

Hydrological change escalates risk of ecosystem stress in Australia's threatened biodiversity hotspot

P Horwitz^{1*}, D Bradshaw², S Hopper³, P Davies⁴,
R Froend¹ and F Bradshaw²

¹School of Natural Sciences, Edith Cowan University, Perth, Australia

²School of Animal Biology and Centre for Native Animal Research,
University of Western Australia, Perth, 6009, Australia

³Royal Botanic Gardens, Kew, Richmond, Surrey TW9 3AB, UK and School of Plant Biology,
University of Western Australia, Perth, 6009, Australia

⁴Centre of Excellence in Natural Resource Management, University of Western Australia, Albany, 6330, Australia

* To whom correspondence should be addressed.

✉ p.horwitz@ecu.edu.au

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Abstract

The southwestern corner of the Australian continent has been identified as a global "biodiversity hotspot", defined as an area where "exceptional concentrations of endemic species are undergoing exceptional loss of habitat". In this paper we reconsider the reasons for this conservation priority. We briefly review significant characteristics of the flora and fauna, and the way threatening processes are escalating ecosystem stress to these conservation values. Our specific aim is to examine the ecological consequences of hydrological change, including emergent issues such as climate change, and focus on the coastal plains in higher rainfall zones where the majority of the Western Australian population resides. Here we argue that human-driven and/or climatically-driven hydrological change deserve greater attention, since they: i) directly escalate the risk of extinction for some components of the biota, or ii) are underlying and/or contributing factors in the manifestation of other threats to the biota, and may complicate or exacerbate some of those threats (such as fire, *Phytophthora* and the spread of weeds). This paper briefly outlines the challenges to the region's biodiversity posed by hydrological change. We suggest a societal adoption of approaches based on water literacy will be necessary to avoid irreversible changes associated with a continued reliance on water resource developments and other energy/water intensive industrial activities.

Keywords: biodiversity, hotspot, conservation, SWAFR, land clearing, salinity, fire, *Phytophthora*, climate change, groundwater extraction, water literacy

Introduction

The southwestern corner of the Australian continent has been identified as a global "biodiversity hotspot", defined as an area where "exceptional concentrations of endemic species are undergoing exceptional loss of habitat" (Myers *et al.* 2000, p. 853). Twenty five such threatened hotspots were identified in 2000, and the number has since been increased to 34 however only one occurs in Australia (Mittermeier *et al.* 2004). The original intention of these determinations has been to raise awareness, and encourage conservation planners to prioritise their investment in mitigating threatening processes. We note that in Western Australia the identification of the southwestern part of the State as a global priority has too-often been one of celebrating international recognition for biodiversity rather than a prompt to reorientate activities to reverse the exceptional loss of habitat. The identification of biodiversity hotspots has also allowed researchers to undertake coarse-scale analyses of emerging threats such as global warming;

Malcolm *et al.* (2006) assessed the 25 biodiversity hotspots using major vegetation types as proxies for natural habitats, and identified southwest Australia as one of six especially-vulnerable regions.

The biodiversity hotspot described in this paper coincides approximately with the South-West Botanical Province (Beard 1980; Beard 1999), updated to the Southwest Australian Floristic Region (SWAFR, *sensu* Hopper & Gioia, 2004). It extends from forested ecosystems dominated by large eucalypts and coastal peatlands, heathlands and fresh perennial wetland systems in the extreme southwest, to species-rich kwongan sandplain heaths in the drier northern and eastern regions between Shark Bay and Israelite Bay, and inland to eucalypt-dominated woodlands and shrublands often called the 'wheatbelt' and mallee regions (see Figure 1). It is often described as an 'island' isolated by ocean to the west and south, and arid areas to the north and east, spanning average annual rainfalls of over 1200 mm close to the southwestern coast to around 300 mm per annum in the interior. Superimposed on these characteristics is a rapidly-expanding human population concentrated along the coastal margins, where rainfall has tended to be higher and less variable.

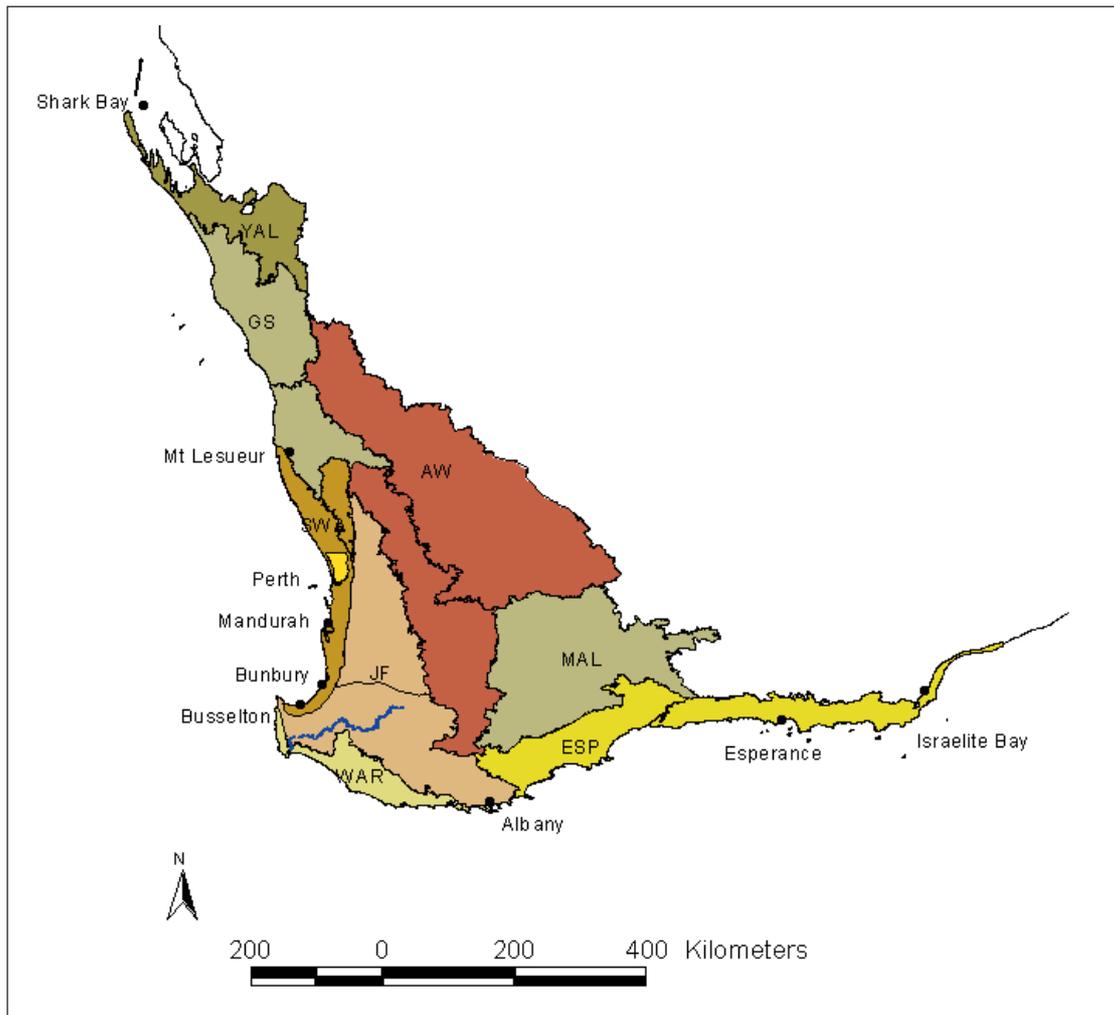


Figure 1. Showing the South West Australian Floristic Region (SWAFR), the location of the Gngangara Mound area (on the Swan Coastal Plain), the middle and lower reaches of the Blackwood River, place names mentioned in the text, and Australian bioregions (where GS= Geraldton Sandplains, YAL=Yalgoo, AW= Avon Wheatbelt, WAR= Warren, SWC = Swan Coastal Plain, ESP= Esperance, and JF= Jarrah Forest). Note: the bioregion of Yalgoo was not recognised as part of the SWAFR by Hopper and Gioia (2004) but is included here because it is regarded as part of the southwestern Australian biodiversity hotspot.

In line with Myers *et al.*'s (2000) intention, in this paper we reconsider the reasons for the conservation priority of southwestern Australia. We commence by briefly reviewing significant characteristics of the flora and fauna, and the way threatening processes may impact on these conservation values. Our aim is to examine the ecological consequences of hydrological change, including emerging issues such as climate change, and particularly focus on the coastal plains in higher rainfall zones where the majority of the State's population resides. Here we argue that hydrological change directly escalates the risk of extinction for some components of the biota, or is an underlying and/or contributing cause for other threats to the biota, and may be exacerbated by some of those threats.

Biological Characteristics of the Southwest Australian Floristic Region

Estimates of the number of native plant species identified in the region vary from 5,469 (Myers *et al.* 2000) to 6,759 (Hopper & Gioia 2004) with 49.0% to 53.9%

being endemic (Beard *et al.* 2000). While representing only about 0.2% of the Earth's surface in area, this diversity of plant life represents 1% of the world's total number of plant species (Hopper & Gioia 2004), and points to the global significance of the region from a biodiversity perspective. This rich biodiversity of the SWAFR is primarily expressed amongst its angiosperms, especially woody families such as Myrtaceae (1283 species/subspecies), Proteaceae (859), Fabaceae (540) and Mimosaceae (503). Other species-rich families include Orchidaceae (374) Ericaceae (including Epacridaceae, 297), Asteraceae (280), Goodeniaceae (207), Cyperaceae (199) and Stylidaceae (178) (Hopper & Gioia 2004).

By March 2006, 351 plant species within the region had been listed as threatened, and approximately 2,500 were of conservation concern according to the State's Department of Environment and Conservation threatened species database. Threatened taxa are mostly woody perennials, one third of which are short-lived disturbance opportunists and species that typically seed after fire such as *Acacia* and *Grevillea* spp. (Atkins 1998;

Bell 2001; Hopper *et al.* 1990). Perennial herbs figure prominently amongst the remaining threatened taxa, more than half being orchids. Spring flowering occurs in two-thirds of the threatened taxa and 40% possess flowers that are probably pollinated by birds and mammals, rather than by insects or wind (Brown *et al.* 1997; Hopper & Burbidge 1986; Keighery 1982).

Invertebrate species also show high levels of regional endemism, with an emphasis on Gondwanan affinities (Edward 1989; Main 1996, 1999). While many invertebrate groups have been inadequately researched, there is sufficient evidence to support generalisations regarding patterns of high endemism: some invertebrate groups are associated with particular habitats (such as cave systems (Jasinska *et al.* 1996) and springs (Knott & Jasinska 1998), and/or pockets of year-round moisture; the terrestrial isopods are a good example (Judd 2005)); others have particular relationships with plants or plant communities (Majer *et al.* 2001) or have speciated locally (for example the non-biting midges Chironomidae (Edward 1989)), while others have a local affinity for freshwater (Horwitz 1997; Pinder *et al.* 2004).

The vertebrate fauna of the southwest is rich, with 456 species listed (Myers, *et al.* 2000), 100 of which are endemic to the ecoregion (How *et al.* 1987). These include eight species of freshwater fish (Morgan *et al.* 1998), 24 amphibians, 50 reptiles, 19 birds, and seven mammals. Five bird species are listed as threatened under the Commonwealth's Environmental Protection and Biodiversity Conservation Act 1999: Carnaby's Black cockatoo, Baudin's Black cockatoo, the Noisy Scrub-bird (*Atrichornis clamosus*), the Western whipbird and the Western bristlebird and a number of species of frogs, reptiles and fish are also listed. Burbidge and McKenzie (1989) noted that the extent of extinction of mammals in Australia since European settlement has no recent parallel on any other continent and southwestern Australia has experienced one of the greatest levels of regional extinction of mammals anywhere in Australia (Short 2004; Woinarski & Braithwaite 1990).

However, although the richness of the southwest region has been recognised at a global level, much of this area has still to be systematically surveyed and catalogued. The Noisy-Scrub bird, *Atrichornis clamosus*, was "rediscovered" at Two People Bay, east of Albany in 1961 (Smith 1985) and the discovery of new genera in recent years, such as the Sunset frog, *Spicospina flammocaerulea*, in 1994 (Roberts *et al.* 1997), and the long-thought-to-be extinct Gilbert's potoroo, *Potorous gilbertii*, also at Two-People Bay (Sinclair *et al.* 1997), should caution against concluding that the biodiversity of this important region is well-known (Main & Main 1991).

This is the case even more so for non-vascular plants, fungi (see May 2002) and other microbes, and even for vascular plants; a third of the 6,759 species known from the SWAFR were described for the first time in the past three decades, and at least another 1000 are estimated to remain unnamed (Hopper & Gioia 2004). Moreover, DNA sequence studies have revealed unexpected lineages of great antiquity. Dasygogonales (the world's most localised order of Angiosperms) has an estimated age of origin of about 120 million years BP, early in the Cretaceous. Perhaps the most surprising recent discovery

has been the recognition of a new order of tiny annuals of temporary seasonal wetlands, the Hydatellales, comprising a single family Hydatellaceae of two genera, *Hydatella* and *Trithuria* (Saarela *et al.* 2007). Hydatellales are richest in the SWAFR, but extend to temperate eastern Australia, New Zealand and India. Previously believed to be obscure monocots, DNA evidence now unequivocally shows that they are among the earliest flowering plant lineages, sister to the water lilies (Nymphaeales), originating even earlier than Dasygogonales.

Recognised Threatening Processes

In their review of biodiversity hotspots, Mittermeier *et al.* (2004) regarded habitat destruction, due to clearing of native vegetation for agriculture, as being the most significant historical process to have led to a loss in biodiversity in the SWAFR. Their principal source of information was vegetation mapping conducted for Western Australia by Shepherd *et al.* (2002). These latter authors claim, *inter alia*, that "A total of 119 associations have been reduced to below 30 per cent of their pre-European extent and of these, 48 have less than or equal to 10 per cent remaining and two are presumed extinct". This clearing of native vegetation in the SWAFR commenced with the arrival of European settlers in 1829 and grew steadily in the early part of the 20th century (Bolton 1972). It accelerated dramatically in the 1960s with the Government's policy of clearing 'a million acres a year' for wheat and sheep farming in the kwongan sandplain areas bordering Mount Lesueur, and in the region between Albany and Esperance. Beard (1999) estimated that the original habitat area of approximately 357 km² in southwest WA has now been reduced by 70% to 107 km². Such habitat destruction and alienation has been identified by fauna specialists as the single most important factor challenging the long-term survival of threatened and endangered species (McDonald *et al.* 2003).

Associated with the clearing of native vegetation for agriculture have been increasing salinity in waterways (Schofield 1990; Bunn & Davies 1992), and the spread of feral predators, competitors and weeds. Salt brought to the surface from rising groundwater contributes to saline runoff into river systems that were previously fresh. Surface flow regulation is also extensive and typically associated with a decline in freshwater biodiversity (Kite *et al.* 1997). The impact of exotic predators, such as foxes and cats, and exotic competitors such as rabbits, sheep and cattle on species extinction is difficult to quantify but universally acknowledged as a major factor in the decline of, especially mammalian, populations (Marshall 1966; Short 2004; Short *et al.* 1992). Mittermeier *et al.* (2004) also regarded the spread of the plant pathogen ("dieback") *Phytophthora cinnamomi*, as the most serious current threat: elsewhere it has been dubbed the 'biological bulldozer' (Shearer 1994; Shearer *et al.* 2004). *Phytophthora cinnamomi* is listed under the EPBC Act 1999 as "a key threatening process to Australia's biodiversity" and of the plant species in the SWAFR, 40% are susceptible and 14% highly susceptible to the pathogen (Shearer *et al.* 2004).

Australia-wide, Cork *et al.* (2006) used expert opinion to rank eight pressures impacting on different aspects of

biodiversity: total grazing, feral animals, weeds, changed fire regime, habitat fragmentation, vegetation clearing, changed hydrology and salinity. They argue that some of these drivers will decline due to adequate control (such as that imposed on land clearing, thereby reducing habitat-modification pressures); some will continue in the future, and some (such as climate change) will increase in importance and severity. They also argued, *inter alia*, that "Increasing direct effects on wetlands and aquatic dependent biodiversity are likely to be made worse with climate change. Inadequate attention has been paid to groundwater-dependent biodiversity."

Burgman *et al.* (2007) explored threat syndromes and conservation strategies for Australian plants, finding that land clearance for agriculture (grazing and cropping) and urbanization have been the primary causes of range contractions and habitat loss in the past, responsible for the current status of the majority of threatened Australian plants. They found that threats growing in importance include disease, salinity, invasive species and changed disturbance regimes. Many species are subject to common, landscape-level threats that often interact as threat syndromes. In some cases, effective mitigation requires 'simple, low-cost changes in policy, such as more stringent controls on land clearance, strategic fire management, and firmer control on the importation of plant species. Other factors will require greater effort and new strategies to mitigate, including social and legal initiatives in urban landscapes and broad strategies for pathogens, climate change and other landscape-level processes.'

The Western Australian Government's most recent State of the Environment Report (Government of Western Australia, 2007) listed 34 environmental issues of priority for the State. Of these, the top priorities were regarded as climate change, population and consumption, greenhouse gas emissions, land salinisation, salinisation of inland waters, introduced animals, weeds, and *Phytophthora* dieback; all were considered likely to have resulted in on-going deterioration over the last ten years. For inland waters, altered water regimes, loss or degradation of wetlands, and loss or degradation of fringing and instream vegetation were listed as belonging to the next most urgent priorities. Within the SWAFR, the Swan Coastal Plain was shown to be the most profoundly affected bioregion (where more than 26 of the State's 34 environmental issues are "active"). Here, intensification of land clearing and continuous development of the coastal margins of the southwest for housing, recreation and tourism is coupled with the State's vigorous resources boom, placing on-going pressure on conservation values with significant alteration to water and nutrient cycles.

These latter arguments suggest that a heightened attentiveness to hydrological change, the declining water availability to ecosystems in the populated coastal margins and Swan Coastal Plain bioregion in particular, is warranted.

Climate change and hydrological change

Our desire to separate causes of environmental degradation ('threats') is problematic when complex systemic factors are at play. Hydrological change on the

Swan Coastal Plain is a good example where underlying or distal causes of hydrological changes must include all of the following, to various degrees:

- I. Climate variability: in particular inter-annual variability in the pattern of rainfall, temperature regimes (air and water), cloud cover, wind direction and strength, and pan-evaporation rates.
- II. Patterns of land-use change: shifts from woodlands or heath to agriculture and horticulture, in some places followed by urban development. For urban areas, land use patterns change with age as suburbs become more vegetated. Each of these shifts in land use is accompanied by different patterns of surface runoff and groundwater recharge from rainfall, and different types of microclimatic feedbacks to the macroclimate.
- III. Patterns of water regulation: damming of catchments has substantially reduced flow from the Darling Scarp onto the Swan Coastal Plain; nearly 120 years of draining has virtually eliminated previously extensive areas of inundation of the Swan Coastal Plain (see for example Bradby 1997).
- IV. Patterns of groundwater extraction: intensive localised extractions for horticulture, agriculture and domestic water supplies plus the extraction of water from private residential bores (see below).
- V. Water infrastructure: patterns of groundwater recharge and behaviour in terms of overconsumptive water use are influenced by inward bound reticulated distribution of potable water through the Integrated Water Supply Scheme (IWSS), and outward bound collection in 'wastewater' facilities before most of it is discharged off-shore. Stormwater runoff is also 'collected' resulting in similar discharge or concentrated recharge in sumps or wetlands (creating a local mounding affect in places; Appleyard *et al.* 1999)
- VI. External drivers: the macroeconomy, lack of adequate water pricing, political ideologies and population growth scenarios influence all of the above.

Hennessy *et al.* (2007) refer explicitly to southwestern Australia for actual and future climate change, particularly increased temperatures and less rainfall. Indian Ocean Climate Initiative (2002) demonstrated this actuality: average May–October and May–July rainfall in the southwest over the last 25 years has been only 85–90% of the preceding 50-year average and stream inflow into Perth's reservoirs over the period 1997–2004 is now only 54% of levels recorded from 1975–1996 (see Figure 2). Nicholls (2006) concluded that the rainfall decrease in southwest Western Australia is likely due to a combination of increased greenhouse gas concentrations, natural climate variability and land-use change (building on observations of atmospheric differentials described by Lyons (2002) between cleared land and uncleared land, and modelling work of others).

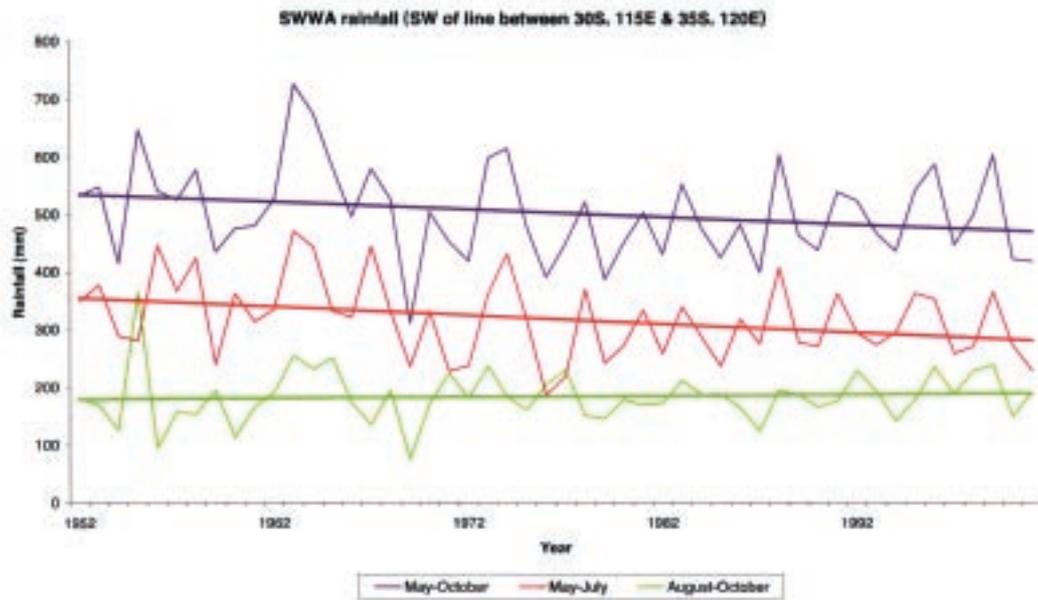


Figure 2. Trends in average yearly rainfall (mm) in the southwest of Western Australia (southwest of a line connecting 30S, 115E & 35S, 120E) from 1952 to 2002 with May–October in blue, May–July in red and August–October in green (from Indian Ocean Climate Initiative 2002).

Perth, the expanding urban area of the Swan Coastal Plain, ranks among those cities most likely to experience future water stress (Flannery 2003; Jenerette & Larsen 2006). This is due to the combined influences above, with sustained *per-capita* water consumption, reduced availability of water, and consequent demand responses. The most accessible groundwater for Perth is that found in the superficial sediments, as unconfined aquifers in the sands of the coastal plains. The most significant of these unconfined aquifers, the Gngangara Mound, occurs under the northern suburbs of Perth and beyond. The exact contribution that this aquifer makes to Perth's water consumption varies from year to year and according to how the figures are calculated but it is substantial; for instance, at least 60% of IWSS water for the Perth metropolitan area comes from the Gngangara Mound, and the more confined, deeper aquifers that underlie it (like the Leederville Formation and the Yarragadee Formation; Davidson 1995). Added to this total extraction is the contribution from unlicensed and unmeasured residential bores; about one third of all homes on the Swan Coastal Plain own such an appliance (Government of Western Australia 2007). In sum, these types of extractions, plus declining rainfall and other extraneous factors, have resulted in groundwater declines of up to 6m on the Mound, and more significant declines in deeper aquifers (Government of Western Australia 2007). A recent report on the management of the Gngangara Mound by the State's Environmental Protection Authority (EPA) gives an estimated loss of 500 GL of water over the last 25 years (Anon 2007). Elsewhere the EPA pointed out that over the last 25 years existing surface storages had been by down-rated by two-thirds of their capacity, and groundwater allocations have increased over the same time to meet demand, including over the past decade. They regarded this situation as not sustainable.

Hydrological change as a threatening process

Broad ecological linkages between hydrology and biology for inland aquatic and terrestrial species, communities and/or ecosystems in coastal margins of the SWA FR are given in Table 1. The Table shows the range of eight possible types of linkages and examples of each. The scheme is based on the principle that linkage between hydrology and biology is a question of degree (similar to Hatton and Evans' (1998) principal criterion that the degree of 'groundwater dependence' is proportional to the fraction of the annual water budget that ecosystem derives from groundwater). The eight types are separated primarily along an axis of water permanence, but secondarily according to the nature of the linkage, related to life history characteristics of organisms and biogeochemical requirements. They therefore build on the categories of groundwater dependence defined by Hatton and Evans (1998) and others (*i.e.* wetlands, aquifer and cave systems, terrestrial vegetation and river base flow systems).

Table 1 shows the consequences for each of these types in response to declining groundwater levels and decreasing rainfall. For instance, perennial streams in the lower reaches of the Blackwood River are fed by fresh groundwater baseflows (see Anon 2006). These tributaries are now the refuge for a number of species of freshwater fish, including Balston's Pygmy perch, *Nannatherina balstoni*, which is listed as vulnerable under the EPBC Act 1999 (Beatty *et al.* 2006; Morgan *et al.* 1998). Such tributaries also significantly freshen the more-saline waters in the river, which have derived from the cleared middle and upper parts of the catchment. The groundwater discharge therefore supports not just populations of freshwater fish in the tributaries, but also flora and fauna in the lower parts of the river dependent upon less saline waters during baseflow conditions (see

Table 1

Broad classes of Hydrology – Biology linkages for inland aquatic and terrestrial species, communities and/or ecosystems in coastal margins of the SWAFR (note does not include marine or estuarine systems where groundwater discharge and surface runoff are important). Examples of linkages are given, along with a prognosis under scenarios of declining groundwater levels, decreasing extent and duration of inundation of surface waters, and decreasing rainfall, and examples from the literature where such effects have been detected or predicted.

Hydrology – Biology linkages	Examples from SWAFR	Prognosis under scenarios of declining groundwater levels and decreasing rainfall
Requirement for seasonal soil moisture	Kwongan vegetation communities Non-phreatophytic terrestrial vegetation Fringing wetland vegetation	Reduced vigour as a result of lower water availability in summer (Zencich <i>et al</i> 2002), decreased rates of surface soil carbon and nutrient cycling. Potentially reduced seed set and shift in population distribution (Groom <i>et. al</i> 2001) and persistence and community composition (Pettit <i>et al.</i> 2001).
Requirement for seasonally moist habitat for aestivation/drought avoidance	Burrowing or sheltering fauna (ie. Salamanderfish <i>Lepidogalaxias salamandroides</i> , see Berra & Allen (1989) and associated species)	Survival provided moisture levels are sustained, however if seasonal inundation fails, less frequent emergence and probably reduced reproduction, may result.
Requirement for a seasonal or intermittent surface saturation	Ephemeral wetland systems (i.e. Sedgeland in Holocene dune swales of the southern Swan Coastal Plain; Semenuik 2007). Riparian habitats in riverine ecosystems, and littoral habitats of Swan Coastal Plain wetlands.	Inundation less frequent (i.e. inundation once every 5 years to once every ten years) or seasonality of inundation changes (decreasing winter-spring inundation and possible incidence of summer inundation). Decreased areal extent and duration of inundation can result in reduced frequency of plant recruitment events (Pettit & Froend 2001), and reduced richness of wetland invertebrates (J Davis, unpublished data).
Terrestrial requirement for access to groundwater table	Phreatophytic vegetation (ie. Banksia woodlands); and the fauna dependent on this vegetation (see Bradshaw <i>et al.</i> 1999, 2007 for the example of the honey possum).	Acute drawdown and low recharge can result in loss of adult individuals of overstorey and understorey species (Groom <i>et al</i> 2000) or local extinction of susceptible species (Froend and Drake, 2006). Less severe circumstances can result in reduced vigour of adults and a shift in the distributions of established juveniles (Groom <i>et al.</i> 2001).
Requirement for groundwater discharge to maintain a particular quality of surface water. This quality can be influenced by physical (ie. surface water temperatures) or chemical (ie. salinity) characteristics.	1. Balston's pygmy perch, other freshwater dependent riverine fauna of tributaries where rivers have increased levels of salt concentrations and lower levels of dissolved oxygen in summer pools. 2. Most stream and river fauna are cold stenotherms and intolerant to elevated water temperature.	1. Contraction of overall range to habitats of suitability (see Morrissy 1978; Nickoll & Horwitz 1999 for the example of marron <i>Cherax cainii</i>). 2. Loss of cold stenotherms (mostly Gondwanan stream and river fauna; Bunn & Davies 1990; Rutherford <i>et al.</i> 2004).
Requirement for permanent surface or subsurface saturation	Permanent lakes, peatlands (ie. waterbirds requiring drought refuge; plants wedded to saturated organic rich sediments; potential acid sulphate soils). Permanent streams-most Gondwanan fauna has annual life histories (e.g. dragonflies)	Change from permanent to temporary stream systems (ie. loss of Gondwanan fauna: Bunn & Davies 1990). Sediments exposed to more frequent drying, potentially displacing biota. Most severe will be drying heating and cracking of sediments that have never been so, changing sediment structure (Horwitz <i>et al.</i> 1999; Semeniuk & Semeniuk 2005) and biogeochemistry; acidification under certain conditions (Sommer & Horwitz 2001).
Requirement for an exchange between surface/subsurface flows and groundwater	Hyporheic fauna in river beds and riparian areas (Boulton <i>et al.</i> 1998)	Altered patterns of carbon and nutrient cycling. Reduced ability to retreat or emerge according to life history requirement. Potential loss of habitat.
Requirement for saturated hypogean (interstitial) spaces (aquifer)	Stygofauna Rootmat communities in caves (Jasinska & Knott 2000)	Where habitat is fixed at a certain stratigraphic level then declines in the saturated zone will strand dependent biota resulting in local extinctions (Boulton <i>et al.</i> 2003). Otherwise distributions of short-range endemics may change according to extent of groundwater drawdown (Humphreys 2006).

Pettit *et al.* 2001 for riparian systems). A decline in rainfall (leading to less groundwater recharge) plus projected declines in groundwater due to local extractions, will have the net effect of reducing the extent of freshwater habitat available for Balston's Pygmy perch in the streams, increasing salinities in the river channel downstream, and presenting the fish with an escalated saline barrier to dispersal into the river channel.

Within the 38 threatened ecological communities currently listed as endangered or critically endangered in Schedules of the Environmental Protection and Biodiversity Conservation Act (1999) (Department of the Environment, Water, Heritage and the Arts 2007), 15 (39%) are in the SWAFR and 10 of these are found on the Swan Coastal Plain or coastal fringe where urban development is occurring. While most are also dependent on groundwater to some extent (i.e. the *Corymbia calophylla* – *Kingia australis* woodlands on heavy soils of the Swan Coastal Plain) some are clearly obligate such as those associated with ironstone outcrops on the Swan Coastal Plain and Scott Coastal Plain (Gibson *et al.* 2000), tumulus (organic) mound springs of the Swan Coastal Plain, aquatic root mat communities in caves north of Perth and in caves on the Leeuwin-Naturaliste Ridge (south of Busselton).

Increased drying associated with groundwater decline will have other biophysical consequences. Periods of inundation will decrease, and periods during which sediments will be exposed to drying, will increase. This consequence would be of particular concern where sediments would otherwise have been exposed to drying only very rarely. Shallow potential acid-sulphate soils form under anaerobic saturated conditions in the presence of iron, sulphur and organic matter. They occur locally but extensively on both the Swan Coastal Plain and the Scott Coastal Plain (Anon. 2003; Degens & Wallace-Bell 2006). Where these soils become dry, acidification is a likely outcome for soils, wetlands and groundwaters (Appelyard *et al.* 2004) posing serious threats to aquatic biodiversity (Sommer & Horwitz 2001).

Together, declines of both groundwater and rainfall can also have interactive effects with existing threatening processes. Inappropriate fire régimes, already a concern (Dixon & Barrett 2003; Hopper 2003; Horwitz *et al.* 2003; Yates *et al.* 2003), may well exacerbate regional drying and their effects may further alter the frequency and intensity of fires, thus influencing the distribution and abundance of plants and animals. Some, such as the endemic trapdoor spiders of the genus *Moggridgea*, which make cocoon-like tubes on tree trunks and short burrows in soil along cuttings and creek banks (Main 1999), and the tiny marsupial Honey possum, *Tarsipes rostratus* (Bradshaw *et al.* 2007; Everaardt 2003; Friend & Wayne 2003), have been found to be particularly susceptible to fire.

The Honey possum is the only terrestrial vertebrate to depend exclusively on flowers for its pollen and nectar diet (Russell & Renfree 1989) and thus is secondarily dependent on water supplies to *Banksia* that form its primary food source (Bradshaw *et al.* 2007). Measurements of rates of food intake in free-ranging animals show that a 10 g Honey possum consumes almost its own body weight per day in nectar and has a turnover of water that is over double the total amount of

water contained in its body (Bradshaw & Bradshaw 1999). The Honey possum is thus highly dependent on nectar production from *Banksia* trees (that are themselves vulnerable to any fall in shallow water tables; Groom *et al.* (2000)).

The examples given above, and in Table 1, show the relevance of direct or indirect reliance of flora and fauna on water, from surface water and groundwater to local pockets of moisture; they are the higher profile tip of hydrology-biology linkages in ecosystems in southwestern Australia. We regard the extraction of groundwater resulting in groundwater declines, and climate change, as seriously exacerbating existing threats such as salinisation, *Phytophthora*, inappropriate fire régimes, and weed proliferation, placing further stress on already strained ecosystems.

Becoming a water literate society

A proposal (Anon 2006) to alleviate Perth's perceived water shortage by extracting and transporting 45 GL per annum from an aquifer some 200 km to its south, the Yarragadee Formation, heightened concerns over ecosystems where hydrology-ecology linkages exist, and where such impacts have not yet been significant. Models predicted that after significant periods of pumping groundwater in southern parts of the Swan Coastal Plain and on the Scott Coastal Plain, the water table would decline where the Yarragadee Formation outcrops (Whincup *et al.* 2005) with concomitant implications for biodiversity: in the region of this formation there were known to be 223 rare and priority flora species and of these a total of 79 taxa had been identified as highly dependent on the maintenance of wetter habitats with shallow water tables (Anon 2006). Although the State Government subsequently shelved the proposal on such environmental grounds, it was replaced with a proposal to build a desalination plant with capacity to produce the same amount of water. Given the projected increase in regional population growth, the threat to the aquifer remains unless the dominant ethic of new resource development is replaced with increased emphasis on the systemic relationships between climate change, land use and local hydrology-biology linkages.

Carpenter *et al.* (1992) drew attention to the possibility for global warming to have consequent local and regional hydrological effects that will have a positive feedback effect and enhance global warming. For instance, the release of greenhouse gases (like methane and carbon dioxide) from wetland sediments that have dried due to declining water levels may exacerbate global warming producing further rainfall declines and lowered water levels. Southwestern Australia is prone to such feedbacks: Horwitz *et al.* (1999) highlighted the release of stored carbon from burning dried and exposed organic-rich sediments. Other feedbacks will come from any realisation of the perceived need to shift to energy intensive (and greenhouse gas emitting) technologies like desalination, or vast interbasin transfers of water, to produce more water for consumption. Similarly, regional extraction and transport of water will potentially dry surface soils at its origin and thereby attract less rainfall. These feedback loops are characteristic of systemic change, and are arguably best dealt with by addressing overconsumption of water by domestic, industrial and

agricultural sectors while being attentive to the six distal causes of hydrological change described above.

Concerted and coordinated action will be needed by natural resource planners and managers if all the threats identified to the plant and animal species in Australia's only threatened biodiversity hotspot are not to result in further losses and extinctions in the coming years (Government of Western Australia 2007). We believe that sustaining the current and projected populations of humans with existing biodiversity in the SWAFR, in the future, will depend on two imperatives:

- i. improving our understanding of the way plants and animals survive with the seasonal and inter-annual delivery of water in the landscape (ecological water requirements); and
- ii. adapting to a different availability of water due to rainfall declines, involving different patterns of land- and water-use.

The aim should be to foster shifts in attitudes to water and the way we behave with respect to water; carefully evaluated public information campaigns (as advocated by Syme *et al.* 2000) and the education sector will therefore play a major role in these imperatives (understanding and interpreting water as an 'ecological literacy' *sensu* Orr (1992)). Mandatory reductions in the domestic consumption of water for metropolitan Perth, matched by dramatic improvements in irrigation efficiencies, will therefore precede further water resource developments, and alternatives will be evaluated. For instance, Coombes and Lucas (2006) have analysed the potential for decentralised options for sustainable water strategies in urbanised parts of southwestern Australia, including rainwater harvesting, water efficient appliances and wastewater reuse strategies. In their analysis of the operation of regional water supply systems they demonstrated that such strategies could provide significant reduction in regional water demand, improvement in regional water security, decreases in greenhouse gas emissions and economic benefits.

Conclusions

Groundwater declines, reduced surface inundations of rivers and wetlands and declining rainfall (all predicted to continue into the future) are evidence of hydrological change in the southwestern Australian floristic region. This paper constructs eight broad ecological linkages between hydrology and the biology for the region, and with examples demonstrates the extent to which ecosystems will be exposed to increased stresses from the hydrological changes. We recommend that our current celebration of the southwestern corner of the continent as a globally-significant biodiversity hotspot needs an urgent refocus: to one of reflection and relearning to both live *with* the land, water and biodiversity, and adapt to the likely consequences of a shift in hydrological patterns in the short to medium term.

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