MEMORANDUM

TO:	Mr Matt Shackleton
CC:	Kristy Sell (MBS Environmental)
SENDER:	Denisse Fierro Arcos; Joy Francis-Hays
REVIEWED:	Phil Whittle
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LAKE WELLS: NDVI, NDWI AND ET CALCULATIONS

Hydrobiology has completed the GIS tasks and extraction of summary data for Normalised Difference Vegetation Index (NDVI) and Normalised Difference Wetness Index (NDWI or Wetness Index) at Lake Wells, WA, the location of Australian Potash Limited's (APL) proposed Lake Wells potash project. The purpose of this analysis is to provide an assessment of possible impacts on surrounding vegetation from elements of the proposed Lake Wells project. Specifically, the analysis of spectral data is proposed as one source of information to evaluate the presence of groundwater-dependent vegetation (GDE) in the project locality.

The years 2006 and 2008 were chosen for analysis of Landsat 4-5 imagery (NDVI and NDWI) based on suitable dry season conditions and availability of high-quality, cloud-free imagery. NDVI provides a reliable measure of chlorophyll content or greenness of the vegetation. It is suggested that low seasonal variance in NDVI values is typically a signature of vegetation that has access to groundwater, and this relationship can often be more apparent at the end of the dry season when water is limited (Barron *et al* 2012).

An assessment was also conducted of Evapotranspiration (ET) for the same years, 2006 and 2008, using the CSIRO MODIS reflectance-based scaling evapotranspiration (CMRSET) data set. GDE is commonly associated with higher rates of ET; hence by calculating ET it may be possible to identify potential GDEs, especially when taken in concert with NDVI and NDWI measures (Guerschman *et al*. 2009).

The use of remote sensing to assess vegetation function has recently become an established technique. "Remote sensing provides a robust and spatially explicit means to assess not only vegetation structure and function, but also relationships amongst these and climate variables" (Eamus *et al.* 2015).

Brief Methods

NDVI and NDWI Method

The general approach to identifying potential GDEs followed Barron *et al*. (2012) – "*Mapping groundwater-dependent ecosystems using remote sensing measures of vegetation and moisture dynamics*". This involved

STREET
7 Forrest Avenue
East Perth 6004
WESTERN AUSTRALIA

POSTAL
PO Box 6917
East Perth 6892
WESTERN AUSTRALIA

CONTACT
+61 (0)8 6218 0900 P
+61 (0)8 6218 0934 F
info@hydrobiology.biz

ABN 68 120 964 650

using multi-spectral imagery to derive NDVI and NDWI measurements using the red, near infrared and short-wave infrared bands. Landsat imagery at a spatial resolution of 30 m × 30 m was obtained from the USGS Earth Explorer web service for the Lake Wells study area (**Error! Reference source not found.**). Images from the end of the wet season (Feb-April) until the end of the dry season (Sept-Nov) were obtained for two years: 2006 and 2008. These years were chosen based on a combination of an extended dry spell of several months and availability of suitable cloud-free imagery for the whole study area. Rainfall data was sourced from the nearest Bureau of Meteorology meteorological station: the Laverton met station, located approximately 180 Km southwest of Lake Wells. Imagery was obtained on a monthly frequency where possible.

Satellite imagery from the Landsat 4-5 archive was determined to be the most appropriate for this analysis as it contained a suitable temporal and spatial coverage. The Landsat 7 imagery (which covers years 2009 to 2013) contains a sensor error that may have made comparison with the older Landsat 4-5 imagery erroneous. The current Landsat 8 imagery is only processed for the study area from 2016 to present, which represents an unusually wet period, so it was not included in the analysis.

Raw imagery in GeoTIFF format was downloaded from the USGS website. Bands 3, 4 and 5 (Table 1) were imported into QGIS software package for further processing. Each image was clipped to a standard coverage area (**Error! Reference source not found.**), and NDVI and NDWI values were calculated using Python scripting within QGIS. A vegetation community (Floristic community) map (**Error! Reference source not found.**) provided by APL (produced by Botanica Consulting) was used to select zones for the generation of statistics for each vegetation type for 2006 and 2008 (

Table 2). **Error! Reference source not found.** and Table 4 provide some background information on the vegetation communities analysed. Descriptive statistics were generated for each vegetation type using the Zonal Statistics module within QGIS.

An additional vegetation/land cover unit classification was created to distinguish the wetting lake bed areas from the more purely terrestrial vegetation units. The reason for this extra classification was to identify and qualify the lake bed signature so that this could be compared with the vegetation units in terms of ET, NDVI and NDWI. This was undertaken to determine if the lake bed was influencing or skewing the results. It can be difficult to delineate the lake bed from the surrounding area because it is typically covered, at least partially, with CD-CSSSF1 vegetation. Delineation of areas that were within the lake bed was achieved using the MODIS product - Water Observations from Space (WOfS), which maps the presence of surface water across Australia. The study area was mapped selecting for areas that have water at least 1% of the time (i.e., ~3 days per year). The resulting lake bed area was named 'Lake Bed CD-CSSSF1'.

Table 1 Landsat 4-5 Thematic mapper band information

Bands	Wavelength (micrometers)	Resolution (meters)
Band 3 - Red	0.63-0.69	30
Band 4 - Near Infrared (NIR)	0.76-0.90	30
Band 5 - Shortwave Infrared (SWIR) 1	1.55-1.75	30

Table 2 Number of images processed per year

Year	Number of NDVI images	Number of NDWI images	Total
2006	8	8	16
2008	7	7	14
TOTAL	**15**	**15**	**30**

Evapotranspiration Method

Estimates of actual evapotranspiration (AET) were calculated for the study area using satellite imagery from the 'CSIRO MODIS reflectance based scaling evapotranspiration' (CMRSET) data set (250 m resolution). This data set was developed by Guerschman *et al.* (2009) and it provides an estimate of AET across Australia (based on MODIS reflectance and short wave infrared data), and gridded meteorological surfaces.

In brief, the CMRSET algorithm uses reflectance data from the MODIS satellite to calculate ET across the Australian continent. AET is calculated from potential ET (PET) by applying a 'crop factor' which incorporates the enhanced vegetation index (EVI) and global vegetation moisture index (GVMI). The algorithm was calibrated by comparing estimated AET with measured AET from seven eddy covariance towers around Australia covering a variety of landscapes (forest, savannah, grassland, floodplain and lake). CMRSET was further validated by comparing estimated AET with 'surrogate AET' (precipitation minus streamflow) in 227 unimpaired catchments around Australia (Guerschman *et al.* 2009).

A cautious approach is required when attempting to make inferences about the presence of GDE from AET for several reasons. The first being that the amount of ET for a given vegetation type can be influenced by other factors, such as vegetation health, leaf area index and water tolerance level of each vegetation type (Gonzalez 2015, Woods *et al*. 2016). Secondly, the calibration method used for the CMRSET was conducted in areas with rainfall greater than 250 mm and not in low rainfall areas, like the current study area. Thirdly, van Dijk *et al*. 2015 found that this method has a tendency to overestimate ET from salt lakes. However, van Dijk *et al*. 2015 showed that the CMRSET method can provide reliable ET estimates in areas other than salt lakes.

Raw imagery in .nc format was downloaded from the NCI (National Computational Infrastructure) website and imported into QGIS software package for processing. The vegetation community (floristic community produced by Botanica Consulting) map was used to generate statistics by vegetation type for 2006 and 2008 (Table 4). Descriptive statistics were generated for each vegetation type using Zonal Statistics module within QGIS.

Table 3 Number of images processed by year

Year	Number of ET images
2006	9
2008	11
TOTAL	**20**

Calculation of Groundwater Evapotranspiration

Groundwater evapotranspiration (ETg) refers to the water losses from groundwater due to transpiration, direct water uptake through roots from GDEs, and direct evaporation (e.g., from any wet surface including soil or land surface). GDE is commonly associated with a comparatively higher rates of evapotranspiration (ETg), hence by identifying areas where ETg exceeds rainfall on an annual basis it is possible to predict potential GDEs (O'Grady *et al*. 2011). It is important to know that this method is a simplification of the system and does not include a direct measure of evaporation and assumes that 100% of the ETg comes from transpiration. Eamus *et al*. 2015 estimated that the average error associated with this method was about 12%, however it is likely to be much greater in environments where groundwater is expressed at the surface and or moist soil (i.e., salt lakes and wetlands). In these types of environments there will be greater groundwater expression and hence higher ETs, and it is highly likely that these high ET values are not due to the presence of GDE but due to limitations of the method. Hence caution needs to be applied when making inferences about GDEs associated with groundwater expressed at the surface. The rainfall data used for this calculation came from the Laverton rain gauge station which is 180 km from the study site, this data was used because it is the closest and most complete data set available. The distance of the rainfall data from the study site is another limitation of this method.

The spatial resolution of the ET data allows for a pixel size of 250 m^2. The vegetation in this area can be highly patchy and may not completely fill a pixel; hence other components may be incorporated into the calculations (e.g., bare salt lake surface, or open ground). This limitation needs to be considered when interpreting the ET results.

Groundwater evapotranspiration (ETg) can be calculated from satellite imagery using NDVI and rainfall using the formula below in which NDVI* is the peak season normalised NDVI. It is important to note that these ETg figures are estimates and to obtain more accurate results it is suggested that the model is calibrated using sites with *in-situ* ET measurements.

$$ETg = (ET - Annual\ Rainfall) \times NDVI^*$$

NDVI* was calculated by subtracting the NDVI for the area that had either the lowest amount of vegetation or no vegetation ($NDVI_z$, i.e. Lake Bed CD-CSSSF1) from the summer peak season NDVI for each vegetation unit ($NDVI_p$) and dividing this by NDVI at saturation ($NDVI_m$, the maximum value obtained by any vegetation unit), minus the $NDVI_z$ (Eamus et al. 2015).

$$NDVI * = \frac{NDVI_P - NDVI_z}{NDVI_m - NDVI_z}$$

The following figures have been provided as a graphical presentation of the results:

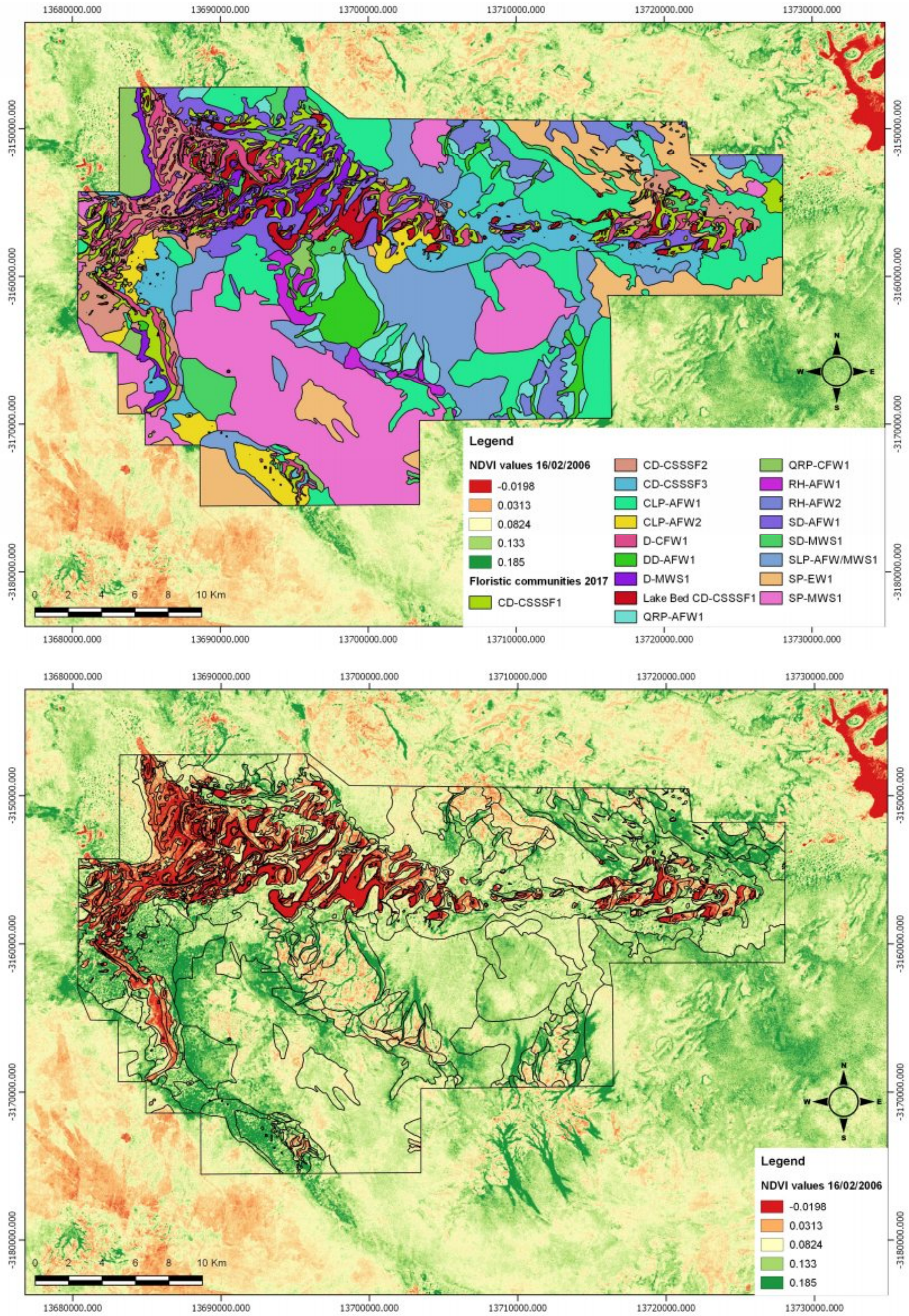

Figure 1 Map of vegetation communities (top panel) used in the NDVI, NDWI and ET analysis. Bottom panel shows NDVI values calculated on February 16, 2006.

Table 4 Description of vegetation communities

Landform	NVIS Vegetation Group	Vegetation Type	Vegetation Code
Closed Depression	Chenopod Shrublands, Samphire Shrublands and Forblands (MVG 22)	Low samphire shrubland of *Tecticornia indica* subsp. *bidens/ Tecticornia* sp. Dennys Crossing (K.A. Shepherd & J. English KS522) in playa	CD-CSSSF1
		Mid heathland of *Cratystylis subspinescens* over low open chenopod shrubland of *Atriplex vesicaria* and open forbland of *Frankenia* spp. on playa edge	CD-CSSSF2
		Mid open shrubland of *Eremophila paisleyi/ Lawrencia squamata/ Lycium australis* over low open chenopod shrubland of *Atriplex* spp. and open forbland of *Frankenia* spp. on playa edge	CD-CSSSF3
Clay-Loam Plain	Acacia Forests and Woodlands (MVG 6)	Low open forest of *Acacia incurvaneura* over mid shrubland of *Eremophila margarethae* and low open tussock grassland of *Eriachne mucronata/ Eragrostis eriopoda* on clay loam plain	CLP-AFW1
	Acacia Forests and Woodlands (MVG 6)	Low woodland of *Acacia caesaneura* over mid open shrubland of *A. burkittii* and mid chenopod shrubland of *Maireana pyramidata/* low open hummock grassland of *Triodia desertorum* on clay loam plain	CLP-AFW2
Drainage Depression	Acacia Forests and Woodlands (MVG 6)	Low open forest of *Acacia caesaneura* over mid open shrubland of *Senna artemisioides* subsp. *filifolia* and low open tussock grassland of *Eragrostis eriopoda* in drainage depression	DD-AFW1
Gypsum Dunefield	Casuarina Forests and Woodlands (MVG 8)	Low open forest of *Casuarina pauper* over tall open shrubland of *Acacia burkittii* and low sparse chenopod shrubland of *Atriplex vesicaria* on gypsum dune	D-CFW1
	Mallee Woodlands and Shrublands MVG 14)	Mid open mallee forest of *Eucalyptus gypsophila* over mid open shrubland of *Senna artemisioides/ Eremophila* spp. and low open chenopod shrubland of *Atriplex vesicaria* on gypsum dune	D-MWS1
Quartz/ Rocky Plain	Acacia Forests and Woodlands (MVG 6)	Low open woodland of *Acacia caesaneura/ A. incurvaneura* over mid open shrubland of *A. burkittii/ Eremophila fraseri* and low open shrubland of *Ptilotus obovatus*/ sparse tussock grassland of *Eragrostis eriopoda* on quartz/rocky plain	QRP-AFW1
	Casuarina Forests and Woodlands (MVG 8)	Low woodland of *Casuarina pauper* over mid shrubland of *Eremophila paisleyi* subsp. *paisleyi/ Senna artemisioides* subsp. *filifolia* and low open shrubland of *Ptilotus obovatus* on quartz/rocky plain	QRP-CFW1
Rocky Hillslope	Acacia Forests and Woodlands	Low open forest of *Acacia quadrimarginea* over mid open shrubland of *Senna artemisioides* subsp. *filifolia/ Senna* sp. Meekatharra (E. Bailey 1-26) and low open shrubland of *Ptilotus obovatus* on rocky hillslope	RH-AFW1

Landform	NVIS Vegetation Group	Vegetation Type	Vegetation Code
	(MVG 6)	Low woodland of *Acacia incurvaneura* over mid open shrubland of *Eremophila jucunda* and tussock grassland of *Eragrostis eriopoda/ Eriachne mucronata* on rocky hillslope	RH-AFW2
Sand Dunefield	Acacia Forests and Woodlands (MVG 6)	Low woodland of *Acacia caesaneura/ A. incurvaneura* over tall open shrubland of *Eremophila* spp./ *Senna* spp./ *Melaleuca interoris* and low open hummock grassland of *Triodia basedowii/* low open tussock grassland of *Eragrostis eriopoda* in dunefield	SD-AFW1
	Mallee Woodlands and Shrublands (MVG 14)	Mid mallee woodland of *Eucalyptus concinna* over low open shrubland of *Aluta maisonneuvei* subsp. *auriculata/ Dodonaea viscosa* and low closed hummock grassland of *Triodia desertorum* in dunefield	SD-MWS1
Sand-Loam Plain	Acacia Forests and Woodlands/ Mallee Woodlands and Shrublands (MVG 6/ 14)	Low open forest of *Acacia caesaneura*/ mid mallee woodland of *Eucalyptus lucasii* over mid open shrubland of *Eremophila latrobei* subsp. *glabra* and low hummock grassland of *Triodia desertorum* on sand-loam plain	SLP-AFW/MWS1
Sandplain	Eucalypt Woodlands (MVG 5)	Low woodland of *Eucalyptus gongylocarpa* over mid open shribland of *Eremophila platythamnos* subsp. *exotrachys* and low hummock grassland of *Triodia desertorum* on sandplain	SP-EW1
	Mallee Woodlands and Shrublands (MVG 14)	Mid mallee shrubland of *Eucalyptus* spp. over mid open shrubland of *Acacia* spp. and low closed hummock grassland of *Triodia basedowii* on sandplain	SP-MWS1

While the present study has used methods consistent with Barron *et al.* (2012), it should be noted that the NDVI values returned between the two studies will differ due to vastly different vegetation communities and seasonal conditions. Figure 2 provides an example of NDVI maps for Lake Wells and the Barron *et al.* (2012) study area for May 2006, showing "greener" conditions for the Swan Coastal Plain area when compared to the dry marginal landscape of Lake Wells.

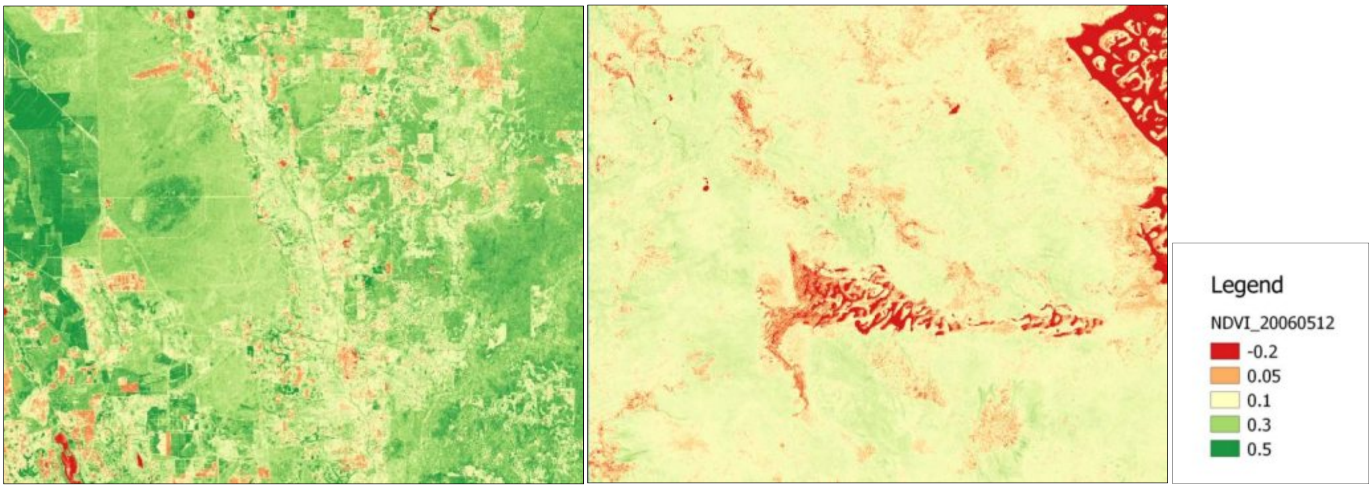

Figure 2 Comparison of NDVI values for Lake Wells on 23/05/2006 (right) and Swan Coastal Plain on 12/05/2006 (left)

Results

NDVI and NDWI

Barron *et al.* (2012) assessed the presence of potential GDEs by plotting changes in NDVI values over the dry season, hypothesizing that those vegetation communities with the least change in greenness are most likely to be supplemented by water sources other than rainfall (i.e., groundwater or perched surface water). Following this method, Figure 3 provides a plot of the late wet season NDVI values (x-axis) against the late dry season NDVI values (y-axis) for each floristic community identified in the study area for years 2006 and 2008. Vegetation units that deviate most from the 1:1 line are classified as 'fast-drying vegetation' (Barron *et al,* 2012), and are very unlikely to be groundwater dependent. Vegetation units with relatively high and unvarying NDVI values, which closely follow the 1:1 plot line are inferred to have a continuing source of water (i.e., are considered to be more likely to be groundwater dependent). Units with consistently low and unvarying NDVI may represent permanent water or wetland surfaces (if they also show high and unvarying NDWI signatures and high ET), or may correspond to sparse vegetation or bare soil (if they have lower NDWI and low cumulative ET). By ranking the ratio of NDVI values from late wet to end of dry season based on their distance to the 1:1 line, we can identify which vegetation unit has the least variable NDVI value (Figure 4).

This method has identified CD-CSSSF1 (Low samphire shrubland of *Tecticornia indica* subsp. *bidens/Tecticornia* sp. Dennys Crossing (K.A. Shepherd & J. English KS522) in playa) and D-CFW1 (Low open Casuarina forest over Acacia shrubland and sparse chenopod shrubland) as having the least variable NDVI values across the dry season for both 2006 and 2008. There is a distinct possibility that the sparseness of vegetation, particularly in the CD-CSSSF1 community, is lowering the NDVI response over the dry season. The NDVI pixels are an average of 30 m × 30 m, which includes any bare ground between plants. Sparse vegetation would comprise a greater degree of non-variable substrate in the form of bare ground and/or dead litter material. Therefore the Barron *et al*. (2012) method is likely to require greater botanic interpretation when applied to the Lake Wells study area.

The relative change in NDVI values across the dry season (as measured by the distance from the 1:1 line) for all vegetation units were greater in 2006 than in 2008. For example, for D-CFW1 the distance unit was 0.03 in 2006 and <0.01 in 2008 (Figure 4 A and B). A comparison of cumulative rainfall for both years (Figure 5) shows that 2008 had significantly lower rainfall throughout the year, which may explain the reduced start of season NDVI values in all vegetation units. Interestingly, the unit with the least change between years was Lake Bed CDSSS1 with NDVI values of 0.01 for 2006 and just under 0.01 for 2008. This indicates that NDVI values for Lake Bed CDSSS1 are not heavily impacted by inter-annual rainfall (including associated groundwater recharge) and supports the theory that this area displays a predominantly lake bed signature. This relatively constant lake bed signature across seasons has been previously observed by Hydrobiology in similar NDVI assessment projects in inland arid Australia.

There was an early rainfall event in late 2008 on 23/11/2008 which brought 40 mm of rain and the vast majority of the vegetation units responded to this rainfall event with an increase of NDVI. However, D-MWS1, CD-CSSF1, D-CFW1 and Lake Bed CDSSS1 units all experienced declines in NDVI values (Figure 9). This can potentially be explained by the presence of pooling water in and around the lake bed which absorbs infrared light causing a reduction in NDVI, while in reality the 'greenness' of the vegetation may have actually increased or remained the same.

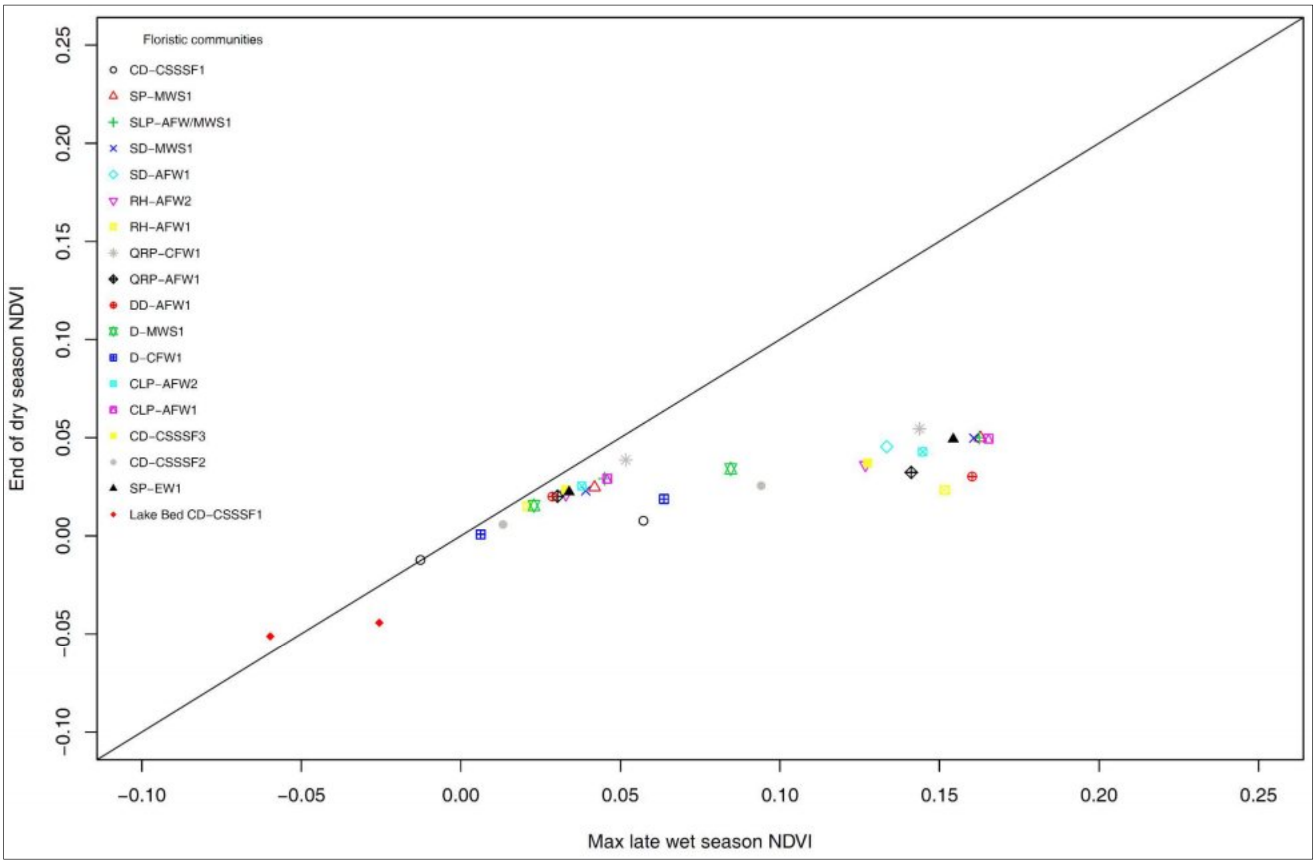

Figure 3 Ratio of NDVI values from late wet to end of dry season (2006 and 2008)

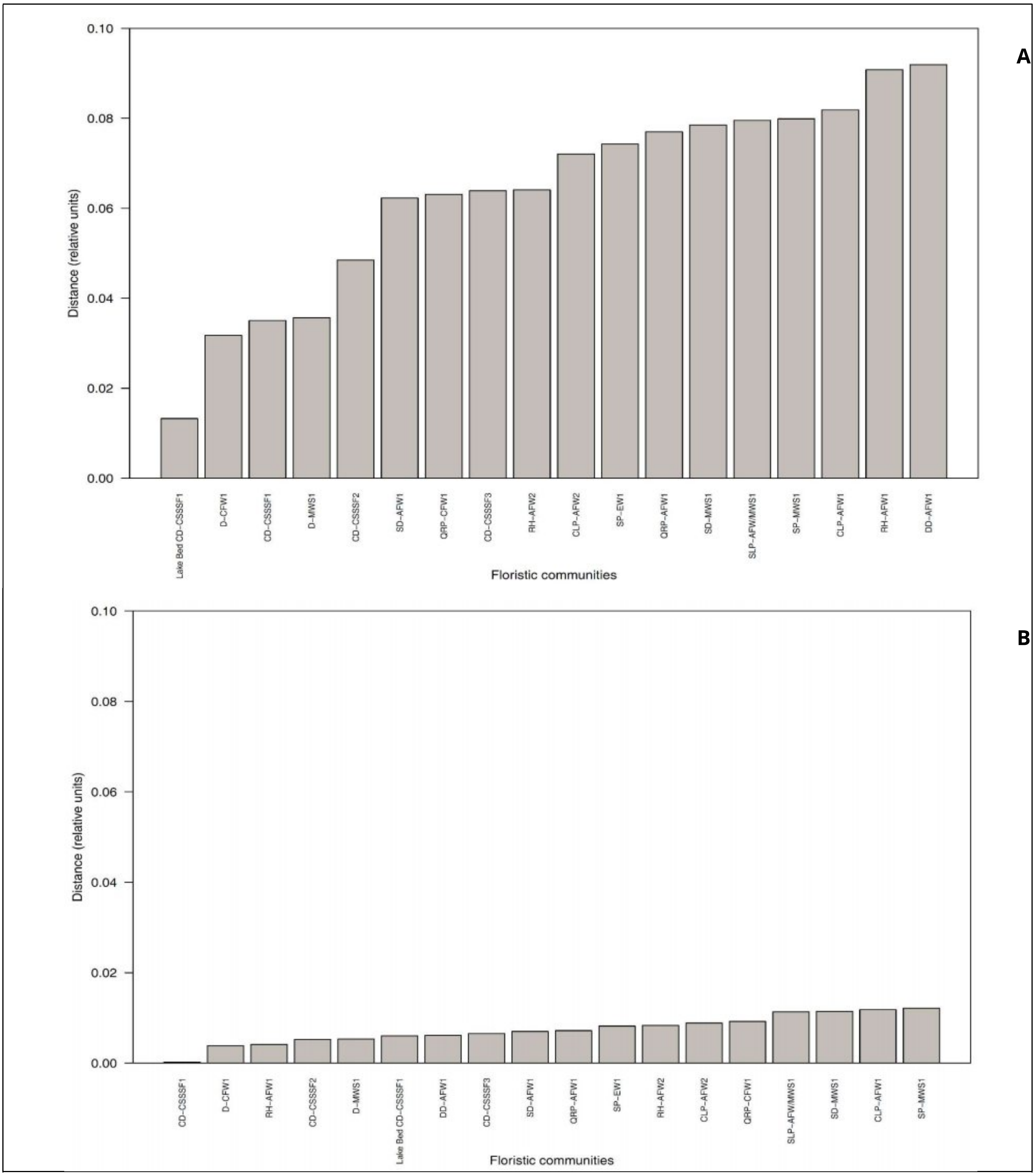

Figure 4 Ranking of 'distance' values from 1:1 (no change over dry season) for all floristic communities for 2006 (A) and 2008 (B)

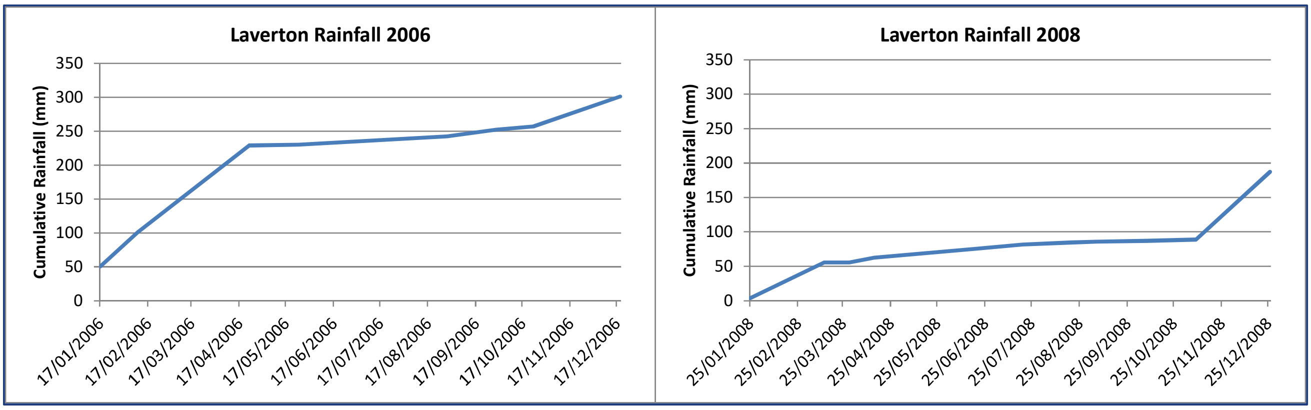

Figure 5 Cumulative rainfall recorded at Laverton rain gauge station in 2006 (left) and 2008 (right)

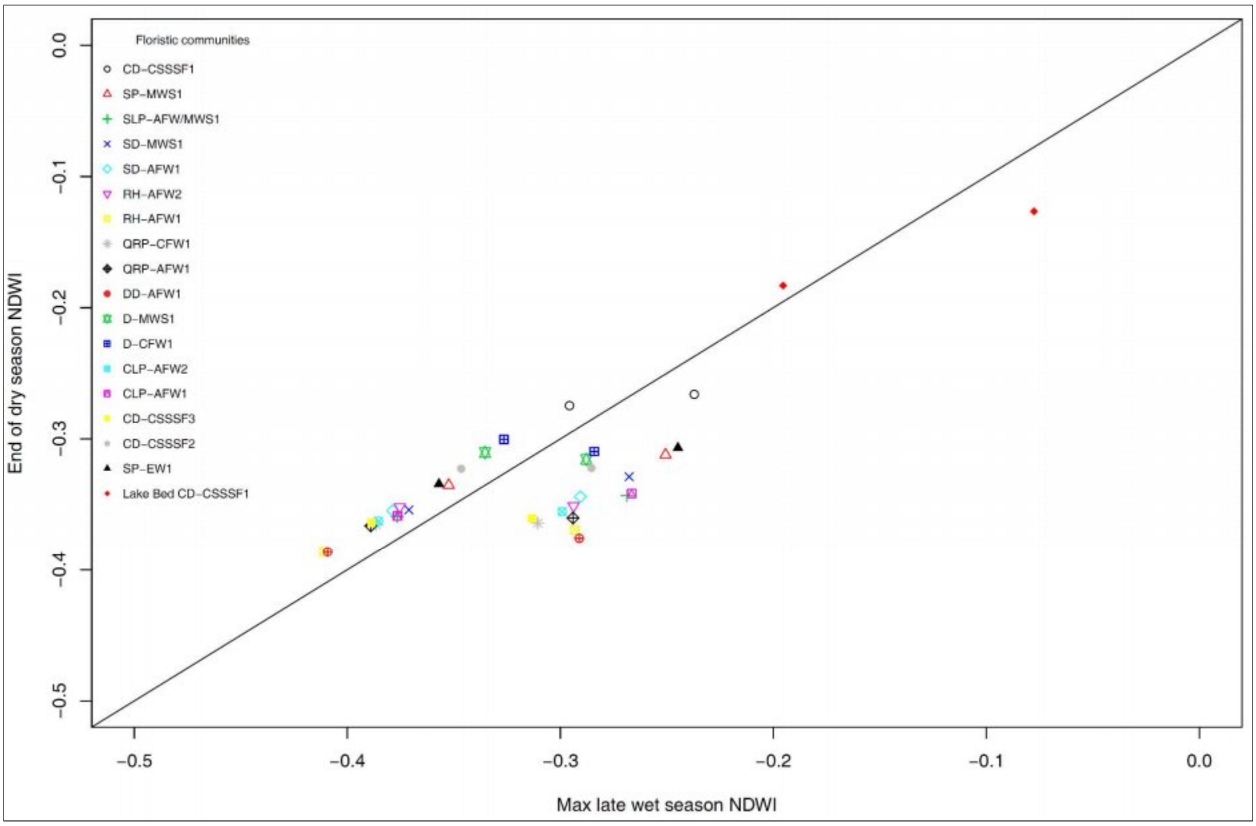

Figure 6 Ratio of NDWI values from late wet to end of dry seasons for 2006 and 2008

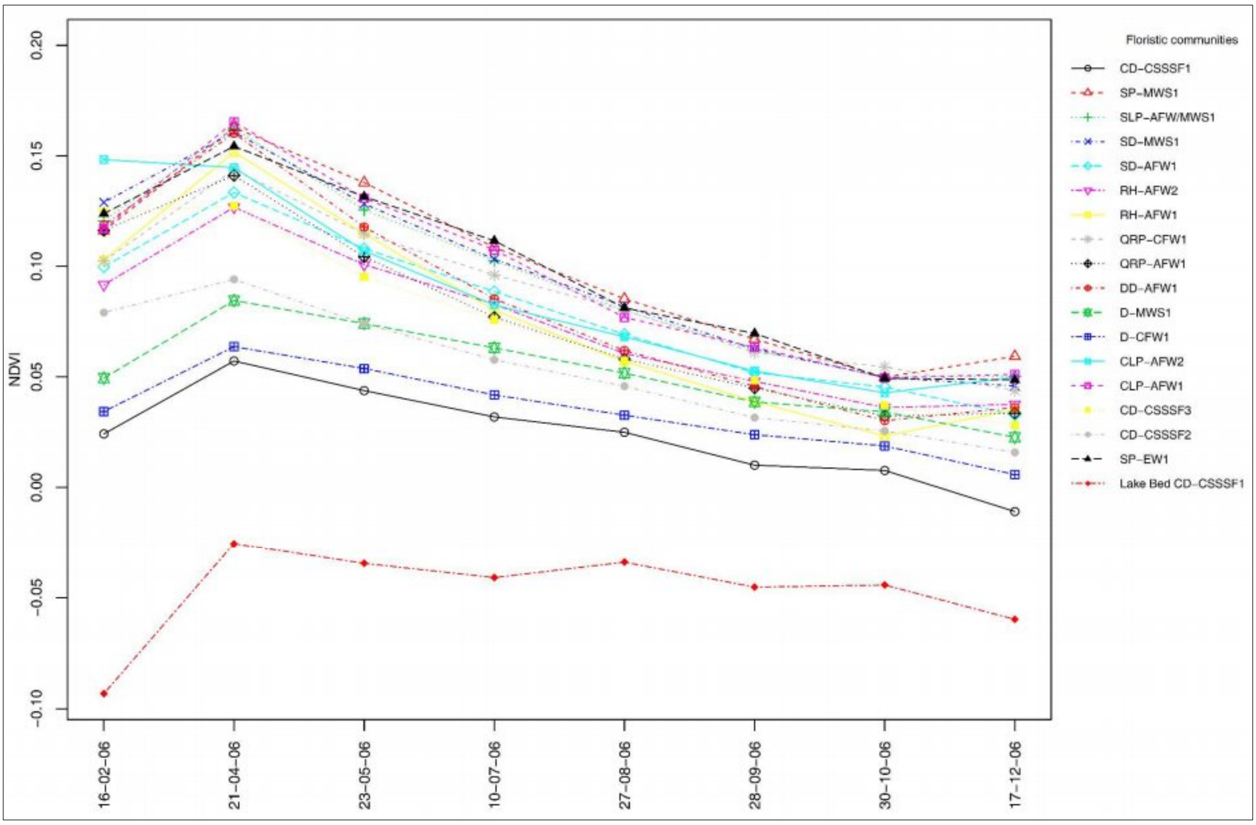

Figure 7 Average NDVI of each vegetation type for 2006

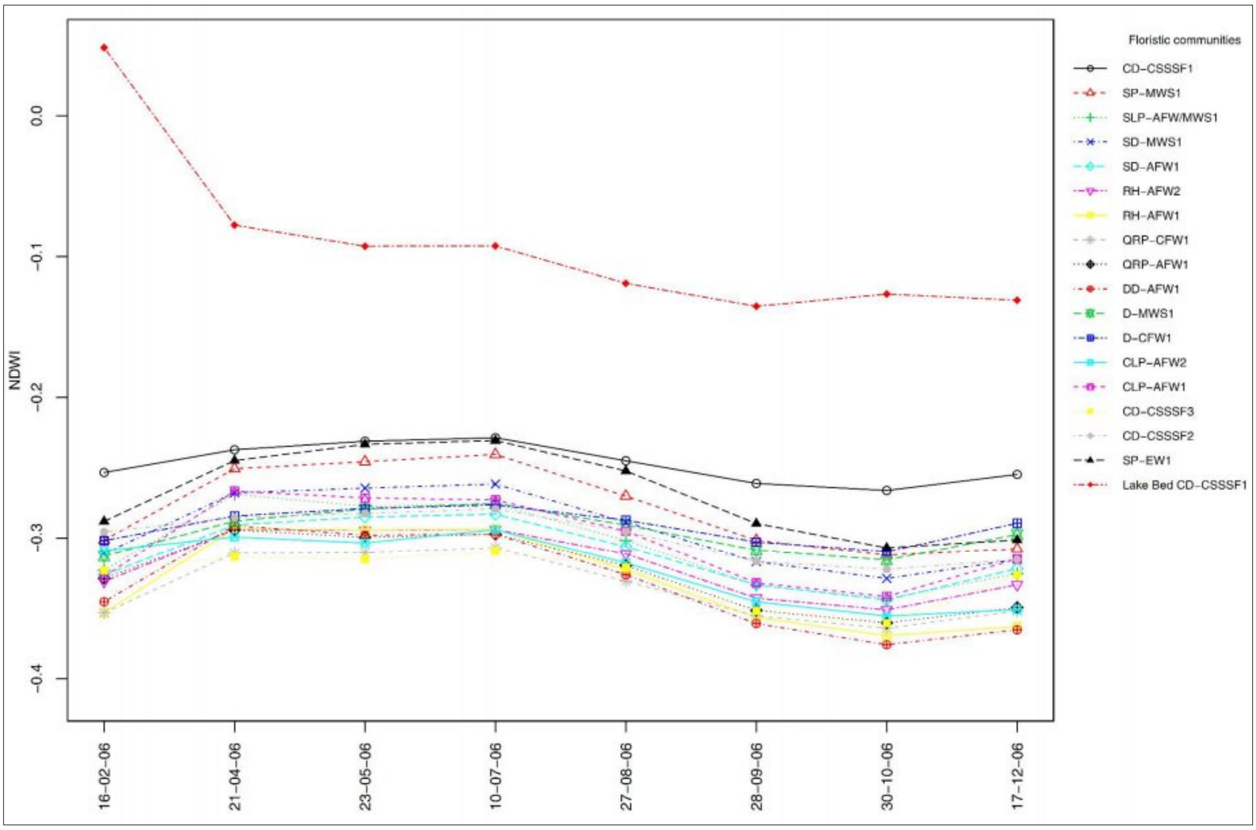

Figure 8 Average NDWI of each vegetation type for 2006

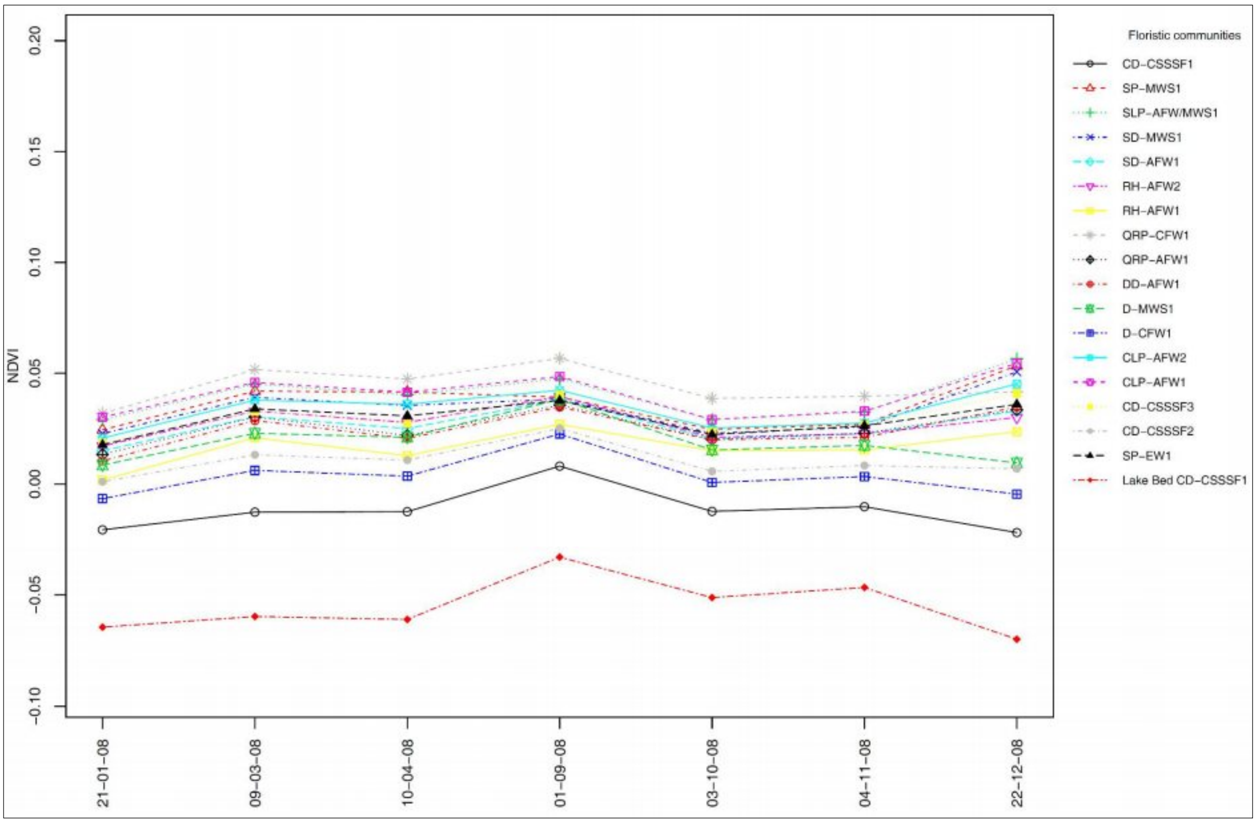

Figure 9 Average NDVI of each vegetation type for 2008 along with cumulative rainfall at Laverton rain gauge station

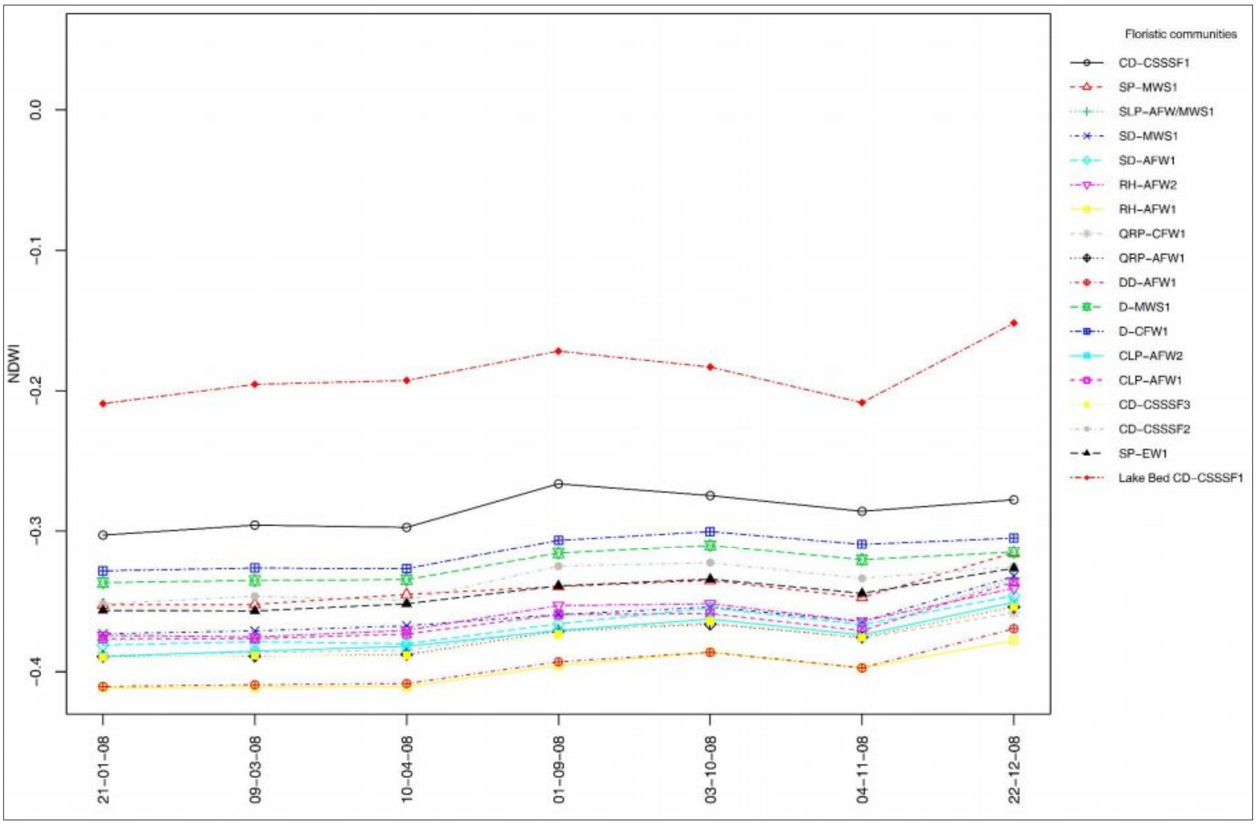

Figure 10 Average NDWI of each vegetation type for 2008

Evapotranspiration (ET)

Cumulative ET

Estimates of actual evapotranspiration (ET) were calculated for the study area using satellite imagery from the CMRSET data set. Cumulative ET was plotted for each year (2006 and 2008) to assess how ET differed over the late wet to late dry season for each of the vegetation types. According to O'Grady *et al.* (2011) GDE-related vegetation classes are likely to have greater ET losses over the dry period than non-GDE-related classes. The results presented in Figure 11 (2006) and Figure 12 (2008) showed that the highest estimated losses to evaporation are associated with the Lake Bed CD-CSSSF1, which is expected due to surface water and moist soil associated with this unit for a much greater proportion of the dry season than the terrestrial vegetation units. None of the vegetation types displayed consistently high ET rates for either 2006 or 2008. This may indicate that they are not using groundwater and hence are not GDE.

It is also important to note that in 2006 none of the ET values exceed cumulative rainfall indicating that groundwater is not being utilised by these vegetation units. To determine conclusively that this is the case further botanic interpretation should be applied to the study area. It is important to note that the rainfall values used in these figures are for Laverton, which is approximately 180km South West of Lake Wells. Rainfall can be highly variable across this area, so this data may not be fully representative of the project area and any conclusions drawn from this data should be done so with this caveat in mind.

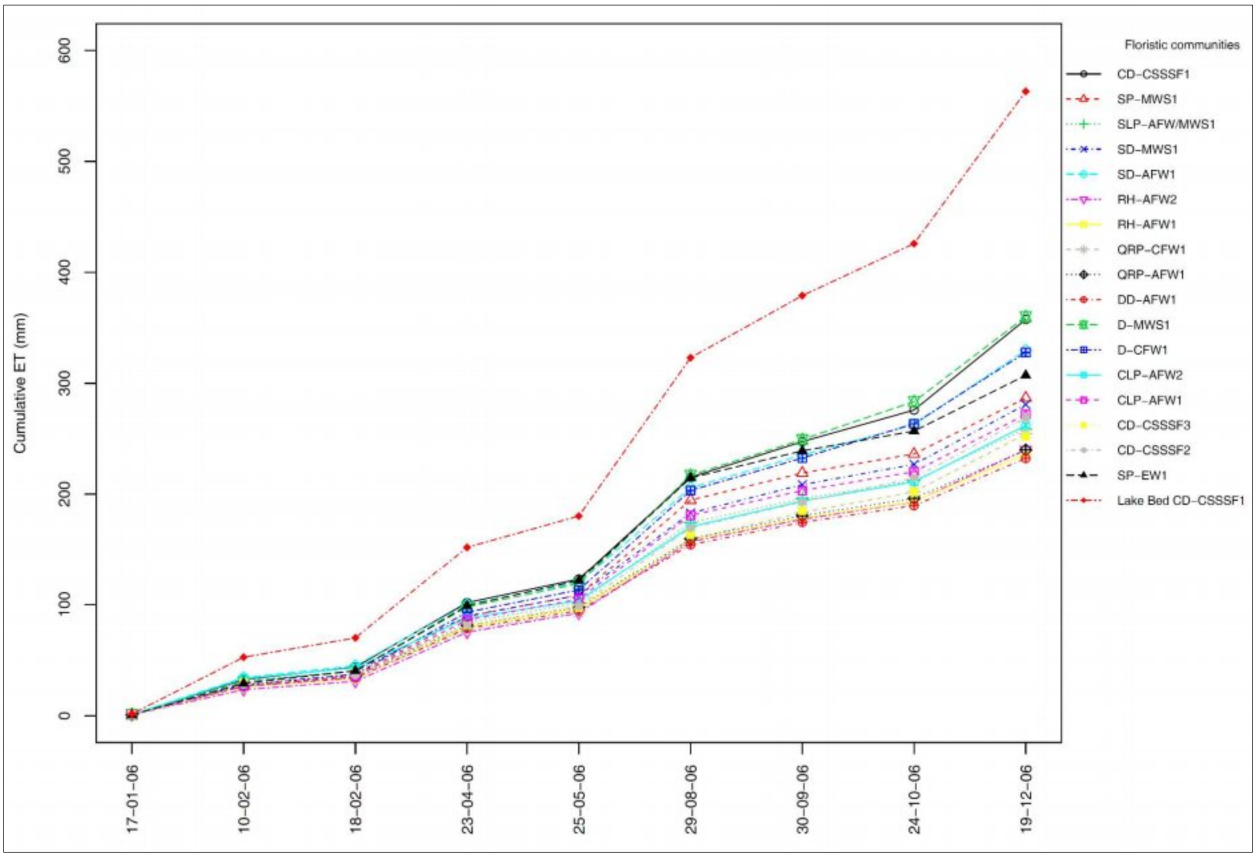

Figure 11 Cumulative ET for each vegetation unit type for 2006

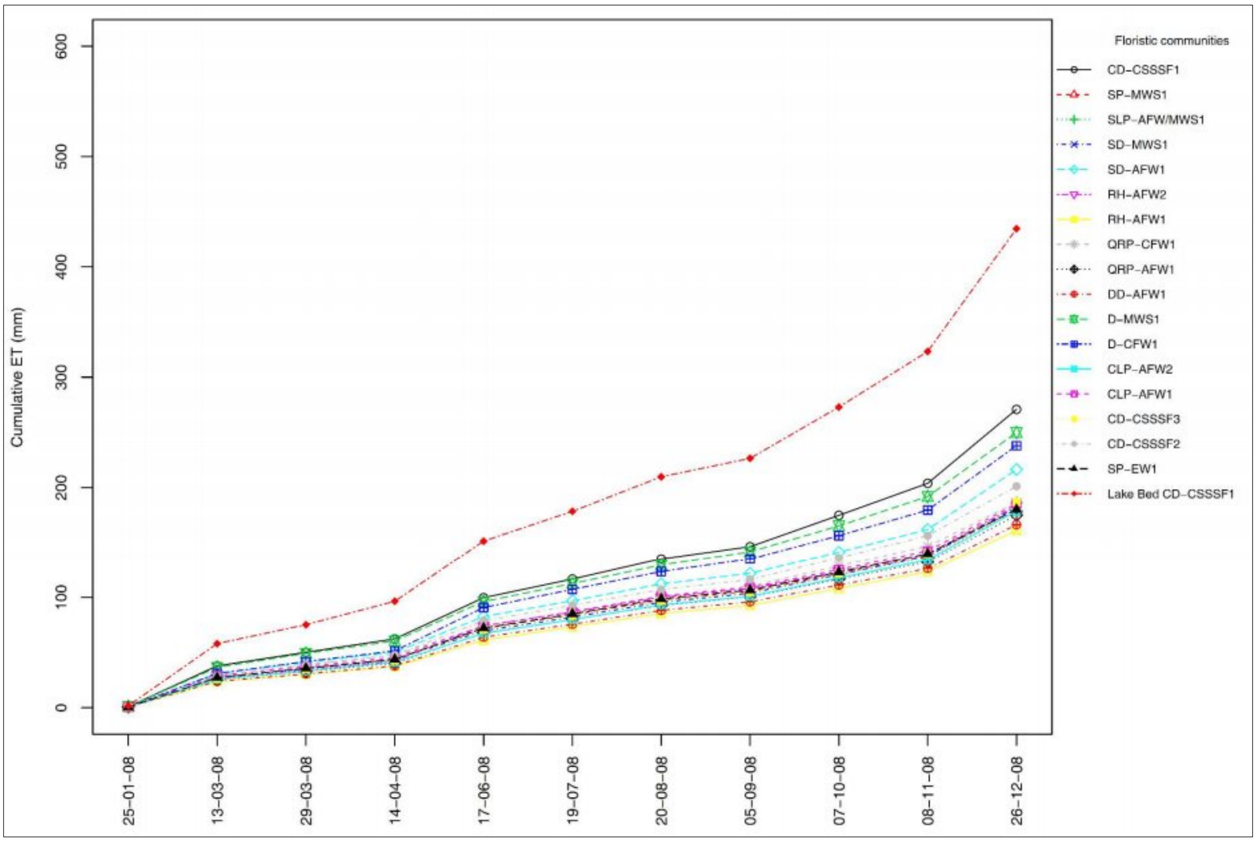

Figure 12 Cumulative ET for each vegetation unit type for 2008

Groundwater Evapotranspiration

The results of the groundwater evapotranspiration (ETg) assessment for 2008 are shown in Figure 13. An extension of this method was devised recently by Doody *et al.* (2017), in which the probability of a vegetation unit using groundwater during the dry season was referred to as the potential inflow dependent ecosystem (pIDE) index was calculated from a ratio of cumulative yearly ET to cumulative yearly rainfall. Table 5 shows ratios and pIDE values for each vegetation unit (excluding Lake Bed unit since this is not a strictly vegetation unit). These results indicate that there is low likelihood (<50%) of pronounced groundwater dependency for most vegetation units included in the study. However, there are two units which are moderately likely to be groundwater dependent: CD-CSSSF2, SD-AFW1, and three units that are highly likely to be GDEs: D-MWS1, D-CFW1 and CD-CSSSF1.

It is important to note that there are limitations to the method used in this study. Recent works by van Dijk et al (2015) have shown that the CMRSET method can be unreliable for vegetation units adjacent to salt lake systems and they are known to overestimate evapotranspiration estimates in these habitats.

In addition, the CMRSET data has limited spatial resolution with a minimum pixel size of 250 m^2. If the size of the vegetation unit is smaller than the pixel size, or if vegetation is extremely patchy, these values can be skewed by the values of surrounding units. This is of particular relevance for vegetation units next to the salt lake system, which are likely to have overestimated ET values due to the influence of the lake bed components in pixels containing both vegetation units. Consequently caution needs to be taken when making assumptions that a particular vegetation unit is groundwater dependant based solely on estimated ET values. To determine conclusively that a unit is a GDE, further botanic interpretation should be applied to the study area.

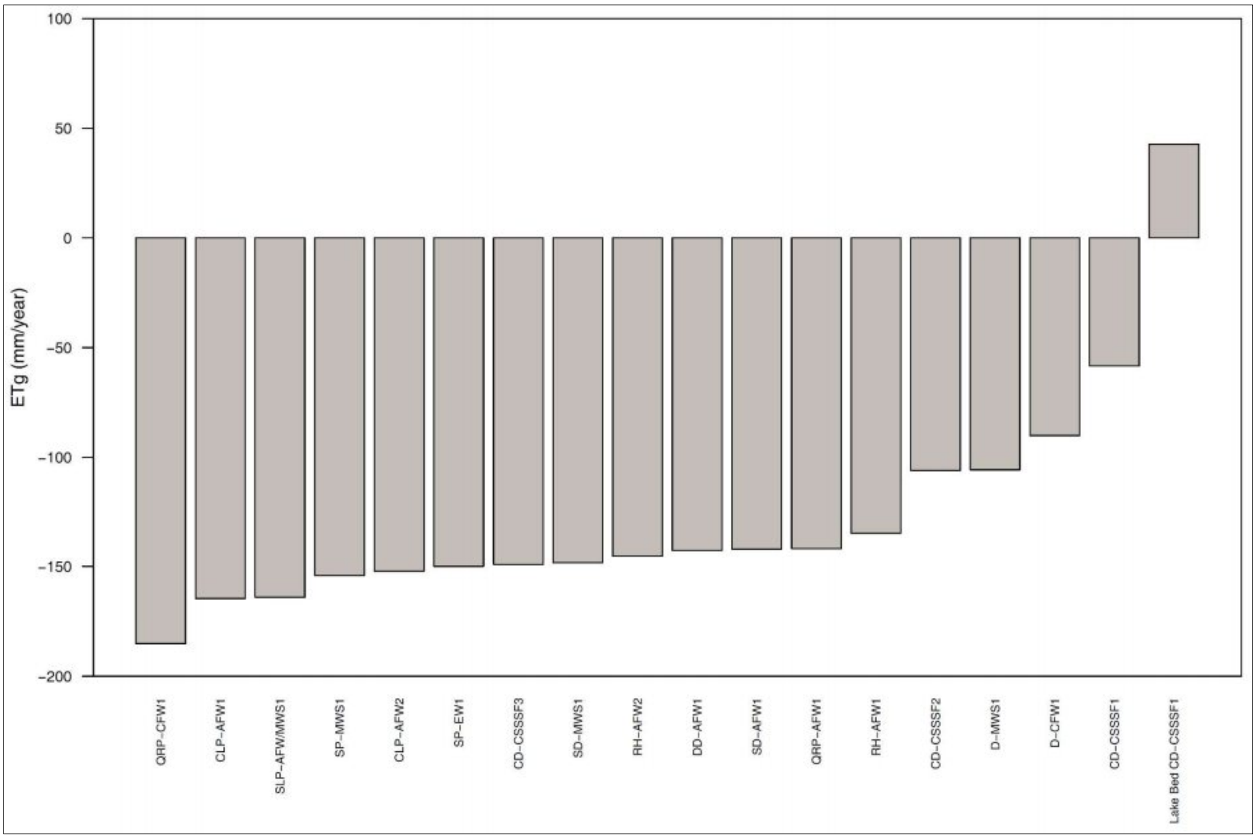

Figure 13 Estimated groundwater evapotranspiration (ETg) for each vegetation unit in 2008

Table 5 The probability of inflow dependence (pIDE) for each vegetation unit for 2008

Floristic Community	ET/Rainfall Ratio	pIDE (%)
RH-AFW1	0.84	20
DD-AFW1	0.87	20
SP-MWS1	0.94	30
SLP-AFW/MWS1	0.93	30
QRP-AFW1	0.91	30
CLP-AFW2	0.93	30
SP-EW1	0.94	30
SD-MWS1	0.95	40
RH-AFW2	0.96	40
QRP-CFW1	0.97	40
CLP-AFW1	0.97	40
CD-CSSSF3	0.98	40
CD-CSSSF2	1.05	60
SD-AFW1	1.13	70
D-MWS1	1.31	90
D-CFW1	1.24	90
CD-CSSSF1	1.42	100

Summary and Conclusions

Spectral data was analysed for two years: 2006 and 2008 at Lake Wells.

- No vegetation unit showed consistently high and unvarying NDVI and NDWI indices (the spectral signature typically associated with groundwater dependent vegetation).
- Two vegetation units (CD-CSSSF1 and D-CFW1) showed low, but relatively constant NDVI values (for both years) and moderate NDWI values for 2008, but with lower and less variable wetness than the playa surface. Typically, this signature would indicate areas of sparse vegetation or bare soil.
- CD-CSSSF2, SD-AFW1, D-MWS1, and D-CFW1, are the only units where estimated ET exceeded rainfall, which suggests these units are likely to be supplemented by water sources other than rainfall (i.e., groundwater or perched surface water). However, it is worth noting that all these units are located in close proximity to the salt lake, which may result in an overestimation of ET values.

- ET values also exceeded rainfall in CD-CSSSF1. However, due to the close proximity of this unit to the salt lake, it is considered that vegetation in this area has access to water from the lake for a longer period of time than surrounding vegetation units.
- There are methodological issues that limit the application of ET estimation on salt lakes. These limitations constrained the use of ET methods in estimating the likelihood of groundwater dependence of vegetation on islands or in close proximity to the playa.

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