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Vegetation, fauna and groundwater interrelations in low nutrient temperate montane peat swamps in the upper Blue Mountains, New South Wales

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Abstract: Newnes Plateau Shrub Swamps are a series of low nutrient temperate montane peat swamps around 1100 m elevation in the upper Blue Mountains, west of Sydney (lat 33° 23' S; long 150° 13'E). Transect-based vegetation studies show a closely related group of swamps with expanses of permanently moist, gently sloping peatlands. Vegetation patterns are related to surface hydrology and subsurface topography, which determine local peat depth. While there is evidence that a group of the highest elevation swamps on the western side of the Plateau are more dependent on rainwater, the majority of swamps, particularly those in the Carne Creek catchment, and east and south of it, may be considered primarily groundwater dependent with a permanently high watertable maintained by groundwater aquifers. An integral part of the swamps are a number of threatened groundwater dependent biota (plants–*Boronia deanei* subsp. *deanei, Dillwynia stipulifera,* dragonfly– *Petalura gigantea,* lizard– *Eulamprus leuraensis*), which are obligate swamp dwellers. This association of dependence leaves the entire swamp ecosystem highly susceptible to threats from any loss of groundwater, the current major one being the impact of damage to the confining aquicludes, aquitards, aquifers and peat substrates as a result of subsidence associated with longwall mining. Impacts on the swamps may also result from changes to hydrology through damming of creeks, mine waste water discharge, increased moisture competition from pine plantations, recreational motorbike and off-road vehicle tracks and climate change.

If these groundwater dependent ecosystems do not receive protection from activities such as longwall mining subsidence, significant ecological damage is unlikely to be avoided or able to be mitigated even where provisions of the Commonwealth *Environment Protection and Biodiversity Conservation* and NSW *Threatened Species Conservation* Acts apply to groundwater dependent swamps and biota. The importance of the highest elevation part of the Plateau for a number of restricted (some endemic) plant species is also discussed.

Keywords: Newnes Plateau Shrub Swamps; Blue Mountains; vegetation patterns; peat swamps; fauna; groundwater dependent; threatened species

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Introduction

Wetlands encompass a range of vegetated ecosystems, including those referred to as marshes, swamps, bogs and fens (Mitsch & Gosselink 2007; Mitsch *et al.* 2009). These systems are characterised by a diversity of hydrological regimes, and may be permanently, seasonally or intermittently inundated or waterlogged, and may also include ephemeral wetlands (DECCW 2010a). Wheeler (1999) noted that even in permanent wetlands, water table depth could vary considerably within a particular wetland and between different permanent wetland types. Such spatial heterogeneity, even within a permanent wetland complex, may result in considerable heterogeneity in vegetation associations and habitat, often across small spatial scales (e.g. Clarke & Martin 1999; Jabłońska *et al.* 2011; Keith & Myerscough 1993; Keith *et al.* 2006). For example, wetland complexes are often characterised by a complex intergrading of fens, bogs, swamps or marshes (Hájek *et al.* 2006; Kirkpatrick & Bridle 1998; Mitsch & Gosselink 2007; Wheeler & Proctor 2000; Yabe & Onimaru 1997), occasionally with dramatic changes in pH and vegetation characteristics at very small spatial scales (e.g. Brown *et al.* 1982).

Mires (peat-forming wetlands) include bogs and fens (Gore 1983; Moore 2002), although the terms are applied somewhat differently in the Australasian context (Whinam & Hope 2005). In New South Wales, mire ecosystems are captured within the Coastal Heath Swamps, and Alpine– and Montane Bogs and Fens vegetation classes of Keith (2004). In the Blue Mountains region in the Central Tablelands west of Sydney, these are represented by a number of mire vegetation types including Blue Mountains Sedge Swamps (BMSS), Newnes Plateau Shrub Swamps (NPSS) and Boyd Plateau Bogs, which are characterised by considerable spatial heterogeneity across a number of environmental gradients within and between individual swamps and swamp types (e.g. Holland *et al*. 1992a; Holland *et al*. 1992b). Variation in vegetation across the hydrological gradient (from ephemeral to permanent waterlogging) is particularly evident within the upland swamps developed on sandstone geology, including those of the Newnes Plateau.

The sandstone soils of the Blue Mountains were not suited for agricultural developments in the 19th century and the Newnes Plateau north of Lithgow remained virtually undisturbed until the building of the railway to the shale mines at Newnes in the adjacent Wolgan Valley in the early 20th century. Other developments on the Newnes Plateau later in the 20th century were underground coal-mining (bord and pillar method) north from Lithgow and extensive clearing for pine planting during the 1970s in Newnes State Forest in the centre of the Plateau. Recent developments since 1980 have increased fragmentation of vegetation on the Plateau.

The Newnes Plateau Shrub Swamps (NPSS) were first formally recognised in the 1980s and reports of their scientific conservation values were presented to government boards of inquiry on proposed coalmining and electricity generation projects at that time (e.g. Benson 1981). These projects would have destroyed major swamps in the Carne Creek catchment, but despite project approval, a major proposal, the Birds Rock Coal Mine and Washery and associated railway did not go ahead. Information on the scientific importance and distribution of the swamps was subsequently included in the broad scale vegetation mapping of the Wallerawang 1:100 000 map sheet (Benson & Keith 1990) and in more detail in 2005 (DEC 2006).

The construction of the Newnes shale railway in 1906–7 had little direct impact on the landscape (it ceased use in the 1930s), though one of its tunnels has become an important site for glow worms *Arachnocampa richardsae* (Diptera). However, during its construction a number of plant collections were made by the chief engineer and amateur botanist, Henry Deane. His collections included the type specimens of *Boronia deanei,* collected in 1906, commenting– "There are acres of it, to the exclusion of almost any other plant." (Maiden & Betche 1906). It was recollected in Happy Valley Springs swamp in November 1981 and is now listed as a Vulnerable species under the NSW *Threatened Species Conservation Act* 1995 (TSC Act) because of its limited distribution and restriction to swamp habitat. The occurrence of other restricted swamp plants (e.g. *Dillwynia stipulifera, Olearia quercifolia, Celmisia longifolia*) also became evident in the 1980s following the period of active botanical field exploration. As well, threatened mire-dependent fauna species have been recorded from these swamps, including the Endangered giant dragonfly *Petalura gigantea*, first recorded in NPSS in 2004 (Baird 2012), and the Endangered Blue Mountains water skink *Eulamprus leuraensis*, first recorded in NPSS in 1979 (NSW Wildlife Atlas).

As a result of increasing evidence of the value of the swamps and of increasing threats, *Temperate Highland Peat Swamps on Sandstone* (THPSS) were listed as an Endangered Ecological Community (EEC) under the Commonwealth *Environment Protection and Biodiversity Conservation Act* 1999 (*EPBC* Act) in 2005 (TSSC 2005). Emphasis was placed on their restricted distribution and the impact of threats from introduced animals, increased fertiliser runoff, residential development, clearing, weeds, fire and peat mining. The listing was broad and included swamps occurring along the eastern tablelands of NSW from the Blue Mountains south to Bombala and included swamps in the upper Blue Mountains, and on the Newnes Plateau north of Lithgow. At about the same time, the swamps on the Newnes Plateau were also listed as an EEC under the TSC Act by the NSW Scientific Committee (2005) as the *Newnes Plateau Shrub Swamps in the Sydney Basin Bioregion* EEC.

Developments on the Newnes Plateau now include exotic pine plantations, native forestry logging, sand quarries, coal mines and small-scale rural holdings, in some cases located immediately adjacent to the swamps or separated by narrow buffer strips. Swamps are threatened by small-scale clearing, fragmentation, erosion and sedimentation (all associated with road works), quarrying and periodic timber harvesting from adjacent plantations. Changes to drainage and moisture conditions in some swamps are caused by damming of swamp watercourses; road crossings of swamps;

sedimentation and erosion associated with roadways, quarries, mines and plantation harvesting within swamp catchments; and disposal of waste water from underground coal mines. Considerable ongoing damage to swamps is also occurring as a result of unregulated trail bikes and off-road recreation vehicles. In addition, mine de-watering discharges into headwater streams and swamp systems has occurred across this area causing substantial degradation. Alteration to the natural flow regimes of rivers, streams, floodplains and wetlands is listed as a *Key threatening Process* under the *TSC* Act (NSW Scientific Committee 2002). Invasion of exotic species, including species of *Pinus*, and changes to fire regimes may pose threats to NPSS in future, especially if these processes result in physical displacement of vegetation, increased influx of sediments and/or nutrients, or significant drying of the swamps.

Extractable coal seams at varying depths underlie the Newnes Plateau and underground longwall and board and pillar mining is currently occurring, or proposed to occur, beneath the majority of the listed swamps. Subsidence of the land surface, and associated fracturing of bedrock, occurs after longwall coalmining, and this may change the hydrology of catchments and swamps they contain (NSW Scientific Committee 2005). Specifically, the conversion of perched water table flows into subsurface flows through mine-related voids may significantly alter the water balance of upland swamps (Young & Wray 2000). Changes to surface morphology within or near the swamps as a result of mine subsidence may also create nick points, which become the focus of severe and rapid erosion (Young 1982). Unlike impacts of some of the above threats (such as damming, *Pinus* invasion and road crossings), which may be reversed to some extent, changes which alter subsurface flows and catchment hydrology pose intractable threats to the persistence and integrity of the swamp community. Longwall mining has been listed as a Key Threatening Process under the *TSC Act* 1995 (NSW Scientific Committee 2005) and there has been clear evidence of subsurface damage to some swamps including Wolgan East swamp (Aurecon 2009, Goldney et al 2010, Enforceable undertaking 2011) and loss of groundwater at Kangaroo Creek lower swamp (Centennial Coal 2009, DECCW 2010b).

Understanding the potential impacts of threats to these swamp ecosystems requires a sound understanding of their developmental processes. Swamp hydrology is the result of interactions between groundwater inputs associated with hydrogeology, and climate, catchment size, geomorphology, overland flows and stream inputs. Climate has a direct influence on the hydrological balance through the interaction between groundwater and the balance between precipitation and evapotranspiration. Evapotranspiration is influenced by other climatic variables such as temperature and wind, and site attributes such as aspect and vegetation (Holland *et al.* 1992a; Holland *et al.* 1992b). The total water balance may be simply expressed as: precipitation = infiltration + run-off + evapo-transpiration. An excess of precipitation over evaporation (positive water balance) is a fundamental requirement for the development of the upland mires (Coastal Heath Swamps, Montane Bogs and Fens) of the study area, and more broadly within the region (e.g. Young 1986a). Groundwater is the result of infiltration and subsequent percolation through permeable (porous or fractured) substrates, with variable residence (storage) times between initial infiltration and any expression at discharge sites. Permeability is a function of porosity and may reflect chemical solution processes, or fracture-controlled or secondary permeability related to joints and bedding planes, fault zones and igneous dykes (McKibben & Smith 2000).

Hydrology and water balance (evapo-transpiration compared to precipitation and other hydrological inputs) are the critical factors in determining the development of peatlands or organic-rich wetland soils; the peaty substrate and its dependence on high moisture levels is a key characteristic of NPSS and THPSSS. A basic requirement for peat formation is that plant biomass production (carbon production) exceeds decomposition (ecosystem respiration or carbon output). Consistently high water tables generally provide the necessary conditions for peat accumulation, particularly in cooler boreal and temperate climatic regions (Gore 1983; Moore 1989, 2002; Moore & Bellamy 1974). Conditions of seasonal drying or widely fluctuating water tables, and/or negative water balance as a result of relatively high evapo-transpiration compared to precipitation, are not conducive to accumulation of peat.

Within the Blue Mountains, peat swamps are characterised by considerable heterogeneity in the distribution, composition and depth of peat or organic-rich soils, within and among swamps (e.g. NPSS, see King 1993). This heterogeneity is often strongly correlated to the spatio-temporal heterogeneity in hydrology within swamp patches, and the distribution of suitable habitat for groundwater dependent species. Particular features of NPSS are the often extensive areas of permanently waterlogged peat.

In this paper we focus on exploring the dependence of the swamps and their taxa on an association with continuing high groundwater levels. In a joint project, with separate author expertise in vegetation (DHB) and mire-dwelling fauna (IRCB), we examined vegetation patterns across and within a range of Newnes Plateau swamps, and by drawing together the occurrences and ecology of threatened biota, assess the crucial importance of water regimes in the composition, structure and function of the listed NPSS community. Given the wide range of threats impacting on these swamps, and in particular those impacts that have potential to change, and in particular reduce water table levels in the swamps, these biodiversity conservation issues need to be faced before actions that potentially result in irreversible damage are set in motion.

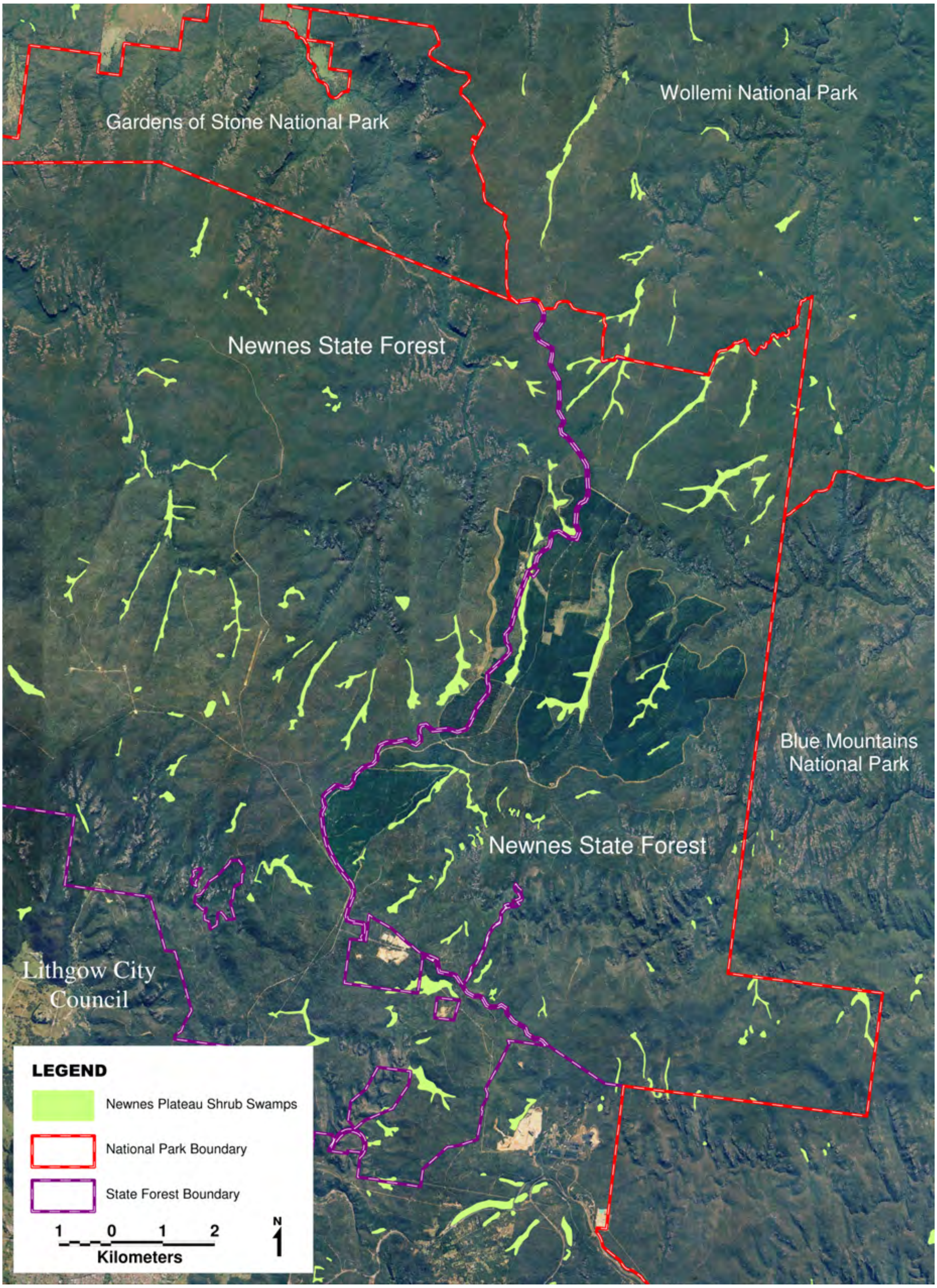

Fig. 1. General distribution of Newnes Plateau Shrub Swamps centred on Newnes Pine Plantation showing clusters of swamps **a)** in upper Carne Creek catchment to the west (Left side) of the Pine Plantation and upper Wolgan River (further west); **b)** to the northeast flowing to Rocky Creek and the Wolgan River; **c)** within the Pine Plantation and southeast flowing to Bungleboori Creek and the Wollangambe River **d)** to the far south around Clarence flowing to Dargans Creek; and **e)** southwest flowing to Marrangaroo Creek and to the south flowing to Farmers Creeks. To the far west is Kangaroo Creek, flowing to the Coxs River. Swamp areas are overestimated for easier identification. The double-dotted north-south line within the Pine Plantation indicates the Glow-worm Tunnel Road..

Study Site

Location

The Newnes Plateau (lat 33° 23' S; long 150° 13'E) is a high elevation sandstone plateau (1000–1180 m elevation) in the western Blue Mountains north of Lithgow. It is mostly under State Forest tenure, with some centrally located exotic pine plantations (*Pinus radiata*), as well as quarries, coal-mines, small rural holdings and a timber mill, surrounded by extensive natural forest, woodland, heath and shrub swamp vegetation. Figure 1 provides an overview of the swamps on the Newnes Plateau. There are few historical names for particular swamps; Browns Swamp at Clarence, and Murrays Swamp used by Deane in 1910 (Australian Railway Historical Society 1979) being exceptions. We have used creek names (where mapped), and the more recent names used in current coal mine company reports (e.g. Springvale Coal 2005, 2008), where applicable. Only one new name has been coined, Broad Swamp, the site of our 1985 and more recent studies. (For names and grid references see Table 4.)

Climate

Rainfall on the Newnes Plateau is relatively high, usually between 880 and 1080 mm p.a. (DEC 2006) with a long-term mean of 1177 mm p.a. (Newnes State Forest Prison Farm records 1939–1998, elevation 1040m). Rainfall is highest in the summer months (Jan– March), but otherwise about 70–75 % of the monthly summer rain falls in other months of the year. Lithgow records are from a lower elevation but show a similar seasonal trend. The Newnes records (1939–1998) pick up the end of the long-term drought (1939–1948) followed by a mild period, but with increasing dryness from 1990 to 1998. Since 1998 drought conditions continued into the mid to late 2000s, followed by higher rainfall in 2011–2012.

Recent work on the geomorphology of the area indicates that during the Last Glacial Maximum (LGM) c. 20 000 years bp, the climate was much drier and the Plateau vegetation was likely to have been treeless (Hesse *et al*. 2003, Wilkinson *et al*. 2005, Wilkinson & Humphreys 2006). With warming climates, swamps began development about 12–14 000 years ago and have been a feature of the vegetation of the Plateau for at least the last 12 000 years (Chalson & Martin 2009).

Newnes Plateau Shrub Swamps

At up to nearly 1200 m, the Newnes Plateau is the highest sandstone area in central southeast Australia, and occupying upland valleys in the headwaters of streams on the Newnes Plateau, at 900–1130 m elevation, and with most above 1000 m are the Newnes Plateau Shrub Swamps, a series of generally narrow elongate low-slope peat swamps. The swamps occasionally occur as hanging swamps on steeper slopes where groundwater seepage occurs as discharge (springs) from rock fracture aquifers or where groundwater is forced to flow laterally to the surface by relatively impermeable strata (aquicludes or aquitards). Swamps develop where the watertable is emergent, and may be associated with perched or extensive unconfined aquifers, or potentially as effluent discharge from confined aquifers (Marshall 2005). Swamps of low gradient valley floors are essentially sediment deposition zones, and have developed in response to impeded drainage and the accumulation of organic-rich sediment and dense hydrophilic graminoid vegetation (e.g. Cyperaceae, Juncaceae, Restionaceae, Xyridaceae, Poaceae). This vegetation further retards surface flow and increases sediment deposition. This process may enhance the development of a perched water table due to its increasing water-holding capacity and slow rates of horizontal seepage. With increasing waterlogging, rates of organic decomposition decrease under more anaerobic conditions leading to the accumulation of peat or at least more organic rich swamp substrates (Keith *et al.* 2006; Young 1986a). Hydrological inputs to these valley floor swamps may include precipitation, overland flows, stream inputs and groundwater inputs where the unconfined (or confined) aquifer emerges within the valley floor. Swamp hydrology is thus a complex interaction between groundwater and climate variables, notably precipitation and temperature, in combination with geomorphic attributes or topographic setting, and permeability of the underlying strata.

The Blue Mountains sandstone aquifer is a complex and poorly understood groundwater-system (DLWC 1999a, b, c). It supports a wide variety of groundwater dependent ecosystems susceptible to changes in groundwater quality and quantity (DLWC 1999c; McKibben & Smith 2000; NSW Government 2002). The best documented of these systems within the study area are those associated with the Narrabeen Group sandstones overlying the Permian Coal Measures in the central-western part of the study area, particularly under the Newnes Plateau and adjoining areas to the west. Bish (1999) reported that both the Illawarra Coal Measures and Narrabeen Group were characterised by fractures that control groundwater flow, and that the regional groundwater system in the Coxs River Catchment included perched, unconfined and confined aquifers. More recent hydrogeological investigations on the western side of the Newnes Plateau (CSIRO 2004) indicated that the study area is characterised by an unconfined aquifer (AQ5) and two confined aquifers (AQ4, AQ3) in Narrabeen Group strata overlying an extensive layer of relatively impervious Mt York Claystone though the Mt York Claystone does not appear to outcrop within the main altitudinal range of NPSS. This, in turn, overlies two additional confined aquifers (AQ2, AQ1) associated with clay-rich or otherwise low permeability strata in the Illawarra Coal Measures (Centennial Coal 2005; CSIRO 2004; Springvale Coal 2005). The extensive unconfined aquifer (AQ5) of this area was reported to be generally responsible for groundwater inputs to the swamps of the Newnes Plateau, although a perched water table has been inferred to occur in association with the small Junction Swamp (Centennial Angus Place 2006; Springvale Coal 2005).

Piezometer data across a number of NPSS and associated headwater streams are gathered for environmental monitoring of the extensive underground coalmines under the area including Angus Place (Centennial Angus Place 2006; Centennial Coal 2005), Springvale (Springvale Coal 2005, 2008), Clarence (Campbell 2007) and Baal Bone Collieries. While descriptions of NPSS have implicitly recognised the importance of moisture levels for the swamp species, there has been a recognition that hydrological regimes vary among individual swamps. Monitoring of some swamps in the western part of the Newnes Plateau (e.g. West Wolgan Swamp) has suggested that these swamps are drier than those on the east and have a greater reliance on precipitation than groundwater inputs compared to other swamps further east on the Plateau. There is also more frequent surface drying (Centennial Angus Place 2006) which is reflected in the relatively low organic content of those swamp soils (see also Benson & Keith 1990). In contrast, those on the eastern side are generally accepted as being associated with an unconfined aquifer that provides permanent groundwater inputs, and consequently are more highly groundwater dependent ecosystems (GDEs). Piezometer data indicate that the water table of Newnes Plateau swamp systems demonstrates a rapid, relatively short-term response to rainfall events (Goldney *et al.* 2010) and gradual longer-term trends in water table drawdown associated with drought cycles (M Krogh pers. comm.). Systems likely to cope with intermittent waterlogging are likely to be more resilient to change than those with permanent moisture requirements. Conversely, the NPSS with permanently high water tables are more highly dependent on groundwater inputs than precipitation, and less likely to be resilient to long-term hydrological changes. These latter swamps are likely to be the habitats of the identified threatened species.

Vegetation

Newnes Plateau Shrub Swamps are characterised by wet heath shrub species including *Baeckea linifolia, Boronia deanei* subsp. *deanei, Callistemon pityoides, Grevillea acanthifolia* subsp. *acanthifolia*, and *Epacris* and *Leptospermum* species (see NSW Scientific Committee 2005). Species abundance varies along gradients of moisture and soil type (Benson & Keith 1990; DEC 2006). Where there is permanent moisture and a relatively high water table, tussock sedgeland with *Gymnoschoenus sphaerocephalus, Xyris ustulata, Empodisma minus*, *Gleichenia dicarpa*, and *Leptospermum* spp.) predominate; while drier sites include herbs such as *Viola* sp., *Xyris gracilis* and *Xanthosia dissecta.* Margins of the swamps with surrounding woodlands are sharp and there is little intermixing of species.

With decreasing altitude, NPSS grade into Blue Mountains Sedge Swamps (BMSS) communities (DEC 2006), the transition occurring between Bell and Clarence at approximately 850–950 m elevation. Other features that distinguish NPSS from BMSS include the presence of high elevation shrub species in the former (such as *Hakea microcarpa*, *Dillwynia stipulifera* and *Boronia deanei)*, and its occurrence on long low slope valley terrain, compared with the often steep seepage slopes and perched headwater valleys (though sometimes including low slope valley swamps) that typifies BMSS habitats at lower elevations in the Blue Mountains.

Blue Mountains Sedge Swamps generally have less cover of shrubs and a greater cover of sedges (particularly *Gymnoschoenus sphaerocephalus*) than NPSS. For example, at Cold Foot Swamp on the Mt Hay road, Holland *et al.*(1992a) recorded an extensive area of permanent swamp dominated by *Gymnoschoenus* with only a fringe of shrubs; though many BMSS are also dominated by dense heath or scrub. Interestingly, the wettest BMSS valley floor swamps may have deeper peats than NPSS.

Key Swamp dependent biota

While most of the swamp-dwelling species are swamp-dependent in that they are generally restricted to moist habitats, many of these species are relatively common and widespread across the range of the THPSS with some common beyond. However, NPSS are also habitat for some taxa that are rare or restricted within the ambit of the THPSS and have been listed individually as threatened flora or fauna. In our view the relationship of swamp hydrology to these key species is a major conservation science issue for these swamps.

Below are notes on key threatened species studied here, and two swamp dependent species, not listed as threatened, but either rare and regionally restricted to NPSS (*Dillwynia*), or that interact with the ecology of the threatened species and may fulfil important ecological and functional roles within these groundwater dependent ecosystems (*Euastacus*). Some additional species are included in the later discussion of rare species on the high elevation plateau (Table 6).

Boronia deanei subsp. *deanei*

Deane's Boronia, *Boronia deanei* subsp. *deanei* (Rutaceae) is a shrub species generally about 1m high, occurring in localised patches that are most distinctive as patches of pink flowers in spring, particularly in the larger NPSS in the Carne Creek catchment and north of Clarence. A separate and disjunct group of populations occur in various swamps on the Boyd Plateau on granite geology (Kodela *et al.* 1996), about 70 km south of Newnes Plateau. *Boronia deanei* subsp. *deanei* is listed as Vulnerable under the NSW TSC Act. (The related subspecies, *Boronia deanei* subsp. *acutifolia,* also listed as Vulnerable, occurs in two disjunct areas on the Southern Tablelands, Fitzroy Falls/Budderoo, and Nalbaugh National Park near the Victorian border).

Petalura gigantea

The giant dragonfly, *Petalura gigantea* (Odonata: Petaluridae) is a very large dragonfly and equally the fifth largest in Australia with a wingspan up to at least 13 cm. Like most petalurid dragonflies, *Petalura gigantea* are characterised by a fossorial (burrowing) larval lifestyle (Baird 2012; Tillyard 1911) that is unique in the Odonata (Corbet 2004). A long larval stage of at least five years has been documented in other fossorial petalurids internationally, and studies to date suggest a larval stage of at least six years, and possibly more than 10 in *Petalura gigantea* (for review,

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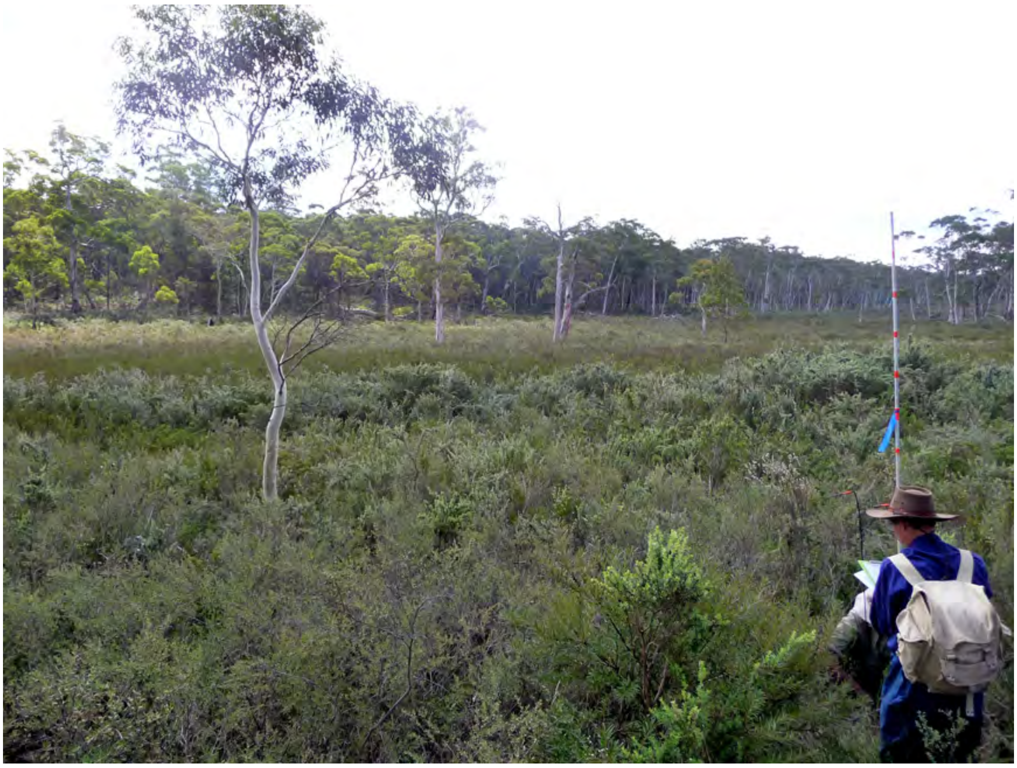


b

Fig. 2. Photos of Broad Swamp in **a)** 1985, view looking east showing trees along shallow interfluve ridge, and **b)** 2012, looking northwest from opposite side, showing similarly placed trees.(photos DHB, M. Krogh)

see Baird 2012). The species has a late spring to summer flying and breeding season, with imagos persisting for one season. *Petalura gigantea* has been recorded from swamps, bogs and seepages along the coast and ranges of NSW, with a patchy distribution extending from near the Victorian border to the far Northern Tablelands, and from near sea level to 1240 m altitude (Baird 2012; Theischinger & Endersby 2009; Trueman 2000). The species appears to be restricted to the following freshwater wetland vegetation classes of Keith (2004): Coastal Heath Swamps, Montane Bogs and Fens, and possibly peripheral to Coastal Freshwater Lagoons. In the latter case, any occurrence may be associated with patches of Coastal Heath Swamp. Within the Blue Mountains region, it has been recorded from a number of swamp or mire types, including NPSS (Baird 2012).

Successful *Petalura gigantea* breeding sites are characterised by a groundwater regime that provides sufficient surface moisture to minimise risk of desiccation of eggs and early larval instars, supports development of organic-rich peatland (mire) soils suitable for larval burrowing, and maintains a water table height that larvae can access within established burrows or adaptively through burrow deepening. For this reason the species is considered to be an obligate groundwater dependent mire dwelling species (Baird 2012).

Petalura gigantea is listed as Endangered under the TSC Act 1995, with declining population size, and loss or degradation of wetland habitats in which it occurs, identified as threats to its survival (NSW Scientific Committee 1998). All swamp types where *Petalura gigantea* has been recorded in the Blue Mountains are either specifically identified within descriptions of Commonwealth (EPBC Act 1999) or NSW (TSC Act 1995) EECs or could be considered covered by one of these listings.

Eulamprus leuraensis

The Blue Mountains water skink, *Eulamprus leuraensis* (Scincidae) is endemic to mid to upper elevation BMSS and to NPSS (Dubey & Shine 2010; LeBreton 1996; NPWS 2001). The species is viviparous and grows to 64 (–72) cm (SV) long (Swan *et al.* 2004). It is known to use burrows of the crayfish *Euastacus australasiensis* as both fire and predation refugia (I.R.C. Baird pers. obs.). In addition to identified threats (urban development, pollution, sedimentation, alteration to hydrological regimes, weed invasion, visitor disturbance, cat predation) (NPWS 2001), climate change has been identified as a potential threat to this stenotopic, patchily distributed reptile (Dubey & Shine 2010). A recent genetic study has identified low rates of genetic exchange and high genetic divergence between discrete swamp populations, and recommended that most populations be treated separately as discrete conservation units (Dubey & Shine 2010). The species is listed as Endangered under the TSC Act 1995 and the EPBC Act 1999.

Dillwynia stipulifera

Dillwynia stipulifera (Fabaceae) is a small shrub restricted to swamps on the Newnes Plateau with disjunct occurrences on the South Coast in wet heath and mallee in Morton National Park at Corang Peak and south of Sassafras.

Euastacus australasiensis

The burrowing Australian crayfish *Euastacus australasiensis* (Decapoda: Parastacidae) occurs in streams and upland swamps of the Sydney region, including the swamps of the Newnes Plateau (Growns & Marsden 1998; Merrick 1998; Morgan 1997; Buchanan 1980; Young 1980); on current knowledge it is the only indigenous upland swamp dwelling crayfish within the Blue Mountains. *Euastacus* may occur in both valley floor swamps and hanging swamps on valley sides and may be locally abundant in individual swamps Although not listed as threatened, its burrows have been observed to provide fire and predation refugia for *Eulamprus leuraensis* (IRCB pers obs.). Burrow investigations within Blue Mountains swamp systems have not been undertaken, but investigations of Tasmanian mire dwelling crayfish (*Parastacoides* spp.) have revealed complex burrow structures, groundwater dependence and unique functional roles (e.g. Growns & Richardson 1988; Richardson & Swain 1980, 1991).

Methods

Swamp selection and measurement

The Newnes Plateau Shrub Swamps occur scattered over an area of c. 440 km². Henson (2010) has included 75 of these swamps in an aerial survey of the Newnes Plateau, but this is far from being a comprehensive list as it excludes many other, particularly smaller swamps. Henson's list also includes swamps of Ben Bullen State Forest and Angus Place to the west of the Plateau, which have been mapped as Coxs River Swamps (see Benson & Keith 1990). The general distribution of NPSS (Figure 1) is centred on Newnes Pine Plantation and consists of clusters of swamps: a) in upper Carne Creek catchment to the west of the Pine Plantation (including study sites underlined– Carne West, Gang Gang West, Carne Central and Broad Swamps) and upper Wolgan River (further west) (West Wolgan, East Wolgan Swamps); b) to the northeast flowing to Rocky Creek and the lower Wolgan River (Deanes Creek Swamp); c) within the Pine Plantation and southeast flowing to Bungleboori Creek and Wollangambe River (Pine Swamp) d) to the far south around Clarence flowing to Dargans Creek; and e) southwest flowing to Marrangaroo Creek (Marrangaroo Swamp) or Farmers Creek and f) to the northwest (Kangaroo Creek Upper and Kangaroo Creek Lower Swamps) flowing to the Coxs River.

In the current study, transects were recorded from 10 swamps, while many others have been visited by us during periods of fieldwork. The concentration of these, including some of the largest ones, in the upper catchment of Carne Creek is a major feature of their distribution, and a series of swamps here were selected for examination. Additional swamps at higher and lower elevations were also sampled. Swamp margins show relatively clearly in air-photo overlays and the physiographic attributes of the study site swamps – length, breadth, elevation, slope – were compiled from 1:25 000 topographic maps.

Vegetation spatial patterns

In February 1985 a series of vegetation transects were recorded in a large swamp (Broad swamp) (lat 33° 22' 44.9", long 150° 13' 41.74", elevation 1046 m) in the Carne Creek headwaters (Figure 2). This swamp included an extensive population of *Boronia deanei* and other characteristic swamp plant species; at the time (1985), the proposed above-ground mining and washery infrastructure of the planned Birds Rock colliery directly threatened this swamp and others nearby.

Analyses of the 1985 data showed species clusters related to soil moisture but were difficult to interpret spatially as surface and sub-surface topography had not been measured. To gain a better understanding of vegetation in relation to surface water and peat depth patterns, additional transects across a representative selection of the main NPSS were recorded in February 2012. Swamps selected ranged from highest elevation westerly sites to lower elevation ones in the northeast, and included a major component of the mid elevation swamps known to be habitat for the particular threatened species listed above. Plant species occurrence was recorded in a pair of 0.5 x 0.5 m quadrats at 5 m intervals along a transect across each swamp from edge to edge, generally at its widest point, and generally transverse to the main drainage line. Transects ranged in length from 35 m to 130 m. At each sampling point sediment/peat depth was measured with a probe, and the relative height of the soil surface measured using a pocket level and measuring staff. This enabled construction of swamp profiles showing soil depth in relation to soil surface.

Our use here of transverse transects with 10 to 30 subplots to characterise swamp vegetation is the first time (apart from 1985) that sampling has taken into account the variation in vegetation that occurs across these swamps, which may be 50–100 m across; previous studies (e.g. DEC 2006) and monitoring has usually relied on only one or two 20 x 20 m quadrats per swamp.

The vegetation data were examined firstly for any clustering of swamps across the Plateau, and then for patterns within individual swamps, mainly in the larger Carne Creek/ Clarence/eastern swamps (Figure 1). To provide an indication of any substantial change over time, 1985 and 2012 patterns within Broad Swamp were compared. Analyses of the vegetation data used multivariate packages in Primer v6 (Clarke and Gorley 2006)[1], with presence/absence data and Bray-Curtis similarity measure to construct MDS ordinations and dendrograms; and PATN (Belbin 2004) using the Bray Curtis similarity measure with Flexible UPGMA (for sites); and Two-step with Flexible UPGMA dendrograms and Two-way tables (for species).

Substrate depth and waterlogging

Substrate depth was determined using a 1.8 m x 8 mm diameter steel rod probe, measuring at each vegetation plot along each swamp transect. The probe was either pushed until it reached bedrock, until it was not possible to easily push further, or until it reached 1.8 m depth (measurements were taken by the same observer to maintain consistency). The rationale was to record the depth of more organic-rich swamp sediment (up to 1.8 m) that could be differentiated from denser mineral substrates due to its higher penetrability. Very few records were >1.8 m deep.

Groundwater dependent biota

The transects included recording occurrence of the identified groundwater dependent biota *Boronia deanei* and *Dillwynia stipulifera*, and observations of any *Eulamprus leuraensis*. To relate potential *Petalura gigantea* breeding (oviposition and larval burrow) habitat to vegetation and substrate attributes, a *Petalura* index was recorded by *Petalura gigantea* expert IRCB (0= not suitable habitat, 1= possible habitat, 2= highly likely habitat). At the same time, surface moisture depth was measured. Based on the experience of IRCB, sites with recorded and potential habitat may be treated similarly in the context of this study, for comparison of habitat attributes.

The occurrences of the swamp-dependent biota were tabulated; including all recorded and potential *Petalura gigantea* sites in Newnes Plateau Shrub Swamps (IRCB records, NSW Wildlife Atlas and this study), and records of *Eulamprus leuraensis* (NSW Wildlife Atlas, IRCB records) and *Boronia deanei* on the Newnes Plateau (National Herbarium of NSW and DHB records).

Additional observations have come from other sources, including vegetation notes from various swamps by DHB (during vegetation mapping and survey 1975–85, 2007–11); studies of *Petalura* and its habitat (between 2003–11 by IRCB as part of his doctoral research); and habitat and behavioural observations of *Eulamprus leuraensis* and *Euastacus australasiensis* (IRCB pers. obs.). For example, Baird (2012) investigated 40 *Petalura gigantea* burrows across four swamp types in the Blue Mountains, and documented burrow morphology and their relationship with groundwater depth within burrows. In addition, observations of the location of hundreds of burrow openings and oviposition locations across more than six years of fieldwork, and the characteristics (organic content and waterlogging determined qualitatively) and depth of the substrate at burrow locations (see Baird 2012) have also informed the analysis.

Results

Physiographic features of the swamps

Typically the NPSS have a narrow elongate shape, though larger swamps have broader lobes associated with side drainage lines. Most swamps are relatively long; those studied ranging from 2 km for Pine Swamp down to 700 m for West Wolgan (Table 1). Longitudinal swamp gradients are relatively gentle with total vertical elevational drops for individual swamps over their lengths ranging from 60 m/

[1] Clare, K.R. and Gorley, R.N. 2006. PRIMER v6: User Manual/ Tutorial. PRIMER-E: Plymouth.

km (3.4° slope) for Marrangaroo to 14 m/km (0.8° slope) for West Wolgan. These drops do not include the relatively steep nick point cascades associated with outcropping sandstone, that terminate most swamps. Maximum swamp widths ranged from about 80 m up to about 150 m for Broad Swamp. Transect lengths ranged from 30m (Pine) to 150m (Broad Swamp). Estimated surface areas based on these measurements, range from small <4 ha to c.10 ha (for Broad Swamp).

The upper margins of the swamps studied begin at elevations between 1000 and 1140 m, with the majority around 1100 m. Swamps terminate at nick point cascades at elevations between 960 to 1130 m. Based on the topographic figures, the swamps fall roughly into three groups; the high elevation swamps (Sunnyside West, West Wolgan and Kangaroo Creek Upper); the swamps of the upper Carne Creek catchment and east and south of it to the Clarence area (with upper margins at about 1100 m; and the lower elevation swamps (<1000 m) (Table 1).

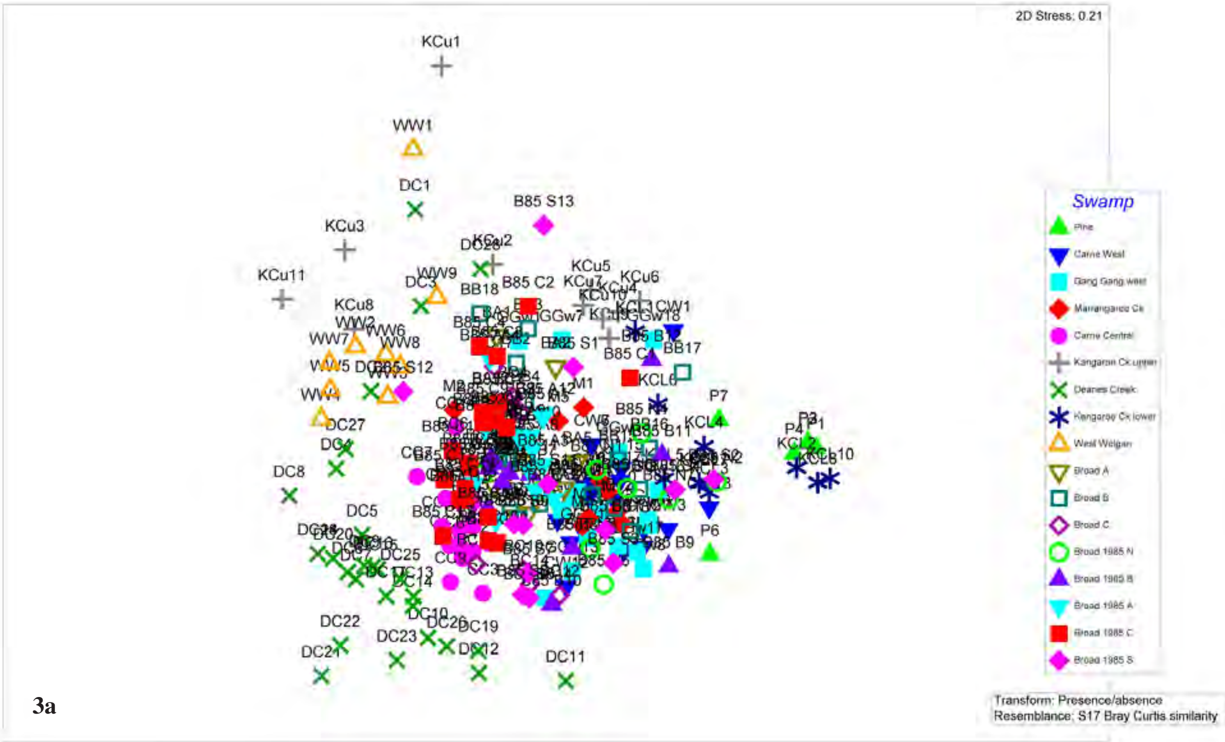
Spatial clustering patterns of swamps

MDS ordination (with Bray-Curtis similarity) of presence/absence data from the 2012 swamp sampling (Figure 3a) show the Carne Creek catchment swamps (CW, GGW, CC, BS), Clarence area and eastern swamps (M, P), and the western KCL form a relatively cohesive group, separate from the other western swamps (WW, KCU) and the northeastern Deanes Creek swamp. Within the Carne Creek/ Clarence/ eastern group the undisturbed Carne Creek catchment swamps (CW, CC, GGW, BS) and some KCL plots cluster strongly, separate from Pine (adjacent to a pine plantation) and remaining KCL. The Carne/eastern/Clarence group swamps are associated with greatest peat thickness (Figure 3b), surface depression (Figure 3c), presence of rock below the peat (Figure 3d), high *Petalura* index (Figure 3e), (Figure 3f) and surface water readings 2–6 cm deep (Figure 3g). In the above analyses, the 2-dimensional stress levels were relatively high (=0.2). According to Clarke and Warwick (2001), MDS ordination stress levels <0.2 still gives a potentially useful 2-dimensional picture, though for values at the upper end of the range too much reliance should not be placed on the detail of the plot. Where stress levels in 2 dimensions approached or exceeded 0.2, 3-dimensional MDS was used to investigate swamp vegetation relationships. Analysing the data in 3-dimensions usually reduced the stress levels to acceptable levels. These analyses indicated that the eastern swamps were all associated with *Empodisma minus, Grevillea acanthifolia* and *Epacris paludosa*, which were virtually absent from the western swamps (which have *Leptospermum myrtifolium, Leptospermum continentale, Epacris microphylla, Boronia microphylla*), and the northeast swamps (*Baeckea utilis*), though other wetter swamps to the northeast, such as Budgary, also have *Empodisma minus, Grevillea acanthifolia* and *Epacris paludosa* (PATN analyses).

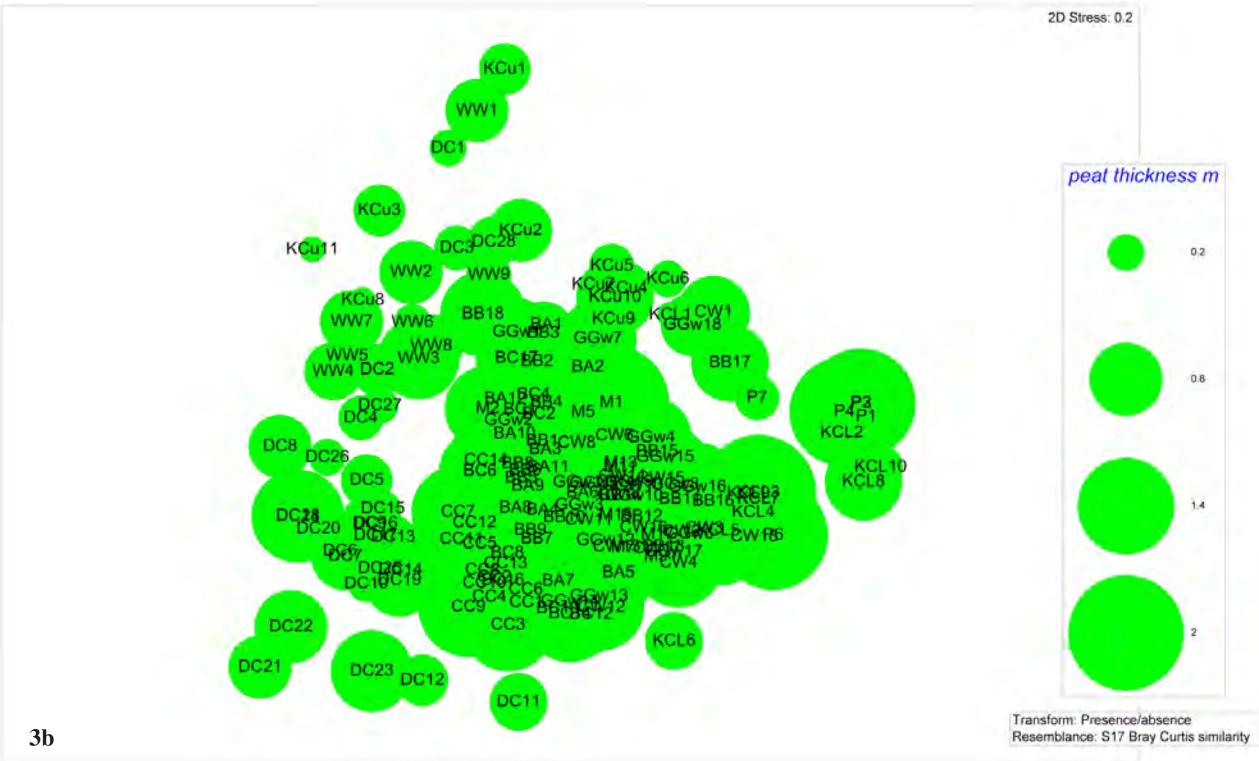
All transects were across essentially undisturbed swamps, though Pine Swamp was shaded by trees from an adjacent mature pine plantation and had an unusually high component of *Blechnum* fern. However we had recorded some transects in 2010 in East Wolgan Swamp which had been severely damaged by discharges of excess mine water in 2007–08, simultaneously undermined by longwall mining in 2008, and subject to instability allowing loss of water to aquifers 70 m below the swamp (Aurecon 2009, Goldney et al 2010). Data from transects through the resulting bare areas and drying swamp showed establishment of weeds such as *Cirsium vulgare* and some native colonising *Senecio* species, as well as seedlings of *Grevillea acanthifolia* (which subsequently died in the ongoing dry conditions) (Figure 4). Including this 2010 transect data with that of all the other sites (Figure 5) shows that while some plots fall within the normal range for NPSS other plots are now quite unrelated to any other swamp. In January 2012 the drying vegetation appeared relatively unchanged and there was still no sign of any surface water flow.

Table 1. Study area swamps sampled by transect in 2012 showing main physiographic features (elevation range, length, width, area, peat depth) ordered by increasing upper elevation limit. Swamps of the Carne Creek-Clarence/ eastern groundwater dependent cluster of swamps are highlighted. Swamp locations are given in Appendix 1.

Swamp	Upper elev m	Lower elev m	Length m	Drop m/ km	Main width m	Estimated area ha	Max depth m	Average depth m	No of plots	Transect length m
Deanes Creek (DC)	1000	960	1500	27			1.3	0.49	28	135
Broad (BS)	1080	1040	1500	27	130	20	1.4		40	150(AB), 85(C)
Carne Central (CC)	1090	1060	750	40	100	5	1.6	1.21	14	65
Gang Gang west (GGw)	1100	1050	1500	33	100	5	1.2	0.82	18	85
Carne west (CW)	1100	1060	1700	24	80	10	>1.8	0.96	18	85
Marrangaroo Creek (M)	1100	1040	1000	60	80	5	>1.8	1.13	9	80
Kangaroo Creek lower (KCL)						5	>1.8	0.68	10	45
Pine (P)	1120	1060	2000	30	80	10	1.8	1.3	7	30
Kangaroo Creek upper (KCU)	1140	1120	800	25	50	5	0.9	0.33	11	50
West Wolgan (WW)	1140	1130	700	14	40	5	1	0.51	9	40

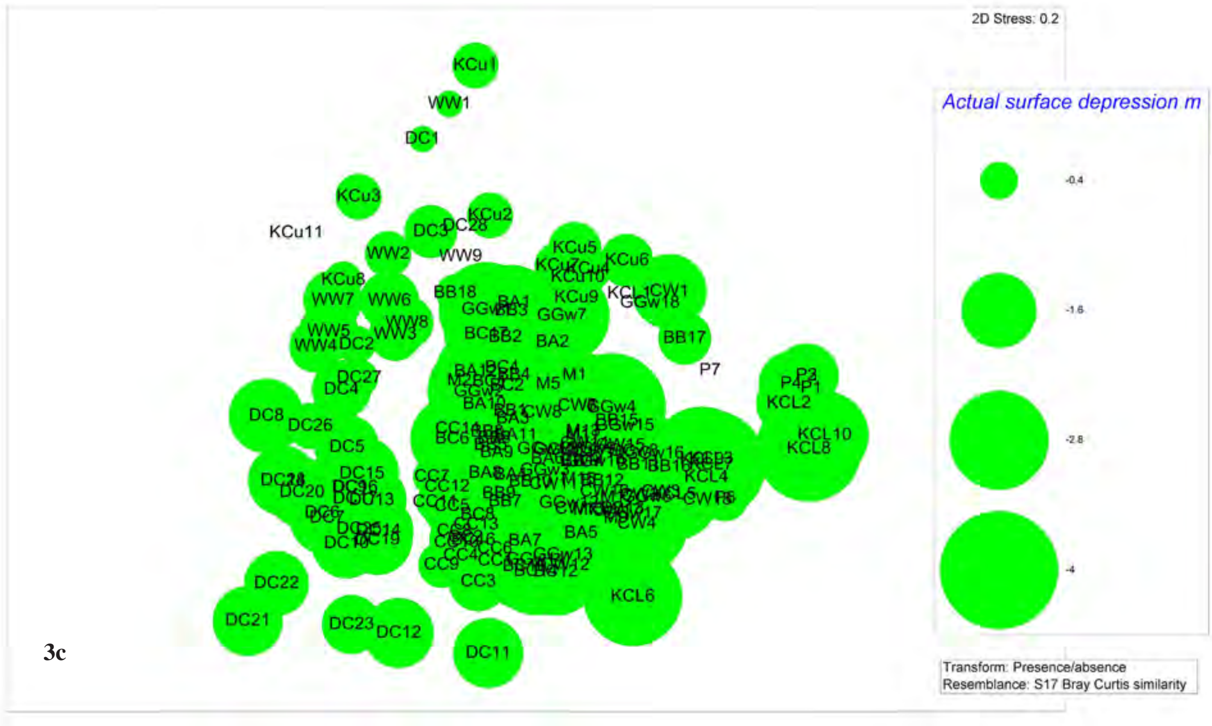


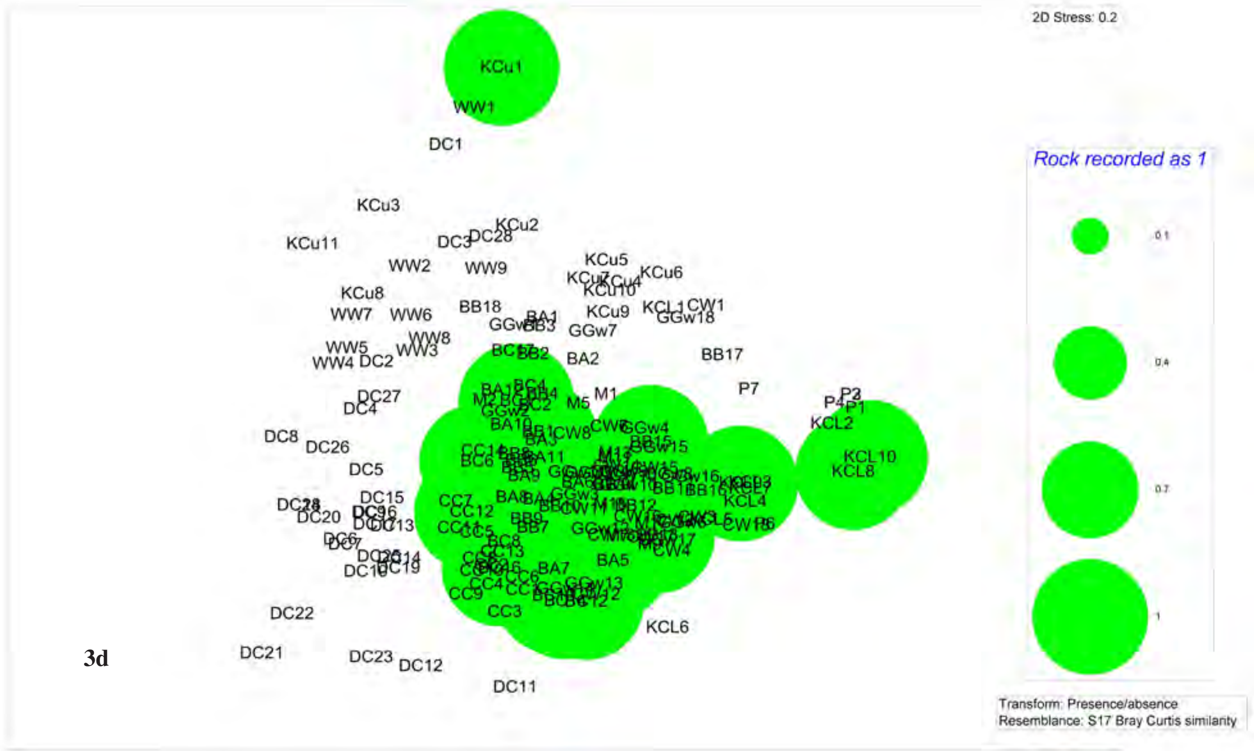
3a

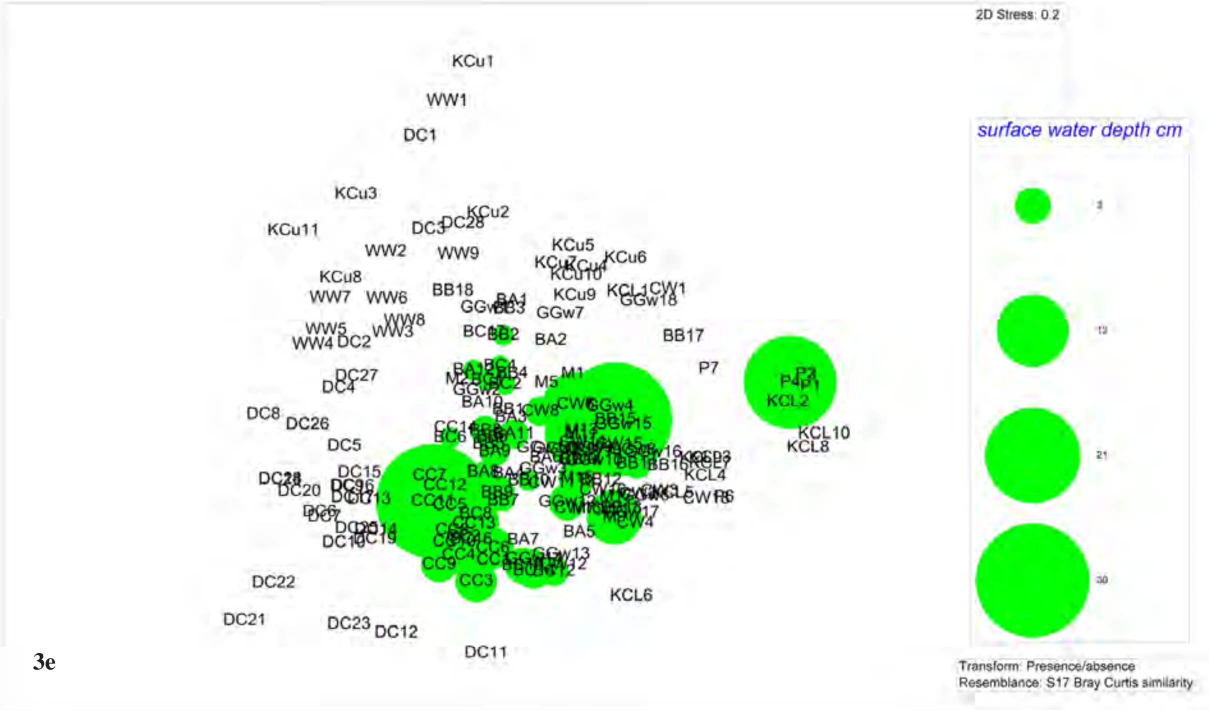


3b

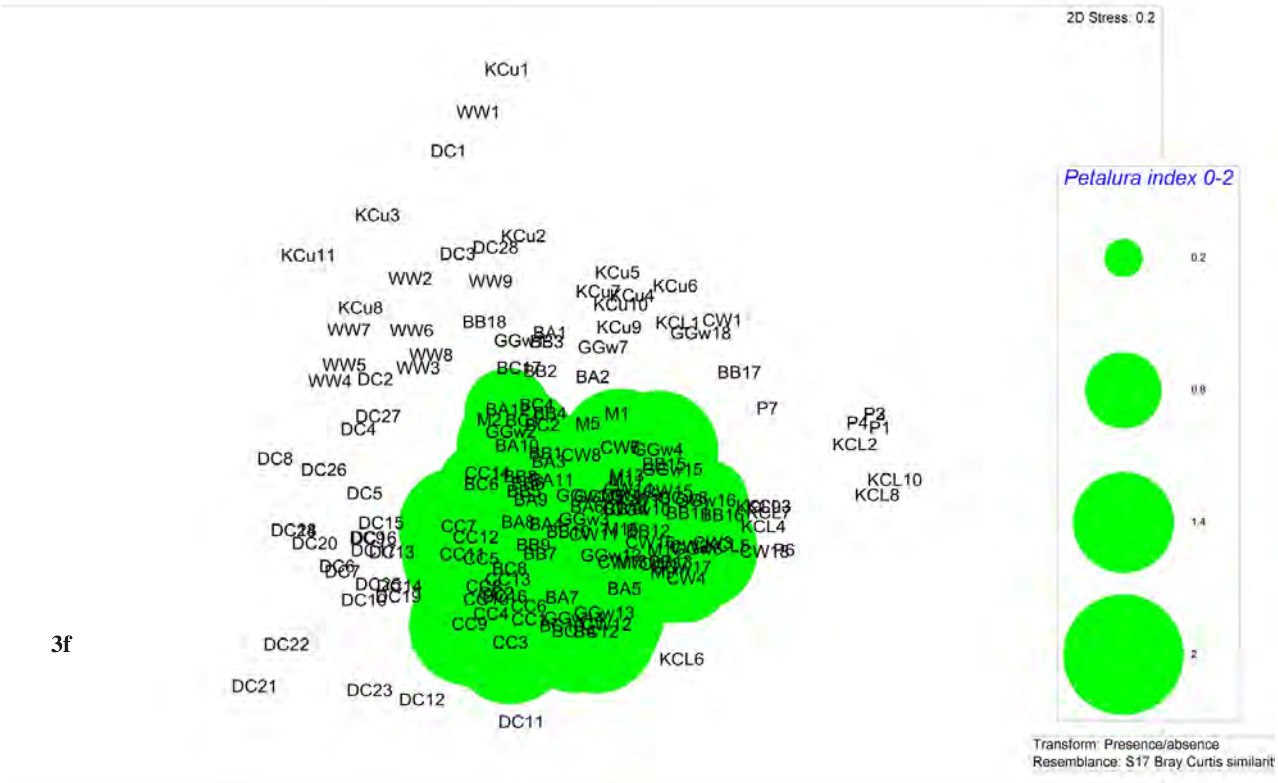
Fig. 3 a-g. Ordination of swamps sites showing **a)** central concentration of wet (Carne/ Clarence/eastern) swamps clustered separately from drier ones, Kangaroo Ck Upper, West Wolgan **(top left)**, and Deanes Ck **(bottom left)**; and swamp sites associated with **b)** greatest peat thickness; **c)** surface depression; **d)** presence of rock below the peat; **e)** surface water; **f)** high *Petalura* index and **g)** *Boronia deanei* occurrence.


2D Stress: 0.2
Actual surface depression m
-0.4
-1.6
-2.8
-4
Transform: Presence/absence
Resemblance: S17 Bray Curtis similarity
3c

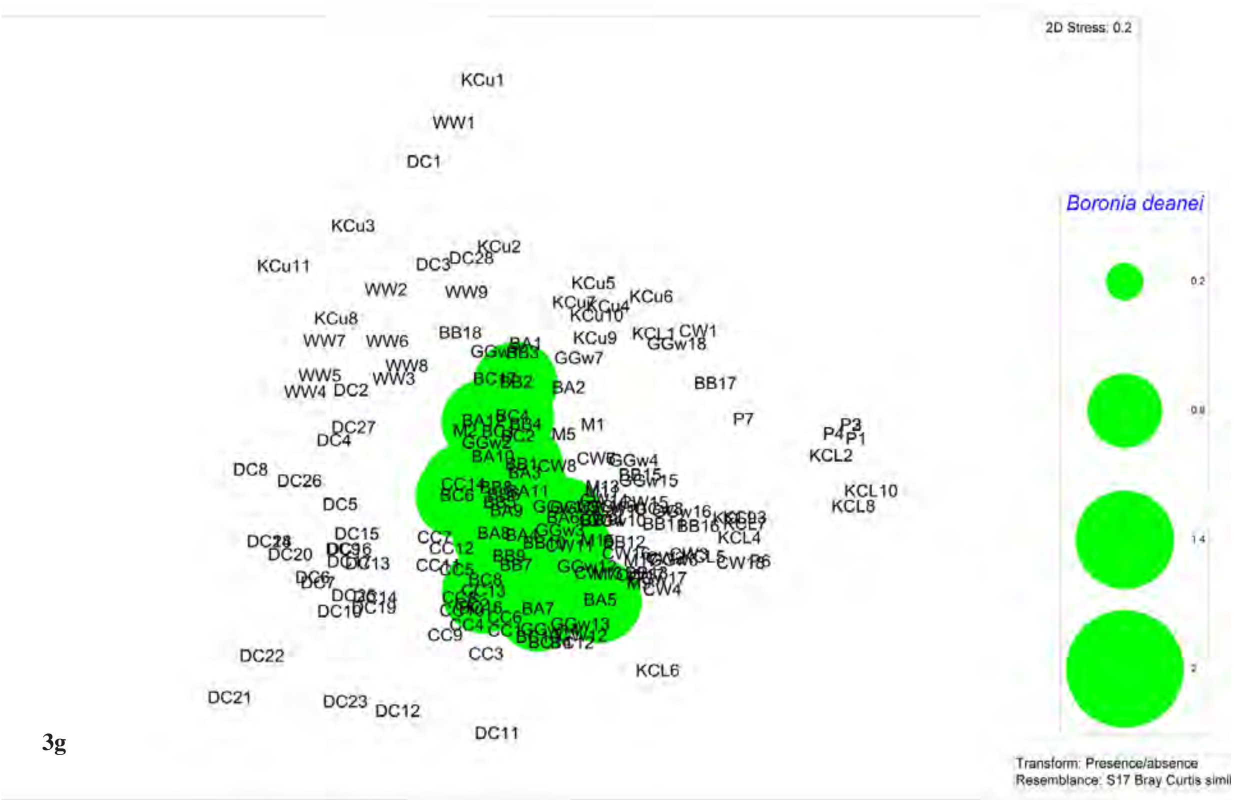

2D Stress: 0.2
Rock recorded as 1
0.1
0.4
0.7
1
Transform: Presence/absence
Resemblance: S17 Bray Curtis similarity
3d


2D Stress: 0.2
surface water depth cm
3
12
21
30
Transform: Presence/absence
Resemblance: S17 Bray Curtis similarity
KCu1
WW1
DC1
KCu3
KCu11
WW2
WW9
KCu8
WW7
WW6
BB18
BA2
BB17
P7
KCL2
KCL10
KCL8
DC8
DC26
DC5
DC22
DC21
DC23
DC12
DC11
KCL6

3e


2D Stress: 0.2
Petalura index 0-2
0.2
0.8
1.4
2
Transform: Presence/absence
Resemblance: S17 Bray Curtis similarit
KCu1
WW1
DC1
KCu3
KCu11
WW2
WW9
KCu8
WW7
WW6
BB18
BA2
BB17
P7
KCL2
KCL10
KCL8
DC8
DC26
DC5
DC22
DC21
DC23
DC12
DC11
KCL6

3f



3g

Surface and subsurface topography and soil depth

Cross-section profiles of the swamps show considerable variation in topography at both surface and subsurface levels (Figure 6, Appendix 1), rather than the simplistic picture of the swamps as broadly concave or bowl-shaped as previously assumed, at least by us. Swamp surfaces are generally asymmetrically concave with lowest depression to one side of the centre-line, generally adjacent to the steepest, but not necessarily highest side; one side of the swamp often extends further upslope than the other (e.g. see Figure 6b– Gang Gang West).

Swamp subsurface levels (i.e. bottom of peat deposit) rarely parallel surface levels, particularly in the narrower swamps, but are more complicated, and with stronger asymmetry. A marked feature of many of the subsurface profiles is that they are biconcave, with an asymmetric central ridge (e.g. see Appendix 1 – West Wolgan; Figure 6a – Carne West). The ridges relate to subsurface interfluves between the main and side drainage lines where these run parallel before converging (presumably reflecting the occurrence of pre-swamp drainage lines). At the surface they result in narrow peninsulas of mineral soils or islands of shallower peat over mineral soils. Where the peat is absent or very shallow these interfluves may support woodland and swamp margin species and even occasional eucalypts, despite being located in the middle of the swamp. The relatively shallower peat showed up in the vegetation along the transect AB across Broad Swamp which cut across one of these 'interfluve ridges' (Figure 6d), though in other swamps the total depth of peat may reduce any vegetation effect.

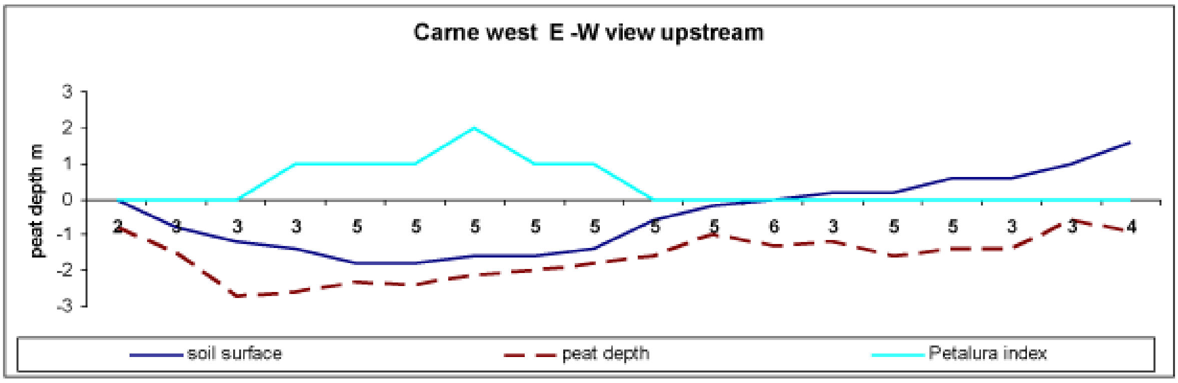
Peat depth depends on the relative shape of the surface and subsurface features. It is closely related to the topography of the underlying valley floor, and is not necessarily apparent from surface vegetation except where shallow as described above. Plots with the deepest peat (mean 1.3 m) were in Kangaroo Creek Lower and Pine, narrow, relatively steep-sided swamps, and associated with *Gleichenia*. Peat depths in the Carne/Clarence/eastern swamps ranged from 0.6 – 1.3 m, but, for the western swamps were substantially less, 0.3–0.6 m.

In addition to depth, soil probes also suggested a complex developmental history for swamp sediments, with considerable variation in substrate characteristics, at and among probe locations within individual swamps. Variation in penetrability and sediment coarseness was able to be determined qualitatively during this exercise, with contrasting layers evident. Fine and coarse sands, clayey material and soft waterlogged peats could all be differentiated during this process as the probe is pushed more deeply. Particularly noticeable were contrasting layers between highly penetrable peat, and dense sands or sandy clays. Probe locations with such contrasting layers were generally located either near swamps edges with adjoining non-swamp habitats upslope, or in association with drainage lines. In both cases, based on the results of the swamp cross-sectional profiling, it may be presumed that these contrasting layers are the result of episodic disturbance events throughout the developmental history of these swamps. These events may result in

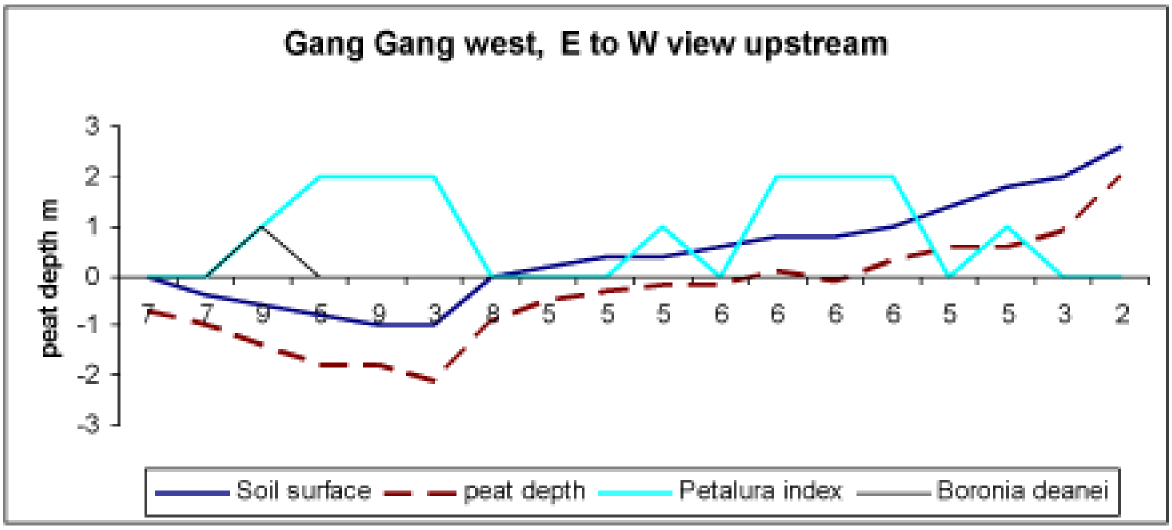
Fig. 4. East Wolgan Swamp in August 2011 showing dead vegetation and bare ground resulting from mining impacts (photo L. von Richter).

Fig. 5. Ordination position of East Wolgan plots (recorded 2010) in relation to data from all other swamps (including 1985 data for Broad Swamp).

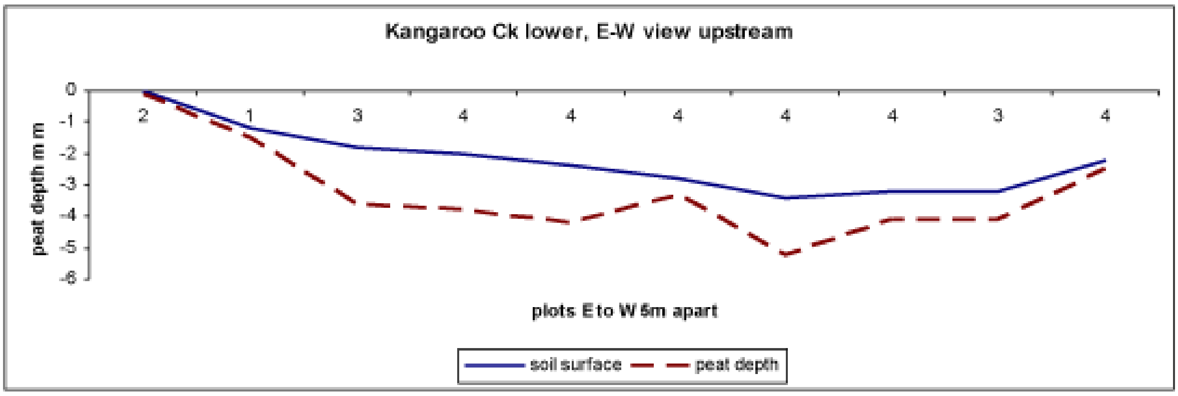
6a


Carne west E -W view upstream
peat depth m
3
2
1
0
-1
-2
-3
2 3 3 3 5 5 5 5 5 5 5 6 3 5 5 3 3 4
soil surface
peat depth
Petalura index

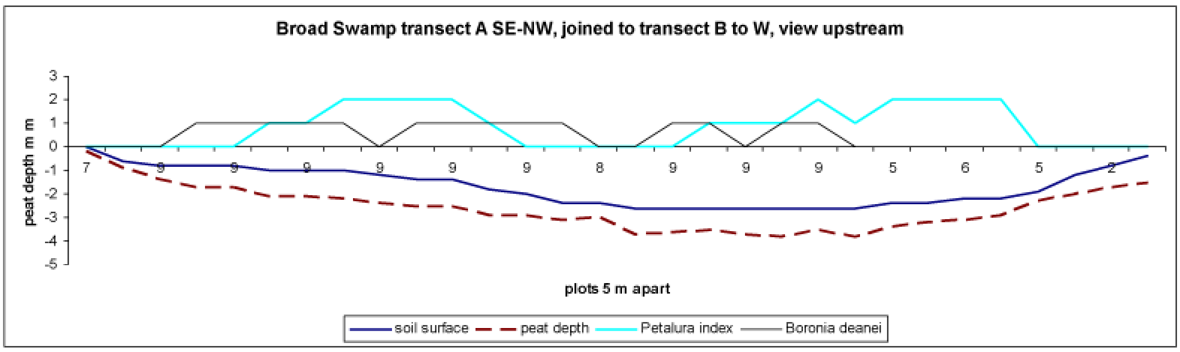
6b


Gang Gang west, E to W view upstream
peat depth m
3
2
1
0
-1
-2
-3
7 7 9 6 9 3 8 5 5 5 6 6 6 6 5 5 3 2
Soil surface
peat depth
Petalura index
Boronia deanei

6c


Kangaroo Ck lower, E-W view upstream
peat depth m m
0
-1
-2
-3
-4
-5
-6
2 1 3 4 4 4 4 4 3 4
plots E to W 5m apart
soil surface
peat depth

6d


Broad Swamp transect A SE-NW, joined to transect B to W, view upstream
peat depth m m
3
2
1
0
-1
-2
-3
-4
-5
7 9 9 9 9 9 9 8 9 9 9 5 6 5 2
plots 5 m apart
soil surface
peat depth
Petalura index
Boronia deanei

6e

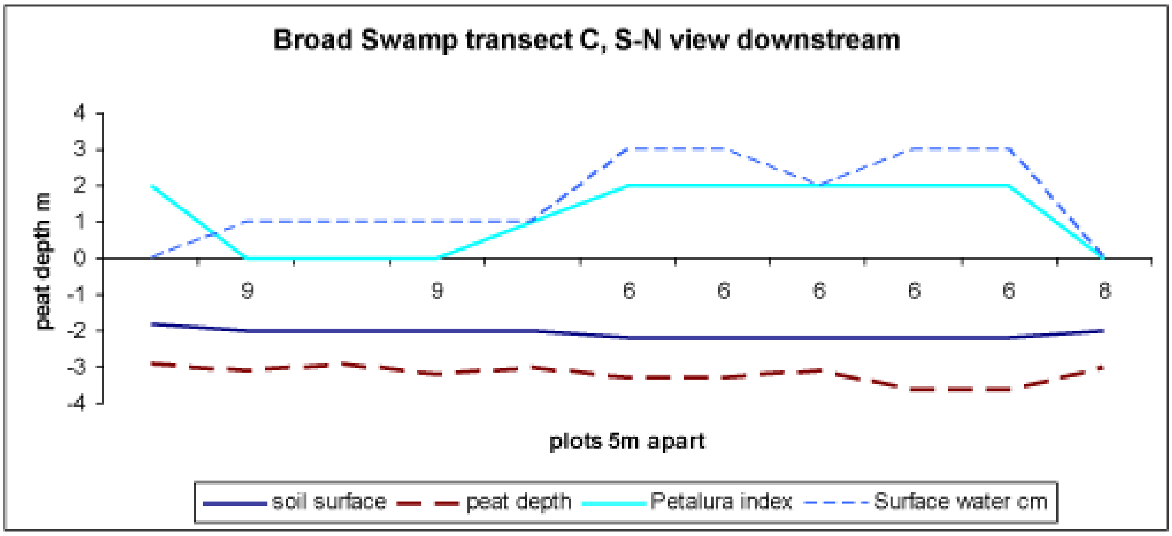


Fig. 6a – e. Cross-sections of Carne West, Gang Gang, Kangaroo Creek Lower and Broad Swamps (2 transects) showing PATN site groups (Figure 7) in relation to surface topography and peat depth.

substantial erosion and transport of upslope sediments into the swamp system as either overland flow from adjoining forest or woodland, or along drainage lines. Typically, the basal layer was composed of dense material, which was presumed, based on the experience of the authors, to be either sands or sandy clays deposited prior to development of the overlying more organic rich peatland soil layers at the probe location. However, it should not be assumed that these basal sediments are necessarily indicative of the earliest date for initiation of swamp sedimentation, as episodic disturbance events (severe fire and/or drought followed by severe erosion) may result in localised loss of swamp sediments through erosion.

In the 1980s the eastern swamps were generally wet underfoot. In 2008–10, following a decade of relatively dry climatic conditions, they were generally dry underfoot except along main surface water channels. In 2012 all parts of the Carne/ Clarence/ eastern swamps had moist subsoil, and all swamps had some overland flow. While most of these swamps have a main drainage line, side drainage lines also provide significant water and areas of surface waterlogging. Some vegetation patterns are related to current surface topography with surface drainage lines following low-lying sections of the swamp.

Vegetation patterns within the Carne/Clarence/eastern swamps

Data from the seven Carne/Clarence/ eastern swamps (99 plots x 55 species, presence/absence data) were analysed separately and interpreted through a PATN two-way table at 10 group level (Figure 7, Table 2). Plots in these swamps are united by all having the almost ubiquitous small sedge *Empodisma minus* (except Pine swamp Group 1 which is affected by adjacent pine plantations, and some Woodland edge plots – Group 2). *Empodisma* is generally associated with peat swamps, and with permanent longterm moisture, and occurs widely in swamps from sea level to alpine areas. It is also the main peat-forming species in ombrotrophic mires in New Zealand (Agnew *et al* 1993) (where it also occurs with *Gleichenia*), and is likely to be a major peat forming species in NPSS.

The 99 plots are more or less evenly divided on the presence of *Gleichenia dicarpa*, an easily recognisable rhizomatous groundfern generally indicative of permanent moisture, and associated with soaks and seepage areas, but not tolerant of longterm or permanent standing water. *Gleichenia* requires high light levels and damp ground, preferring situations where its roots are wet and its fronds are in the sun. It colonises disturbed seeping ground and requires constant moisture to survive. Mature plants do not respond well to disturbance. Five site groups with *Gleichenia* are recognised; *Gleichenia* – *Blechnum* fernfield (Pine Swamp plots probably affected by adjacent pine plantation shading/competition), Woodland intrusion/ margin plots, two *Gleichenia* – *Empodisma* fernfield units (depending on presence or absence of surface water), and *Baeckea* shrubland. These plots all tend to be in the narrower swamps.

The 5 site groups without *Gleichenia* are; a Woodland intrusion/margin group (7), and a group (8) with similar species (including *Velleia montana*) associated with shallow peat over "interfluve ridges". The other three groups are associated with surface water and deep peat. Of these, Shrub-rich swamp (9), including almost all occurrences of *Boronia deanei,* is restricted to large embayments in Broad swamp, where surface water is likely to depend on rainfall events (such areas were very dry during the recent drought). Buttongrass sedgeland (6) was related to main drainage lines which are likely to have more permanent flows. *Empodisma* dominated sedgeland (10) was only found in Carne Central swamp, which has a much shallower and less concave surface profile than the other deep swamps (mean surface

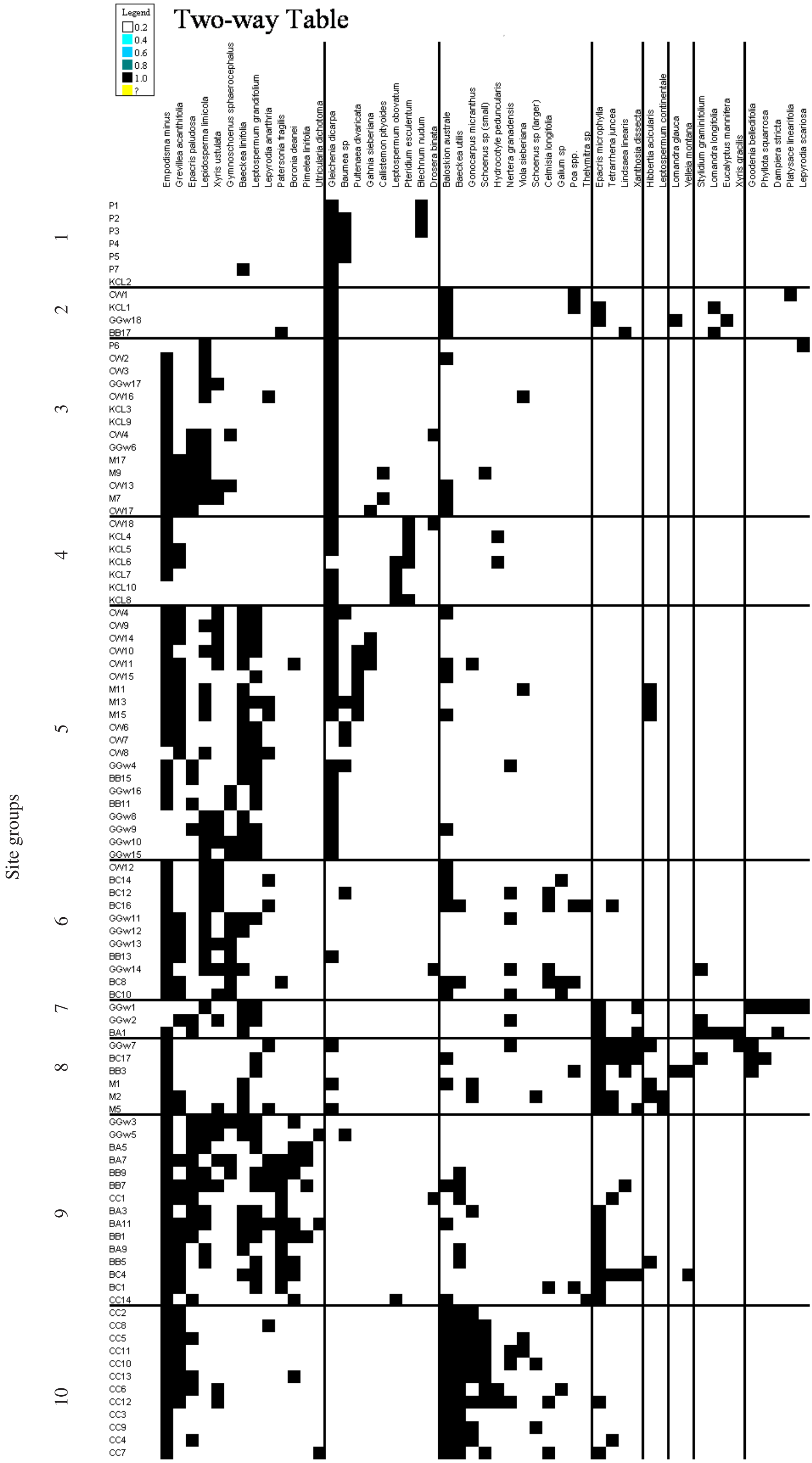


Fig. 7. PATN two-way table (99 plots x 55 species) showing 10 site groups with related species composition. (see also Figure 6 and Table 2)

Table 2. Site groups (from PATN analyses) for 99 plots in seven Carne/ Clarence/eastern swamps, showing occurrence of *Empodisma* and *Gleichenia*, associated species, plot parameters means (KW values), possibly attributable as state/transition components.

Empodisma present	*Gleichenia* present	Plot conditions	Peat thickness	Other species	PATN site group	Notional state/ transition name	Percent of plots	Mean Petalura index 0-2	Mean distance from edge m	Mean surface water depth cm	Mean peat thickness m	Mean surface depression m	Mean rock presence 0-1
0	+	Edge plots	shallow	*Baloskion*	2	Woodland margin intrusion	4%	0	1.3	0	0.6	0.6	0
0	+	Pine Swamp	deep	*Blechnum,* few species	1	*Blechnum* fernland	7%	0	6.4	2.9	1.1	0.9	0
+	+	Dry surface, Kangaroo Ck Lower	shallow	*Leptospermum obovatum,* few others	4	*Gleichenia -Empodisma* fernland	7%	0	11.4	0	0.6	2.3	0.3
+	+	Surface water,	shallow	*Grevillea acanthifolia, Baeckea linifolia, Leptospermum grandifolium*	5	*Baeckea/Leptospermum grandifolium* shrubswamp	20%	0.9	26.3	3.6	0.7	2.2	0.1
+	+	Surface water	deepest	*Grevillea, Lepidosperma limicola*	3	*Gleichenia -Empodisma* fernland	14%	0.2	13.6	0.5	1.2	1.8	0.1
+	0	Edge plots, shallow, dry	shallow	*Baeckea linifolia, Epacris microphylla, Xanthosia dissecta, Stylidium*	7	Woodland margin intrusion	3%	0	1.7	0	0.5	1.9	0
+	0	Surface water	deep	*Grevillea, Lepidosperma, Gymnoschoenus*	6	Buttongrass swamp	11%	1.6	26.4	1.6	1	2	0.6
+	0	Surface water, deep peat, non-edge, not main channel	deep	*Grevillea, Epacris paludosa, Patersonia, Boronia deanei, Leptospermum grandifolium, Lepidosperma, Epacris microphylla*	9	Shrub-rich swamp	15%	0.7	35.3	0.7	0.9	1.8	0.4
+	+	Dry, non-edge, shallow peat	shallow	*Epacris microphylla, Baeckea linifolia, Gleichenia*	8	Intra-swamp ridge species	6%	0	21.7	0	0.8	1.5	0
+	0	Deep surface water, shallow surface depression, Carne Central swamp	deepest	*Grevillea, Baloskion, Baeckea utilis, Gonocarpus micranthus*	10	*Empodisma* sedgeland	12%	1.8	17.5	6.1	1.2	0.6	0.1
							KW value	38.4	37.1	31.7	31.6	26.6	9.9

depression 0.6 m compared to 1.8 m (Group 3) to 2.2 m Group 5), and may have an impact on subsurface moisture movement perhaps resulting in shorter periods of saturation. Group 10 had the highest surface water depth (mean = 6 cm), the highest incidence of *Petalura* occurrence and the deepest peat (mean = 1.2m).

There are clearly relationships between site/species groups and surface/subsoil moisture conditions, and swamp physiographic conditions (Figure 6). The fieldwork was carried out after a particularly wet season and we could not assess how long surface water is likely to remain, though deep channels are likely to be permanent flows. Associations with peat depth are mainly evident at shallower depths, differences in depths greater than 1 m do not appear to have much direct effect, though there is little information about the importance of root depth for swamp species.

Notional state/transition names have been applied to the site/species groups but at this stage it is not clear how consistent and repeatable from swamp to swamp these units are. The major swamp species appear to be long-lived, and though their distribution relates to current physical properties, some features such as peat depth are likely to be permanent, but others, such as surface water depths are likely to vary depending on climatic conditions. Species composition in Woodland margin/intrusion sites may indicate relatively recent responses to disturbance regimes including fire, drought or sediment movement.

Overall, despite the potential spatial variation in hydrological characteristics within swamps the main core species of NPSS are surprisingly consistent. Long-lived, tall growing and mostly lignotuberous shrubs– *Grevillea acanthifolia*, *Epacris paludosa*, *Leptospermum grandifolium*, *Baeckea linifolia*, and rhizomatous graminoids *Lepidosperma limicola*, *Lepyrodia anarthria*, *Xyris ustulata* and *Gymnoschoenus sphaerocephalus* occur in most site groups, with the ubiquitous but shorter growing, *Empodisma minus.* Ecological attributes of the main plant species are shown in Table 3 but a better understanding of the individual ecology of these species, and particularly the rhizomatous fern *Gleichenia dicarpa*, which may be a key identifier of particular longterm water movement, is now needed.

Table 3 Ecological attributes of main swamp plant species showing three clusters:- resprouters/distance dispersed; resprouters/local dispersal; short-lived/soil seedbank. (y=yes, n=no, ?=unknown)

Species	Family	long-lived soil seedbank	resprouts	long-lived	vegetative spread	large canopy	distance dispersal
1) resprouters/ distance dispersal							
Baeckea linifolia	Myrtaceae	n	y	y	n	?	y
Drosera binata	Droseraceae	n	y	y	?	n	y
Gleichenia dicarpa	Gleicheniaceae	n	y	y	y	y	y
Leptospermum grandifolium	Myrtaceae	n	y	y	n	y	y
Juncus planifolius	Juncaceae	?	y	y	n	n	y
Baeckea utilis	Myrtaceae	n	y	y	n	n	?
2) resprouters/ local dispersal							
Boronia deanei	Rutaceae	y	y	y	n	n	n
Epacris paludosa	Ericaceae	y	y	y	n	n	n
Grevillea acanthifolia	Proteaceae	y	y	y	n	?	n
Empodisma minus	Restionaceae	?	y	y	y	n	n
Lepyrodia scariosa	Restionaceae	?	y	y	y	y	n
Patersonia fragilis	Iridaceae	?	y	y	n	n	n
Gonocarpus micranthus	Haloragaceae	y	y	y	y	n	?
Gymnoschoenus sphaerocephalus	Cyperaceae	?	y	y	n	y	?
Lepidosperma limicola	Cyperaceae	?	y	y	y	y	?
Lepyrodia anarthria	Restionaceae	?	y	y	?	n	?
Baloskion australe	Restionaceae	?	y	y	y	n	?
Xyris ustulata	Xyridaceae	?	y	y	n	y	?
3) short-lived/ soil seedbank							
Xanthosia dissecta	Apiaceae	y	y	n	n	n	?
Epacris microphylla	Ericaceae	y	n	n	n	n	n
Epacris obtusifolia	Ericaceae	y	n	n	n	n	n
Pimelea linifolia	Thymelaeaceae	y	n	n	n	n	n
Sprengelia incarnata	Ericaceae	y	n	n	n	n	n
Viola hederacea	Violaceae	?	n	y	y	n	?
Gonocarpus tetragynus	Haloragaceae	y	?	n	n	n	?

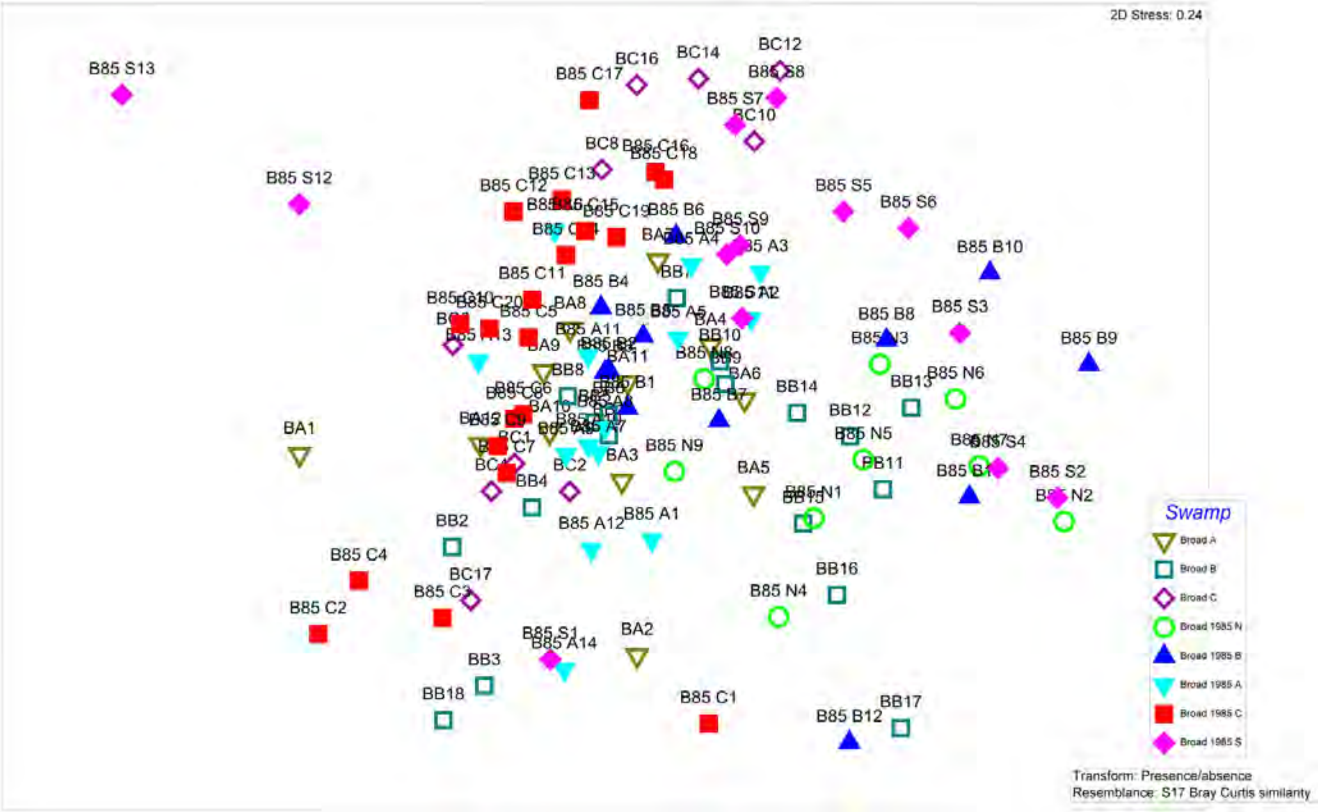


Fig. 8. Ordination of plots from Broad Swamp in 1985 (closed symbols) and 2012 (open symbols) shows a similar spread of plots for both time periods indicating stable vegetation. Transects A, B and C correspond, but N and S were not remeasured in 2012.

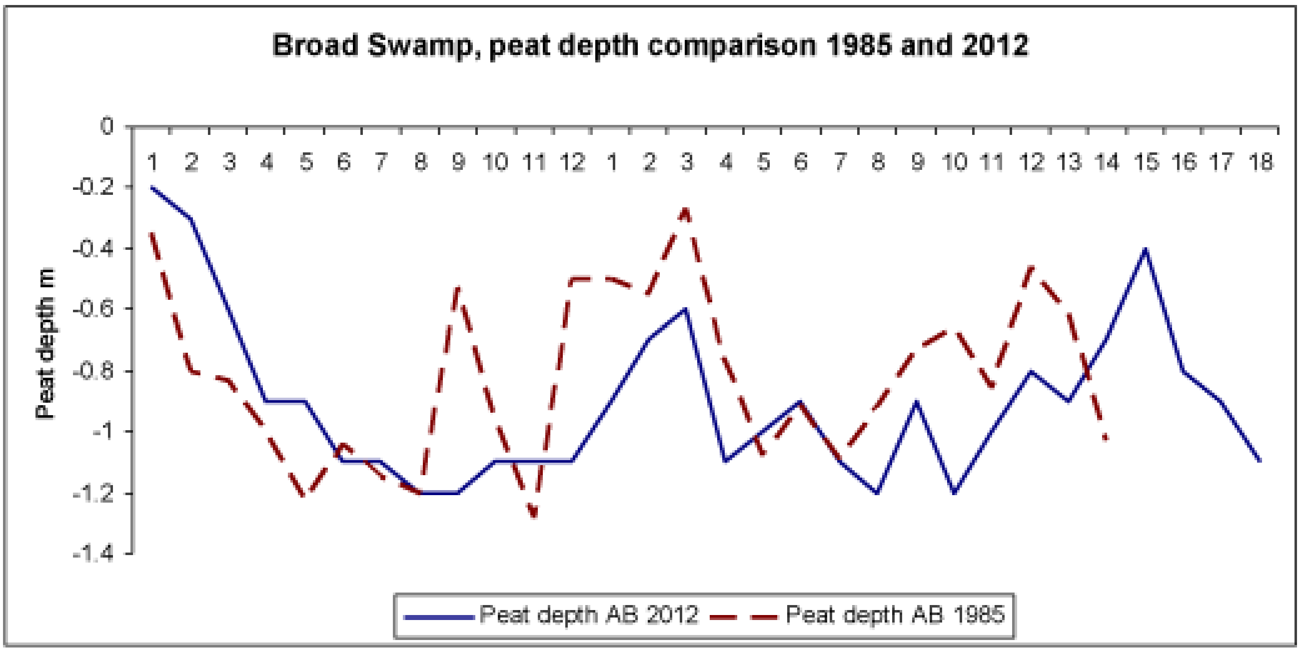


Fig. 9. Peat depths in Broad Swamp recorded across the main channel along Transects A and B in 1985 (dotted) and 2012 show surprising correspondence, evidence of the stability of the system

a

b

Fig. 10. Deanes Swamp in 2012, showing **a)** dead lignotubers (probably *Baeckea utilis* and *Leptospermum grandifolium*) evidently resulting from a large fire in Summer 2003, a period of very dry weather; and **b)** *Gymnoschoenus* clumps in centre of swamp. The previous fire at Deanes was a hot fire in 1982-83.(photos L. von Richter).

Comparison of 1985 and 2012 vegetation transects

A combined ordination of plots from Broad Swamp in 1985 and 2012 shows a similar spread of plots from the two time periods, with transect locations showing broad correspondence, despite only approximate positioning of the 2012 transect in relation to the 1985 ones (Figure 8). As well, the peat depths recorded along Transect AB show surprising correspondence between 1985 and 2012, indicating the stability of the subsurface conditions (Figure 9). The result indicates stable vegetation with little change over the 27-year interval. The vegetation patterns in the swamps are likely to be relatively fixed depending on long-term groundwater and peat conditions. Most species resprout after fire from lignotubers or rhizomes and likely to be very long-lived (Table 3). A few are capable of vegetative spread, some have long-lived soil seedbanks, and there are many we don't know much about. There does not appear to have been any fire over that time for the swamps studied except Deanes Swamp. However Deanes Swamp had an extensive area of dead lignotubers (probably *Baeckea utilis* and *Leptospermum grandifolium*), evidently resulting from a large fire in Summer 2003 (NP&WS fire records), a period of very dry weather. Deanes Swamp is also at a lower elevation than the other swamps and likely to receive lower rainfall. The previous fire at Deanes was a hot fire in 1982–83 (Figure 10).

Threatened swamp-dependent biota

All the Newnes Plateau records for the swamp-dependent biota *Petalura gigantea* (Baird 2012), *Eulamprus leuraensis* (NSW Wildlife Atlas, excluding several possibly inaccurate locations) and *Boronia deanei* (National Herbarium of NSW and this study) have been listed (Table 4). While overall ranges of the taxa are not coincident there is a concentration of them in the swamps in the eastern Newnes Plateau, particularly in the Carne, Bungleboori, Rocky, Budgary and Farmers Creek catchments. Within an individual swamp they may however occupy different microhabitats. For example, *Petalura* and *Boronia* both occur in Gang Gang West, Carne Central and Broad Swamp, with relatively little overlap of habitat except in Broad Swamp, though here the *Petalura* habitat is more extensive (Figure 4 b,d,e; Appendix 1 e,h,i,j). Notes on the distribution and ecology of individual species follow.

Boronia deanei subsp. deanei

On the Newnes Plateau *Boronia deanei* is restricted to swamps in upper Carne Creek and to some in upper Farmers Creek and upper Wollangambe River (Table 4, Figure 2g). It is generally a locally abundant species where it occurs, and in flower its extent can be recognised at a distance by the conspicuous pink coloured patches (e.g. notable in Broad swamp in November-December 2009). Similarly its absence can be inferred at the same time (it was absent from the similar structured Browns Swamp despite searches in 1980s, and in 2008–9 in the Dargans Creek catchment).

Of the 10 swamps with transects, *Boronia deanei* occurred in three, all in the Carne Creek catchment, though abundance from swamp to swamp varied with frequency of occurrence along transects being 5% in Gang Gang West (1/18 plots), 14% in Carne Central (2/14) and 35% in Broad Swamp (14/40). At these plots peat thickness ranged from 0.7–1.2 m deep (mean=0.97 +/- 0.04), with surface water recorded at 8 of 17 plots, with depths up to 6 cm (generally there is still some surface water present in all but the driest times- I Baird pers. comm.). *Boronia deanei* was associated with the Shrub-rich swamp group (Group 8 of PATN analysis).

Plant density in a typical dense population was 1.6 plants /0.25 m^2 (se= 0.4, n=10) (measured with a 0.25 m^2 quadrat). Individual plants were up to 1 m high with stem thickness at base up to 2 cm. Plants are generally multi-stemmed. No seedlings or small juvenile plants were noted recently or in searches made after fire events in the 1980s (D. Benson pers. obs.) despite the abundance of adult plants. *Boronia deanei* occurrences were in the *Epacris microphylla* heath, but also in the drier end of the wet heath and in the marginal sites with deep soil.

Recent remote sensing by Fletcher and Erskine (2012) confirms the limited occurrence of *Boronia deanei* on the Newnes Plateau. They report 58 distinct populations covering 5.08 ha within five swamp communities in Carne Creek catchment with individual clusters ranging from <10 m^2 to >0.5 ha, but only 3 populations covering more that 4046 m^2 (1 acre).

Petalura gigantea

Petalura gigantea has been recorded from a number of Newnes Plateau Shrub Swamps, with potential breeding habitat identified in others (Baird 2012) (Table 4). Extensive burrow investigations and observation of hundreds of oviposition and burrow locations across a range of mire types in the Blue Mountains (2003–2011) (Baird 2012) confirm *Petalura gigantea* as an obligate, groundwater dependent, mire-dwelling species. All observed oviposition occurred into waterlogged substrate, fissures in the substrate, amongst or under moist litter overlying the substrate, amongst roots at the base of plants in moist substrate, or into *Sphagnum*.

Petalura burrow depth was recorded to range from 18 to 75 cm (the deepest depth recorded for a petalurid larval burrow), with a mean depth of 37 cm (n = 27) (seven burrows < 30 cm, seven burrows > 39 cm, one burrow > 60 cm). Figure 11 shows a typical larval burrow. In some cases, burrows terminated when larvae encountered bedrock or dense sands and gravels overlaying the bedrock and in these cases, adaptive burrowing deepening in response to a lowering water table would be impossible. All burrows were characterised by the presence of groundwater and burrows are occupied for the duration of the larval stage. As currently understood, this period is at least 6 years, but may extend beyond 10 years. The recording period (2003–2011) began at the end of a major drought and continued into wetter conditions. These burrow measurements thus confirm that regardless of short-term fluctuations associated with rainfall events, and evidence of some adaptive burrow deepening putatively associated with a lowering water table during the drought period, that groundwater levels in these swamps are relatively stable over long periods. This is backed up by piezometer level measurements in Sunnyside and Carne West swamps (Centennial Coal 2009, DECCW 2010b).

A number of burrows showed evidence of adaptive burrow deepening during a period of drought. In these situations there was a descending burrow section (with a terminal chamber) that had been excavated below what appeared to be a previously established terminal chamber. This behaviour was assumed to be a response of larvae to a lowering of the water table across a number of years since burrow establishment. This observation further suggested obligate groundwater dependence in the species and is consistent with documented observations of groundwater in burrows of other fossorial petalurids within Australia and Internationally (*Petalura hesperia*, *Uropetala* spp., *Tanypteryx* spp.). This assumption was supported by the observation that in a large proportion of burrows, the depth of one of the lateral chambers effectively coincided with the water level within the burrow at the time of excavation. A high proportion of burrows had more than one lateral chamber, which also suggested adaptation associated with changing groundwater levels. In terms of larval ecology, this also suggested an important functional relationship between these lateral chambers and the water table (Baird 2012).

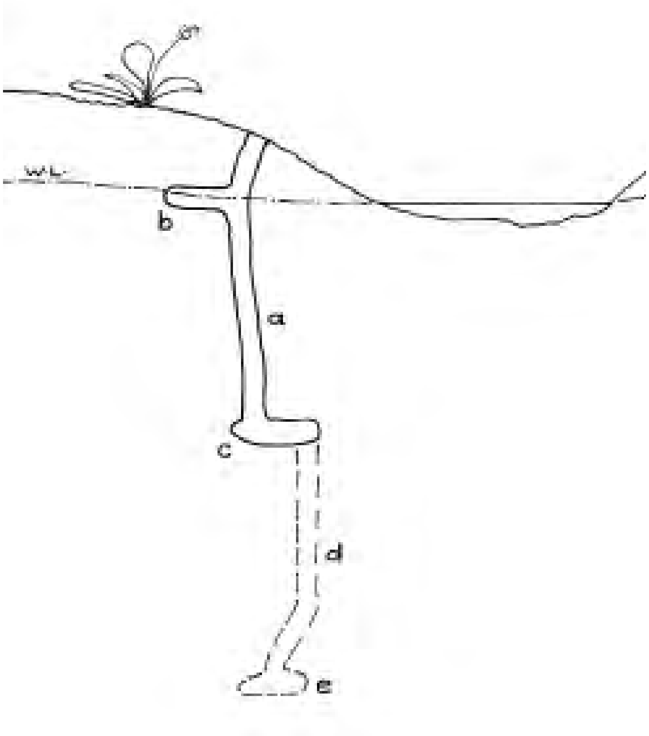


Fig. 11. Illustration of a simple larval burrow of *Petalura gigantea*, showing water level (W.L.), descending burrow section **(a)**, single lateral chamber **(b)** and terminal chamber **(c)**. Putative adaptive burrow deepening with secondary descending burrow section **(d)** and new terminal chamber **(e)** shown (dashed line).

Eulamprus leuraensis

All swamps where *Eulamprus* has been recorded are characterised by the presence of permanent groundwater seepage or waterlogging in at least part of the swamp (including during drought), and typically include small, often braided, perennial seepage streamlets. While some of these seepage streamlets may lose surface water during drought, the drainage lines are still characterised by the presence of a shallow water table and at least moist substrate surface in localised areas. *Eulamprus leuraensis* may be observed anywhere within these swamps, but is observed most frequently (during spring and summer when active) in association with more waterlogged areas, and sometimes in water during hot weather.

Euastacus australasiensis

Euastacus is widely distributed in NPSS, occurring in the typical valley floor swamps and occasional valley side swamps, where conditions are suitable, and appears to be restricted to swamps with permanent groundwater seepage in at least part of the swamp. Larger burrows (of presumably larger and older individuals) may be located away from the wettest parts of the swamps, but are presumed to connect to the watertable. Burrows are more frequently observed, however, in waterlogged seepage areas and along perennial seepage streamlets, which frequently drain these swamps. Excavated material associated with burrow deepening or maintenance frequently includes quartz pebbles and mineral soils, which may be associated with basal sediment layers deposited prior to peatswamp formation (in addition to intermediate layers associated with subsequent deposition events). Burrows of juvenile crayfish appear to be restricted to the wetter areas, often associated with emergent groundwater seepage, and are difficult to differentiate from burrows of *Petalura gigantea* larvae.

Dillwynia stipulifera

Plants of *Dillwynia stipulifera* were very infrequently recorded along transects and it appears to be a very rare species in the swamps. In view of its limited occurrence and threats to its swamp habitats it would appear that there may be a good case for listing it as a threatened species as well.

Rulingia prostrata

Our survey also recorded the TSC Act listed Endangered prostrate plant species *Rulingia prostrata* (family Sterculiaceae) in Deanes Creek Swamp, the first recording of this species in the Blue Mountains, though it has been previously recorded from THRPS listed swamp sites in Penrose State Forest area. Unlike the other listed species its ecological habitat appears to be swamp margins where it germinates in sites made bare by dry conditions. Deanes Creek Swamp was the lowest elevation swamp we surveyed.

Discussion

Swamp classification

In their mapping of the swamps of the Newnes Plateau, Benson and Keith (1990) grouped all permanent swamps together as NPSS, but noted that swamps on the western side of the plateau (e.g. West Wolgan, Kangaroo Creek-Upper) tend to be drier and have a greater component of *Leptospermum* shrubland, perhaps indicative of less-permanently high watertable (perhaps more rainfall-dependant than groundwater dependant). Distinctions between 'dry' and 'wet' swamps have been made in the context of potential impacts of subsidence from underground longwall mining (Aurecon 2009), implying that subsidence is unlikely to affect 'dry' swamps, and there is some evidence to suggest some of these swamps (e.g. West Wolgan -M. Krogh pers. comm.) may be less susceptible to subsidence impacts than the groundwater dependent swamps further east due to the lower level of incision of the drainage lines. However, as longwall mining is progressing from west to east (from the Wolgan River to Carne Creek catchments) the wetter swamps are now in line to be impacted.

Table 4. Swamps on the Newnes Plateau (by decreasing elevation) with records of threatened swamp-dependent biota. All recorded and potential *Petalura gigantea* sites in Newnes Plateau Shrub Swamps (IRCB), with recorded presence of *Eulamprus leuraensis* (NSW Wildlife Atlas), and *Boronia deanei* and *Dillwynia stipulifera* (National Herbarium and fieldwork records - DHB).

Swamp name	1:25k map	Easting	Northing	Drains to	Altitude m	*Petalura gigantea*	*Eulamprus leuraensis*	*Boronia deanei*	*Dillwynia stipulifera*
Junction Swamp	Li	235860	6302770	Wolgan	1160				
Kangaroo Ck Upper	Li	235200	6302400	Coxs	1130				
West Wolgan	Li	234600	6304750	Wolgan	1130				
Sunnyside	CB	237834	6304082		1120	Recorded			
- tributary of Farmers Creek	Li	239108	6296549	Farmers	1110	potential			
Marrangaroo Creek	Li	239105	6299040	Marrangaroo	1100	potential			
Carne West	Li	239179	6302913	Carne	1090	Recorded		2010	
Pine	Li	241700	6300900	Bungleboori	1090				
Farmers Creek	Li	241600	6295200	Farmers	1080				1989
Browns	Li	242605	6292840	Dargans	1080	potential		?1906	
Paddys	Li	241255	6298915	Bungleboori	1080	potential.		1981	1981
Carne Central	Li	241200	6302500	Carne	1080	potential	Recorded	2012	
Kangaroo Ck Lower	Li	233250	6304300	Coxs	1080				
East Wolgan	CB	236500	6304395	Wolgan	1080				
Narrow	CB	236100	6305250	Wolgan	1080				
Happy Valley Springs	Li	241639	6297024	Farmers	1075	Recorded	Recorded	1981	1981
Gang Gang West	Li	239997	6302962	Carne	1070	Recorded		2012	
Dargans Creek	Li	243105	6293290	Dargans	1070	potential			1970
North Pine	Li	242007	6301239	Bungleboori	1070	potential	Recorded		
Sunnyside east	Li	239230	6303710	Carne	1070	potential			
Gang Gang East	Li	240470	6303124	Carne	1055	Recorded	Recorded	2009,10	
Murrays	Li	243132	6303138	Carne	1055	potential	Recorded	2010	
Broad Swamp	Li	242005	6302840	Carne	1055	potential	Recorded	1985,10,12	2012
Upper Dingo Creek	Li	244409	6302518	Bungleboori	1030	Recorded			
-	CB	244092	6306029	Carne	1020	Recorded			
Upper Dingo Creek	Wo	244882	6303775	Bungleboori	1015	Recorded			
-	CB	237255	6311790	Carne	1010	potential			
Upper Dingo Creek	RH	244970	6304199	Bungleboori	1000	Recorded			
Budgary Creek	RH	246519	6308150	Lower Wolgan	980	Recorded	Recorded		
-	RH	247445	6307058	Bungleboori	975	Recorded			
Rocky Creek	RH	245260	6309048	Lower Wolgan	975	Recorded			
- Upper Dinner Gully swamp	RH	247742	6308591	Lower Wolgan	960	Recorded	Recorded		
-	RH	247991	6307307	Bungleboori	955	Recorded			
Deanes Creek	RH	244705	6314190	Lower Wolgan	940	potential			
-	RH	246675	6316893	Lower Wolgan	925	potential			
-	RH	249172	6310109	Lower Wolgan	835	Recorded			

Our analyses confirm that across the plateau rainfall and geomorphology relate to the occurrence of a cluster of swamps characterised by a high water table, more or less permanent moisture conditions and the associated development of peaty substrate up to 2 m deep. These groundwater dependent swamps are concentrated on the eastern half of the Newnes Plateau, including those in the headwater creeks of Carne, Bungleboori, Budgary, Rocky, Marrangaroo, Farmers, and some in Wolgan. The largest and most extensive swamps are in the headwaters of Carne Creek. These swamps are also the prime habitat for the particular groundwater dependent biota *Petalura gigantea*, *Eulamprus leuraensis* and *Boronia deanei* discussed below.

We also confirm that some of the western swamps (notably West Wolgan and Kangaroo Creek-Upper, and Sunnyside West) are distinctly different from the main body of groundwater dependent NPSS, have shallower and less developed peat, predominance of *Leptospermum* species, and are likely to be more rainwater dependent. However, there is not a simple east/west division. The floristic composition of the nearby Kangaroo Creek–Lower swamp on the western side, is closer to the groundwater dependent /permanent swamps than the nearby dry swamps. This may be related to groundwater dependence since a spring emanating from clay layers is observable in the creek bed immediately upstream of Kangaroo Creek–Lower swamp.

Groundwater-dependent biota

The importance of groundwater and its function in maintaining the health and viability of many ecosystems has been recognised nationally (Clifton & Evans 2001; Davis *et al.* 2001; Eamus & Froend 2006; Hatton & Evans 1998; Murray *et al.* 2003) and in New South Wales (NSW Government 2002). Hatton and Evans (1998) have suggested that wetlands included the most diverse and extensive group of Australian ecosystems with groundwater dependency. Both Hatton and Evans (1998) and Clifton and Evans (2001) recognised five classes of ecosystem dependency on groundwater. Their class of *Ecosystems with proportional dependence on groundwater* appears to include all known and potential habitats for *Petalura gigantea*, *Eulamprus leuraensis* and other groundwater dependent species identified in this study. Such ecosystems are included within the Coastal Heath Swamps and Montane Bogs and Fens vegetation classes of Keith (2004). For these ecosystems Hatton & Evans (1998) suggested that 'it is likely that a unit change in the amount of groundwater will result in a proportional change in the health or extent of that ecosystem'.

When commenting on the level of groundwater dependency of wetland ecosystems, Clifton and Evans (2001) highlighted the importance of maintaining adequate groundwater levels in unconfined aquifers and adequate groundwater discharge flux for most wetland ecosystems to maintain the necessary level of wetness or waterlogging for key ecological stages: 'Changes in water table level may have important implications for these communities. Prolonged lowering or raising of the water table is likely to result in changes in species composition, favouring species adapted to drier or wetter conditions, respectively'. This dynamic may be critical to the long-term persistence of *Petalura gigantea,* because of its swamp or mire dependent fossorial larvae, the microhabitat requirements of ovipositing sites, the spatio-temporal distribution of such microhabitat within swamp patches, and the environmental tolerance of eggs and early larval instars. Changes in burrow groundwater quality or substrate attributes associated with temporal changes in groundwater depth may also play an important role in the persistence of this and other species (e.g. *Euastacus australasiensis*) within these wetlands. The International and Australian literature highlight the richness of groundwater dependent fauna and suggests that additional groundwater dependent fauna within these NPSS may potentially include stygofauna (e.g. Gilbert *et al.* 1994b; Humphreys 2008), pholoteros (e.g. Lake 1977; Suter & Richardson 1977), and/or other specialised spring (e.g. Hahn 2000; Hoffsten & Malmqvist 2000; Williams & Danks 1991), mire (e.g. Larson & House 1990; Mikkola & Spitzer 1983; Spitzer & Danks 2006) or moorland (e.g. Butterfield & Coulson 1983; Greenslade & Smith 1999) invertebrates.

Freshwater burrowing crayfish such as *Euastacus australasiensis* in upland swamps of the Sydney region, *Parastacoides tasmanicus* and *Engaeus leptorhyncus* in buttongrass *Gymnoschoenus sphaerocephalus* moorland of Tasmania (Richardson & Horwitz 1988; Richardson & Swain 1980, 1991;Horwitz *et al.* 1985); and *Cherax plebejus* in swampy seepages in southwest Western Australia (Horwitz & Knott 1983), have been identified as a significant component of Australian mire and moorland ecosystems. Groundwater filled crayfish burrows may provide fire and predation refugia for the Blue Mountains water skink *Eulamprus leuraensis*. *Parastacoides* spp. are known to increase respiration of surrounding soil in Tasmania (Richardson 1983), and may affect vegetation through soil aeration and root grazing within underground feeding chambers beneath plants (Richardson & Wong 1995).

Petalura gigantea burrows may also be similarly utilised by other species. For example, spiders, various insect taxa (e.g. Blattodea, Orthoptera), and a frog were observed within the entrance of a *Petalura gigantea* burrow (I.R.C. Baird pers. obs.). These diverse ecological relationships, and the shared reliance of different taxa upon groundwater, highlight the complexity of functional roles of these fossorial groundwater dependent organisms and their importance in these groundwater dependent ecosystems (GDEs).

The threatened shrub *Boronia deanei* and the rare shrub *Dillwynia stipulifera* are confined to the eastern NPSS and associated particularly with the extensive areas of moist peat in the broad swamps there. Drying of substrate resulted in death of adult plants in Murrays Swamp (in 2008–10) and no evidence of seedling recruitment has been noted despite increased rainfall. These two species have been observed to resprout following fire, though basal resprouting will be largely dependent on the presence of moist substrate at the time of a fire event. The conditions necessary for seedling recruitment are unknown though the species are likely to have soil stored seedbank with dormancy broken by fire. Presumably moist conditions are needed for seedling establishment and growth. Unlike the widespread swamp species *Grevillea acanthifolia*, which appears to be a successful coloniser of open sites, and where seedlings appear rapidly in exposed or drying sites (though do not necessarily survive), *Boronia* and *Dillwynia* populations are restricted to much narrower groundwater dependent habitat; loss of groundwater is likely to lead to reduction in their populations.

Because of their occurrence in separate valleys isolated from each other by extensive areas of dry woodland, and often in separate major catchments, genetic diversity in these swamps is often restricted. Dubey and Shine (2010) have highlighted the genetic divergence among swamp populations of *Eulamprus leuraensis*, recommending that most populations be treated as discrete conservation units, with clear implications in the event of extirpation of individual swamp populations. The distinctiveness of individual swamp populations is also supported by Hose's

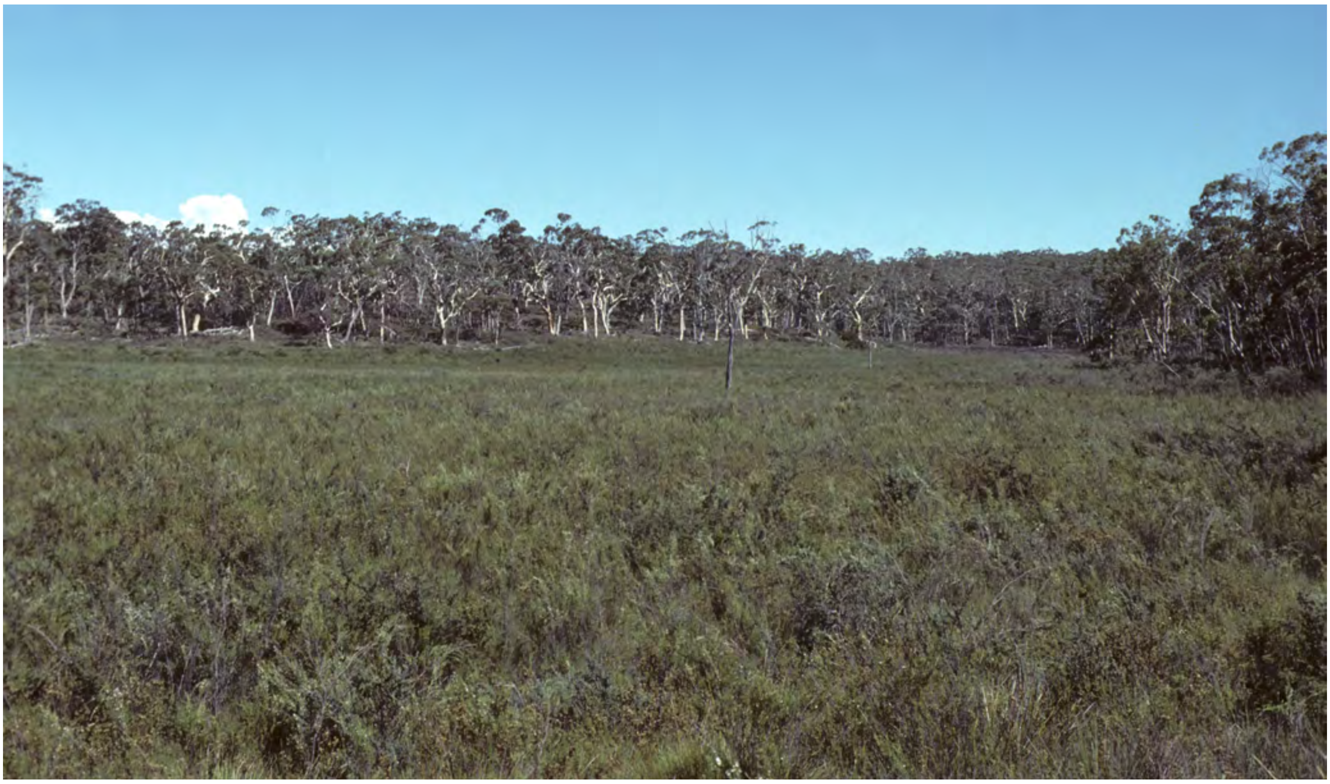


Fig. 12. Broad swamp in 1980. There was no sign of any recent fire at this time (photo DHB).

Table 5. Summary of evidence (both direct and indirect) from various sources that a long-term permanent watertable has indeed been present in the Carne Creek-Clarence swamps.

Evidence	Indicative time period
Piezometer records for Carne West since 2005 show little fluctuation (Aurecon 2009)	6 years
Petalura burrow measurements confirm that regardless of short-term fluctuations associated with rainfall events, and evidence of some adaptive burrow deepening putatively associated with a lowering water table during the drought period, that groundwater levels in these swamps are very stable over long periods.	5-10 years
Vegetation patterns in Broad swamp show little change between 1985-2012	30 years
Large size of rootstocks of swamp species (e.g. *Gymnoschoenus*, *Boronia deanei*, *Leptospermum grandifolium*, *Baeckea linifolia*) indicates longevity under stable moisture conditions and survival beyond normal two-decade droughts is the norm. These species are unaffected by periodic fires and resprout vigorously. Loss of permanent moisture will lead to death however.	30-50 years
Air photo from 1970s and field experience from that time (DHB) show similar swamp patterns to today	40 years
First recording of *Boronia deanei* in 1906 in habitat and abundance similar to today indicate longevity and consistency of habitat structure.	100 years
Development and maintenance of peat up to 2 m thick indicates long period of high moisture and stability	Very long
Records of peat in swamps 12000 years ago	Very long

(2009) work on stygofauna in swamps on the Woronora Plateau. Genetic diversity among the plant species is also likely to vary, depending on the particular pollination and seed dispersal mechanisms of individual taxa, though there has been little research on this subject despite its importance for guiding longterm conservation management.

Longevity of swamp patterns

The ecology of the native biota, both rare and common species, and characteristics of NPSS indicate that a permanently high watertable is an integral and necessary condition for their survival. Table 5 provides a (necessarily speculative) summary of evidence that a permanently high watertable has indeed been the case over the past centuries. Such evidence comes from various sources. The earliest date for swamps sediments appear to be c.12 000 years ago (Chalson & Martin 2009) and the swamps are likely to have persisted since their formation, though the age of basal sediments at individual core locations may not necessarily reflect the date of initiation of swamp development. In the absence of sediment cores in this study, any interpretation of the observations of contrasting layers of sediment during soil depth probes in different locations within swamps, including dense sands and sandy clay basal layers is hypothetical. Nevertheless, based on research from other sandstone-based swamp systems within the Sydney region (e.g. Woronora Plateau; Young 1982, 1986a, 1986b) it may be presumed that contrasting layers of dense sands and sandy clays interspersed among peat or other organic-rich layers are the result of depositional events associated with rainfall events, most likely following fire and/or drought. Young, and Tomkins & Humphreys (2006) considered that the Woronora swamps were characterised by cycles of sedimentation (mire development) and erosion that may confound interpretation of the oldest sediment dates. Similar episodic degradation and aggradation cycles associated with climate and fire are likely in the mires developed on sandstones in the Blue Mountains.

Notes associated with the collection of *Boronia deanei* in 1906 suggest the swamps were similar to today, while airphotos from the 1960s, and our fieldwork in the 1970s, indicate similar conditions, though with many less disturbed swamps and no evidence of exotic weed species. Swamps visited in the 1970s were moist underfoot and there was invariably water running out at the nick-point discharges visited. An important indicator of temporal vegetation change, individual species longevities, is difficult to determine for species with long-term regeneration structures such as lignotubers, but in the absence of any other leads is probably the only potentially useful measure.

Increasing threats to swamps

With the exception of the construction of the Newnes Valley railway in 1906–07 (which incidentally lead to the discovery of *Boronia deanei*), NPSS survived virtually undisturbed up to the 1970s when major eucalypt forest areas were cleared and planted with exotic *Pinus radiata*. Swamps associated with pine-dominated catchments may now have a major *Leptospermum* component, possibly due to less water runoff, or have increased shading from mature pines and invasion by pine wildings.

Increased demand for electricity and coal in the 1980s lead to proposals for a power station near Birds Rock (relocated to Mount Piper), and the subsequent approval of a major coalmine and washery near the same site, that would have destroyed the main Carne Creek swamps with infrastructure and coal waste dumps. These did not go ahead; instead since the 1990s coalmining using increasingly wider longwall mining technologies have pushed under the plateau from the edges. Though this has reduced the direct impacts of infrastructure on surface vegetation there have still been

Table 6. Plant species essentially restricted to the highest elevation plateau (>1100 m) of Newnes Plateau, i.e. Clarence to Bungleboori, with conservation status and notes on any disjunct occurrences elsewhere.

Species	Cons status	Occurrence on Newnes Plateau	Occurrence elsewhere
Persoonia hindii	TSC	WL and heath, >1100 m	Newnes Plateau endemic
Leptospermum blakelyi		heath, Clarence, >1100 m	Newnes Plateau endemic
Eucalyptus gregsoniana	3RCa	Mallee heath, Clarence, >1100 m	Southern Tablelands, Wadbilliga
Olearia quercifolia	3RC-	wet places, >1000 m	confined to Bl Mtns, wet places
Boronia deanei subsp. deanei		NPSS, >1100 m	Kanangra-Boyd swamps
Veronica blakelyi		WL, Clarence	Nullo Mtn, Mt Horrible
Dillwynia stipulifera	3RCa	NPSS, >1100 m	Budawangs
Celmisia longifolia		NPSS	Kanangra-Boyd swamps, Southern Tablelands, Kosciuszko, >900 m
Scaevola hookeri		NPSS	Blue Mountains Sedge Swamps, disjunct occurrences at high elevations south from Ebor
Isopogon prostratus		WL, heath >1100 m (Benson & von Richter 2010)	disjunct occurrences on Southern Tablelands
Hakea microcarpa		high elevation swamps, 1130 m	widespread on Tablelands, WL and heathy swamps
Velleia montana		NPSS, 1050 m	higher altitudes on Tablelands

major impacts from excess mine water discharges pumped into the swamps, as well as a plethora of surface roads allowing more access to the area. There are also increasing impacts associated with subsidence, as longwall panels as wide as 310 m have been used. However, with an increased number of direct impacts, together with indirect impacts affecting swamp processes, subsidence and climate change are likely to have major impacts on NPSS in the future.

Changes in groundwater regime will potentially impact the biota of Groundwater Dependent Ecosystems at species and community level. This will be caused by changes to critical habitat attributes, either variably, or (potentially) across threshold levels (Clifton & Evans 2001). Where groundwater levels are lowered, even seasonally, effects may include changes in the wetland vegetation community composition (Boulton & Brock 1999; Breeuwer *et al.* 2009; Wheeler 1999). With longer term and/or persistent lowering of the water table, effects may include succession from swamps to drier heath, sedgeland, grassland or forest communities, extirpation of groundwater dependent species, changes in groundwater quality and soil chemistry (Wheeler 1999) and degradation of peat (Shearer 1997) and peatlands (Moore 2002; Whittington & Price 2006).

In particular, according to NSW Scientific Committee (2005), subsidence of the land surface and associated fracturing of bedrock occurs after longwall coalmining, and this may change the hydrology of catchments and swamps they contain (Krogh 2007). Recent mining related disturbance at East Wolgan has led to loss of stream flow from the swamp; long-term effects are unknown, though there is already death of permanent moisture dependent species such as *Gleichenia* and degradation of the peaty swamp soil (Aurecon 2009, Goldney et al 2010). These effects are likely to be long-term as long as drainage loss continues and oxidation of peat destroys its water holding capacity, allowing woodland plant species to replace the swamp species.

Local disturbance and scouring caused by contaminated mine water discharges has caused erosive channelling, mortality of swamp flora and invasion of exotic weeds such as wind/water dispersed herbs *Cirsium vulgare* and *Sonchus oleraceus* into pristine creek-lines. In contrast, swamp vegetation has recovered well from heavy rain scour reported from Woronora (Tomkins & Humphreys 2006) except for Flatrock Swamp, Swamp 18 and 19, all affected by longwall mining.

Potential impacts associated with a lowering of the water table include weed invasion and increased fire risk (DECC 2005; Keith *et al.* 2006; Kodela *et al.* 2001), and woody weed invasion of swamps by exotic pines, blackberries and other species across the plateau has been documented recently (Henson 2010). Where drying of organic-rich, peaty swamp substrates occurs, fire effects may include burning of

Fig. 13. Pink patch of flowering *Boronia deanei* in Broad Swamp in November 2008. (photo L. von Richter).

the organic soil component and soil seed-banks. This has the potential to leave sterilised and (often) hydrophobic sandy or peaty soils, with an increased risk of erosion, in turn leading to channelisation and further lowering of shallow water tables (e.g. Young & Wray 2000). Fire induced changes may also include changes in water quality and loss of biodiversity (e.g. Horwitz & Sommer 2005). Drying related oxidisation and/or combustion of the organic component of these peatlands leads to their shrinkage. Degradation of the hydrological function of these peatland ecosystems may also occur (DECC 2005; Keith *et al.* 2006).

Fire is considered one of the main threats to Australian peatlands (Pemberton 2005). A more intense fire regime may cause unsustainable loss of peatland soils, as in peatlands in southwestern Australia (Horwitz *et al.* 1999; Horwitz & Smith 2005; Semeniuk & Semeniuk 2005) and Tasmania (Bridle *et al.* 2003; Kirkpatrick & Dickinson 1984; Whinam 1995; Whinam *et al.* 2001). Extensive fire effects in *Sphagnum* peatland communities have also been reported in NSW (Hope *et al.* 2005; Threatened Species Scientific Committee 2009; Walsh & McDougall 2004) and Victoria (Coates *et al.* 2006; Taranto *et al.* 2004; Walsh & McDougall 2004). Fire effects are exacerbated where groundwater levels are lowered due to drought or anthropogenic influences (e.g. climate change, groundwater extraction, long wall coal mining) and by more intense fire regimes, for example, as reported also in New Zealand peatlands and bogs (Clarkson 1997; Johnson 2001; Timmins 1992). An increase in periods where peatland soils are bare following fire events (or in response to drought) will also contribute to increased rates of peatland photodegradation and loss of organic matter (Rutledge *et al.* 2010). Lowering of the groundwater table will compound these effects.

Destruction of peat substrates as a result of fire has been reported in BMSS (Keith 1996; Stricker & Wall 1995) and the upland swamps of the Woronora Plateau (Keith *et al.* 2006; Young 1982, Krogh 2007). The temporal and spatial scales, and the intensity at which these fire disturbance events occur in particular swamp types are, however, critical to whether fire regimes result in long-term loss of organic terrains at a rate that exceeds net accumulation of organic matter, or exceeds fire regime thresholds for swamp plant (e.g. *Sphagnum* spp., obligate seeders) and animal species (e.g. *Rattus lutreolus*) (Keith 1996; Keith *et al.* 2002; Morrison 2002; Morrison *et al.* 1995; Watson 2006a, b). Fire impacts are directly correlated to swamp water levels and surface wetness (e.g. Horwitz & Smith 2005; Horwitz & Sommer 2005).

Reduced groundwater availability, particularly combined with a more intense fire regime and/or a hotter and drier climate, will result in long-term degradation, and contraction of these mire ecosystems. The result will be reduced spatio-temporal distribution of suitable breeding habitat for *Petalura gigantea* and will also threaten the persistence of other groundwater dependent species (e.g. *Boronia deanei*, *Eulamprus leuraensis*, *Euastacus australasiensis*). Maintenance of a suitable hydrological regime and groundwater levels will be fundamental to the persistence of these mire ecosystems and their groundwater dependent species, but there are considerable gaps in our knowledge of the ecology of these species, particularly in relation to groundwater hydrology and the nexus between hydrology and fire. With the likelihood of significant impacts and considerable uncertainty associated with climate change projections, the precautionary principle should underpin conservation management of these mire ecosystems.

Connecting important landscape elements of the Newnes Plateau

Perusal of the topography shows that most of the typical groundwater dependent swamps are located on or just below the 1100 m contour, and that this level also applies to Kangaroo Creek Lower, and Narrow and East Wolgan swamps (see Table 1). It is likely that the 1100 m zone relates more or less to the perched unconfined aquifer supplying water to the main groundwater dependent swamps, particularly those in the Carne, Wolgan, Bungleboori, Budgary and Rocky Creek catchments. The western dry swamps (Sunnyside West, West Wolgan and Kangaroo Creek-upper) are located on the Plateau at a higher elevation; their *Leptospermum*–dominated vegetation and shallower less peaty substrate is consistent with the view that they are more rainfall dependent than groundwater dependent. This interpretation helps clarify the position of the somewhat anomalous (now dry) Junction Swamp, which previously, before drying, had permanent moisture, areas of *Sphagnum* moss (not a characteristic species of the main NPSS), and confirmed records of *Eulamprus,*; drying is likely to be a result of the impacts of mining subsidence (Goldney *et al.* 2010). At 1155 m elevation Junction Swamp, the highest elevation swamp, should be a high level dry western swamp, but its small catchment (30 ha), perched aquifer, odd, relatively steep north-eastern aspect, topographic position at the headwater of the upper Wolgan River, and the relatively small area of land at this elevation, make it a unique swamp.

As well as the swamp systems, the Newnes Plateau has particular geodiversity features that add to its scientific values. Below the swamps, at the termination of the adjacent ridges, there are the geologically distinctive and unique sandstone pagoda formations (generally occupying the 800–1050 elevation zone), resulting from millennia of iron-water transport and re-deposition (Washington & Wray 2011). As well, the relict sand dunes described by Hesse (2003) provide a strong indication of climatic conditions at the height of the Last Glacial Maximum (c. 20 000 years ago).

Our fieldwork for the swamps also drew our attention to restricted high elevation vegetation in their catchments. Above the 1100 m contour (the general upper level of the swamps), the Plateau surface rises to nearly 1200 m (e.g. 1190 m on the catchment divide between Marrangaroo, Farmers and Bungleboori creeks; 1180 m at Bald Trig and 1181m at Birds Rock). This 1100–1200 m cap includes a range of vegetation, primarily broadly mapped as Newnes Plateau Woodland map unit 10f (Benson & Keith 1990), but including areas of forest of *Eucalyptus dalrympleana*, woodland of *Eucalyptus dives*, *Eucalyptus radiata*, *Eucalyptus pauciflora* and *Eucalyptus mannifera*, and areas of heath with *Allocasuarina nana*. This area also includes the dry swamps (e.g. West Wolgan, Sunnyside West) and the anomalous Junction Swamp (discussed above). The pattern of occurrence of these vegetation types is substrate-controlled (Wilkinson & Humphreys 2006, Wilkinson et al 2005), which explains the occurrence of heath on relatively sheltered areas below woodland, rather than on exposed sites as around Katoomba or Blackheath. The nature of the friable sandstone (Triassic Narrabeen Group – Banks Wall Sandstone) leads to deep well-drained soils (Pecover 1984, King 1993), which presumably allow easy entry for water movement into aquifers supporting the swamps, but make it highly sought after for sand mining. The high level vegetation (given its relatively small overall area) is important habitat for a large number of rare plants, many with disjunct connections with other high-level montane sites, particularly on the Southern Tablelands (See Table 6). Heath includes *Eucalyptus gregsoniana*, and woodland includes the locally endemic Endangered *Persoonia hindii* (confined to 1100–1200 m), *Isopogon prostratus* (only above 1100 m) and *Acacia meiantha* (1100 m). Forest includes *Veronica* (*Derwentia) blakelyi*. It is tempting to speculate that some of these species occurrences (and some of the prostrate species on the Plateau) are indicative of the prior flora of the site in colder drier conditions, during and following the Last Glacial Maximum, and subsequently invaded by taller growing eucalypts and shrubs. This timing (post LGM) is concurrent with development of the swamps of the Plateau. Such speculation provides testable hypotheses (e.g. see recent genetic studies on *Telopea* (Rossetto *et al.* 2011) and *Lomatia* (M.Rossetto pers comm. 2011) which include Newnes Plateau as a study site). Scientists need to draw attention to this scientifically important high elevation part of the Plateau, none of which is in the nearby national parks, and which is currently faced with such an array of serious threats. In a recent publication, Laurance *et al.* (2011) identify the top ten Australian ecosystems vulnerable to tipping points, in which modest environmental changes can cause disproportionately large changes in ecosystem properties. Elevationally restricted montane ecosystems are listed as the most vulnerable.

Conclusion

Our Newnes Plateau Shrub Swamp studies show a closely-related group of swamps with extensive areas of gently sloping peatlands with subsurface topography determining local peat depth. While there is evidence that a group of the highest elevation swamps on the western side of the Plateau are more dependent on rainwater, the majority of swamps and those in the Carne Creek catchment, and to its east and south to Clarence in particular, have permanently high water tables maintained by groundwater, and are associated with the concurrence of a number of threatened groundwater dependent biota restricted to these sites. This association makes them highly susceptible to threats of loss of groundwater, the major one being the impact of subsidence caused by longwall mining; though other impacts may come from changes to hydrology as a result of damming, mine waste water discharge, increased moisture competition from pine plantations, and climate change. Our view is that if groundwater hydrology is impacted by activities such as longwall mining and associated subsidence, potential significant ecological damage is unlikely to be avoided or mitigated. Where provisions of the EPBC and TSC Acts apply to groundwater dependent swamps and biota, mining under swamps needs to be avoided.

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References

Agnew A. D. Q., Rapson G. L. Sykes, M. T.& Wilson, J.B. (1993) The functional ecology of *Empodisma minus* (Hook, f.) Johnson & Cutler in New Zealand ombrotrophic mires. *New Phytologist* 124**,** 703–710.

Aurecon (2009). *Newnes Plateau Shrub Swamp Management Plan – Investigation of Irregular Surface Movement within East Wolgan Swamp*. Centennial Coal. 26 June 2009. Report Reference: 7049–010-Rev 3.

Australian Railway Historical Society. (1979) *The Wolgan Valley Railway – its construction, incorporating The Wolgan Valley Railway* by Henry Deane, read before the Sydney University Engineering Society, Sept 21 1910. (Australian Railway Historical Society NSW Division: Sydney).

Baird I.R.C. (2012) The wetland habitats, biogeography and population dynamics of *Petalura gigantea* (Odonata: Petaluridae) in the Blue Mountains of New South Wales. PhD thesis, University of Western Sydney.

Belbin, L. (2004) *PATN Pattern analysis package*. CSIRO Division of Wildlife Ecology: Canberra.

Benson D. H .(1981) Flora Report. Appendix A Birds Rock Colliery Environmental Impact Statement. January 1981. Birds Rock Colliery Pty. Ltd.

Benson D. H. & Keith D. A. (1990) Natural vegetation of the Wallerawang 1:100,000 map sheet. *Cunninghamia* 2, 305–35.

Benson D. H. & von Richter L. (2010) Recent ecological observations on growth rates and seed production in *Isopogon prostratus* (Proteaceae), a little-known prostrate shrub from south-eastern NSW and Victoria. *Cunninghamia* 11, 283–6.

Bish S. (1999) Hydrogeological Assessment for Coxs River Catchment, Sydney-South Coast Region. NSW Department of Land and Water Conservation, Sydney.

Boulton A. J. & Brock M. A. (1999) *Australian Freshwater Ecology: Processes and Management*. Gleneagles Publishing, Adelaide.

Breeuwer A., Robroek B. J. M., Limpens J., Heijmans M. M. P. D., Schouten M. G. C. & Berendse F. (2009) Decreased summer water table depth affects peatland vegetation. *Basic and Applied Ecology* 10, 330–9.

Bridle K. L., Cullen P. & Russell M. (2003) *Peatland Hydrology, Fire Management and Holocene Fire Regimes in Southwest Tasmanian Blanket Bogs. Nature Conservation Report No. 03/07*. Nature Conservation Branch, Department of Primary Industries, Water and Environment, Hobart.

Brown M. J., Crowden R. K. & Jarman S. J. (1982) Vegetation of an alkaline pan-acidic peat mosaic in the Hardwood River Valley, Tasmania. *Austral Ecology* 7, 3–12.

Buchanan R. A. (1980) The Lambert Peninsular, Ku-ring-gai Chase National Park. Physiography and the distribution of podzols, shrublands and swamps, with details of the swamp vegetation and sediments. *Proceedings of the Linnean Society of NSW* 104, 73–94.

Butterfield J. & Coulson J. C. (1983) The carabid communities on peat and upland grasslands in northern England. *Holarctic Ecology* 6, 163–74.

Campbell N. (2007) Clarence Colliery Environmental Monitoring Program. [Accessed September 23rd 2009]. Available from http://www.centennialcoal.com.au/index.php?option=com_content&view=article&id=40:clarence&catid=14:operations-a-community&Itemid=48

Centennial Angus Place. (2006) Angus Place Colliery Subsidence Management Plan: Newnes Plateau Shrub Swamp Management Plan. [Accessed September 23rd 2009]. Available from http://www.centennialcoal.com.au/index.php?option=com_content&view=article&id=35&Itemid=43

Centennial Coal. (2005) Angus Place Colliery Longwalls 930–980 Subsidence Management Plan Application. Centennial Angus Place.

Centennial Coal 2009. Springvale Colliery Subsidence Management Status Report. Four Monthly Update. 7th March 2009.

Chalson, J. M. & Martin, H.A. (2009) A Holocene history of the vegetation of the Blue Mountains, New South Wales. *Proceedings of the Linnean Society of NSW* 130, 77–109.

Clarke K.R. and Warwick R.M. 2001. *Change in Marine Communities: An Approach to Statistical Analysis and Interpretation*. 2nd Edition. PRIMER-E Ltd. Plymouth Marine Laboratory, UK.

Clarke P. J. & Martin R. H. (1999) *Sphagnum* peatlands of Kosciuszko National Park in relation to altitude, time and distance. *Australian Journal of Botany* 47, 519–36.

Clarkson B. R. (1997) Vegetation recovery following fire in two Waikato peatlands at Whangamarino and Moanatuatua, New Zealand. *New Zealand Journal of Botany* 35, 167–79.

Clifton C. & Evans R. (2001) *Environmental Water Requirements of Groundwater Dependent Ecosystems, Environmental Flows Initiative Technical Report Number 2*. Commonwealth of Australia, Canberra.

Coates F., Sutter G. & Mavromihalis J. (2006) Regeneration of treeless subalpine vegetation after recurrerent fires at Mt Buffalo National Park. Technical Series Report No. 160. Arthur Rylah Institute for Environmental Research, Melbourne.

Corbet P. S. (2004) *Dragonflies. Behaviour and Ecology of Odonata*. Revised edition. Cornell University Press, Ithaca, NY.

Creaser E. P. (1931) Some cohabitants of burrowing crayfish. *Ecology* 12, 243–4.

CSIRO. (2004) Interpretation of hydrological data at Springvale Colliery. Exploration and mining report P2004/62. CSIRO Exploration & Mining, Kenmore, Qld.

Davis J. A., Froend R. H., Hamilton D. P., Horwitz P., McComb A. J. & Oldham C. E. (2001) *Environmental Water Requirements to Maintain Wetlands of National and International Importance, Environmental Flows Initiative Technical Report Number 1*. Commonwealth of Australia, Canberra.

DEC (2006) The Vegetation of the Western Blue Mountains including the Capertee, Coxs, Jenolan & Gurnang areas. Volume 2: Vegetation community profiles. Newnes Plateau shrub swamp. NSW Dept of Environment and Conservation, Hurstville.

DECCW (2010a) *NSW Wetlands Policy*. NSW Dept of Environment, Climate Change & Water, Hurstville.

DECCW (2010b) Review of Piezometer Monitoring Data in Newnes Plateau Shrub Swamps and their relationship with Underground Mining in the Western Coalfield. NSW Department of Environment, Climate Change and Water. January 2010.

DEH (2005) *Nationally threatened Species and Ecological communities: Temperate Highland Peat Swamps on Sandstone*, Australian Govt Dept of Environment and Heritage.

DLWC. (1999a) Blue Mountains – Richmond Interim Groundwater Management Plan. Department of Land and Water Conservation, Parramatta, NSW.

DLWC. (1999b) Blue Mountains Sandstone Aquifer Current Groundwater Management Practices and Issues. Department of Land and Water Conservation, Parramatta, NSW.

DLWC. (1999c) Blue Mountains Sandstone Aquifer Status Report. Department of Land and Water Conservation, Parramatta, NSW.

Dubey S. & Shine R. (2010) Restricted dispersal and genetic diversity in populations of an endangered montane lizard (*Eulamprus leuraensis*, Scincidae). *Molecular Ecology* 19, 886–97.

Eamus D. & Froend R. (2006) Groundwater-dependent ecosystems: the where, what and why of GDEs. *Australian Journal of Botany* 54, 91–6.

Enforceable undertaking (2011) – Enforceable Undertaking - undertaking to the Minister for Sustainability, Environment, Water, Population and Communities given for the purpose of section 486DA by Springvale Coal Pry Limited and Centennial Angus Place Pty Limited (PDF - 47KB) http://www.environment.gov.au/epbc/compliance/pubs/enforceable-undertaking-centennial.pdf

Fletcher A. T. & Erskine P. D. (2012) Mapping of a rare plant species (*Boronia deanei*) using hyper-resolution remote sensing and concurrent ground observation. *Ecological Mangement and Restoration* 13, 195–198.

Gilbert J., Danielopol D. L. & Stanford J. A. (1994a) *Groundwater Ecology*. Academic Press, San Diego.

Gilbert J., Stanford J. A., Dole-Olivier M.-J. & Ward J. V. (1994b) Basic attributes of groundwater ecosystems and prospects for research. In: *Groundwater Ecology* (eds J. Gilbert, D. L. Danielopol and J. A. Stanford) pp. 10–3. Academic Press, San Diego.

Goldney D., Mactaggart B. & Merrick N. (2010) Determining whether or not a significant impact has occurred on Temperate Highland Peat Swamps on Sandstone within the Angus Place Colliery Lease on the Newnes Plateau. Prepared for

Department of the Environment, Water, Heritage and the Arts, January 2010.

Gore A. J. P. (1983) *Ecosystems of the World 4A. Mires: Swamp, Bog, Fen and Moor*. Elsevier, Amsterdam.

Greenslade P. & Smith D. (1999) The epigaeic arthropod fauna of buttongrass moorland in Tasmanian Wilderness World Heritage Area. In: *The Other 99%: the Conservation and Biodiversity of Invertebrates* (eds W. F. Ponder and D. Lunney) pp. 90–4. Transactions of the Royal Zoological Society of New South Wales, Mosman, NSW.

Growns I. O. & Marsden T. (1998) Altitude separation and pollution tolerance in the freshwater crayfish *Euastacus spinifer* and *E. australasiensis* (Decapoda:Parastacidae) in coastal flowing streams of the Blue Mountains, New South Wales. *Proceedings of the Linnean Society of NSW* 120, 139–45.

Growns I. O. & Richardson A. M. M. (1988) Diet and burrowing habits of the freshwater crayfish, *Parastacoides tasmanicus tasmanicus* Clark (Decapoda : Parastacidae). *Marine and Freshwater Research* 39, 525–34.

Hahn H. J. (2000) Studies on classifying of undisturbed spring in southwestern Germany by macrobenthic communities. *Limnologica – Ecology and Management of Inland Waters* 30, 247–59.

Hájek M., Horsák M., Hájková P. & Díte D. (2006) Habitat diversity of central European fens in relation to environmental gradients and an effort to standardise fen terminology in ecological studies. *Perspectives in Plant Ecology, Evolution and Systematics* 8, 97–114.

Hatton T. & Evans R. (1998) *Dependence of Ecosystems on Groundwater and its Significance to Australia*. LWRRDC Occasional Paper No. 12/98. Land and Water Resources Research & Development Corporation, Canberra.

Hesse P. P., Humphreys G. S., Selkirk P. M., Adamson D. A., Gore D. B., Nobes D. C.,Price D. M., Schwenninger J. -L., Smith B., Tulau M. & Hemmings F. (2003) Late Quaternary aeolian dunes on the presently humid Blue Mountains, Eastern Australia. *Quaternary International* 108, 13–32.

Hoffsten P.-O. & Malmqvist B. (2000) The macroinvertebrate fauna and hydrogeology of springs in central Sweden. *Hydrobiologia* 436, 91–104.

Holland W. N., Benson D. H. & McRae R. H. D. (1992a) Spatial and temporal variation in a perched headwater valley in the Blue Mountains: geology, geomorphology, vegetation, soils and hydrology. *Proceedings of the Linnean Society of NSW* 113, 271–95.

Holland W. N., Benson D. H. & McRae R. H. D. (1992b) Spatial and temporal variation in a perched headwater valley in the Blue Mountains: solar radiation and temperature. *Proceedings of the Linnean Society of NSW* 113, 297–309.

Hope G., Whinam J. & Good R. (2005) Methods and preliminary results of post-fire experimental trials of restoration techniques in the peatlands of Namadgi (ACT) and Kosciuszko National Parks (NSW). *Ecological Management & Restoration* 6, 214–7.

Horwitz P. & Knott B. (1983) The burrowing habit of the Koonac *Cherax plebejus* (Decapoda: Parastacidae). *West Australian Naturalist* 15, 113–7.

Horwitz P., Pemberton M. & Ryder D. (1999) Catastrophic loss of organic carbon from a management fire in a peatland in southwestern Australia. In: *Wetlands for the Future* (eds A. J. McComb and J. A. Davis) pp. 487–501. Gleneagles Publishing, Adelaide, South Australia.

Horwitz P. & Smith R. (2005) Fire and wetland soils and sediments on the Swan Coastal Plain: an introduction. *Journal of the Royal Society of Western Australia* 88, 77–9.

Horwitz P. & Sommer B. (2005) Water quality responses to fire, with particular reference to organic-rich wetlands and the Swan Coastal Plain: a review. *Journal of the Royal Society of Western Australia* 88, 121–8.

Horwitz P. H. J. & Richardson A. M. M. (1986) An ecological classification of the burrows of Australian freshwater crayfish. *Marine and Freshwater Research* 37, 237–42.

Horwitz P. H. J., Richardson A. M. M. & Cramp P. M. (1985) Aspects of the life history of the burrowing crayfish *Engaeus leptorhyncus* at Rattrays Marsh, north-east Tasmania. *Tasmanian Naturalist* 82, 1–5.

Hose G (2009) 'Stygofauna baseline assessment for Kangaloon borefield investigations – Southern Highlands, NSW. Supplementary report – stygofauna molecular studies.' Report to Sydney Catchment Authority. Access Macquarie Ltd, North Ryde.

Humphreys W. F. (2008) Rising from down under: developments in subterranean biodiversity in Australia from a groundwater fauna perspective. *Invertebrate Systematics* 22, 85–101.

Irwin J. T., Costanzo J. P. & Lee Jr R. E. (1999) Terrestrial hibernation in the northern cricket frog, *Acris crepitans*. *Canadian Journal of Zoology* 77, 1240–6.

Jabłońska E., Pawlikowski P., Jarzombkowski F., Chormański J., Okruszko T. & Kłosowski S. (2011) Importance of water level dynamics for vegetation patterns in a natural percolation mire (Rospuda fen, NE Poland). *Hydrobiologia* 674, 105–17.

Johnson P. N. (2001) Vegetation recovery after fire on a southern New Zealand peatland. *New Zealand Journal of Botany* 39, 251–67.

Keith D. A. (1996) Fire–driven extinction of plant populations: a synthesis of theory and review of evidence from Australian vegetation. *Proceedings of the Linnean Society of NSW* 116, 37–78.

Keith D. A. (2004) *Ocean Shores to Desert Dunes: the Native Vegetation of New South Wales and the ACT*. Department of Environment and Conservation (NSW), Hurstville.

Keith D. A. & Myerscough P. J. (1993) Floristics and soil relations of upland swamp vegetation near Sydney. *Australian Journal of Ecology* 18, 325–44.

Keith D. A., McGaw L. & Whelan R. J. (2002) Fire regimes in Australian heathlands and their effects on plants and animals. In: *Flammable Australia: the Fire Regimes and Biodiversity of a Continent* (eds R. A. Bradstock, J. E. Williams and A. M. Gill). Cambridge University Press, Cambridge.

Keith D. A., Rodoreda S., Holman L. & Lemmon J. (2006) Monitoring change in upland swamps in Sydney's water catchments: the roles of fire and rain. Sydney Catchment Authority Special Area Strategic Management Research and Data Program. Project number RD07: Long term responses of upland swamps to fire. Final Report. Department of Environment and Conservation, Hurstville, NSW.

King D. P. (1993) *Soil Landscapes of the Wallerawang 1:100,000 Sheet Report*. Department of Conservation and Land Management, Sydney.

Kirkpatrick J. B. & Bridle K. L. (1998) Environmental relationships of floristic variation in the alpine vegetation of southeastern Australia. *Journal of Vegetation Science* 9, 251–60.

Kirkpatrick J. B. & Dickinson K. J. M. (1984) The impact of fire on Tasmanian alpine vegetation and soils. *Australian Journal of Botany* 32, 613–29.

Kodela P., James T. A. & Hind P. D. (1996) Vegetation and flora of swamps of the Boyd Plateau, Central Tablelands, New South Wales. *Cunninghamia* 4, 525–30.

Kodela P. G., Sainty G. R., Bravo F. J. & James T. A. (2001) Wingecarribee Swamp flora survey and related management issues. Unpublished report to Sydney Catchment Authority, New South Wales.

Krogh, M. 2007. Management of Longwall Coal Mining Impacts in Sydney's Southern Drinking Water Catchments. *Australasian Journal of Environmental Management*, 14, 155–165.

Lake P. S. (1977) Pholoteros – the faunal assemblage found in crayfish burrows. *Australian Society of Limnology Newsletter* 15, 57–60.

Lake P. S. & Newcombe K. J. (1975) Observations on the ecology of the crayfish *Parastacoides tasmanicus* (Decapoda: Parastacidae) from south-western Tasmania. *Australian Journal of Zoology* 18, 197–214.

Larson D. J. & House N. L. (1990) Insect communities of Newfoundland bog pools with emphasis on the Odonata. *Canadian Entomologist* 122, 469–501.

Laurance W. F., Dell B., Turton S. M., Lawes M. J., Hutley L. B., McCallum H., Dale P., Bird M., Hardy G., Prideaux G., Gawne B., McMahon C. R., Yu R., Hero J. -M., Schwarzkopf L., Krockenberger A., Douglas M., Silvester E., Mahony M., Vella K., Saikia U., Wahren C. -H., Xu Z., Smith B. & Cocklin C. (2011) The 10 Australian ecosystems most vulnerable to tipping points. *Biological Conservation* 144: 1472–80.

LeBreton M. (1996) Habitat and distribution of the Blue Mountains swamp skink (*Eulamprus leuraensis*). B. Zool. (Hons.) thesis. University of New South Wales, Sydney.

Maiden J. H. & Betche E. (1906) Notes from the Botanic Gardens, Sydney No. 12. *Proceedings of the Linnean Society of NSW* 31, 732–42.

Marshall B. (2005) *Groundwater: Lifeblood of the Environment*. Blue Mountains Conservation Society, Wentworth Falls, NSW.

McKibben D. & Smith P. C. (2000) Sandstone hydrogeology of the Sydney region. In: *Sandstone City: Sydney's Dimension Sandstone and other Sandstone Geomaterials: Proceedings of a Symposium held on 7 July 2000* (eds G. H. McNally and B. J. Franklin) pp. 83–97. Geological Society of Australia, Springwood.

Merrick J. R. (1998) *Endemic Crayfishes of the Sydney Region: Distribution, Biology and Management Options*. Macquarie University, North Ryde, NSW.

Mikkola K. & Spitzer K. (1983) Lepidoptera associated with peatlands in central and northern Europe: a synthesis. *Nota Lepidopterologica* 6, 216–29.

Mitsch W. J. & Gosselink J. G. (2007) *Wetlands*. John Wiley & Sons, Hoboken, New Jersey.

Mitsch W. J., Gosselink J. G., Anderson C. J. & Zhang L. (2009) *Wetland Ecosystems*. John Wiley & Sons, Hoboken, New Jersey.

Moore P. D. (1989) The ecology of peat-forming processes: a review. *International Journal of Coal Geology* 12, 89–103.

Moore P. D. (2002) The future of cool temperate bogs. *Environmental Conservation* 29, 3–20.

Moore P. D. & Bellamy D. J. (1974) *Peatlands*. Elek Science, London.

Morgan G. J. (1997) Freshwater crayfish of the genus *Euastacus* Clark (Decapoda: Parastacidae) from New South Wales, with a key to all species of the genus. *Records of the Australian Museum* Supplement 23 (1997), 110 pp.

Morrison D. A. (2002) Effects of fire intensity on plant species composition of sandstone communities in the Sydney region. *Austral Ecology* 27, 433–41.

Morrison D. A., Cary G. J., Pengelly S. M., Ross D. G., Mullins B. J., Thomas C. R. & Anderson T. S. (1995) Effects of fire frequency on plant species composition of sandstone communities in the Sydney region: inter-fire interval and time-since-fire. *Australian Journal of Ecology* 20, 239–47.

Murray B. R., Zeppel J. B., Hose G. C. & Eamus D. (2003) Groundwater-dependent ecosystems in Australia: it's more than just water for rivers. *Ecological Management & Restoration* 4, 110–3.

NPWS. (2001) Blue Mountains Water Skink. Threatened species profile. National Parks & Wildlife Service of NSW, Sydney.

NSW Government. (2002) *The NSW State Groundwater Dependent Ecosystems Policy*. Department of Land and Water Conservation and the State Groundwater Policy Working Group, Sydney.

NSW Scientific Committee. (1998) Giant dragonfly – endangered species listing. NSW Scientific Committee final determination. [Accessed August 13th 2008]. Available from http://www.environment.nsw.gov.au/determinations/GiantDragonflyEndSpListing.htm

NSW Scientific Committee. (2002) Alteration to the natural flow regimes of rivers, streams, floodplains and wetlands. NSW Scientific Committee Key Threatening Process final determination. [Accessed December 10th 2009]. Available from http://www.environment.nsw.gov.au/threatenedspecies/AlterationNaturalFlowKTPListing.htm

NSW Scientific Committee. (2004) Montane Peatlands and Swamps of the New England Tableland, NSW North Coast, Sydney Basin, South East Corner, South Eastern Highlands and Australian Alps bioregions – endangered ecological community listing. NSW Scientific Committee final determination. [Accessed August 13th 2008]. Available from http://www.environment.nsw.gov.au/determinations/MontanePeatlandsEndSpListing.htm

NSW Scientific Committee. (2005) Newnes Plateau Shrub Swamp in the Sydney Basin Bioregion – endangered ecological community listing. NSW Scientific Committee final determination. [Accessed August 13th 2008]. Available from http://www.environment.nsw.gov.au/determinations/NewnesPlateauShrubSwampEndSpListing.htm

NSW Scientific Committee. (2005) Alteration of habitat following subsidence due to longwall mining. NSW Scientific Committee Key Threatening Process final determination. [Accessed May 29th 2005]. Available from http://www.environment.nsw.gov.au/determinations/LongwallMiningKtp.htm

Pecover S. R. (1984) Friable sandstones of the Sydney Basin – a major source of industrial and construction for the Sydney market. *Geological Society of Australia Abstracts* 12, 430–2.

Pemberton M. (2005) Australian peatlands: a brief consideration of their origin, distribution, natural values and threats. *Journal of the Royal Society of Western Australia* 88, 81–9.

Richardson A. M. M. (1983) The effect of the burrows of a crayfish on the respiration of the surrounding soil. *Soil Biology and Biochemistry* 15, 239–42.

Richardson A. M. M. & Horwitz P. H. J. (1988) Habitat partitioning by Australian burrowing crayfish. *Freshwater Crayfish* 7, 91–7.

Richardson A. M. M. & Swain R. (1980) Habitat requirements and distribution of *Engaeus cisternarius* and three subspecies of *Parastacoides tasmanicus* (Decapoda: Parastacidae), burrowing crayfish from an area of south-western Tasmania. *Australian Journal of Marine and Freshwater Research* 31, 475–84.

Richardson A. M. M. & Swain R. (1991) Pattern and persistence in the burrows of two species of the freshwater crayfish, *Parastacoides* (Decapoda: Parastacidae), in southwest Tasmania. *Memoirs of the Queensland Museum* 31, 283.

Richardson A. M. M. & Wong V. (1995) The effect of a burrowing crayfish, *Parastacoides* sp., on the vegetation of Tasmanian wet heathlands. *Freshwater Crayfish* 10, 174–82.

Rossetto M., Thurlby K.A.G., Offord, C.A., Allen, C.B. & Weston, P.H. (2011) The impact of distance and a shifting temperature gradient on genetic connectivity across a heterogeneous landscape. *BMC Evolutionary Biology* 11:126.

Rutledge S., Campbell D. I., Baldocchi D. & Schipper L. A. (2010) Photodegradation leads to increased carbon dioxide losses from terrestrial organic matter. *Global Change Biology* 16, 3065–74.

Semeniuk V. & Semeniuk C. A. (2005) Wetland sediments and soils on the Swan Coastal Plain, southwestern Australia: types, distribution, susceptibility to combustion, and implications for fire management. *Journal of the Royal Society of Western Australia* 88, 91–120.

Shearer J. C. (1997) Natural and anthropogenic influences on peat development in Waikato/Hauraki Plains restiad bogs. *Journal of the Royal Society of New Zealand* 27, 295–313.

Spitzer K. & Danks H. V. (2006) Insect biodiversity of boreal peat bogs. *Annual Review of Entomology* 51, 137–61.

Springvale Coal. (2005) Springvale Colliery Longwalls 411–418 Subsidence Management Plan Application. Springvale Coal.

Springvale Coal. (2008) Springvale Colliery 2008 Annual Environmental Management Report. [Accessed September 23rd 2009]. Available from http://www.centennialcoal.com.au/index.php?option=com_content&view=article&id=35&Itemid=43

Stricker J. S. & Wall C. A. (1995) Wetlands of the Nepean – Hawkesbury Catchment. Sydney Water Corporation, Sydney.

Suter P. J. & Richardson A. M. M. (1977) The biology of two species of *Engaeus* (Decapoda : Parastacidae) in Tasmania. III. Habitat, food, associated fauna and distribution. *Marine and Freshwater Research* 28, 95–103.

Swan G., Shea G. & Sadlier R. (2004) *A Field Guide to Reptiles of New South Wales*. Reed New Holland, Sydney.

Taranto M., Downe J., Coates F. & Oates A. (2004) Recovery of Montane Swamp Complex after bushfires in north-east Victoria 2003. Arthur Rylah Institute for Environmental Research Technical Report Series No. 152. Department of Sustainability and Environment, Heidelberg.

Theischinger G. & Endersby I. (2009) *Identification Guide to the Australian Odonata*. Department of Environment, Climate Change and Water NSW, Hurstville, NSW.

Threatened Species Scientific Committee (TSSC). (2005) Commonwealth Listing Advice on Temperate Highland Peat Swamps on Sandstone. [Accessed October 16th 2009]. Available from http://www.environment.gov.au/biodiversity/threatened/publications/temperate-highland-peat-swamps.html

Threatened Species Scientific Committee. (2009) Alpine *Sphagnum* Bogs and Associated Fens ecological community Listing Advice. [Accessed September 6th 2010]. Available from http://www.environment.gov.au/cgi-bin/sprat/public/publicshowcommunity.pl?id=29&status=Endangered

Tillyard R. J. (1911) Studies in the life-histories of Australian Odonata. 4. Further notes on the life-history of *Petalura gigantea* Leach. *Proceedings of the Linnean Society of NSW* 36, 86–96.

Timmins S. M. (1992) Wetland vegetation recovery after fire: Eweburn Bog, Te Anau, New Zealand. *New Zealand Journal of Botany* 30, 383–99.

Tomkins K.M. & Humphreys G.S. (2006) Technical Report No 2. Upland swamp development and erosion on the Woronora Plateau during the Holocene. Sydney Catchment Authority (SCA).

Trueman J. W. H. (2000) Survey for *Petalura gigantea* Leach (Giant Dragonfly) in New South Wales: 1999–2000 flight season. Unpublished report to NSW National Parks and Wildlife Service.

Turbott E. G. (1949) Discovery of the breeding habits of *Leiopelma hochstetteri* Fitzinger. *Records of the Auckland Institute & Museum* 3, 373–6.

Walsh N. G. & McDougall K. L. (2004) Progress in the recovery of the flora of treeless subalpine vegetation in Kosciusko National Park after the 2003 fires. *Cunninghamia* 8, 439–52.

Washington H. G. & Wray, R. A. L. (2011) The geoheritage and geomorphology of the sandstone pagodas of the north-western Blue Mountains region (NSW). *Proceedings of the Linnean Society of NSW* 132, 131–43.

Watson P. (2006a) *Hotspots Fire Project: Fire and the Vegetation of the Southern Rivers Region*. Nature Conservation Council of NSW and the NSW Government Environmental Trust, Sydney.

Watson P. (2006b) *Hotspots Fire Project: Fire Frequency Guidelines and the Vegetation of the Northern Rivers Region*. Nature Conservation Council of NSW and the NSW Government Environmental Trust, Sydney.

Wheeler B. D. (1999) Water and plants in freshwater wetlands. In: *Eco-hydrology: Plants and Water in Terrestrial and Aquatic Environments* (eds A. J. Baird and R. L. Wilby) pp. 127–80. Routledge, London.

Wheeler B. D. & Proctor M. C. F. (2000) Ecological gradients, subdivisions and terminology of north-west European mires. *Journal of Ecology* 88, 187–203.

Whinam J. (1995) Effects of fire on Tasmanian *Sphagnum* peatlands. In: *Bushfire '95: Presented papers, Australian Bushfire Conference, 27–30 September 1995*. Forestry Tasmania, Parks and Wildlife Service, Tasmanian Fire Service, Hobart, Tasmania.

Whinam J., Barmuta L. A. & Chilcott N. (2001) Floristic descriptions and environmental relationships of Tasmanian *Sphagnum* communities and their conservation management. *Australian Journal of Botany* 49, 673–85.

Whinam J. & Hope G. S. (2005) The peatlands of the Australasian region. In: *Moore: von Sibirien bis Feuerland – Mires: from Siberia to Tierra del Fuego* (ed G. M. Steiner) pp. 397–434. Biologiezentrum der Oberoesterreichischen Landesmuseen Neue Serie 35, Linz.

Whittington P. N. & Price J. S. (2006) The effects of water table draw-down (as a surrogate for climate change) on the hydrology of a fen peatland, Canada. *Hydrological Processes* 20, 3589–600.

Williams D. D. & Danks H. V. (1991) Arthropods of springs: Introduction. *Memoirs of the Entomological Society of Canada* 155, 3–5.

Wilkinson M. T. & Humphreys G. S. (2006) Slope aspect, slope length and slope inclination controls of shallow soils vegetated by sclerophyllous heath—links to long-term landscape evolution. *Geomorphology* 76, 347–62.

Wilkinson M. T., Chappell J., Humphreys G. S., Fifield K., Smith B. & Hesse P. (2005) Soil production in heath and forest, Blue Mountains, Australia: influence of lithology and palaeoclimate. *Earth Surface Processes and Landforms* 30, 923–34.

Yabe K. & Onimaru K. (1997) Key variables controlling the vegetation of a cool-temperate mire in northern Japan. *Journal of Vegetation Science* 8, 29–36.

Young A. R. M. (1980) Swampy treeless dells on the Nepean Ramp, N.S.W. In: *Newcastle (16th) Conference of the Institute of Australian Geographers* pp. 437–41. Department of Geography, University of Newcastle, Newcastle.

Young A. R. M. (1982) Upland swamps (dells) on the Woronora Plateau. PhD thesis. University of Wollongong.

Young A. R. M. (1986a) The geomorphic development of dells (upland swamps) on the Woronora Plateau, N.S.W., Australia. *Zeitschrift fur Geomorphologie* 30, 317–27.

Young A. R. M. (1986b) Quaternary sedimentation on the Woronora Plateau and its implications for climatic change. *Australian Geographer* 17, 1 – 5.

Young R. W. & Wray R. A. L. (2000) The geomorphology of sandstones in the Sydney region. In: *Sandstone City: Sydney's Dimension Sandstone and other Sandstone Geomaterials: Proceedings of a Symposium held on 7 July 2000* (eds G. H. McNally and B. J. Franklin). Geological Society of Australia, Springwood.

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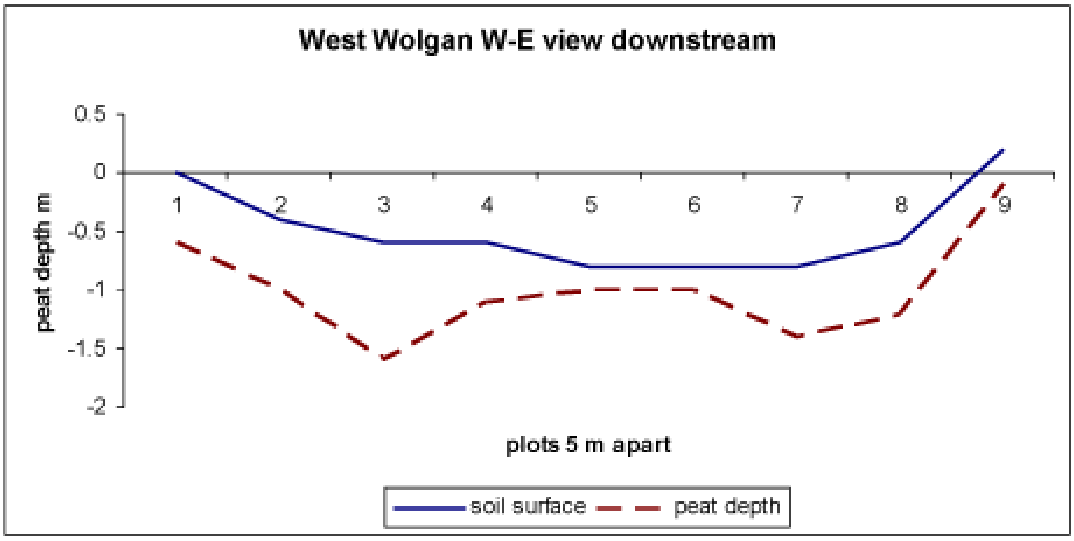
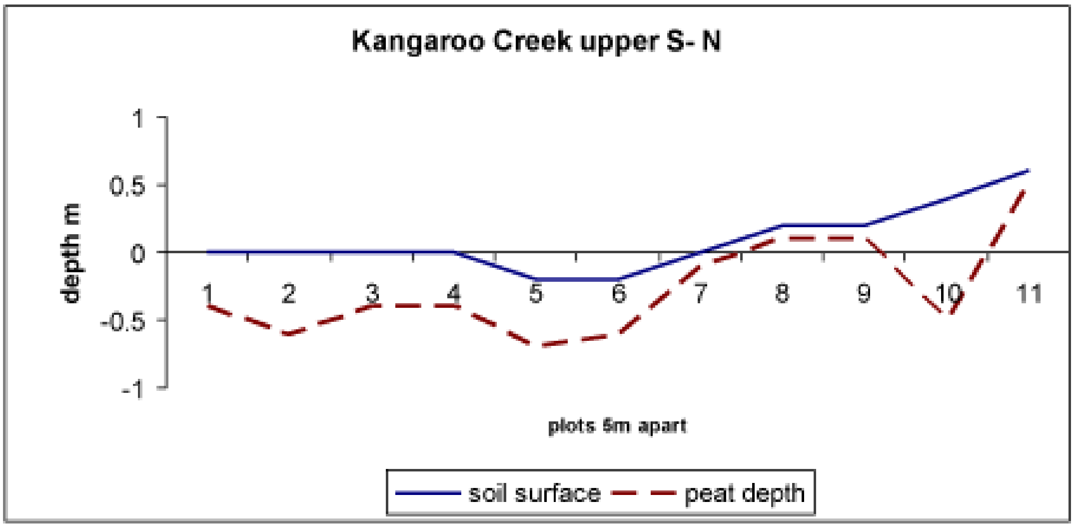
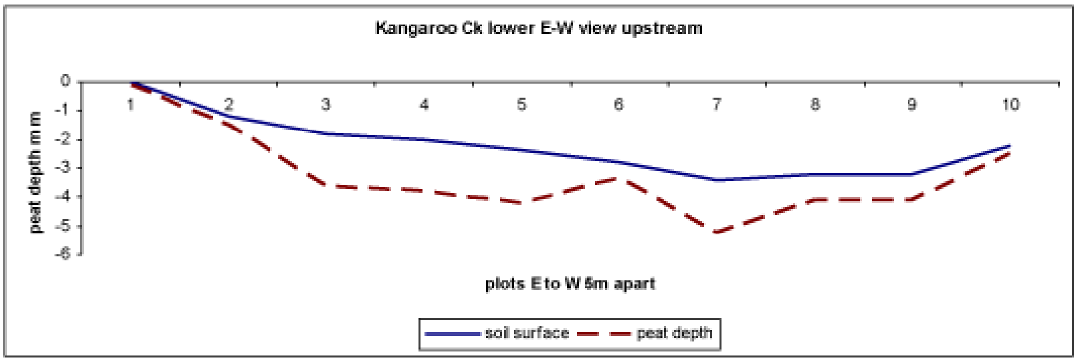
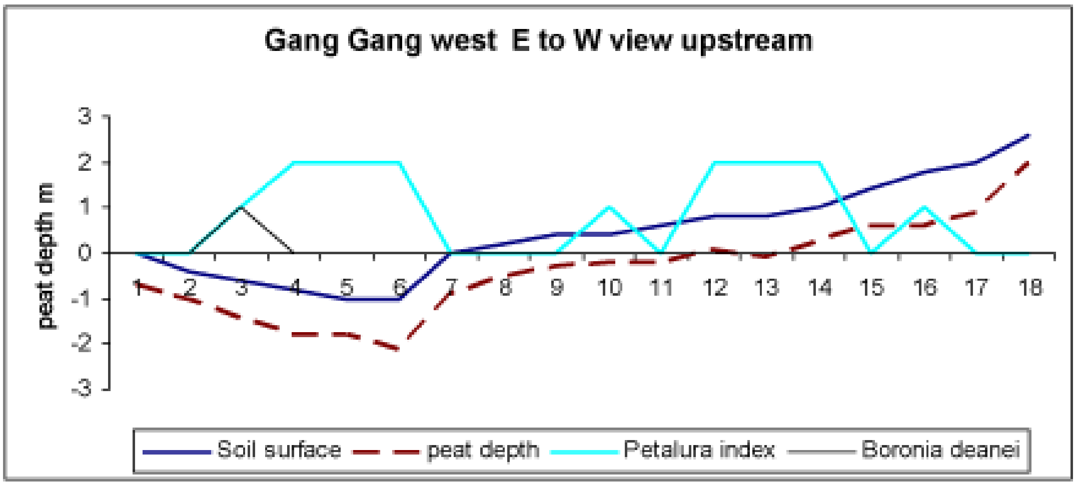
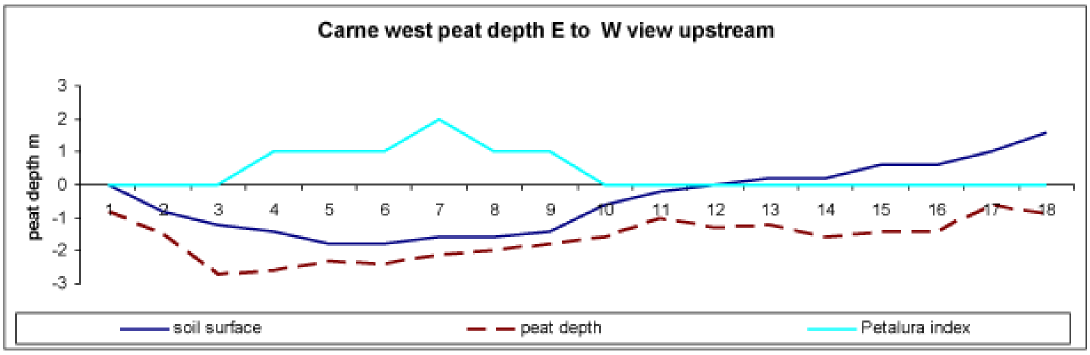
APPENDIX 1 Cross sections of swamps ordered by decreasing elevation, compiled from 5m interval transect points showing surface topography, peat depth (m) and surface water (cm), *Petalura* index (1–3) and *Boronia deanei* presence where recorded (1).

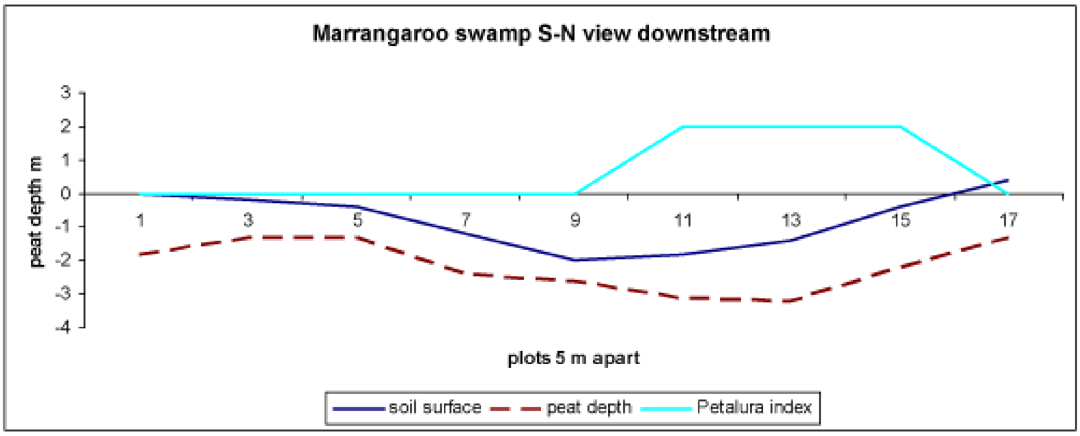


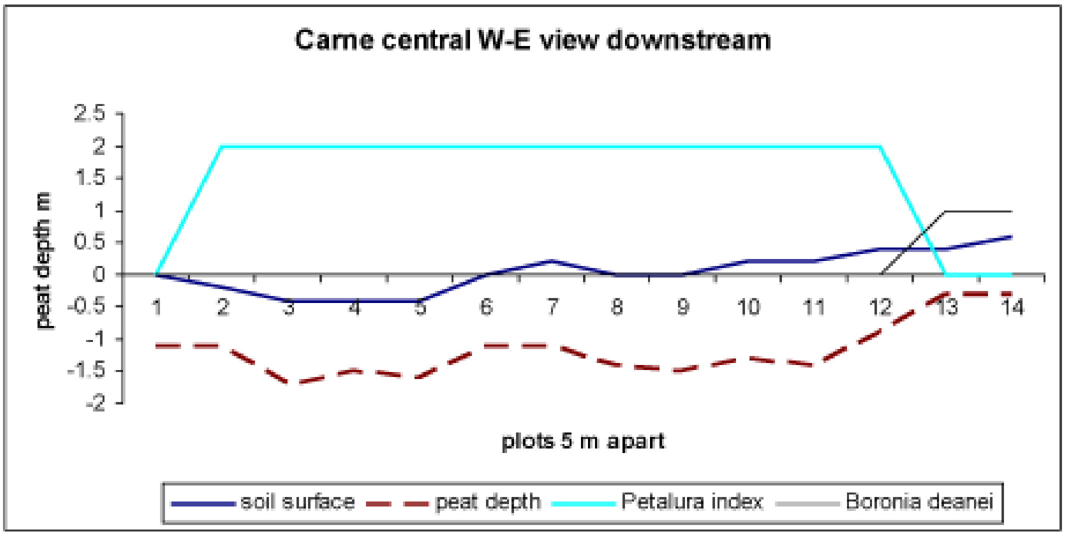


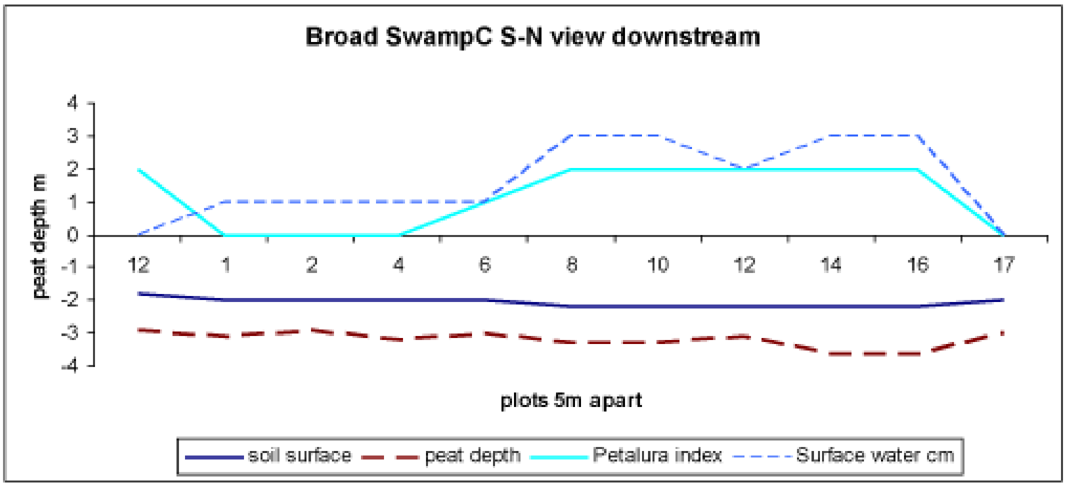

Kangaroo Ck lower E-W view upstream
peat depth m m
plots E to W 5m apart
soil surface
peat depth

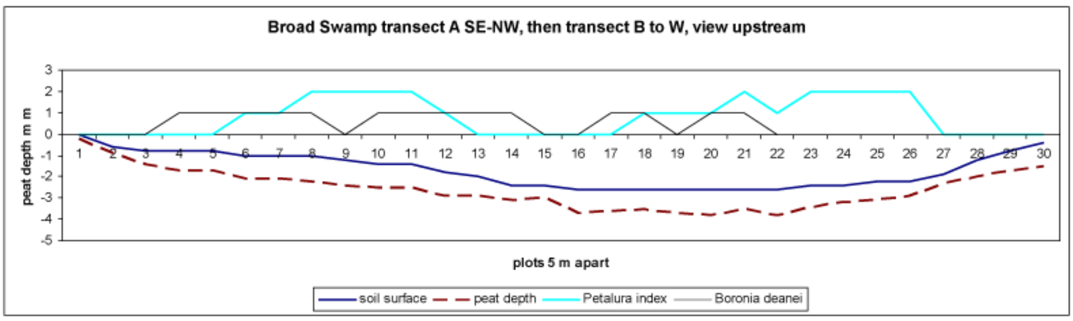

Gang Gang west E to W view upstream
peat depth m
Soil surface
peat depth
Petalura index
Boronia deanei

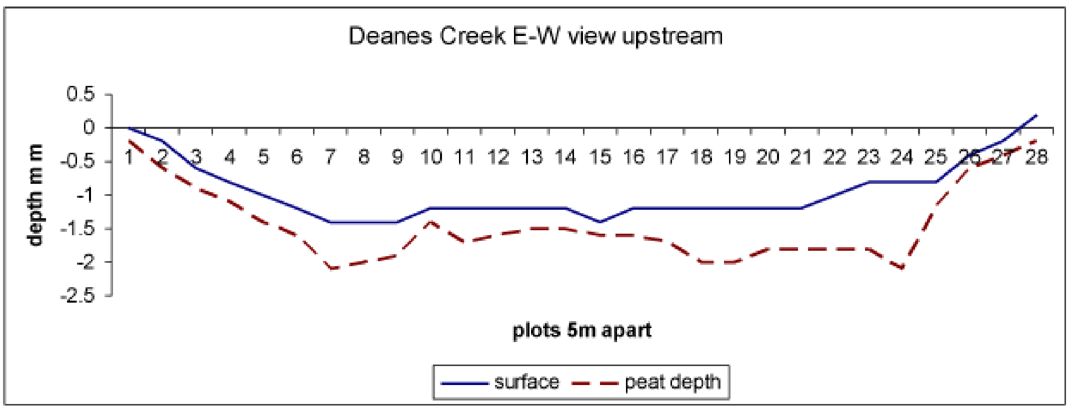

Carne west peat depth E to W view upstream
peat depth m
soil surface
peat depth
Petalura index


Marrangaroo swamp S-N view downstream
peat depth m
plots 5 m apart
soil surface
peat depth
Petalura index


Carne central W-E view downstream
peat depth m
plots 5 m apart
soil surface
peat depth
Petalura index
Boronia deanei


Broad SwampC S-N view downstream
peat depth m
plots 5m apart
soil surface
peat depth
Petalura index
Surface water cm


Broad Swamp transect A SE-NW, then transect B to W, view upstream
peat depth m m
plots 5 m apart
soil surface
peat depth
Petalura index
Boronia deanei


Deanes Creek E-W view upstream
depth m m
plots 5m apart
surface
peat depth

Appendix 2 List of plant species recorded from transect plots in Newnes Plateau Shrub Swamps in 2012, showing percentage frequency in each swamp. Swamps are ordered from highest elevation.

For images of many species see Plants of the Newnes Plateau web pages: www.rbgsyd.nsw.gov.au/science/Evolutionary_Ecology_Research/plants)of_the_newnes_plateau

	Kang Ck upper	West Wolgan	Marangaroo	Carne west	Kang Ck lower	Pine	Carne Central	Gang Gang west	Broad ABC trans	Deanes Creek
No of plots	**11**	**9**	**9**	**18**	**10**	**7**	**14**	**18**	**40**	**28**
Swamp elevation m	**1130**	**1130**	**1100**	**1090**	**1090**	**1090**	**1080**	**1080**	**1050**	**980**
Almalea incurvata	0	0	0	0	0	0	0	0	0	4
Anisopogon avenaceus	0	0	0	0	0	0	0	0	3	0
Baeckea linifolia	0	44	67	44	0	14	0	67	40	11
Baeckea utilis	0	0	0	0	0	0	93	0	30	75
Baloskion australe	0	33	33	44	10	0	93	11	28	0
Banksia cunninghamii	0	0	0	0	10	0	0	0	0	0
Banksia spinulosa	0	0	11	0	0	0	0	0	0	0
Baumea sp	0	0	11	17	0	57	0	11	3	0
Blechnum nudum	0	0	0	0	0	43	0	0	0	0
Boronia deanei	0	0	0	0	0	0	14	6	40	0
Boronia microphylla	45	22	0	6	0	0	0	0	0	4
Bossiaea rhombifolia	0	0	0	0	0	0	0	0	0	4
Callistemon pityoides	0	0	22	0	0	0	0	0	0	0
Celmisia longifolia	0	0	0	0	0	0	14	6	10	0
Comesperma ericinum	0	0	0	6	0	0	0	0	0	0
Conosperma taxifolium	0	0	0	0	0	0	0	6	0	0
Coronidium scorpioides	9	11	0	0	0	0	0	0	0	0
Coronidium waddelliae	0	0	0	0	0	0	0	0	0	4
Dampiera stricta	0	0	0	0	0	0	0	6	3	14
Daviesia latifolia	0	11	0	0	10	0	0	0	0	0
Dawsonia sp (moss)	9	0	0	0	0	0	0	0	0	0
Dianella revoluta	0	0	0	6	0	0	0	0	0	4
Dichondra repens	0	0	0	0	0	0	0	0	3	0
Dillwynia stipulifera	0	0	0	0	0	0	0	0	3	0
Drosera binata	0	0	0	11	0	0	7	6	0	0
Drosera spathulata	0	0	0	0	0	0	0	6	0	0
Empodisma minus	0	0	100	89	60	0	100	61	93	0
Epacris microphylla	45	78	33	0	10	0	21	22	50	11
Epacris paludosa	9	0	33	17	0	0	43	33	45	0
Eucalyptus dalrympleana	9	0	0	0	0	0	0	0	0	7
Eucalyptus mannifera	0	0	0	0	0	0	0	6	5	0
Eucalyptus pauciflora juv	0	11	0	0	0	0	0	0	3	0
Gahnia filifolia	0	0	0	0	0	0	0	0	8	0
Gahnia sieberiana	0	0	0	22	0	0	0	0	0	0

	Kang Ck upper	**West Wolgan**	**Marangaroo**	**Carne west**	**Kang Ck lower**	**Pine**	**Carne Central**	**Gang Gang west**	**Broad ABC trans**	**Deanes Creek**
No of plots	**11**	**9**	**9**	**18**	**10**	**7**	**14**	**18**	**40**	**28**
Swamp elevation m	**1130**	**1130**	**1100**	**1090**	**1090**	**1090**	**1080**	**1080**	**1050**	**980**
Galium sp	0	11	0	0	0	0	7	0	10	0
Gleichenia dicarpa	55	0	89	78	90	100	0	56	20	0
Gonocarpus micranthus	0	44	22	6	0	0	64	0	3	39
Gonocarpus tetragynus	0	11	0	0	0	0	0	0	3	7
Goodenia belledifolia	0	22	0	0	0	0	0	11	13	7
Grevillea acanthifolia	0	0	89	56	20	0	64	22	58	0
Grevillea laurifolia	27	0	0	0	0	0	0	0	0	4
Gymnoschoenus sphaerocephalus	0	0	0	11	0	0	0	44	23	18
Hakea microcarpa	0	78	0	0	0	0	0	0	0	0
Hibbertia acicularis	0	0	56	0	0	0	0	6	5	0
Hibbertia sp (*riparia*??)	0	0	0	6	0	0	0	0	0	0
Hydrocotyle peduncularis acicularis	0	11	0	0	20	0	14	0	3	4
Hypericum gramineum	0	11	0	0	0	0	0	0	3	4
*Hypochoeris radicata**	0	0	0	0	0	0	0	0	0	11
Juncus sp	0	0	0	0	10	0	0	0	0	0
Lepidosperma laterale	0	0	0	0	0	0	0	0	0	14
Lepidosperma limicola	0	0	67	50	0	14	0	72	43	29
Leptospermum continentale	27	33	22	0	0	0	0	0	0	14
Leptospermum grandifolium	9	0	11	44	0	0	0	56	68	18
Leptospermum myrtifolium	100	56	0	0	0	0	0	0	5	0
Leptospermum obovatum	0	0	0	0	40	0	7	0	0	0
Lepyrodia anarthria	0	33	33	11	0	0	7	6	20	21
Lepyrodia scariosa	0	0	0	0	0	14	0	6	0	4
Lindsaea linearis	0	0	0	0	0	0	0	6	20	0
Lomandra glauca	0	0	0	0	0	0	0	6	3	4
Lomandra longifolia	0	22	0	0	10	0	0	0	8	7
Microlaena stipoides	9	0	0	0	0	0	0	0	0	0
Mirbelia platyloboides	9	0	0	0	0	0	0	0	0	0
Monotocca scoparia	0	0	0	0	0	0	0	0	0	4
Nertera granadensis	0	44	0	0	0	0	21	28	13	4
Patersonia fragilis	0	0	0	0	0	0	7	0	60	0
Patersonia sericea	0	0	0	0	0	0	0	0	0	4
Persoonia hindii	0	0	0	6	0	0	0	0	0	0
Petrophile canescens	0	0	0	0	0	0	0	0	0	4
Phyllota squarrosa	0	0	0	0	0	0	0	6	3	4
Pimelea linifolia	0	0	0	0	0	0	0	0	10	0
Platysace linearifolia	0	0	0	6	0	0	0	6	0	0
Poa sp	36	22	0	6	10	0	0	0	23	0
Polyscias sambucifolia	0	0	0	0	0	0	0	0	0	4

	Kang Ck upper	**West Wolgan**	**Marangaroo**	**Carne west**	**Kang Ck lower**	**Pine**	**Carne Central**	**Gang Gang west**	**Broad ABC trans**	**Deanes Creek**
No of plots	**11**	**9**	**9**	**18**	**10**	**7**	**14**	**18**	**40**	**28**
Swamp elevation m	**1130**	**1130**	**1100**	**1090**	**1090**	**1090**	**1080**	**1080**	**1050**	**980**
Poranthera microphylla	0	0	0	0	0	0	0	0	0	7
Pteridium esculentum	0	0	0	6	40	0	0	0	0	4
Pultenaea divaricata	0	0	33	17	0	0	0	0	0	0
Rulingia prostrata	0	0	0	0	0	0	0	0	0	11
Schoenus sp (larger)	0	0	11	0	0	0	14	0	0	0
Schoenus sp (small)	9	0	11	0	0	0	57	0	0	0
Selaginella uliginosa	0	0	0	0	0	0	0	0	0	18
Sprengelia incarnata	0	0	0	0	0	0	0	6	0	0
Stackhousia viminea	0	0	0	0	0	0	0	0	0	4
Stylidium graminifolium	36	11	0	0	0	0	0	11	10	32
Tetrarrhena juncea	0	0	22	0	0	0	14	6	10	0
Thelymitra sp	0	0	0	0	0	0	7	0	3	4
Utricularia dichotoma	0	0	0	0	0	0	7	6	3	0
Velleia montana	0	0	0	0	0	0	0	0	10	0
Viola betonicifolia	0	11	0	0	0	0	0	0	0	0
Viola sieberiana	64	44	11	6	0	0	14	0	0	46
Wahlenbergia gracilis	0	11	0	0	0	0	0	0	0	0
Xanthosia dissecta	0	0	11	0	0	0	0	11	13	0
Xyris gracilis	0	44	0	0	0	0	0	6	3	7
Xyris ustulata	0	0	22	39	0	0	14	50	25	36