Changing water system vulnerability in Western Australia's Wheatbelt region

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Abstract

Within a changing world where freshwater resources are coming under increasing pressure, assessing water system vulnerability is critical for enabling adequate water resource management. Quantitative assessments of socio-economic and environmental factors which contribute to water system vulnerability can provide a strong evidence base on which to base decision-making. A range of drivers including population growth, agricultural intensification and industrial activity are placing greater demand on freshwater supplies in Western Australia. In combination with changing climatic conditions resulting in a warmer and drier environment in southwest Western Australia, these pressures have diminished the quantity of available freshwater supplies for agricultural districts. In this paper we provide a quantitative assessment of water supply and demand vulnerabilities for the Wheatbelt region of the state of Western Australia (WA). This region provides significant agricultural and mi neral resource contributions to the state economy. The potable water supply for human consumption in this region is almost entirely drawn from a different geographic area, and conveyed by means of an extensive pi peline network to the Wheatbelt region. Competition for freshwater resources is high with increasing population pressures from expansion of the state's capital city, Perth, encroaching north- and eastwards into the Wheatbelt. To assess water vulnerability we conceptualise the water system components and select a series of socio-eco nomic and environmental indicators which best represent the inherent vulnerabilities associated with water supply and demand in the Wheatbelt. Water supply, demand and overall system vulnerabilities were spatially assessed for the years 2001, 2006 and 2011. Results indicate that biophysical indicators of supply capacity have the greatest influence on overall vulnerability for each time period, however the spatial variability of specific vulnerability factors is much more nuanced. Our assessment of water vulnerability will enable water resources managers and policy-makers within the Wheatbelt and at the state level to better assess water supply and de mand pressures. However, our robust methodology also allows for transferability to other locations experiencing water stress as a comprehensive approach for examining historic and future impacts of water resource avail ability on socio-ecological systems.

1. Introduction

Water availability is concerned not only with physical reserves of water, but also with the accessibility, use and sharing of water resources. Water availability plays a fundamental role in sustaining the environment, promoting wellbeing and providing opportunity for development, and is essential for attaining water, energy and food security (Biggs et al., 2015; Hoff, 2011). Exposure of the water system to shocks, stress, disturbance or increases in sensitivity can result in water resource vulnerability, and the ability of water system users to cope, recover or adapt following a disturbance to the system influences the magnitude of vulnerability (Adger, 2006; Turner et al., 2003). Although these aspects of social-ecological system functions are notoriously difficult to quantify and model, comprehensive analyses of vulnerability have been undertaken in many sectors, particularly for climate change (Preston, Yuen, & Westaway, 2011) and environmental hazards (Cutter, Boruff, & Shirley, 2003), but also with regard to agricultural systems (Sietz, Lüdeke, & Walther, 2011), livelihoods (Kok et al., 2016), water (Vörösmarty et al., 2010), and even phosphorus (Cordell & Neset, 2014). There is no universally accepted method for assessing the vul nerability of water resources, yet an integrated water vulnerability index has the potential to result in more effective social-ecological system function by addressing aspects of water scarcity, promoting sustainable development, providing information for decision-

making and enabling better disaster risk reduction strategies (Bitterman, Tate, Van Meter, & Basu, 2016; Sullivan, Cohen, Faurés, & Santini, 2008).

Consequently, this research develops a comprehensive framework using an integrated water vulnerability index to assess water system vulnerability in the Western Australian Wheatbelt. The framework was applied using a Geographic Information System (GIS) as an analytic tool, incorporating multiple socio-economic and environmental data sets to assess the spatial variability and temporal dynamics of water system vulnerability through components of supply and demand. The paper describes a conceptual framework and detailed methodology for assessing water vulnerability, and reports results for quinquennial change (2001–2011) in water system vulnerabilities across the study area. Our framework builds on existing published methods used to assess water vulnerability and incorporates locally relevant system in formation, providing a detailed and transferrable model that can be used in other regions as a planning tool for identifying key contributing factors to water system vulnerability.

2. Measuring water vulnerability

Assessment of water vulnerability has focussed on the vulnerability of water supplies to contamination (e.g. Doerfliger, Jeannin, & Zwahlen, 1999; Rupert, 2001), the vulnerability of physical water supply infrastructure (Chen, Niu, Bai, & Wang, 2014; Sahin & Stewart, 2013), and 'water stress' through the use of indicators comparing water withdrawals and surface water runoff (Jackson et al., 2001; Vörösmarty, Green, Salisbury, & Lammers, 2000). The need to include social, economic and institutional factors in water resource vulner ability assessment is gaining greater recognition as water security can be more closely tied to governance and management than to the phy sical abundance of water (e.g. Biggs, Duncan, Atkinson, & Dash, 2013; Cook, Fisher, Andersson, Rubiano, & Giordano, 2009; Kemp-Benedict et al., 2011; Pandey, Babel, Shrestha, & Kazama, 2010; Srinivasan, Lambin, Gorelick, Thompson, & Rozelle, 2012). However, socio-eco nomic factors are rarely considered in as much detail as biophysical factors even in 'integrated' water vulnerability assessment tools (Plummer, de Loë, & Armitage, 2012, 2013). Recent work has identified the possibilities of developing complex models of 'socio-hydrology' (Elshafei, Sivapalan, Tonts, & Hipsey, 2014; Sivapalan et al., 2014; Thompson et al., 2013) and mapping socio-hydrological vulnerability across space and time (Boori & Voženílek, 2014). However, as Bitterman et al. (2016) highlight, complex human-environmental in teractions, non-linear processes, and local geographies are all important considerations and often neglected when examining water security.

A recent systematic review (Plummer et al. (2012) identified at least 50 different integrated water vulnerability assessment tools, including measures of water security, water stress, water poverty, and water quality. The complexity of vulnerability assessment and water resources management has impeded the development of an agreed framework for understanding water vulnerability (Gain, Giupponi, & Renaud, 2012). However, even without an agreed conceptual framework, indicators are still commonly used to approximate or measure the various facets of vulnerability. Past work on water-related vulnerability has selected indicators to reflect aspects of the 'Driving force-Pressure-State-Impact Response' (DPSIR) model (e.g. Argent, 2016; Bitterman et al., 2016; Hamouda, Nour El-Din, & Moursy, 2009; Varis, Kummu, & Salmivaara, 2012), the 'exposure-sensitivity-coping capacity' model (e.g. Alessa et al., 2008; Gain et al., 2012; Goharian, Burian, Lillywhite, & Hile, 2016; Nelson et al., 2010a), a combination of the two (Bär, Rouholahnejad, Rahman, Abbaspour, & Lehmann, 2015), conceptual models developed for specific geographic contexts (Pandey et al., 2010; Plummer et al.,

2013), exogenous and endogenous stressors (Padowski, Gorelick, Thompson, Rozelle, & Fendorf, 2015), or simply the supply and demand for water within a region (Chang et al., 2013; Qian, Wang, & Zhang, 2014; Sullivan, 2011; Sun, Kuang, Xiang, & Che, 2016).

A common criticism levelled at vulnerability assessment is that it can be difficult to interpret and apply in a policy context, as the concepts involved are complex, and assessment tools may not address the needs of decision-makers (Hinkel, 2011; Nelson, Kokic, Crimp, Meinke, & Howden, 2010b; Vollmer, Regan, & Andelman, 2016). However, quantifying water vulnerability at the appropriate spatial scale can provide key information for generating effective adaptation responses and coping mechanisms for impending changes in water resources (Sullivan, 2011; Sullivan & Huntingford, 2009; Vörösmarty et al., 2010) although most assessments provide a temporally static snapshot of vulnerability, with even fewer including scenarios for future change. Past trends are infrequently assessed (a notable exception being Sun et al.'s (2016) water vulnerability assessment of the Yangtze River basin for the period 1994–2013), even though this could be useful in determining future trajectories.

As water supply and system demand is complex, measures of water supply should include all possible sources of water (including ground water and soil moisture), rather than considering only precipitation, runoff and/or dam storage (e.g. Bolin, Seetharam, & Pompeii, 2010; Schyns, Hoekstra, & Booij, 2015). Conversely, water demand should take into account socio-ecological stressors influencing water use and needs (Bitterman et al., 2016). To this end, we attempt to address many of the concerns through the development of a robust water vulner ability assessment approach incorporating multi-scalar components of both water system supply and demand. The conceptual framework guiding the selection of appropriate vulnerability indicators was de veloped through expert consultation, is context specific, and incorporates socio-ecological stressors on the system. Data used to mea sure the various components of water system vulnerability are publicly available for transparency, replicability and ease of use, and persist through time allowing for an examination of past trends whilst providing a foundation for modelling trajectories. Our approach provides a transferable methodology that can be adapted and applied in a variety of geographic contexts.

2.1. Water vulnerability in Australia

Global-scale studies indicate that Australian drylands can be classified as vulnerable or at risk of water insecurity (Kok et al., 2016; Sietz et al., 2011; Vörösmarty et al., 2010). Aside from the Australia state of the environment report (Argent, 2016), there have been few detailed regional-level analyses concerning the vulnerabilities of both the water system and water users. There has been a national quantitative as sessment of vulnerability of agriculture to climate change (Nelson et al., 2010a); qualitative assessments of risks to water supply security in surface water catchments (Preston & Jones, 2008); water vulnerability in urban areas (Werbeloff & Brown, 2011) and regional towns (Albrecht, Allison, Ellis, & Jaceglav, 2010); emerging research on water systems vulnerability in south-east Queensland (Sahin & Stewart, 2013); and much discussion of system sustainability in the Murray Darling basin in eastern Australia (e.g. Connell & Grafton, 2008; Kandasamy et al., 2014; Srinivasan et al., 2012). Australia's exposure to the impacts of climate change was the impetus for a regional quantitative assessments of future sustainable water yields, primarily in areas of denser population and where irrigated agriculture is prevalent (CSIRO, 2008, 2009). By contrast, the Wheatbelt region of the state of Western Australia (WA) is sparsely populated with predominantly rain fed agriculture. The region has experienced a greater decline in pre cipitation than any other wheat-producing area in

Australia (Asseng & Pannell, 2013), with further decline in precipitation expected (Hope, Drosdowsky, & Nicholls, 2006). Yet, there has not been a spatially and temporally detailed exploration of water system vulnerability for this area.

3. Methods

3.1. Study area: the Western Australian Wheatbelt

The Wheatbelt region (defined by the Western Australian Planning and Development Act 2005) covers 155,000 km² across 43 local gov ernment areas (LGAs), with a population of ~75,000, half living in town centres and the others across dispersed settlements and rural properties (Western Australian Planning Commission, 2011a) (Fig. 1). Approximately one third of the population are engaged in agricultural industries (Western Australian Planning Commission, 2011a). Land use is dominated by annual cereal cropping (wheat, oats, canola, barley) and pasture grazing (sheep), often in mixed systems. There is localised growth in mining and manufacturing (Davies & Tonts, 2010). The value of mineral products from the Wheatbelt increased fourfold from 2005 to 2006 to AU$2.6 billion in 2012–13, and was focussed in remote eastern districts (Clifton & Boruff, 2010; Department of Mines and Petroleum, 2013).

The ancient age and stability of the Wheatbelt landscape (developed on an Archaen-age shield of crystalline rock) has preserved palaeo drainage features, which have a strong influence on river positions, hydrogeology and groundwater resources, which are typically saline (Beard, 2003; Clarke, 1994; Ferdowsian, McFarlane, & Ryder, 1996; van de Graaff, Crowe, Bunting, & Jackson, 1977). The landscape fea tures a west-to-east transition in topography, rainfall and vegetation systems (Beard, 2003; Commander, Schoknecht, Verboom, & Caccetta, 2001). The western portion has higher rainfall, with a steeper and more dissected landscape (Beard, 1980, 1981). To the east, the landscape is flatter with reduced rainfall. Large-scale clearing of the original eu calypt woodlands and heathlands accelerated after World War II and continued until the 1970s. In many catchments, less than 10% of native vegetation remains (Metcalfe & Bui, 2016).

The Mediterranean climate, produces average annual rainfall from approximately 1000 mm along the Darling Range, to 300 mm at the limit of seasonal agriculture in the east (Fig. 1). There is high annual rainfall variability, with a marked decreasing trend since the mid-1970s (Bates, Hope, Ryan, Smith, & Charles, 2008; Callow & Smettem, 2007; Hope et al., 2006). Streamflow has decreased to around 60–80% of pre 1970s levels in some catchments (Barron et al., 2012; McFarlane et al., 2012; Smettem & Callow, 2014; Smettem, Waring, Callow, Wilson, & Mu, 2013).
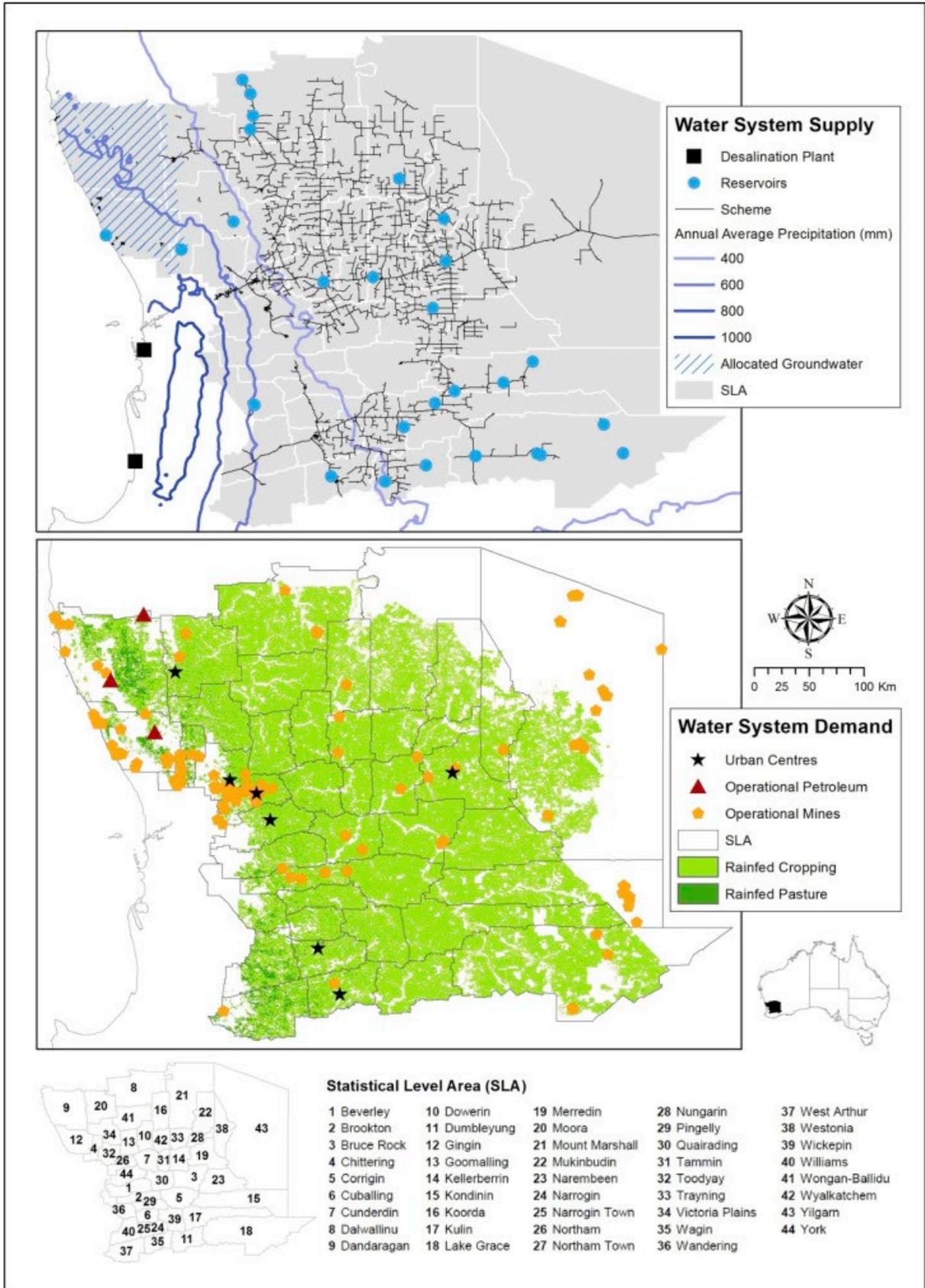
Fig. 1. The Western Australian Wheatbelt with major water supply components.

3.1.1. The Wheatbelt's water system

The majority of reticulated water in the Wheatbelt is supplied through the Goldfields Agricultural Water Supply Scheme (GAWSS), which links to the Integrated Water Supply System (IWSS) for Perth and southwest Western Australia. GAWSS was constructed to supply the arid goldfields with water, and allowed expansion of agriculture along the pipeline (Murphy-White, 1997). The Great Southern Towns Water Supply Scheme (GSTWS) provides water supplies to the southern Wheatbelt; water can be transferred between the GSTWS and IWSS. Together, water from these sources is referred to as 'Scheme' water; the pipelines are illustrated in Fig. 1.

Water within the Scheme is drawn from three sources: reservoirs formed by dams across several rivers flowing westward across the Darling Range; groundwater drawn from superficial aquifers on the Swan Coastal Plain; and processed seawater from two desalination plants. Declining rainfall and surface runoff (McFarlane et al., 2012; Silberstein et al., 2012), declining groundwater levels, and over-allo cation of groundwater (Bekesi, McGuire, & Moiler, 2009), have led to increased reliance on desalination. In the summer of 2015, desalination and groundwater each contributed around 40% of water supplied by the scheme (Water Corporation, 2015).

Settlements that cannot access the Scheme or local groundwater supplies depend on alternative water sources including: on farm dams; runoff from granite outcrops (Laing & Hauck, 1997); residential rain water harvesting; strategic community water supply facilities; and off grid groundwater bores (Wheatbelt Development Commission, 2012). Populations without access to Scheme water or groundwater are par ticularly vulnerabile to climatic variation and projected declines in precipitation (Bates et al., 2008; Hope et al., 2006; Hughes, 2003; Ludwig & Asseng, 2006).

3.2. Development of a water vulnerability index for the Wheatbelt

3.2.1. The water system framework

A framework to assess water vulnerability across the Wheatbelt was developed on the concept of water supply and demand. This approach drew upon aspects of existing water vulnerability indices (Cohen & Sullivan, 2010; Sullivan, 2011; Sullivan & Huntingford, 2009; Sullivan et al., 2008) to enable the identification of water supply and demand vulnerabilities within system components. A context-specific frame work for the Western Australian Wheatbelt was developed (Fig. 2) and an index constructed to measure water system supply and demand vulnerabilities across the region. To capture system vulnerability ac curately, the framework and index were specific to the water system studied; limited research has developed water vulnerability indices for adoption outside the geographic area of origin (Alessa et al. (2008) being an exception).

Drawing upon a review of academic literature, government reports, and local knowledge, a context-specific framework of the Wheatbelt's water system components, linkages, and drivers was conceptualised. To validate the context-specific framework (Fig. 2), an expert workshop was held in Northam, Western Australia, in July 2013. The workshop brought together experts on water use, infrastructure and demand, and drew stakeholders from organisations including the Wheatbelt Devel opment Commission, Wheatbelt Natural Resource Management In corporated, the WA Department of Agriculture and Food, and the WA Department of Water. The experts were asked to identify the compo nents of the Wheatbelt's water systems in the context of supply and demand. Participants were then asked to identify forcing factors of water supply and demand for the region. Finally, our initial

Wheatbelt water system framework was presented to the experts for comment. Feedback from the workshop was incorporated in the final Wheatbelt water system framework and used to select appropriate variables for measuring water system vulnerability across the region.
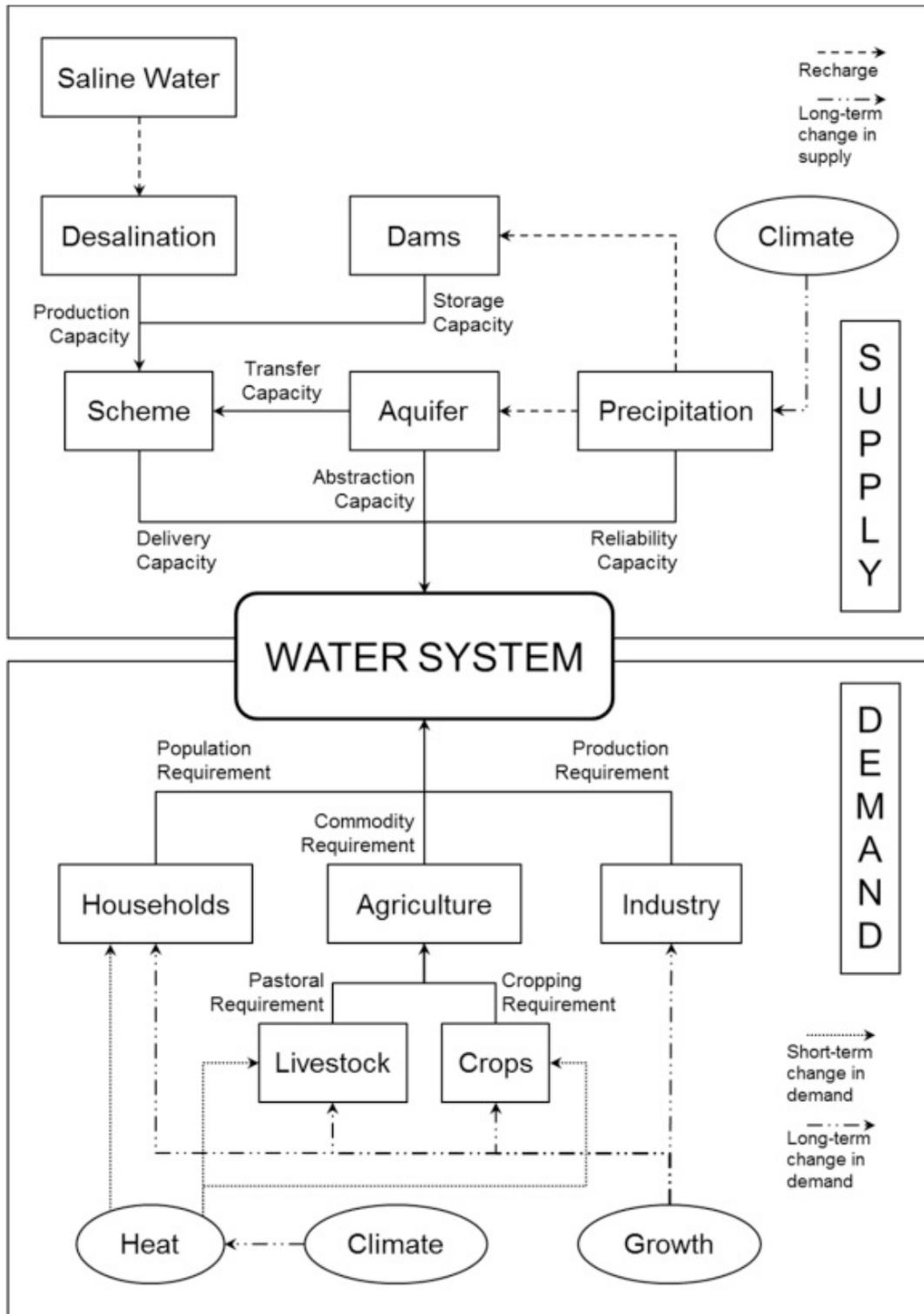

Fig. 2. Components of the water system in the Wheatbelt. Oval components influence supply capacities and demand levels of the system. Vulnerability of the system is measured based on variables representing the change in water supply and demand for water over the short and long term.

The resulting index enables the disaggregation of the components of water supply and demand, and the pressures acting on the system. This is critical for decision-makers to spatially ascertain where high water demand vulnerability and water supply vulnerability co-occur. The index for Water System Vulnerability (WSV) incorporates compensatory factors aggregated using an additive approach and mediating factors aggregated using a multiplicative approach (Bitterman et al., 2016). The WSV is determined by:

$$WSV = WSSV + WSDV \qquad (Equation\ 1)$$

where WSSV is the water system supply vulnerability and WSDV is the water system demand vulnerability. These two vulnerability compo nents consider the influences of water supply and demand by using measures to assess the vulnerability of the system to changes in both (Table 1). The higher the overall vulnerability score for the adminis trative unit, the greater the water vulnerability relative to those across the Wheatbelt region.

3.2.2. Water supply

Water System Supply Vulnerability (WSSV) in the Wheatbelt is calculated as:

$$WSSV = \mu(CV,V) + (AY) + (S_D * SC) \quad (Equation\ 2)$$

where CV is the coefficient of variation of mean annual precipitation, V is the difference between the annual precipitation value and long-term mean, AY is the proportion of the total locally-available groundwater allocation limit that is available to residents for future public and pri vate water supply (i.e., not currently licensed to private users), S_D is the density of Scheme pipelines, and SC is the ratio of total capacity available for supply to the total sustainable Scheme capacity which is determined by:

$$SC = (C + D + Y_{abs})/(C + D + Y_{lim}) \qquad (Equation\ 3)$$

where C is the annual volume of desalinated water production, D is the annual volume of surface water generated (calculated as the sum of dam carryover storage from the previous year and annual inflow), Y_{abs} is the annual volume of groundwater abstracted for public (i.e., Scheme) water supply, and Y_{lim} is the volume of groundwater re presenting the long-term sustainable yield from aquifers supplying the Scheme.

3.2.3. Water demand

Water System Demand Vulnerability (WSDV) in the Wheatbelt is calculated as:

$$WSDV = h[(g_P(P)) + (g_L(A_L)) + (g_C(A_C))] + g_I(I) \qquad (Equation\ 5)$$

where h is a measure of heat and moisture availability calculated as

$$h = \mu(h_T, AI) \quad (Equation\ 6)$$

where h_T is the variation in temperature from the long-term mean and AI is an aridity index (Zomer, Trabucco, van Straaten, & Bossio, 2006) calculated as

$$AI = map/mae \quad (Equation\ 7)$$

Table 1: Variables used to quantify water system vulnerability in the Wheatbelt for (i) *WSSV* and (ii) *WSDV*

Component	Variable and *Description*	Measure	Symbol	Units	Data Source
(i) *WSSV* (water system supply vulnerability)					
Capacity Reliability	Precipitation reliability *Inter-annual supply to recharge system*	Coefficient of variation of mean annual precipitation	CV	mm	Bureau of Meteorology (BoM) and CSIRO
	Ability to supply historical demand *Intra-annual supply to recharge system*	Variation of total annual precipitation from long-term mean (1975-2010)*	V	mm	BoM and CSIRO
Local Water Abstraction	Water reserves drawn from local aquifer *Capacity to supply direct users*	Percent of allocation limit currently available for future public or private use	AY	%	Department of Water (DoW)
Water Production	Desalination potential *Buffer supply to Scheme*	Total desalination production per year	C	ML year^{-1}	Water Corporation
Water Collection	Water reserves from reservoir *Capacity to supply Scheme*	Sum of dam carryover storage and annual inflow	D	ML year^{-1}	DoW
Water Abstraction	Water reserves drawn from regional aquifers *Capacity to supply Scheme*	Total volume abstracted per year by public water supply utility	Y_{abs}	ML year^{-1}	DoW
Sustainable Abstraction	Sustainable yield of aquifer *Sustainable capacity to supply Scheme*	Long-term sustainable abstraction for public water supply per year	Y_{lim}	ML year^{-1}	DoW
Delivery Capacity	Pipeline infrastructure *Ability to deliver Scheme supply to users*	Pipeline density*	S_D	km km^{-2}	Water Corporation
(ii) *WSDV* (water system demand vulnerability)					
Heat (h) *(intra-annual variation)*	Temperature *Direct impact on household and livestock consumption*	Variation of maximum average annual temperature from long-term maximum mean	h_T	°C	CSIRO
	Aridity *Direct impact on moisture availability*	Aridity Index*	AI	N/A	CSIRO
	Precipitation *Direct impact on crop consumption (rain-fed and irrigated)*	Total annual precipitation	map	mm year^{-1}	CSIRO
	Potential evapotranspiration *Direct impact on crop consumption (rain-fed and irrigated)*	Total annual potential evapotranspiration	mae	mm year^{-1}	CSIRO

Component	Variable and *Description*	Measure	Symbol	Units	Data Source
(ii) *WSDV continued*					
Population requirement (*P*)	Proximity to Scheme *Closer households are more likely to be able to exploit Scheme (subject to connection)*	Average Euclidean distance to pipeline	P_S	km	Water Corporation
	Proximity to aquifer *Households on or near aquifer more likely to be able to exploit Scheme (subject to licence and available allocation)*	Average Euclidean distance to aquifer with allocation limit	P_A	km	Water Corporation
	Population demand *Pressure on the Scheme*	Population density	P_D	Residents km^{-2}	ABS
	Socioeconomic disadvantage *Reduced likelihood of being able to exploit water resources (e.g. cost of access and consumption)*	SEIFA (index of relative socio-economic disadvantage)	P_E	N/A	ABS
Commodity requirement (*A*)	Livestock demand *Pressure on reserves*	Density of livestock	A_L	Livestock km^{-2}	ABARES
	Crop demand *Pressure on irrigation and reserves*	Area of cleared land used for cropping	A_C	%	ABARES
Production requirement (*I*)	Industrial employment *In water-dependent sectors*	Employment in industrial sectors as a percentage of total employment	I_{Em}	%	ABS
Growth (*g*) *(quinquennial variation)*	Population *Number of people demanding resources*	Growth rate in population	g_P	%	ABS
	Livestock *Number of livestock demanding resources*	Growth rate in number of livestock	g_L	%	ABARES
	Croplands *Quantity of cropland demanding resources*	Growth rate in area cropped	g_C	%	ABARES
	Industry *Quantity of industry demanding resources*	Growth rate in employment in industrial sectors	g_I	%	ABS

*   Denotes variable inverted

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where map is the total annual precipitation and *mae* is the total annual evaporative demand (potential evapotranspiration), g is the quinquennial growth rate from the previous time period to the current time period, for population g_P, density of livestock g_L, area cropped g_c, and employment in industry g_I. These are respectively multiplied by the three component influences on water demand: (i) agricultural re quirements A, comprised of the density of livestock A_L and percentage of cleared land under cropping A_c; (ii) population requirements P, calculated as:

$$P = P_S * P_A * P_D * P_E \ (Equation\ 8)$$

where P_s is the average Euclidian distance to pipeline within the SLA, P_A is the average Euclidian distance to local aquifers with allocated, potable water, P_D is population density and P_E is the Socio-Economic Indexes for Areas (SEIFA) index of relative socio-economic dis advantage (Australian Bureau of Statistics, 2011)); and (iii) industrial production requirement or I, as the percent employment in industrial sectors. Note that due to inconsistencies in the Australian Bureau of Statistics (ABS) means of reporting values for livestock and poultry across years, demand values could not be calculated for two SLAs where large-scale poultry rearing occurs (Chittering and Gingin) for all years.

3.3. Assessing vulnerability

Variables were selected to measure components of the vulnerability of supply capacities and demand requirements within the water supply demand framework for the Wheatbelt. Table 1 provides an overview of each variable.

3.3.1. Supply capacities

Delivery of Scheme water depends on adequate infrastructure and sufficient water replenishment. Infrastructure can be approximated by pipeline density, with a greater density indicating reduced vulnerability and an increased capacity to deliver water. Water supply to the Scheme is reliant on desalinisation, reservoir storage and groundwater ab straction. Excess desalination capacity, high reservoir levels and a high sustainable yield of aquifers indicate reduced supply vulnerability. Vulnerability of groundwater supplies drawn from local aquifers de pends on the sustainable yield of the aquifer. Water not supplied from the Scheme or locally available groundwater is obtained directly from precipitation. Therefore, the inter-annual and intra-annual variation in precipitation are important to assess the reliability of recharge supply. High variability in precipitation indicates increased vulnerability, as does a shortfall in precipitation relative to other years.

3.3.2. Demand requirements

Access to services and infrastructure is a critical issue for the Wheatbelt (Western Australian Planning Commission, 2011b). For household demand, population density provides an estimate of demand vulnerability, with greater populations placing increased pressure on the water system. Distance to Scheme pipelines and local aquifers with available groundwater provides an estimate of user access to potable water; those further from these sources are more vulnerable as their demand is directly correlated with precipitation. Household socio economic conditions are considered; those with greater socio-economic disadvantage are less likely to cope with reduced water availability. Vulnerabilities to demand for agricultural depends on livestock popu lations and the area of land under cultivation; high values indicate increased demand on resources and increased vulnerability. To factor industrial

production within water demand vulnerability, employment in water-dependent sectors (mining, manufacturing and construction) captures the potential requirements of industries.

3.3.3. System variation

In addition to the main supply-demand system components, im portant environmental influences for the Wheatbelt were considered. A heat component was introduced to assess intra-annual variation on household, livestock and cropping demand. It was assumed that in creased temperature would lead to increased water demand. Temperature is positively associated with water consumption by people and livestock (Gato et al., 2007; Howden, Crimp, & Stokes, 2008; Hoffmann, 2010; Taylor, 2012), and potential evapotranspiration is a key indicator of both rain-fed and irrigated cropping requirements (Mavi & Tupper, 2004). The impact of growth (from one census to the next) across all components was considered, as growth in population, agriculture and water-dependent industry are likely to have an impact on water demand.

3.4. Geographical area units and time points

Variables were measured at the Statistical Local Area (SLA), an Australian spatial unit used to collect and disseminate socio-economic statistics, and represent incorporated bodies of local government (i.e. directly related to planning guidelines). Water system vulnerability in the Wheatbelt was assessed for three time periods coincident with ABS socio-economic data collection: 2001, 2006 and 2011. The total number (42) of SLAs within the Wheatbelt development region have remained consistent throughout this period (Fig. 1), although marginal changes in boundary locations have occurred. Climate variables were derived from gridded data supplied by the Bureau of Meteorology and CSIRO with a spatial resolution of $0.05° \times 0.05°$; climate data were spatially averaged by SLA.

3.5. Creating a composite index

Each sub-component measuring WSSV and WSDV was standardized, and inverted where necessary to ensure higher values equated to in creased vulnerability. To standardise variables, a Min-Max normal isation approach was adopted where indicator values fall between a range from [0, 1] (Nardo et al., 2005).

3.6. Determining drivers of change

To determine the dominant influences on water vulnerability for each quinquennia, a stepwise linear regression was performed with WSV as the dependent variable and all measured subcomponents of water system vulnerability as independent variables (S_b, AY, CV, V, AI, h_T, P_s, P_A, P_D, P_E, A_L, A_C I_{Em} g_P g_L $g_{C, and}$ g_I), (e.g. the approach used by Boruff, Emrich, & Cutter, 2005). In this case, independent variables were not used to predict or model the dependent variable, but de termine the relative influence of each on WSV using standardized beta coefficients.

4. Results

4.1. Quinquennial change in water system vulnerability: 2001–2011

Fig. 3 details the relative pattern of change in water vulnerability in the Wheatbelt at three time periods (2001, 2006 and 2011). For water system supply components, the relative pattern of vulnerability was similar across all time points. SLAs in the northwestern part of the study area (e.g. Dandaragan, Gingin, Moora, Victoria Plains and Chittering) are consistently among the least vulnerable, while SLAs along the northern and eastern boundaries of the study area are consistently among the most vulnerable (for example Dalwallinu, Mount Marshall and Yilgarn). SLAs located in the central portion of the study region (York, Beverley, Brookton, Kondinin and Narambeen) have supply vulnerability scores above 0.6 for all time points. A group of SLAs on the southwestern edge of the study region (Wandering, Williams and West Arthur) have relatively high supply vulnerability scores (> 0.8) in 2001 and 2006, with intermediate values for 2011. The Shires (≈SLAs) of Wickepin, Narrogin and Merredin appear as spatial outliers for the inland portion of the region, with consistently low (≤0.4) relative va lues for supply vulnerability.

The pattern of water system demand vulnerability was more spa tially variable across the three time points. In 2001, SLAs with high demand vulnerability encompassed a swathe of SLAs along the central north-south axis of the region (including Moora, Northam, York and Wagin), while in 2006 vulnerable SLAs were primarily concentrated along the western edge of the Wheatbelt. Central northern SLAs (Dalwallinu, Mount Marshall, Mukinbudin and Koorda) had some of the lowest (≤0.2) demand vulnerability values for 2006. In 2011 the areas along the southern periphery of the Wheatbelt (e.g. Lake Grace, Dumbleyung, Wagin and West Arthur) had relatively low (≤0.2) de mand vulnerability, with the most vulnerable shires scattered across the central and northwest sections of the region. Chittering and Westonia displayed the highest demand vulnerability values for 2011.

The combined water system vulnerability map incorporates both supply and demand vulnerabilities. In 2001, the most vulnerable SLAs included those in the central and northern portions of the region, while in 2006 the southwestern and eastern SLAs exhibited the highest overall vulnerability. In 2011, SLAs on the northeastern periphery were most vulnerable (Yilgarn and Westonia), together with Brookton in the central west. The southwestern portion of the study area formed the largest contiguous area of relatively low (≤0.2) system vulnerability for the same time point. The water system vulnerability of individual SLAs was fairly variable over time; exceptions include Toodyay, which scored above 0.6 for relative vulnerability over time; and Koorda, Mukinbudin, Nungarin and Kelleberin which scored in the middle of the range of system vulnerability.

4.2. Quinquennial change in water system vulnerability subcomponents: 2001–2011

Fig. 4 illustrates the three main water supply components which influence variability in vulnerability across the region. The spatial pattern for water supply remains similar over time as the location of infrastructure and aquifers are relatively fixed. SLAs on the periphery tend to have higher values for vulnerability related to Scheme access, while only those Shires in the northwest with access to potable groundwater recorded low values for vulnerability. Spatial patterns of vulnerability related to precipitation varied across years; in 2011 there was a marked north-east/south-west gradient, while in 2001 and 2006 this trend was less pronounced with greater variability in precipitation related vulnerability across the region.
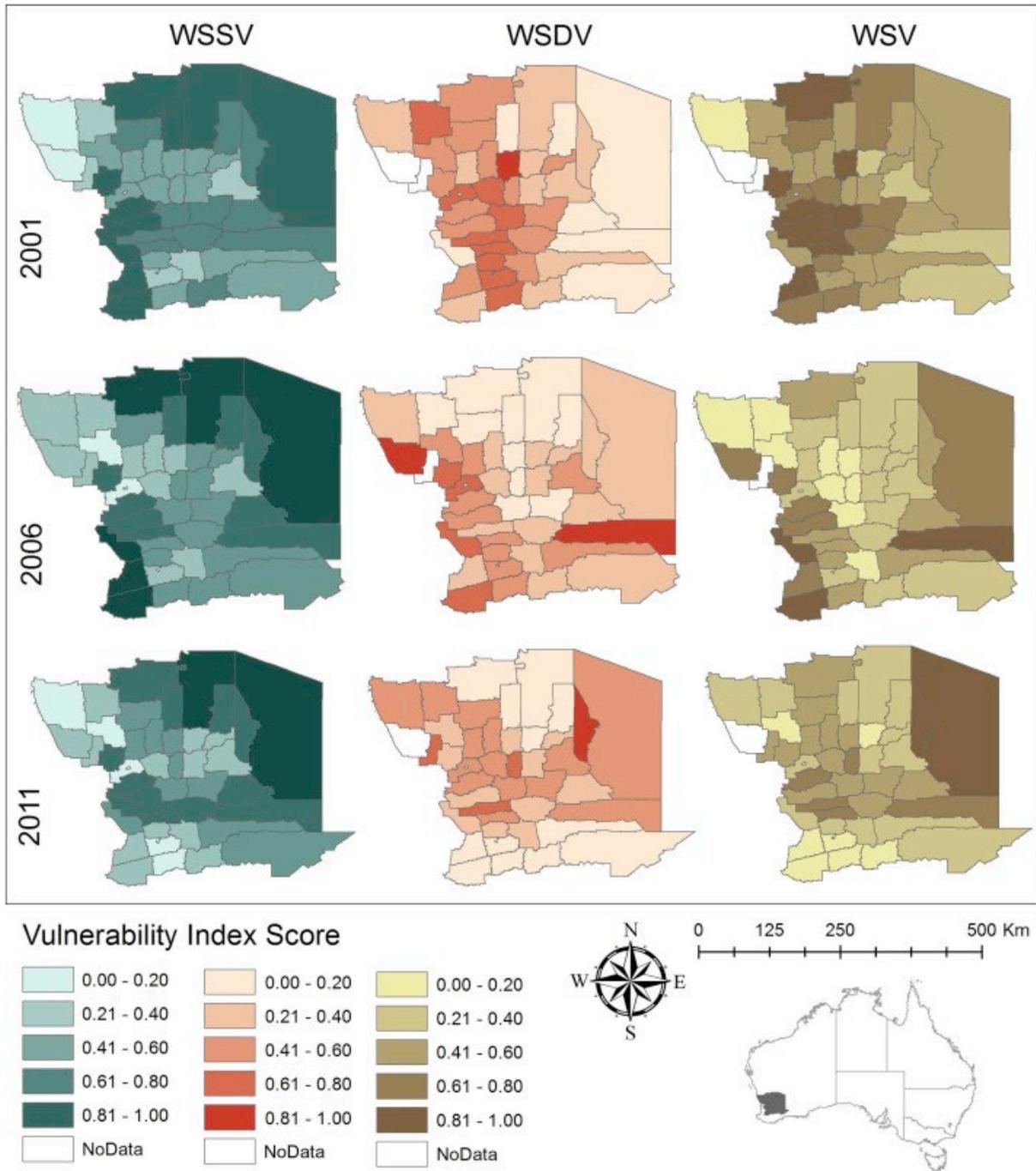
14

*Fig. 3. Vulnerability in the Western Australian Wheatbelt water system for (i) WSSV (ii) WSDV and
(iii) WSV at time point (a) 2001 (b) 2006 and (c) 2011. Values range from 0 (least vulnerable) to 1
(most vulnerable).*

The spatial variability in the four main components of the water demand subindex are shown in Fig. 5.
With household demand, the spatial pattern in the western half of the region remained relatively
consistent over time, with several SLAs in the central portion of the region exhibiting relatively high
levels of vulnerability across each time period. From 2001 to 2011, the relative demand vulnerability

for households on the eastern periphery increased markedly, notably Yilgarn, Kondinin and Westonia. The spatial pattern of vulnerability has remained relatively constant across the study period for livestock de mand, with the south west experiencing the highest vulnerability, and eastern SLAs showing the lowest vulnerability. A large increase in Gingin's livestock numbers influenced the values displayed for 2006.

There were subtle differences in the pattern of crop demand vulnerability across the three time periods. SLAs in the central portion of the Wheatbelt experienced the greatest relative vulnerability. Industry demand was driven by large, localised, short-term increases in industrial employment. The number of people employed in the industrial sector was very similar for 1996, 2001 and 2006 (averaging around 3500), with an increase (to 5000) in 2011, driven by mining and construction employment associated with a resources boom. However, from a spatial perspective, industry demand vulnerability was relatively low and homogenous across the region in 2011. This resulted from the mediating effect of low industrial employment on moderate growth rates as well as the inclusion of at least one outlier positively skewing this indicator (Westonia).
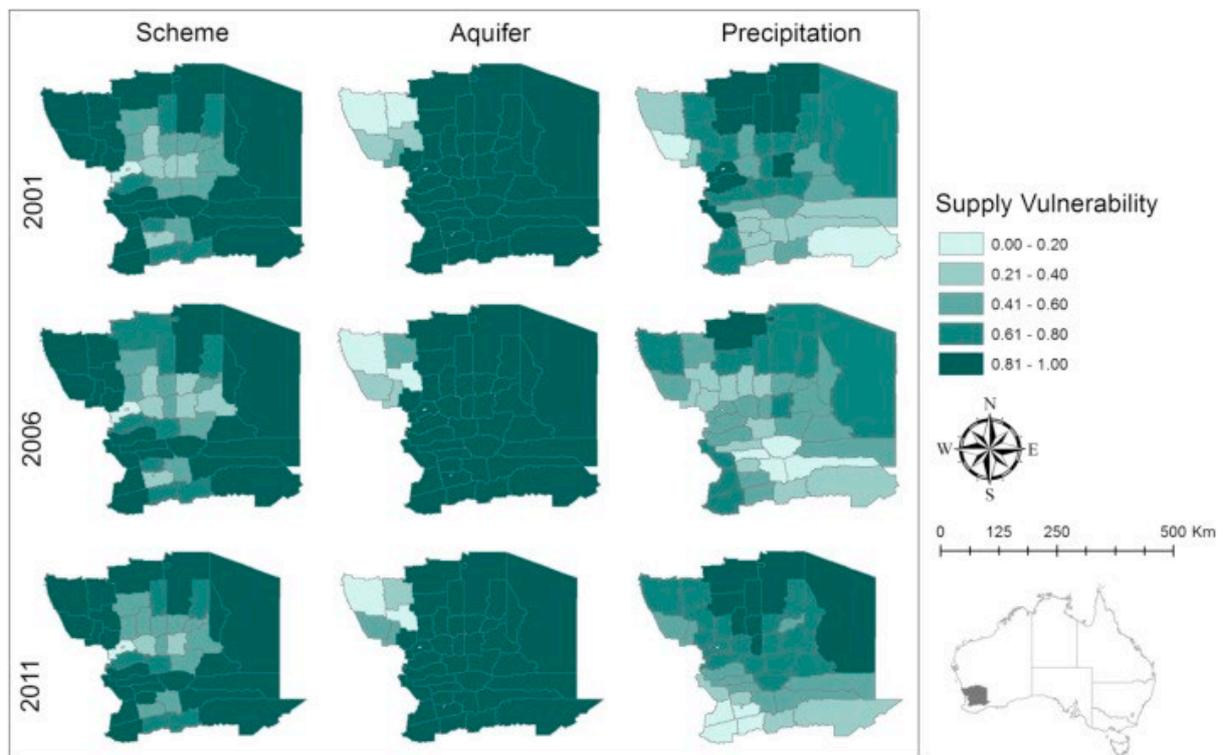

Fig. 4. Supply Vulnerability in the Western Australian Wheatbelt water system for (i) Scheme (ii) Aquifer and (iii) Precipitation at time point (a) 2001 (b) 2006 and (c) 2011. Values range from 0 (least vulnerable) to 1 (most vulnerable).

4.3. Drivers of change

Based on regression analysis, factors associated with the ability to supply the region with sufficient water resources had the greatest in fluence on water system vulnerability across the three time points (Table 2). Specifically, 'variation of total annual precipitation from long-term mean', 'pipeline density', and 'percent of allocation limit currently available for future public or private use' consistently ex hibited high levels of influence on overall vulnerability in 2001, 2006 and 2011. 'Variation of total annual precipitation from long-term mean' highlights the ability/inability of the system to recharge

reserves and provide increased consumption. The level of influence of 'pipeline density' on
vulnerability is a reminder of the Wheatbelt's reliance on water resources originating outside the region.
This vulnerability is further highlighted by the 'percent of allocation limit currently available for future
public or private use' as the majority of SLAs in the region do not have access to potable water in local
aquifers. Of less importance across each time point, except for 2006, was the 'coefficient of variation
of mean annual precipitation' which may indicate that within year variation is not as important as
historic trends.

Livestock, crop and industrial demand exhibited variability in their influence on water system
vulnerability across the three time periods. 'Livestock density' showed a high level of influence in 2006
which may be relative to livestock numbers. However, Gingin, excluded from the analysis in 2001 and
2011, reported the highest livestock numbers of any SLA in 2006 potentially skewing results. Of note
is that 'aridity' was the second most influential factor on overall water system vulnerability in 2001 and
2011 (but not 2006). This may result from higher levels of precipitation in 2001 and 2011 (compared
to 2006), highlighting the influence of moisture availability on demand.
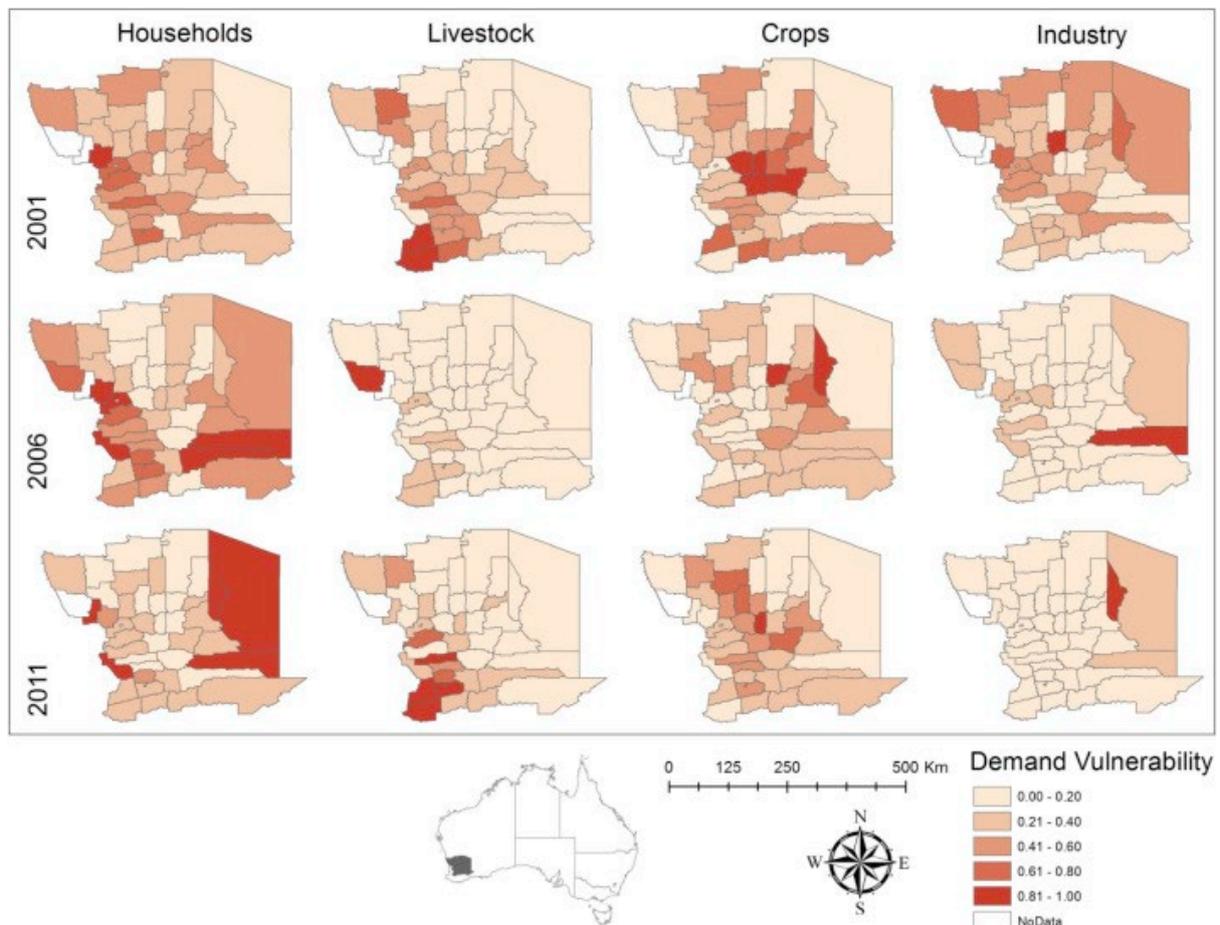

Fig. 5. Demand Vulnerability in the Western Australian Wheatbelt water system for (i) Households (ii)
Livestock (iii) Crops and (iv) Industry at time point (a) 2001 (b) 2006 and (c) 2011. Values range from
0 (least vulnerable) to 1 (most vulnerable).

Table 2: Ranking of supply and demand variables based on standardized beta coefficients (β) for each time point (2001, 2006, and 2011).*

2001[a,b]		2006[a]		2011[b]	
Variable	ß	Variable	ß	Variable	ß
Variation of total annual precipitation from long-term mean	0.723	**Percent of allocation limit currently available for future public or private use**	0.508	**Pipeline density**	0.598
Aridity	0.604	**Pipeline density**	0.497	Aridity	0.475
Pipeline density	0.575	**Coefficient of variation of mean annual precipitation**	0.446	**Variation of total annual precipitation from long-term mean**	0.458
Percent of allocation limit currently available for future public or private use	0.557	Density of livestock	0.343	**Percent of allocation limit currently available for future public or private use**	0.458
Growth rate in area cropped	0.229	**Variation of total annual precipitation from long-term mean**	0.309	Area of cleared land used for cropping	0.317
Employment in industrial sectors as a percentage of total employment	0.229	Growth rate in employment in industrial sectors	0.287	Growth rate in employment in industrial sectors	0.241
Area of cleared land used for cropping	0.212	Growth rate in area cropped	0.263	Employment in industrial sectors as a percentage of total employment	0.197
Growth rate in employment in industrial sectors	0.196	Growth rate in population	0.210	Growth rate in population	0.191
Growth rate in population	0.165	Population density	0.187	Growth rate in number of livestock	0.182
Growth rate in number of livestock	0.158	Index of relative socio-economic disadvantage	0.113	Population density	0.157

Notes:

* Significant at $p < 0.05$ or better. Derived from a standardized step-wise regression equation. **Bold type** indicates supply variables.

[a] Chittering SLA excluded due to missing values.

[b] Gingin SLA excluded due to missing values.

5. Discussion

5.1. The value of our water system vulnerability index

There is no universally accepted method for assessing the vulner ability of water resources however, there is a growing consensus con cerning elements for considered. These include implementation at an appropriate scale (Sullivan, 2011), the inclusion of all water sources ('blue' and 'green') (e.g. Bolin et al., 2010; Schyns et al., 2015), atten tion to geographic setting, and recognition of socio-ecological stressors influencing water use (Bitterman et al., 2016). However, in all but a few cases, water

vulnerability assessments have been static in time im peding the observation of trends or examination of future scenarios. In this study we build upon previous research and address these issues by providing a simple, holistic, conceptualisation of water system vulner ability for WA's Wheatbelt that allows decision-makers to observe trends over time. The comprehensive framework uses an integrated index approach, incorporating multiple socio-economic and environmental datasets, with locally relevant system information in a detailed model that can be transferred to other regions using place specific biophysical, socio-economic and infrastructure variables. Using a Geographic Information System (GIS) as an analytic tool. Finally, stakeholder participation in framework discussions provided validation for selection of system components.

5.2. Future water supply and demand in the Wheatbelt

The Water Services Association of Australia (2010) has projected Australian urban water consumption will increase between 39 and 49 per cent by 2026 (base year 2009), therefore population growth within Perth and the Wheatbelt could place increased pressure on the system. However, increased demand will be spatially variable with the greatest population increases projected for coastal areas and the 'Avon Arc' (Beverley, Cunderdin, Dowerin, Goomalling, Koorda, Northam, Quairading, Tammin, Toodyay, Wyalkatchem and York) (Western Australian Planning Commission, 2012). Based on our assessment, these areas have exhibited relatively high levels of water supply and demand vulnerability across each time point. If these trends continue, sustaining community needs becomes costly and potentially unattainable.

Furthermore, Regional Development Australia (RDA), is pursuing development outside the nation's major metropolitan areas (Regional Development Australia Wheatbelt Inc, 2016). Under this initiative, the Wheatbelt's five-year strategic outlook (2013–2018) calls for infra structure that meets current demand and allows for future economic growth in tourism, agriculture and niche industries. However, to accommodate such growth, particularly in the Avon Arc where vulnerability is already high, would be very costly (Wheatbelt Development Commission, 2012). To this end, the Western Australian Planning Commission (2011b) has identified that development should be di verted from areas where water availability is a constraint, but until now there has not been research to support these decisions.

There are some positive trends for water use in the Western Australian Wheatbelt. Small scale water reuse such as stormwater capture and storage provide for incremental reductions in water de mand (Countryman WA, 2013). Furthermore, as Asseng and Pannell (2013) highlight, despite decreasing rainfall and increasing temperatures across the region, there has been limited impact on wheat yields due to enhanced agricultural practices. In the future, underground water stores could meet industrial and household water demands as increases in water prices render desalination an economically viable alternative (Regional Development Australia Wheatbelt Inc, 2016).

5.3. Application beyond the Wheatbelt: addressing user needs

Rainfed cropping is a large portion of the world's agriculture ac counting for approximately 90% of production in Latin America, 75% in Africa, and more than 60% in Southeast Asia (Wani, Sreedevi, Rockström, & Ramakrishna, 2009). Climate variability is a major constraint as dramatic reductions in yield can occur with even minor de creases in annual rainfall (coefficient of variation) (Wani et al., 2009). The livelihoods of individuals living in regions dominated by rainfed agriculture are highly

vulnerable to water related stress which often results in increased levels of poverty and hunger (Falkenmark, 1986). However, maintaining water security requires an understanding of the system as a whole in order to identify how system pressures manifest as constraints on water supply and increased demand.

To this end, a number of reviews have examined water scarcity assessment tools (Rijsberman, 2006), water vulnerability assessment techniques (Plummer et al., 2012), and the advantages and disadvantages of various assessment approaches for supporting decision making (Vollmer et al., 2016). As there is substantial variability in the components of a water system and the indicators used to measure socio ecological processes, it is important that "water indices strive to reach a balance across salience, legitimacy, and credibility" (Vollmer et al., 2016, p. 775). Although no single index or assessment tool can measure every component of a water system and meet the needs of all end users, we argue that the framework presented in this paper provides an im portant step forward in addressing the needs of a variety of stakeholders.

Drawing upon Vollmer et al.'s (2016) typology of freshwater index uses, the WSV index presented in this paper provides a comprehensive approach that would appeal to a broad set of end users. Our quin quennial trend analysis offers an example of how water vulnerability indices can be used to 'benchmark and monitor' change by providing a system baseline through which adjustments can be tracked across time. The composite picture of overall WSV and its supply and demand subcomponents is the first complete depiction of the Wheatbelt's water system vulnerability and highlights that while addressing the scale at which biophysical processes act on a system is important, examining system vulnerability at a scale that is commensurate with decision making process can facilitate integrated water resource management and strategic spatial planning.

5.4. Limitations

There are limitations which should be considered in interpreting the results of this study. First, it is important to understand and account for all sources of water supplying a system and although there have been long-established approaches for rainwater harvesting (e.g. roaded catchments) in WA, capture for domestic use is less common. Limited information is available on domestic rainwater harvesting, and therefore excluded this source from our calculations. Likewise, water captured and stored in on-farm dams for agricultural purposes is difficult to ascertain and was consciously omitted. However, rainwater supply for agricultural production and household use was accounted for by measures of inter and intra-annual precipitation variation.

Second, as our framework was developed for rainfed agricultural systems, the methodology would need adaptation for use in irrigated landscapes. However, it should be noted that our framework provides a more detailed picture of water vulnerability in rainfed, dryland agriculture than some global assessments of water resources which often capture 'water withdrawals' for use in irrigation (e.g. Molden et al., 2007, chap. 2; Smakhtin, Revanga, & Döll, 2005). In addition, we do not consider environmental demand, which can be particularly significant in systems where surface and groundwater are being withdrawn directly for agriculture.

Finally, the use of 'number of employees' and 'employment growth' in water related industries may not be the most appropriate proxy for industrial demand as water use within the industrial sector varies

widely. In addition, we measured human capacity to cope with, and adapt to pressures on supply availability using the ABS SEIFA index of relative socio-economic disadvantage (Australian Bureau of Statistics, 2011). Whilst the index incorporates measures of income, employment, occupation, education, and housing and household characteristics, there may be alternative context-specific factors influencing adaptation and coping capacity.

6. Conclusions

As southwest Western Australia faces further decreases in annual precipitation, uncertainty in the adequacy of future water supplies is a tangible concern. With over 40% of the region's water currently sup plied through desalination, the extent to which further economic development can be sustained is a topic of debate. However, to identify current and future vulnerabilities in water system supply and demand first requires a sound understanding of the system being modelled, and the biophysical processes acting upon the system. The vulnerability framework developed for this study provides a validated tool for understanding the components of the region's water system as well as the various pressures affecting supply and demand. Factors influencing the system's ability to supply current and historic demands have had the greatest influence on system vulnerability with the eastern reaches of the Wheatbelt region most vulnerable to decreasing water availability. The question concerning the extent to which these trends will persist into the future still remains. However, for the first time, policymakers have access to an enhanced historic perspective of water vulnerability and empirical evidence to inform future decisions concerning the region's water security.

Acknowledgements

References

Adger, W. N. (2006). Vulnerability. Global Environmental Change, 16, 268–281. Albrecht, G., Allison, H., Ellis, N., & Jaceglav, M. (2010). Resilience and water security in two outback cities. Gold Coast, Australia: National Climate Change Adaptation Research Facility.

Alessa, L., Kliskey, A., Lammers, R., Arp, C., White, D., Hinzman, L., et al. (2008). The arctic water resource vulnerability Index: An integrated assessment tool for com munity resilience and vulnerability with respect to freshwater. Environmental Management, 42, 523–541.

Argent, R. M. (2016). Inland water: Introduction. Australia state of the environment 2016. Canberra, Australia: Australian Government Department of the Environment and Energy.

Asseng, S., & Pannell, D. (2013). Adapting dryland agriculture to climate change: Farming implications and research and development needs in Western Australia. Climatic Change, 118, 167–181.

Australian Bureau of Statistics (2011). Socio-economic Indexes for areas (SEIFA). Technical paper 2033.0.55.001Canberra, Australia: Australian Bureau of Statistics. Barron, O., Silberstein, R., Ali, R., Donohue, R., McFarlane, D. J., Davies, P., et al. (2012). Climate change effects on

water-dependent ecosystems in south-western Australia. Journal of Hydrology, 434–435, 95–109.

Bär, R., Rouholahnejad, E., Rahman, K., Abbaspour, K. C., & Lehmann, A. (2015). Climate change and agricultural water resources: A vulnerability assessment of the black Sea catchment. Environmental Science & Policy, 46, 57–69.

Bates, B., Hope, P., Ryan, B., Smith, I., & Charles, S. (2008). Key findings from the Indian Ocean Climate Initiative and their impact on policy development in Australia. Climatic Change, 89, 339–354.

Beard, J. S. (1980). A new phytogeographic map of Western Australia. Western Australian Herbarium Research Notes, 3, 37–58.

Beard, J. S. (1981). Vegetation survey of Western Australia; Swan 1:1,000,000 vegetation series explanatory notes: The vegetation of the Swan area. Perth, Australia: University of Western Australia Press.

Beard, J. S. (2003). Palaeodrainage and the geomorphic evolution of passive margins in Southwestern Australia. Zeitschrift Fur Geomorphologie, 47, 273–288.

Bekesi, G., McGuire, M., & Moiler, D. (2009). Groundwater allocation using a ground water level response management method - Gnangara groundwater system, Western Australia. Water Resources Management, 23, 1665–1683.

Biggs, E. M., Bruce, E., Boruff, B., Duncan, J. M. A., Horsley, J., Pauli, N., et al. (2015). Sustainable development and the water-energy-food nexus: A perspective on liveli hoods. Environmental Science & Policy, 54, 389–397.

Biggs, E. M., Duncan, J. M. A., Atkinson, P. M., & Dash, J. (2013). Plenty of water, not enough strategy: How inadequate accessibility, poor governance and a volatile gov ernment can tip the balance against ensuring water security: The case of Nepal. Environmental Science & Policy, 33, 388–394.

Bitterman, P., Tate, E., Van Meter, K. J., & Basu, N. B. (2016). Water security and rain water harvesting: A conceptual framework and candidate indicators. Applied Geography, 76, 75–84.

Bolin, B., Seetharam, M., & Pompeii, B. (2010). Water resources, climate change, and urban vulnerability: A case study of Phoenix, Arizona. Local Environment, 15, 261–279.

Boori, M. S., & Voženílek, V. (2014). Socio-hydrological vulnerability: A new science through remote sensing and GIS. Global Journal of Researches in Engineering: E Civil and Structural Engineering, 14, 37–41.

Boruff, B. J., Emrich, C., & Cutter, S. L. (2005). Erosion hazard vulnerability of US coastal counties. Journal of Coastal Research, 21, 932–942.

Callow, J. N., & Smettem, K. R. J. (2007). Channel response to a new hydrological regime in southwestern Australia. Geomorphology, 84, 254–276.

Chang, H., Jun, I.-W., Strecker, A., Wise, D., Lafrenz, M., Shandas, V., et al. (2013). Water supply, demand and quality indicators for assessing the spatial distribution of water resource vulnerability in the Columbia River Basin. Atmosphere-Ocean, 51, 339–356.

Chen, Y., Niu, Z., Bai, J., & Wang, Y. (2014). Seismic vulnerability assessment of water supply network in Tianjin, China. Frontiers of Environmental Science & Engineering, 8, 767–775.

Clarke, J. D. A. (1994). Evolution of the lefroy and cowan palaeodrainage channels, Westerm Australia. Australian Journal of Earth Sciences, 41, 55–68.

Clifton, J., & Boruff, B. J. (2010). Assessing the potential for concentrated solar power development in rural Australia. Energy Policy, 38, 5272–5280.

Cohen, A., & Sullivan, C. (2010). Water and poverty in rural China: Developing an in strument to assess the multiple dimensions of water and poverty. Ecological Economics, 69, 999–1009.

Commander, P., Schoknecht, N., Verboom, B., & Caccetta, P. A. (2001). The geology, physiography and soils of wheatbelt valleys. Conference on dealing with salinity in Wheatbelt valleys: Processes, prospects and practical options, Merredin, Australia.

Connell, D., & Grafton, R. Q. (2008). Planning for water security in the Murray-Darling basin. Public Policy, 3, 67–86.

Cook, S. E., Fisher, M. J., Andersson, M. S., Rubiano, J., & Giordano, M. (2009). Water, food and livelihoods in river basins. Water International, 34, 13–29. Cordell, D., & Neset, T. S. S. (2014). Phosphorus vulnerability: A qualitative framework for assessing the vulnerability of national and regional food systems to the multi dimensional stressors of phosphorus scarcity. Global Environmental Change, 24, 108–122.

Countryman WA (2013). Stormwater set to green towns. Countryman WA, Perth, Australia, 13 June 2013.

CSIRO (2008). Water availability in the Murray-Darling basin. A report to the Australian government from the CSIRO Murray-Darling basin sustainable yields projectCanberra, Australia: CSIRO.

CSIRO (2009). Water yields and demands in South-West Western Australia. A report to the Australian government from the CSIRO South-West Western Australia sustainable yields projectPerth, Australia: CSIRO Water for a Healthy Country Flagship CSIRO.

Cutter, S. L., Boruff, B. J., & Shirley, W. L. (2003). Social vulnerability to environmental hazards. Social Science Quarterly, 84, 242–261.

Davies, A., & Tonts, M. (2010). Economic diversity and regional socioeconomic Performance: An empirical analysis of the Western Australian grain belt. Geographical Research, 48, 223–234.

Department of Mines and Petroleum (2013). Western Australia mineral and Petroleum statistics digest. Perth, Australia: Government of Western Australia.

Doerfliger, N., Jeannin, P. Y., & Zwahlen, F. (1999). Water vulnerability assessment in karst environments: A new method of defining protection areas using a multi-attri bute approach and GIS tools (EPIK method). Environmental Geology, 39, 165–176.

Elshafei, Y., Sivapalan, M., Tonts, M., & Hipsey, M. R. (2014). A prototype framework for models of socio-hydrology: Identification of key feedback loops and parameterisation approach. Hydrology and Earth System Sciences, 18, 2141–2166.

Falkenmark, M. (1986). Fresh water - time for a modified approach. Ambio, 15, 192–200. Ferdowsian, R., McFarlane, D. J., & Ryder, A. T. (1996). Wetlands on Tertiary sandplains need to be

managed to reduce secondary salinity. 4th national conference and work shop on the productive use and rehabilitation of saline lands (PURSL). Albany, Australia: Promaco Conventions.

Gain, A. K., Giupponi, C., & Renaud, F. G. (2012). Climate change adaptation and vul nerability assessment of water resources systems in developing countries: A gen eralised framework and a feasibility study in Bangladesh. Water, 4(2), 345–366. http://dx.doi.org/10.3390/w4020345.

Gato, S., Jayasuriya, N., & Roberts, P. (2007). Temperature and rainfall thresholds for base use urban water demand modelling. Journal of Hydrology, 337, 364–376. Goharian, E., Burian, S. J., Lillywhite, J., & Hile, R. (2016). Vulnerability assessment to support Integrated Water Resources Management of metropolitan water supply sys tems. Journal of Water Resources Planning and Management, 143(3), 04016080. http:// dx.doi.org/10.1061/(ASCE)WR.1943-5452.0000738.

van de Graaff, W. J. E., Crowe, R. W. A., Bunting, J. A., & Jackson, M. J. (1977). Relict early cainozoic drainages in arid Western Australia. Zeitschrift Fur Geomorphologie, 21, 379–400.

Hamouda, M., Nour El-Din, M., & Moursy, F. (2009). Vulnerability assessment of water resources systems in the Eastern Nile basin. Water Resources Management, 23, 2697–2725.

Hinkel, J. (2011). "Indicators of vulnerability and adaptive capacity": Towards a clar ification of the science-policy interface. Global Environmental Change, 21, 198–208. Hoff, H. (2011). Understanding the Nexus: Background paper for the bonn 2011 Conference: The water, energy and food security nexus. Stockholm, Sweden: Stockholm Environment Institute.

Hoffmann, I. (2010). Climate change and the characterization, breeding and conservation of animal genetic resources. Animal Genetics, 41, 32–46.

Hope, P., Drosdowsky, W., & Nicholls, N. (2006). Shifts in the synoptic systems influ encing southwest Western Australia. Climate Dynamics, 26, 751–764. Howden, S. M., Crimp, S. J., & Stokes, C. J. (2008). Climate change and Australian li vestock systems: Impacts, research and policy issues. Australian Journal of Experimental Agriculture, 48, 780–788.

Hughes, L. (2003). Climate change and Australia: Trends, projections and impacts. Austral Ecology, 28, 423–443.

Jackson, R. B., Carpenter, S. R., Dahm, C. N., McKnight, D. M., Naiman, R. J., Postel, S. L., et al. (2001). Water in a changing world. Ecological Applications, 11, 1027–1045. Kandasamy, J., Sounthararajah, D., Sivabalan, P., Chanan, A., Vigneswaran, S., & Sivapalan, M. (2014). Socio-hydrologic drivers of the pendulum swing between agricultural development and environmental health: A case study from Murrumbidgee River basin, Australia. Hydrology and Earth System Sciences, 18, 1027–1041.

Kemp-Benedict, E., Cook, S., Allen, S. L., Vosti, S., Lemoalle, J., Giordano, M., et al. (2011). Connections between poverty, water and agriculture: Evidence from 10 river basins. Water International, 36, 125–140.

Kok, M., Lüdeke, M., Lucas, P., Sterzel, T., Walther, C., Janssen, P., et al. (2016). A new method for analysing socio-ecological patterns of vulnerability. Regional Environmental Change, 16, 229–243.

Laing, I. A. F., & Hauck, E. J. (1997). Water harvesting from granite outcrops in Western Australia. Journal of the Royal Society of Western Australia, 80, 181–184. Ludwig, F., & Asseng, S. (2006). Climate change impacts on wheat production in a Mediterranean environment in Western Australia. Agricultural Systems, 90, 159–179. Mavi, H. S., & Tupper, G. J. (2004). Agrometeorology. Principles and application of climate studies in agriculture. Binghamton, NY, USA: Haworth Press.

McFarlane, D., Stone, R., Martens, S., Thomas, J., Silberstein, R., Ali, R., et al. (2012). Climate change impacts on water yields and demands in south-western Australia. Journal of Hydrology, 475, 488–498.

Metcalfe, D., & Bui, E. (2016). Land: Regional and landscape-scale pressures: Land clearing. Australia state of the environment 2016. Canberra, Australia: Australian Government Department of the Environment and Energy.

Molden, D., Frenken, K., Barker, R., de Fraiture, C., Mati, B., Svendsen, M., et al. (2007). Trends in water and agricultural development. In D. Molden (Ed.). Water for food, water for life: A comprehensive assessment of water management in agriculture. Colombo: Earthscan, London and International Water Management Institute.

Murphy-White, S. (1997). Farm water for the north-eastern and eastern Wheatbelt of Western Australia. Perth, Australia: Department of Agriculture and Food.

Nardo, M., Saisana, M., Saltelli, A., Tarantola, S., Hoffman, A., & Giovannini, E. (2005). Handbook on constructing composite indicators: Methodology and user guide. Statistics working paper, STD/DOC 3. Paris, France: Organisation for Economic Co-operation and Development.

Nelson, R., Kokic, P., Crimp, S., Martin, P., Meinke, H., Howden, S. M., et al. (2010a). The vulnerability of Australian rural communities to climate variability and change: Part II-integrating impacts with adaptive capacity. Environmental Science & Policy, 13, 18–27.

Nelson, R., Kokic, P., Crimp, S., Meinke, H., & Howden, S. M. (2010b). The vulnerability of Australian rural communities to climate variability and change: Part I-con ceptualising and measuring vulnerability. Environmental Science & Policy, 13, 8–17.

Padowski, J. C., Gorelick, S. M., Thompson, B. H., Rozelle, S., & Fendorf, S. (2015). Assessment of human–natural system characteristics influencing global freshwater supply vulnerability. Environmental Research Letters, 10, 104014.

Pandey, V. P., Babel, M. S., Shrestha, S., & Kazama, F. (2010). Vulnerability of freshwater resources in large and medium Nepalese river basins to environmental change. Water Science and Technology, 61, 1525–1534.

Plummer, R., de Grosbois, D., Armitage, D., & de Loë, R. (2013). An integrative assess ment of water vulnerability in First Nation communities in Southern Ontario, Canada. Global Environmental Change, 23, 749–763.

Plummer, R., de Loë, R., & Armitage, D. (2012). A systematic review of water vulner ability assessment tools. Water Resources Management, 26, 4327–4346. Preston, B. L., & Jones, R. N. (2008). Screening climatic and non-climatic risks to Australian catchments. Geographical Research, 46, 258–274.

Preston, B., Yuen, E., & Westaway, R. (2011). Putting vulnerability to climate change on the map: A review of approaches, benefits, and risks. Sustainability Science, 6, 177–202.

Qian, L., Wang, H., & Zhang, K. (2014). Evaluation criteria and model for risk between water supply and water demand and its application in Beijing. Water Resources Management, 28, 4433–4447.

Regional Development Australia Wheatbelt Inc (2016). Wheatbelt strategic regional plan. Gingin, Australia: Regional Development Australia Wheatbelt Inc.

Rijsberman, F. R. (2006). Water scarcity: Fact or fiction? Agricultural Water Management, 80, 5–22.

Rupert, M. G. (2001). Calibration of the DRASTIC ground water vulnerability mapping method. Ground Water, 39, 625–630.

Sahin, O., & Stewart, R. (2013). Life cycle assessment of urban water supply vulnerability costs: A systems dynamics approach. In M. Ban, N. Duić, Z. Guzović, N. Markovska, & D. R. Schneider (Eds.). Proceedings of the 8th conference on sustainable development of energy. Dubrovnik, Croatia: Water and Environmental Systems.

Schyns, J. F., Hoekstra, A. Y., & Booij, M. J. (2015). Review and classification of in dicators of green water availability and scarcity. Hydrology and Earth System Sciences, 19, 4581–4608.

Sietz, D., Lüdeke, M. K. B., & Walther, C. (2011). Categorisation of typical vulnerability patterns in global drylands. Global Environmental Change, 21, 431–440. Silberstein, R. P., Aryal, S. K., Durrant, J., Pearcey, M., Braccia, M., Charles, S. P., et al. (2012). Climate change and runoff in south-western Australia. Journal of Hydrology, 475, 441–455.

Sivapalan, M., Konar, M., Srinivasan, V., Chhatre, A., Wutich, A., Scott, C. A., et al. (2014). SocioHydrology: Use-Inspired water sustainability science for the anthro pocene. Earth's Future, 2, 225–230.

Smakhtin, V., Revanga, C., & Döll, P. (2005). Taking into account environmental water re quirements in global-scale water resources assessments. Comprehensive Assessment of Water Management in Agriculture Research Report 2. Colombo, Sri Lanka: International Water Management Institute (IWMI).

Smettem, K. R. J., & Callow, J. N. (2014). Impact of land use change on the interplay between effective rooting depth and runoff in South-west Western Australia. Water, 6, 2539–2551.

Smettem, K. R. J., Waring, R. H., Callow, J. N., Wilson, M., & Mu, Q. (2013). Satellite derived estimates of forest leaf area index in southwest Western Australia are not tightly coupled to interannual variations in rainfall: Implications for groundwater decline in a drying climate. Global Change Biology, 19, 2401–2412.

Srinivasan, V., Lambin, E. F., Gorelick, S. M., Thompson, B. H., & Rozelle, S. (2012). The nature and causes of the global water crisis: Syndromes from a meta-analysis of coupled human-water studies. Water Resources Research, 48, W10516.

Sullivan, C. (2011). Quantifying water vulnerability: A multi-dimensional approach. Stochastic Environmental Research and Risk Assessment, 25, 627–640. Sullivan, C., Cohen, A., Faurés, J.-M., & Santini, G. (2008). The rural water livelihoods index., FAO Working Paper. Rome, Italy: Food and Agriculture Organisation of the United Nations.

Sullivan, C., & Huntingford, C. (2009). Water resources, climate change and human vulnerability. In R. Anderssen, R. Braddock, & L. Newham (Eds.). 18th world IMACS congress and MODSIM09 international congress on modelling and simulation. Modelling and simulation society of Australia and New Zealand and international association for mathematics and computers in simulation, cairns, Australia (pp. 3984–3990). .

Sun, F., Kuang, W., Xiang, W., & Che, Y. (2016). Mapping water vulnerability of the Yangtze River basin: 1994–2013. Environmental Management, 58, 857–872. Taylor, B. A. (2012). Predicting normalised monthly patterns of domestic external water demand using rainfall and temperature data. Water Science and Technology: Water Supply, 12, 168–178.

Thompson, S. E., Sivapalan, M., Harman, C. J., Srinivasan, V., Hipsey, M. R., Reed, P., et al. (2013). Developing predictive insight into changing water systems: Use-inspired hydrologic science for the anthropocene. Hydrology and Earth System Sciences, 17, 5013–5039.

Turner, B. L., Kasperson, R. E., Matson, P. A., McCarthy, J. J., Corell, R. W., Christensen, L., et al. (2003). A framework for vulnerability analysis in sustainability science. Proceedings of the National Academy of Sciences, 100, 8074–8079.

Varis, O., Kummu, M., & Salmivaara, A. (2012). Ten major rivers in monsoon Asia-Pacific: An assessment of vulnerability. Applied Geography, 32, 441–454.

Vollmer, D., Regan, H. M., & Andelman, S. J. (2016). Assessing the sustainability of freshwater systems: A critical review of composite indicators. Ambio, 45, 765–780. Vörösmarty, C. J., Green, P., Salisbury, J., & Lammers, R. B. (2000). Global water Resources: Vulnerability from climate change and population growth. Science, 289, 284–288.

Vörösmarty, C. J., McIntyre, P. B., Gessner, M. O., Dudgeon, D., Prusevich, A., Green, P., et al. (2010). Global threats to human water security and river biodiversity. Nature, 467, 555–561.

Wani, S. P., Sreedevi, T. K., Rockström, J., & Ramakrishna, Y. S. (2009). Rainfed agri culture – past trends and future Prospects. In S. P. Wani, J. Rockström, & T. Oweis (Eds.). Rainfed Agriculture: Unlocking the potential (pp. 1–35). Cambridge, USA: Centre for Agriculture and Biosciences International(CABI).

Water Corporation (2015). Rainfall, dam storage and water supply. Perth, Australia: Water Corporation.

Water Services Association of Australia (2010). Implications of population growth in Australia on urban water resources. Sydney, Australia: Water Services Association of Australia Occasional Paper No. 25.

Werbeloff, L., & Brown, R. (2011). Working towards sustainable urban water manage ment: The vulnerability blind spot. Water Science and Technology, 64, 2362–2369. Western Australian Planning Commission (2012). Draft Wheatbelt planning & infrastructure framework. Perth, Australia: Western Australian Planning Commission. Western Australian Planning Commission (2011a). Wheatbelt regional profile. Background and context report to support the Wheatbelt land use planning strategyPerth, Australia: Western Australian Planning Commission.

Western Australian Planning Commission (2011b). Wheatbelt land use planning strategy. Draft for public comment. Perth, Australia: Western Australian Planning Commission. Wheatbelt

Development Commission (2012). Wheatbelt snapshot Series: Potable water. Discussion Paper Overview, March 2012Perth, Australia: Wheatbelt Development Commission.

Zomer, R. J., Trabucco, A., van Straaten, O., & Bossio, D. A. (2006). Carbon, land and water: A global analysis of the hydrologic dimensions of climate change mitigation through afforestation/reforestation. Colombo, Sri Lanka: International Water Management Institute.