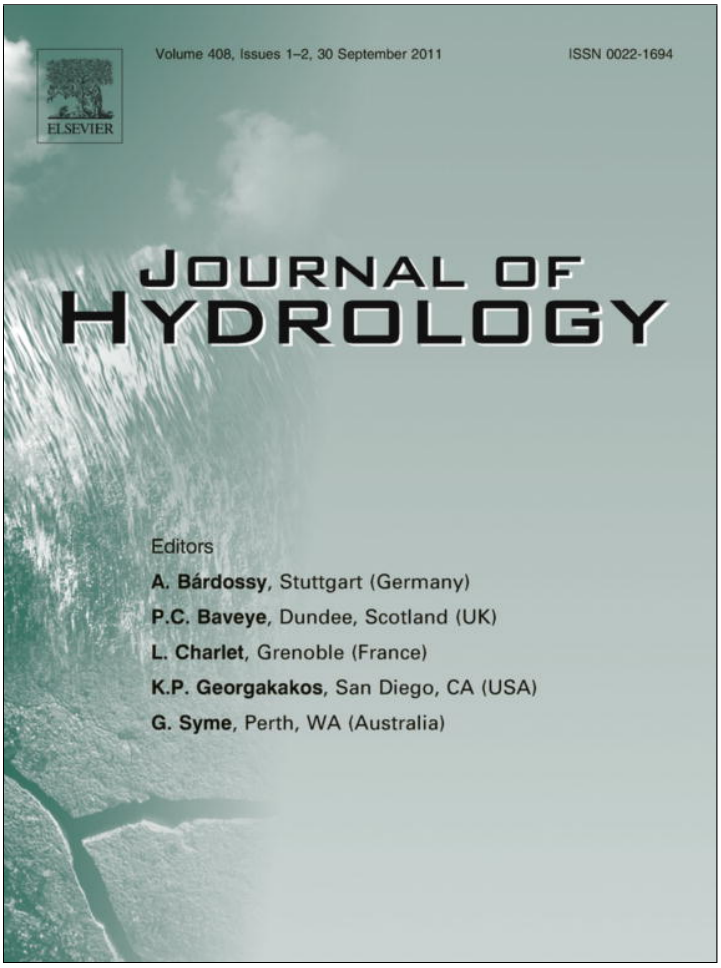
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A new approach to monitoring spatial distribution and dynamics of wetlands and associated flows of Australian Great Artesian Basin springs using QuickBird satellite imagery

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SUMMARY

This study develops an expedient digital mapping technique using Very High Resolution satellite imagery to monitor the temporal response of permanent wetland vegetation to changes in spring flow rates from the Australian Great Artesian Basin at Dalhousie Springs Complex, South Australia. Three epochs of QuickBird satellite multispectral imagery acquired between 2006 and 2010 were analysed using the Normalised Difference Vegetation Index (NDVI). A regression of 2009 NDVI values against vegetation cover from field botanical survey plots provided a relationship of increasing NDVI with increased vegetation cover ($R^2 = 0.86$; $p < 0.001$). On the basis of this relationship a vegetation threshold was determined (NDVI $\geqslant$ 0.35), which discriminated perennial and ephemeral wetland vegetation from surrounding dryland vegetation in the imagery. The extent of wetlands for the entire Dalhousie Springs Complex mapped from the imagery increased from 607 ha in December 2006 to 913 ha in May 2009 and 1285 ha in May 2010. Comparison of the three NDVI images showed considerable localised change in wetland vegetation greenness, distribution and extent in response to fires, alien vegetation removal, rainfall and fluctuations in spring flow. A strong direct relationship ($R^2 = 0.99$; $p < 0.001$) was exhibited between spring flow rate and the area of associated wetland vegetation for eight individual springs. This relationship strongly infers that wetland area is an indicator of spring flow and can be used for monitoring purposes. This method has the potential to determine the sensitivity of spring wetland vegetation extent and distribution to associated changes in spring flow rates due to land management and aquifer extractions. Furthermore, this approach is timely and provides reliable and repeatable monitoring, particularly needed given the projected increased demand for groundwater extractions from the GAB for mining operations.

1. Introduction

The Australian Great Artesian Basin (GAB) is one of the largest artesian basins in the world, containing an estimated 64,900,000 GL of water within a confined aquifer. The GAB underlies approximately 1.76 million km^2 (22%) of the Australian continent, encompassing a number of states and territories (Queensland, New South Wales, South Australia and the Northern Territory) (Gotch et al., 2006). The GAB supports a unique and diverse range of wetland ecosystems termed GAB springs, formerly known as mound springs, which contain a number of rare and relic endemic flora and fauna (Fensham and Fairfax, 2003; Framenau et al., 2006; Gotch et al., 2008; Ponder, 2004). The GAB springs are of great national and international importance for their ecological, scientific and economic values, and are culturally significant to indigenous Australians (Ah Chee, 2002). They also provide a vital source of water in the arid inland heart of Australia (Badman et al., 1996; Boyd, 1990; Mudd, 2000). The GAB springs are considered threatened ecosystems and a number of their endangered plant and animal species are protected by Australian national environmental protection and conservation legislation. In recent decades the ecological sustainability of the springs has become uncertain as demands on the GAB for this precious water resource increase. The eco-hydrogeological impacts of existing water extractions for mining and pastoral activities, along with their land use impacts are unknown. This situation is further compounded by the likelihood of future increasing demand for extractions, particularly from proposed mining and petroleum activities.

Despite the importance of the GAB springs, few have been documented in terms of water flows or wetland vegetation extent and composition: accurate, repeatable and cost-effective methods for inventory and monitoring are required for these remote and spatially dispersed ecosystems. Previous mapping and monitoring of wetland vegetation associated with selected mound springs in

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South Australia has relied on visual interpretation and classification of aerial photography, combined with considerable field work (BHP Billiton, 2009). Williams and Holmes, (1978) developed a method of estimating discharge from springs at the Dalhousie Springs Complex (DSC) using aerial photography, current meter and bucket and stop-watch measurements. However, these approaches are time consuming and site specific, and also particularly limiting for discriminating wetland from dryland vegetation. The advancement in remote sensing technologies means that mapping and monitoring using satellite imagery is now achievable and cost effective. A remote sensing approach has the potential to provide an expedient, reliable and repeatable method which can cover the broad spatial extent needed to capture these disparate groundwater dependent ecosystems in the arid landscape.

The study presented in this paper forms part of a larger research program, Allocating Water and Maintaining Springs in the Great Artesian Basin, that is developing new tools for monitoring GAB spring sensitivity to water allocations and land use in South Australia and the Northern Territory. The remote sensing component of this program is developing a suite of new advanced remote sensing methods for mapping and monitoring the wetland vegetation supported by the groundwater-fed GAB springs, to identify potential impacts of aquifer water extractions (White and Lewis, 2009, 2010a,b,c). The current paper provides a pivotal contribution to this wider program by linking GAB surface flows with their groundwater-dependent wetland ecosystems using advanced remote sensing techniques.

In this paper, we develop an expedient method for determining the response of GAB spring perennial wetland vegetation to changes in spring flow rates using Very High Resolution (VHR) digital satellite imagery. Particular objectives are to delineate the extent and distribution of perennial wetland associated with the springs, to discriminate this from ephemeral wetland and surrounding dryland vegetation, to quantify changes in the wetlands over time and to relate the extent of wetland vegetation to spring flow rates. This approach will provide a reliable and repeatable methodology to assess the temporal dynamics of mound spring wetland vegetation associated with changes in spring flow rates, which can be used for groundwater allocation plan management decisions and associated policies.

1.1. Study area

The Dalhousie Springs Complex (DSC) is located at latitude −26.45° and longitude of 135.51°, 50 km south of the Northern Territory (NT) border and 50 km west of the western edge of the Simpson Desert in South Australia (SA) (Fig. 1). The DSC traverses a region of approximately 19,000 ha, with average climate conditions at Oodnadatta airport SA (latitude: −27.56; longitude: 135.45, 100 km south of DSC, the closest Australian Bureau of Meteorology automatic weather station providing synoptic climatological data; Fig. 1) of mean annual rainfall 179.4 mm, maximum mean annual relative humidity of 44%, and maximum annual average temperatures ranging between a minimum of 19.6 °C in July and maximum of 37.8 °C in January. The DSC is selected for this study because of its ecological and conservation importance within South Australia, Australia and internationally, and because it includes the most extensive and diverse spring-fed wetlands in the GAB. The GAB spring wetlands are listed collectively as threatened ecological communities, and many of their endangered plant and animal species protected under the Australian Environmental Protection and Biodiversity Conservation Act 1999 (Department of Sustainability, Environment, Water, Population and Communities, 2011). DSC is included in the Australian Government Register of the National Estate and the National Heritage List and is also protected by its inclusion in the Witjira National Park in 1985. Within the DSC there are 30 endemic, relict or rare species of significance listed (Gotch, 2005). The springs at Dalhousie are a permanent historical source of water and are therefore important features in the landscape for indigenous Australians, in particular to the traditional Irrwanyere owners. Their long-term use is evidenced from many *Altyerre* (Lower Southern Arrernte word for traditional lore and customs) and extensive archaeological deposits (Ah Chee, 2002; Gotch et al., 2006; Department for Environment and Heritage, 2009). The DSC and surrounding region are also currently under threat from proposed extensive GAB aquifer water extraction associated with mining activities in the surrounding NT and SA regions.

The hydrogeology of the DSC consists of several main aquifers within several distinct geological units of Jurassic and Cretaceous age. The aquifer ranges in thickness from approximately 250 m in SA up to 1000 m in the NT (Love et al., 2000; Matthews, 1997), overlain by regional aquitard shales with maximum thickness of 400 m (Habermehl, 1980; Herczeg and Love, 2007). At DSC the confined Algebuckina Sandstone aquifer (depths of 50–200 m) is brought near the surface by the mid-Cainozoic Dalhousie anticline and the artesian flow is focused along a series of faults that breach the anticline's eroded crest (Clarke et al., 2007; Krieg, 1985, 1989; Williams and Holmes, 1978). The 148 springs at DSC (Gotch unpublished data) are supported by the natural outflow of the GAB at an estimated 54 ML/day along these north–northeast trending faults (Gotch et al., 2006; Williams and Holmes, 1978). In the geological time frame, the springs are dynamic, with abundant evidence of cyclic waxing, waning and extinction, but previous work has also documented considerable short term fluctuation in flow (Harris, 1992; BHP Billiton, 2009; Ponder et al., 1989).

The region around the springs at Dalhousie is dominated by extensive stone-covered clay plains, known as gibber, which support sparse low herb vegetation dominated by chenopodiaceous species, typically with a more open than vegetated surface (Boyd, 1990; Purdie, 1984). Smaller areas of limestone pavement also support sparse herbaceous vegetation, saline flats have restricted halophytic vegetation and some ephemeral rain-fed creeks and floodplains support a richer flora of perennial shrubs, trees (*Acacia* spp. and *Eucalyptus* spp.) and a range of herbs (Boyd, 1990).

The surface geomorphological formation of the DSC GAB springs comprises travertine mounds and terraces, soft sand/silt mounds, seeps and soaks (Fatchen and Fatchen, 1993; Gotch et al., 2006). Individual springs are defined as surface outlets where artesian water discharges and consist of several components: the vent, the mound and the tail. The vent is an area where water issues from the ground; it can vary in form from an active spring with pool of open water, either circular or elongate in shape, to a damp soak. GAB spring mounds are defined as a wet region immediately surrounding the vent (Clarke et al., 2007; Fatchen and Fatchen, 1993; Gotch et al., 2006). Many of the GAB spring mounds at DSC have formed from the precipitation of dissolved solids present in the groundwater along with both the deposition of particles derived from the aquifers, and the trapping of aeolian sand and silt in the vegetation that often grows on the mounds (Gotch et al., 2006; Krieg, 1989). Mounds at DSC are low features attaining heights of 6 m and widths of 180 m and consist of autochthonous materials (largely carbonates, sulphates, and oxides–hydroxides of iron and manganese) precipitated by the spring waters and allochthonous materials (sand, mostly quartz with minor feldspar, and clay with some carbonate) (Clarke et al., 2007). The tail results from the outflow of spring water away from the vent, which can take the form of a single channel, braided multiple interconnecting channels, or a uniform flow radiating out from the vent (Clarke et al., 2007; Fatchen and Fatchen, 1993; Gotch et al., 2006).

Biologically, the GAB springs represent unusually specialised aquatic habitats, their discontinuity being analogous to islands and the isolation just as great for species with limited dispersal

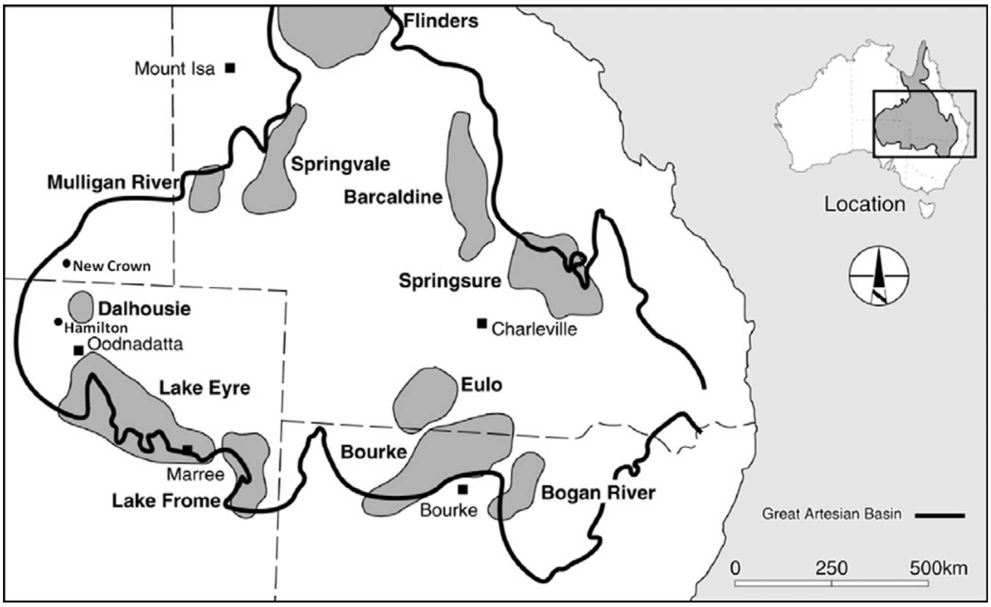

Fig. 1. Location of Great Artesian Basin showing principal areas of spring activity and Dalhousie Springs Complex study area (modified from Habermehl, 1980; Ponder, 1986; Harris 1992).

abilities (Harris, 1992). The vegetation of the spring mounds, tails and intervening country exhibits complexity in both plant species composition and the spatial distribution of species and plant communities. The wetland communities of DSC are the most extensive, diverse and best developed of the artesian-fed ecosystems in arid Australia. While open-forests and woodlands of *Melaleuca glomerata* (white tea-tree) are the most conspicuous vegetation type, *Phragmites australis* reed beds are by far the most dominant vegetation at DSC in terms of aerial extent and biomass (Gotch et al., 2006). The spring-related vegetation also includes rushes (*Juncus* spp.), numerous species of sedges including *Baumea* spp. and *Cyperus* spp. and the bulrush, *Typha domingensis*. On the saline flats adjacent to the springs *Nitraria billardierii* (nitre bush) shrublands occur, while at locations further from the mounds, *Halosarcia* spp. (samphire) shrublands are widespread. A range of shrub species occur less frequently in the spring wetlands, including *Acacia* spp., *Eremophila longifolia*, *Pittosporum phylliraeoides* and *Senna* spp. The surrounding drylands carry very low open shrubs and herbs including the chenopodiaceous *Atriplex* spp. (saltbushes), *Maireana* spp. (bluebushes) and *Sclerolaena* spp. (Gotch et al., 2006; Mollemans, 1989). In general terms, dense stands of *Melaleuca* occur closest to spring outflows and vents, giving way to extensive stands of *Phragmites* in the upstream permanent swamps, and sparser communities of rushes and sedges on the furthest reaches of the flows. These terminal fringes of the wetlands are often ephemeral in nature as spring flow fluctuates over time.

Although the wetlands in the DSC largely comprise indigenous species, many restricted in their distribution in central Australia, date palms (*Phoenix dactylifera*) were planted at the site in 1899 and subsequently spread to many of the springs. The date palms are considered an invasive species, since they out-compete the native flora and disrupt the ecosystem, resulting in extinctions of spring endemics and a notable reduction in the biodiversity of the springs. Controlled management of the date palms since 1986 has included mechanical removal and controlled burning (Gotch et al., 2006; Department for Environment and Heritage, 2009). Because the DSC lies within Witjira National Park, the wetlands and surrounding dry vegetation are not grazed by domestic stock, although limited feral populations of camels, wild horses and donkeys migrate through the area (Department for Environment and Heritage, 2009).

2. Data and methods

2.1. Data collection and pre-processing

2.1.1. QuickBird image data and pre-processing

Three epochs of QuickBird VHR multispectral satellite imagery were acquired to explore the temporal dynamics of DSC spring wetland vegetation: 26 December 2006 (archival imagery), 6 May 2009 and 10 May/10 June 2010 (new acquisitions). The images have ground sample distance (GSD) resolution of 2.4 m in three visible (654.0 nm – red; 546.5 nm – green; and 479.5 nm – blue) and one near-infrared (814.5 nm) wavebands. The images were provided partially orthorectified (coarse terrain corrections and projected to a constant base elevation) and partially radiometrically corrected (DigitalGlobe, 2009). Positional errors were less than 10 m, although further image-to-image co-registration was performed as part of subsequent change analysis. Further radiometric correction, to convert the images to apparent surface reflectance, was conducted using a modified MODerate spectral resolution atmospheric TRANSmittance (MODTRAN) algorithm, Fast Line-of-sight Atmospheric Analysis of Spectral Hypercubes (FLAASH) in the Atmospheric Correction Module of ENVI 4.7 remote sensing software (DigitalGlobe, 2009; Cook et al., 2009). The QuickBird scene tiles for each of the image epochs were subsequently colour balanced and mosaicked to give full seamless coverage of the DSC study area. ENVI V.4.7 software (ITT Visual Information Solutions, Boulder, CO) was used for this and subsequent image analysis.

2.1.2. Vegetation data

A botanical vegetation survey of sample plots was conducted at DSC in March 2009, as part of a more comprehensive field campaign to validate satellite and airborne imagery (White and Lewis, 2009, 2010a,b,c). Vegetation cover and composition were recorded within sample plots of 9×9 m (Fig. 2), designed to allow for geolocation errors and geometric accuracy of the imagery, as well as the scale of vegetation stands and variation. A total of 10 sample plots were recorded, representative of the range of vegetation types and cover within the DSC springs complex. Relative vegetation cover values were recorded for each sample plot based on a

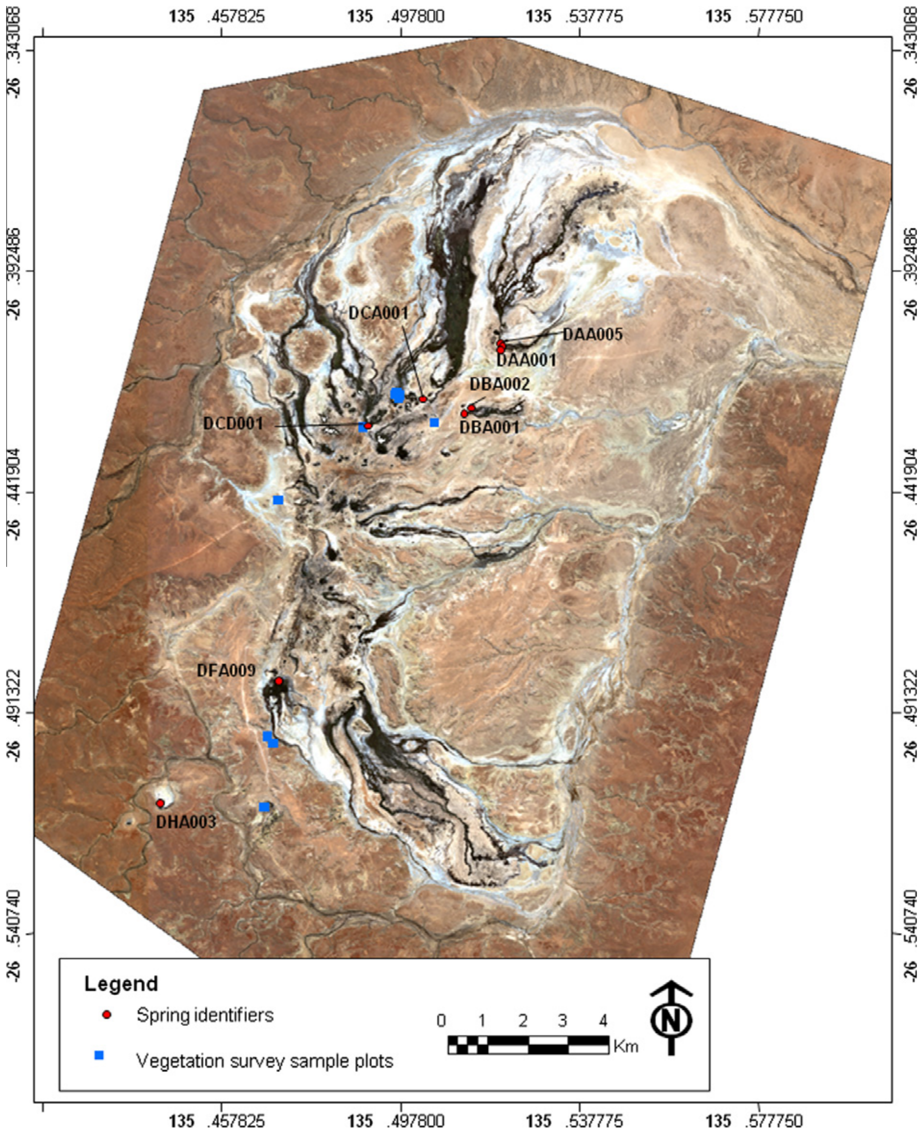

Fig. 2. Dalhousie Springs Complex study area, including location of vegetation survey plots and identification of key springs.

modified version of the Braun–Blanquet relevé method (ASTM, 2008) and the cover classes suggested for use in wetland delineation by Tiner (1999). Voucher herbarium specimens of wetland plants were also collected to botanically identify all species present. Differential GPS locations were recorded at the corners of the survey plots to enable their later identification on the imagery.

In addition to this vegetation survey, detailed knowledge of the distribution of DSC springs, wetland communities, their management and history was provided by ecologists who have studied the site in recent years (Pers. Comm. T. Gotch). This information assisted interpretations of the imagery and environmental change.

2.2. Ancillary data

2.2.1. Digital elevation data

Shuttle Radar Topography Mission (SRTM) ~30 m Digital Elevation Model (DEM) Australian 2010 release was obtained for the study area and analysed in ArcGIS using hydrology tools. The Australian 2010 release of the SRTM DEM has an absolute vertical accuracy relative to the Australian Height Datum of 7.582 m at the 95th percentile. The DEM-S, with adaptive smoothing applied to reduce noise and improve representation of surface shape, has vertical accuracy of approximately ±5 m and a horizontal accuracy of within ±7.2 m for 90% of tested areas (Gallant and Tickle, 2010; Gallant, 2011). The SRTM DEM-S data were compared with dGPS data acquired at DSC, providing a correlation of 0.96 and an RMSE of 1.32 m between the two data sets. The DEM was analysed to identify flow paths, flow accumulation and localised catchments, which were then aggregated to provide a discharge-based boundary to delineate spring-related groundwater flows from rain-fed streams and upland areas (Fig. 3). This method provided an objective means of identifying wetland vegetation associated with spring groundwater flows and excluding non-spring ephemeral or dryland vegetation from calculations of wetland area. Furthermore, this boundary provided a consistent basis for comparing year on year changes in wetland extent for the DSC.

2.2.2. Digital colour aerial photography

Digital colour (red, green, blue) aerial photography at 0.3 m GSD was acquired in March 2009 for the entire DSC study area. The high resolution photography was used to assist with interpretation of the wetland extent output from the QuickBird image analysis.

2.2.3. Groundwater discharge and rainfall data

Weir flow gauge data were obtained from the South Australian Department of Environment and Natural Resources (DENR) for four

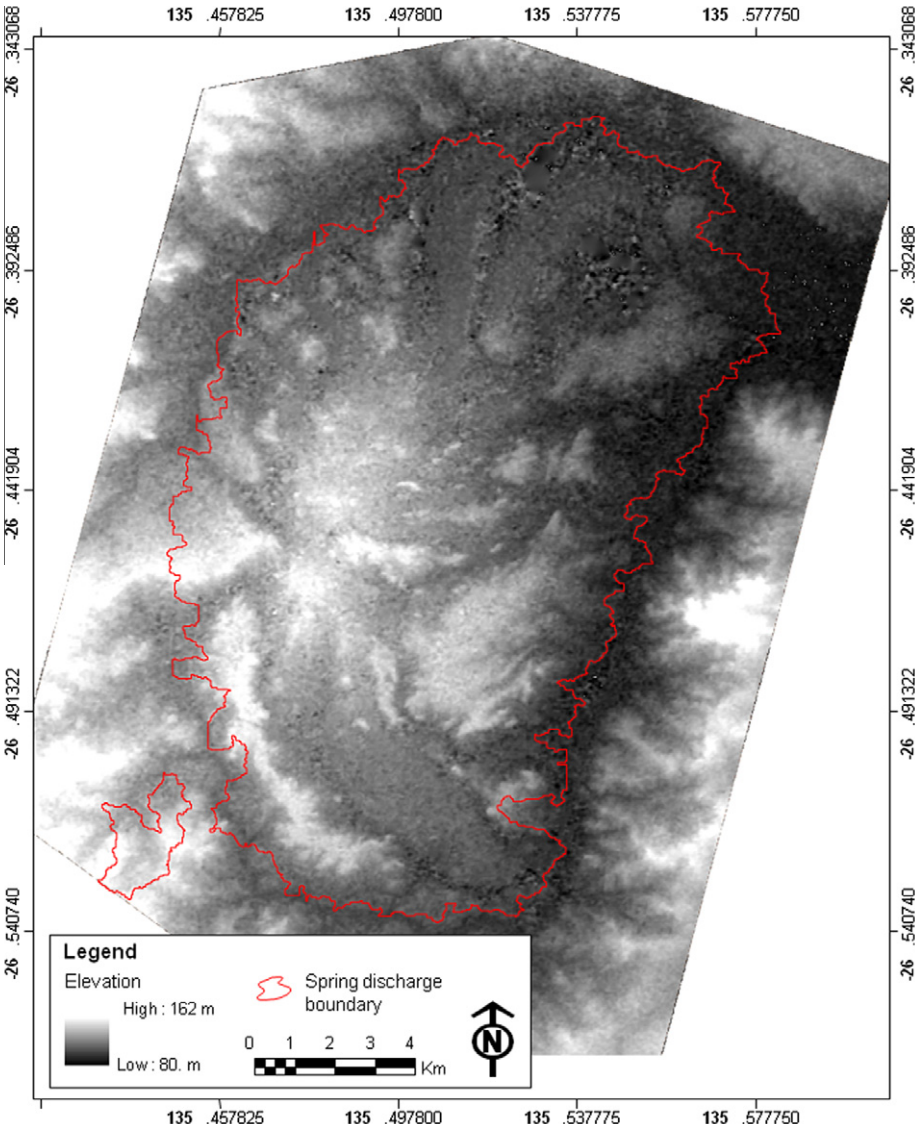

Fig. 3. Shuttle Radar Topography Mission (SRTM) Digital Elevation Model (DEM) covering the DSC study area. The red line is a discharge-based boundary delineating spring-related groundwater flows from rain-fed streams and upland areas. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

weirs at DSC (located at springs DBA001, DCA001, DAA001, DCD001[1]) (Fig. 2). This data consisted of current meter records taken on a biannual basis from October 1997 to present. Salt dilution gauge data for three additional springs (DBA001, DBA002, DAA003, DHA003) (Fig. 2) were obtained in July 2009 (Pers. Comm. B. Wolaver). Monthly total rainfall data were obtained from the Australian Bureau of Meteorology weather stations, which record rainfall data, geographically closest to DSC: Hamilton Station, SA (latitude: −26.71; longitude: 135.08, 50 km southwest of DSC) and New Crown in the NT (latitude: −25.68; longitude: 134.83, 100 km northwest of DSC) (Fig. 1).

2.3. Image analysis

The QuickBird imagery was initially analysed to establish the capability of multispectral VHR (2.4 m) satellite scenes capturing a large area (the entire DSC) to accurately map wetland extent.

[1] Spring nomenclature follows that adopted in the Allocating Water and Maintaining Springs in the Great Artesian Basin program.

2.3.1. Delineating wetland extent using NDVI

The Normalised Difference Vegetation Index (NDVI – (Rouse et al., 1974; Tucker, 1979), a widely used vegetation index (Lu et al., 2003; Weiss et al., 2004) which provides a measure of vegetation greenness, was applied to each of the three epochs of QuickBird imagery. The NDVI exploits the strong contrast between red and infrared reflectance (R), which in the case of the QuickBird imagery is recorded by wavebands 654.0 nm and 814.5 nm, respectively, and takes the following form:

$$\mathrm{NDVI} = \frac{R_{914.5} - R_{654}}{R_{914.5} + R_{654}} \qquad (1)$$

The NDVI images were spatially subset using the discharge-based boundary GIS file derived from the SRTM DEM to delineate spring-related vegetation and provide a consistent basis for comparing changes in wetland extent between the three epochs of QuickBird imagery (Fig. 3). To determine the relationship between QuickBird image NDVI values and percentage vegetation cover a regression analysis was performed of May 2009 NDVI image pixel values against vegetation cover in corresponding 9 × 9 m field sample plots. From this relationship an NDVI threshold was determined which separated wetland vegetation from dryland sites.

2.3.2. Temporal dynamics of wetland extent

Further analysis was conducted to ascertain the temporal dynamics of wetland vegetation extent for the entire DSC and for three springs known to be influenced by land management practices and changes in flow rates (DCA001, DFA009 and DAA001). Change detection analysis of the three NDVI images was performed in ENVI 4.7 using the Spectral Processing Exploitation and Analysis Resource (SPEAR) change detection tool. The three NDVI images were accurately co-registered, with nearest neighbour resampling used to preserve NDVI image values. Pairs of images were compared: December 2006 with May 2009 and May 2009 with May/June 2010. Interpretation of relative change in NDVI between the three images was facilitated by multi-date colour image display: the first image epoch was displayed as red and the second image epoch displayed as cyan. Areas increasing in NDVI appear as cyan, while decreases in NDVI display as red. These colours were used to highlight potential areas of change in wetland greenness, distribution and extent over the three image epochs.

2.3.3. Associating spring flow rates with wetland extent

We explored the potential of the image-based digital mapping technique to be used as an estimate for spring flow rates. Establishing a relationship between individual spring wetland extent and groundwater flow rates provides a potential technique for monitoring changes in spring flows associated with changes in aquifer pressure. Williams and Holmes (1978), using black and white aerial photography and manual planimeter measurements, purported that the flow rate from springs was directly proportional to the area of wetland vegetation supported.

Seven individual springs, providing eight flow records (weir gauge and salt dilution gauge measurements were collected for spring DBA001), for which discharge data were available were selected for comparison of spring flow rate and wetland area. The wetland area associated with outflow from each spring was delineated by heads-up digitising on the NDVI threshold imagery. Where springs were interconnected, their associated wetlands were distinguished using a suite of ancillary data: spring vent dGPS coordinates (Gotch, 2010), proximity to spring flow monitoring GPS locations, and expert knowledge of the DSC (Pers. Comm. T. Gotch). The polygons produced from the digitising were intersected with the NDVI wetland extent image to produce accurate delineations of wetland extent for the springs of interest. The area of each spring was also computed. This delineation of individual spring wetland areas was conducted for each of the three epochs of QuickBird imagery.

To determine the relationship between groundwater flow rate from springs and the area of perennial wetland vegetation supported by them, a regression analysis was performed. The discharge records used for the regression were selected as close as possible to the time of capture of the three epochs of QuickBird imagery. The mean and first standard deviation were computed for both discharge and wetland areas from the three dates of measurement: December 2006, May 2009 and May 2010.

3. Results and discussion

3.1. Delineating wetland extent

The vegetation communities indicative of the DSC are well differentiated in terms of percentage cover, estimated in the field sample plots, and NDVI derived from the May 2009 QuickBird image (Fig. 4). Dryland vegetation exhibited the lowest NDVI values with means ranging between 0.11 and 0.32. Ephemeral wetland vegetation, including spring tails, and the fringes of perennial wetland vegetation stands have moderate NDVI values (means 0.37–0.51), while the perennial wetland samples composed of tall, dense, homogenous stands of *P. australis*, *P. dactylifera* (date palms) and *M. glomerata* (white tea-tree) exhibit relatively higher NDVI values ranging between 0.56 and 0.73. NDVI values exhibit a range of variability within the sample plots with generally low variation for arid vegetation (sd ⩽ 0.07), and much greater variation for the edges of perennial wetland stands (sd ⩽ 0.15) and dense homogenous stands of date palms (sd = 0.15).

The distinct differences in NDVI and cover of the different vegetation types evident in Fig. 4 can be attributed to the contrasting canopy structure and growth patterns between these communities. The dryland vegetation is low, extremely sparse and during late summer (time of vegetation sampling) and late autumn (the acquisition time for the 2009 QuickBird imagery) largely non-photosynthetic, resulting in low vegetation cover (<25%) and corresponding low mean NDVI (a measure of vegetation greenness; 0.11–0.32). The extremely sparse cover and non-photosynthetic nature of the arid vegetation also accounts for the low variation between NDVI values within the sample plots.

The ephemeral wetland vegetation, primarily associated with the spring tails and the fringes of the perennial wetland vegetation, presents as heterogeneous stands with a more complex canopy structure and range of vegetation types. The vegetation shows some photosynthetic activity (higher mean NDVI) because of proximity to spring flows. The vegetation plots have similar moderate mean NDVI values, and sparse to moderate cover (25–50%). The more varied NDVI values (sd = 0.15) for the perennial wetland fringe plots potentially result from the sporadic and sparse nature of the vegetation cover and the more complex canopy structure associated with homogenous stands of reeds and reeds mixed with salt couch grass. Furthermore, NDVI can become less reliable at lower levels of vegetation cover and with increased soil moisture, which is evident within these wetland environments.

The perennial wetland samples include three quite different vegetation types: homogenous stands of reeds (*Phragmites*) have lower mean (<0.60) and less variable NDVI values, while tea-tree and date palm tree stands in particular have higher mean (>0.60) and more variable NDVI. The relative difference in NDVI between dense homogenous tree canopies and reed stands can be explained by the multiplicative effect of reflectance and transmittance of light between leaves/fronds and branches within the tree canopies, particularly in the NIR wavelength region (Campbell, 2008; Horler

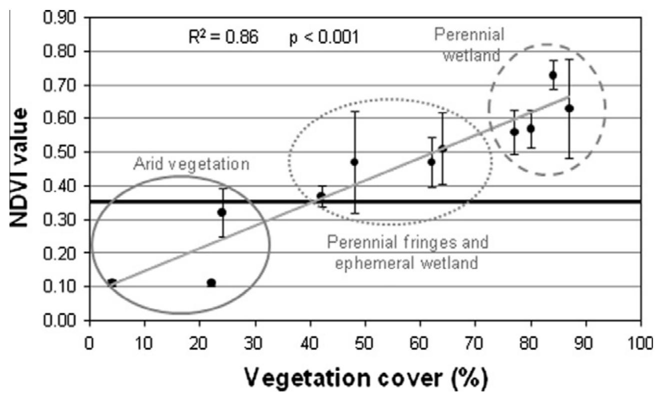

Fig. 4. Regression of Normalised Difference Vegetation Index (NDVI) values against vegetation cover in 11 sample plots representative of vegetation types at DSC. The black line represents 0.35 NDVI threshold value. Vertical bars represent the variation (±first standard deviation) in NDVI values.

et al., 1983), which is received by the QuickBird sensor. The layering of leaves and branches is somewhat reduced for reed stands, which are generally not as tall, with no branches and narrower/smaller leaves, in comparison to the tree canopies. Variation in the standard deviation around the mean NDVI values was particularly notable for date palms at ±0.15, which can be explained by considerable variation in canopy structure (position and angle of fronds, dryer understory of dead fronds, different tree heights) for this vegetation type.

A strong linear relationship can be established between the field estimates of vegetation cover and NDVI (Fig. 4). 86% of the variation in image NDVI values is explained by the percentage cover of the sample plots ($R^2 = 0.86$, $p < 0.001$), indicating that NDVI is a useful surrogate for plant cover in this context. On the basis of this relationship a threshold of 0.35 was established, above which NDVI values were considered to be indicative of wetland vegetation. Implementing this threshold also enabled discrimination of perennial and ephemeral wetland vegetation from dryland vegetation.

3.2. Temporal dynamics of wetland extent

The mapping of wetlands derived from the NDVI threshold applied to three epochs of QuickBird imagery (Fig. 5) is the first comprehensive and objective documentation of the extent and distribution of wetlands associated with the 148 springs within DSC. The majority of springs occur in a central zone, roughly following the north–northeast line of faults in the crest of the Dalhousie anticline, as described by Williams and Holmes (1978). Wetlands associated with springs in the northern part of the complex follow lines of flow to the north, northeast and east, with much interbraiding of flow paths. The largest springs and wetlands occur in this northern zone. Wetlands associated with springs in the southern part of the complex extend along lines of flow to the south and southeast. To the south west, an isolated group of small springs near the old Dalhousie Station ruins support wetlands extending to the southwest. Because the wetlands follow lines of outflow from the numerous spring vents, most are linear in form, extending up to 5 and even 10 km from source, with the most extensive wetlands close to the vents. The flow paths of the springs follow the surface landforms, with the spring flows often braiding into multiple channels.

Comparison of the three epochs of imagery indicates that the overall distribution of wetlands remained relatively stable, but with notable changes in some spring tails (Fig. 5). Total wetland area, calculated as area over the NDVI 0.35 threshold, increased from 607 ha in December 2006 (Fig. 5a), to 913 ha in May 2009 (Fig. 5b), and 1285 ha in May 2010 (Fig. 5c). Overall an increase is depicted in the extent of all springs from vent to tail over the three epochs of satellite imagery. The most notable change in wetland extent over this period is the extensive increase in the northern extremities of the main northern spring (DCA001) (Fig. 5).

The increase in total mapped wetland area of 306 ha from December 2006 to May 2009 and 372 ha between May 2009 and May 2010 can be explained by the interplay of several processes: seasonality, rainfall and climatic conditions, and vegetation regeneration in response to disturbance. Antecedent rainfall (Fig. 6) has an influence on overall wetland greenness and area. Conditions prior to the November 2006 image were dry, particularly from August 2006, and the area of wetland mapped at this time was the lowest. By contrast, extremely high rainfalls occurred in the six months preceding the May 2009 and May 2010 images. Major rains fell in November/December 2008 (65 and 45 mm at Hamilton; 72 and 40 mm at New Crown), with follow-up rains in March–May 2009. Similarly, very high rainfall events occurred in November/December 2009 and February 2010, with monthly totals of 32, 77.5 and 43.5 mm at Hamilton and 10, 20 and 96.4 mm (New Crown). The wetlands showed marked increases in area after these high rainfalls. In addition, seasonal changes in wetland vegetation growth are a further contributor to the differences documented here. The greenness and extent of the wetlands fluctuate markedly throughout the year, and are at a maximum in May (Petus et al., in review), the conditions captured by the 2009 and 2010 images, whereas plant growth is less extensive in November.

The most marked changes in the NDVI threshold wetland extent over the 3.5 year study period are evident at the spring tails. Three springs, DCA001, DFA009 and DAA001 (Figs. 2 and 5), representative of the overall nature of change occurring between image dates, are highlighted and more detailed interpretation of the changes made to provide insights into the ecological processes taking place within these wetlands.

DCA001, the main spring within DSC, increased in area in the northern portion of its tail by 52.7 ha between December 2006

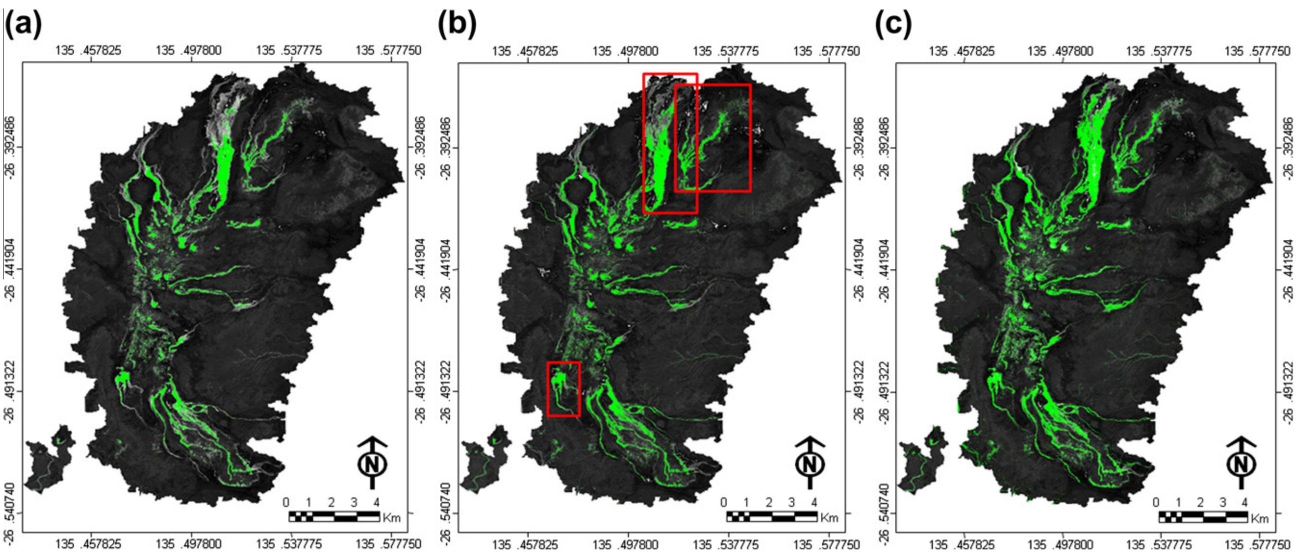

Fig. 5. Extent of wetland area, based on 0.35 NDVI threshold (green regions), for the three epochs of QuickBird imagery: (a) December 2006; (b) May 2009; and (c) May 2010. Red squares represent springs DCA001, DFA009, and DAA001 selected for change detection.

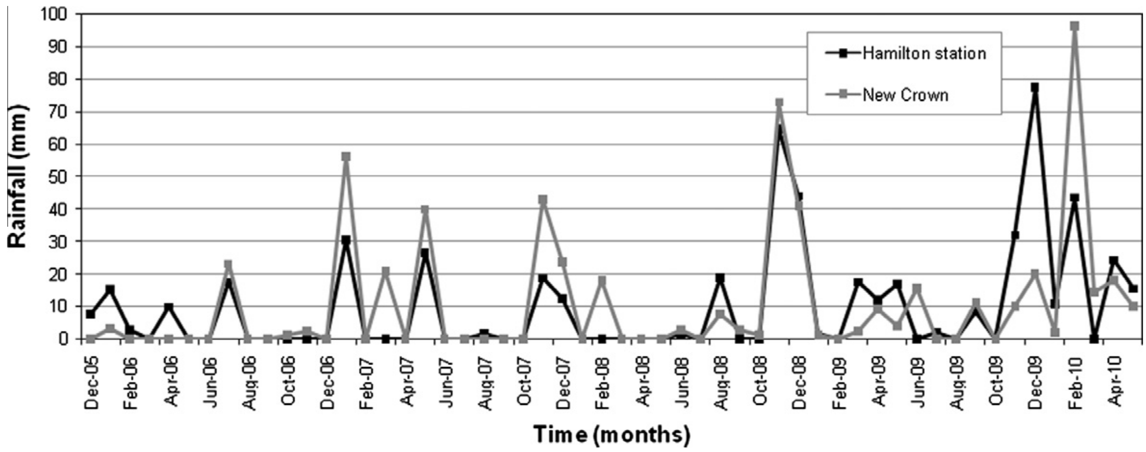

Fig. 6. Australian Bureau of Meteorology automatic weather station monthly total rainfall data for Hamilton Station and New Crown, recorded from December 2005 to May 2010.

and May 2009; and 86.8 ha between May 2009 and May 2010, as measured by the area of vegetation over the NDVI threshold of 0.35 (Fig. 7). The relatively smaller area for this spring in December 2006 (Fig. 7a) can be explained by an extensive fire caused by a lightning strike in early 2006 which burnt approximately ~200 ha of the wetland: field observations at the time confirmed the substantial decrease in vegetation at this very large spring. The northern extremities of DCA001 decreased in NDVI between 2006 and 2009, while there was some increase to the southeast and southwest (Fig. 7b). The main wetland area closer to the spring did not change in magnitude or distribution over this period. The increase in NDVI towards southeast and southwest extremities of the main spring are likely the result of greening up of samphire due to preferential surface water flow along this portion of the tail (confirmed with 2009 colour aerial photography). This may have also have been coupled with a diversion of flow along the northern extremities of the spring tail, resulting in the decrease in NDVI in this area. The diversion of flow is due to the build up of dense *Phragmites* (known to be present from field observations in 2009) making the transit of water to this area difficult.

Change between May 2009 and May 2010 for the DCA001 spring is quite pronounced with a notable increase in NDVI over the northern region of the spring tail and decrease over the central and southern region (Fig. 7c). The increases in NDVI are likely the

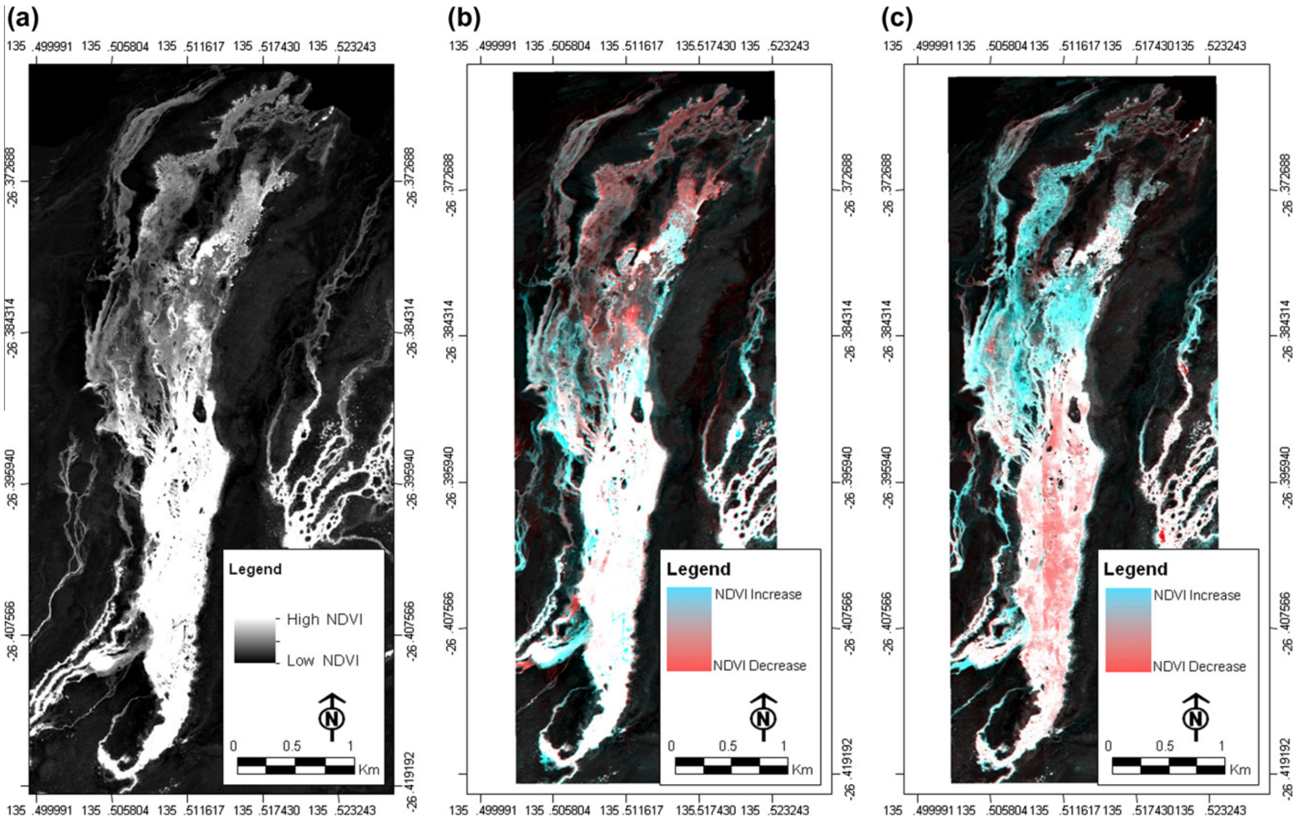

Fig. 7. Change detection and temporal dynamics of spring DCA001: (a) December 2006 NDVI image; (b) NDVI change between December 2006 and May 2009; and (c) NDVI change between May 2009 and May 2010.

result of new-growth vegetation, predominantly *Phragmites* (confirmed from colour aerial photography and field observations), in response to improved flows after the 2006 fire and two high magnitude rainfall events. The decrease in NDVI over the central and southern region is likely due to initial new-growth of vegetation occurring in this region between 2006 and 2009 (not captured on the imagery). This would lead to a drying and dying off of the *Phragmites*, which has a 4–5 year growth cycle (Roberts, 2011), corroborating with the burn date in early 2006. The drying of the dense *Phragmites* stands was confirmed with comparison of spectral profiles of reflectance between the 2009 and 2010 images for the *Phragmites* regions displaying a decrease in chlorophyll absorption (approximated to the red waveband at 654.0 nm in the QuickBird imagery).

Because spring DCA001 accounts for ~21% of the total wetland area at DSC the increases in vegetation following the 2006 fire (a 26% increase in vegetated area between December 2006 and May 2009) contributed substantially to the overall increase in wetland area for the whole DSC. Similarly, the 43% increase in area of this large wetland substantially contributed to the overall increase in total wetland area for the whole complex between May 2009 and 10 May 2010.

Spring DFA009 provides an excellent illustration of the short-term dynamic nature of vegetation on spring tails in the DSC. Overall the wetland increased by 7.5 ha from December 2006 to May 2009, and by 14.4 ha between May 2009 and May 2010. Change in the location of the spring main tail between December 2006 and May 2009 is depicted as adjoining narrow regions of increased and decreased NDVI along the fringes of the tail: the flow path generally moved west by 70–200 m (Fig. 8). Noteworthy regions of decreased vegetation vigour are also evident around the western and southern extremities of the densely vegetated spring head surrounding the spring vent. Continuing changes in the location of the spring tail, due to changes in the preferential flow path of discharge from the spring, are also highly visible between May 2009 and May 2010. Most notable is a general increase in NDVI throughout the spring tail, particularly on the eastern fringes and southern extremity of the wetland. Moreover, peppering of lower NDVI pixels within the vegetation surrounding the spring vent of spring DFA009 is also evident and likely due to overstorey shadow by *Melaleuca* or the presence of standing water.

Spring DAA001, in the northeast of DSC, is an example of more complex temporal changes in wetlands on a multiple-tailed spring. Overall the spatial extent of the wetland vegetation at DAA001 increased by 24.5 ha between December 2006 and May 2009 and by 19.7 ha between May 2009 and May 2010 (Fig. 9). Between December 2006 and May 2009 some increase in NDVI occurred at the extremities of two major tails towards the northern limit of the spring and in a minor tail located towards the southeast. The increase in vegetation growth is likely due to increased flow along the tails from the November 2008 rainfall or groundwater flows enabling greening-up of the adjacent dryland Nitre bush. Nitre bush appears to perform better in close proximity to springs where water and nutrients are more freely available (confirmed with 2009 colour aerial photography). Decreases in NDVI are evident on the north eastern extremity of the primary tail over the same period, which could potentially be caused by a continued reduction in preferential water flow along this tail. It is interesting to note that spring DAA005, adjacent to DAA001, exhibits an increase in NDVI between December 2006 and May 2009, which can be explained by regrowth of *Phragmites* over the increased flows following managed date palm removal in 2006.

A noticeable shift in the dynamics of the multiple spring tails for DAA001 is evident between May 2009 and May 2010, with a more pronounced extension (increased NDVI) of the second major northern tail and minor southeast tail. These changes exhibit the same trend and are likely caused by the same factors as those described for the 2006–2009 period. Increased NDVI is also evident at the central extremity of the primary tail surrounded by areas of reduced NDVI. This is probably the result of increased flows from the high rainfall greening-up the ephemeral vegetation in the central extremity of the tail but not reaching the flanks either side

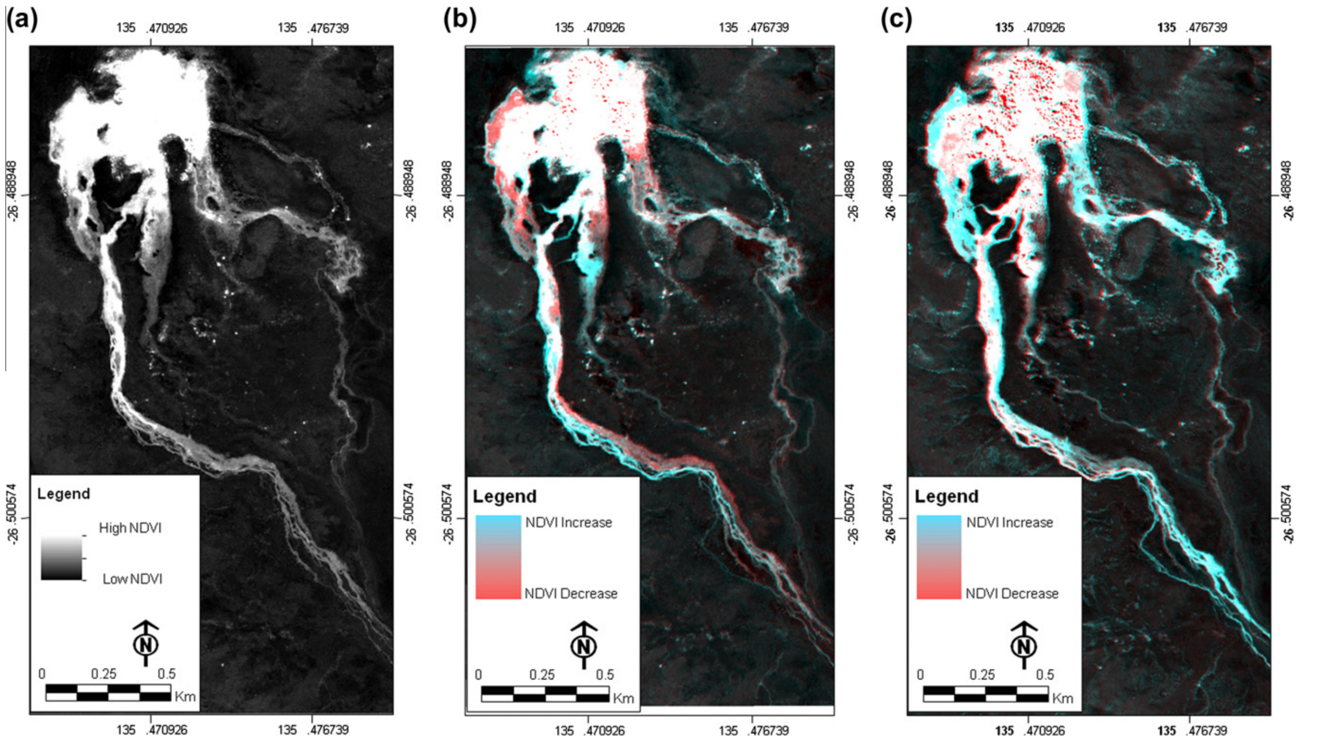

Fig. 8. Change detection and temporal dynamics of spring DFA009: (a) December 2006 NDVI image; (b) NDVI change between December 2006 and May 2009; and (c) NDVI change between May 2009 and May 2010.

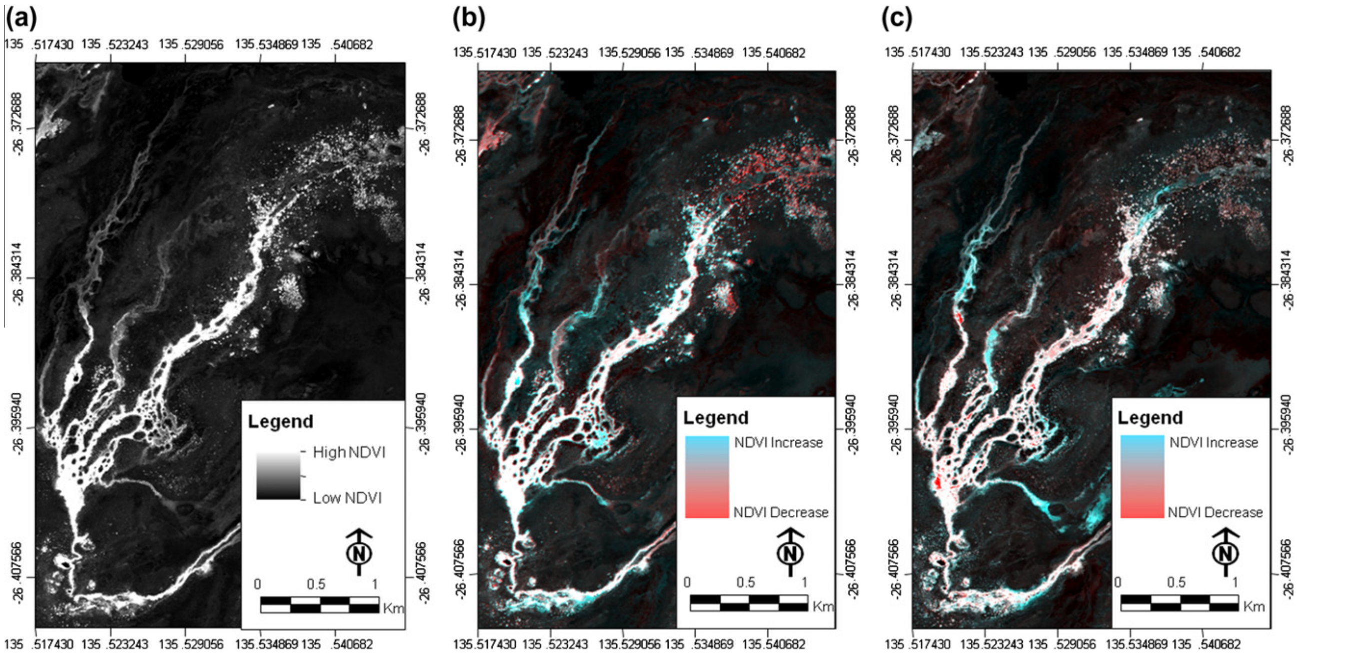

Fig. 9. Change detection and temporal dynamics of spring DAA001 and DAA005: (a) December 2006 NDVI image; (b) NDVI change between December 2006 and May 2009; and (c) NDVI change between May 2009 and May 2010.

where the nitre bush remained dry. The central northern tail remained changed little between May 2009 and May 2010.

3.3. Associating spring flow rates with wetland extent

There is a very strong positive linear relationship between spring wetland area and flow at the individual spring level ($R^2 = 0.99$, $p < 0.001$; Fig. 10). The regression relationship is:

$$y = 1.301x - 0.5191$$

where x is flow (L/s^{-1}) and y is spring wetland area (ha).

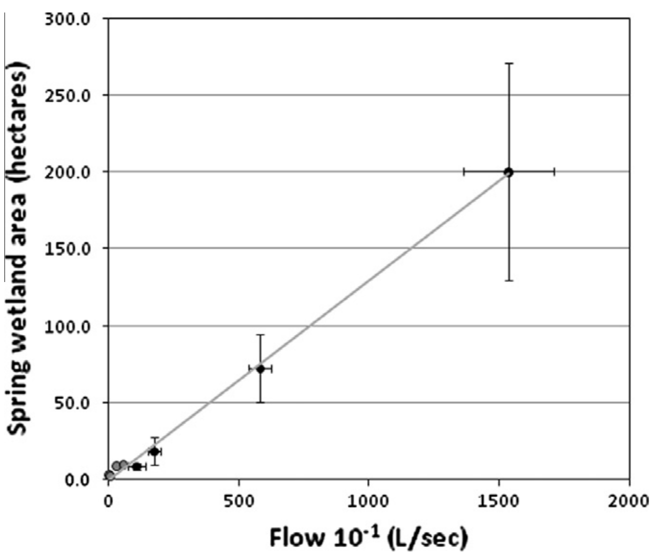

Fig. 10. Regression of eight Dalhousie Springs Complex spring wetland areas against groundwater flow rate. Grey data points represent salt dilution gauge data; solid black points represent weir gauge data. Horizontal bars represent variation (±first standard deviation) in spring flow over dates closest to satellite image capture. Vertical bars represent variation (±first standard deviation) in spring wetland extent over dates of satellite image capture.

Variability in the spring wetland area calculations are most likely due to the interplay of several factors: changes in wetland area over the 3.5 years of this study (resulting from fire, date palm removal and rainfall, as described in the previous section), seasonal changes in vegetation greenness, and relatively small variations in spring flow rates. Change in spring wetland area is greatest for the two largest springs, the main spring DCA001 (sd = 70.4 ha) and spring DAA001 with a standard deviation of 22.1 ha. Flow rates coinciding with the three epochs of QuickBird imagery exhibit relatively little variation, although the two largest springs also showed the greatest variation in flows (DCA001 sd = 172.5 L/s $\times$ 10^{-1}; DAA001 sd = 43.2 L/s $\times$ 10^{-1}). The apparent relatively low variation in spring flow rates could be a response to natural fluctuations in discharge from the GAB and the range of error associated with current meter and salt dilution gauge measurements (Carter and Davidian, 1989). Variability of discharge measurements is compounded at DSC and the South Australian GAB springs by the dynamic nature of the flow channels, which are often impeded by vegetation and difficult to access to obtain accurate measurements of a stable and reliable channel cross-section (Pers. Comm. V. Berens; Williams and Holmes, 1978).

The underlying relationship between spring wetland area and flow rates at DSC corroborates that developed previously by Williams and Holmes (1978), although they only investigated one epoch in time. This relationship is very significant, as it confirms the underlying premise of the larger research program of this study, that wetland area is an indicator of spring flow and can be used for monitoring purposes using remote sensing techniques.

3.4. Long-term trends at Dalhousie springs complex

The findings of this paper provide valuable insights into the botanical and hydrogeological dynamics of the DSC. Short-term changes in the extent of perennial spring wetlands are evident and can be explained by natural impacts (2006 lightning strike and fire) and management practices (date palm removal) leading to subsequent vegetation regrowth. Moreover, seasonal conditions

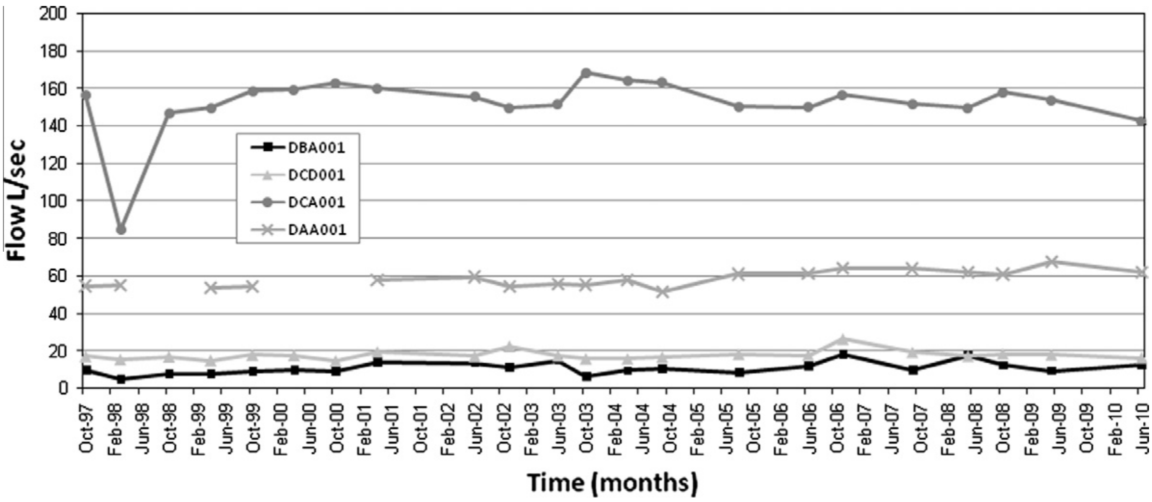

Fig. 11. Weir gauge groundwater flow rates for springs DBA001, DCA001, DAA001, DCD001, recorded from October 1997 to May 2010 at DSC.

and small variations natural flow also contributed to the short-term variability of perennial spring wetland extent.

The average total wetland area computed for DSC from the QuickBird imagery over the 3.5 years of this study is 935 ha, which corresponds well with the Williams and Holmes (1978) estimate of 880 ha over three decades ago. This earlier estimate is well within the range of short-term variation in wetland area that we have demonstrated, and points to longer term stability in spring flows and wetland extent. Differences between these two values could be explained by a number of contributing factors: (i) very high rainfall contributing to unusually abundant greening up of the wetland vegetation, particularly in 2010; (ii) the manual planimeter method used by Williams and Holmes (1978) for measuring the wetland area from black and white aerial photography may have limited accurate delineation; and (iii) the generalisation method and inclusion of open pools of water by Williams and Holmes (1978) may have reduced the accuracy of their wetland area estimates.

Weir gauge flow rates at the springs for which records are available from October 1997 to present (springs DBA001, DCA001, DAA001, DCD001), provide further evidence for long-term trends, with flow rates remaining relatively stable over this period (Fig. 11). Flow rates obtained from salt dilution gauge data (recorded in July 2009) were consistent with the weir gauge data (spring DBA001) and the regression relationship established with wetland area (springs DBA002, DAA003, DHA003). The increases in total wetland area mapped in the current study using QuickBird imagery corroborate well with the trend reported by Petus et al. (in review) over the same time periods (26 December 2006, 6 May 2010, 10 May/June 2010) with MODIS imagery. The greater overall increase in the total wetland area mapped from the QuickBird imagery, in comparison with the MODIS imagery (250 m GSD) is most likely due to differences in sensor resolution along with the inclusion of ephemeral wetland vegetation in our calculations.

4. Conclusions

This paper provides the first comprehensive, high resolution mapping of the distribution and extent of the DSC wetlands. As such, it provides information of potential value to ecologists, geomorphologists and hydrologists who seek to understand the DSC environment, its dynamics and history. Furthermore, the mapping, repeated over three years and under varying climatic conditions, provides a strong baseline for future monitoring of the wetlands at DSC.

The wetland vegetation patterns revealed are complex, with the major wetlands and interbraiding spring tails documented at high spatial resolution. Short-term changes in the area and distribution of perennial spring-fed wetlands are evident, influenced by ecological processes, vegetation management practices, seasonal conditions and natural flow variations. On-going monitoring of wetland area as an indicator of spring ecosystem status needs to acknowledge the strong influence of season and preceding rainfall on extent of the wetlands. Changes in total wetland extent derived from the QuickBird imagery marry well with the field botanical and rainfall records and knowledge of wetland vegetation phenology of the site. Further evidence of the trend over this period is provided by the findings of Petus et al. (in review) using MODIS imagery. Longer term stability in spring flow rates and wetland extent is reflected in the close corroboration of our average value for wetland extent and those estimated over three decades ago by Williams and Holmes (1978). Weir gauge measurements from 1997 to present provide further evidence for the relative stability of flow rates over this period.

This study has demonstrated and successfully applied a new approach to mapping and monitoring spring-fed wetlands in the GAB. A relationship has been developed between field measurements of vegetation cover and NDVI derived from Very High Resolution multispectral satellite imagery, indicating that NDVI can be used as a surrogate for vegetation cover over the range of arid and wetland vegetation types sampled at DSC. This relationship was based on a limited number of field and image samples because of the inhospitable terrain, dense vegetation and difficulty of access at some sites, and would be strengthened with the addition or more field samples. This relationship may vary somewhat over time under differing growth conditions. However, the linear relationship is not being used to calibrate the QuickBird NDVI to quantify percentage cover, but rather to identify an NDVI threshold for delineating spring wetlands from dryland vegetation. The greenness responses of the dryland and wetland vegetations are sufficiently different that the same threshold could be applied to the different dates of imagery. Establishment of NDVI – percentage cover relationships for different dates and greenness conditions in the wetlands would help confirm the generality of the threshold used.

The NDVI threshold derived from this relationship effectively differentiated the wetland vegetation, with higher NDVI, from the less green arid vegetation surrounding and interspersed with the springs. The effectiveness of the delineation based on this objective criterion was confirmed by interpretation of high-resolution aerial photography and the consistency of mapping over three image epochs. Relationships between NDVI, vegetation cover and other parameters such as biomass and Leaf Area Index have been developed previously for many land types and at different spatial scales (e.g. Rouse et al., 1974; Tucker, 1979). Here we have established a relationship that is specific to the arid wetlands of DSC and at a high spatial resolution appropriate to the scale of the communities.

A strong direct one-to-one relationship was identified between spring flow rate and wetland area, confirming that developed previously by Williams and Holmes (1978). However, our relationship is based on fuller and more objective data than the previous study: three epochs of closely coinciding flow and high resolution imagery and objective, digital mapping of wetland areas. The correspondence of our results for wetland extent and flow with Williams and Holmes (1978) findings and Australian Bureau of Meteorology rainfall data provide confidence in the use of wetland area as a monitoring surrogate for spring flow. These results indicate that NDVI threshold analysis of digital multispectral QuickBird imagery is a viable tool for mapping the extent of GAB spring wetland vegetation. Furthermore, this method has the potential to determine the sensitivity of spring wetland vegetation extent, distribution and diversity, to associated changes in spring flow rates due to land management and aquifer water extractions.

Once a strong relationship between image NDVI and field vegetation cover has been established for an epoch of imagery, 2009 in this instance, this calibration can be applied to other images captured at different dates without the requirement for further field work. This is a particular advantage of this approach and highlights its capability to expediently monitor changes in the wetlands over time.

The NDVI threshold, associating spring flows with wetland extent, and change detection techniques developed in this paper also have great potential for use not only at other GAB spring complexes within Australia but also to a range of GDEs. Further application of these techniques to other GAB spring groups and complexes would clarify whether the relationship between spring flows and supported perennial wetland vegetation and their temporal dynamics differs in other contexts. Holmes et al. (1981) have alluded that this indeed may be the case with differing responses for different spring groups. There is also sufficient flexibility in advanced remote sensing techniques developed in this paper that they could also be applied more widely to other important GDEs both nationally and internationally.

This research will ultimately help monitor the sensitivity of mound spring permanent wetland vegetation to water allocations, thus influencing and improving the effectiveness of ground water allocation plan management decision and associated policies. The techniques developed in this paper will provide a valuable tool to assist in monitoring the sensitivity of these GAB ground water fed springs to anticipated future water extractions in the region.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.jhydrol.2011.07.032.

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