such "unseen water
406 reserves" from space are a significant new addition to hydrological studies that can
407 substantially improve our knowledge of below- and aboveground water resources and
408 associated changes to vegetation functioning and GDE's. However, GRACE is not able to
409 estimate rates of actual groundwater-use by GDEs.

410 Technically, the GRACE satellites detect changes in the Earth's gravity field by monitoring
411 the changes in distance between the two spacecraft as they orbit Earth. The relative distance
412 will change in response to variations in the Earth's mass, including changes in mass of both
413 above- and below-ground water reservoirs (groundwater, soil moisture, snow, ice, and
414 surface waters). The GRACE satellite data directly measures changes in total water storage
415 (TWS) and not changes of the individual hydrologic components (e.g., surface water, soil
416 moisture, and groundwater). Groundwater storage changes from GRACE are thus inferred by
417 isolating and removing the contributions of all other TWS components, using either
418 independent hydrologic datasets and/or land surface models.

419 In most cases, soil moisture becomes the sole component that must be removed from the
420 gravity data to estimate groundwater changes, since variability of snow and surface water is

421 relatively insignificant to total water storage variability. By subtracting the soil moisture
422 contribution, the remaining time-variable change in GRACE's measure of total water storage
423 will be due to changes in groundwater. Thus:

$$424 \quad DTWS = DSW + DSM + DGW \quad (8)$$

425

426 Where ΔTWS , ΔSW , ΔSM and ΔGW are changes in total water store, soil moisture,

427 Many studies have compared changes in groundwater storage obtained from GRACE data
428 with in situ data for validating the accuracy of GRACE data at either regional or continental
429 scales (Henry et al., 2011; Leblanc et al., 2009 ; Rodell et al., 2009, 2007; Scanlon et al.,
430 2012a,b; Syed et al., 2009).

431 GRACE is not a way to measure exact water storage amounts from space and cannot be used
432 to measure how much water is stored in a river basin at a particular instant in time. Instead,
433 gravity information is used to assess relative changes in water storage over large areas at
434 monthly, seasonal or annual time steps. Seasonal changes in water storage may be the easiest
435 to detect using the GRACE technique because such changes tend to be large.

436 In general, GRACE data are more accurate for large areas over long time intervals. For
437 example, GRACE can detect seasonal and annual changes in water storage over large areas-
438 and can detect month-to-month changes over entire river basins (of the order of millions of
439 square kilometers). Presently, GRACE can confidently detect water storage changes in areas
440 larger than 200,000 square kilometers.

441 Rodell and Famiglietti (2001) showed that GRACE data can estimate annual groundwater
442 change over the High Plains, USA within about 8.7 mm of their actual value. This level of
443 accuracy may not always be an improvement for well-sampled and instrumented aquifers, but
444 for most places in the world, estimates of water levels within a centimeter or less are
445 extremely valuable and will help reveal groundwater depletion in areas of the world where
446 such measurements are not systematically recorded.

447 Despite these coarse scales, such information can be extremely useful for water resource
448 managers, especially as GRACE data continues to be refined to provide improved estimates
449 of groundwater fluctuations and depletion. Regional monitoring of groundwater levels is
450 limited by the lack of ground-based measurements and the lack of a sufficiently extensive
451 network of monitoring wells. Thereby, the GRACE technique offers an objective, unbiased
452 method for monitoring water storage changes at large scales.

453 Although many advances in TWS monitoring have been made using GRACE data, the
454 practical application of GRACE data for local water resources management has been limited
455 by the low spatial ($>150,000 \text{ km}^2$) and temporal (>10 days) resolution of GRACE
456 measurements and by difficulties in disaggregating the various TWS components (Rodell et
457 al., 2007). There is a trade-off between coarse spatial resolution and accuracy, and it remains
458 to be determined whether better spatial resolutions can be achieved without degrading or
459 increasing the uncertainties. However, Houborg et al., (2012) show the potential value of

460 GRACE data to significantly improve drought prediction capacity through assimilation of
461 these data into the Catchment Land Surface Model using ensemble Kalman smoother and
462 forcing data from North American and Global Land Data Assimilation Systems Phase 2
463 (NLDAS-2). Similarly, Sun et al., (2012) imposed GRACE observations as constraints when
464 recalibrating a regional-scale groundwater model, further highlighting the value of GRACE
465 data to the study of groundwater and GDEs.

466

467 *3.3.1 Downscaling of GRACE*

468 To fully realize the potential of GRACE data for hydrological applications, downscaling,
469 both in space and time are required. This will enable better predictions of changes in
470 groundwater level (Houborg et al., 2012). Sun et al., (2013) explored various downscaling
471 techniques for GRACE data for useful predictions of changes in water level. They developed
472 artificial neural network (ANN) model schemes to predict such changes directly by using a
473 gridded GRACE product and other publicly available hydrometeorological data sets. Their
474 statistical downscaling approach can be readily integrated into local water resources planning
475 activities, especially in the absence of continuous in situ groundwater observations. They
476 noted that downscaled GRACE data could potentially fill the gap created by the declining
477 coverage of in situ groundwater monitoring networks and ‘index’ wells used to gauge the
478 wellbeing of aquifers.

479

480 *3.3.2 Groundwater depletion studies and GRACE*

481 GRACE satellite data have been used to estimate groundwater depletion associated with
482 severe droughts in Europe, U.S., China, and India (LeBlanc et al., 2009; Rodell et al., 2009).
483 Groundwater pumping of aquifers often increases during severe droughts for urban,
484 agriculture, livestock, and industry needs. This results in the decline of groundwater levels
485 and the decrease of ground-water discharge to springs, surface water bodies and riparian
486 zones (Peters et al., 2003). Leblanc et al., (2009) attempted to attribute groundwater loss
487 during the recent drought in Murray-Darling Basin in Australia to groundwater pumping.
488 However, they found that the pumping rate represented only less than 10% of the decline rate
489 in groundwater storage as observed by GRACE from 2003 to 2008 (Fig. 2). They concluded
490 that the observed decline is mostly be explained by reductions of groundwater recharge and
491 the vast amount of groundwater transpired during the drought by the widespread presence of
492 deep rooted trees (GDEs) as well as capillary rise from the saturated to the unsaturated zone.

493

494 Fig 2 here

495

496

497 3.4 Remote sensing limitations and challenges in studies of GDEs

498

499 Remote Sensing applications in studies of GDEs vary greatly, from basic detection, mapping,
500 and monitoring of GDEs to more complex and quantitative measurements of ET, functioning,
501 and energy and water balance. In most cases, mapping of GDE locations at appropriate
502 management scales is prerequisite to more detailed studies, such as groundwater assessments
503 that may require accurate estimates of ET (Gou et al., 2015).

504

505 Regardless of the application, there will be certain limitations in the use of remote sensing
506 that need to be considered. Other geospatial data sources will often need to be integrated to
507 make the best use of remote sensing, including climate, soils, landscape morphology, and
508 ecologic data layers that will enable potential areas for GDEs to be delineated (Bertand et al.,
509 2012). Multiple sensors and image data sets are best suited for studies of GDEs because of
510 the inherent spectral-spatial-temporal limitations of single sensor systems. For example the
511 use of fine spatial resolution Landsat (30 m) and high temporal frequency MODIS data (1-2
512 day) allow us to identify potential GDE vegetation patches (Landsat) and track changes in
513 their seasonal and inter-annual dynamics (MODIS spectral vegetation indices, VIs). Thus,
514 vegetated areas that maintain high VI ‘greenness’ values during extended dry periods can be
515 flagged as ‘*high GDE potential*’, under the premise that GDEs exhibit low seasonality in
516 greenness and ET between dry and wet seasons and low inter-annual variability across years.

517

518 However, many ecosystems may contain trees and shrubs that are non-GDE yet also exhibit
519 weak seasonality and inter-annual variation due to their evergreen phenologies. In these
520 mixed tree- grass landscapes, seasonal variability follows the very dynamic herbaceous grass
521 layer that is strongly coupled to rainfall rather than groundwater availability. The stronger
522 seasonality present in the grass layer can readily mask GDE signals from the tree layer and
523 confuse GDE detection. This “mixed-pixel” problem restricts many remote sensing
524 applications, particularly when the matrix background of an area with GDEs has insufficient
525 thermal or greenness contrast to enable GDE detection. The detection of ‘cool’ thermal
526 patches (transpiring GDE trees) from relatively warmer backgrounds (soil) will be a function
527 of the size and magnitude of the cold patch relative to the pixel area. The ‘greener’ and
528 ‘cooler’ signals from a groundwater dependent tree may be averaged out by the non-GDE
529 plants present in the same pixel and a stressed GDE tree can gradually fade into the warmer
530 soil background matrix. Spatial heterogeneity may overwhelm detection. Finer resolution
531 imagery will improve detection capabilities but temporal information is then made poorer,
532 due to inherent sensor resolution trade-off’s.

533

534 It should be noted that although remote sensing is a useful diagnostic tool and proxy for the
535 detection and sensing of GDE’s, most detection and mapping is done by inference and careful
536 user interpretation. Remote sensing often cannot directly ascertain causes and mechanisms
537 for GDEs and much remains to be done to assess GDE influences on the water balance, their
538 sensitivity to changing water availability, and responses to stress conditions. Future sensor
539 systems planned for launch in the next few years include follow-on GRACE twin satellite

540 missions with improved sensing capabilities allowing more detailed analyses groundwater,
541 soil moisture, and surface water distributions and trends. The soil moisture active passive
542 (SMAP) mission, launched in 2014, provides improved soil moisture retrievals which will
543 improve upon the detection and differentiation of soil-moisture induced vegetation dynamics
544 from those associated with groundwater use.

545

546 **4 Hydrological modelling of water-use by GDEs**

547 **4.1 Conceptual water balance approaches**

548 **A spreadsheet tool**

549 O’Grady and co-workers have developed a simple but useful first-order approximation to
550 estimate groundwater use of vegetation in an Excel spreadsheet tool (Leaney et al., 2011;
551 <http://www.csiro.au/products/recharge-discharge-estimation-suite>). This toolbox includes
552 three methods to estimate rates of groundwater discharge by vegetation:

- 553 1. Groundwater Risk Model
- 554 2. Ecological Optimality Model
- 555 3. Groundwater Discharge Salinity Model (not described here)

556

557 The groundwater risk model uses historical monthly rainfall and evaporation data for a site to
558 produce a water balance. Soil texture is used to estimate soil moisture characteristics in each
559 layer of the model, and groundwater uptake by vegetation is assumed to occur when ET
560 exceeds rainfall, when also accounting for soil water storage for each month. ET is estimated
561 from total evaporation using the Budyko framework (Budyko 1974; Donohue et al., 2007;
562 Yang et al., 2008; Roderick and Farquhar 2009). The risk model in Leaney et al., (2011) uses
563 the Choudhury-Yang formulation of the Budyko equation:

$$564 \quad ET_a = (P - ET_p) \left/ \left(P^n + [ET_p]^n \right)^{1/n} \right. \quad (9)$$

565 where P is rainfall and n is a fitting parameter that determines the shape of the curve.
566 Determining the value of n is difficult, but a close approximation can be derived from the
567 climate wetness index ($CWI = P/ET_p$). When the $CWI > 0.3$, n is approximately equal to
568 CWI and when $CWI < 0.3$, n is approximately 1.8 (Leaney et al., 2011). The influence of
569 variation in n and the Budyko formulation is shown in Figure 3.

570

571 Figure 3 here

572

573 The model is run using historical monthly rainfall and estimated ET. Pan evaporation rates
 574 can be used instead of ET_p , in which case $ET_p = 0.75E_{pan}$. Modest agreement between
 575 modelled and observed rates of groundwater discharge was found in two Australian studies
 576 where ET exceeded rainfall in the Wattle Range by 2 to 440 $mm\ y^{-1}$ (Benyon and Doody
 577 2004), although the range of estimated groundwater discharge rates was large: 107 to 671
 578 $mm\ y^{-1}$ (Benyon and Doody 2004) and 380–730 $mm\ y^{-1}$ (Benyon et al., 2006).

579 As an alternative method to the risk assessment just described, Leaney et al., (2011) applied
 580 Eagleson's theory of ecological optimality (Eagleson 1978). This proposes that the LAI of a
 581 site is maximised according to long-term rainfall and soil water holding capacity such that
 582 productivity is maximised whilst minimising the development of water stress. In this
 583 hypothesis, native vegetation is assumed to be at equilibrium with the local hydrological
 584 regime (Nemani and Running 1989). Ellis and Hatton (2008) have shown that the LAI of a
 585 site is proportional to a climate wetness index ($CWI = P/ET_p$), whilst Eamus et al., (2001)
 586 used the Baldocchi-Meyers index (foliar [N] x P/E_{eq} , where foliar [N] is the concentration of
 587 nitrogen in leaves and E_{eq} is equilibrium evapotranspiration) and found a strong ($R^2 = 0.95$
 588 for 16 sites globally) curvilinear relationship with LAI, supporting the essentials of
 589 Eagleson's optimality theory. Similarly, Zeppel (2013) examined multiple species across sites
 590 in Australia and found strong convergence in daily rates of tree water-use and leaf area across
 591 five evergreen sclerophyllous genera. In the Eagleson optimality method of Leaney et al.,
 592 (2011), the relationship between LAI and the CWI of Ellis and Hatton (2008) is used:

593

$$594 \quad LAI = (3.31 \cdot CWI) - 0.04 \quad (10)$$

595

596 In GDEs, groundwater discharge combines with precipitation to supply ET (O'Grady et al.,
 597 2011), thus:

$$598 \quad CWI_g = (P + GW) / ET_p \quad (11)$$

599

600 where CWI_g is the climate wetness index that includes the groundwater component (GW).
 601 Likewise, the Budyko curve can be modified to include the contribution of groundwater
 602 discharge to ET:

$$603 \quad ET / ET_p = 1 + (P / ET_p) - \left(1 + [P / ET_p]^w \right)^{1/w} \quad (\text{Zhang et al., 2004}) \quad \text{and} \quad (12)$$

$$604 \quad \left(ET / ET_p \right)_g = 1 + ([P + GW] / ET_p) - \left(1 + \{ [P + GW] / ET_p \}^w \right)^{1/w} \quad (\text{O'Grady et al., 2011})$$

605 (13)

606 Within zones of the same CWI, sites with access to shallow groundwater maintain a larger
607 LAI than sites without access to groundwater (O'Grady et al., 2011). To determine GW, the
608 pairs of equations (CWI , CWI_g ; ET/ET_p , $[ET/ET_p]_g$) were optimised by obtaining the
609 difference in rainfall required to attain a given LAI with a known CWI value (O'Grady et al.,
610 2011).

611

612 **4.2 Groundwater flow and variable saturation models: MODFLOW and HYDRUS**

613 Two models, MODFLOW and HYDRUS, are commonly used to investigate the hydrologic
614 state of the coupled surface water–groundwater–soil–vegetation system (McDonald and
615 Harbaugh, 1988; Doble et al., 2006; Shah et al., 2007; Lowry and Loheide, 2010; Loheide
616 and Booth, 2011; Ajami et al., 2012). HYDRUS applies Richard's equation to simulate water,
617 heat and solute movements in soil, whereas MODFLOW is fully distributed and coupled
618 hydrologic model of groundwater flow (Orellana et al., 2012). Hydrologic models that apply
619 Richard's equation in a soil medium of variable saturation are important for evaluating the
620 mechanisms that generate groundwater hydrographs and flow. MODFLOW can also perform
621 spatial scaling of ET as a function of depth-to-groundwater, although the form of ET depends
622 upon parameterisation of the model. Often, ET is determined as ET_p or ET_0 , but
623 measurements of ET_a from eddy covariance can also be used. In one example, Wilcox et al.,
624 (2007) estimated ET from Cleverly et al., (2002) to evaluate the interaction between riparian
625 ET and surface water–groundwater interactions.

626 Variable saturation models have improved our understanding of the interactions between
627 groundwater and soil moisture in the vadose zone. Root water uptake (RWU) creates soil
628 moisture deficits in the vadose zone and the capillary fringe, thereby causing vadose zone
629 water content to fluctuate with depth-to-groundwater (Nachabe et al., 2005; Shah et al., 2007;
630 Logsdon et al., 2010). Using HYDRUS 1-D, Lowry and Loheide (2010) integrated ET_g and
631 RWU from the vadose zone by estimating the groundwater subsidy as the difference between
632 RWU from the shallow groundwater and RWU from free drainage. Further complicating the
633 relationship between groundwater and soil moisture, hydraulic redistribution of moisture
634 from deep in the soil column to the surface (i.e., hydraulic lift) can reduce the amplitude of
635 fluctuations in depth-to-groundwater, increase the amount of ET_g that is lost to groundwater
636 evaporation, and decrease the nocturnal recovery in depth-to-groundwater (Orellana et al.,
637 2012).

638 One of the goals of ecohydrological modelling in GDEs is the prediction of vegetation state
639 based upon groundwater regime (Loheide and Booth, 2011). Likewise, the principle drivers
640 of water use by vegetation in GDEs were aquifer attributes (S_y , regional groundwater flow),
641 meteorology (solar radiation, vapour pressure deficit), environmental stress, and vegetation
642 attributes (LAI, species composition) (Cleverly et al., 1997; Perkins and Sophocleous, 1999;
643 Dahm et al., 2002; Cleverly et al., 2006; Butler et al., 2007; Lautz, 2008; Abudu et al., 2010).
644 In general, these controls are observed in the wider literature on the controls of vegetation
645 water use (Eamus et al., 2006b; Whitley et al., 2009). As the meteorological, environmental

646 and vegetation effects on ET have been thoroughly described, we will focus on the regional
647 aquifer effects on ET_g here.

648 One geomorphologic attribute of the aquifer that controls the flow of groundwater and
649 thereby affects the distribution of groundwater-dependent vegetation depends upon whether
650 the aquifer is gaining (i.e., water flows into the aquifer from its surroundings) or losing (i.e.,
651 an area where groundwater is lost to adjacent unsaturated soils) (Cleverly, 2013). A larger
652 ET_g can lead to contrasting effects on seepage from streams to aquifers, depending upon
653 whether along a losing or gaining reach (Ajami et al., 2011). Similarly, fluctuations in depth-
654 to-groundwater can differ between gaining and losing reaches, of which the occurrence of the
655 latter is where groundwater inflow might be insufficient to support large recovery rates in
656 depth-to-groundwater (Schilling, 2012). The relationships between plant water use, aquifer
657 dynamics, and seasonality (e.g., Logsdon et al., 2010; Ajami et al., 2011) are influenced by
658 the rooting patterns and groundwater depth- ET_g relationships of the specific plant functional
659 types that inhabit the GDE (Baird and Maddock, 2005).

660

661 **5 Field based measurements of water-use by GDEs**

662 *5.1 Sub-daily fluctuation in groundwater depth*

663 An idealised representation of the “White method” in a shallow unconfined aquifer is shown
664 in Figure four.

665

666 Figure 4 here

667

668 In Figure four the oscillating curve represents the cycle of groundwater drawdown arising
669 from evapotranspiration (ET) during the day followed by a “rebound” of the water table when
670 ET returns to zero at night. The dashed straight line (with slope = r) provides an estimate of
671 the recovery rate, which is how fast the water table rises in the absence of groundwater use
672 (Butler et al., 2007). After accounting for recovery, the daily drawdown of the water table is
673 scaled by the effective specific yield (S_y), or the volume of water (per unit surface area of an
674 unconfined aquifer) released from the soil pores with a given change in depth-to-groundwater
675 (White, 1932):

676

$$677 \quad ET_g = S_y (24r + s) \quad (14)$$

678

679 where s is the change in aquifer storage and is determined from the 24-hr change in depth-to-
680 groundwater. This approach has been successfully applied in the Okavango Delta in

681 Botswana (Bauer et al., 2004), an upland grassland catchment in central Argentina (Engel et
682 al., 2005), an oak/grassland site on the Great Hungarian Plain of eastern Hungary (Nosetto et
683 al., 2007), the Sopron Hills of western Hungary (Gribovszki et al., 2008), the Gobi Desert of
684 northwest China (Wang et al., 2014), and various sites in the USA (Butler et al., 2007; Lutz
685 et al., 2008; Martinet et al., 2009).

686 The White method tends to over-estimate ET_g (Loheide et al., 2005; Martinet et al., 2009). A
687 major source of error is estimation of S_y , to which this method is very sensitive (Loheide et
688 al., 2005; Gribovszki et al., 2008; Lutz, 2008; Logsdon et al., 2010; Miller et al., 2010).
689 Furthermore, representative measurements of the readily available S_y are difficult to make
690 and are complicated by capillary flux, trapped air, hysteresis, and departure of the soil–water
691 ecosystem from an equilibrium (Logsdon et al., 2010). The value of S_y is dependent upon
692 soil texture (Loheide et al., 2005), thus Martinet et al., (2009) applied a value of S_y that varied
693 with the soil texture in contact with the capillary fringe of the water table. With a measure of
694 ET_g (e.g., from eddy covariance), the White equation can be inverted to investigate the
695 variation in S_y (Miller et al., 2010). Using an inversion of the White method, estimates of S_y
696 account for spatial heterogeneity in soil texture and scaling effects on S_y , but further studies
697 are required before comprehensive predictions of S_y can be obtained without independent
698 measurements of ET_g . Alternatively, Nachabe et al., (2005) used a more direct estimate of S_y
699 in the soil column by combining measured fluctuations of depth-to-groundwater and soil
700 moisture across the vadose (i.e., unsaturated) zone. In either case, additional instrumentation
701 to measure ET_g or soil moisture profiles improved the estimation of S_y .

702 Several modifications to the White method were evaluated in a study by Fahle and Dietrich
703 (2014), in which they compared errors in estimation of S_y , recovery and ET_g . No model
704 outperformed the others in each of these error benchmarks, thus illustrating that errors in the
705 estimation of S_y are compensated by errors in the estimation of recovery (Fahle and Dietrich,
706 2014). The methods that provided the best estimates for recovery of the groundwater used
707 approaches to estimate sub-daily rates of ET_g and recovery (Gribovszki et al., 2008; Loheide
708 and Ii, 2008). In both methods, recovery was estimated from the previous and following
709 nights, although application to other methods might require site-specific parameterisation of
710 the time period that is most representative for their study conditions (e.g., 18.00–6.00; Fahle
711 and Dietrich, 2014). In the method of Gribovszki et al., (2008), recovery was estimated from
712 the time rate of change in depth-to-groundwater, and this important upgrade reduced the error
713 of recovery estimates (Gribovszki et al., 2010; Fahle and Dietrich, 2014).

714 Groundwater hydrographs include the impact of regional fluctuations in the aquifer that are
715 not associated with local changes arising from ET of vegetation (Engel et al., 2005). A
716 regional effect that can cause problems with the White method occur when tides from nearby
717 water bodies generate two daily peaks in the groundwater hydrograph (Miller et al., 2010),
718 thereby requiring measurements of the water body that is causing the effect. After
719 accounting for the regional hydrograph, soil moisture content in the vadose zone can still
720 affect the correlation between sap flow measurements of ET_g and groundwater fluctuations
721 (Engel et al., 2005). This was consistent with the modelling results of Loheide et al., (2005),
722 who found that daily fluctuations were dampened by root water uptake from the vadose zone

723 alone. Spectral methods (e.g., windowed Fourier decomposition) are effective at identifying
724 break points in the daily signal like those associated with regional groundwater and soil
725 moisture effects, although variations in ET_g can result in loss of amplitude, consequently
726 rendering spectral analysis unsuitable for quantitative analysis without an adequate scaling
727 factor (Schilling and Zhang, 2012; Soylu et al., 2012).

728

729 5.2 *Using stable isotopes to estimate rates of groundwater use*

730 Estimates of the proportion of total vegetation water use derived from groundwater can be
731 determined from stable isotope analyses (Querejeta et al., 2007; Maguas et al., 2011; Feikema
732 et al., 2010; Kray et al., 2012; McLendon et al., 2008). Two types of information are
733 required to quantitatively partition ET_g from ET. The first is an independent estimate of ET_0
734 or ET_a as derived from eddy covariance (Kelliher et al., 1992; Baldocchi and Vogel, 1996;
735 Baldocchi and Ryu, 2011), sapflow (Cook and O'Grady, 2006; O'Grady et al., 2006; Zeppel,
736 2013) or RS techniques (Nagler et al., 2009; Nagler et al., 2013). The second is the stable
737 isotope composition of water in soil, groundwater and xylem. Upon determination of the
738 proportion of ET that is due to ET_g (Section 3.2), the amount of ET_g , for example in $mm\ d^{-1}$,
739 is the product of that proportion and ET.

740 Three generalities can be identified in the results of stable isotope studies of GDEs. First,
741 multi-species comparisons at a common site generally confirm niche separation (spatially or
742 temporally) in patterns of water uptake, thereby minimising competition for water
743 (Lamontagne et al., 2005; Querejeta et al., 2007; Kray et al., 2012). Second, increased depth-
744 to-groundwater results in a declining proportion of groundwater use (O'Grady et al., 2006),
745 although this can vary amongst different vegetation communities (McLendon et al., (2008).
746 Finally, as time since last rain increases, the proportion of groundwater used by vegetation
747 usually increases (McLendon et al., 2008), but not always (Kray et al., 2012). Consequently
748 seasonality of groundwater use may occur when rainfall is highly seasonal and groundwater
749 availability is maintained throughout the dry season (O'Grady et al., 2006).

750 Stable isotope composition varies with depth (Table 1; Querejeta et al., 2007). Consequently
751 taking an average value to represent the entire rooting depth can lead to errors. Whilst use of
752 two independent isotopes allows the relative contribution of three sources to be determined,
753 obtaining independence of both isotopes is very difficult. As an alternative, Cook and
754 O'Grady (2006) developed a model that estimates the relative water uptake by vegetation
755 from different soil depths. This model is based upon the following axioms: the rate of water
756 uptake is determined by (a) the gradient in water potential between bulk soil and leaves; (b)
757 root distribution through the soil profile; and (c) a lumped hydraulic conductance parameter.
758 Soil isotopic composition as a function of depth and of xylem water is used to constrain root
759 distributions within the model. This has the advantage over end-member analyses (an analytic
760 tool to determine the relative contributions of soil water and groundwater to transpiration;
761 Phillips and Gregg 2003) because: (i) it produces a quantitative estimation of the proportion
762 of water extracted from multiple depths (including groundwater); (ii) it doesn't require

763 distinct values of isotope composition for end-member analyses and therefore can deal with
764 the more typical grading of isotope composition observed through the soil profile; and (iii) it
765 is based on simple ecophysiological principles. Cook and O’Grady (2006) applied this
766 model and demonstrated that two co-occurring species obtained 7–15 % of their
767 transpirational water from the water table, a third species accessed 100 % from the water
768 table, and a fourth species derived 53–77 % from groundwater.

769

770 **6 Functional responses of GDEs to changes in GW depth**

771 **6.1 Effects of groundwater on growth and dendrochronological traits**

772 A reduced growth rate in response to declining water availability is a universally observed
773 plant response (Kelliher et al., 1980; Osmond et al., 1987; Oberhuber et al., 1998; Sarris et
774 al., 2007). In most GDEs rainfall and groundwater provide important supplies of water, and
775 the ratio of rainfall to groundwater uptake varies spatially and temporally. Consequently,
776 increases in groundwater depth may be expected *a priori* to have the potential to affect plant
777 growth. Dendrochronology (the study of growth in tree rings) has a long history in ecological
778 research spanning many decades (Drew and Downes 2009; McCarroll and Loader, 2004).
779 However, its application to the study of GDEs is much more recent (e.g. Giantomasi et al.,
780 2012). Similarly, recording point dendrometers, which are sensitive stem gauges that
781 monitor growth increment at hourly time-scales, recently have been used for expanding
782 applications. In this section we briefly review some of the insights gained from
783 dendrochronology and dendrometry in the study of GDEs.

784 Tree rings represent the history of past growth events, which are often but not always annual
785 (Prior et al., 2012). Quantification of growth rates from tree rings can be used to reconstruct
786 fluctuations in the supply water from precipitation and groundwater (Oberhuber et al., 1998;
787 Bogino and Jobbagy, 2011; Perez-Valdivia and Sauchyn, 2011; Xiao et al., 2014). In
788 mountainous regions where the regional water supply is derived from snowmelt, tree growth
789 and groundwater depth are correlated with precipitation during the year prior to growth
790 because much of the snow received in the winter melts in the year after it fell (Oberhuber et
791 al., 1998; Perez-Valdivia and Sauchyn, 2011). Likewise, tree ring growth and groundwater
792 fluctuations are correlated to the dominant climate driver in an area (e.g., the Pacific decadal
793 oscillation and El Niño–Southern Oscillation in California, USA) (Hanson et al., 2006). In
794 some circumstances, the effect of groundwater can be disentangled from climate through the
795 use of spectral analysis (Bogino and Jobbagy, 2011), but in other cases depth-to-groundwater
796 was not found to be a significant factor in explaining differences in either ring width or basal
797 area increment (Stock et al., 2012).

798 The timing of groundwater dependence can influence the presence of a climate signal in tree
799 rings: climate signals can be weaker during formation of late wood, when growth rates are
800 small (Oberhuber et al., 1998); or during the dry season, when precipitation rates are
801 negligible and growth is supported by groundwater (Drake and Franks, 2003). Thus, analysis
802 of tree ring chronologies can provide an insight into the importance of access to groundwater

803 on plant growth. Individual events can be identified in the tree ring growth record (Hultine et
804 al., 2010), as can long-term trends in depth-to-groundwater (Bogino and Jobbagy, 2011). In
805 riparian cottonwood trees and willows, Hultine et al., (2010) identified rapid, large and
806 reversible responses of tree ring width to draining and refilling of a reservoir (Fig. 5).

807

808 Figure 5 here

809 Longer-term trends in depth-to-groundwater have impacted dendrochronologies in both
810 directions, toward lower growth rates with groundwater extraction (Lageard and Drew, 2008)
811 and toward increasing growth rates with decreasing depth-to-groundwater, except in response
812 to root anoxia arising from flooding (Bogino and Jobbagy, 2011). However, specific
813 responses depend upon depth-to-groundwater and individual differences amongst functional
814 types; for example, riparian cottonwood trees (*P. fremontii*) responded to rewetting with
815 growth that was larger and faster than the response of co-occurring willow (*S. exigua*), a
816 small-stature, thicket-forming shrub that is restricted to streamside areas with very shallow
817 groundwater (Scurlock, 1998; Rood et al., 2011). From an understanding of the relationships
818 between tree growth and depth-to-groundwater, historical periods of sensitivity to
819 hydrological drought (i.e., affecting groundwater levels) *versus* meteorological drought (i.e.,
820 below-average precipitation) can be identified (Potts and Williams, 2004; Adams and Kolb,
821 2005; Coccozza et al., 2011). Such insights have value in developing a long-term
822 understanding of the relationships amongst GDEs, climate and groundwater depth.

823 Wood formed during drought is enriched in ^{13}C , reflecting decreases in stomatal conductance
824 relative to photosynthesis and the consequential ratio of $[\text{CO}_2]$ within and outside of the leaf
825 (C_i/C_a) (McCarroll and Loader, 2004; Coccozza et al., 2011) (Horton et al., 2001, Maguas et
826 al., 2011). Interpretation of $\delta^{13}\text{C}$ in tree rings can be complicated by the effects of phloem
827 loading (Gessler et al., 2009) and by photosynthetic re-fixation in the bark (Cernusak et al.,
828 2001), although with independent confirmation, xylem $\delta^{13}\text{C}$ can explain differences in
829 groundwater use and water stress in groundwater-dependent trees. In one such comparison,
830 $\delta^{13}\text{C}$ was constant across xylem from *Populus* along a perennial stream (thereby implying
831 access to groundwater) but changed with moisture conditions in an intermittent reach (Potts
832 and Williams, 2004). Likewise, changes in ring width over time were reflected by $\delta^{13}\text{C}$
833 from leaves (Hultine et al., 2010), such that less negative values of $\delta^{13}\text{C}$ indicated increased
834 water-use-efficiency when the supply of water was reduced.

835 On small time-scales (hourly-to-daily), incremental stem growth (and shrinkage) is measured
836 using precision dendrometers that contain linear-variable-displacement transducers (Zweifel
837 et al., 2005, Drew et al., 2008, Drew and Downes 2009). Changes in maximum daily trunk
838 shrinkage arising from reduced water availability occur earlier and stronger than changes in
839 stomatal conductance, stem water potential or transpiration (Ortuno et al., 2006, Conejero et
840 al., 2007, 2011, Galindo et al., 2013). Nonetheless, rates of sapflow declined with maximum
841 daily stem shrinkage, both of which responded exponentially to changes in depth-to-
842 groundwater (Ma et al., 2013). Similarly February et al., (2007) and Drake et al., (2013)

843 found that increased groundwater supply (actual or simulated) resulted in increased stem
844 increment, sapflow and xylem water potential.

845

846 **7.0 Two case studies**

847 Two case studies are now presented, one from Australia and one from the USA. These case
848 studies serve several purposes. First, they provide examples of the multiple approaches
849 required in the study of GDEs (physiological, remote sensing, ecological). Second, they
850 provide a valuable bridge between sections 2 – 6 (water-use, remote sensing, modelling) and
851 section 8 (vegetation response trajectories to changes in groundwater depth). Finally, they
852 integrate the results of many years of concentrated study in two diverse ecosystems.

853 *7.1 The Gnangara Mound*

854 The Gnangara Mound is a shallow unconfined aquifer of the Swan Coastal Plain in Western
855 Australia. Increased depth-to-groundwater has occurred over the past several decades as the
856 result of long-term declines in annual rainfall, increased human abstraction and increased
857 discharge arising from the development of a plantation industry in the region (Elmahdi and
858 McFarlane, 2012). The impacts of groundwater abstraction on woodlands have been
859 documented in this region (Groom et al., 2000; Canham et al., 2009; Canham et al., 2012;
860 Stock et al., 2012). In 1985 large rates of summer abstraction in this Mediterranean climate
861 was associated with increased and widespread mortality of native woodlands (up to 80 %
862 mortality close to abstraction bores; Mattiske and Associated 1988).

863 To determine long-term floristic changes associated with groundwater abstraction, a series of
864 transect studies were initiated in 1988. A 2.2 m increase in depth-to-groundwater coupled to
865 higher-than-normal summer temperatures resulted in further adult mortality of overstorey
866 species by as much as 80 %; additionally, 64 % mortality was recorded in understory species
867 2 years after the start of groundwater abstraction (Groom et al., 2000). Increased rates of
868 mortality were not observed at control sites that were not subject to groundwater pumping.

869 Large inter-specific differences in rates of mortality were observed in these Gnangara studies.
870 Consequently, a further study examined the vulnerability of individual species to increased
871 depth-to-groundwater (Froend and Drake 2006; Canham et al., 2009). Using xylem
872 embolism vulnerability curves as a measure of sensitivity to water stress, Froend and Drake
873 (2006) compared three *Banksia* and one *Melaleuca* species. They found that xylem
874 vulnerability reflected the broad ecohydrological distribution of species across a topographic
875 gradient, and they identified a threshold leaf water potential below which increased mortality
876 was likely. Similarly Canham et al., (2009) examined Huber values (the ratio of sapwood to
877 leaf area), leaf-specific hydraulic conductivity (k_l) and xylem vulnerability of two obligate
878 phreatophytes and two facultative phreatophytes. At sites where depth-to-groundwater was
879 shallow there were no inter-specific differences in vulnerability to water stress. However, by
880 comparing across a topographic gradient, Canham et al., (2009) showed that two facultative

881 phreatophytes (but not the obligate phreatophytes) were more resistant to xylem embolism at
882 the upper slope (larger depth-to-groundwater) than the lower slope.

883 It is not only aboveground tissues that adapt to changes in groundwater depth. Differences in
884 root growth also respond to changes in depth-to-groundwater. Thus Canham et al., (2012)
885 found that root growth varied with depth within the soil column: at the surface, root growth
886 responded to seasonality and microclimate; at depth, root growth occurred all year and was
887 dependent upon soil aeration (i.e., roots elongated rapidly followed a declining water table
888 during the summer and died back in the following winter as the groundwater rebounded).
889 These results are consistent with the increases in ET following groundwater decline that were
890 observed by Cleverly et al., (2006). The ability to rapidly increase root depth during the (dry)
891 summer is a critical attribute of phreatophytes occupying sites with seasonally dynamic
892 depth-to-groundwater.

893 The development of ecosystem response trajectories for the impact of groundwater
894 abstraction is an important resource management imperative. Froend and Sommer (2010)
895 examined a rare, 40-year vegetation survey dataset from the Gngangara Mound. Whilst the
896 long-term average (1976–2008) rainfall was 850 mm, the annual average for the recent past
897 was about 730 mm and depth-to-groundwater has increased by 1 m in the past 50 years.
898 Depth-to-groundwater fluctuates about 0.5–3 m seasonally, and maximal depth occurs at the
899 end of summer. Two transects were compared: a “control” where gradual increases in depth-
900 to-groundwater (9 cm y^{-1}) have occurred as a result of the decline in annual rainfall; and an
901 “impacted” transect where large rates of increase in depth-to-groundwater have occurred (50
902 cm y^{-1}). Principal component analyses were used to identify three vegetation communities:
903 those associated with down-slope, mid-slope and upper-slope positions. Species having a
904 high reliance on consistent water supplies (mesic species) were dominant at the down-slope
905 site while xeric species dominated the upper-slope sites.

906 On the control transect it was hypothesised that groundwater decline would result in a
907 replacement of the mesic by the xeric species. However, this hypothesis was not supported.
908 Indeed, most of the compositional and structural attributes of the three communities remained
909 unchanged. The principle community-scale response was a change in the abundance of mesic
910 and xeric species rather than complete replacement of one species for another. In contrast to
911 the results of Shatfroth et al., (2000), mesic species at sites with shallow groundwater were
912 not more sensitive to increases in depth-to-groundwater than xeric species. By contrast,
913 changes in composition on the impacted transect were far more pronounced, and mass
914 mortality was observed across all classes (mesic to xeric) species. This study emphasises the
915 importance of the rate of change in depth-to-groundwater as a determinant of the response of
916 species and communities.

917

918 7.2 *Riparian forest vegetation in the southwestern USA*

919 In the southwestern USA, the majority of GDEs are riparian or littoral, where a shallow
920 aquifer is formed by runoff from snowmelt in the mountainous headwaters. Much of the

921 agriculture in the region is found along the rivers due to the large amount of surface water
922 that flows past. The focus of irrigation to the riparian corridors has placed intense
923 competition between water resources for people *versus* the environmental flows that are
924 required to maintain shallow aquifers and associated GDEs. Of further risk to riparian GDEs
925 and agriculture, groundwater extraction and land use change threaten riparian ecosystems
926 (Scott et al., 1999; Nippert et al., 2010; Pert et al., 2010). Thus, many studies have been
927 undertaken over several decades to investigate the water use of GDEs in southwestern North
928 America (van Hylckama, 1970; Gay and Fritschen, 1979; Sala et al., 1996; Devitt et al.,
929 1998; Goodrich et al., 2000a; Cleverly et al., 2002; Scott et al., 2004; Nagler et al., 2005b).

930 Sunlight is plentiful in the southwestern USA, thus riparian GDEs are strong carbon sinks
931 (Kochendorfer et al., 2011). However, seasonal variability in surface water discharge and
932 aquifer recharge can create cycles of hypoxia and drought stress (Lowry et al., 2011), both of
933 which act to reduce production (Shah and Dahm, 2008). Often existing between these two
934 states of stress, riparian vegetation can transpire substantial amounts of water, reaching near
935 the theoretical maximum (ca. 12 mm d^{-1}) (Cleverly, 2013). This general release from
936 limitations due to energy, moisture and stress results in rates of latent heat flux that exceed
937 precipitation (i.e., $ET/P > 1$) (Scott et al., 2000; Cleverly et al., 2006; Scott et al., 2006b) and
938 net radiation (Devitt et al., 1998). Even when little or no groundwater use can be identified in
939 the vegetation (e.g., in *Sporobolus*), ET losses from the riparian corridor can exceed
940 precipitation inputs (Scott et al., 2000), implying that soil moisture in the vadose zone can be
941 recharged by groundwater and that riparian GDEs need not use the groundwater directly.

942 In southwestern North America, vegetation in riparian corridors and adjacent rangelands or
943 shrublands is classified by reliance upon access to groundwater (i.e., obligate or facultative
944 phreatophyte; Smith et al., 1998) or plant functional type (obligate wetland, shallow-rooted or
945 deep-rooted riparian, transitional riparian, or upland; Pockman and Sperry, 2000; Baird and
946 Maddock, 2005; Baird et al., 2005). The result of groundwater depletion has distinct effects
947 on the vegetation in each functional type. Shallow-rooted, obligate phreatophytes (e.g.,
948 cottonwood, *Populus* spp.) can be very sensitive to groundwater decline, resulting in
949 reductions of ET, productivity and canopy conductance as a consequence of increases in
950 vapour pressure deficit that are correlated with depth-to-groundwater (Gazal et al., 2006;
951 Kochendorfer et al., 2011). Branch sacrifice, partial crown dieback and mortality commonly
952 occur in *Populus* following substantial groundwater drawdown (Mahoney and Rood, 1991;
953 Kranjcec et al., 1998; Scott et al., 1999; Rood et al., 2000; Cooper et al., 2003; Rood et al.,
954 2003). However, stomatal closure and crown dieback in *Populus* can prevent total hydraulic
955 failure, and thereby minimise mortality rates, by maintaining favourable xylem water
956 potentials within the remainder of the crown (Amlin and Rood, 2003).

957 Decreased baseflow and drawdown of groundwater levels has been associated with a shift in
958 dominance to xerophytic species in the American Southwest at the expense of forbs and
959 obligate phreatophytes (Stromberg et al., 1996; Stromberg et al., 2006; Stromberg et al.,
960 2007; Stromberg et al., 2010). Xerophytes in the riparian corridors of the American
961 Southwest include deep-rooted phreatophytes (e.g., *Proposis*, *Tamarix*) and upland species
962 (e.g., *Chrysothamnus*), any of which may be opportunistic users of groundwater or

963 groundwater-independent. Stress tolerance, opportunistic use of groundwater and use of
964 multiple water sources (e.g., soil moisture) have contributed to the invasive success of
965 *Tamarix* (Busch et al., 1992; Cleverly et al., 1997; Di Tomaso, 1998; Nippert et al., 2010).
966 Consequently, *Tamarix* inhabit sites with variable depth-to-groundwater (Lite and Stromberg,
967 2005), which results in an amount of ET that is equivalently variable in time and space
968 (Cleverly et al., 2002; Cleverly, 2013).

969 The effective area of riparian vegetation has historically increased in the American Southwest
970 due to expansion of deep-rooted phreatophytes like *Tamarix* and *Prosopis* (Hultine and Bush,
971 2011). The upland vegetation that previously occupied riverine upper terraces and grasslands
972 supported small rates of ET (Shafroth et al., 2005; Hultine and Bush, 2011), thus expansion
973 of phreatophytes into these areas has resulted in an increase in ET losses (Scott et al., 2006b;
974 Cleverly, 2013) and thereby has placed a potential strain on groundwater resources. In the
975 case of expansion by *Tamarix*, groundwater extraction may result in enhancement of ET
976 (Cleverly et al., 2006), contrasting with post-extraction reductions in ET by native, shallow-
977 rooted phreatophytes such as *Populus* (Cooper et al., 2006; Gazal et al., 2006) and thus
978 representing a shift in the ecohydrology of riparian corridors throughout the semi-arid regions
979 of south western North America.

980

981 **8 Integrating multiple-scale responses**

982 *8.1 Multiple traits across leaf, branch, whole-tree and stand*

983 The responses of vegetation to differences in depth-to-groundwater have been examined
984 extensively at leaf, tree, canopy and population scales. Rates of leaf-scale photosynthesis,
985 stomatal conductance, whole plant hydraulic conductance, tree- and canopy-scale
986 transpiration and plant density are known to decline in response to reduced supply of
987 groundwater (Table 3). Similarly, increased Huber value, crown dieback and mortality in
988 response to reduced supply of groundwater have been observed (Table 3). Consequently,
989 response functions for individual traits are readily apparent; examples include changes with
990 depth-to-groundwater in rates of photosynthesis (Horton et al., 2001), plant cover (Elmore et
991 al., 2006), NDVI (Lv et al., 2012) and crown dieback (Horton et al., 2001). However, few
992 studies have examined *multiple traits across multiple scales* and then provided an integrated
993 “ecosystem-scale” response function to differences in groundwater availability. Integrated
994 ecosystem-scale responses to changes in groundwater availability have been hypothesised to
995 be linear (Fig. 6), curvi-linear or a step function with which minimal damage occurs until a
996 threshold is reached (Leffler and Evans, 1999; Eamus et al., 2006).

997 Information on how vegetation adapts to differences in water supply is critical for predicting
998 vegetation survival, growth and water-use, which have important impacts on site hydrology
999 (McDowell et al., 2008; Carter and White, 2009). The development of integrated response
1000 curves to reduced groundwater availability would significantly enhance our understanding of
1001 water requirements and lead to the identification of response thresholds. Such thresholds
1002 could be used to identify the limits of reduction in water-source availability, a useful

1003 parameter for characterising water requirements for resource and conservation management
1004 (Froend and Drake, 2006).

1005

1006 Table 3 here

1007 In a recent comprehensive, three-year study, Zolfaghar (2014) examined leaf, branch, tree
1008 and stand-scale functional and structural attributes of woodlands across a gradient of depth-
1009 to-groundwater (2.4 m to 37.5 m) in mesic Australia. She examined eighteen traits, including
1010 stand-scale basal area and tree height, leaf turgor loss point, sapwood hydraulic conductivity,
1011 sensitivity to xylem embolism and above ground net primary productivity. An increase in
1012 depth-to-groundwater across these sites was hypothesised to result in:

- 1013 1. reduced standing biomass;
- 1014 2. adjustment of leaf-, tree- and plot-scale plant traits with associated repercussions on
1015 plant water relations;
- 1016 3. increased drought tolerance; and
- 1017 4. increased water-use-efficiency.

1018

1019 Fig 6 here

1020

1021 Figure seven provides a summary of the observed responses of each trait to increasing depth-
1022 to-groundwater. Refer to Table four for the abbreviations used in Figure seven.

1023

1024

1025 Fig 7 here.

1026

1027

1028 Table 4 here

1029

1030 It is clear from Figure seven that increased depth-to-groundwater was associated with
1031 declines in basal area, tree height and LAI, and hence light interception, of native woodlands.
1032 As a consequence, aboveground net primary productivity was reduced as groundwater
1033 availability declined. Increased drought tolerance, as indicated by increased water-use-
1034 efficiency, increased Huber value and reduced water potential at turgor loss and solute
1035 potential at full turgor, supported the principle over-arching hypothesis that increasing depth-
1036 to-groundwater results in a suite of leaf-branch and tree-scale adaptations that increase tree
1037 tolerance to reduced water supply.

1038 A key aspect of this research was to develop an ecosystem-scale response function for depth-
1039 to-groundwater. Zolfaghar (2014) normalised the responses (0 to 1) such that a response of 1
1040 indicates no effect of differences in depth-to-groundwater and 0.5 indicates a 50 %
1041 decline/increase in the maximal/minimum value of a particular trait. The normalised response
1042 function is presented in Figure eight. Despite the large number of traits and species across the
1043 seven sites, the standard error of the ecosystem-scale average for each data point was
1044 remarkably small, indicating significant convergence in normalised responses to differences
1045 in depth-to-groundwater. Convergence of functional variations in traits across sites and
1046 species is increasingly observed with respect to rainfall or other climatic variables (Wright et
1047 al., 2004; Kattge et al., 2011). Indeed, identification of plant functional types (PFTs) is a
1048 practical means for models of land surface-atmosphere interactions across biomes to integrate
1049 the physiology of vegetation. Similarly, improved accuracy can be obtained from dynamic
1050 global vegetation models (DGVMs) through the construction of large datasets (cf. Wright et
1051 al., 2004, Kattge et al., 2011) that include a representation of groundwater-dependent
1052 ecosystems.

1053 A second feature apparent in the response function of Fig. 8 is the large R^2 of the sigmoidal
1054 regression, reflecting the relatively high degree of confidence in this threshold response. The
1055 response curve further suggests that extraction of groundwater beyond 7 – 9 m depth is likely
1056 to result in significant changes in ecosystem structure and function. Although we cannot
1057 pinpoint the exact break point with precision, it is clearly apparent that a breakpoint does
1058 occur in the data. Furthermore, two recent reviews based on water balance concluded that
1059 groundwater uptake ceased when depths exceeded 7.5 m (Benyon et al., 2006) or 8 – 10 m
1060 (O’Grady et al., 2010), whilst Cook et al., (1998) established a limit of approximately 8 m for
1061 a Eucalypt savanna. Finally, Kath et al., (2014) identified thresholds of groundwater depth
1062 across 118 sites in SE Australia for two tree species ranging from 12.1 m to 26.6 m further
1063 supporting our identification of a breakpoint in the responses of trees to groundwater depth.
1064 Such a strong response, consistent across multiple traits, should provide a strong management
1065 signal to guide future groundwater abstraction.

1066

1067 Figure 8 here

1068 8.2 *Co-ordination across traits*

1069 Some plant traits are a better indicator of plant sensitivity to water stress than others. Leaf
1070 water potential at turgor loss is recognised as a physiological measure of plant sensitivity to
1071 water stress (McDowell et al., 2008). Similarly, measurements of vulnerability to xylem
1072 cavitation and safety margins are critical determinants of drought tolerance (Markesteijn et
1073 al., 2011; Sperry et al., 2008). Safety margins are equal to the difference between minimum
1074 daily branch water potential and PLC_{50} (Meinzer et al., 2008; Sperry et al., 2008). A strong
1075 linear correlation between these two traits (Fig. 9) in the Kangaloon study (Zolfaghar 2014)
1076 reveals co-ordination in the response of leaf (cell traits) and xylem (branch trait) anatomy, as
1077 has been observed previously in a study of eight tropical dry forest species (Brodribb et al.,

1078 2003). This relationship indicates that as depth-to-groundwater increased, sensitivity to
1079 drought at both leaf cell and branch-scale decreased (lower leaf water potential is needed to
1080 reach turgor loss point and PLC_{50} declined).

1081

1082 Figure 9 here

1083

1084 **9 Concluding remarks**

1085 The existence of GDEs has been known for several centuries. The ecological, social, cultural
1086 and economic importance of GDEs, however, has only been understood more recently.
1087 Whilst inferential methods were the main means for determining the presence/location of
1088 GDEs for many decades these have now been replaced by more direct methodologies which
1089 include the use of stable isotopes and hourly direct measurements of fluctuations in shallow
1090 groundwater depth. The most revolutionary recent development has, perhaps, been the
1091 application of remote sensing techniques to identify the location of GDEs but also to reveal
1092 key features of their functional behaviour.

1093 Increasing frequencies, spatial and temporal extent and severity of drought and resulting
1094 drought-induced mortality of forests have been recorded extensively (Dai 2011; Eamus et al.,
1095 2013) in the past two decades. Climate-change-induced changes in rainfall distribution and
1096 amounts pose a new stress to both groundwater resources and associated GDEs. For the first
1097 time, remotely sensed information on both the structure (e.g LAI) and functioning (e.g. rates
1098 of water-use and primary productivity) of GDEs are now available across several decades.
1099 The challenge now is to use this long history of remotely sensed and meteorological data as a
1100 unique natural experiment to determine response functions of multiple GDEs to changes in
1101 climate (and groundwater depth) globally to inform both the science of ecology and the
1102 practical needs of water and land resource managers into the future.

1103

1104 **10 References**

1105

- 1106 Abudu, S., Bawazir, A.S., King, J.P.: Infilling Missing Daily Evapotranspiration Data Using
1107 Neural Networks. *J. of Irrig. and Drainage Engin.* 136:317-325. DOI:
1108 10.1061/(asce)ir.1943-4774.0000197, 2010
- 1109 Adams, H.D., Kolb, T.E.: Tree growth response to drought and temperature in a mountain
1110 landscape in northern Arizona, USA. *J. Biogeog.* 32:1629-1640. DOI:
1111 10.1111/j.1365-2699.2005.01292.x, 2005.
- 1112 Aguilar, C., Zinnert, J.C., Jose Polo, M., Yound, D.R.: NDVI as an indicator for changes in
1113 water availability to woody vegetation. *Ecol. Appl.* 23: 290 – 300, 2012.

1114 Ajami, H., Maddock, T., Meixner, T., Hogan, J.F., Guertin, D.P.: RIPGIS-NET: A GIS tool
1115 for riparian groundwater evapotranspiration in MODFLOW. *Ground Water* 50:154-
1116 158. DOI: 10.1111/j.1745-6584.2011.00809.x, 2012.

1117 Ajami, H., Meixner, T., Maddock, T., Hogan, J.F., Guertin, P.: Impact of land-surface
1118 elevation and riparian evapotranspiration seasonality on groundwater budget in
1119 MODFLOW models. *Hydrogeol. J.* 19:1181-1188. DOI: 10.1007/s10040-011-0743-0,
1120 2011.

1121 Akasheh, O.Z., Neale, C.M.U., Jayanthi, H.: Detailed mapping of riparian vegetation in the
1122 middle Rio Grande River using high resolution multi-spectral airborne remote
1123 sensing. *J. Arid Env.* 72:1734-1744, 2008.

1124 Allen, R. G., Pereira, L. S., Raes, D., and Smith, M.: “Crop evapotranspiration:
1125 Guidelines for computing crop requirements.” Irrigation and Drainage Paper No. 56,
1126 FAO, Rome, Italy, 1998.

1127 Amlin, N., Rood, S.: Drought stress and recovery of riparian cottonwoods due to water table
1128 alteration along Willow Creek, Alberta. *Trees: Structure and Function* 17:351-358,
1129 2003.

1130 Baird, K.J., Maddock, T.: Simulating riparian evapotranspiration: A new methodology and
1131 application for groundwater models. *J. Hydrol.* 312:176-190, 2005.

1132 Baird, K.J., Stromberg, J.C., Maddock, T.: Linking riparian dynamics and groundwater: An
1133 ecohydrologic approach to modeling groundwater and riparian vegetation. *Environ.*
1134 *Manag.* 36:551-564, 2005.

1135 Baldocchi, D.D, Ryu Y.: A synthesis of forest evaporation fluxes – from days to years – as
1136 measured with eddy covariance. Pages 101-116 *in* Levia DF, Carlyle-Moses D, and
1137 Tanaka T, editors. *Forest Hydrology and Biogeochemistry: Synthesis of Past*
1138 *Research and Future Directions*. Springer Sciences+Business Media B.V., Dordrecht,
1139 Netherlands, 2011.

1140 Baldocchi, D.D., Vogel, C.A.: Energy and CO₂ flux densities above and below a temperate
1141 broad-leaved forest and a boreal pine forest. *Tree Phys.* 16:5-16, 1996.

1142 Barron, O.V., Emelyanova, I., van Niel, T.G., Pollock, D., Hodgson G.: Mapping
1143 groundwater dependent ecosystems using remote sensing measures of vegetation and
1144 moisture dynamics. *Hydrol. Proc.* 28: 372 – 385, 2014.

1145 Bauer, P., Thabeng, G., Stauffer, F., and Kinzelbach, W.: Estimation of the
1146 evapotranspiration rate from diurnal groundwater level fluctuations in the Okavango
1147 Delta, Botswana. *J. Hydrol.* 288, 344-355, 2004.

1148 Benyon, R.G., Doody, T.M. :Water Use by Tree Plantations in South East South
1149 Australia. CSIRO Forestry and Forest Products Technical Report Number 148.
1150 CSIRO, Mount Gambier SA, 2004.

1151 Benyon, R.G., Theiveyanathan, S., Doody, T.M.: Impacts of tree plantations on groundwater
1152 in south-eastern Australia. *Aus. J. Bot.* 54:181-192, DOI: 10.1071/bt05046, 2006.

1153 Bertrand, G., Goldscheider, N., Gobat, J.M., Hunkeler, D.: Review: From multi-scale
1154 conceptualization to a classification system for inland groundwater-dependent
1155 ecosystems. *Hydrogeology J.* 20: 1, 1–21, 2012.

1156 Bogino, S.M., Jobbagy, E.G.: Climate and groundwater effects on the establishment, growth
1157 and death of *Prosopis caldenia* trees in the Pampas (Argentina). *For. Ecol. and Manag.*
1158 262:1766-1774. DOI: 10.1016/j.foreco.2011.07.032, 2011.

1159 Brodribb, T.J., Holbrook, N.M., Edwards, E.J., and Gutierrez, M.V.: Relations between
1160 stomatal closure, leaf turgor and xylem vulnerability in eight tropical dry forest trees.
1161 *Pl. Cell and Environ.* 26: 443-450. 2003.

1162 Brown, L.: Water tables falling and rivers running dry: international situation. *Int. J. Environ.*
1163 3, 1-5, 2007.

1164 Brown, J., Bach, L., Aldous, A., Wyers, A., DeGagne, J.: Groundwater-dependent
1165 ecosystems in Oregon: an assessment of their distribution and associated threats.
1166 *Front. In Ecol. and Envi.* 9:97-102, 2010.

1167 Brunner, P., Franssen, H-J H., Kgotlhang, L., Bauer-Gottwein, P., and Kinzelbach, W.: How
1168 can remote sensing contribute in groundwater modeling? *Hydrogeol. J.*, 15(1), 5-18,
1169 2007, 2007.

1170 Budyko, M.I.: *Climate and life*. Academic Press, San Diego, CA. 508 pp, 1974.

1171 Busch, D.E., Ingraham, N.L., Smith, S.D.: Water uptake in woody riparian phreatophytes of
1172 the Southwestern United States: a stable isotope study. *Ecol. Appl.* 2:450-459, 1992.

1173 Butler, J.J., Kluitenberg, G.J., Whittemore, D.O., Loheide, S.P., Jin, W., Billinger, M.A.,
1174 Zhan, X.Y.: A field investigation of phreatophyte-induced fluctuations in the water
1175 table. *Water Res. Res.* 43:W02404. DOI: 10.1029/2005WR004627, 2007.

1176 Campos, G.E.P., Moran, M.S., Huete, A., Zhang, Y., Bresloff, C., Huxman, T.E., Eamus, D.,
1177 Bosch, D.D., Buda, A.R., and Gunter, S.A.: Ecosystem resilience despite large-scale
1178 altered hydroclimatic conditions. *Nature* 494:349-352, 2013.

1179 Canham, C.A., Froend, R.H., and Stock, W.D.: Water stress vulnerability of four *Banksia*
1180 species in contrasting ecohydrological habitats on the Gnangara Mound, Western
1181 Australia. *Pl. Cell and Environ.* 32, 64-72, 2009.

1182 Canham, C.A., Froend, R.H., Stock, W.D., and Davies, M.: Dynamics of phreatophyte root
1183 growth relative to a seasonally fluctuating water table in a Mediterranean-type
1184 environment. *Oecologia* 170, 909-916, 2012.

1185 Carlson, T.N., Ripley, D.A.: On the relation between NDVI, fractional vegetation cover, and
1186 leaf area index. *Rem. Sens. Env.* 62:241-252. DOI: 10.1016/s0034-4257(97)00104-1,
1187 1997.

1188 Carter, J.L., White, D.A.: Plasticity in the Huber value contributes to homeostasis in leaf
1189 water relations of a mallee Eucalypt with variation to groundwater depth. *Tree*
1190 *Physiol*:tpp076. DOI: 10.1093/treephys/tpp076, 2009.

1191 Cernusak, L.A., Marshall, J.D., Comstock, J.P., Balster, N.J.: Carbon isotope discrimination
1192 in photosynthetic bark. *Oecologia* 128:24-35. DOI: 10.1007/s004420100629, 2001.

1193 Chimner, R.A., Cooper, D.J.: Using stable oxygen isotopes to quantify the water source used
1194 for transpiration by native shrubs in the San Luis Valley, Colorado USA. *Plant and*
1195 *Soil* 260:225-236. DOI: 10.1023/B:PLSO.0000030190.70085.e9, 2004.

1196 Cleverly, J.: Water use by *Tamarix*. Pages 85-98 in Sher A and Quigley MF, editors.
1197 *Tamarix. A Case Study of Ecological Change in the American West*. Oxford
1198 University Press, New York, NY, 2013.

- 1199 Cleverly, J.R., Dahm, C.N., Thibault, J.R., Gilroy, D.J., Coonrod, J.E.A.: Seasonal estimates
1200 of actual evapo-transpiration from *Tamarix ramosissima* stands using three-
1201 dimensional eddy covariance. *J. Arid Env.* 52:181–197. DOI: 10.1006/jare.2002.0972,
1202 2002.
- 1203 Cleverly, J.R., Dahm, C.N., Thibault, J.R., McDonnell, D.E., Coonrod, J.E.A.: Riparian
1204 ecohydrology: Regulation of water flux from the ground to the atmosphere in the
1205 Middle Rio Grande, New Mexico. *Hydro. Proc.* 20:3207-3225, 2006.
- 1206 Cleverly, J.R., Smith, S.D., Sala, A., Devitt, D.A.: Invasive capacity of *Tamarix ramosissima*
1207 in a Mojave Desert floodplain: the role of drought. *Oecologia* 111:12-18, 1997.
- 1208 Clifton, C.A., and Evans, R.: Environmental water requirements to maintain groundwater
1209 dependent ecosystems. Environmental Flows Initiative Technical Report Number 2.
1210 Canberra: Commonwealth of Australia, 2001.
- 1211 Coccozza, C., Giovannelli, A., Traversi, M.L., Castro, G., Cherubini, P., Tognetti, R.: Do tree-
1212 ring traits reflect different water deficit responses in young poplar clones (*Populus x*
1213 *canadensis* Monch 'I-214' and *P. deltoides* 'Dvina')? *Trees-Structure and Function*
1214 25:975-985. DOI: 10.1007/s00468-011-0572-8, 2011.
- 1215 Conejero, W., Alarcon, J.J. *et al.*: Daily sapflow and maximum daily trunk shrinkage
1216 measurements for diagnosing water stress in early maturing peach trees during the
1217 post harvest period. *Tree Physiol.* 27, 81 -88, 2007.
- 1218 Conejero, W., Mellisho, C.D., Ortuno, M.F.: Using trunk diameter sensors for regulated
1219 irrigation scheduling in early maturing peach trees. *Env. Exp. Bot.* 71, 409-415, 2011.
- 1220 Contreras, S., Jobbagy, E.G., Villagra, P.E., Noretto, M.D., Puigdefabregas, J.: Remote sensing
1221 estimates of supplementary water consumption by arid ecosystems of central
1222 Argentina. *J. of Hydrol.* 397: 10- 22, 2011.
- 1223 Cook, P.G., Hatton, T.J., Pidsley, Herczeg, D., Held, A.L., O'Grady, A., Eamus, D.: Water
1224 balance of a tropical woodland ecosystem, northern Australia: a combination of
1225 micro-meteorological, soil physical and groundwater chemical approaches. *J. of*
1226 *Hydrol.* 210: 161–177.doi:10.1016/S0022-1694(98)00181-4, 1998.
- 1227 Cook, P.G., O'Grady, A.P.: Determining soil and ground water use of vegetation from heat
1228 pulse, water potential and stable isotope data. *Oecologia* 148:97-107. DOI:
1229 10.1007/s00442-005-0353-4, 2006.
- 1230 Cooper D., D'Amico D., Scott M.: Physiological and morphological response patterns of
1231 *Populus deltoides* to alluvial groundwater pumping. *Environ. Manag.* 31:215-226,
1232 2003.
- 1233 Cooper, D.J., Sanderson, J.S., Stannard, D.I., Groeneveld, D.P.: Effects of long-term water
1234 table drawdown on evapotranspiration and vegetation in an arid region phreatophyte
1235 community. *J. Hydrol.* 325:21-34, 2006.
- 1236 Dahm, C.N., Cleverly, J.R., Coonrod, J.E.A., Thibault, J.R., McDonnell, D.E., Gilroy, D.F.:
1237 Evapotranspiration at the land/water interface in a semi-arid drainage basin.
1238 *Freshwater Bio.* 47:831-843, 2002.
- 1239 Dai, A.: Drought under global warming: a review. *Wiley Interdisciplinary Reviews – Climate*
1240 *Change* 2, 45 -65, 2011.
- 1241 Dawson, T.E., Ehleringer, J.R.: Streamside trees that do not use stream water. *Nature*
1242 350:335-337. DOI: 10.1038/350335a0, 1991.

1243 Devitt, D.A., Sala, A., Smith, S.D., Cleverly, J.R., Shaulis, L.K., Hammett, R.: Bowen ratio
1244 estimates of evapotranspiration for *Tamarix ramosissima* stands on the Virgin River
1245 in southern Nevada. *Water Res. Res.* 34:2407-2414, 1998.

1246 Di Tomaso, J.M.: Impact, biology, and ecology of saltcedar (*Tamarix* spp.) in the
1247 southwestern United States. *Weed Technology* 12:326-336, 1998.

1248 Doble, R., Simmons, C., Jolly, I., Walker, G.: Spatial relationships between vegetation cover
1249 and irrigation-induced groundwater discharge on a semi-arid floodplain, Australia. *J.*
1250 *Hydrol.* 329:75-97. DOI: 10.1016/j.jhydrol.2006.02.007, 2006.

1251 Donohue, R.J., Roderick, M.L., and McVicar, T.R.: On the importance of including
1252 vegetation dynamics in Budyko's hydrological model. *Hydrology and Earth System*
1253 *Sciences* 11, 983-995, 2007.

1254 Doody T.M., Benyon, R.G., Theiveyanathan, S., Koul, V., Stewart, L.: Development of pan
1255 coefficients for estimating evapotranspiration from riparian woody vegetation.
1256 *Hydrol. Proc.* 28:2129-2149. DOI: 10.1002/hyp.9753, 2014.

1257 Drake, P.L., Franks, P.J.: Water resource partitioning, stem xylem hydraulic properties, and
1258 plant water use strategies in a seasonally dry riparian tropical rainforest. *Oecologia*
1259 137:321-329. DOI: 10.1007/s00442-003-1352-y, 2003.

1260 Drake, P.L., Coleman, B.F., and Vogwill, R.: The response of semi-arid ephemeral wetland
1261 plants to flooding: linking water use to *Hydrol. Proc.* *Ecohydrology* 6, 852-862,
1262 2013.

1263 Dresel, P.E, Clark, R., Cheng, X., Reid, M., Terry, A., Fawcett, J., and Cochrane, D.:
1264 Mapping Terrestrial GDEs: Method development and example output. Victoria
1265 Department of Primary Industries, Melbourne VIC. 66 pp, 2010.

1266 Drew, D.M, and Downes, G.M.: The use of precision dendrometers in research on daily stem
1267 size and wood property variation: A review. *Dendrochronologia* 27, 169 – 172, 2009.

1268 Drew, D.M., O'Grady, A.P., Downes, G.M., Read, J., and Worledge, D.: Daily patterns of
1269 stem size variation in irrigated and unirrigated *Eucalyptus globulus*. *Tree Phys.* 28,
1270 1573-1581, 2008.

1271 Eagleson, P.S.: Climate, soil and vegetation: 1. Introduction to water balance
1272 dynamics. *Water Res. Res.* 14:705-712, 1978.

1273 Eamus, D., Boulain, N., Cleverly, J., Breshears, D.D.: Global change-type drought induced
1274 tree mortality: vapour pressure deficit is more important than temperature *per se* in
1275 causing decline in tree health. *Ecology and Evolution* 3, 2711-2729, 2013.

1276 Eamus, D., Hatton, T., Cook, P., Colvin, C.: *Ecohydrology: vegetation function, water and*
1277 *resource management*. CSIRO, Melbourne, 2006.

1278 Eamus, D., Hutley, L.B., O'Grady, A.P.: Daily and seasonal patterns of carbon and water
1279 fluxes above a north Australian savanna. *Tree Phys.* 21: 977–988, 2001.

1280 Eamus D., Froend, R., Loomes, R., Hose, G., and Murray, B.: A functional methodology for
1281 determining the groundwater regime needed to maintain the health of groundwater-
1282 dependent vegetation. *Aus. J. Bot.* 54, 97-114, 2006, 2006.

1283 Ehleringer, J.R, Dawson, T.E.: Water uptake by plants: perspectives from stable isotope
1284 composition. *Pl. Cell and Environ.* 15:1073-1082, 1992.

1285 Ellis, T.W. and Hatton, T.J.: Relating leaf area index of natural eucalypt vegetation to climate
1286 variables in southern Australia. *Ag. Water Manag.* 95:743-747, 2008.

1287 Elmahdi, A., McFarlane, D.: Integrated multi-agency framework: sustainable water
1288 management. Proceedings of the Institution of Civil Engineers-Water Management
1289 165:313-326. DOI: 10.1680/wama.11.00003, 2012.

1290 Elmore, A.J., Manning, S.J., Mustard, J.F., and Craine, J.M.: Decline in alkali meadow
1291 vegetation cover in California: the effects of groundwater extraction and drought. J.
1292 App. Ecol. 43:770-779, 2006.

1293 Engel, V., Jobbagy, E.G., Stieglitz, M., Williams, M., Jackson, R.B.: Hydrological
1294 consequences of eucalyptus afforestation in the argentine pampas. Water Res. Res.
1295 41. DOI: 10.1029/2004wr003761, 2005.

1296 Everitt, J.H, DeLoach, C.J.: Remote sensing of Chinese Tamarisk (*Tamarix chinensis*) and
1297 associated vegetation. Weed Science 38:273-278, 1990.

1298 Everitt, J.H, Judd, F.W, Escobar, D.E, Alaniz, M.A, Davis, M.R, MacWhorter, W.: Using
1299 remote sensing and spatial information technologies to map sabal palm in the lower
1300 Rio Grande Valley of Texas. Southwestern Naturalist 41:218-226, 1996.

1301 Fahle, M, Dietrich, O. (2014). Estimation of evapotranspiration using diurnal groundwater
1302 level fluctuations: Comparison of different approaches with groundwater lysimeter
1303 data. Water Res. Res. 50:273-286. DOI: 10.1002/2013wr014472, 2014.

1304 February, E.C, Higgins, S.I, Newton, R, and West, A.G.: Tree distribution on a steep
1305 environmental gradient in an arid savanna. J. Biogeog. 34, 270-278, 2007.

1306 Feikema, P.M, Morris, J.D, Connell, L.D.: The water balance and water sources of a
1307 *Eucalyptus* plantation over shallow saline groundwater. Plant and Soil 332, 429-449,
1308 2010.

1309 Ford, C.R., Mitchell, R.J., Teskey, R.O.: Water table depth affects productivity, water use
1310 and the response to nitrogen addition in a savvan system. Can. J. For. Res. 38: 2118-
1311 2127, 2008.

1312 Froend, R.H, Drake, P.L.: Defining phreatophyte response to reduced water availability:
1313 preliminary investigations on the use of xylem cavitation vulnerability in *Banksia*
1314 woodland species. Aus. J. Bot. 54:173-179, 2006.

1315 Froend, R., Sommer, B.: Phreatophytic vegetation response to climatic and
1316 abstraction-induced GW drawdown: examples of long-term spatial and temporal
1317 variability in community response. Ecolog Engineering 36, 1191-1200, 2010.

1318 Galindo, A, Rodrigues, P, Mellisho, C.D, Torrecillas, E, Moriana, A, Cruz, Z.N,
1319 Conejero, W, Moreno, F and Terrecillas, A.: Assessment of discreetly
1320 measured indicators and maximum daily trunk shrinkage for detecting water stress in
1321 pomegranate trees. Ag. For. Met. 180, 58 – 65, 2013.

1322 Gamon, J, Field, C, Goulden, M, Griffin, K, Hartley, A, Joel, G, Penuelas, J, Valentini, R.:
1323 Relationships between NDVI, canopy structure, and photosynthesis in 3 Californian
1324 vegetation types. Ecol. Appl. 5:28-41, 1995.

1325 Gay, L.W, Fritschen, L.J.: An energy budget analysis of water use by saltcedar. Water Res.
1326 Res. 15:1589-1592, 1979.

1327 Gazal, R.M, Scott, R.L, Goodrich, D.C, Williams, D.G.: Controls on transpiration in a
1328 semiarid riparian cottonwood forest. Ag. For. Met. 137:56-67, 2006.

1329 Gessler, A, Brandes, E, Buchmann, N, Helle, G, Rennenberg, H, Barnard, R.L.: Tracing
1330 carbon and oxygen isotope signals from newly assimilated sugars in the leaves to the

1331 tree-ring archive. *Pl. Cell Environ.* 32:780-795. DOI: 10.1111/j.1365-
1332 3040.2009.01957.x, 2009.

1333 Giantomasi, M. A., Roig-Juñent, F. A. and Villagra, P. E.: Use of differential water sources
1334 by *Prosopis flexuosa* DC: a dendroecological study, *Plant Ecol.*, 214(1), 11–27,
1335 doi:10.1007/s11258-012-0141-2, 2012.

1336 Giordano, C. V., Guevara, A., Boccalandro, H. E., Sartor, C. and Villagra, P. E.: Water
1337 status, drought responses, and growth of *Prosopis flexuosa* trees with different access
1338 to the water table in a warm South American desert, *Plant Ecol.*, 212(7), 1123–1134,
1339 doi:10.1007/s11258-010-9892-9, 2011.

1340 Giordanos, M.: Global groundwater? Issue and solutions. *Ann. Rev. Environ. Res.* 34, 153-
1341 178.2009.

1342 Guevara, A., Giordano, C. V., Aranibar, J., Quiroga, M. and Villagra, P. E.: Phenotypic
1343 plasticity of the coarse root system of *Prosopis flexuosa*, a phreatophyte tree, in the
1344 Monte Desert (Argentina), *Plant Soil*, 330(1-2), 447–464, doi:10.1007/s11104-009-
1345 0218-4, 2009.

1346 Glenn, E.P, Huete, A.R, Nagler, P.L, Hirschboeck, K.K, Brown, P.: Integrating remote
1347 sensing and ground methods to estimate evapotranspiration. *Crit. Rev. in Pl. Sci.*
1348 26:139-168. DOI: 10.1080/07352680701402503, 2007.

1349 Gleick, P and Palaniappan, M.: Peak water limits to freshwater withdrawal and use. *Proc.*
1350 *Nat. Acad. Sci.* 107, 11155-11162, 2010.

1351 Glazer, A.N and Likens, G.E.:The water table: the shifting foundation of life on land. *Ambio*
1352 41, 657-669, 2012.

1353 Glenn, E.P, Nagler, P.L, Huete, A.R.: Vegetation Index Methods for Estimating
1354 Evapotranspiration by Remote Sensing. *Surveys in Geophysics* 31:531-555. DOI:
1355 10.1007/s10712-010-9102-2, 2010.

1356 Gonzalez, E, Gonzalez-Sanchis, M, Comin, F.,A, Muller, E,: Hydrologic thresholds for
1357 riparian forest conservation in a regulated large Mediterranean river. *River Res. And*
1358 *Appl.* 28: 81-80, 2012.

1359 Goodrich D.C, Chehbouni A, Goff B, MacNish B, Maddock T, Moran S, Shuttleworth W.J,
1360 Williams D.G, Watts C, Hipps L.H, Cooper DI, Schieldge J, Kerr YH, Arias H,
1361 Kirkland M, Carlos R, Cayrol P, Kepner W, Jones B, Avissar R, Begue A, Bonnefond
1362 JM, Boulet G, Branam B, Brunel JP, Chen LC, Clarke T, Davis M.R, DeBruin H,
1363 Dedieu G, Elguero E, Eichinger W.E, Everitt J, Garatuza-Payan J, Gempko VL,
1364 Gupta H, Harlow C, Hartogensis O, Helfert M, Holifield C, Hymer D, Kahle A,
1365 Keefer T, Krishnamoorthy S, Lhomme J.P, Lagouarde J.P, Lo Seen D, Luquet D,
1366 Marsett R, Monteny B, Ni W, Nouvellon Y, Pinker R, Peters C, Pool D, Qi J, Rambal
1367 S, Rodriguez, J, Santiago. F, Sano. E, Schaeffer. S,M,, Schulte. M., Scott, R., Shao,
1368 X., Snyder, K.A., Sorooshian, S., Unkrich, C.L, Whitaker, M, Yucel I.: Preface paper
1369 to the Semi-Arid Land-Surface-Atmosphere (SALSA) Program special issue. *Ag. For.*
1370 *Met.* 105:3-20, 2000a.

1371 Goodrich, D.C, Scott, R., Qi, J., Goff, B., Unkrich, C.L, Moran. M.S, Williams, D.,
1372 Schaeffer, S., Snyder, K., MacNish, R., Maddock, T., Pool, D., Chehbouni, A.,
1373 Cooper. D.I., Eichinger, W.E., Shuttleworth ,W.J., Kerr, Y., Marsett, R., Ni, W.:
1374 Seasonal estimates of riparian evapotranspiration using remote and *in situ*
1375 measurements. *Ag. For. Met.* 105:281-309, 2000b.

1376 Gou, S, Gonzales, S, Miller, G.: Mapping potential groundwater-dependent ecosystems for
1377 sustainable management. *Ground Water* 53: 99–110, 2015.

1378 Gribovszki, Z., Kalicz, P., Szilagyi, J., Kucsara, M.: Riparian zone evapotranspiration
1379 estimation from diurnal groundwater level fluctuations. *J. Hydrol.* 349:6-17, 2008.

1380 Gribovszki, Z., Szilagyi, J., Kalicz, P.: Diurnal fluctuations in shallow groundwater levels
1381 and streamflow rates and their interpretation - A review. *J. Hydrol.* 385:371-383.
1382 DOI: 10.1016/j.jhydrol.2010.02.001, 2010.

1383 Gries, D., Zeng, F., Foetzki A., Arndt S.K., Bruelheide, H., Thomas F.M., Zhang, X., Runge,
1384 M.: Growth and water relations of *Tamarix ramosissima* and *Populus euphratica* on
1385 Taklamakan desert dunes in relation to depth to a permanent water table. *Pl. Cell and*
1386 *Environn* 26, 725-736, 2003.

1387 Groeneveld, D.P., and Baugh, W.M.: Correcting satellite data to detect vegetation signal for
1388 eco-hydrologic analyses. *J. Hydrol.* 344, 135-145. 2007.

1389 Groeneveld, D.P, Baugh, W.M., Sanderson, J.S., and Cooper, D.J: Annual groundwater
1390 evapotranspiration mapped from single satellite scenes. *J. Hydrol.* 344, 146-156,
1391 2007.

1392 Groeneveld, D.P.: Remotely-sensed groundwater evapotranspiration from alkali scrub
1393 affected by declining water table. *J. Hydrol.* 358, 294-303, 2008.

1394 Groom B.P, Froend R.H, Mattiske E.M.: Impact of groundwater abstraction on *Banksia*
1395 woodland, Swan Coastal Plain, Western Australia. *Ecolog. Manag. & Restoration* 1,
1396 117-124, 2000.

1397 Hanson R.T, Dettinger M.D, Newhouse M.W.: Relations between climatic variability and
1398 hydrologic time series from four alluvial basins across the southwestern United States.
1399 *Hydrogeol. J.* 14:1122-1146. DOI: 10.1007/s10040-006-0067-7, 2006.

1400 Hatton T and Evans R.: Dependence of ecosystems on groundwater and its significance to
1401 Australia. Occasional Paper No 12/98. Land and Water Res. Res. and Dewvelopment
1402 Corporation. CSIRO Australia, 1998.

1403 Henry, C. M., D. M. Allen, and J. Huang.: Groundwater storage variability and annual
1404 recharge using well-hydrograph and GRACE satellite data, *Hydrogeol. J.*, 19(4), 741-
1405 755, 2011.

1406 Horton, J.L, Kolb, T.E and Hart, S.C.: Responses of riparian trees to inter-annual
1407 variation in groundwater depth in a semi-arid river basin. *Pl. Cell & Environ.* 24, 293
1408 – 304, 2001

1409 Houborg, R., M. Rodell, B. Li, R. Reichle, and B.F. Zaitchik.: Drought indicators
1410 based on model assimilated GRACE terrestrial water storage observations. *Water*
1411 *Res. Res.*, 48, W07525, doi:10.1029/2011WR011291, 2012.

1412 Howard, J, Merrifield, M.: Mapping groundwater dependent ecosystems in California. *PLoS*
1413 *ONE* 5: e11249, 2010.

1414 Huete A, Didan K, Miura T, Rodriguez EP, Gao X, Ferreira LG.: Overview of the
1415 radiometric and biophysical performance of the MODIS vegetation indices. *Rem.*
1416 *Sens. Env.* 83:195-213. DOI: 10.1016/s0034-4257(02)00096-2, 2002

1417 Hultine KR, Bush SE. (2011). Ecohydrological consequences of non-native riparian
1418 vegetation in the southwestern United States: A review from an ecophysiological
1419 perspective. *Water Res. Res.* 47:W07542. DOI: 10.1029/2010wr010317.

- 1420 Hultine K.R, Bush S.E, Ehleringer J.R.: Ecophysiology of riparian cottonwood and willow
 1421 before, during, and after two years of soil water removal. *Ecol. Appl.* 20:347-361.
 1422 DOI: 10.1890/09-0492.1, 2010
- 1423 Jin X.M, ME Schaepman, JG Clevers, Z.B Su and G Hu.: Groundwater depth and vegetation
 1424 in the Ejina area, China. *Arid Land Res. Manag.* 25, 194-199, 2011.
- 1425 Jobbagy, E.G, Noretto, M.D, Villagra, P.E, Jackson, R.B.: Water subsidies from mountains to
 1426 deserts: their role in sustaining groundwater fed oases in a sandy landscape. *Ecol.*
 1427 *Appl.* 21: 678 – 694, 2011.
- 1428 Jung, M, Reichstein M, Margolis H.A, Cescatti A, Richardson A.D, Arain M.A, Arneth A,
 1429 Bernhofer C, Bonal D, Chen J.Q, Gianelle D, Gobron N, Kiely G, Kutsch W, Lasslop
 1430 G, Law B.E, Lindroth A, Merbold L, Montagnani L, Moors E.J, Papale D,
 1431 Sottocornola M, Vaccari F, Williams C.: Global patterns of land-atmosphere fluxes of
 1432 carbon dioxide, latent heat, and sensible heat derived from eddy covariance, satellite,
 1433 and meteorological observations. *J. of Geophys. Res.* 116:G00J07. DOI:
 1434 10.1029/2010jg001566, 2011.
- 1435 Kanniah, K.D, Beringer J, Hutley L.B.: Response of savanna gross primary productivity to
 1436 interannual variability in rainfall: Results of a remote sensing based light use
 1437 efficiency model. *Prog. Phys. Geog.* 37:642-663, 2013.
- 1438 Kath, J., Reardon-Smith, K., Le Brocq, A.F., Dyer, F.J., Dafny, E., Fritz, L., and
 1439 Batterham, M.: Groundwater decline and tree change in floodplain landscapes:
 1440 Identifying non-linear threshold responses in canopy condition. *Glob. Ecol. And*
 1441 *Conserv.* 2: 148-160, 2014.
- 1442 Kattge, J, Diaz S, Laborel S, Prentice C, Leadley P, Bonisch G *et al.*. TRY – a global
 1443 database of plant traits. *Glob. Chng. Biol.* 17, 2905 – 2935, 2011.
- 1444 Kelliher, F.M., Kirkham, M.B, Tauer C.G.: Stomatal resistance, transpiration and growth of
 1445 drought-stressed eastern cottonwood. *Can. J. For. Res.* 10:447-451, 1980.
- 1446 Kelliher, F.M, Kostner B.M.M, Hollinger D.Y, Byers J.N, Hunt J.E, McSeveny T.M, Meserth
 1447 R, Weir P.L, Schulze E.D.: Evaporation, xylem sapflow and tree transpiration in a
 1448 New Zealand broad-leaved forest. *Ag. For. Met.* 62:53-73. DOI: 10.1016/0168-
 1449 1923(92)90005-o, 1992.
- 1450 Kochendorfer, J, Castillo EG, Haas E, Oechel W.C, Paw U KT.: Net ecosystem exchange,
 1451 evapotranspiration and canopy conductance in a riparian forest. *Ag. For.*
 1452 *Met.* 151:544-553, 2011.
- 1453 Kranjcec, J, Mahoney J.M, Rood .SB.: The responses of three riparian cottonwood species to
 1454 water table decline. *For. Ecol. and Manag.* 110:77-87, 1998.
- 1455 Kray, J. Cooper, D., and Sanderson, J.: Groundwater use by native plants in response to
 1456 changes in precipitation in an intermountain basin. *J. Arid Env.* 83, 25-34, 2012.
- 1457 Lagueard J.G.A, Drew I.B.: Hydrogeomorphic control on tree growth responses in the Elton
 1458 area of the Cheshire Saltfield, UK. *Geomorphology* 95:158-171. DOI:
 1459 10.1016/j.geomorph.2007.05.017, 2008.
- 1460 Lamontagne S, PG Cook, A O'Grady and D Eamus.: Groundwater use by vegetation in a
 1461 tropical savanna riparian zone (Daly River, Australia). *J. Hydrol.* 310, 280-293, 2005.
- 1462 Lautz, L.K.: Estimating groundwater evapotranspiration rates using diurnal water-table
 1463 fluctuations in a semi-arid riparian zone. *Hydrogeol. J.* 16:483-497, 2008.

- 1464 Leanay, F, Crosbie, R, O'Grady, A, Jolly, I, Gow, L, Davies, P, Wilford, J and Kilgour, P.:
 1465 Recharge and discharge estimation in data poor areas. Scientific reference guide.
 1466 CSIRO: Water for a Healthy Country National Research Flagship. 61 pp. Canberra
 1467 Australia, 2011.
- 1468 Leblanc, M., Leduc, C., Razack, M., Lemoalle, J., Dagherne, D., Mofor, L.: Application of
 1469 remote sensing and GIS for groundwater modelling of large semiarid areas: example
 1470 of the Lake Chad Basin, Africa. Hydrology of Mediterranean and Semiarid Regions
 1471 Conference, Montpieller, France, April 2003, IAHS (Red Books Series), Wallingford,
 1472 UK, no. 278, pp 186–192, 2003a.
- 1473 Leblanc, M, Razack, M., Dagherne, D., Mofor, L., Jones, C.: Application of Meteosat thermal
 1474 data to map soil infiltrability in the central part of the Lake Chad basin, Africa.
 1475 Geophys. Res. Lett. 30(19):1998, 2003b.
- 1476 Leblanc, M. J., Tregoning, P., Ramillien, G., Tweed, S.O., and Fakes, A.: Basin-scale,
 1477 integrated observations of the early 21st century multiyear drought in southeast
 1478 Australia. Water Resour. Res., 45, W04408, doi :10.1029/2008WR007333, 2009.
- 1479 Leffler, A.J., Evans A.S.: Variation in carbon isotope composition among years in the
 1480 riparian tree *Populus fremontii*. Oecologia 119:311-319, 1999.
- 1481 Li, F., and Lyons, T.: Estimation of regional evapotranspiration through remote sensing. J.
 1482 Appl. Met. 38, 1644-1654, 1999.
- 1483 Lite S.J., Stromberg J.C.: Surface water and ground-water thresholds for maintaining
 1484 *Populus-Salix* forests, San Pedro River, Arizona. Biol. Cons. 125:153-167, 2005.
- 1485 Logsdon, S.D., Schilling, K.E., Hernandez-Ramirez, G., Prueger, J.H., Hatfield, J.L., Sauer,
 1486 T.J.: Field estimation of specific yield in a central Iowa crop field. Hydrol. Proc.
 1487 24:1369-1377. DOI: 10.1002/hyp.7600, 2010.
- 1488 Loheide, S.P., Booth, E.G.: Effects of changing channel morphology on vegetation,
 1489 groundwater, and soil moisture regimes in groundwater-dependent ecosystems.
 1490 Geomorph. 126:364-376, 2011.
- 1491 Loheide, S.P, Butler, J.J, Gorelick, SM.: Estimation of groundwater consumption by
 1492 phreatophytes using diurnal water table fluctuations: A saturated-unsaturated flow
 1493 assessment. Water Res. Res. 41:W07030. DOI: 10.1029/2005wr003942, 2005.
- 1494 Loheide, S.P.: A method for estimating subdaily evapotranspiration of shallow groundwater
 1495 using diurnal water table fluctuations. Ecohydrology 1:59-66, 2008.
- 1496 Lowry, C.S, Loheide, S.P.: Groundwater-dependent vegetation: Quantifying the groundwater
 1497 subsidy. Water Res. Res. 46:W06202. DOI: 10.1029/2009wr008874, 2010.
- 1498 Lowry, C.S, Loheide, S.P, Moore ,C.E, Lundquist, J.D.: Groundwater controls on vegetation
 1499 composition and patterning in mountain meadows. Water Res. Res. 47:W00J11. DOI:
 1500 10.1029/2010wr010086, 2011.
- 1501 Lv, J., Wang, X.S., Zhou, Y., Qian, K., Wan, L., Eamus, D., and Tao, Z.: Groundwater-
 1502 dependent distribution of vegetation in Hailiutu River catchment, a semi-arid region
 1503 in China. Ecohydrology 6, 142-149, 2012.
- 1504 Ma X., Huete A., Yu Q., Coupe NR., Davies K., Broich M., Ratana P., Beringer J., Hutley
 1505 L.B., Cleverly J., Boulain N., Eamus D.: Spatial patterns and temporal dynamics in
 1506 savanna vegetation phenology across the North Australian Tropical Transect. Rem.
 1507 Sens. Env. 139:97-115. DOI: 10.1016/j.rse.2013.07.030, 2013.

1508 Máguas, C., K Rascher, A Martins-Loucao, P Carvalho, P Pinho, M Ramos, O Correia and C
1509 Werner, C: Responses of woody species to spatial and temporal ground water changes
1510 in coastal sand dune systems. *Biogeosciences Discussions* 8, 1591-1616, 2011.

1511 Mahoney, J.M, Rood, S.B.: A device for studying the influence of declining water table on
1512 poplar growth and survival. *Tree Phys.* 8:305-314, 1991.

1513 Markesteijn, L., Poorter, L., Paz,, H., Sack, L., and Bongers, F.: Ecological differentiation in
1514 xylem cavitation resistance is associated with stem and leaf structural traits. *Pl. Cell
1515 and Environ.* 34:137-148, 2011.

1516 Martinet, M.C, Vivoni, E.R, Cleverly, J.R, Thibault, J.R, Schuetz, J.F, Dahm, C.N.: On
1517 groundwater fluctuations, evapotranspiration, and understory removal in riparian
1518 corridors. *Water Res. Res.* 45:W05425. DOI: 10.1029/2008WR007152, 2009.

1519 McCarroll, D., Loader, N.J.: Stable isotopes in tree rings. *Quaternary Sci. Rev.* 23:771-801.
1520 DOI: 10.1016/j.quascirev.2003.06.017, 2004.

1521 McDonald, M.G, Harbaugh, A.W.: *A modular three-dimensional finite-difference ground-
1522 water flow model*. US Geological Survey, Department of Interior, 1988.

1523 McDowell, N., Pockman, W.T., Allen, C.D., Breshears, D.D., Cobb, N., Kolb, T., Plaut, J.,
1524 Sperry, J., West, A., Williams, D.G., Yezpez, E.A.: Mechanisms of plant survival and
1525 mortality during drought: why do some plants survive while others succumb to
1526 drought? *New Phyt.* 178:719-739. DOI: 10.1111/j.1469-8137.2008.02436.x, 2008.

1527 McLendon, T., Hubbard, P.J., and Martin, D.W: Partitioning the use of precipitation-and
1528 groundwater-derived moisture by vegetation in an arid ecosystem in California. *J .
1529 Arid Env.* 72, 986-1001, 2008.

1530 Meinzer, F.C., Campanello, P.I., Domec, J-C., Gatti, M.G., Goldstein, G., Villalobos-Vega,
1531 R., and Woodruff, D.R.: Constraints on physiological function associated with branch
1532 architecture and wood density in tropical forest trees. *Tree Phys.* 28:1609-1617, 2008.

1533 Merritt, D.M., Bateman, H.L.: Linking stream flow and groundwater to avian habitat in a
1534 desert riparian system. *Ecol. Appl.* 22: 1973-1988, 2012.

1535 Miller, G.R., Chen, X., Rubin, Y., Ma, S., Baldocchi, D.D.: Groundwater uptake by woody
1536 vegetation in a semiarid oak savanna. *Water Res. Res.* 46:W10503. DOI:
1537 10.1029/2009wr008902, 2010.

1538 Moore, G.W, Cleverly, J.R, Owens, M.K.: Nocturnal transpiration in riparian *Tamarix*
1539 thickets authenticated by sap flux, eddy covariance and leaf gas exchange
1540 measurements. *Tree Phys.* 28:521-528, 2008.

1541 Münch, Z., and Conrad, J.: Remote sensing and GIS based determination of groundwater
1542 dependent ecosystems in the Western Cape, South Africa. *Hydrogeol. J.* 15, 19-28,
1543 2007.

1544 Murray, B.R., Hose, G.C., Eamus, D and Licari, D.: Valuation of groundwater-dependent
1545 ecosystems: a functional methodology incorporating ecosystem services. *Aus. J. Bot.*
1546 54, 221-229, 2006.

1547 Nachabe, M., Shah, N., Ross, M., Vomacka, J.: Evapotranspiration of two vegetation covers
1548 in a shallow water table environment. *Soil Sci. Soc. of Amer. J.* 69:492-499, 2005.

1549 Nagler, P., Glenn, E., Nguyen, U., Scott, R., Doody, T.: Estimating riparian and agricultural
1550 actual evapotranspiration by reference evapotranspiration and MODIS enhanced
1551 vegetation index. *Remote Sensing* 5:3849-3871, 2013.

1552 Nagler, P.L, Glenn, E., Thompson, T., Huete, A.: Leaf area index and NDVI as predictors
1553 of canopy characteristics and light interception by riparian species on the Lower
1554 Colorado River. *Ag. For. Met.* 116, 103 – 112, 2004.

1555 Nagler, P.L, Cleverly, J., Glenn, E., Lampkin, D., Huete, A., Wan Z.M.: Predicting riparian
1556 evapotranspiration from MODIS vegetation indices and meteorological data. *Rem.
1557 Sens. Env.* 94:17-30, 2005.

1558 Nagler P.L, Morino K, Didan K, Erker J, Osterberg J, Hultine K.R, Glenn EP. (2009). Wide-
1559 area estimates of saltcedar (*Tamarix* spp.) evapotranspiration on the lower Colorado
1560 River measured by heat balance and remote sensing methods. *Ecohydrology* 2:18-33.
1561 DOI: 10.1002/eco.35, 2009.

1562 Nagler P.L, Scott R.L, Westenburg C., Cleverly J.R, Glenn E.P, Huete A.R.:
1563 Evapotranspiration on western US rivers estimated using the Enhanced Vegetation
1564 Index from MODIS and data from eddy covariance and Bowen ratio flux towers.
1565 *Rem. Sens. Env.* 97:337-351. DOI: 10.1016/j.rse.2005.05.011, 2005.

1566 Naumburg, E., Mata-Gonzalez, R., Hunter, R. G., McLendon, T. and Martin, D. W.:
1567 Phreatophytic vegetation and groundwater fluctuations: a review of current research
1568 and application of ecosystem response modeling with an emphasis on great basin
1569 vegetation., *Environ. Manage.*, 35(6), 726–40, doi:10.1007/s00267-004-0194-7, 2005.

1570 Neale C.M.U.: Classification and mapping of riparian systems using airborne multispectral
1571 videography. *Restor. Ecol.*5:103-112, 1997.

1572 Nemani R.R, and Running S.W.: Testing a theoretical climate soil leaf-area hydrological
1573 equilibrium of forests using satellite data and ecosystem simulation. *Ag. For. Met.* 44:
1574 245-260, 1989.

1575 Nippert, J.B, Butler, J.J, Kluitenberg ,G.J, Whittemore, D.O, Arnold, D., Spal, S.E, Ward,
1576 J.K.: Patterns of *Tamarix* water use during a record drought. *Oecologia* 162:283-292.
1577 DOI: 10.1007/s00442-009-1455-1, 2010.

1578 Noretto, M.D., Jobbagy, E.G., Toth, T., Bella, C.M.D.: The effects of tree establishment on
1579 water and salt dynamics in naturally salt-affected grasslands. *Oecologia* 152, 695 –
1580 705, 2007.

1581 O'Grady, A.P., Carter, J.L., Bruce J.: Can we predict groundwater discharge from terrestrial
1582 ecosystems using existing eco-hydrological concepts? *Hydrology and Earth System
1583 Sci.* 15:3731-3739, 2011.

1584 O'Grady, A.P, Carter, J.L, Holland, K.: Review of Australian groundwater discharge studies
1585 of terrestrial systems. CSIRO: Water for a Healthy Country National Research
1586 Flagship. CSIRO, Melbourne. 2010.

1587 O'Grady, A.P., Cook, P.G., Howe, P., Werren, G.: Groundwater use by dominant tree species
1588 in tropical remnant vegetation communities. *Aus. J. Bot.* 54:155-171. DOI:
1589 10.1071/bt04179, 2006a.

1590 O'Grady, A.P., Eamus, D., Cook, P.G. and Lamontagne, S.: Groundwater use by riparian
1591 vegetation in the wet–dry tropics of northern Australia. *Aus. J. Bot.* 54:145-154,
1592 2006b.

1593 Oberhuber, W., Stumbock, M., Kofler, W.: Climate tree-growth relationships of Scots pine
1594 stands (*Pinus sylvestris* L.) exposed to soil dryness. *Trees-Structure and Function*
1595 13:19-27, 1998.

1596 Oishi, A.C., Oren, R., Stoy, P.C.: Estimating components of forest evapotranspiration: A
1597 footprint approach for scaling sap flux measurements. *Ag. For. Met.* 148:1719-1732.
1598 DOI: 10.1016/j.agrformet.2008.06.013, 2008 .

1599 Orellana, F., Verma, P., Loheide, S.P., Daly E.: Monitoring and modelling water-vegetation
1600 interactions in groundwater-dependent ecosystems. *Rev. of Geophys.* 50:Rg3003.
1601 DOI: 10.1029/2011rg000383, 2012.

1602 Ortuno, M.F, Garcia-Orellana, Y. Stem and leaf water potentials, gas exchange,
1603 sapflow and trunk diameter fluctuation for detecting water stress in lemon trees. *Trees*
1604 20, 1-8, 2006.

1605 Osmond, C.B., Austin, M.P., Berry, J.A., Billings, W.D., Boyer, J.S., Dacey, J.W.H., Nobel,
1606 P.S., Smith, S.D., Winner, W.E.: Stress physiology and the distribution of plants.
1607 *Bioscience* 37:38-47, 1987.

1608 Perez-Valdivia, C., Sauchyn, D.: Tree-ring reconstruction of groundwater levels in Alberta,
1609 Canada: Long term hydroclimatic variability. *Dendrochronologia* 29:41-47. DOI:
1610 10.1016/j.dendro.2010.09.001, 2011.

1611 Perkins S.P, Sophocleous M.: Development of a comprehensive watershed model applied to
1612 study stream yield under drought conditions. *Ground Water* 37:418-426, 1999.

1613 Pert, P.L, Butler, J.R.A., Brodie, J.E., Bruce, C., Honzak, M., Kroon, F.J, Metcalfe, D.,
1614 Mitchell, D., Wong, G.: A catchment-based approach to mapping hydrological
1615 ecosystem services using riparian habitat: A case study from the Wet Tropics,
1616 Australia. *Ecolog. Complexity* 7:378-388. DOI: 10.1016/j.ecocom.2010.05.002, 2010.

1617 Peters, E., P. J. Torfs, H. A. Van Lanen, and Bier, G.: Propagation of drought through
1618 groundwater— A new approach using linear reservoir theory. *Hydrol. Processes*, 17,
1619 3023-3040,doi:10.1002/hyp.1274, 2003.

1620 Phillips D.L and Gregg J.W.: Source partitioning using stable isotopes: coping with too many
1621 sources. *Oecologia* 136, 261-269, 2003.

1622 Pockman W, Sperry J.: Vulnerability to xylem cavitation and the distribution of Sonoran
1623 desert vegetation. *Amer. J. Bot.* 87:1287-1299, 2000.

1624 Post V.E.A., von Asmuth J.R.: Review: Hydraulic head measurements-new technologies,
1625 classic pitfalls. *Hydrogeol. J.* 21:737-750. DOI: 10.1007/s10040-013-0969-0, 2013.

1626 Potts D.L, Williams D.G.: Response of tree ring holocellulose delta C-13 to moisture
1627 availability in *Populus fremontii* at perennial and intermittent stream reaches. *Western*
1628 *North American Naturalist* 64:27-37. 2004.

1629 Prior L.D, Grierson P.F, McCaw W.L, Tng D.Y.P, Nichols S.C, Bowman D.: Variation in
1630 stem radial growth of the Australian conifer, *Callitris columellaris*, across the world's
1631 driest and least fertile vegetated continent. *Trees-Structure and Function* 26:1169-
1632 1179. DOI: 10.1007/s00468-012-0693-8, 2012.

1633 Querejeta J.I., Estrada-Medina, H., Allen, M.F., and Jiménez-Osornio, J.J.: Water source
1634 partitioning among trees growing on shallow karst soils in a seasonally dry tropical
1635 climate. *Oecologia* 152: 26-36, 2007.

1636 Rodell, M., and Famiglietti, J.S.: Terrestrial water storage variations over Illinois : Analysis
1637 of observations and implications for Gravity Recovery and Climate
1638 Experiment (GRACE). *Water Res. Res.* 37(5): 1327-1340, 2001.

1639 Rodell, M., Chen, J.L., Kato, H., J Famiglietti, J.S., Nigro, J., and Wilson , C.R.: Estimating

1640 groundwater storage changes in the Mississippi River basin (USA) using GRACE.
1641 Hydrogeol. J. 15(1): 159-166, 2007.

1642 Rodell, M., Velicogna, I., and Famiglietti, J.S.: Satellite-based estimates of groundwater
1643 depletion in India. Nature 460(7258): 999-1002, 2009.

1644 Roderick .ML and Farquhar G.D.: Water availability and evapotranspiration in the Murray
1645 Darling Basin: A look at the past and a glimpse into the future. Murray-Darling
1646 BasinAuthority, Canberra, 2009.

1647 Rood S, Braatne J, Hughes F.: Ecophysiology of riparian cottonwoods: stream flow
1648 dependency, water relations and restoration. Tree Phys. 23:1113-1124, 2003.

1649 Rood S, Patino S, Coombs K, Tyree M.: Branch sacrifice: cavitation-associated drought
1650 adaptation of riparian cottonwoods. Trees: Structure and Function 14:248-257, 2000.

1651 Rood S.B, Goater L.A, Gill K.M, Braatne J.H.: Sand and sandbar willow: A feedback loop
1652 amplifies environmental sensitivity at the riparian interface. Oecologia 165:31-40,
1653 2011.

1654 Rossini, M., Cogliati S., Meroni, M., Migliavacca, M., Galvagno, M, Busetto L, Cremonese
1655 E, Julitta, T., Siniscalco, C., di Cella, U.M., Colombo, R.: Remote sensing-based
1656 estimation of gross primary production in a subalpine grassland. BiogeoSciences
1657 9:2565-2584. DOI: 10.5194/bg-9-2565-2012.

1658 Sala A, Devitt D.A, Smith S.D.: Water use by *Tamarix ramosissima* and associated
1659 phreatophytes in a Mojave Desert floodplain. Ecol. Appl. 6:888-898.

1660 Sarris D, Christodoulakis D, Korner C.: Recent decline in precipitation and tree growth in the
1661 eastern Mediterranean. Glob. Chng. Biol. 13:1187-1200. DOI: 10.1111/j.1365-
1662 2486.2007.01348.x, 2007.

1663 Scanlon, B. R., L. Longuevergne, and Long, D: Ground referencing GRACE satellite
1664 estimates of groundwater storage changes in the California Central Valley, USA,
1665 Water Resour. Res., 48, W04520, doi :10.1029/2011WR011312, 2012a.

1666 Scanlon, B. R., C. C. Faunt, L. Longuevergne, R. C. Reedy, W. M. Alley, V. L. McGuire,
1667 and McMahon, P.B.: Groundwater depletion and sustainability of irrigation in the US
1668 High Plains and Central Valley. Proc. Nat. Acad. Sci. 109(24): 9320-9325, 2012b.

1669 Schilling KE, Zhang YK.: Temporal scaling of groundwater level fluctuations near a stream.
1670 Ground Water 50:59-67. DOI: 10.1111/j.1745-6584.2011.00804.x, 2012.

1671 Scott M.L, Shafroth P.B, Auble G.T.: Responses of riparian cottonwoods to alluvial water
1672 table declines. Environ. Manag. 23:347-358, 1999.

1673 Scott R, Edwards E, Shuttleworth W, Huxman T, Watts C, Goodrich D.: Interannual and
1674 seasonal variation in fluxes of water and carbon dioxide from a riparian woodland
1675 ecosystem. Ag. For. Met. 122:65-84, 2004.

1676 Scott R.L, Cable W.L, Huxman T.E, Nagler P.L, Hernandez M, Goodrich D.C.: Multiyear
1677 riparian evapotranspiration and groundwater use for a semiarid watershed. J . Arid
1678 Env. 72:1232-1246, 2008.

1679 Scott R.L, Huxman T.E, Cable W.L, Emmerich W.E.: Partitioning of evapotranspiration and
1680 its relation to carbon dioxide exchange in a Chihuahuan Desert shrubland. Hydrol.
1681 Proc. 20:3227-3243, 2006a.

1682 Scott .RL, Huxman T.E, Williams D.G, Goodrich D.C.: Ecohydrological impacts of woody-
1683 plant encroachment: seasonal patterns of water and carbon dioxide exchange within a

1684 semiarid riparian environment. *Glob. Chng. Biol.* 12:311-324. DOI: 10.1111/j.1365-
1685 2486.2005.01093.x, 2006b.

1686 Scott R.L., Shuttleworth W.J, Goodrich D.C, Maddock T.: The water use of two dominant
1687 vegetation communities in a semiarid riparian ecosystem. *Ag. For. Met.* 105:241-256,
1688 2000.

1689 Scurlock D.: *From the Rio to the Sierra: An Environmental History of the Middle Rio*
1690 *Grande Basin*. General Technical Report RMRS-GTR-5, USDA Forest Service,
1691 Rocky Mountain Research Station, Fort Collins, CO, 1998.

1692 Seckler D, Barker, R. and Amarasinghe, U.: Water scarcity in the twenty-first century. *Int. J.*
1693 *Water Res. Dev.* 15, 29-42, 1999.

1694 Shafroth P.B, Cleverly J.R, Dudley T.L, Taylor J.P, Van Riper C, Weeks E.P, Stuart J.N.:
1695 Control of *Tamarix* in the Western United States: Implications for water salvage,
1696 wildlife use, and riparian restoration. *Environ. Manag.* 35:231-246, 2005.

1697 Shah J.J.F, Dahm C.N.: Flood regime and leaf fall determine soil inorganic nitrogen
1698 dynamics in semiarid riparian forests. *Ecol. Appl.* 18:771-788, 2008.

1699 Shah N, Nachabe M, Ross M.: Extinction depth and evapotranspiration from ground water
1700 under selected land covers. *Ground Water* 45:329-338, 2007.

1701 Shiklomanov I.A.: World water resources: A new appraisal and assessment for the 21st
1702 century, United Nations Educational, Scientific and Cultural Organisation.

1703 Smith S.D, Devitt D.A, Sala A, Cleverly J.R, Busch D.E.: Water relations of riparian plants
1704 from warm desert regions. *Wetlands* 18:687-696, 1998.

1705 Soylu M.E, Lenters J.D, Istanbuluoglu E, Loheide S.P, II.: On evapotranspiration and
1706 shallow groundwater fluctuations: A Fourier-based improvement to the White
1707 method. *Water Res. Res.* 48:W06506. DOI: 10.1029/2011wr010964, 2012.

1708 Sperry, J.S., Meinzer, F.C., and McCulloh, K.A.: Safety and efficiency conflicts in hydraulic
1709 architecture: scaling from tissues to trees. *Pl. Cell and Environ.* 31:632-645, 2008.

1710 Stock W.D, Bourke, L., and Froend, R.H.: Dendroecological indicators of historical
1711 responses of pines to water and nutrient availability on a superficial aquifer in south-
1712 western Australia. *For. Ecol. and Manag.* 264: 108-114, 2012.

1713 Stromberg J.C, Beauchamp V.B, Dixon M.D, Lite S.J, Paradzick C.: Importance of low-flow
1714 and high-flow characteristics to restoration of riparian vegetation along rivers in and
1715 south-western United States. *Freshwater Biol.* 52:651-679, 2007.

1716 Stromberg J.C, Lite S.J, Dixon M.D.: Effects of stream flow patterns on riparian vegetation
1717 of a semiarid river: implications for a changing climate. *River Research and Applic.*
1718 26:712-729. DOI: 10.1002/rra.1272, 2010.

1719 Stromberg J.C, Lite S.J, Rychener T.J, Levick .LR, Dixon M.D, Watts J.M.: Status of the
1720 riparian ecosystem in the upper San Pedro River, Arizona: Application of an
1721 assessment model. *Envir. Mon. Assess.* 115:145-173, 2006.

1722 Stromberg J.C, Tiller R, Richter B.: Effects of groundwater decline on riparian vegetation of
1723 semiarid regions: The San Pedro, Arizona. *Ecol. Appl.* 6:113-131, 1996.

1724 Sun, A. Y.: Predicting groundwater level changes using GRACE data. *Water Res. Res.* 49:
1725 doi :10.1002/ wrcr.20421, 2013.

- 1726 Syed, T. H., Famiglietti, J.S., and Chambers, D.P.: GRACE-based estimates of terrestrial
 1727 freshwater discharge from basin to continental scales. *J. Hydromet.* 10: 22-40, doi:
 1728 10.1175/2008JHM993.1, 2009.
- 1729 Tapley, B. D., Bettadpur, S., Watkins, M., and Reigber, C.: The gravity recovery and
 1730 climate experiment : Mission overview and early results. *Geophys. Res. Lett.*, 31,
 1731 L09607, doi :10.1029/2004GL019920, 2004.
- 1732 Thorburn, P.J., Walker, G.R., Woods P.H.: Comparison of diffuse discharge from shallow-
 1733 water tables in soils and salt flats. *J. Hydrol.* 136:253-274, 1992.
- 1734 Thorburn, P., Hatton, T., and Walker, G.R.: Combining measurements of transpiration and
 1735 stable isotopes to determine groundwater discharge from forests. *J. Hydrol.* 150: 563–
 1736 587, 1993.
- 1737 Tweed, S. O., LeBlanc, M., Webb, J. A. and Lubczynski, M. W.: Remote sensing and GIS for
 1738 mapping groundwater recharge and discharge areas in salinity prone catchments,
 1739 southeastern Australia. *Hydrogeol. J.* 15, 75-96, 2007.
- 1740 van Hylckama T.E.A.: Water use by salt cedar. *Water Res. Res.* 6:728-735, 1970.
- 1741 Wada, Y., Van Beek, L.P.H., Van Kempen, C.M., Reckman, J.W.T.M., Vasak, S. &
 1742 Bierkens, M.F.P.: Global depletion of groundwater resources. *Geophys. Res. Lett.* 37,
 1743 L20402, 2010.
- 1744 Wang, P, Yu J.J, Pozdniakov S.P, Grinevsky S.O, Liu C.M.: Shallow groundwater dynamics
 1745 and its driving forces in extremely arid areas: a case study of the lower Heihe River in
 1746 northwestern China. *Hyd. Proc.* 28:1539-1553. DOI: 10.1002/hyp.9682, 2014.
- 1747 Wang, P, Zhang, Y.C, Yu, J.J,Fu, G.B, Ao, F,: Vegetation dynamics induced by groundwater
 1748 flucturations in the lower Heihe River Basin northwestern China. *J. Pl. Ecol.* 4: 77-90,
 1749 2011.
- 1750 White, W.N.: A method of estimating ground-water supplies based on discharge by plants
 1751 and evaporation from soil: Results of investigations in Escalante Valley, Utah. Page
 1752 105 *in* Interior, editor. U.S. Geological Survey, 1932.
- 1753 Whitley, R. and Eamus, D.: How much water does a woodland or plantation use: a review of
 1754 some measurement methods, Canberra, Land & Water Australia, 2009.
- 1755 Wilcox L.J, Bowman R.S, Shafike N.G.: Evaluation of Rio Grande management alternatives
 1756 using a surface-water/ground-water model. *J. Am. Water Res. Ass.* 43:1595-1603,
 1757 2007.
- 1758 Wright, I.J., P.K. Groom, B.B. Lamont, P. Poot, L.D. Prior, P.B. Reich, E.D. Schulze, E.J.
 1759 Veneklaas and Westoby, M.: Leaf trait relationships in Australian plant species. *Func.*
 1760 *Pl. Biol.* 31:551-558, 2004.
- 1761 Xiao, S.C, Xiao, H.L, Peng, X.M, Tian, Q.Y.: Intra-annual stem diameter growth of *Tamarix*
 1762 *ramosissima* and association with hydroclimatic factors in the lower reaches of
 1763 China's Heihe River. *Journal of Arid Land* 6:498-510. DOI: 10.1007/s40333-013-
 1764 0248-x, 2014.
- 1765 Yang H, Yang D, Lie Z and Sun F.: New analytical derivation of the mean annual
 1766 water energy balance equation. *Water Res. Res.*, 44: W03410, 2008.
- 1767 Yang X, Smith PL, Yu T and Gao H,:Estimating ET from terrestrial GDEs using
 1768 Landsat images. *Int. J. of Digital Ear.* 4: 154-170, 2011.

1769 Yuan W.P, Liu S.G, Yu G.R, Bonnefond J.M, Chen J.Q, Davis K, Desai A.R, Goldstein A.H,
1770 Gianelle D, Rossi F, Suyker AE, Verma S.B.: Global estimates of evapotranspiration
1771 and gross primary production based on MODIS and global meteorology data. Rem.
1772 Sens. Env. 114:1416-1431. DOI: 10.1016/j.rse.2010.01.022, 2010.

1773 Zencich S.J, RH Froend, J.V Turner and V Gailitis,: Influence of groundwater depth on the
1774 seasonal sources of water accessed by *Banksia* tree species on a shallow, sandy
1775 coastal aquifer. Oecologia 131: 8-19, 2002.

1776 Zeppel M,: Convergence of tree water use and hydraulic architecture in water-limited
1777 regions: a review and synthesis. Ecohydrology 6: 889 – 900, 2013.

1778 Zinko, U., Seibert, J., Merritt, D.M., Dynesius M., Nilsson, C,: Plant species numbers
1779 predicted by a topography-based groundwater flow index. Ecosystems 8: 430-441,
1780 2005.

1781 Zhang, L., K. Hickel, W.R. Dawes, F.H.S. Cheiw, A.W. Western and P.R. Briggs, P.R.: A
1782 rational function approach for estimating mean annual evapotranspiration. Water
1783 Res. Res. 40: DOI 10.1029/2003WR002710, 2004.

1784 Zolfaghar, S.: Comparative ecophysiology of *Eucalyptus* woodlands along a depth-to-
1785 groundwater gradient. PhD thesis, University of Technology Sydney. 228 pp, 2014.

1786 Zunzunegui, M, Barradas M.C.D., Novo, F.G.: Different phenotypic responses of *Halimium*
1787 *halimifolium* in relation to groundwater availability. Pl. Ecol. 148: 165-174, 2000.

1788 Zweifel, R, Zimmermann, L and Newbery, D.M (2005). Modelling tree water deficit from
1789 microclimate: an approach to quantifying drought stress. Tree Phys. 25: 147-
1790 156, 2005.

1791

1792

1793

1794

1795

1796

1797

1798

1799

1800

1801

1802

1803

1804
 1805
 1806
 1807
 1808
 1809
 1810
 1811
 1812
 1813
 1814
 1815
 1816
 1817
 1818
 1819
 1820
 1821
 1822

Table 1: Deuterium analysis of xylem, soil, river water and groundwater in a study of three species growing in the Northern Territory of Australia. The $\delta^2\text{H}$ values (‰) of soil became more negative as distance from groundwater increased due to enrichment during surface evaporation. At shallow sites (*Melaleuca argentea*) the groundwater is near the surface and xylem water $\delta^2\text{H}$ values match soil water and groundwater. As depth-to-groundwater increased (because of local topography: the site slopes up from the river) xylem water isotope composition was increasingly more negative than groundwater because groundwater was unavailable to the roots. From Lamontagne *et al.* (2005).

	Depth-to-groundwater (m)	River water	Soil water	Xylem water	Groundwater
Daly River	0	-44			
<i>M. argentea</i>	< 0.25		-44	-43 to -48	-43
<i>B. acutangula</i>	3		-80	-46 to -40	-45
<i>C. bella</i>	> 15		-56 to -91	-59 to -71	Not available to roots

1823
 1824
 1825
 1826

1827
 1828
 1829
 1830
 1831
 1832
 1833
 1834
 1835
 1836
 1837
 1838

Table 2: Some examples of the application of remote sensing to the study of groundwater dependent ecosystems.

Notes on methods	Application	Reference
eVI (MODIS) + MODIS land surface temp + water balance equation	Calibrated, empirical model of riparian ET; groundwater use quantified from $ET_g = ET - (P - \Delta S)$	Scott et al., 2008
eVI (MODIS) + empirical relationship of ET, eVI and ET_o	Calibrated, empirical model of riparian ET; groundwater use quantified	Tillman et al., 2012
“Green island method”: Calculate standard deviation in NDVI across 14 y pixel by pixel	Identifying location of GDEs by determining where veg activity shows minimal seasonal variation	Tweed et al., 2007
“Green island method”: Calculate standard deviation in eVI across years and seasonally	Identifying location of GDEs by determining where veg activity shows minimal seasonal/inter annual variation	Dresel et al., 2010
“Green island method”: Calculate LAI for adjacent pixels ; find regions with larger LAI with GW access	Identifying location of GDEs by determining larger LAI	Colvin et al., 2007
NDVI (MODIS) + groundwater depth from bore data	Relationship between GW depth and vegetation cover	Jin et al., 2011

NDVI (MODIS) + groundwater depth from bore data	Relationship between GW depth and vegetation cover	Lv et al., 2012
Surface energy balance (SEBAL) + Landsat surface temp; LAI derived from MODIS	Estimating ET from GDEs at pixel-by-pixel resolution	Yang et al., 2008; 2011
SEBAL + NDVI (MODIS)	Estimating ET at 90 m resolution	Bindhu et al., 2013
SEBAL + MODIS	Estimating ET	Tang et al., 2013
SEBAL + SWAT model (hydrology)	Estimating groundwater recharge	Githui et al., 2012
SEBAL + LANDSAT images	Estimating arid zone shallow aquifer discharge	Matic et al., 2011
Penman-Monteith equation with RS estimates of LAI, NDVI and used to estimate land surface conductance	km-scale estimates of ET	Cleugh et al., 2007
EVI + surface temperature + canopy fractional cover	Partitions ET into vegetation and soil components	Mu et al., 2007
$ET_a^* = (ET_a - \text{rainfall}) / (ET_o - \text{rainfall})$ ET_a linearly correlated with NDVI* $ET_g = (ET_o - \text{rainfall}) \cdot NDVI^*$	Estimated GW use (ET_g) rather than ET_a	Groeneveld 2008
MODIS veg indices compared; PM equation used to find G_c and regress G_c against MODIS veg indices	Estimate ET_a and G_c	Yebra et al., 2013
MODIS reflectance + residual moisture index (from eVI) + Global veg moisture index Actual ET calculated from PET*crop factor and crop factor is derived from EVI	Estimate ET at 1 km spatial resolution	Guerschman et al., 2009

1839

1840

1841

1842

1843

1844
 1845
 1846
 1847
 1848
 1849
 1850
 1851
 1852
 1853
 1854
 1855
 1856
 1857
 1858

Table 3: A summary of some of the recent literature documenting the response of vegetation, across multiple scales, to reduced availability of groundwater.

Process/trait	Response to reduced availability of groundwater and range of depths	References
Leaf-scale photosynthesis	Decreased (zero to -9 m DGW);	Horton et al., 2001
Stomatal conductance	Decrease (zero to -9 m DGW); Decreased (zero to >-1 m DGW increased) ; Stomatal resistance increased from 38.8 to 112.5 (zero to >-3 m DGW) Decreased (-7 to -23 m DGW) Decreased (-2 to -4 m DGW)	Horton et al., 2001 Cooper et al., 2003 Zunzunegui et al., 2000 Gries et al., 2003 Kochendorfer et al., 2011
Canopy conductance	Decreased (-1.5 to >-5 m DGW) Decreased (-2 to -4 m DGW)	Carter and White 2009b Kochendorfer et al., 2011
Leaf and stem water potential	Ψ_{pd} decrease from -0.5 to -1.7 MPa (zero to -9 m); Ψ_{pd} decreased from 0.2-0.4 to -0.4 to -0.8 MPa (zero to >-1 m DGW increased) ; Decreased from -0.79 to -2.55 MPa (<-2 to >-20 m DGW);	Horton et al., 2001 Cooper et al., 2003 Froend and Drake 2006 Zunzunegui et al., 2000 Gries et al., 2003

	Decreased from -1.85 to -3.99 (zero to >-3 m DGW) Ψ_{midday} decreased (-7 to -23 m DGW)	
Transpiration rate	Total Et decreased 32% (-0.9 to -2.5 m DGW); Et decreased (-2 to -4 m DGW) E decreased from 966 to 484 mm (-1.1 to -3.1 m DGW) Annual E decreased (zero to -8 m DGW)	Cooper et al., 2006 Kochendorfer et al., 2011 Gazal et al., 2006 Ford et al., 2008
Resistance to xylem embolism	Increased (-1.5 to -30 m DGW); PLC ₅₀ decreased from -1.07 to -3.24 MPa (<-2 to >-20 m DGW)	Canham et al., 2009 Froend and Drake 2006
Growth rate	Decreased (zero to >-1 m DGW increased); Decreased (-7 to -23 m DGW)	Scott et al. 1999 Gries et al. 2003
Leaf area index	Decreased from 3.5 to 1.0 (-1.5 to >-5 m DGW) Decreased Decreased from 2.5 to 0.66 (zero to >-3 m DGW) Decreased from 2.7 to 1.7 (-1.1 to -3.1 m DGW)	Carter and White 2009b O'Grady et al. 2011 Zunzunegui et al. 2000 Gazal et al., 2006
Huber value (SWA/ LA)	Increased from 3.3 to 4.7 (-1.1 to -3.1 m DGW) No change (-1.5 to -30 m DGW) increased from 3.4 to 4.3 x10 ⁻⁴ (-1.5 to >-5 m DGW)	Gazal et al., 2006 Canham et al., 2009 Carter and White 2009b
Plant density	Vascular species number decreased; Species composition changed (-0.9 to -2.5 m DGW); plant cover type changed (-1.1 to -2.5 m DGW); vegetation cover and diversity decreased (-1 to -110 m DGW)	Zinko et al., 2005 Cooper et al., 2006 Merritt and Bateman 2012 Lv et al., 2013
NDVI	Decreased (-1 to -110 m DGW); Decreased (zero to -1.5 m DGW increased) Decreased (-1.8 to -3.5 m DGW)	Lv et al., 2013 Aguilar et al., 2012 Wang et al., 2011
Crown die-back	Increased between <40% to >50% (zero to -9 m); Leaf loss 34% (zero to >-1 m DGW increased)	Horton et al., 2001 Cooper et al., 2003
Mortality	Increased (>-2.2 DGW increased); Increased (zero to >-1 m DGW increased) Increased (-0.4 to -5 m DGW)	Groom et al., 2000 Scott et al., 1999 González et al., 2012

1859

1860

1861

1862

1863

1864
 1865
 1866
 1867
 1868
 1869
 1870
 1871
 1872
 1873
 1874

1875 **Table 4:** The meaning of the abbreviations/ traits used in Figure 7.

Abbreviation	Explanation/definition
Ψ_{TLP}	The water potential of leaves at which turgor is zero
Π_{100}	The solute potential at a relative water content of 100 %
RWC_{TLP}	The relative water content at which leaf turgor is zero
SWD	The saturated water content of wood
K_s	Sapwood-specific hydraulic conductivity of branch xylem
K_L	Leaf-specific hydraulic conductivity of branch xylem
PLC_{50}	The water potential at which 50 % of the hydraulic conductivity is lost
PLC_{88}	The water potential at which 88 % of the hydraulic conductivity is lost
H_v	Huber value: the ratio of leaf area to sapwood area
BA	Total basal area of trees within a plot
LAI	Leaf area index of a stand of trees
AGB	Above-ground biomass
ANPP	Above-ground net primary productivity

WUE	Water-use-efficiency; calculated as the ratio of ANPP/stand water-use
Height	Average height of the trees in a plot
Water-use	Rates of stand water-use; up-scaled from sapflow measurements
Stem density	The number of trees per hectare
Litterfall	Rates of annual litterfall within a plot

1876

1877

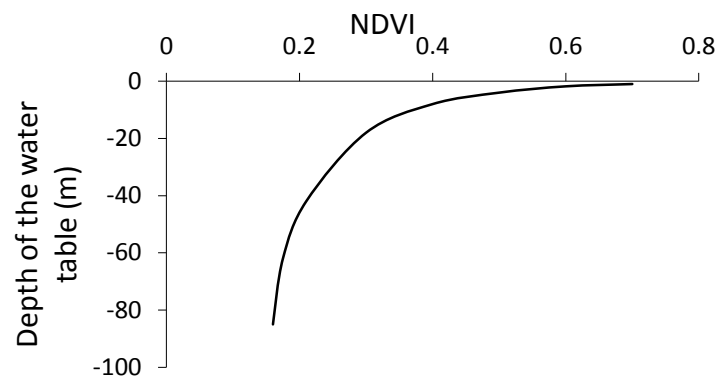
1878

1879

1880

1881

1882



1883

1884

1885

1886 **Figure 1:** The relationship between NDVI and depth to the water table for the Hailiutu
 1887 River catchment in northern China. Redrawn from Lv et al. (2012).

1888

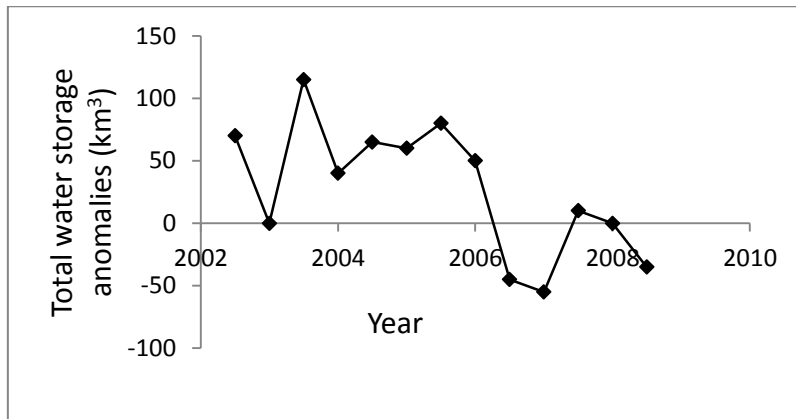
1889

1890

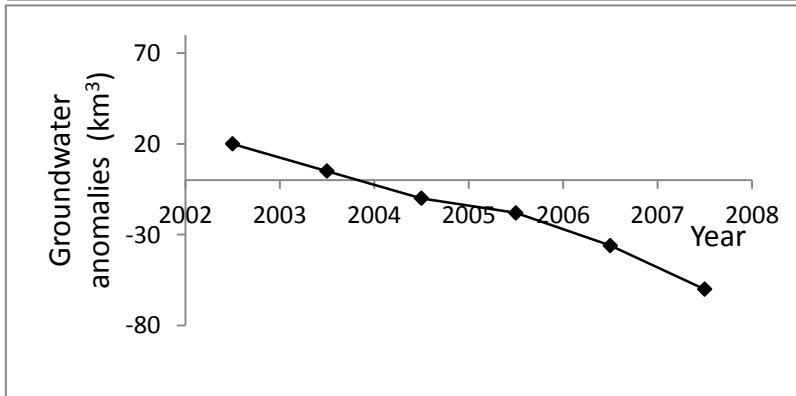
1891

1892

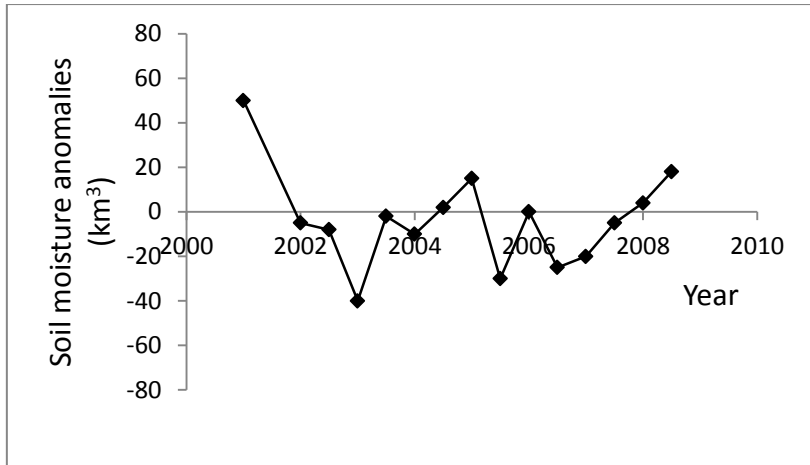
1893



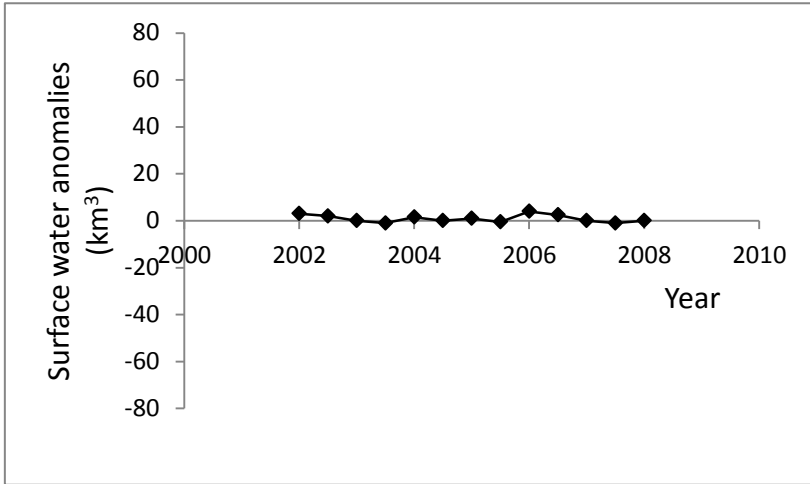
1894



1895



1896



1897

1898 **Figure 2:** Change of (a) total water storage anomalies; (b) groundwater anomalies; (c) soil
 1899 moisture storage anomalies; and (d) surface water anomalies relative to the mean of
 1900 the Murray-Darling Basin during the multiyear drought. Redrawn from Leblanc et al.
 1901 (2009).

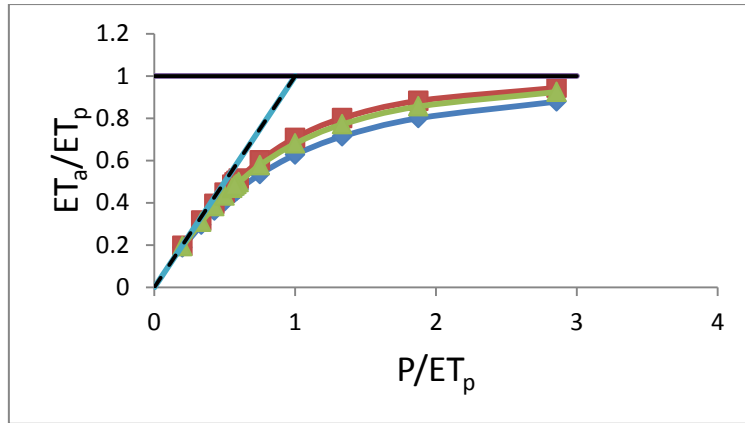
1902

1903

1904

1905

1906



1907

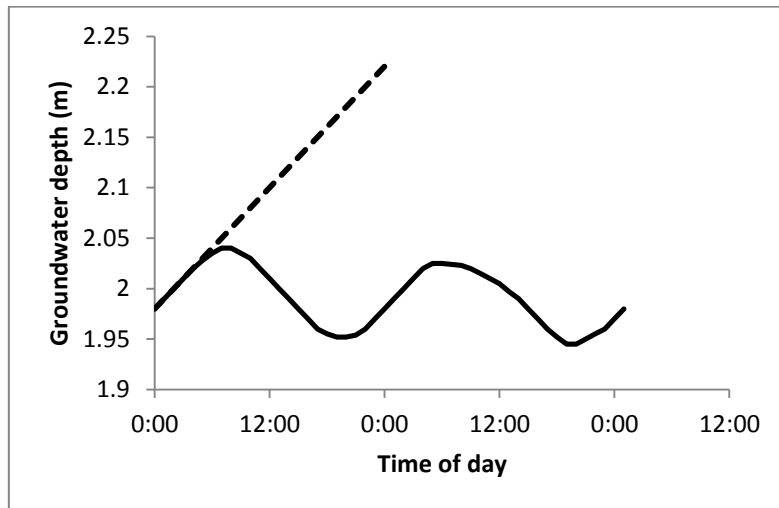
1908

1909 **Figure 3:** A representation of the Budyko formulation using the Choudhury-Yang
 1910 formulation with three different values of n (from 1.5 to 2.0). Redrawn from
 1911 Leaney et al., (2011).

1912

1913

1914

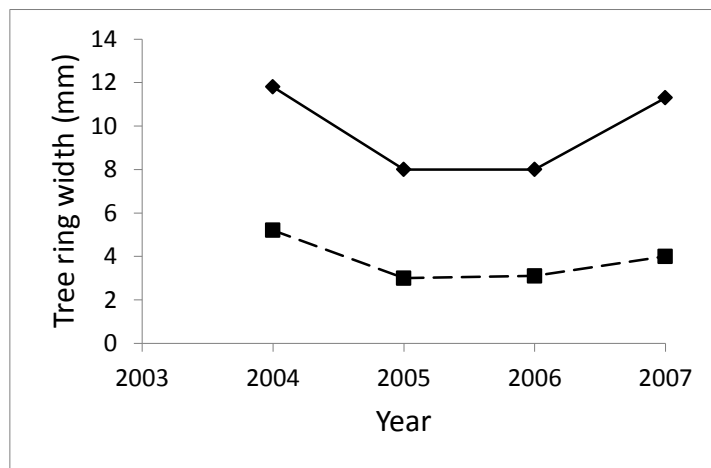


1915

1916 **Figure 4:** An idealised representation of changes in depth-to-groundwater over a
 1917 48 h period. The water table declines (depth increases) during the day
 1918 because of transpiration by vegetation but increases (depth decreases)
 1919 at night when transpiration tends to zero and recharge exceeds loss.
 1920 The dashed line represents the trajectory of overnight recharge in the

1921
1922
1923
1924
1925
1926
1927
1928
1929

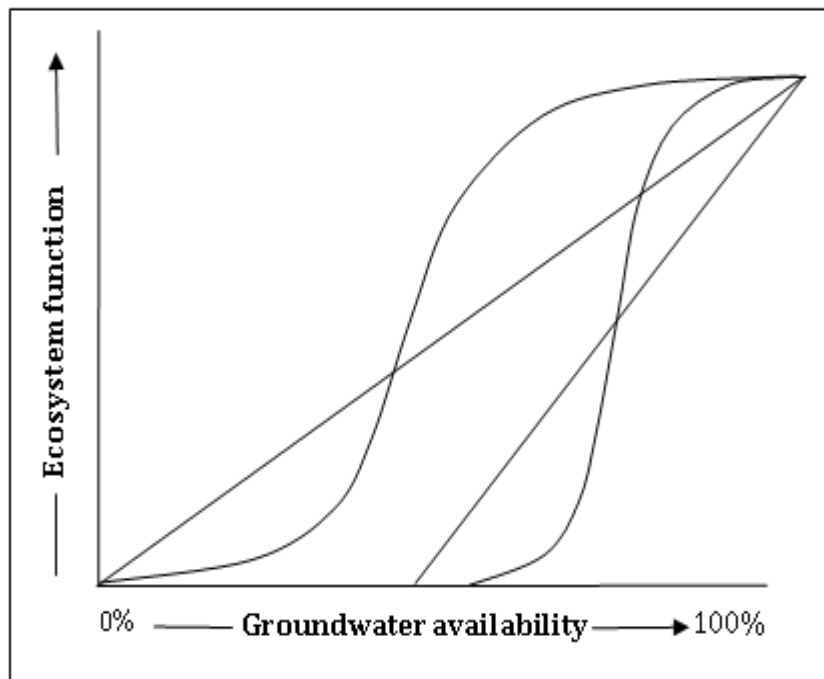
absence of transpiration on the following day. See text for further discussion of this.



1930
1931
1932
1933
1934
1935
1936
1937

Figure 5: Change in tree ring width of cottonwood (solid line, diamonds) and willow (dashed line, squares) before (2004) during (2005 – 2006) and after draining the reservoir (early 2005) and refilling (mid 2006). Redrawn from Hultine et al. (2010).

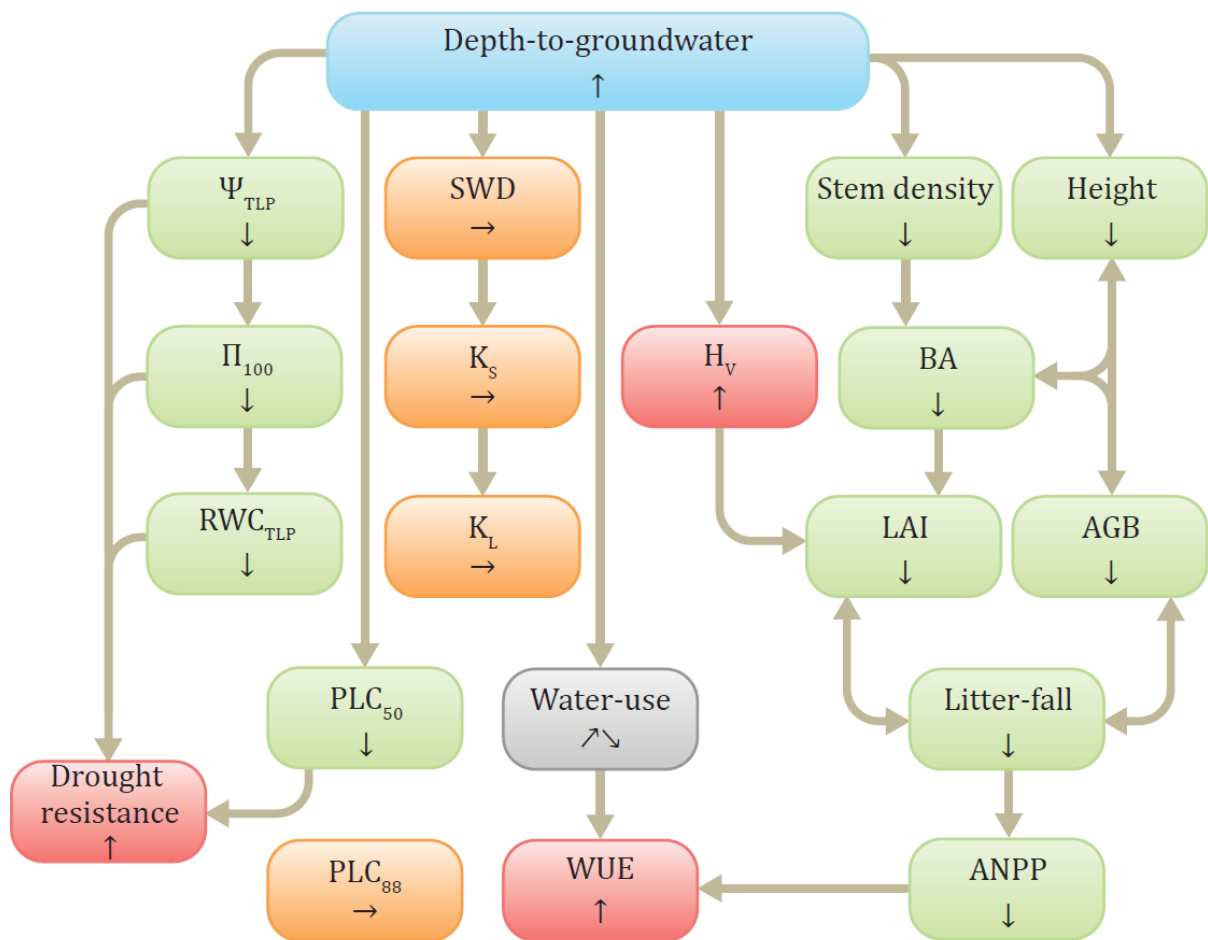
1938
1939
1940
1941
1942
1943
1944
1945
1946



1947
1948
1949
1950

Figure 6: Hypothetical response functions for ecosystem function to differences groundwater availability. From Eamus *et al.* (2006).

1951
 1952
 1953
 1954
 1955
 1956
 1957
 1958



1959
 1960

1961

1962 **Figure 7:** A summary of the traits examined and the general trend in response of those
1963 traits to increased depth-to-groundwater along a natural topographic gradient.
1964 Upward/downward pointing arrows within a coloured text box indicate
1965 increasing/decreasing values of the plant trait as depth-to-groundwater
1966 increases. Horizontal arrows indicate no change. Table four provides the
1967 definition of all abbreviations used in this figure.
1968

1969

1970

1971

1972

1973

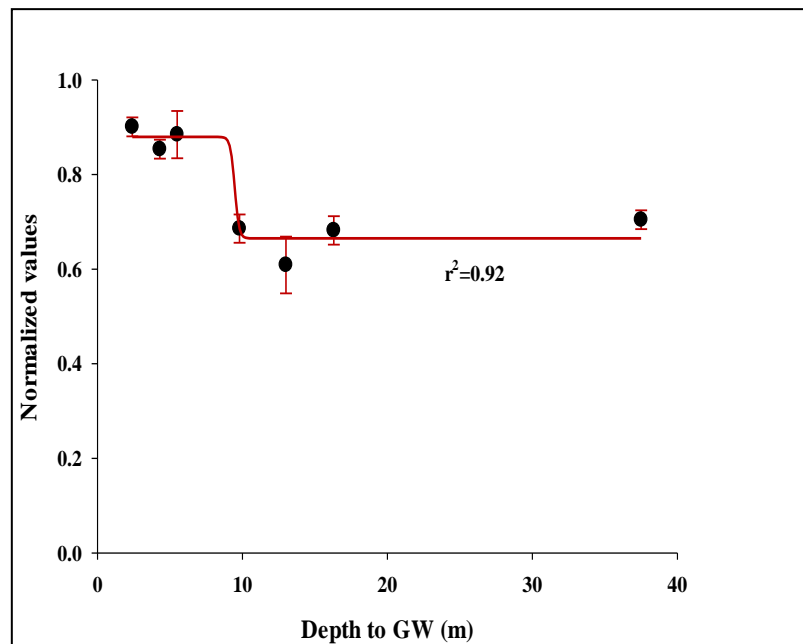
1974

1975

1976

1977

1978



1979

1980 **Figure 8:** Ecosystem response to increase in depth-to-groundwater, fitted with 4
1981 parameter sigmoidal function. From Zolfaghar (2014).

1982

1983

1984
1985
1986
1987
1988
1989
1990
1991
1992
1993
1994
1995
1996
1997
1998
1999
2000
2001
2002
2003
2004
2005
2006
2007

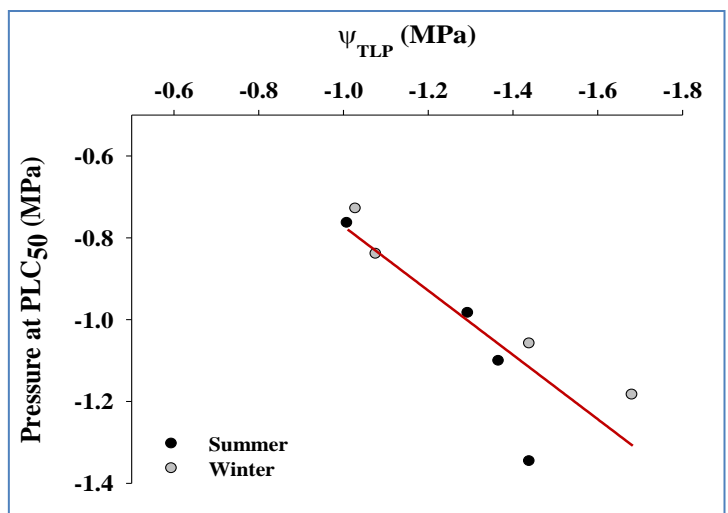


Figure 9: Co-ordination in the response of a leaf-scale and branch-scale trait and drought sensitivity. From Zolfaghar (2014).