Preliminary restoration planning for the endangered Riverbank Paperbark Swamp Forests of Blaxland Waste Management Facility

Contents

1 | Introduction

Blaxland Waste Management Facility (BWMF) is an active landfill and resource recovery centre located in the lower Blue Mountains near Sydney, Australia (figure 1.1). It is the only remaining active landfill within the Blue Mountains, with landfilling planned to continue for the next ten to fifteen years. Like previous landfills in the Blue Mountains, the operational area of BWMF is sited in a swampy valley.

BWMF covers an area of 108 hectares and is composed of four separate parcels of crown land managed by Blue Mountains City Council. Of this land, the operational area covers only 15 hectares, while the remaining 93 hectares is covered in bushland. This land straddles two headwater valleys of the Cripple Creek catchment.

BWMF contains two areas (referred to here as Main Swamp and Winnicoopa Swamp, see figure 1.1) of endangered *Riverflat Paperbark Swamp Forest*. While only comprising an area of 5.5 hectares, these small pockets of swamp forest ate highly significant since only 160 hectares of this once widespread ecological community remain within the entire Sydney region (OEH 2016).

Unfortunately, since the mid-Twentieth century the pockets of swamp forest within BWMF have been degraded by various human activities including landfilling, quarrying, sand mining and urban development of the surrounding ridges. These activities have lead to changes in the hydrology and geomorphology of the catchment. In turn, this has caused a loss of edge of swamp vegetation communities, reduction in the extent of swamp axis vegetation communities, and the infestation of the forest understorey by *Ligustrum sinense* (narrow leaf privet) and other weeds.

Despite these changes in the wider catchment, until the last decade, Main swamp remained in a reasonable, albeit weedy, condition. In 2008, a groundwater cutoff wall was installed along the up-gradient Eastern edge of Main Swamp blocking the flow of leachate impacted groundwater. As a result of this wall, the groundwater in the Western portion of Main Swamp has fallen by approximately three metres, precipitating the cutting of a deep channel through the central axis of the swamp. This channel has directly caused the collapse of many large, old

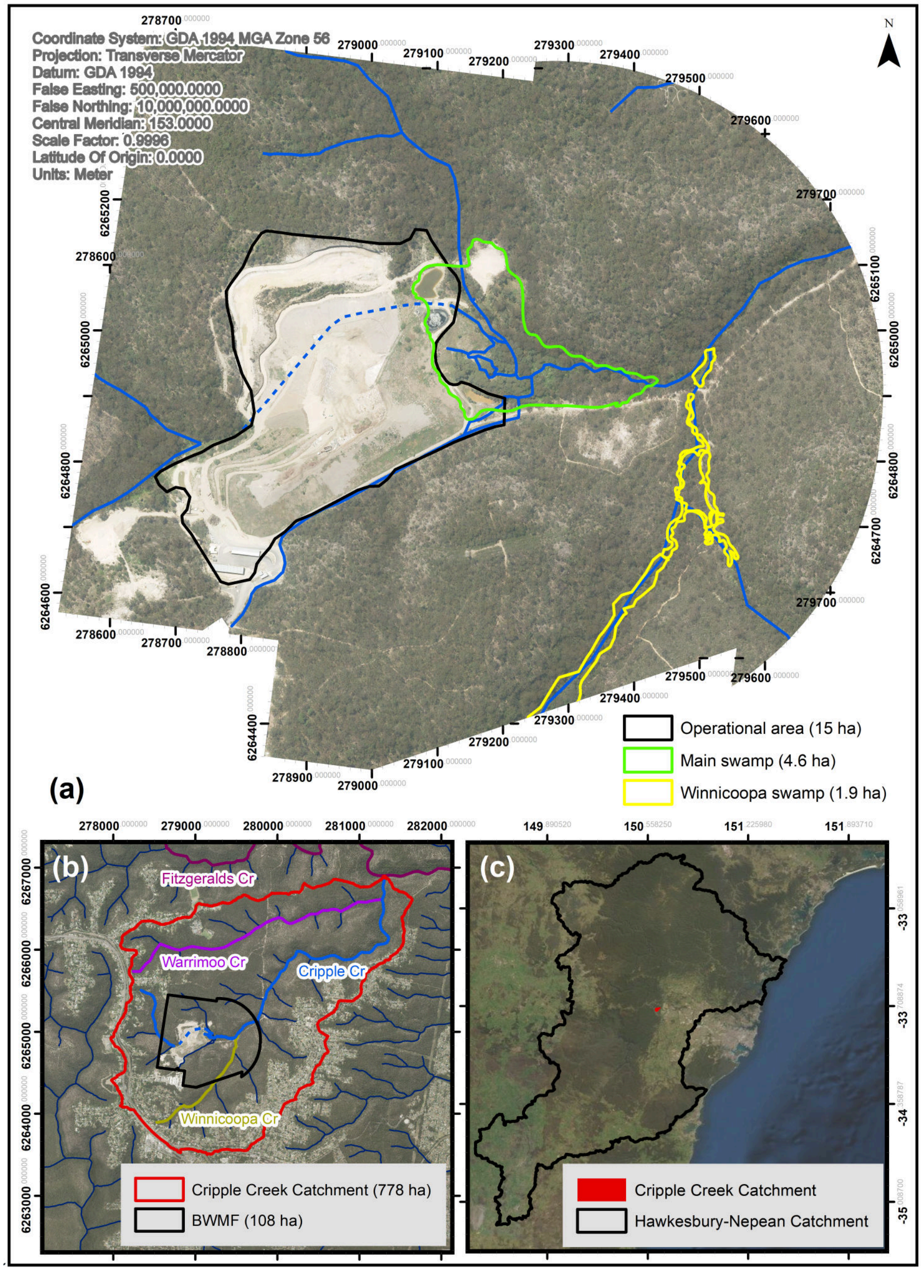


Figure 1.1: **Map of Blaxland Waste Management Facility and its hydrological context.** (**a**) *Extent of the combined BWMF land parcels, showing location of operational footprint, Main Swamp, Winnicoopa Swamp and major drainage lines. Note that Cripple Creek travels through the operational area in an underground pipe, shown as a dashed line.* (**b**) *Cripple Creek Catchment, showing the location of major creeks referred to below.* (**c**) *Cripple Creek catchment within the context of the larger Hawkesbury-Nepean catchment.*

Melaleuca linariifolia (snow in summer) trees, while the dewatering of the peat has caused it to begin oxidising, releasing large quantities of dissolved organic matter and previously bound toxins from historical leachate into Cripple Creek. The lowered watertable may also have encouraged weed growth.

Over the last several years, weed management and channel stabilisation work has been conducted within the Main Swamp area. While successful, in reducing the extent of *L. sinense* and other weeds, and in slowing the rate of expansion of the channel, this work has not addressed the underlying hydrological causes of degradation.

The upstream area of Winnicoopa Swamp is in moderate condition with some areas of channelisation and an understorey of endemic species grading into an understorey of *L. sinense* closer to urban areas. By contrast, the downstream area of Winnicoopa Creek can no longer be referred to as a swamp. This area bears the scars of historical sand mining. It is heavily degraded with the total loss of organic rich sediments, a deeply incised geomorphologically unstable channel, and an almost entire loss of desirable swamp species. While some areas of this degraded area have been invaded by the surrounding eucalypt woodland, others have been colonised by a dense monoculture of *L. sinense*.

In what follows the geographic, geological and historical context of the Cripple Creek catchment is sketched. Next, a conceptual model of an intact reference swamp is presented. This is followed by a second conceptual model describing the drivers of the present degraded condition of Main Swamp and Winnicoopa Swamp. These two models are then used as the basis for the generation of a preliminary restoration target and a series of restoration goals. Finally, a research and monitoring programme is presented to collect the necessary missing data in the conceptual models and to provide the basis for the ongoing adaptive management of these valuable, but venerable, ecosystems.

2 | Background

The Cripple Creek catchment is bounded by the towns of Blaxland and Warrimoo to the East and Mount Riverview to the Southwest. It is drained by two officially named streams, Cripple Creek and Warrimoo Creek (figure 1.1). The Warrimoo Creek sub-catchment has only been lightly impacted by development and is in generally good condition. By contrast, the rest of the Cripple Creek catchment has been moderately to heavily impacted by development. Along most of its length, Cripple Creek is incised, has actively eroding banks and a simplified bedform dominated by slugs of clean unvegetated sand.

2.1 Climate

No long term climate data is available for BWMF, however Bureau of Meteorology data is available for nearby Penrith Lakes as well as Valley Heights. As can be seen in figure 2.1, there is a substantial difference in recorded precipitation between the two sites. This is primarily due to an attitudinal difference in precipitation, however the size of this effect is exaggerated by the shorter period of the Penrith Lakes record. With an altitude ranging between 165 and 242m AHD, precipitation received by BWMF can be expected to lie somewhere between that reported for these two neighbouring weather stations.

Figure 2.1 shows that the Cripple Creek catchment has summer dominant rainfall, with precipitation, on average, likely exceeding evapotranspiration throughout the year. However, the use of average rainfall hides the extreme level of year to year variability. Over winter, at both weather stations, the first decile of monthly precipitation is in single digits, while it does reach 30mm in any month, leaving it well below potential evapotranspiration throughout the year. Similarly, ninth decile monthly precipitation exceeds 100mm over the winter months and can reach up above 300mm during the summer months.

Although no long-term discharge data exists for the Cripple Creek catchment, this high level of variability in catchment inputs would be expected to be reflected in a highly variable streamflow. In an average decade there are likely be both cease-to-flow events in some tributaries as well as overbank flooding

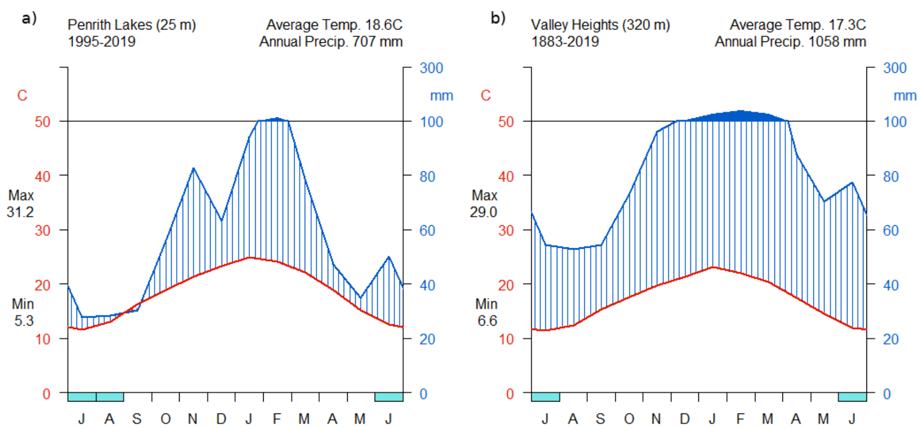


Figure 2.1: **Ombrothermic diagrams for BOM weather stations at (a) Penrith Lakes and (b) Valley Heights.** *The red line represents average monthly temperature (lhs), while the blue line represents average monthly precipitation (rhs). Aqua shading along the x-axis represents months with potential frosts. At a first level of approximation, where the blue line is above the red line, precipitation can be expected to exceed evapotranspiration. Note the change in scale at 50°C/100mm.*

events.

2.2 Geology

The Blue Mountains are an uplifted, Eastward sloping, heavily dissected, predominantly quartzite sandstone plateau (Goldbery 1969). For present purposes, the plateau can be roughly divided into the Upper and Lower Mountains. In the Upper Mountains a tall escarpment formed by the Illawarra Coal measures separates a plateau of Wianamatta Group sandstones from wide valleys of Shoalhaven Group sandstones and basement granites (David and Pickett (1997)). By contrast the Lower Mountains lacks wide valleys and is instead composed of a broad plateau of Hawkesbury Sandstone with patches of Ashfield Shale along certain ridge lines (figure 2.2). Narrabeen Group sandstones are exposed in the narrow valleys surrounding the largest rivers (Jones and Clark 1991).

Features referred to as diatremes are common across the lower Blue Mountains (figure 2.3). These ancient small volcanic features are formed by a thin pipe of rising magma explosively heating groundwater (Martyn 2018). This explosion forms a breccia of the surrounding country rock (Hawkesbury sandstone) and igneous materials. Because the softer igneous rocks are preferentially eroded, diatremes present as a characteristic shallow depression supporting a productive vegetation community fed by the rich soil formed from mafic parent materials (Jones and Clark 1991). An area immediately North of Main Swamp is mapped as being a possible diatreme[1].

2.2.1 Geological drivers of swamp development

The geological division between the Upper and Lower Blue Mountains leads to a geomorphological division favouring the development of swamps in the Upper Mountains. Swamps are defined by the presence of water and so, with the important exception of hanging swamps, occur in flat places where water naturally ponds. Streams that are in dynamic equilibrium with a homogeneous lithography become progressively flatter along their length (Fryirs and Brierley 2013). Because of this swamps typically occur at the downstream end of watercourses.

On the Upper Mountains plateau, the escarpment creates a discontinuity in the long profiles of streams, effectively creating ‘downstream areas’ where streams meet the escarpment. These low slope areas naturally form swamps, and although these swamps face many threats, they are nevertheless abundant (Fryirs, Cowley, and Hose 2016). By contrast, because of the lack of an escarpment, most streams in the Lower Mountains possess the steep long profiles typical of headwater reaches. Because of this, they don’t, generally, develop swamps.

[1] It should be noted that this assessment was not ground truthed, and was made based solely on the basis of topography and aerial photography (Jones and Clark 1991)

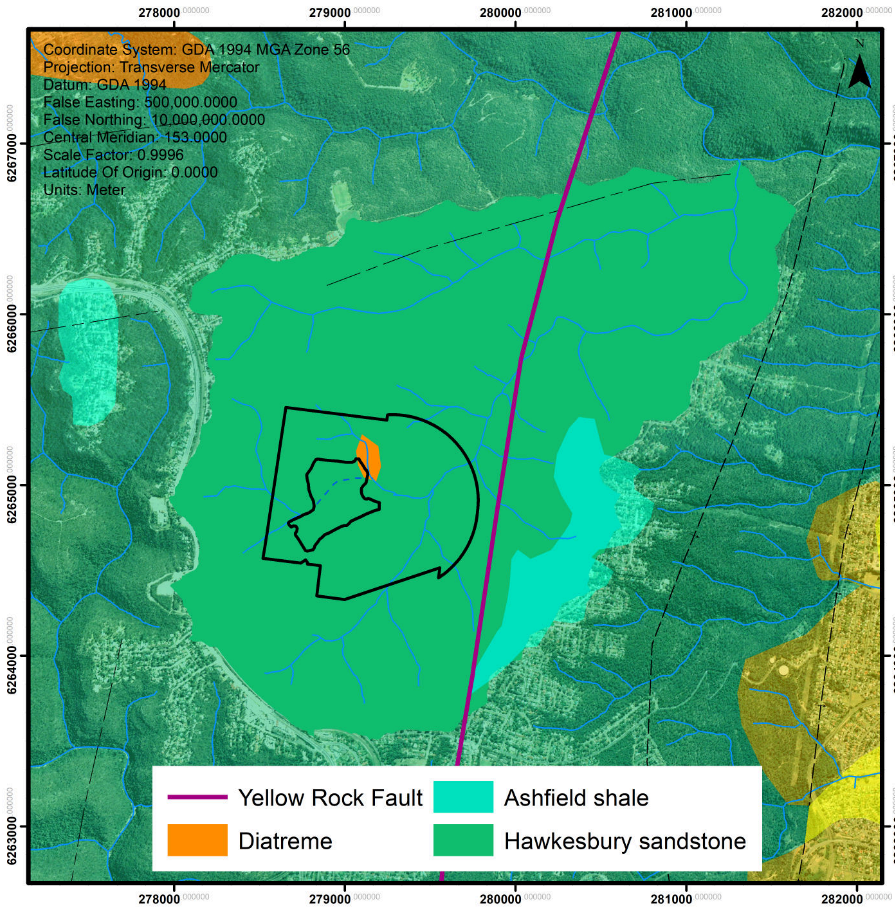


Figure 2.2: **Geology of the Cripple Creek catchment.** *BWMF land parcel and operational area outlined in black.*

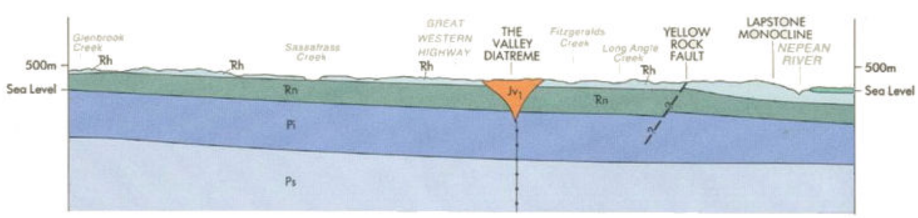


Figure 2.3: **West-East geological profile through an area just North of Cripple Creek catchment.** *The Western edge of the profile, near Faulconbridge, is the approximate Western boundary of the lower Mountains, while the Nepean River marks the Eastern boundary. Adapted from Jones and Clark (1991).*

The Eastern margin of the Lower Mountains is marked by a geological structure known as the Lapstone Structural Complex (Branagan and Pedram 1990). This complex is composed of the Lapstone Monocline and the parallel Kurrajong Fault System (figure 2.3). The Kurrajong Fault System is a series of *en echelon* North-South reverse faults that, together with the monocline, probably stem from a single deep fault (Kirkby, Clark, and McPherson 2009). Like the escarpment in the Upper Mountains, the Kurrajong Fault System acts as a discontinuity in the long profile of the creeks passing over it, providing the low slope conditions necessary for swamp development (figure 2.4).

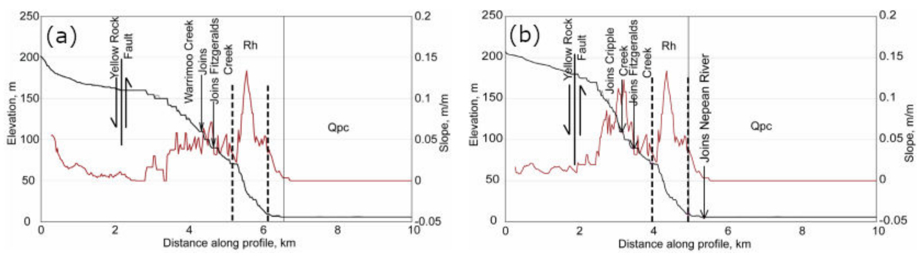


Figure 2.4: **Long profiles of (a) Cripple Creek and (b) Warrimoo Creek.** *Black line: elevation; red line: 250m running average of slope; dashed line: boundaries of Lapstone Monocline; Rh: Hawkesbury sandstone; Qpc: Quaternary alluvium. Adapted from Kirkby, Clark, and McPherson (2009).*

The Kurrajong Fault System differs in several important ways to the Upper Mountains escarpment. The escarpment has been actively eroding for around sixty million years (Beek, Pulford, and Braun 2001), ample time for the geomorphology of the streams that cross it to reach a dynamic equilibrium. By contrast, although the age of the Kurrajong Fault System is debated, there is compelling evidence that the last period of significant uplift occurred less than fifty thousand years ago (Clark and Rawson 2009).

The recent age of uplift has created a heterogeneity of responses by streams based on their catchment size. Large streams, such as the Grose River, have had sufficient stream power to adapt by eroding deep, narrow valleys in the area where they cross the fault (Kirkby, Clark, and McPherson 2009). By contrast streams with very small catchments have lacked the stream power to cross the fault system at all and have created small lakes such as Glenbrook Lagoon. Between these two extremes are medium catchment streams that are partially dammed, setting up the conditions necessary for the creation of valley bottom swamps.

The presence of an underlying clay layer in several current valley bottom swamps has led Rawson (1990) to suggest that immediately after the uplift event, all but the largest streams were fully dammed, creating the conditions for lacustrine clay deposition. Since this time, streams have progressively escaped their impoundments, leaving only the smallest streams still ending in modern lakes.

The scale of the escarpment and the Kurrajong Fault System also differ. Fryirs, Cowley, and Hose (2016) mapped 458 swamps in the Upper Mountains, of which 338 were in good condition. By comparison, although not a comprehensive survey, Kirkby, Clark, and McPherson (2009) located only 18 streams that crossed the Kurrajong Fault System. Of the four streams crossing the Yellow Rock fault (one of six faults making up the fault system) that I have surveyed, one is too large to form a swamp (Fitzgeralds Creek) while another is too small to cross the fault (Glenbrook Lagoon). Of the remaining two streams, only Warrimoo Creek contains a valley bottom swamp in good condition.

Given both the limited distribution of the geological setting for Lower Mountains swamps as well as their structural heterogeneity, each swamp is clearly of very high conservation value, quite apart from the fact that the swamps host an endangered ecological community.

2.3 Soils

The Cripple Creek catchment is mapped as containing three soil landscapes (figure 2.5). What follows is based entirely on the soil mapping conducted by Bannerman and Hazelton (1990). Relatively flat areas on top of ridges are mantled by the *Faulconbridge soil landscape*. This is a thin, sandy, residual soil. It is strongly to extremely acid (pH 4.5 - 3) leading to associated low fertility and aluminium toxicity. Its low clay content makes it poorly structured and highly permeable with a low water holding capacity.

The topsoil has a low to very low level of erodibility while exposed subsoil is moderately erodible. However, significant sheet erosion can often occur after bushfires. Cleared land is calculated to lose soil at a rate of six tonnes per hectare. This increases to eighteen tonnes per hectare if subsoil is exposed. Almost all urban development in Blaxland and surrounding suburbs has been on Faulconbridge soils. The small areas of remnant vegetation are open eucalypt woodland with an open understorey of sclerophyll shrubs.

The very steep hills formed by the Yellow Rock Fault are mantled by the colluvial *Hawkesbury soil landscape* between areas of outcropping bedrock and boulders. The rough geology makes this a heterogeneous soil landscape with the soil in some areas very thin while in other areas, such as along joints, it can be moderately deep (>2m). A sandy topsoil overlies either bedrock or a clayey sand to medium clay subsoil. It is strongly to moderately acid (pH 4 - 5.5) with associated very low fertility and aluminium toxicity.

The topsoil is highly permeable with a very low water holding capacity, however the more clayey subsoil is less permeable with moderate water holding capacity. The topsoil displays a low level of erodibility but is prone to gully erosion after bushfires. The subsoil displays a moderate level of erodibility. The Hawkesbury soil landscape is predominantly covered in native vegetation. This ranges from low open eucalypt woodland on ridges, to open sclerophyll forests on side slopes

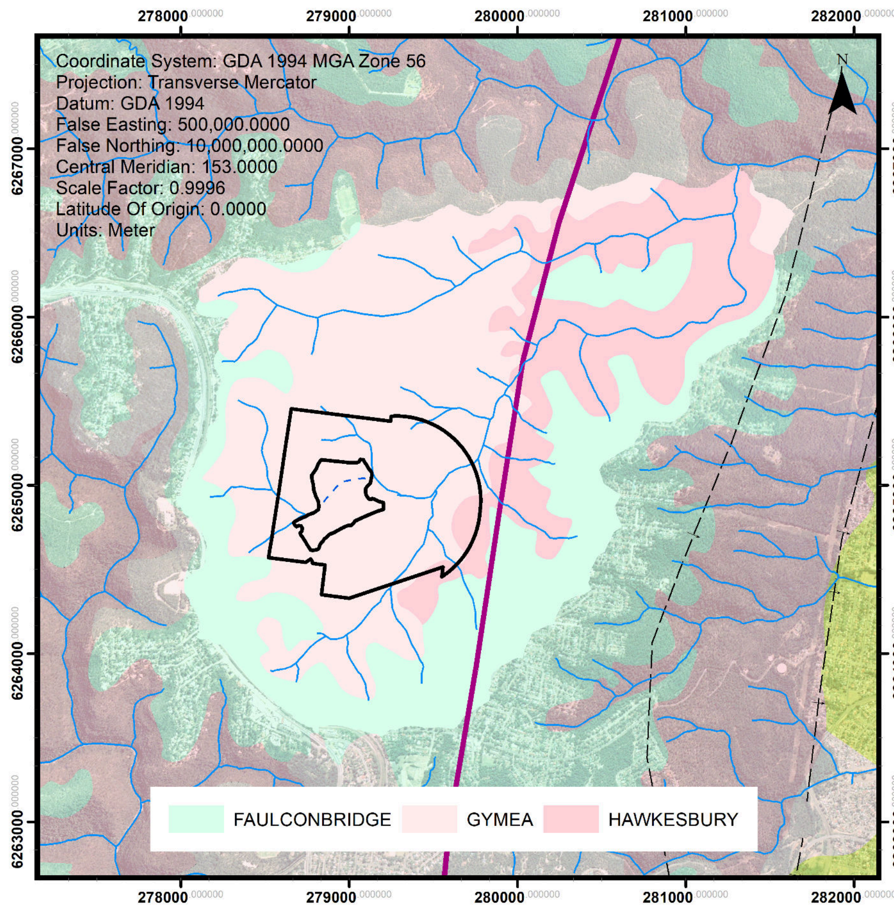


Figure 2.5: **Soil landscapes of the Cripple Creek catchment.** *BWMF land parcel and operational area outlined in black. Yellow Rock Fault shown in purple.*

to closed wet sclerophyll forests with patches of rainforest in gullies.

The gentler hills found to the West of the Yellow Rock Fault are mantled by the *Gymea soil landscape*. These hills are characterised by a series of short benches forming discontinuous scarps or small cliffs (figure 2.6). Soil depth varies along a bench from very shallow immediately up-gradient of a scarp to moderately deep directly down-gradient of one. Depending on depth, a coarse grained sandy loam topsoil overlies either bedrock or a clayey sand subsoil. It is strongly to slightly acid (pH 4-6.5) with associated very low fertility and aluminium toxicity.

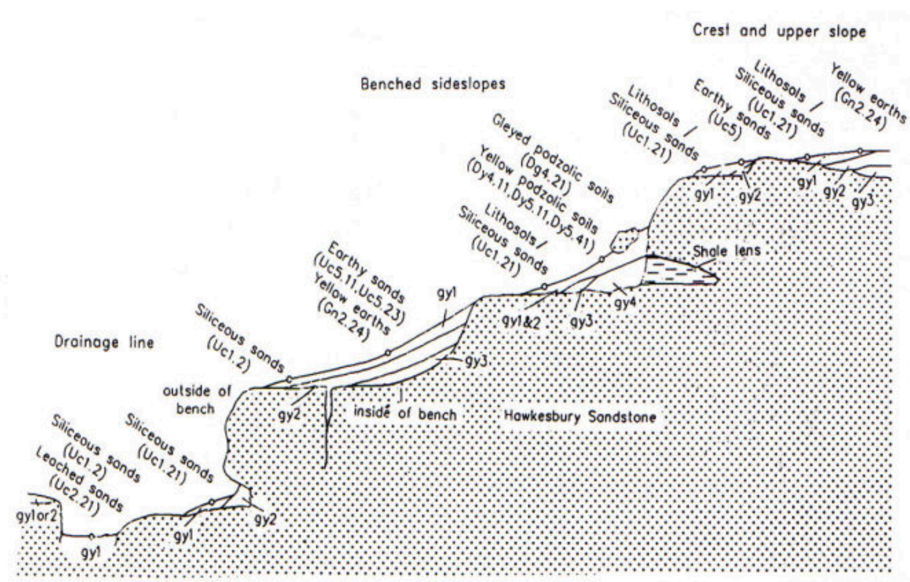


Figure 2.6: **Conceptual model of a Gymea soil landscape formed on a series of Hawkesbury sandstone benches.** *Adapted from Bannerman and Hazelton (1990). gy1, gy2, gy3 & gy4 refer to named horizons of the Gymea soil landscape. Alphanumeric codes in parentheses refer to soil types from Northcote (1979).*

The soil is highly permeable with a low water holding capacity. The large sand grains display a low level of erodibility, however where the soil forms on shale lenses, the subsoil can display an extreme susceptibility to erosion with rates of loss up to 464 tonnes per hectare per year. Gymea soils are vegetated with eucalypt woodland or open forest with a sclerophyll shrub understorey.

2.4 Vegetation

Figure 2.7 shows the location of the vegetation mapping units as used in the "Blue Mountains Local Environmental Plan" (2015). It maps the *Blue Mountains Swamp* and *Melaleuca linariifolia Low Open-forest* vegetation communities as surrounding drainage lines to the West of the Kurrajong Fault. These should actually be mapped as a single vegetation unit and will be described in detail in the reference model below. To the South of these swamp units is *Eucalyptus sclerophylla Bench Woodland* (henceforth referred to as Bench Woodland). This occurs on relatively well drained alluvial/colluvial benches and is dominated by an open stratum of tall *E. sclerophylla* (scribbly gums) which are sometimes co-dominant with *Angophora bakeri* (narrow-leaved apple). These trees overlie a diverse closed to sparse shrub stratum and a herbaceous stratum with a diverse range of grasses and forbs (personal observation).

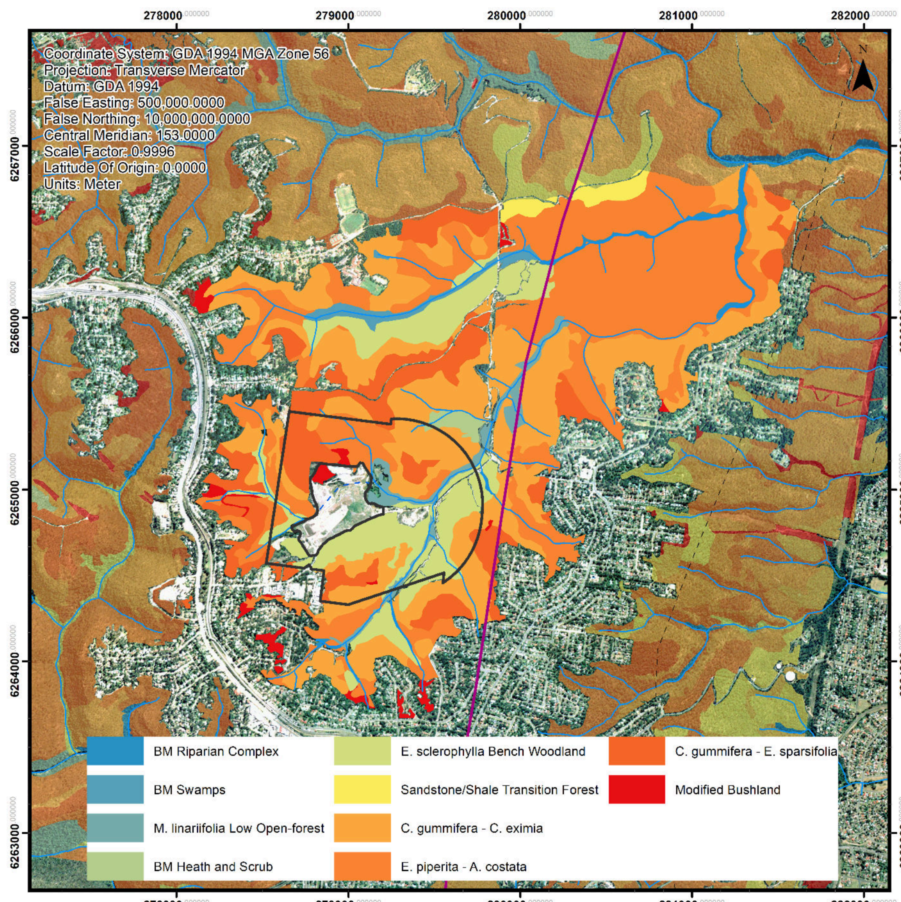


Figure 2.7: **Vegetation communities of the Cripple Creek catchment**. A full description of the mapping units is provided in BMCC (2002).

Bench Woodland is found abundantly along the flatter areas of Cripple Creek. This community has likely invaded areas previously occupied by swampier heath communities due to a lowering of the watertable caused by channel incision throughout the highly disturbed areas of Cripple Creek. Along the less disturbed Warrimoo Swamp it is separated from the central swamp axis community by a wide strip of wet heath.

Surrounding the swamp and bench communities are a mixture of eucalypt woodlands featuring *Corymbia gummifera* (red bloodwood) including *Corymbia gummifera/Corymbia eximia woodland*, *Corymbia gummifera/Eucalyptus sparsifolia woodland* and *Eucalyptus piperita/Angophora costata woodland*. These occur on thin, rocky slopes and ridges and may contain a range of co-dominant eucalypts, a low tree stratum of *Banksia serrata* or *Allocasuarina littoralis* and a diverse shrub and herbaceous stratum. These communities may intergrade both with each other, and also with Bench Woodland.

2.5 Catchment history

2.5.1 Pre-invasion history

Despite being generally referred to as Dharug country, the Cripple Creek catchment is in fact Darkiñung country[2] (Ford 2010). BWMF contains at least one preserved archaeological site while a further five sites are recorded within two kilometres of BWMF (BMCC 1985). The less disturbed area where Cripple Creek joins Fitzgerald Creek contains many more sites (Cameron 1998). The river flats and riparian areas of the neighbouring Sun Valley are known to have been economically and culturally important areas for the Darkiñung (Cameron 1998), as were swamps and riparian areas across the region (BMCC 1985), a pattern repeated across Eastern Australia (Beck, Haworth, and Appleton 2015; BMCC 1985; Cahir, Clark, and Clarke 2018). Given this it is likely that the swamps of Cripple Creek were significant areas before the British invasion of Australia.

Much of the evidence of the occupation of Cripple Creek catchment has likely been destroyed. For example, the National Parks and Wildlife Service database of archaeological sites lists site 45-5-66 as occurring within BWMF land, however this was unable to be relocated by archaeologists in 1985 (BMCC 1985). The site had over 25 grinding grooves as well as human, emu and kangaroo tracks. The site occurred next to a small waterfall of a similar description to the currently preserved site.

Although it is possible that the two sites are one and the same, given that only eight grinding grooves are known for the preserved site it is more likely that either the location of the site was incorrectly recorded or that the site had already been destroyed by the time that archaeological work was carried out in 1985.

[2]At the time of the British invasion, Dharug country was centred on the Georges River, whereas the floodplains and foothills around the Hawkesbury-Nepean were Darkiñung country (Ford 2010). Both Dharug and Darkiñung country fall under the modern jurisdiction of the Deerubbin Land Council.

2.5.2 Post-invasion history

In 1789, only a year after the founding of the fledgling colony at Sydney Cove, William Dawes probably travelled through what is now BWMF (figure 2.8). Unfortunately he only left a difficult to interpret sketch map of the journey along with a short description stating that the valleys in the Blue Mountains generally contained "a small run of good Water abt a foot wide, in some Places forming Ponds from 4 and 5 to 15 feet wide" (Dawes 1791).

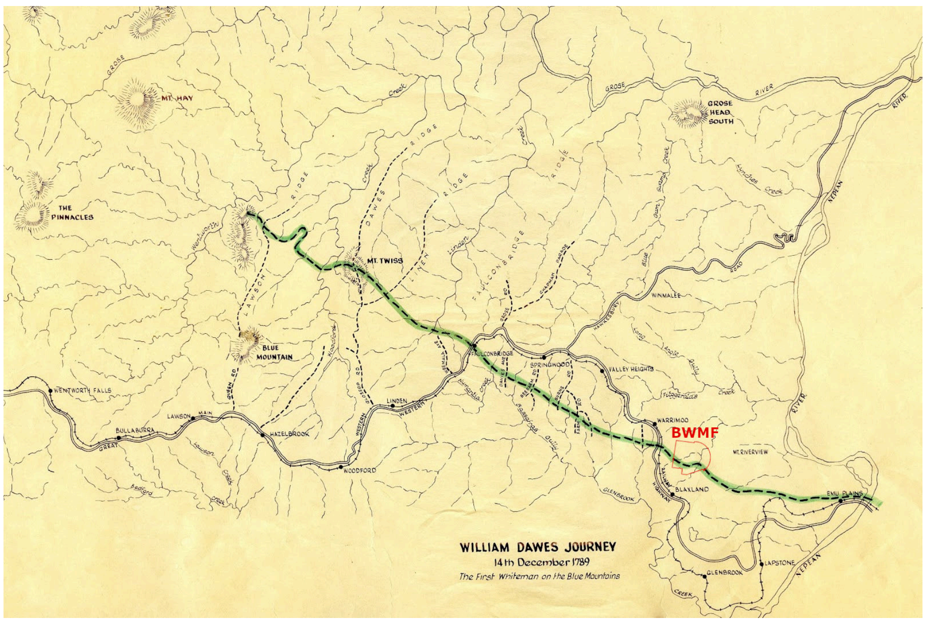


Figure 2.8: **Reconstructed route taken by William Dawes through the Lower and Mid Blue Mountains in December of 1789.** *Approximate location of BWMF shown as red outline. Adapted from Paish (1989).*

With the exception of Woodford Creek, all of the "foot wide" streams Dawes passed over were first or second order streams draining catchments of similar sizes to Cripple Creek as it leaves BWMF. The present day channel incised by Cripple creek as it leaves BWMF is over two metres wide. Interestingly, in Blue Mountain swamps still in good condition (including Warrimoo Swamp), where shallow channels do exist, they are, like the streams recorded by Dawes, approximately a foot wide (personal observation).

By the early 1800s, farms had been established along the Nepean. These farms came under sustained attack by the Darkiñung, led by the resistance hero Yaragowhy. In late April of 1805, Andrew Thompson, a settler, led a large group of men across the Nepean and towards present day Springwood to massacre the locals (Ford 2010). It is likely that many of the families living in the Cripple Creek catchment and other Yellow Rock Fault swamps were killed by

Thompson and his men at this time.

In 1813, Blaxland, Lawson and Wentworth made their famous crossing of the Mountains. On the 12th of May they probably crossed the Eastern edge of the Cripple Creek catchment but the journals of the three men give minimal description. They did note the presence of kangaroos, emus, eagles and dingoes as well as several "native huts" in the vicinity of Blaxland's eponymous modern suburb (Richards 1979). Blaxland described this area as "scrubby brush-wood, very thick in places, with some trees of ordinary timber, which much incommoded the horses" (Richards 1979), however this was clearly in reference to the ridge rather than the valley floor.

The first permanent British settlers in the Blaxland region arrived in the second half of the 1800s, attracted by the opening of the train line in 1868. The population was mostly engaged in small scale farming operations on flat ridge land around the railway line (Curnow 2007). By 1950 the town was still essentially rural with a population of around 500. In 1957 electric trains were introduced onto the Blue Mountains line leading to rapid urbanisation. By 1961 the town's population had exploded almost four-fold to 1725 (Curnow 2007).

In either the late 1940s or early 1950s, the current BWMF operational area began being used as an official dump for both garbage and night soil (Blaxland Garbage Service 1949; Work on Roads 1951). Around the same time, unofficial sand mining began near the confluence of Winnicoopa Creek and Cripple Creek. Up to four truck loads of sand per day were carted out of the valley over the course of several decades (Curnow 2007). The clayey sands and sandy clays of the Gymea soil landscape subsoil were highly valued by bricklayers for use as 'fatty sand' (Curnow 2007).

In the neighbouring Sun Valley, valley bottoms were extensively logged (Cameron 1998). It is likely that Winnicoopa valley and the valley containing the operational area of BWMF suffered a similar fate. Certainly, the absence of old trees in either valley suggest that they were.

In the mid eighties, as other landfills in the Blue Mountains began closing, BWMF began an expansion programme to allow it to increase capacity (BMCC 1985). This has involved a slow process of quarrying out the area to the North of the original Cripple Creek and then mounding rubbish in the newly created hole. This process has significantly effected both the topography and hydrology of the site.

Figure 2.9 shows the approximate topography of the site as it was in 1985. The Southeastern portion of the current operational area was a broad, relatively flat bench. The scarp defining the edge of the bench was at its steepest where Cripple Creek cut between it and the opposing scarp. Further away from the creek, the scarp petered out into a steep incline. The Northern portion of the current operational area was likewise defined by a scarp, however rather than a broad bench, this area was terraced by additional discontinuous scarps defining two or three benches (the exact location of these higher scarps is not clear and so is not shown in figure 2.9).

These two scarps created a pinch point in Cripple Creek allowing the development of a small swampy area at the Western edge of the current operational area. A second pinch point just downstream of the present day location of Main Swamp created a much larger swampy area extending from the West of the current operational area through to the centre. The Eastern third of this larger swampy area remains as the present day Main Swamp whereas the smaller swamp at the Western edge of the operational area has been almost entirely destroyed with only a small portion directly surrounding Cripple Creek remaining.

As can be seen in figure 2.9, the original rubbish dump began in a swampy area to the South of Cripple Creek and moved West. Once this original area was filled, the Southeastern raised bench was then filled followed by the Northern side of Cripple Creek. As dumping began on the other side of the Creek, the natural Creek was diverted into a pipe with its outflow at the upstream end of Main Swamp. As the area to the North of the Creek was filled areas of the Northern sandstone bench terraces have been progressively quarried out to make more room (BMCC 1985).

In 2008 as part of the environmental approvals for the further Northward enlargement of the operational area, the pipe carrying Cripple Creek through the operational area was replaced with a new pipe. This moved the discharge point approximately 60m to the North and away from the natural drainage axis. At the same time, two groundwater cutoff walls were installed, one at the upstream end of the operational area and the other at the downstream end.

The upstream cutoff wall pumps captured groundwater into the diversion pipe while the downstream cutoff wall pumps to a dam that also receives leachate collected from the lined landfill cells (all post-1985 landfill). In this dam the volatilisation of ammonia is encouraged by raising the pH of the contaminated water combined with constant aeration. From this dam the contaminated water is pumped to a second holding dam which is then pumped to sewer.

The new diversion pipe and groundwater cutoff walls were installed to protect the Main Swamp area from leachate contamination. This allowed the Main Swamp to be used as an environmental offset area for the destruction of vegetated areas elsewhere on site. Unfortunately, these engineering devices had the opposite to their planned effect. Since their installation, groundwater has fallen by approximately three metres and large eroded channels have formed in the Western end of Main Swamp. Since 2016, these channels have been partly reshaped and stabilised with rocks and geofabric in an attempt to prevent their further expansion (Blue Tongue 2018).

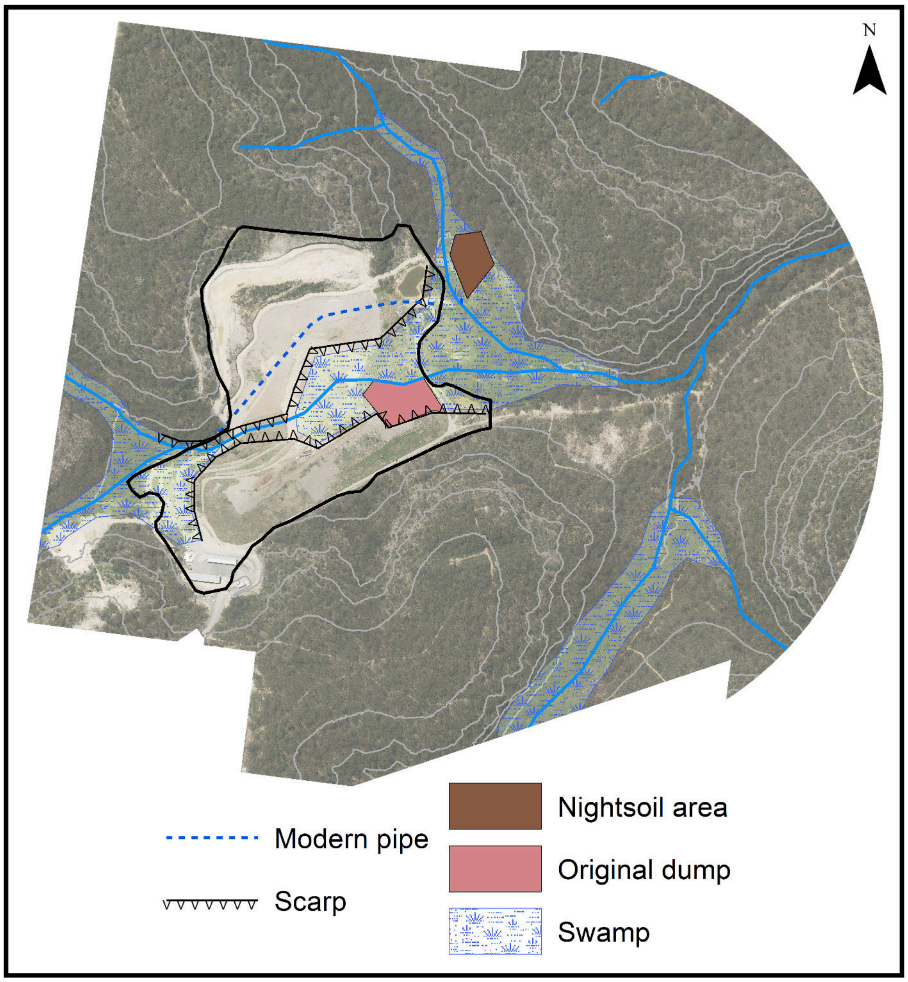


Figure 2.9: **Approximation of the topography of BWMF in 1985.** *Borders are based on written descriptions and paper maps in BMCC (1985). Position and scale of features is not exact. Note that by 1985 the extent of Winnicoopa Swamp and the swamp along downstream Cripple Creek would have already been significantly diminished by sand mining*

3 Reference model

Three major sources of evidence were used in the construction of a conceptual reference model. These were informal analyses of the ecosystems at Warrimoo Swamp and Glenbrook Lagoon; published descriptions of other Paperbark Swamp Forests from elsewhere in the Sydney region; and theoretical and empirical accounts of different types of swamp systems, especially those found within the Sydney region.

In what follows seven facets of the reference model are described. Six of these facets correspond to the six attributes found in the SERA (2017) recovery wheel, although the 'absence of threats' facet has had its scope expanded to become 'disturbance regime'.

An additional 'human context' facet has also been included because these swamps have likely been semi-cultural ecosystems for most of their history. Further, their continued existence at the urban-bush interface is intimately tied up with and dependent on humans.

Note that although the reference model draws on actually occurring swamps (reference sites), the model is not a model of a single existing site. Instead it is a generic model of a healthy Yellow Rock Fault Paperbark Swamp Forest. For a fuller discussion of the difference between reference models and reference sites see Clewell and Aronson (2013).

3.1 Human context

3.1.1 Legislative context

The swamps of the Kurrajong Fault System are protected under both state and Federal legislation. They are protected as atypical examples of the *Temperate Highland Peat Swamps on Sandstone* endangered ecological community under the Federal "Environment Protection and Biodiversity Conservation Act" (1999) as well as examples of the *Coastal Swamp Forests (Riverflat Paperbark Swamp Forest)* endangered ecological community under the NSW "Biodiversity Conservation Act" (2016).

3.1.2 Cultural context

Many plants and animals found in Yellow Rock Fault swamps are economically, religiously and medically important species. The bark of many species of *Melaleuca* are recorded as being used in house building, as wraps for cooking, as clothing and bedding, as bandages, in medicines (used both orally and as a poultice) and to carry various items including babies (Brophy, Craven, and Doran 2013). Similarly, *Melaleuca* leaves have been recorded as being used in medicines, as insect repellents and as a spice (Brophy, Craven, and Doran 2013).

Lizards, snakes, turtles, frogs, crayfish, emus and other large ground dwelling birds, waterfowl, macropods, water rats, possums and bats would all have been abundant in Kurrajong Fault System valleys providing a diverse diet (Beck, Haworth, and Appleton 2015; BMCC 1985; Brophy, Craven, and Doran 2013). While the seeds and roots of *Bolboschoenus*, *Eleocharis*, *Glyceria*, *Juncus*, *Macrozamia* and *Pteridium* would have provided year-round sources of staple carbohydrates (Ford 2010; Beck, Haworth, and Appleton 2015; BMCC 1985). Other locally abundant species of economic importance include *Gleichenia dicarpa* (tangle fern), which was used for birth control (Bursill, Donaldson, and Jacobs 2015), various sedges which have medicinal effects (Barrett 2013) and saw-sedges, lomandras and other monocots used for weaving.

In 1877 William Parr wrote of coming across “an abundance of Carrots” along Wheeny Creek (approximately 40km to the North of BWMF). They were “rather small yet in every other respect, as to appearance, taste and smell they [had] the resemblance of carrots” (Macqueen 2004). The exact identity of Parr’s ‘carrots’ is debated, though they are most likely to have been either *Trachymene incisa* (native parsnip) or *Dioscorea transversa* (pencil yam)[1], but they are just one example, of many, of the farming of root vegetables on the floodplains and swampy areas close to the Hawkesbury-Nepean (Pascoe 2014; Gammage 2012).

While understanding the pre-invasion history of these semi-cultural ecosystems is important to allow for the protection of their inherent cultural and historic value, it is also important ecologically (Clewell and Aronson 2013). Humans have probably been the top predators within the Kurrajong Fault System swamps since their formation as modern swamps after the last ice age (Nanson 2009; Mould and Fryirs 2017; Attenbrow 2010). As such they will have played a keystone role in structuring the ecological community, especially the faunal component. In addition to their direct trophic effects, people also engaged in wide-scale land management (intentional and unintentional) through ecosystem engineering and niche construction (Gammage 2012; Laland and O’Brien 2010; Kendal, Tehrani, and Odling-Smee 2011).

In 1817 upon viewing the vegetation surrounding Boggy Swamp Creek in Putty Valley in the Northern Blue Mountains William Parr wrote:

[1] Macqueen (2004) suggests that these may have indeed been European carrots which the Darkiñung had appropriated from British farms further to the East and grown using the same methods as used for traditional yams.

> "I never saw anything so picturesque and fine in all my travels. The surface is, as if covered with a fine young wheat and not a bush nor bough of a tree to be seen upon it [...] the trees which are Apple and Gum are very thin upon the ground, but the Apple trees are the largest I ever saw. I measured three, the circumferences of which were 23 feet 6 inches [7.16m], 22 [6.7m] and 20 [6.1m] feet. [... The] grass has the appearance of a rich meadow in England being for several acres without a bush, and the trees which are Apple and Gum are very large but thinly set on the land, in some places two or three acres together has not a single tree or bush upon it" (Macqueen 2004).

This thinly treed grassland/sedgeland is today an open wet eucalypt forest with a *Melaleuca linariifolia* understorey (DECC 2008). While Boggy Swamp Creek is located North of the Kurrajong Fault System, it displays a similar, though slightly drier, vegetation community to those found today in the fault system swamps.

Elsewhere, the intervention of colonists has caused an almost symmetric ecosystem shift to occur. In some areas of the Northern Blue Mountains, closed wet eucalypt forests, similar in form to the wetter areas of Bench Woodland found in the Cripple Creek catchment, were logged in the early days of the colony. This led to a reduction in the rate of evapotranspiration and a rise in the watertable. This higher watertable has allowed the successful invasion of these areas by *Melaleuca linariifolia* swamp forests, preventing the re-establishment of eucalypt forest (DECC 2008).

Disentangling the effects of the loss of traditional management practices from the effects of colonial practices along the length of the Kurrajong Fault System is complicated by the cryptic nature of many ecosystem state changes. While a full understanding of the pre-European impact of humans is impossible, nevertheless, several inferences are able to be made from the available evidence.

Despite the flammability of the vegetation, charcoal fragments are rare in the soil (Bannerman and Hazelton 1990) suggesting that large fires were suppressed in the region. Further evidence for this is provided by the vulnerability of hillslope topsoils to sheet erosion after large bushfires (Bannerman and Hazelton 1990). Although empirical data of soil production rates is lacking, it is likely that erosion from frequent large fires would overwhelm soil production leading to wide scale exposure of subsoil or bedrock on slopes. That this hasn't occurred argues that large bushfires have been relatively uncommon over the last several millennia.

Camp sites were likely to have been on, or near, flat valley bottoms. The daily use of fire for cooking, heating and ceremonial purposes would have kept these areas free of easily moved woody debris and easily cut timber species (shrubs and small trees). This clearing of wood may have been magnified by purposeful cultivation of certain economically important herbaceous plants (Pascoe 2014).

The combination of decreased cover, disturbance and nutrient inputs from human activities would likely have favoured weedy herbfields immediately around campsites transitioning to open and then increasingly closed grassy woodland as distance from the campsite increased. The presence of large open grassy areas in valley bottoms is further supported by the presence of emus, kangaroos and eagles reported by Blaxland (Richards 1979).

The widespread harvesting of plant material for tools, clothing and housing is well attested (Brophy, Craven, and Doran 2013; Attenbrow 2010 and references therein). Of particular note are *Melaleuca* bark and the leaves of various monocots. The thick papery bark of *Melaleuca* provides excellent protection from injury by fire (Brophy, Craven, and Doran 2013). Wide scale removal of this bark may have increased the vulnerability of individual trees to fire. Importantly, bark harvesting would target larger individuals which would be able to provide larger sheets. If this effected mortality from fires, it may also have impacted stand dynamics, generating open, multi-aged stands instead of the closed, single-aged stands more commonly found today.

The harvesting of plant and animal foods and plant fibres would have led to the creation and maintenance of track networks. These track networks would then be available for the movement of not only other animals (Naude et al. 2019) but also for the spread of plant species. Ferguson, Kirkpatrick, and Pharo (2010) found that paths impacted both soil properties and vegetation distribution and that this effect was much larger in sedgeland swamps than in eucalypt woodland. They found that epizoochorous seed dispersal along paths was much more important for locally rare plants than it was for locally dominant plants, suggesting that paths play an important role in maintaining biodiversity and in linking populations separated by areas of inhospitable conditions.

3.2 Geophysical conditions

3.2.1 Chemical conditions

Biodegradation

The central edaphic attribute of swamps is the presence of saturated or nearly saturated soils. In such soils, water fills the interstitial space, reducing gas exchange to very low levels. In such conditions, as microbial respiration consumes available oxygen it cannot be replaced so the redox potential of the soil progressively decreases (White 2006).

As the redox potential falls, and oxygen becomes scarce, respiration by the microbial community begins using other compounds, such as NO_3^-, CO_2 or S^0, as terminal electron acceptors. These compounds are utilised following a set order, with each new electron acceptor able to extract less energy from the oxidation of organic compounds than the previous electron acceptor (Berg, Tymoczko, and Stryer 2002).

As the soil becomes increasingly reduced, the total energy available to the soil microbial community decreases, slowing the rate of decomposition. Eventually the soil environment can become so reduced that there are no longer any electron receptors remaining able to provide sufficient energy to support the metabolic requirements of the microbial community. Once this happens biodegradation stops entirely (White 2006).

Peat

Where the rate of addition of organic matter to a system is greater than the rate of its loss through biodegradation or export, organic matter necessarily builds up. While in highly reduced environments, this organic matter is not able to be fully broken down, it is nevertheless transformed. Oxygen accounts for greater than forty percent of the weight of fresh organic matter (Boron, Evans, and Peterson 1987). Because this oxygen is at a premium in reduced conditions, oxygen containing functional groups are selectively decomposed by the anaerobic microbial community leaving behind increasingly aromatic compounds[2] (Boron, Evans, and Peterson 1987). This process is referred to as humification and is responsible for converting fresh organic matter into peat.

Peat is classically divided into two layers, an upper acrotelm[3] layer and a lower catotelm[4] layer (Ingram 1978). The acrotelm is above the permanent watertable and contains fresher organic matter inputs. Since the acrotelm is both less reduced and younger, it is a microbially active environment and its peat is less humified. The catotelm by contrast is below the permanent watertable, is highly reduced and contains organic matter that has been modified over a longer period. The catotelm hosts very little microbial activity and is highly humified (Ingram 1978).

Fryirs, Gough, and Hose (2014) found that this classic two layer model of peat swamps developed for Northern Hemisphere swamps did not fully account for the nature of Australian upland swamps. Specifically, Australia has a much more variable hydrology than other continents (Ladson 2008) which leads to a much more variable watertable. So while acrotelm and catotelm layers can still be distinguished by the degree of decomposition, the catotelm within Australian swamps is not necessarily permanently submerged.

Water filtration by peat

The large amorphous humic compounds that characterise peat allows it to act as a filter which immobilises charged ions including both plant nutrients and toxic

[2]There has long been controversy over the source of humified compounds with some authors arguing that they are modified plant compounds whereas other authors argue that they are compounds manufactured *de novo* by microbes (Tan 2014). For present purposes the mechanics of the biochemical processes is less important than their outcome: an increase in aromaticity and a decrease in oxygen bearing functional groups with organic matter age and depth in the soil.

[3]**acro-**: *Gk. κρος, topmost*; **-telm**: *Gk. τλμ, marsh*

[4]**cato-**: *Gk. κτω, down*; **-telm**: *Gk. τλμ, marsh*

trace metals. Winde (2011) describes the dominant immobilisation process as consisting of two steps.

The first step involves the weak surface sorption of ions to the peat. This relies on the cation exchange capacity (CEC) of the peat which varies with depth. Because the CEC of organic matter is primarily a function of oxygen containing functional groups, acrotelmic (younger and more aliphatic) peat has a higher CEC than catotelmic (older and more aromatic) peat (Gogo, Shreeve, and Pearce 2010). Thus acrotelmic peat has a high surface sorption capacity, whereas catotelmic peat has a lower sorption capacity.

Once a charged ion has been removed from the soil water by surface sorption it becomes vulnerable to a variety of forms of long term immobilisation, of which the most important is complexation by carboxyl functional groups. Complexation favours high atomic weight, high valence ions, resulting in the selective complexation of toxic trace metals (Winde 2011).

Winde (2011) concludes that the efficiency of the peat as an ion filter relies on the surface area of peat that an ion is exposed to and the CEC of that surface area. This means that water that slowly percolates through the acrotelmic layer of peat will be effectively cleansed whereas water that moves quickly through either above aboveground channels or through sub-surface soil pipes will not. Thus an intact swamp will act as an effective water filter while an incised one may not.

Fertility

The relatively high rate of precipitation coupled with the hilly terrain surrounding the valleys along the Yellow Rock Fault encourages the leaching of soil nutrients (White 2006). While most of the hillslope soil is naturally very low fertility (section 2.3), shale lenses and diatremes provide areas of higher fertility (Bannerman and Hazelton 1990). Plant nutrients are most likely to leach from these higher fertility areas during comparatively wet periods when watertables in swamps are high (White 2006). At these times, because most groundwater flow is likely to move through the more hydraulically conductive, and higher CEC acrotelm, intact swamps are likely to effectively remove most nutrients from the water, preventing their export to downstream environments.

In addition to the immobilisation of geologically derived nutrients, swamps may also effectively remove nitrogen from water, however this may be dependent on the condition of the peat. In oxic conditions with sufficient labile carbon and a close to neutral pH, NH_4^+ is rapidly oxidised to NO_3^- by nitrifying bacteria (White 2006). If NO_3^- then moves into a reduced environment, denitrifying microbes will utilise NO_3^- as a terminal electron acceptor, producing gaseous forms of nitrogen (N_2O, N_2) which will then diffuse into the atmosphere (White 2006).

Heavey (2003) found that acrotelmic peat contained sufficient oxic micro-sites to effectively nitrify NH_4 from landfill leachate. The NO_3^+ produced by this reaction was then further denitrified within reduced micro-sites. Heavey (2003) found that this process was so successful that leachate leaving the peat had nitrogen levels at the edge of detectable levels.

Although the edaphic environment of the Lower Mountains is generally low fertility, any nutrients that do enter an intact swamp as groundwater are likely to be either immobilised or denitrified within the swamp. This helps to maintain the low nutrient environment downstream that is responsible for the high levels of biodiversity found on Eastern Australian sandstone soils (Rice and Westoby 1983).

3.2.2 Physical conditions

The vertical decomposition gradient found in peat swamps results not only in chemical changes down the soil profile, but also physical and hydrological changes.

Water movement through swamps is controlled by two primary factors: hydraulic conductivity and hydraulic gradient (Kasahara et al. 2009; Boano et al. 2014). Hydraulic conductivity is a measure of the ease with which water can move through a porous medium, while hydraulic gradient is a measure of the slope down which water moves.

The surficial acrotelm has a hydraulic conductivity several orders of magnitude greater than the lower catotelm (Fryirs, Gough, and Hose 2014). This means that subsurface water can flow relatively quickly through the top layer of peat but moves orders of magnitude more slowly through lower layers.

However, this simple picture is complicated by the presence of soil pipes. Soil pipes are naturally formed pipes that exist in regolith where there is a significant hydraulic gradient but low hydraulic conductivity (Holden 2009). They often form along passages created by tree roots or from faunal bioturbation, but may also be generated without biological input (Holden and Burt 2003). They are associated with inputs of water that are above the infiltration capacity of the soil, and so commonly occur at the interface of a moderate conductivity horizon with an underlying low conductivity horizon (Holden 2009).

Although studies on Australian peatlands are lacking, in some Welsh peats pipeflow has been shown to contribute up to fifty percent of total subsurface flow, while in other peatlands it contributes less than ten percent of flow (Holden and Burt 2003). Eastern Australian swamps are likely to have relatively high levels of pipe flow due to the peaky nature of Australian hydrographs (Ladson 2008) which favour infiltration-excess flow over saturation-excess flow. This suggests that much of the water entering Eastern Australian swamps, especially during significant rain events, moves quickly through the swamps.

3.2.3 Hydrological conditions

As Fryirs, Gough, and Hose (2014) point out, the alleged role of Eastern Australian swamps as 'sponges', absorbing and then slowly releasing water, is asserted much more often than it is demonstrated. To rectify this they intensively measured the hydrological function of a valley floor swamp in the Southern highlands. They found their swamp displayed four distinct hydrological responses based on antecedent conditions and inputs (figure 3.1).

The first response type occurred when an extended rainfall event follows an extended dry period. Because of the extended dry period, both the acrotelm and some of the catotelm have slowly dried out so that the watertable sits below the acrotelm-catotelm boundary. Once the rainfall event begins, the watertable rises quickly as the acrotelm fills from the first flush of overland runon. This initial infiltration-excess rise in groundwater is followed by a series of oscillations as excess water in macropores is absorbed by the peat or conveyed through soil pipe networks to downstream. As the peat slowly reaches saturation and slower moving throughflow begins to enter the swamp, the watertable stabilises just below the surface as water inputs equal outputs. Over the following days to weeks, the areas surrounding the central swamp axis begin to dry out and throughflow tails off, causing the watertable to slowly drop until it stabilises at the acrotelm-catotelm boundary.

The second response is similar to the first, but occurs after a short dry period followed by a moderate rain event. Here the catotelm is still saturated so the watertable sits at the acrotelm-catotelm boundary. Again most of the initial runon is quickly lost from the system as infiltration-excess flow. However, because both the acrotelm and the soil in the catchment are already wet (but not saturated) only a small amount of further rainfall is required to saturate the soil and lead to significant throughflow. As in response type one, once saturation-excess throughflow in the areas surrounding the swamp is achieved, the watertable remains near to the surface for an extended period before slowly dropping back to the acrotelm-catotelm boundary.

The third response type occurs where a very short burst of rainfall follows a short or extended dry period. The watertable quickly rises in response to infiltration-excess runon, but the rainfall event is too small or too short to saturate the catchment soil and so significant levels of throughflow do not eventuate, leading the watertable to quickly fall back to the same level as before the rainfall.

The final response type is similar to the first, except that spikes of very high rainfall cause short periods of overland flow along the swamp axis. Interestingly, Fryirs, Gough, and Hose (2014) found that for all four response types, after the initial sudden rise in groundwater level, the groundwater level often quickly fell to below its stable pre-rain level. A possible explanation for this strange behaviour is that the sudden spike in water pressure due to the higher groundwater level cleaned out blockages within the swamp's soil pipe network which then allowed the groundwater in the swamp to quickly drain to a level below its

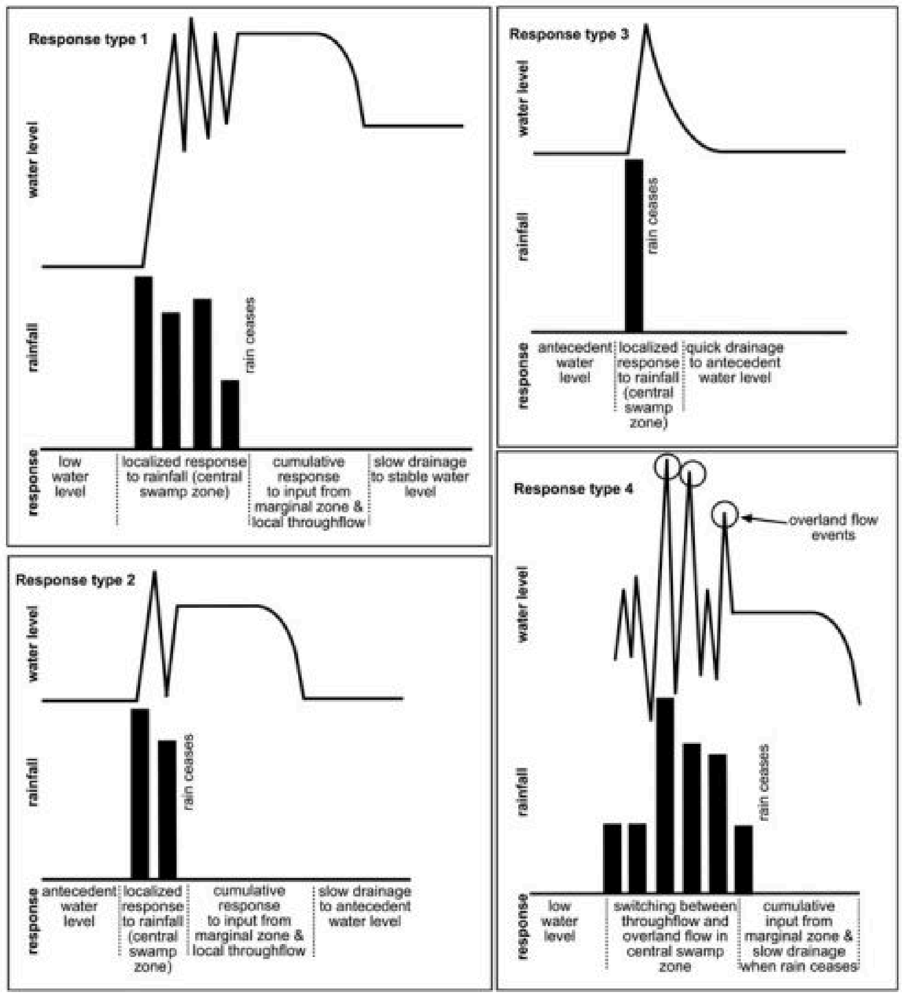


Figure 3.1: **Model of four major hydrological responses for an Eastern Australian upland swamp.** *For each response type, the top line represent groundwater level in the central swamp axis while the black bars represent rainfall occurring over the catchment. The x axis represents time. Note that while this stylised model does not show groundwater levels falling below the initial groundwater level, this was a common feature of the actual data. Adapted from figure 7 of Fryirs, Gough, and Hose (2014).*

initial starting point (Wilson 2009). This interpretation of Fryirs, Gough, and Hose (2014)'s groundwater depth record is strengthened by the fact that these periods of low groundwater level were short-lived. Pipe networks are inherently unstable and after a quick burst of discharge often re-clog due to mass wastage of the sediment surrounding the pipes (Wilson 2009).

These distinct hydrological responses demonstrate that highly flashy rainfall events tend to pass straight through Sydney region swamps resulting in minimal groundwater recharge of the swamp and hence little attenuation of the downstream hydrograph. By contrast, longer events are able to initiate throughflow in the surrounding catchment. Importantly, it is this effective throughflow from the broader catchment, rather than surface flow during a rain event that appears to be primarily responsible for recharging Sydney region swamps and providing a continuing source of baseflow for downstream.

This emphases the importance of the catchment-swamp connection. On the one hand, the catchment provides the storage capacity that feeds the throughflow that keeps the swamp watertable high. On the other hand, the high watertable and low hydraulic conductivity of the swamp, especially the catotelm, provides a plug at the base of a catchment that slows the draining of throughflow out of the catchment.

3.3 Ecosystem composition

3.3.1 Flora

Figure 3.2 presents a compilation of plant species likely to occur in Yellow Rock Fault swamps. This list was determined by compiling thirteen species lists from relevant map units of the following sources: BMCC (1985), Benson (1992), Smith and Smith (1995), Ryan, Fisher, and Schaeper (1996), BMCC (2002), DECC (2008) and OEH (2016). Each mention of a species was awarded a value of one unless it was listed by the author as dominant, significant or diagnostic of the vegetation community, in which case it is was awarded a value of two. Values were then summed and species with a value less than two (ie. species mentioned in only one source) were dropped. Values greater than four, six, eight and ten were given increasingly dark backgrounds.

These values should only be taken as indicative as the dataset was heterogeneous and vegetation strata were not surveyed with equal effort by all authors. Further, not all map units were descriptions of Yellow Rock Fault swamps.

In the Cripple Creek catchment, Paperbark Swamp Forests intergrade with both surrounding Bench Forest and downstream riparian vegetation, so the descriptions of these communities from BMCC (2002) were also included. The official community description for Riverflat Paperbark Swamp Forests (OEH 2016) is based on lower altitude communities, while DECC (2008) describes areas in the Northern Blue Mountains, so each probably contains some species

Trees	
Angophora bakeri	Narrow-leaved Apple
Angophora floribunda	Rough-barked Apple
Eucalyptus amplifolia	Cabbage Gum
Eucalyptus botryoides	Bangalay
Eucalyptus deanei	Mountain blue gum
Eucalyptus pilularis	Blackbutt
Eucalyptus piperita	Sydney Peppermint
Eucalyptus robusta	Swamp mahogany
Eucalyptus sclerophylla	Hard-leaved Scribbly Gum
Melaleuca linariifolia	Snow-in-summer
Melaleuca styphelioides	Prickly-leaved Tea Tree

Ferns	
Adiantum aethiopicum	Maidenhair fern
Calochlaena dubia	Soft bracken
Gleichenia dicarpa	Tangle fern
Gleichenia microphylla	Scrambling Coral-fern
Hypolepis muelleri	Ground fern
Lomaria nuda	Fishbone waterfern
Pteridium esculentum	Bracken
Sticherus flabellatus	Umbrella Fern
Todea barbara	King fern

Sedges	
Carex appressa	Tall sedge
Eleocharis sphacelata	Tall spikerush
Gahnia clarkei	Tall sawsedge
Gahnia sieberiana	Red-fruit saw-sedge
Isolepis cernua	Nodding Club-rush
Isolepis inundata	Swamp club-rush
Lepidosperma laterale	Variable swordsedge
Lepironia articulata	Grey rush
Machaerina rubiginosa	Soft twig rush
Schoenus melanostachys	Black Bog-rush

Grasses	
Echinopogon ovatus	Forest Hedgehog Grass
Entolasia marginata	bordered panic grass
Entolasia stricta	wiry panic
Imperata cylindrica	kunai grass
Microlaena stipoides	weeping grass
Oplismenus imbecillis	Creeping Beard Grass
Themeda australis	kangaroo grass

Other monocots	
Lomandra longifolia	Spiny-head mat-rush
Typha orientalis	Cumbungi

Shrubs	
Acacia filicifolia	Fern-leaved wattle
Acacia longifolia	Golden wattle
Acacia parramattensis	Parramatta wattle
Acacia rubida	Red stem wattle
Acmena smithii	Lilly Pilly
Backhousia myrtifolia	Grey myrtle
Baeckea linifolia	Weeping baeckea
Banksia oblongifolia	Fern-leaved Banksia
Banksia serrata	Old-man Banksia
Bauera rubioides	River Rose
Callicoma serratifolia	Black wattle
Casuarina glauca	Swamp oak
Duboisia myoporoides	Corkwood
Glochidion ferdinandi	Cheese tree
Hakea dactyloides	Finger hakea
Hakea sericea	Silky hakea
Leptospermum juniperinum	Prickly Tea-tree
Leptospermum polygalifolium	Tantoon
Lomatia myricoides	River Lomatia
Melaleuca citrina	Crimson bottlebrush
Pimelea linifolia	Slender rice flower
Tristania neriifolia	Water Gum
Tristaniopsis laurina	Water Gum

Forbs	
Centella asiatica	Pennywort
Dichondra repens	Kidney Weed
Geranium homeanum	Northern Cranesbill
Hydrocotyle laxiflora	Stinking Pennywort
Hydrocotyle sibthorpioides	Lawn marshpennywort
Lobelia purpurascens	Whiteroot
Ludwigia peploides	Water Primrose
Persicaria decipiens	Slender knotweed
Persicaria lapathifolia	Pale Knotweed
Persicaria praetermissa	Spotted Knotweed
Ranunculus pleibeus	Forest Buttercup
Rununculus inundatus	River buttercup
Viola hederacea	Ivy-leaved Violet

Climbers	
Kennedia rubicunda	Dusky coral pea
Cayratia clematidea	Native Grape
Eustrephus latifolius	Wombat Berry
Smilax glyciphylla	Sweet Sarsaparilla

Figure 3.2: **Flora of the Yellow Rock Fault Swamps.** *Background colour is a first approximation of ecological importance.*

unlikely to be found in the Lower Blue Mountains.

Values are probably reasonably comparable within each strata, however they are definitely not comparable between strata. There was a clear sampling bias toward woody plants within several of the datasets while no dataset included any non-vascular plants despite my own observation of mosses in all Paperbark Swamp Forests that I have visited.

A final reservation regarding this dataset is the issue of functional redundancy. *Acacia spp.* were included in all of the descriptions consulted and were often referred to as dominant within the shrub or low tree stratum. However, there was great diversity in the particular *Acacia* species found in different swamps. Because of this each individual *Acacia* species appears to be of only minor importance in the list, however as a group, they are clearly a central component of the swamp ecosystem[5].

A similar case of redundancy appears to hold for the tall smooth barked eucalypts which exist as a sparse emergent canopy in nearly all descriptions, but are, again, represented by a diverse range of species. The diversity of ferns, forbs and monocots may also hide important recurring morphologies or functions. As such, care must be taken when using figure 3.2 as the basis for the creation of planting lists.

3.3.2 Fauna

Figure 3.3 presents a compilation of animal species that occur near the Yellow Rock swamps. This list should be treated with more caution than the flora list since fewer sources were available for animals and their place within swamp communities, as opposed to surrounding woodland, was less certain. A value of one was given if an author listed an animal as present, two if an animal was common and three if an animal was abundant.

An internal council database of geo-referenced animal sightings was also searched. All animal sightings recorded as occurring within both two kilometres of the Yellow Rock Fault as well as one hundred metres of a creek were counted. For this dataset if the number of sightings was between one and four a value of one was given. If there were between five and nineteen sightings a value of two was given and if there was twenty or more sightings a value of three was given. Obligate aquatic animals such as fish and platypus were removed from the dataset as these animals could not occur in intact swamps.

[5] Indeed, it could well be possible that their nitrogen fixation is vital in preventing the invasion of the various related *swamp oak forest* communities (OEH 2016) which are dominated by nitrogen fixing *Casuarina*.

Birds

Acanthiza lineata	Striated thornbill
Acanthiza pusilla	Brown Thornbill
Acanthorhynchus tenuirostris	Eastern spinebill
Aegotheles cristatus	Australian Owlet-nightjar
Alisterus scapularis	Australian king parrot
Anas superciliosa	Pacific Black Duck
Anthochaera carunculata	Red Wattlebird
Anthochaera chrysoptera	Little wattlebird
Cacatua galerita	Sulphur-crested cockatoo
Cacomantis flabelliformis	Fan-tailed Cuckoo
Cacomantis pallidus	Pallid cuckoo
Caligavis chrysops	Yellow-faced Honeyeater
Callocephalon fimbriatum	Gang-gang cockatoo
Calyptorhynchus funereus	Yellow-tailed black cockatoo
Calyptorhynchus lathami	Glossy black cockatoo
Climacteris leucophaeus	White-throated treecreeper
Colluricincla harmonica	Grey shrikethrush
Coracina novaehollandiae	Black-faced cuckooshrike
Corvus coronoides	Australian Raven
Cracticus tibicen	Australian Magpie
Cracticus torquatus	Grey butcherbird
Dacelo novaeguineae	Laughing kookaburra
Edolisoma tenuirostre	Common cicadabird
Eopsaltria australis	Eastern yellow robin
Eurystomus orientalis	Oriental dollarbird
Gerygone mouki	Brown Gerygone
Gerygone olivacea	White-throated gerygone
Lichenostomus leucotis	White-eared honeyeater
Malurus cyaneus	Superb fairywren
Malurus lamberti	Variegated Fairy-wren
Manorina melanocephala	Noisy Miner
Meliphaga lewinii	Lewin's honeyeater
Melithreptus brevirostris	Brown-headed honeyeater
Melithreptus lunatus	White-naped honeyeater
Menura novaehollandiae	superb lyrebird
Microeca fascinans	Jacky winter
Myiagra rubecula	Leaden flycatcher
Neochmia temporalis	Red-browed finch
Nesoptilotis leucotis	White-eared Honeyeater
Ninox novaeseelandiae	Morepork
Ninox strenua	Powerful owl
Origma solitaria	Rockwarbler
Pachycephala pectoralis	Golden Whistler
Pachycephala rufiventris	Rufous whistler
Pardalotus punctatus	Spotted pardalote
Pardalotus striatus	Striated pardalote
Petroica boodang	Scarlet robin
Phaps elegans	Brush bronzewing
Philemon corniculatus	Noisy Friarbird
Phylidonyris niger	White-cheeked honeyeater
Phylidonyris novaehollandiae	New Holland honeyeater
Phylidonyris novaehollandiae	Eastern Rosella
Platycercus elegans	Crimson rosella
Podargus strigoides	Tawny frogmouth
Psophodes olivaceus	Eastern whipbird
Ptilonorhynchus violaceus	satin bowerbird
Pycnonotus jocosus	Red-whiskered Bulbul
Rhipidura albiscapa	Grey fantail
Rhipidura leucophrys	Willie wagtail
Rhipidura rufifrons	Rufous fantail
Sericornis frontalis	White-browed Scrubwren
Stagonopleura bella	Beautiful firetail
Strepera graculina	Pied currawong
Streptopelia chinensis	Spotted Turtle-Dove
Taeniopygia bichenovii	Double-barred finch
Todiramphus sanctus	Sacred kingfisher
Trichoglossus haematodus	Rainbow Lorikeet
Zosterops lateralis	Silvereye

Reptiles

Chelodina longicollis	Eastern long-necked turtle
Ctenotus taeniolatus	Copper-tailed Skink
Dendrelaphis punctulata	Common tree snake
Eulamprus quoyii	Eastern water skink
Intellagama lesueurii	Eastern Water Dragon
Lampropholis delicata	Dark-flecked Garden Sunskink
Lampropholis guichenoti	Pale-flecked Garden Sunskink
Morelia spilota	Carpet python
Phyllurus platurus	Broad-tailed gecko
Pseudechis porphyriacus	Red-bellied black snake
Saproscincus mustelinus	Weasel Skink
Varanus varius	Lace monitor
Vermicella annulata	Bandy-bandy

Mammals

Acrobates pygmaeus	Feathertail glider
Antechinus stuartii	Brown antechinus
Canis lupus dingo	Dingo
Cercartetus nanus	Eastern pygmy possum
Chalinolobus gouldii	Gould's Wattled Bat
Chiroptera spp.	Various bats
Dasyurus maculatus	Tiger quoll
Macropus rufogriseus	Red-necked wallaby
Perameles nasuta	Long-nosed bandicoot
Petauroides volans	Greater glider
Petaurus breviceps	Sugar glider
Phascolarctos cinereus	Koala
Pseudocheirus peregrinus	Common ringtail possum
Rattus fuscipes	Bush rat
Trichosurus vulpecula	Common brushtail possum
Wallabia bicolor	Swamp wallaby

Amphibians

Crinia signifera	Common Eastern Froglet
Heleioporus australiacus	Giant Burrowing Frog
Limnodynastes peronii	Striped marsh frog
Limnodynastes tasmaniensis	Spotted grass frog
Litoria caerulea	Green tree frog
Litoria dentata	Bleating tree frog
Litoria fallax	Eastern Dwarf Tree Frog
Litoria latopalmata	Broad-palmed frog
Litoria lesueurii	Lesueur's frog
Litoria peronii	Peron's Tree Frog
Litoria phyllochroa	Leaf-green Tree Frog
Litoria tyleri	Tyler's tree frog
Litoria verreauxii	Verreaux's Frog
Litoria wilcoxii	Stony-creek frog
Mixophyes balbus	Stuttering frog
Pseudophryne australis	Red-crowned Toadlet
Uperoleia laevigata	Smooth Toadlet

Invertebrates

Hemicordulia australiae	Australian emerald dragonfly
Ischnura heterosticta	Common bluetail
Orthetrum caledonicum	Blue skimmer
Papilio aegeus	Large Citrus Butterfly
Petalura gigantea	Giant Dragonfly
Pommerhelix monacha	
Rhyothemis graphiptera	Graphic Flutterer
Xanthagrion erythroneurum	Red and Blue Damsel

Figure 3.3: **Fauna of the Yellow Rock Fault Swamps.** *Background colour is a first approximation of ecological importance.*

3.3.3 Microbial life

Bray (2005) found that the soils of *Melaleuca quinquenervia*[6] swamp forests had a lower fungi:bacteria ratio[7], and higher levels of 16:1 2OH and 18:2w6c gram negative bacteria than did comparison sites in the alternative ecosystem state of sedgeland. The increase in antibiotic resistant gram negative bacteria is likely due to the abundance of anti-microbial compounds produced by *Melaleucas* (Brophy, Craven, and Doran 2013; Shirdashtzadeh et al. 2017).

Many native plants growing in the very low nutrient and acid Hawkesbury Sandstone soils are likely to be reliant on mycorrhizal fungi for both nutrient acquisition and resistance to aluminium toxicity (Brundrett 2009). Although, nutrient subsidies from the slopes mean that valley floors are likely to be somewhat more fertile, the impact of these subsidies is likely to be counteracted in swamps by the tendency of peat to immobilise nutrients (see section 3.2.1). Unsurprisingly then, mycorrhizal nutrient acquisition is a common strategy used by trees in low nutrient Australian swamps (Khan 1993).

Although mycorrhizae formation appears to be impeded by water-logging, they are found abundantly in swampy areas above the watertable and are able to quickly recover from temporary flooding (Khan and Belik 1995). In rice plants, mycorrhizae have also been found below the watertable. This is thought to be enabled by the transportation of oxygen though the aerenchyma found in rice roots (Khan and Belik 1995). Since *Melaleuca* also posses oxygen transporting aerenchyma (Shepherd et al. 2015), it is likely that they are also able to maintain mycorrhizae below the water table during protracted flood events.

One of the reasons for the ecological success of *Myrtaceae* appears to be related to its ability to maintain a range of both arbuscular and ecto-mycorrhizal relationships which are differentially exploited depending on current ecological conditions (Adjoud-Sadadou and Halli-Hargas 2017). This *Myrtaceae*-wide strategy of maintaining a range of mycorrhizal partners appears to hold for swamp adapted *Melaleuca* (Colton and Murtagh 1999; Khan 1993). Similarly, ferns appear to develop multiple mycorrhizal partners, though these partners are almost exclusively arbuscular (Cooper 1976; Brundrett and Tedersoo 2018).

By contrast sedges are largely non-mycorrhizal, although they may develop arbuscular mycorrhizal relationships under stressful conditions (Muthukumar, Udaiyan, and Shanmughavel 2004; Barrett 2013). Instead they have developed a nutrient acquisition strategy referred to as dauciform roots, similar to the better known cluster roots of the *Proteaceae*. Both dauciform and cluster roots release bursts of carboxylates which strip mine the surrounding soil of nutrients (Barrett 2013).

The contrasting nutrient acquisition strategies of *Melaleuca* and ferns, on the one hand, with sedges and *Proteaceae* shrubs, on the other, may help to explain

[6] A close sister species of *M. linariifolia* (Boland et al. 2006).
[7] Note that this ratio does not include arbuscular mycorrhizal fungi.

some of the sharp boundaries of stands of mycorrhizal and non-mycorrhizal plants apparent in Warrimoo Swamp. However, below-ground interactions are notoriously complex[8] and there are also many places in Warrimoo Swamp where mycorrhizal and non-mycorrhizal plants successfully grow together.

3.4 Ecosystem structure

3.4.1 Strata

A clear trend is apparent from the vegetation surveys summarised as figure 3.2. The main swamp axis is composed of tall, straight, smooth barked eucalypts which are either fringing, emergent or form an open canopy above an open to closed canopy of *Melaleuca linariifolia*. Either beneath this, or on its fringes is a sparse to closed shrub stratum of one or multiple *Acacia spp.*, *Callicoma serratifolia* (black wattle), *Leptospermum polygalifolium* (tantoon) and/or *Melaleuca citrina* (crimson bottlebrush). The herbaceous stratum is variable depending on the degree of canopy closure, hydrological regime and soil. It may be either a diverse range of sparse to dense grasses, forbs and/or ferns, with emergent *Gahnia clarkei* or a dense, tall near-monoculture of either *Gleichenia dicarpa* or one of the sedges.

3.4.2 Spatial organisation of vegetation communities

The central structuring element of Eastern Australian valley floor swamp vegetation communities is topography. It directly controls the movement of sediment and water which in turn controls the edaphic and hydrological regime of each zone within a valley. (Keith and Myerscough 1993; Cowley et al. 2019; Cowley, Fryirs, and Hose 2016). On the nearby Woronora Plateau, Keith and Myerscough (1993) developed an idealised toposequence of swamp vegetation communities (figure 3.4) which has been adopted by many later studies of Sydney region swamps (eg. Keith et al. 2007; Mason, Keith, and Letten 2017).

Generally slope is negatively correlated with both the content and temporal variability of soil moisture as well as soil depth, while it is positively correlated with soil particle size (Keith and Myerscough 1993). Thus steeper, narrower areas of the valley (typically upstream) are relatively drier and have relatively coarser and shallower soils. Keith and Myerscough (1993) note that these upstream areas do not generally display the full range of communities found in the wetter, deeper, finer soils of wider downstream areas.

Keith and Myerscough (1993) describes **Ti-tree Thicket** as occurring along major drainage lines. It is characterised by a dense shrub stratum over a very tall stratum of *Gleichenia dicarpa* (tangle fern), *Gahnia* (sawsedge) or *Baumea*

[8] For example, Lambers and Teste (2013) found that while root-derived carboxylates did indeed limit the growth of mycorrhizal fungi, they nevertheless facilitated the growth of neighbouring mycorrhizal plants.

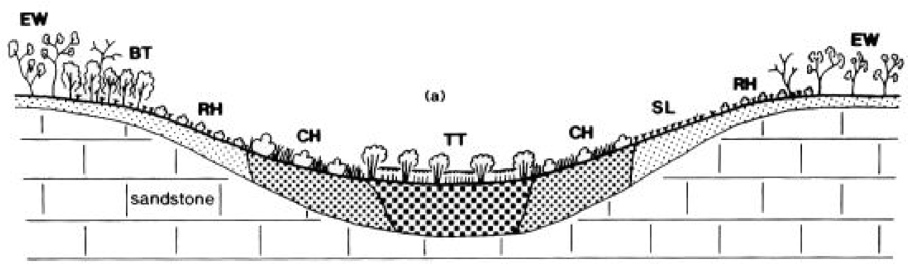


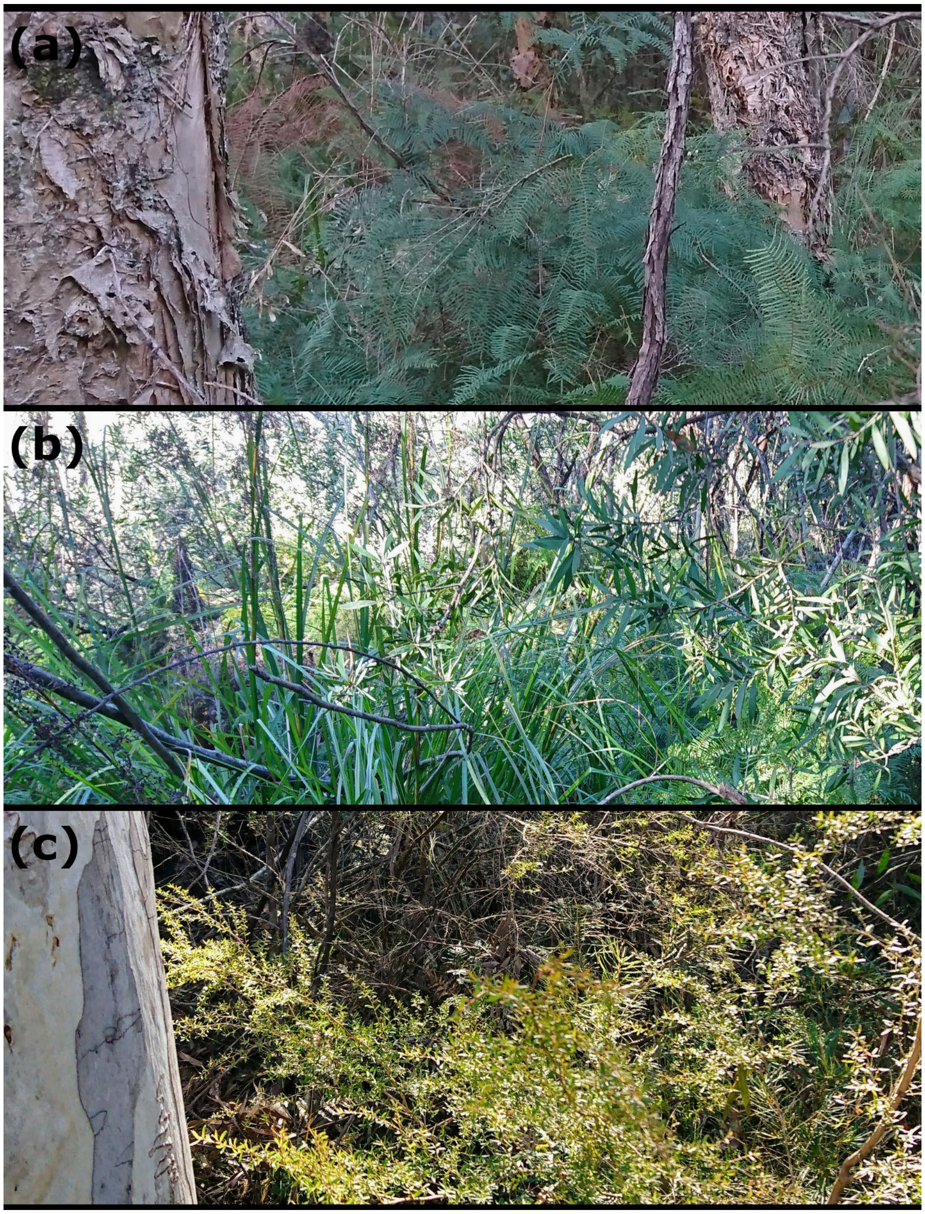
Figure 3.4: **Idealised toposequence of large valley floor swamps on the Woronora Plateau**. **EW:** *Eucalyptus woodland.* **BT:** *Banksia Thicket.* **RH:** *Restioid Heath.* **CH:** *Cyperoid Heath.* **TT:** *Ti-tree Thicket.* **SL:** *Sedgeland. From upslope to downslope, the three soil groups indicated are yellow earths/grey-brown sands; organic sands; and organic fines. Adapted from figure 4 of Keith and Myerscough (1993).*

(twig rush). **Cyperoid Heath** occurs on deep organic sands and contains a dense stratum of tall sedges with occasional spreading shrubs. **Sedgeland** occurs on small seepage zones on shallow soils with a continuous stratum of small sedges and occasional tall slender shrubs. **Restioid Heath** occurs on thinner soils with more variable moisture regimes. It contains a mixture of spreading *Banksia* and *Hakea* intermixed with a wide diversity of short slender shurbs, forbs and restiads. **Banksia Thicket** is characterised by a dense, tall shrub stratum dominated by *Banksia* and *Hakea* over an open cover of short shrubs and sedges.

While many of of the species listed by Keith and Myerscough (1993) for the Woronora Plateau are not found as dominant species in Warrimoo Swamp, their roles are generally replaced by morphologically similar plants. For example, while *Banksia ericifolia* dominates Banksia Thicket in both Keith and Myerscough's scheme and at Warrimoo swamp, in Cyperoid Heath, Keith and Myerscough list *Banksia oblongifolia* as being dominant, whereas at Warrimoo Swamp the same niche is filled by *Melaleuca citrina*.

The two most notable differences between Keith and Myerscough (1993)'s communities and those found in Warrimoo Swamp is the lack of a sedgeland grouping and the absence of *Restionaceae* in Restioid heath. Both of these differences may be due to the deeper soils found in Kurrajong Fault swamps compared to the swamps of the Woronora Plateau.

Restioid heath occurs within an ecotone between Woronora Plateau swamps and surrounding eucalypt woodland in areas with impeded drainage (Keith and Myerscough 1993). Two types of eucalypt woodland surround Warrimoo Swamp, Bench Woodland on deep sands to the South and *Corymbia* woodland on steeper rockier soil to the North (figure 2.7). The ecotone between the swamp and the *Corymbia* woodland is structurally similar to Keith and Myerscough (1993)'s



Examples of vegetation communities within Warrimoo Swamp. ***(a) Ti-tree thicket:*** Melaleuca linariifolia *(snow in summer) visible above very tall* Gleichenia dicarpa *(tangle fern).* ***(b) Cyperoid Heath:*** *Tall* Gahnia clarkei *(tall sawsedge) beneath* Melaleuca citrina *(crimson bottlebrush) tall shrubs.* ***(c) Restioid Heath:*** *Emergent* Eucalyptus sclerophylla *(scribbly gum) above* Banksia spinulosa *(hairpin banksia) and other shrubs. Cyperoid Heath in background.*

Restioid heath, but with the *Restionaceae* replaced with other monocots. The Southern ecotone between the swamp and the well drained soils of the Bench Woodland matches the description of Banksia Thicket.

In the Woronora Plateau swamps the central swamp axis Ti-tree Thicket is dominated by *Leptospermum* species. This is also seen in the swamps of the Upper Blue Mountains (personal observation). By contrast the deeper soils of the Kurrajong Fault swamps allow taller *Melaleuca spp.* to dominate. Interestingly, near the downstream end of Warrimoo Swamp a shallow weir has been constructed to allow a fire trail to cross the swamp. For a distance of approximately one hundred metres upstream of this weir *Leptospermum polygalifolium* (Tantoon) replaces *Melaleuca* as the dominant woody species, suggesting that it is the lower watertables associated with the deeper soils that is the key in allowing *Melaleuca* to out compete *Leptospermum*.

While Keith and Myerscough's toposequence accurately describes the swamp cross-section in the downstream half of Warrimoo swamp, in the upstream half the spatial variation of species is more complex. While *M. linariifolia* dominates the central swamp axis over most of the length of the swamp the larger Ti-tree thicket community only becomes established in the downstream half of the swamp. By contrast the upstream half of the swamp is characterised by a mosaic of ecotones which do not fit cleanly into any of Keith and Myerscough's communities.

At the upstream end of the swamp *M. linariifolia* forms an open second canopy beneath *Eucalyptus sclerophylla* (scribbly gum). This bench woodland ecotone features an open *Calochlaena dubia* (soft bracken) herbaceous stratum and scattered shrubs. Moving downstream, the *M. linariifolia* canopy closes while *E. sclerophylla* becomes emergent and *C. dubia* is replaced by a shifting mosaic of either an open *Schoenus melanostachys* (black bog-rush) herbaceous stratum, a closed *Callicoma serratifolia* (black wattle) shrub stratum or bare ground. Further downstream the understorey shifts to a closed stratum of tall *Gahnia clarkei* (tall sawsedge) or *Gleichenia dicarpa* (tangle fern) with scattered *C. serratifolia* or *Melaleuca citrina* (crimson bottlebrush). This understorey finally gives way to very tall, impenetrable *G. dicarpa* with no shrub stratum coinciding with a loss of *E. sclerophylla* emergents.

3.4.3 Trophic interactions

As already mentioned, little is known about the natural fauna of swamps in the Lower Mountains. Of the natural predators eagles, dingoes, red bellied black snakes and humans are likely to have played particularly important roles in structuring the rest of the animal community.

Although controversial, there is evidence that dingoes suppress smaller predators (Glen and Dickman 2005; Kennedy et al. 2012; Moseby et al. 2012; Greenville et al. 2014; but see also Allen, Allen, and Leung 2015 for a contrary view). By suppressing meso-predators dingoes may indirectly increase small herbivore abundance, while at the same time directly reducing large herbivore abundance (Glen and Dickman 2005). However, the current abundance of Swamp Wallabies in Warrimoo Swamp in the presence, until recently, of dingoes, combined with the apparent ease with which Blaxland, Lawson and Wentworth were able to kill Kangaroos (Richards 1979), suggests that predation was not sufficient to keep large macropod abundance at a low level.

Similarly, evidence of a relatively high abundance of foxes in the Cripple Creek catchment suggests that dingoes have not been successful in suppressing meso-predators in recent years. Johnson and VanDerWal (2009) found that in Eastern Australian forests, dingoes only have an impact on meso-predator abundance when dingoes are themselves highly abundant. If this is the case, it is possible that any meso-predator release enjoyed by the small herbivores of the Yellow Rock Fault swamps due to historically higher dingo abundance, would have been negated by increased predation from dingoes themselves.

In a swamp system in Tasmania, Taylor and Comfort (1993) found that native rodents and *Antechinus* were much more common in areas with a dense, tall sedge/fern herbaceous stratum under *Melaleuca* than in surrounding eucalypt forest or shorter, more open sedgeland lacking a tree/shrub stratum. Interestingly, the small predator *Dasyurus viverrinus* (Eastern Quoll) was most common in the short open sedgeland. Although, this does not demonstrate causation, this would certainly be consistent with with dense tall sedges or ferns with a shrub/tree overstorey providing protection from predation for small mammals. However, the mechanism by which a shrub or tree stratum would increase protection over and above a dense herbaceous stratum is not clear.

3.5 Ecosystem function

3.5.1 Faunal habitat and interactions

At least 24 Australian mammal species, including small and large macropods, rodents, possums, bats and wombats, have all been recorded as using species of the *Lepidosperma* genus as either shelter or food (Barrett 2013). It is likely that other, morphologically similar sedges play an equally important role. Because many sedges are long-lived clonal organisms resistant to most disturbances, they can provide long-term stability of habitat to faunal populations (Barrett 2013).

In Warrimoo Swamp, tall dense stands of *Gahnia clarkei* (tall sawsedge) and *Gleichenia dicarpa* (tangle fern) have extensive tracks leading to occasional patches of cleared ground covered by a dome of vegetation. These have presumably been constructed by Swamp Wallabies or other large macropods as shelter sites.

Sedges are generally reliant on faunal mutualisms for seed dispersal. Ants and other insects appear to be particularly important for short distance transport while birds are responsible for most long distance dispersal (Barrett 2013). The importance of bird enabled dispersal is readily evident in Blue Mountains swamps by the frequent presence of *Gahnia spp.* underneath trees with good perch sites (personal observation).

The common name for *Melaleuca linariifolia*, snow-in-summer, is in reference to their stunning summer floral display (Brophy, Craven, and Doran 2013). While most *Melaleuca* appear to be primarily insect pollinated, the nectar and pollen are also important food resources for nectarivorous birds, arboreal mammals and bats (Brophy, Craven, and Doran 2013). The mass of pollinating insects attracted to the flowers are likely also a food source for a wide range of vertebrate and invertebrate predators.

In addition to their provision of nectar, *Melaleuca linariifolia* also provide other faunal resources. Koalas are recorded as utilising them as a secondary browse species (Phillips and Callaghan 1996) while *Ninox connivens* (barking owl) has been recorded as using them for nesting sites (Kavanagh 2004).

3.5.2 Productivity and nutrient cycling

As discussed above, despite nutrient subsidies from the surrounding slopes, Kurrajong Fault swamps are nevertheless naturally low fertility environments. The universal presence of *Acacia spp.* and legume forb genera in all vegetation surveys of Paperbark Swamp Forests confirms that Nitrogen is a limiting element. Where legumes are present, these nitrogen fixing plants may balance the losses of nitrogen from the system through denitrification caused by low redox soils (White 2006).

Two broad nutrient acquisition pathways are possible: external cycling and internal cycling. External cycling involves extracting nutrients from decomposing litter whereas internal cycling involves removing nutrients from leaves and other tissues before their loss. The resource availability hypothesis (Endara and Coley 2011) predicts that plants that rely on external cycling will grow in high nutrient environments, have fast growth rates, short leaf turnover rates, low levels of secondary metabolites and high levels of herbivory. By contrast plants that rely on internal cycling will grow in low nutrient environments, have slow growth rates, long leaf turnover rates, high levels of secondary metabolites and low levels of herbivory (Endara and Coley 2011).

The very high levels of terpenes found in the leaves of *Melaleuca* (Brophy, Craven, and Doran 2013), firmly put it in the internal cycling group. Interestingly, these terpenes do not act solely as anti-herbivore chemicals (Bustos-Segura, Külheim, and Foley 2015), but also slow the decomposition of both their own and other plant's litter (Boon and Johnstone 1997; Bailey et al. 2003). This slowing of external cycling would be expected to inhibit the growth of seedlings and saplings too small to engage in internal cycling as well as all growth stages of plants that rely on a fast growth, high leaf turnover strategy.

At a system level, very slow nutrient cycling driven by *M. linariifolia* derived terpenes may create a niche for *Acacia spp.* and other legumes. The relative abundance of these nitrogen-fixers within Paperbark Swamp Forests likely controls available nitrogen and may be an important predictor of the abundance of other species.

3.5.3 Resilience

The inhibition of litter decomposition by *Melaleuca* not only slows nutrient cycling, but also changes the physical condition of the swamp (Wallis and Raulings 2011). Because it is produced in very abundant quantities (Boon and Johnstone 1997), and breaks down very slowly, *Melaleuca* leaf litter tends to accumulate, especially when it is above the permanent watertable (Bailey et al. 2003; Wallis and Raulings 2011). This contributes to the formation of the hummocks that characterise the surface topography of many *Melaleuca* wetlands (Wallis and Raulings 2011) and may act to aggrade and repair areas of nascent channelisation.

Many sedges and ferns posses rhizomes from which they can resprout after a disturbance (Clarkson 1997; Barrett 2013). While *Gleichenia dicarpa* (tangle fern) is able to resprout from its rhizome, because the rhizome is so close to the surface it is only able to survive minor disturbances. Many sedges on the other hand have deeper rhizomes making them resilient to larger disturbances such as intense fires (Clarkson 1997).

Allelopathy appears to be widespread amongst ferns and may contribute to the development of monospecific colonies (Kato-Noguchi 2015). Although no published studies have been preformed on *Gleichenia dicarpa* (tangle fern), other members of the genus have been shown to produce allelopathic compounds that led to the total inhibition of germination of a diverse range of angiosperms (Kato-Noguchi et al. 2013). If these glasshouse results transfer to the field, they would make stands of *Gleichenia* highly resistant to invasion by other species.

3.6 External exchanges

3.6.1 Landscape flows

As already discussed Kurrajong Fault swamps act as sinks for upstream nutrient and sediment flows. They also slow water movement out of the catchment, however this function is more complex than often assumed, with the peak of the hydrograph transferred downstream largely unchanged, while throughflow is slowed (see section 3.2.3).

Due to their more or less permanent access to water, they are likely to be relatively high productivity areas within the context of their catchments. As discussed above, *Melaleuca linariifolia* and other swamp vegetation are important food sources for a range of animals. This will lead to an export of some nutrients from the swamp to the surrounding slopes as animals feed in the swamp but return to nest in the surrounding hills. However, given the high habitat quality of the tall dense sedge and fern stratum in the swamp, the opposite pattern (nesting in the swamp but foraging outside) likely leads to at least a balance and possibly a net import of nutrients by fauna.

3.6.2 Gene flow

Each Kurrajong Fault swamp is isolated by eucalypt woodland on three sides while a substantially different riparian zone vegetation community occupies the areas downstream of the fault. Some species, such as *Melaleuca linariifolia*, are minor components of downstream riparian zones (BMCC 2002) and so should be able to maintain gene flow via short distance seed dispersal. Other species such as *Gahnia spp.* rely on animal dispersal to maintain inter-valley genetic connectivity (Barrett 2013).

Some species will experience only minor gene flow between valleys. This is likely the case for species making up a minor component of the community. Similarly, certain species of sedge which fruit rarely and poorly, and mostly rely on clonal reproduction are at risk of genetic isolation (Barrett 2013).

Most macropods consume fungal fruiting bodies, however both the frequency of mycophagy as well as the suite of fungal species consumed varies between macropod species (Vernes 2010) suggesting a low level of functional redundancy between macropod species. Of particular importance may be large marsupials such as swamp wallabies who, because of their larger home ranges and longer gut retention times, may be particularly important in the long distance dispersal of fungal spores (Danks 2012). Because swamps provide habitat for such a wide range of macropods and other mycophagous mammals, it may be that swamps, and especially those areas directly around nests, are fungal diversity hotspots that act as nodes within fungal dispersion networks.

3.7 Disturbance regime

3.7.1 Long cycles

Eastern Australian valley fill swamps are characterised by thick layers of peaty sands and silt typically overlaying gravely sediments on top of bedrock (Fryirs et al. 2014). These are geomorphologically active landforms which are characterised by recurrent cut and fill cycles where a large part of the sediment on a site is lost in a sudden cut event and then slowly refilled over the course of centuries or millennia (Johnston and Brierley 2006; Tomkins and Humphreys 2006; Fryirs, Cowley, and Hose 2016). The current crop of Sydney region swamps appear to generally have begun this cycle some time in the Holocene (Nanson 2009; Fryirs, Cowley, and Hose 2016; Mould and Fryirs 2017), presumably in response to long term climatic changes (Falster et al. 2018).

Destabilising cut events appear to be caused by a combination of intrinsic and extrinsic triggers. The major intrinsic trigger is the development of an unstable slope due to long term aggradation (Fryirs, Cowley, and Hose 2016). Natural extrinsic triggers include fire, drought, flood and geological events (Tomkins and Humphreys 2005), while anthropogenic extrinsic triggers include changes in catchment hydrology due to increased levels of impervious surfaces in the catchment, artificial storm water drainage systems and groundwater extraction (Fryirs, Cowley, and Hose 2016).

Natural extrinsic triggers should be related to millennial-scale climatic cycles (Falster et al. 2018), however the lack of synchrony of cut events between swamps in the same region (Fryirs, Cowley, and Hose 2016) suggests that either intrinsic triggers dominate, or that there is some unexplained stochasticity intervening between extrinsic triggers and the initiation of cut events. One possibility is that multiple triggers are required to occur at the same time. This seems to be confirmed by Tomkins and Humphreys (2005) who compared the periodicity of major disturbance events with dated cut events in the sediment record. They concluded that swamps in the Sydney catchment are resistant to individual large scale disturbance events, but not to multiple synchronous or near-synchronous external triggers. Thus, a swamp may be resilient in the face of a major bushfire, for example, but not in the face of a major bushfire followed soon after by a flood.

3.7.2 Short cycles

Keith and Myerscough (1993) showed that in Woronora Plateau swamps, fire regime is a significant structuring element of vegetation communities. Although they found that water and nutrient gradients were the major structuring elements of the herbaceous stratum, the shrub and low tree strata were primarily structured by fire history and regime. The importance of fire in controlling the floristics of wet heaths has been confirmed by numerous other studies (eg. Brown and Podger 1982; Williams and Clarke 2006 amongst others).

As predicted by Keith and Myerscough (1993), at Warrimoo Swamp, the distribution of ferns and sedges appears to be primarily related to slope and hydrology with a clear sequence of *Calochlaena dubia* → *Schoenus melanostachys* → *Gahnia clarkei* → *Gleichenia dicarpa* along the central swamp axis. By contrast, the distribution of woody plants appears to be more complex.

Plants can be divided into various plant functional types describing the manner in which they respond to disturbances (Keith et al. 2007). For example, there is a classic division between seeders and resprouters. For woody plants, a frequent disturbance regime will generally select against seeders because they will not have time to grow to a seed-bearing age in the short interval between disturbances. By contrast, an infrequent disturbance regime will select against resprouters because their lower growth rates and fecundity exposes them to competitive effects from seeders (Keith et al. 2007).

These differences in plant functional types appear to an important control on the edge of swamp wet heath species (*Backhousia*, *Baeckea*, *Banksia*, *Hakea*, *Leptospermum*, etc), however they do not appear able to explain the distribution of *Melaleuca* along the central swamp axis.

While both *Melaleuca linariifolia* and *M. citrina* survive with thick skirts of adventitious roots in periodically flooded areas, they also flourish in neighbouring rarely flooded areas, or as rare shrubs in deeply drained Bench Woodland, or even as as non-irrigated street trees in ridge areas (personal observation). And yet, it is only along drainage lines with deep soils and an average depth to groundwater of around a metre that they are dominant or even abundant. Thus, in the Cripple Creek catchment, *Melaleuca* demonstrate a very wide fundamental niche, but a much more constrained realised niche. A major control on the realised niche of *Melaleuca* appears to be seedling survival with seedlings of *M. alternifolia*[9] showing a 97% reduction in growth rate when exposed to competition (predominately for nitrogen and light) from monocots (Virtue 1999).

At Warrimoo Swamp, the dominant herbaceous species found beneath *Melaleuca* are *Gleichenia dicarpa* (tangle fern) and a variety of sedges. Interestingly, *M. linariifolia* grows prolifically above very tall, dense and impenetrable stands of *G. dicarpa* but only above open canopies of sedges while *M. citrina* grows as dense stands above both very tall and dense *G. dicarpa* or *Gahnia clarkei* (tall sawsedge). While *G. dicarpa* is a resprouter, the rhizomes of *G. dicarpa* are very shallow exposing them to hot fires (Johnson 2001), unlike the deeper rhizomes of most sedges (Barrett 2013; Johnson 2001). This leads to differing rates of regeneration after fire, with sedges returning to their previous dominance soon after a fire, while *G. dicarpa* may take over a decade (Clarkson 1997; Johnson 2001).

From distribution patterns apparent at Warrimoo Swamp, it appears that *M. linariifolia* is only able to re-establish in areas of slowly regenerating *G. dicarpa* or sparsely regenerating sedges, but not densely regenerating sedges. By contrast, *M. citrina*, possibly due to its much larger fruits (Brophy, Craven, and Doran 2013), is able to regenerate amongst either dense *G. dicarpa* or dense sedges. Where both *M. linariifolia* and *M. citrina* are able to successfully regenerate, *M. linariifolia* out competes *M. citrina* due to its much larger size, relegating *M. citrina* to the sparse shrub stratum.

[9] A close sister species to *M. linariifolia* (Boland et al. 2006).

4 | Intervention site model

4.1 Human context

4.1.1 Regulatory context

In 2009 Main Swamp was deemed as an environmental offset area under the EPA consent XM/11062008/A. This was to allow for the construction of new facilities elsewhere on site. The swamp is further protected as an endangered ecological community under both state and federal legislation (see section 3.1.1). Although Main Swamp and remnant patches along Winnicoopa Creek are only small, because there are only 160 hectares of Riverflat Paperbark Swamp Forest remaining (OEH 2016), they are nevertheless significant. The small size and generally poor condition of remaining swamp forest elsewhere in the Sydney Basin should improve the chances of securing funding from the NSW Environmental Trust, Local Land Services or Landcare for restoration.

BWMF is sited on crown land which is managed by council. The land parcel covering the area of Winnicoopa Creek upstream of BWMF is owned by Sydney Water. Most of Cripple Creek downstream of BWMF is council land.

4.1.2 Cultural context

As well as being a functioning landfill, BWMF is the 'backyard' of the residents of Blaxland, Warrimoo and Mount Riverview. Although discouraged by management, the operational area is frequently used by walkers and mountain bikers to gain access to the fire trail network in the adjoining bush. In addition to these users, dirt bikers also use the fire trail network despite signs forbidding the practice. Users of the Cripple Creek bushland areas have actively extend the official path network.

The fire trail that runs along Cripple Creek downstream of Main Swamp contributes large quantities of coarse sandy sediment to the creek. Along the downstream portion of Warrimoo Creek, Dirt bike tracks are causing significant damage to the stream banks, and while there is currently only minor damage caused by these unofficial tracks within the BWMF area, the damage caused to downstream Warrimoo Creek suggests that it is also a live possibility along Cripple Creek.

Although these groups of users have no formal legal rights to the use of BWMF land, they, along with residents of neighbouring properties, are nevertheless stakeholders in the management of the land. As shown by the presence of unofficial path networks, they will use the land irrespective of official sanction. Because of this, successful restoration will require that their viewpoints are considered (Clewell and Aronson 2013).

4.2 Geophysical conditions

4.2.1 Chemical conditions

The most important chemical change that has occurred in Main Swamp is the change in redox environment brought about by the dropping of the watertable. This has led to previously reduced material becoming oxidised and thus vulnerable to microbial decomposition (Chesworth, Martínez Cortizas, and García-Rodeja 2006). This means that not only is new peat unlikely to be formed, but old peat is also being lost. The results of this are visible in the discharge from the swamp which is stained a dark brown from the release of humic and fulvic compounds (figure 4.1).

Figure 4.1: **Water exiting Main Swamp stained red by humic and fulvic compounds.** *Note the more stable bank at the downstream end of Main Swamp compared to the upstream end seen in figure 4.5. Note also the abundant privet seedlings established along the bank.*

As noted above, geological mapping of the Cripple Creek catchment identified a possible diatreme directly to the North of Main Swamp (figure 2.2). While no igneous material has been excavated at BWMF in the last decade (S Thompson & N Campbell, pers comm), the area of the potential diatreme has not been subject to active quarrying in this time. In other parts of the Sydney basin, diatremes have been extensively quarried for road base (Martyn 2018) and it is possible that this has previously been the case at BWMF.

Interestingly, test bore holes dug within Main Swamp immediately down-gradient from the potential diatreme found that surface silty/sandy peat layers were underlain by a heavy clay whereas bores along the main Cripple Creek flow line showed that peaty sands and silts were the primary constituents of the entire profile (Douglas Partners (2004)).

It is not clear whether the heavy clay underlying the Northern parts of Main Swamp are of an igneous origin, are derived from an unmapped shale lens or are even remnant lacustrine deposits. Whatever the case, it is likely to be higher fertility than the surrounding sandy soils. If it is of an igneous origin, it will likely have significant shrink-swell properties (White 2006), whereas lacustrine or shale derived clays of the region will have only minimal shrink-swell properties (Jones and Clark 1991).

The potential diatreme area also has a long history as a dumping ground for night soil (figure 2.9) so, irrespective of the providence of the clay, the soil within the Northern portion of Main Swamp will have extremely fertile soil. Similarly, the Southern portion of Main Swamp has received decades of nutrient enrichment from landfill leachate.

As well as nutrients the flow of leachate likely contained various toxic trace metals. Much of this would have been immobilised in the peat (Winde 2011). Now that this peat is drying out and has begun oxidising, these trace metals are likely being released (Cowley et al. 2018). While there is no obvious signs of acute toxicity symptoms in the vegetation of Main Swamp, less obvious poisoning of primary or secondary consumers may be occurring (Walker et al. 2003).

Using an in-house assessment scheme, Cripple Creek has consistently been rated as being in poor to fair health with no clear trend. While, figure 4.2 shows a marked improvement in both EC and macroinvertebrate diversity coinciding with the installation of the cutoff wall, unfortunately, at the same time, the monitoring site was also moved from directly downstream of Main Swamp to one kilometre downstream, making interpretation of these results difficult. Nevertheless, the presence of a relatively diverse community suggests that any loss of toxic metals from the sediments in Main Swamp has not had a significant downstream impact. This may be because any metals lost from the swamp are complexed to dissolved organic matter (Chesworth, Martínez Cortizas, and García-Rodeja 2006), and so in a less toxic form.

Metal toxicity can also have positive ecological impacts. At a low pH, the CEC of variably charged soil colloids is reduced while the solubility of most metals in the soil is increased (White 2006). This leads to an increase in metal (especially aluminium) concentrations in the soil water while also reducing the availability of nutrients (White 2006). In naturally highly acid environments, such as soils developed on Hawkesbury Sandstone (Bannerman and Hazelton

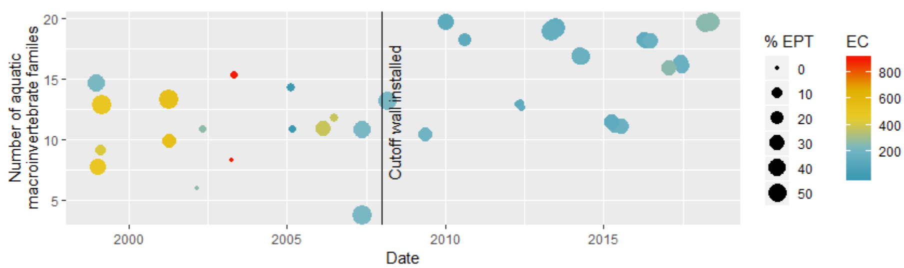


Figure 4.2: **Number of aquatic macroinvertebrate families found in Cripple Creek.** *EPT refers to families belonging to the orders* Ephemeroptera*,* Plecoptera *and* Trichoptera*. These orders are often taken as diagnostic of a healthy community. Note that the monitoring site was moved one kilometre downstream at the same time as the cutoff wall was installed.*

1990), this mixture of low nutrient availability combined with metal toxicity is a part of the niche of the natural vegetation communities (Benson 1992).

An increase in soil pH due to basic urban runoff increases the CEC of variably charged colloids, increases nutrient availability and decreases metal toxicity (White 2006). This soil syndrome of higher pH and higher nutrient availability is linked to weed invasions on Hawkesbury sandstone (King and Buckney 2000; Leishman and Thomson 2005).

As well as increased pH due to surface runoff, the leachate pond next to Main Swamp provides an additional source of basicity. Before being pumped to sewer, the leachate captured form the landfill is held in a pond where carbonate is added to raise the pH of the leachate. This drives the conversion of ${NH_4}^+$ to volatile NH_3. An aerator in the pond further encourages volatilisation by physical means.

Initial pH_{field} testing of Main Swamp shows that surface sediments downwind of the dam are basic while deeper sediments in the same locations, as well as both surface and deep sediments in the rest of the swamp are all 5.5 or below (the cutoff pH_{field} where aluminium toxicity becomes pronounced (White 2006)). This suggests that high pH leachate from the dam is being redeposited in the swamp downwind of the dam.

In addition to this direct wet deposition of leachate, volatilised NH_3 is often re-precipitated as dry deposition in tree canopies close to the point of volatilisation (Skiba et al. 2004). Given that the Western end of the Melaleuca swamp forest is directly downwind of the leachate pond, it is likely that much of the NH_3 lost from the pond ends up adding to the nitrogen load in the swamp.

Winnicoopa Creek is likely to have suffered much less nutrient enrichment than Main Swamp, however it is nevertheless likely to have been impacted from runoff from surrounding urban areas. Like Main Swamp, this runoff has a much higher pH and higher levels of phosphorous and other nutrients than the natural runoff from the ridges (Bannerman and Hazelton 1990; Crowns et al. 1995; King and Buckney 2000).

4.2.2 Physical conditions

Channelisation of Main Swamp

At the same time that the two cutoff walls (one upstream and one downstream of the operational area) were installed, a new diversion pipe was also installed. This moved most of the surface flow coming into Main Swamp, as well as the subsurface flow now captured by the upstream cut off wall and pumped into the diversion pipe, Northwards by approximately 70m (figure 4.3). To bring this flow back to the up-gradient end of the *Melaleuca* swamp forest, a berm was built to guide the flow to just East of where it had previously exited the old diversion pipe. From here it was to rejoin the original channel.

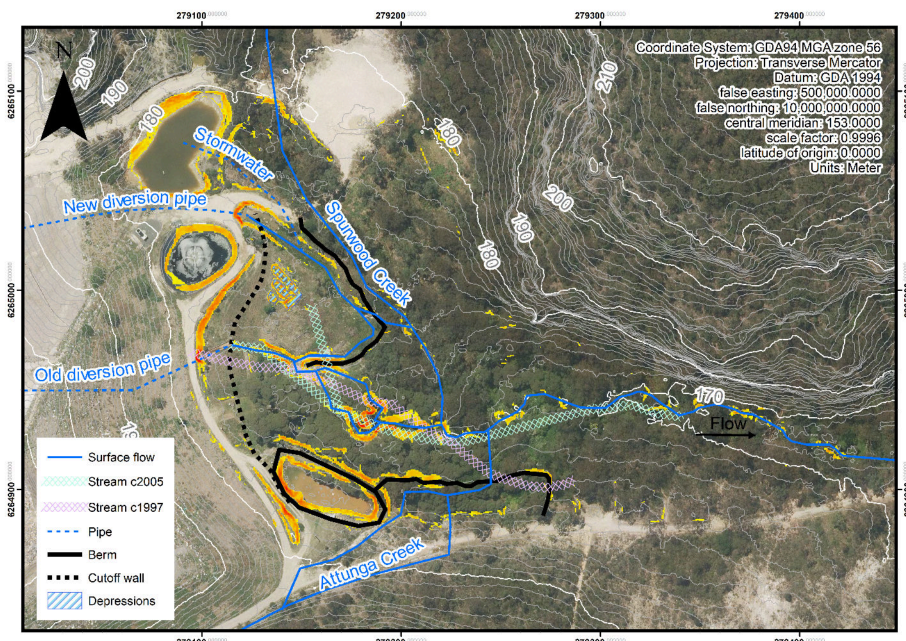


Figure 4.3: **Map of present and historical surface water flow in Main Swamp.** *Within Main Swamp, areas of steep slope are represented by a colour gradient of yellow (20°) to red (90°). Major contour lines are 10m, minor contour lines are 1m. The location of Cripple Creek circa 1997 and 2005 is based on orthorectified engineering drawings and is not exact.*

By looking at the depth of test bores, as well as the depth of the groundwater cutoff wall (the base of which is keyed into bedrock), the location of natural groundwater flows in Main Swamp can be approximated. Unsurprisingly, figure 4.4 shows that the natural flow of groundwater essentially mirrors the location of the natural surface drainage lines.

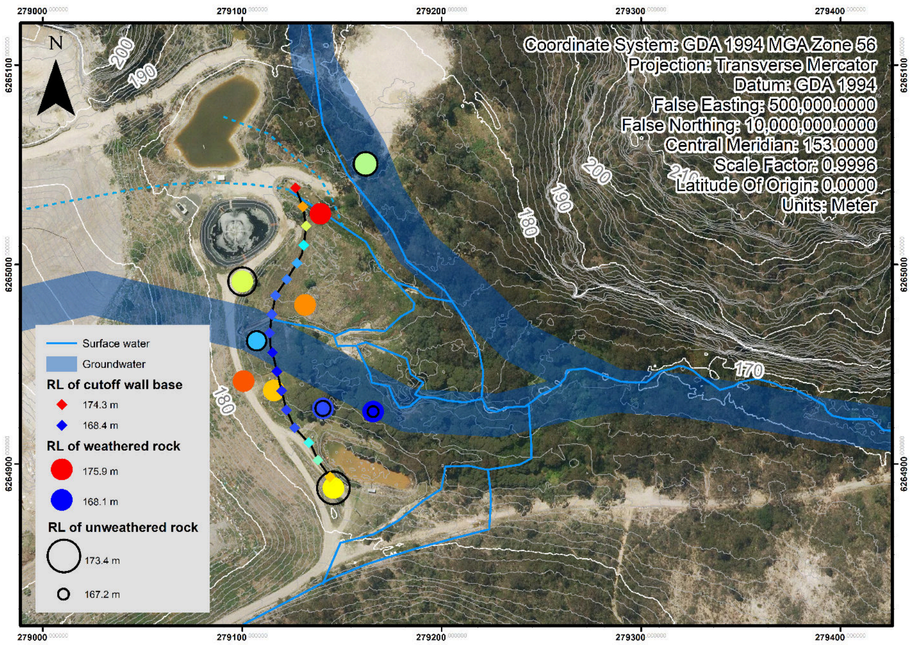


Figure 4.4: **Groundwater flow lines in Main Swamp.** *Note that the depths recorded for the cutoff wall are the depths as built, rather than the depth to bedrock. The top of the bedrock will be at least as deep as the base of the wall, but the wall is not necessarily keyed into the bedrock to the same depth at all points. 'RL' stands for 'reduced level', an engineering term for height above an arbitrary datum. The engineering documents and bore logs did not state the datum used, but it is presumably AHD.*

In the absence of the berm, the surface water discharged from the diversion pipe would flow directly into Spurwood Creek. Given this, it seems reasonable to suppose that any of the water from the diversion pipe that infiltrates into the soil moves along the groundwater flow path associated with Spurwood Creek rather than flowing up gradient to the Western end of the swamp.

The change to groundwater flow, due to the combined effects of the cutoff wall and the Northward movement of the diversion pipe, has led to a drop in the groundwater level in the Western end of the *Melaleuca* forest. In this area the watertable fell from an average of one to one and a half metres below the surface, to between three and four metres below the surface.

After this drop in the watertable, along the areas where the channel had been recorded in 1997 and 2005 (figure 4.3), several large sinkholes formed (eg. figure 4.5). The hyporheic zone of these old channels likely contained high density macropore/pipe networks formed by past ground-surface water exchanges (Boano et al. 2014). The draining of this macropore/pipe network reduced the compressive strength of the soil sufficiently to cause subsidence. Once these sinkholes had formed, high velocity surface flows during severe rain events led to their upstream and lateral extension (Blue Tongue, n.d.).

Figure 4.5: **Sinkhole in Main Swamp.** *Note the vertical banks and the mature* Melaleuca *that have collapsed into the hole. Stabilising works can be seen along the some of the bank.*

By the time this damage was noticed the holes were at least three metres deep in parts (Blue Tongue, n.d.). To halt the further expansion of this damage the berm was cut and the majority of surface water flow was diverted into the Spurwood Creek flow line. Previously, Spurwood Creek had existed as a series of minor indentations in the ground surface marked by marshy species. However the increased flow volumes necessitated the formation of a geofabric lined channel downstream of its confluence with the channel from the diversion pipe.

In the Western portion of the swamp, the worst areas of subsidence were reshaped and lined with geofabric. However, the presence of surrounding mature *Melaleuca* trees limited the degree of reshaping that was possible, and large parts of the channel are still over two metres deep with near vertical banks. In several places, further bank slumping is evident.

The stabilisation work covered an area approximately forty metres in length and ended where the two old flow lines merge in a very deep pool (figure 4.3). Exiting this pool the channel runs about ten metres before entering another wider pool, which is followed almost immediately by a third pool where a geofabric lined spout marks the confluence of Spurwood Creek with the old channel. From here the depth of the channel slowly decreases and the slope of the banks improve. At the same time, the adjacent hill pushes in and the swamp becomes narrower until it transitions into the downstream riparian zone.

In addition to the sinkholes in the Western portion of the swamp, three parallel depressions, each approximately one and half metres deep, can be seen in the Northwestern portion of Main Swamp (figure 4.3). While it is possible that these are also sinkholes, they are formed on clayey sand, rather than peat (Douglas Partners 2004), and are not above a groundwater or surface water flow line. It is more likely that these were formed during the construction of the cutoff wall.

That the formation of sinkholes appears to have been limited to the Western (up gradient) portion of the swamp points to the maintenance of the watertable in the Eastern portion of the swamp. Since the confluence of Spurwood Creek with the old channel marks the Eastern boundary of sinkhole development as well as the point where small quantities of baseflow appear in the channel, it appears that groundwater moving through the flow line underneath Spurwood Creek is sufficient to maintain the watertable in the Eastern portion of the swamp, despite the overall reduction in groundwater flow due to the cutoff wall.

The confluence of Spurwood Creek and the old channel is between two and three and half metres above the three monitoring bores in the Western portion of the swamp[1]. These three bores had an average groundwater level of just over one metre below the surface before the installation of the groundwater cutoff wall. Since the installation, they have seen a drop in average standing water level of between two and three metres, bringing it approximately level with the watertable of Spurwood Creek. It would seem, then, that the groundwater level throughout the entire swamp is now essentially controlled by the flow of groundwater beneath Spurwood Creek.

Loss of material from Main Swamp

A rough estimation shows that the channelisation of Main Swamp has led to the loss of over 1000 cubic metres of soil[2]. However, this quantity is probably dwarfed by the quantity lost as a result of oxidation.

Figure 4.6, based on data from swamps in the Upper Blue Mountains, shows the likely magnitude of increased carbon export since Main Swamp was channelised. The channelised swamps measured by Cowley et al. (2018) were losing up to 2% of their carbon stocks each year compared to less than 0.05% for the intact swamps. If we assume that the carbon export from the intact swamps is at equilibrium with carbon additions, we can use this data with a simple model for the rate of carbon loss from channelised swamps:

$$C_t = C_{initial} \times (1 - e)^t + a \times t$$

Where C_t is the carbon stock of the swamp at time t, $C_{initial}$ is the initial carbon stock of the swamp, e is the annual rate of carbon export and a is the annual carbon addition to the swamp.

[1] Note that these bores are not shown in figure 4.4 because their bore logs were not sufficiently detailed to be able to determine the depth of bedrock.

[2] Upstream of the confluence with Spurwood Creek: $180 \times 3 \times 2m = 1080m^3$; Downstream of the confluence with Spurwood Creek: $200 \times 2 \times 1m = 400m^3$

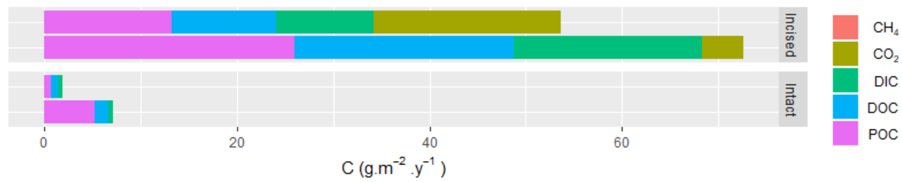


Figure 4.6: **Total annual carbon export from incised and intact swamps.** Export estimates are from Table 3 of Cowley et al. (2018).

Figure 4.7 shows the modelled rates of carbon loss from Upper Blue Mountains swamps using the minimum, average and maximum rate of carbon export and carbon addition reported by Cowley et al. (2018). Although a very simplistic model, figure 4.7 demonstrates that, for reasonable values of carbon export and addition, the rate of export determines the speed of the process, whereas the rate of addition determines the point at which equilibrium is re-established. Further, since carbon is lost at an exponential rate, the first several decades after channelisation are critical to saving a swamp.

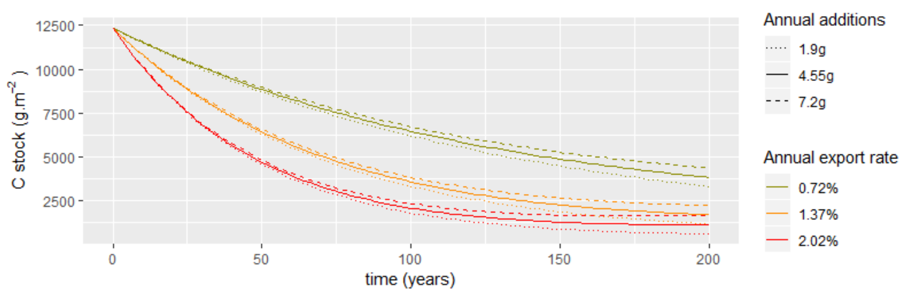


Figure 4.7: *Modelled carbon loss from incised swamps given varying rates of carbon loss and addition*

In the worst case scenario from Cowley et al. (2018) almost a quarter of the initial carbon stock is lost in each of the first two decades after channelisation. Given that Cowley et al. (2018) found that export peaked in the warmer months, and summer in the Lower Blue Mountains is substantially warmer than the Upper Blue Mountains, the loss of carbon from the BWMF swamps may well be occurring at an even faster rate than the maximum rate found by Cowley et al. (2018). If this is the case, then Main Swamp may have already lost a quarter of its initial carbon stock and is at risk of losing a similar amount in the coming decade if channelisation is not addressed.

The incised section of Winnicoopa Creek provides a stark demonstration of what will occur if the loss of peat in Main Swamp is not halted. The swamp vegetation communities have been entirely replaced by a combination of Bench Woodland and weeds, while the peat has been replaced with clayey sands (figure 4.8).

Figure 4.8: **Vertical bank of Winnicoopa Creek cut into clayey sands.** Gleichenia dicarpa *is colonising the talus slope at the toe of the bank. The wetting front of recent rain is clearly visible.*

4.2.3 Hydrological conditions

Main Swamp surface flow

The catchment of Main Swamp can be divided into four sub-catchments (figure 4.9) corresponding to the four drainage lines flowing into Main Swamp (figure 4.3). Railway catchment can be further divided into two subcatchments, one large sub-catchment draining the bushland slopes and another smaller sub-catchment draining parts of the BWMF operational area. Unfortunately, further field work is required to ground truth the various constructed drainage lines within the operational area making mapping of the boundaries of these smaller sub-catchments impossible at this stage.

While water from the Spurwood, Railway and Internal catchments all enter Main Swamp from the North, the Attunga catchment enters from the South (figure 4.3). This water originates from the industrial area to the West of BWMF and flows down a rock drain along the side of a dirt road running along the Southern Edge of the operational area. Just East of the operational area, a ridge in the road prevents the further Eastward flow of this water. This forces the channel to cross the road where it enters the Southern edge of the swamp.

At some point a second berm was constructed to hold this flow from Attunga Creek. This berm has been undermined by subsurface erosion and a hole has formed allowing water to pass over it. North of the berm, this water moves over the swamp as unchannelised surface flow until it reaches the channel. Areas of headwall retreat are evident at several points where this surface flow enters the channel.

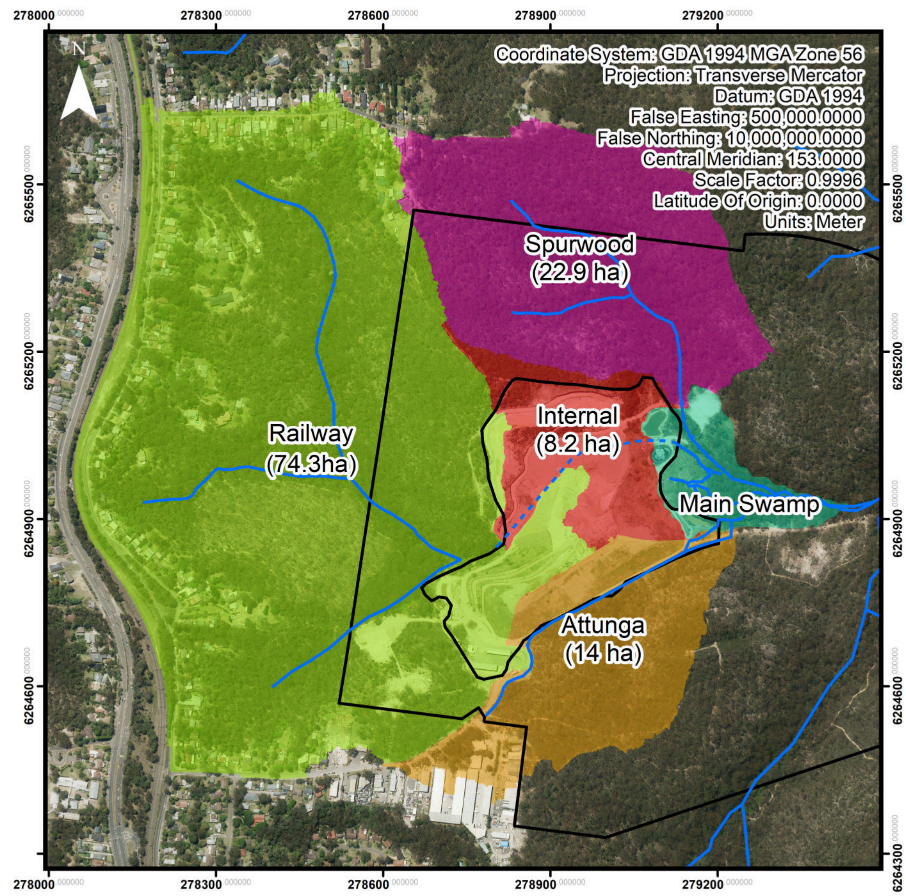


Figure 4.9: **Catchments feeding Main Swamp.** *Except for the internal catchment, catchments are named for the street that runs along their outer bounds. These names correspond to the creek names in figure 4.3 except for the internal catchment which is labelled as 'stormwater'.*

During high flow events, Attunga Creek splits in two and a second channel takes a separate path into the Southern edge of the swamp. During such events, despite the hole, the area enclosed by the berm fills to a depth of ten to twenty centimetres above the surface.

Due to the ongoing drought, the discharge of only a single rain event has been able to be measured (Table 1). This event lasted 4 days and resulted in 122mm of precipitation. Rain fell as fairly constant drizzle over the entire period rather than as intense bursts. Although it could not be directly measured, visual inspection of flow lines in both Attunga and Railway catchments showed that the vast majority of surface flow coming from these catchments originated from non-vegetated areas.

Table 1: Estimated discharge ($l.s^{-1}$) into and out of Main Swamp during a single rain event. *Discharge calculated using area slope method (Ladson 2008). Values for Manning's n were estimated using the method from Witheridge (2003).*

Date	Attunga	Internal	Railway	Spurwood	**Total**	Output
17/09/19	3.2	*no data*	2.7	0	**5.9**	4.7
	54%		46%	0%	*100%*	80%
18/09/19	0.83	0.08	1.5	0	**2.41**	2.8
	34%	3%	62%	0%	*100%*	116%

Despite only representing a single rain event, it is nevertheless clear from this small amount of data that the relatively small cleared areas of the catchment made a disproportionate contribution to surface flow. In fact, the total absence of runoff from Spurwood catchment suggests that in this rain event, the vegetated areas of the catchment had a runoff coefficient close to zero. It is not clear from this data how much rain would be required to lift this coefficient. Given the moderately deep, sandy soils developed on the bench geology of the region (section 2.3), infiltration excess runoff is only likely to occur during very intense rainfall while saturation excess runoff is likely to be attenuated by the moderately deep zones of soil immediately beneath scarps (figure 2.6).

Because of the different runoff coefficients demonstrated in the discharge data, it is likely that the catchment has two broad hydrological response types. The first response occurs during low-moderate rainfall and is seen in the discharge data above. Almost all runoff comes from the small areas of cleared land. Because these areas have a runoff coefficient close to one, runoff from these areas will approximate a linear function of precipitation.

The second response type occurs during very intense rainfall or where the soil of the vegetated areas has been saturated by an extended wet period creating either infiltration- or saturation-excess runoff. Because these areas are starting from a runoff coefficient of close to zero, their response to precipitation will approximate an exponential function. This means that every additional millimetre of rain will generate more litres per second of runoff than the previous millimetre did.

Although a fuller discharge record will be required to distinguish these two response types, given that the 122mm event recorded above only generated the first response type, it is likely that the second response type is rare. Nevertheless, the second response type is likely to be particularly important in doing geomorphological work throughout the catchment, and in maintaining an ecologically important disturbance regime (Fryirs and Brierley 2013).

Winnicoopa Creek

Except for the furthest downstream portion, most of Winnicoopa Creek is in reasonable hydrological condition. For most of its length, the flow line is marked by a series of shallow discontinuous channels. These channels appear to be geomorphologically active with degradation being mostly balanced by aggradation. Large woody debris, leaf litter, roots and herbaceous plants seem to be able to successfully block the downstream end of channels initiating repair processes.

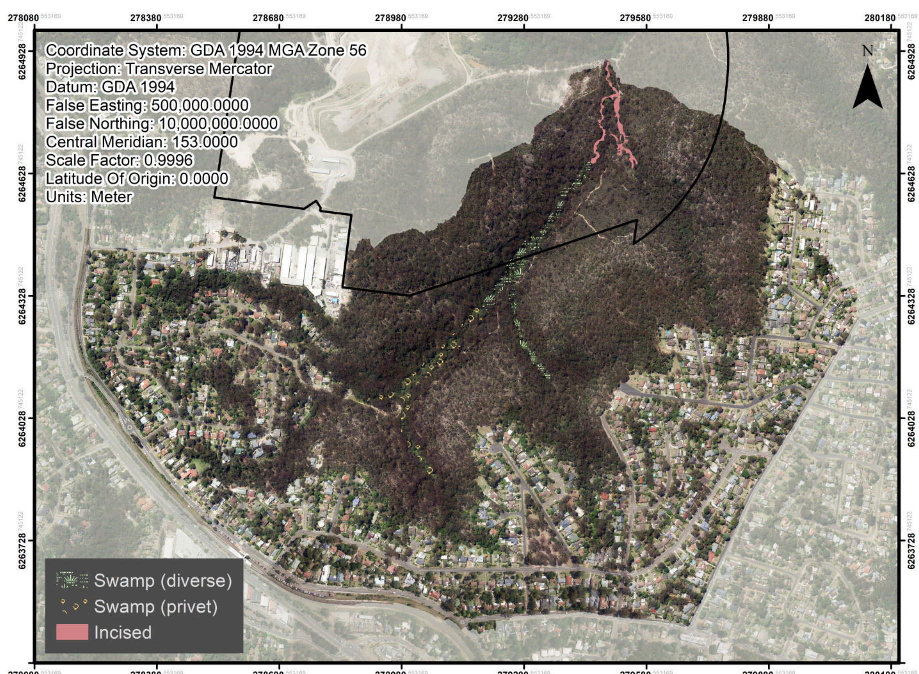


Figure 4.10: **Three zones of Winnicoopa Creek.** *The upstream end is in reasonable hydrological condition but has a high weed burden. The hydrological condition deteriorates along the length of the middle section, however the weed burden reduces substantially. The downstream section, scarred by past sand mining, is deeply incised, geomorphologically unstable, and is completely lacking in peat or swamp forest.*

The lower section of Winnicoopa Creek contains remnants of past sand mining. In this portion of the valley all peaty substrate has been lost and the channel is instead cut into deep clayey sands (figure 4.8). The channel in this section of the valley appears to be highly unstable with vertical banks on the outside edge of meanders and stepped alluvial benches lacking any vegetation older than a decade on the inside. This geomorphologically active area (labelled as 'incised' in figure 4.10) is approximately half a hectare in size, although this is likely an underestimate as it only counts the immediately eroding area, and not areas that were previously active but are now benches.

This unstable area extends a short distance past the confluence of Winnicoopa Creek with Cripple Creek. Here an area of about 800m^2 has been recently removed and then redeposited with an alluvial bench which is vegetated by a thick stand of *Ligustrum sinense* (narrow leaf privet) with no individuals more than a few years old.

The downstream portion of the 'swamp (diverse)' area (immediately upstream of the incised area) is more deeply channelised than the rest of the 'swamp (diverse)' area. However despite these channels being close to two metres deep at their maximum, large woody debris and other litter has effectively dammed the channel at multiple points creating a series of pools. Without any longitudinal observations, it is unclear whether this zone between the shallow discontinuous upstream channels and the deep incised downstream channel represents an upstream moving zone of degradation or a downstream moving zone of aggradation. However, the precautionary principle as well as evidence from swamps on the Woronora Plateau (Tomkins and Humphreys 2006), suggest that it is better to treat them as zones of degradation.

Groundwater

As has been noted in other Blue Mountains valley floor swamps, once a swamp becomes channelised, its ability to provide a consistent baseflow to downstream is compromised due to a lower and more variable watertable within the swamp (Cowley, Fryirs, and Hose 2018). This fits with the work of Fryirs, Gough, and Hose (2014) (described in section 3.2.3) which emphasised the importance of the water stored in the phreatic zone of the wider catchment in maintaining steady watertables within swamps.

A channel within a swamp acts as a zone of essentially infinite hydraulic conductivity, allowing groundwater from the catchment to bypass the low conductivity peat. This prevents the swamp as acting like a plug for the surrounding valley's groundwater. Without an intact swamp the speed of groundwater movement within the catchment is then limited not by low conductivity peat but by the high conductivity sands of the surrounding soils. This leads to much faster draining of the surrounding catchment.

The faster draining of the catchment leads to a drying of the swamp leading to further channelisation. This positive feedback loop may partly explain why valley fill swamps seem to experience rapid cut events, but slow re-filling (see section 3.7.2). Preventing further channelisation and reversing existing channelisation of swamps will slow groundwater movement within the Cripple Creek catchment and improve the resilience of its swamps.

4.3 Ecosystem composition and structure

4.3.1 Flora

Main Swamp

A formal vegetation survey of Main Swamp has yet to be conducted. The following is based on an initial qualitative survey of the area.

Main Swamp consists of a stand of low closed *Melaleuca linariifolia* forest surrounding the original flow line of Cripple Creek (figure 4.11). Due to the subsidence and erosion in the Western end of this stand, many mature *Melaleuca* have collapsed over the last decade. This has opened up the canopy of this part of the stand, allowing more light through to the understorey.

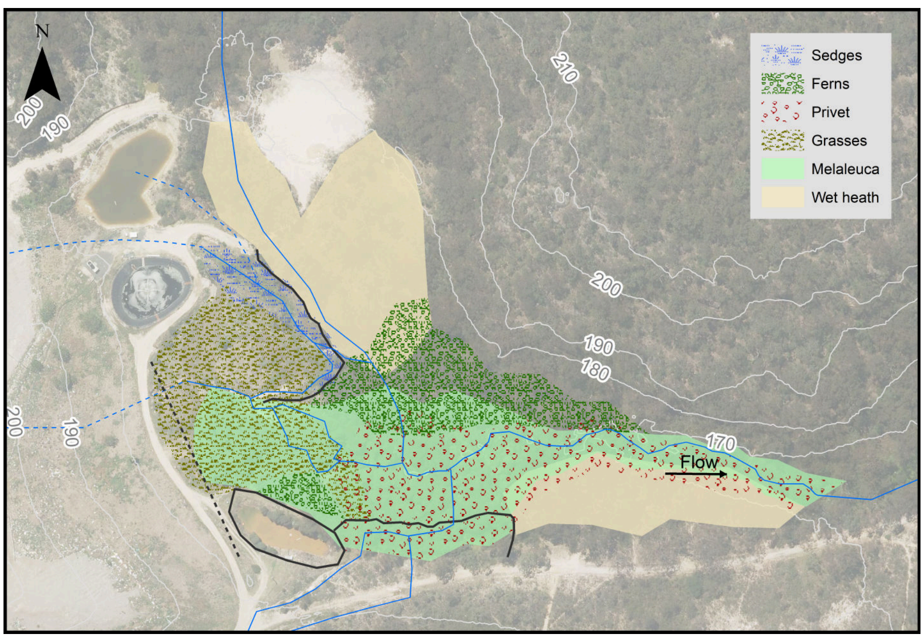


Figure 4.11: **Vegetation zones in Main Swamp.** *Boundaries are approximate.*

The *Melaleuca* forest does not continue up the Spurwood Creek drainage line. Historical areal photographs show that before the installation of the cutoff wall, a dense canopy of an unidentified (non-*Melaleuca*) tree was growing directly surrounding Spurwood Creek. No evidence of this tree is now visible and it is not clear what occurred to cause its disappearance. From their position within Main Swamp, it appears likely that the trees were adversely effected by either regular inundation or sedimentation from the upstream diversion pipe, rather than by any lowering of the watertable due to the cutoff wall.

The Spurwood Creek drainage line is now covered by an open wet heath community. For most of its length, this heath is underlain by a mixture of grasses and sedges. Just upstream of the confluence with the old Cripple Creek channel, the herbaceous layer changes to one dominated by a diversity of ferns. This heath and fern community become a dry heath underlain by *Pteridium esculentum* (bracken) as it transitions into the understorey of the *Corymbia* woodland of the neighbouring slope. In the other direction, as it moves towards the old main channel, the heath becomes wetter with an open overstorey of *Eucalyptus sclerophylla* (scribbly gum) and *Angophora* and then *M. linariifolia*. At the same time, the herbaceous stratum becomes increasingly dominated by *Gleichenia dicarpa* (tangle fern).

The natural shape of Main Swamp is more complex than the simplified toposequence developed by Keith and Myerscough (1993), due to the convergence of Spurwood Creek with Cripple Creek. Nevertheless, the general spatial pattern sketched in section 3.4.2 appears to hold. Ti-tree thicket (a closed canopy of *M. linariifolia*) follows the original drainage line. In parts, this is surrounded by wet heath species which then grade into surrounding eucalypt woodland.

Conspicuous by its absence from Main Swamp is Cyperoid heath (*M. citrina* over sedges) between the Ti-tree thicket and surrounding wet heath communities. The closest analogue to Cyperoid heath is a thicket of *Acacia spp.* that has formed along part of the berm.

After over a decade of weed removal efforts, the Western area of the swamp forest is mostly clear of woody weeds, although there remains a dense understorey of *Ligustrum sinense* (narrow leaf privet) in the Eastern end of the swamp. These woody weeds seem to only be able to survive within swampy or riparian areas and have entirely failed to invade surrounding *Corymbia* or *Eucalyptus* woodlands.

Research on the spread of *L. sinense* suggests that this is due to a combination of factors. Hagan et al. (2014) found that where bushland was in its climax state, with resources utilised to their maximal capacity, the bush was resistant to invasion. Similarly, King and Buckney (2000) found that the addition of nutrient-laden urban runoff to Sydney bushland was a strong predictor of weed invasion. Interestingly, they found that, despite the famously low phosphorous soils of the Sydney region, the alleviation of aluminium toxicity was a stronger predictor of weediness than was the addition of phosphorus.

Interestingly, Mitchell, Lockaby, and Brantley (2011) found that once *L. sinense* successfully invaded an area, it increased the rate of nutrient cycling raising the pH and nutrient status of the soil. This ecosystem engineering constructs a niche resulting in the continued dominance of *L. sinense* and the exclusion of native species. This means that even after the successful removal of *L. sinense*, the soil will take time, probably many years, to revert back to a state that favours natives over *L. sinense*. Perhaps because of this, where the *L. sinense* shrub stratum of the *Melaleuca* forest has been removed it has not been replaced by native shrub species, but by exotic grasses and forbs.

A large number of *Melaleuca linariifolia*, as well as a smaller number of *Melaleuca styphelioides*, have been planted in the open grassy area in the Northeast of Main Swamp. While the *M. styphelioides* have grown fairly well, the *M. linariifolia* have grown much more slowly. This is unsurprising since both the location of surface flow lines as well as test bores drilled in the area suggest that this region of Main Swamp is naturally much less swampy than the area surrounding the surface flow lines (figure 4.4). Because of this, grasses and forbs adapted to well drained soils have out-competed *M. linariifolia* (Virtue 1999).

A scrambling legume bearing a resemblance to vetch is dominant or co-dominant over most of the grassy area. This, as well as the *Acacia spp.* thicket, suggests that nitrogen is a more limiting nutrient than phosphorous within the swamp (White 2006). This would be consistent with numerous agronomic studies of *Melaleuca* plantations grown in swampy conditions that have found nitrogen to be the most limiting nutrient (Virtue 1999).

Main swamp catchment

Upstream of Main Swamp, Spurwood Creek hosts a diverse wet heath community along a shallow discontinuous channel, while Railway Creek hosts a monoculture of *Gleichenia dicarpa* (tangle fern) along the main drainage line and a monoculture of *Schoenus melanostachys* (Black bog-rush) along a secondary drainage line.

Winnicoopa Creek

An open to closed forest of *Melaleuca linariifolia* surrounds Winnicoopa Creek everywhere upstream of the area labelled as ‘incised’ in figure 4.10. This forest can be roughly divided into two sections. In the upstream section the understorey is dominated by a shrub stratum of mature *Ligustrum sinense* (narrow leaf privet) while the ground is carpeted with *L. sinense* seedlings mixed with *Zantedeschia aethiopica* (calla lily). The downstream section also contains *L. sinense* and *Z. aethiopica* but at much lower densities. Instead the shrub stratum contains *Melaleuca citrina* (crimson bottlebrush), *Callicoma serratifolia* (black wattle) and *Acacia spp.* while the herbaceous stratum contains a sparse mixture of ferns and sedges.

In both the upstream and downstream sections (though not the incised section), wet heath communities fill the ecotone between the drainage line and surrounding eucalypt woodland. However, like Main Swamp, Winnicoopa Swamp appears to be missing the Cyperoid heath community between the Ti-tree thicket and wet heath communities. Although in Winnicoopa Swamp, a reduced form

Figure 4.12: **Vegetation along (a) upstream and (b) downstream Winnicoopa Creek.** ***(a)*** *Mature* Ligustrum sinense *trunk in the foreground. Carpet of* L. sinense *and* Zantedeschia aethiopica *cover the ground.* M. linariifolia *trunks in background.* ***(b)*** Calochlaena dubia *and* Gahnia clarkei *on the ground with* M. linariifolia *behind.*

of this community exists as *M. citrina* shrubs underneath the central *M. linariifolia* canopy. This simplification of the toposequence may be due to some combination of disturbance and reduced throughflow inputs from surrounding Bench Woodland due to the channelisation of the incised area of Winnicoopa Creek.

4.3.2 Fauna

No fauna survey of either Main Swamp or Winnicoopa Creek has been conducted so far. Nevertheless, it is possible to say that a wide variety of small and medium sized birds frequent Main Swamp, especially in areas where the thick *Ligustrum sinense* (narrow leaf privet) undergrowth has yet to be cleared. An area of eroded bank has an abundance of native bee nest holes while small burrows, probably constructed by rodents or small marsupials, are abundant throughout both Main Swamp as well as the downstream portion of Spurwood Swamp (figure 4.13). A single large burrow, possibly built by a wombat, is evident on the edge of Spurwood Creek, however no wombat scats are evident in the vicinity.

A family of wild dogs/dingos inhabited the Cripple Creek catchment until their unfortunate recent removal due to safety concerns. Foxes are abundant within the catchment (personal observation) while cats, both domestic and feral, are likely to be similarly common. The abundance and hunting success of these meso-predators may increase now that dingos have been removed (see

Figure 4.13: **Small mammal burrows in a berm in Main Swamp.**

section 3.4.3). Any increase in predation pressure is likely to have a disproportionate impact on smaller mammals and birds.

Blaxland mentions having witnessed an eagle kill a kangaroo somewhere close to or in the present town of Blaxland (Richards 1979), while Warrimoo, the name of the neighbouring town, is thought to be based on the Darkiñung word for eagle (Searle 1977). However eagles, and indeed all birds of prey other than owls, are conspicuous by their absence in animal sightings from the mid-Twentieth century onwards (see figure 3.3). This loss may be due to some combination of the loss of open grassy areas used for hunting, the loss of large old trees suitable for nesting (due to both development on the ridges as well as logging in the valleys), and/or active hunting by humans (Leopole and Wolfe 1970).

An ongoing baiting programme targeting introduced rodents around the landfill is likely to also negatively effect a range of native mammals, especially rodents. Secondary impacts on predators such as owls or snakes are also possible.

Red bellied black snakes are likely to be the dominant reptilian predator of vertebrates in the swamps (Talalaj 2013; BMCC 1985). Interestingly, cats appear to be immune to black snake venom (Talalaj 2013), and are probably the major predator of this snake (Whitaker and Shine 2000). Unfortunately, humans are likely to be an even greater cause of mortality in areas such as BWMF at the urban-bush interface (Whitaker and Shine 2000).

4.4 Ecosystem function

4.4.1 Faunal habitat and interactions

The lack of a dense herbaceous stratum in both Main Swamp and Winnicoopa Swamp have reduced the potential habitat for both small mammals and larger macropods. The importance of this habitat is confirmed by the presence of Swamp wallabies in Railway catchment, where areas of thick *Gleichenia dicarpa* (tangle fern) and *Schoenus melanostachys* (black bog rush) provide good shelter, and their absence from Main Swamp. This reduced mammal abundance would have flow on effects both up and down the food chain with less prey available for larger predators as well as reduced insect, fungi and plant consumption by the mammals themselves.

Elsewhere in the Blue Mountains, Swamp Wallabies have been observed eating *Ligustrum sinense* (narrow leaf privet, Williams et al. 2001). This herbivory may give areas with large populations of swamp wallabies some resistance to invasion from *L. sinense*. Along with the effects of allelopathy and nutrient competition, this may explain why Warrimoo Swamp has remained immune to invasion by *L. sinense* despite a constant flow of propagules from both birds as well as in runoff from surrounding residential areas. As such, re-establishing swamp wallaby habitat should be a restoration priority.

4.4.2 Productivity and nutrient cycling

While the secondary metabolites in *Melaleuca* leaf litter retard the biodegradation of leaf litter of co-occurring species, *Ligustrum sinense* (narrow leaf privet) does the opposite. Its low C:N ratio facilitates the breakdown of other, more resistant litter (Mitchell, Lockaby, and Brantley 2011; Hagan et al. 2014). This speeds up the nutrient cycle making the environment more conducive to the further growth of *L. sinense* and other weed species. Evidence for the effectiveness of this niche construction is the absence of nitrogen-fixing *Acacia* in areas with *L. sinense*[3].

The faster cycling of nutrients not only creates a positive feedback favouring the growth of weed species, but also inhibits the formation of peat, hummock formation and the repair of channels through the build-up of litter in small logjam dams. The removal of *L. sinense* should, therefore, be seen not merely as a necessity for improved ecosystem composition, but also as necessary for restoring geophysical condition and ecological functioning.

4.4.3 Resilience

The swamps of the Cripple Creek catchment appear to have two stable ecosystem states each controlled by positive feedback cycles. In the natural state exemplified by Warrimoo Swamp, *Melaleuca linariifolia* slows nutrient cycling, promoting peat formation, channel aggradation and creating niches for slow growing sedges and ferns. These in turn produce allelopathic substances and provide habitat for herbivores which together with the low pH and low nutrient environment successfully excludes fast growing weeds.

[3] Elevated pH and nutrient levels are clearly not due solely to faster nutrient cycling. Nutrient levels in the upstream section of Winnicoopa Swamp are primarily governed by runon from surrounding urban areas. However, the incised area at the base of Winnicoopa Creek, a significant distance from any urban areas, also has a large stand of privet, without any *Acacia*. The nutrient levels in this areas are likely more closely controlled by *in situ* nutrient cycling than *ex situ* inputs.

A second stable ecosystem state occurs where an area become infested with *Ligustrum sinense* (narrow leaf privet). This speeds up nutrient cycling, reduces or reverses peat formation, and promotes channel degradation. By raising pH which reduces aluminium toxicity and increases nutrient levels it removes the niche for slow growing ferns and sedges, removing competitors and reducing herbivore habitat. This creates an environment favourable to the further flourishing of weed species. This state can be seen in the upstream section of Winnicoopa Swamp and the Eastern section of Main Swamp.

The transition from the intact state to the impaired state seems to be primarily due to the input of nutrients from an external source (landfill leachate in Main Swamp and urban runoff in Winnicoopa Swamp). Successful return to the intact state will require both the removal of the external forcing as well as the removal of *L. sinense*. However, even once both of these are achieved, returning to the resilient intact state will require time as soil pH and nutrient levels will remain high until the existing stock of basicity and nutrients is either immobilised *in situ* or exported off site.

Some restoration schemes have used active biomass removal to reduce nutrient levels (Marrs 2002). At present, *L. sinense* branches are being piled up in Main Swamp to produce habitat mounds. These appear to be well used by small birds. It is not clear whether the nutrient reduction benefits of removing these branches would outweigh the habitat value they provide.

4.5 External exchanges

4.5.1 Landscape flows

The flow of water, sediment and nutrients have all been altered in both Main Swamp and Winnicoopa Swamp. Development in both catchments has released up-gradient sediment. In Main Swamp more than thirty centimetres of this post invasion alluvium has collected above the peat in the Western end of the swamp. This aggradation may have contributed to the geomorphological instability of this part of the swamp. Similar, smaller deposits are present in the area of Winnicoopa Swamp directly down-gradient of Winnicoopa Road. An initial survey of the banks of down stream Cripple Creek has not found any other areas of bank deposition.

Along its entire length, the bed of Cripple Creek is covered in thick slugs of clean coarse sand. The presumed major sources of this sand are cleared areas of the catchment, especially areas of the BWMF operational facility, historical sand mining along Winnicoopa Creek, ongoing bank erosion in the incised section of Winnicoopa Creek, and sheet and rill erosion of the paths and fire trail along Cripple Creek. This coarse mobile bed load has caused undercutting of the bank in multiple locations.

The finer peaty sediments lost during channelisation of the swamps appears to have been lost to further downstream, possibly settling out in the Nepean. The aromatic nature of the peat-derived dissolved organic matter means that it was likely lost directly to aquatic microbial respiration rather than cycled through microbial biomass (Fasching et al. 2015).

Since the installation of the groundwater cutoff wall stopped the flow of leachate into Main Swamp, incoming nutrients are now likely to be primarily derived from surrounding urban areas (via Attunga Creek) as well as surface runoff from the operational area of BWMF. Similarly, the major source of incoming nutrients in Winnicoopa Swamp is surface flow from urban runoff.

4.5.2 Gene flow

Although small mammals are clearly present in Main Swamp, their numbers, and likely diversity, are significantly reduced due to a lack of habitat, poison baits targeting introduced rodents and predation from foxes[4] and cats (Kinnear, Sumner, and Onus 2002). Similarly, while swamp wallabies exist within BWMF, they are at a much lower density than in Warrimoo Swamp. This reduced abundance and diversity of swamp dependent mycophagous mammals may have reduced the movement of ecto-mycorrhizal fungi not only within the swampy areas of BWMF, but within the surrounding eucalypt forests as well.

Zantedeschia aethiopica (arum lily) - a weed in Winnicoopa Swamp - has only recently become an important weed of riparian and swampy areas in NSW (Scott 2012). It spreads primarily by rhizome expansion, with each plant able to produce more than fifty daughter rhizomes each year (Scott 2012). Because of its ability to re-sprout, treatment with herbicide is generally ineffective, while cultural management is possible but requires multiple treatments to remove all rhizomes. Various micro-organisms have been suggested as potential biological controls, however none have so far been developed commercially (Scott 2012).

Z. aethiopica also reproduces sexually with seed distribution probably enabled by a combination of water and animals (Scott 2012). Fortunately these seeds are only viable for a short period of time so do not build up a persistent soil seed bank. (Scott 2012). Because the spread of *Z. aethiopica* is relatively slow, its potential to spread into undisturbed swamp is not yet clear (Scott 2012). However, given the enormous damage *Z. aethiopica* has caused in parts of Western Australia and South Australia where it has been naturalised for a longer period of time (Scott 2012, personal observation), a precautionary attitude should be adopted to its elimination within the Cripple Creek catchment.

Ligustrum sinense (narrow leaf privet) produces an abundance of small fruit which are spread by both water and animals (Grove and Clarkson 2005). Like *Z. aethiopica* it does not form a persistent soil seed bank (Klock 2009). This

[4] In a predator removal experiment, Banks (1999) found that foxes did not effect the abundance of native rodents, but rather consumed 'the doomed surplus'. However, other studies have found significant impacts on macropod, reptile and bird abundance (Saunders, Gentle, and Dickman 2010).

means that for invasion to be successful, it requires constant re-introduction into an area until a period of favourable conditions occur. However, once established within an area, it can quickly expand asexually through underground clonal growth (Grove and Clarkson 2005). This allows an infestation to expand even when conditions necessary for seedling growth do not occur.

Many endemic sedges and ferns are also clonal. However, unlike *L. sinense* do not produce abundant propagules (Barrett 2013). This makes them slow to re-invade a disturbed area. Initial plantings of these functionally important species will likely be required after weed removal to prevent weed re-colonisation.

4.6 Disturbance regime

Bore logs from Main Swamp record gravely basal sediments below alternating layers of finer and courser sediments (Douglas Partners 2004). This follows the pattern observed in other valley fill swamps in the Sydney region (see section 3.7.1), suggesting that the swamp has been formed through multiple cut and fill events. The Northern end of Main Swamp also contains thick clay horizons. As previously discussed, this may be due to either an ancient lacustrine environment or to *in situ* weathering of either igneous rock or a shale lens.

Figure 4.14 shows the recorded fire boundaries from the NSW National Parks and Wildlife Service fire database. Since 1977, Warrimoo Swamp catchment has had one recorded wildfire and two very small prescribed burns, covering a total of 125 hectares. Over the same time period, despite being only two thirds the size of the Warrimoo Swamp catchment, BWMF has had two wildfires and seven prescribed burns within its boundaries, covering a total of 193 hectares. This higher frequency may have opened up the vegetation to weed invasion and soil erosion.

Warrimoo swamp has remained intact, both geomorphologically and ecologically, despite being disturbed by fire. By contrast both Winnicoopa Swamp and Main Swamp have suffered various degrees of geomorphological and ecological degradation. However, the context in which these fires have occurred has been quite different. Both Winnicoopa Swamp and Main Swamp have been subjected to ongoing non-fire disturbances while Warrimoo Swamp has not. This pattern supports the suggestion by Tomkins and Humphreys (2005) that two or more near-simultaneous disturbances are required to degrade swamps in the Sydney region.

In Winnicoopa swamp the ongoing impacts of sand mining continue to destabilise the downstream area, while the related drop in base level impacts channel stability further upstream. Meanwhile, erosive forces have increased due to a peakier hydrograph from urban runoff and infestation by *Ligustrum sinense* (narrow leaf privet) has natural channel repair processes by out-competing the endemic plants of the herbaceous stratum, reducing the capture of sediment and organic matter, and decreasing the biochemical resistance of the litter layer,

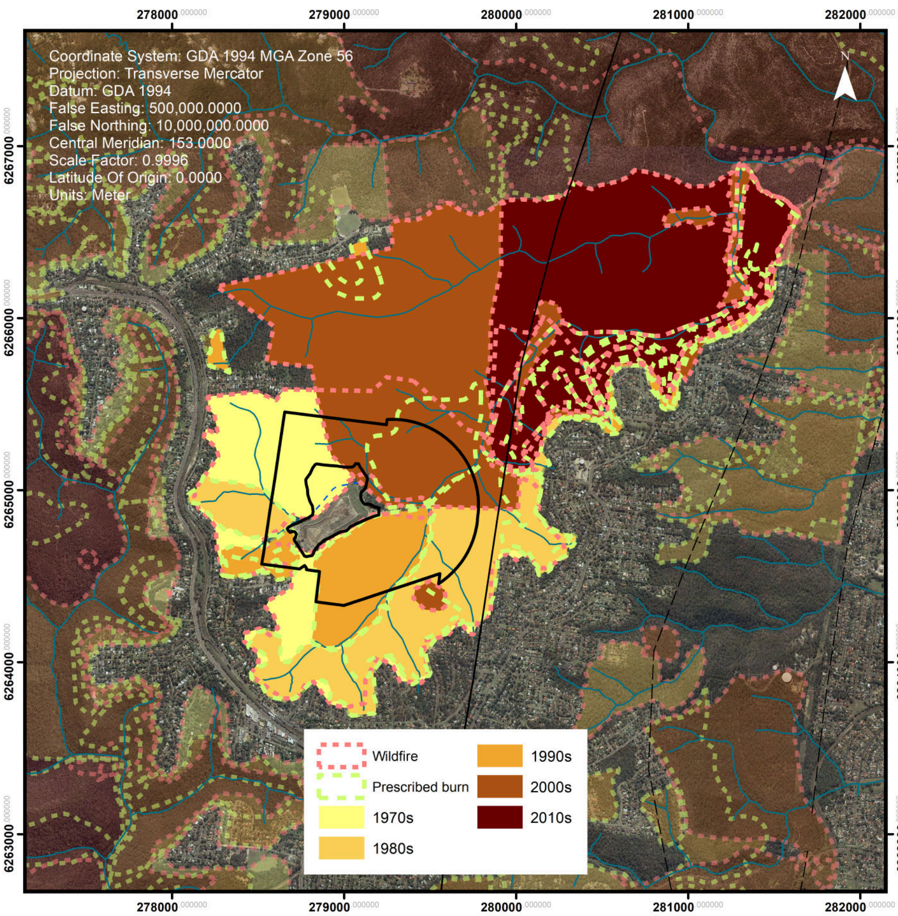


Figure 4.14: **Fire history of the Cripple Creek catchment.** *Note that where fires overlap, only the age class of the most recent fire can be seen.*

hampering peat formation.

In Main Swamp, the lowering of the watertable due to the groundwater cutoff wall and increased slope due to post invasion alluvium has particularly effected the Western section of the swamp. A peakier hydrograph due to runoff from the light industrial area in Attunga Catchment and the BWMF operational area in the Railway Catchment as well as impaired natural repair due to *L. sinense* invasion has effected most of Main Swamp.

The combined disturbances in Main Swamp and Winnicoopa Swamp appear to have primarily effected the shrub and herbaceous strata while leaving the *Melaleuca linariifolia* low tree stratum intact except in the incised area of Winnicoopa Creek, where meandering incisions have removed all swamp vegetation, and the Western portion of Main Swamp, where some large *M. linariifolia* trees have collapsed due to bank instability. Interestingly, in the middle section of Winnicoopa Swamp, areas with an intact shrub stratum almost always co-occur with areas with an intact herbaceous stratum and *vice versa*. This suggests either a facilitative impact of one stratum upon the other, or that both are similarly impaired by invasion of *L. sinense*.

5 | Restoration target and goals

The swamp ecosystems of BWMF are not only keystone areas within the Cripple Creek catchment, but also rare and special ecosystems in their own right. The swamps host significant patches of endangered Riverflat Paperbark Swamp Forest, and are made all the more valuable for their unusual geological setting. Restoring the BWMF swamps will have flow on effects to the wider catchment and will also help safeguard nearby Warrimoo swamp by improving gene flow and habitat linkages.

An analysis of the reference and intervention site models suggest that altered water, sediment and nutrient flows are the ultimate cause of much of the degradation. Improving these flows into and out of the site should be the first priority. Restoring functional hydrological and geophysical regimes will create the conditions necessary to allow the full restoration of ecosystem composition, structure and function.

Both Main Swamp and Winnicoopa Creek exist within wider hydrological and socio-cultural contexts. To be successful, the restoration project must look beyond the geographic boundary of the swamps. Embedding the project within these wider contexts will help to ensure the long term sustainability of the restoration project.

With these considerations in mind, the proposed restoration target is as follows:

> **The restoration of a hydrological and geophysical regime appropriate for a Yellow Rock Fault Swamp, leading to the medium to long term restoration of a healthy swamp ecosystem with strong links to the swamps' hydrological and socio-cultural context.**

The restoration of the hydrological and geophysical regime has three key components, one physical, one ecological and one cultural. The physical component is the installation of a variety of water slowing and nutrient trapping structures

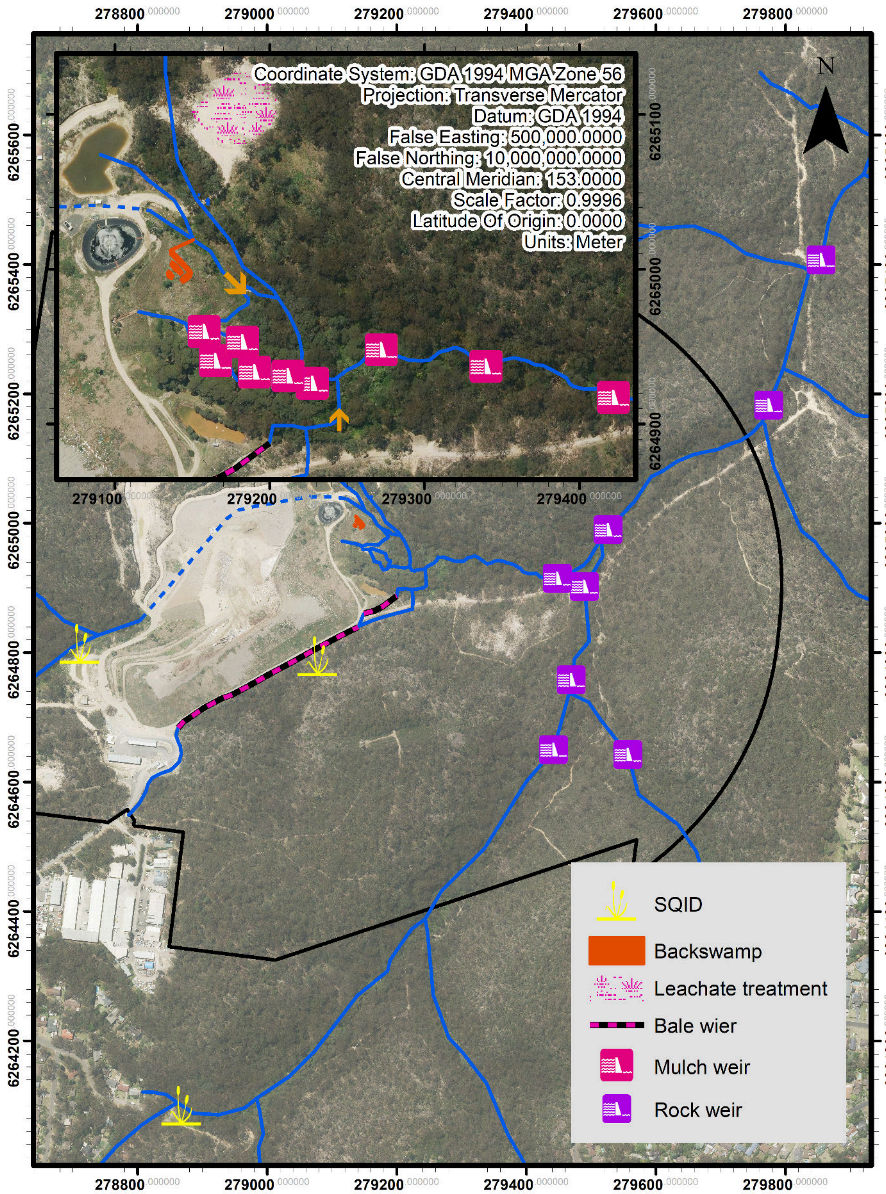


Figure 5.1: **Planned locations for built structures.** *Inset shows Main Swamp. SQID: Stormwater Quality Improvement Device.*

as shown in figure 5.1. The ecological component is the reintroduction of a functional herbaceous stratum to facilitate self-repair. The cultural component is the creation of community knowledge and care for the swamps to ensure the long term viability of the swamps.

Following the SERA (2017) standard, in what follows, the restoration target is broken down into a series of goals. Because this is a preliminary document, these goals are not yet broken down into specific objectives with measurable indicators. However, where appropriate, the reasoning for and implementation of these goals is discussed.

5.1 Human context

- **Designate the portion of Spurwood Creek within the BWMF boundary as a protected offset area** as part of the forthcoming BWMF vegetation management plan.

- **Initial contact made with management stakeholder groups** *including other branches of council, the Environmental Protection Agency, Sydney Water (managers of upstream Winnicoopa Swamp area), Deerubbin land council, National Parks and Wildlife Service, and the Rural Fire Service within nine months.

- **Initial contact made with potential funding bodies including the NSW Environmental Trust, Local Land Services, and Landcare** within one year.

- **Initial contact made with different user groups of the Cripple Creek catchment** within one year.

  Of particular note are potentially problematic users, especially mountain and dirt bikers. Although impacts from these users are not yet severe within the Cripple Creek catchment, these activities have been growing in popularity for several decades, with growth showing no signs of slowing (Burgin and Hardiman 2012; Villanueva 2019). Villanueva (2019) found that many dirt bikers are concerned about their environmental impact, suggesting that fruitful dialogue about their use of the Cripple Creek catchment is possible. Proactive management may be able to prevent problems before they occur.

- **Interpretive signage along Winnicoopa Creek, Cripple Creek and Warrimoo Swamp** within two years.

  These should describe both the cultural and ecological importance of the swamps.

- **Establishment of a local bushcare group for Winnicoopa Swamp** within two years.

There is a large body of evidence showing that restoration projects are more successful and have greater sustainability when local communities are involved in the project (Morris et al. 2013). Different levels of involvement should be made available with interpretive signage providing a low level of engagement to a wide cross-section of locals, while a bushcare group allows for deeper engagement by a smaller number of more passionate individuals.

- **Consideration given to returning an area of flat valley bottom to open grassy woodland** within five years.

  As discussed in section 3.1.2, before the British invasion, the Cripple Creek catchment probably had larger grassy areas than it does now. As well as being culturally important areas, these also would have provided food for the larger herbivores recorded by the early explorers. A discussion involving the Deerubbin land council and the rural fire service should be started to gauge interest and capability to conduct small scale cultural burns in a specified area with the intention of increasing food resources for herbivores, especially the large wallabies that shelter within the swamps.

  Consideration should also be given, in consultation with the Deerubbin land council, to other non-fire methods of opening up the area. Strategies to prevent the spread of weeds into this area would need to be developed before implementation.

5.2 Geophysical conditions

- **A series of leaky weirs are constructed to slow the movement of water and sediment through incised areas of swamp** within one year.

  Main Swamp

  A series of barriers should be constructed in the Main Swamp channel to produce a chain of pools, like those found within the middle section of Winnicoopa Swamp. A difficulty with working within the *Melaleuca* swamp forest is access for heavy machinery. Because of this constraint, the traditional approach of constructing weirs using rocks or boulders is unrealistic. An alternative, more natural approach is the use of woody material.

  Mulched tree waste should be mixed with the sediment that is currently cleared out of slit traps and detention basins around site. This silt/mulch mixture can be carted through the sensitive areas of the swamp using wheelbarrows. It should be placed in a series of mounds within the channel. During placement the mulch should be tamped down repeatedly to reduce later subsidence.

These mounds should reach to just below the top of the banks and be covered in geofabric which should be stapled into the surrounding bed, bank and ground surface to keep it in place. At the top of the mound two sheets of geofabric should be overlapped to allow for refilling following subsidence. On the downstream side, coir logs should be stapled to the geofabric to slow surface flow and direct it to the centre of the channel. The geofabric should be extended along the downstream channel bed a short distance to prevent undercutting.

Tube stock of sedges such as *Schoenus melanostachys* (black bog rush) should be planted on the upper slopes of the mounds. Once subsidence of the mounds reduces to low levels, these plantings should be extended to the top of the mounds. As well as stabilising the mounds, these plantings will help to trap sediment, woody debris and leaf litter restoring natural aggradation processes.

In the portion of the old channel before its confluence with Spurwood Creek additional mulch/sediment should be used to fill in the pools to a depth of around one metre. Because the stability of a vertical wall is inversely proportional to its height (Young and Young 1992), this will increase the stability of the banks. The absence of high flows through this part of the channel will not necessitate covering this mulch with geofabric.

Winnicoopa Creek

Several rock weirs should be installed along the area marked as incised in figure 4.10, following the pattern described in Witheridge (2010). These weirs should be installed such that the top of each weir is level or above the toe of the previous weir. This pattern reduces bank scour caused by bed load movement (Witheridge 2010). Because the channel is cut into unstable clayey sands, preference should be given to a greater number of shorter weirs rather than fewer larger structures. This will minimise the hydraulic gradient associated with any particular structure, reducing the likelihood of rerouting of the channel around the structures.

Although it will take time for swampy conditions to re-establish, *M. linariifolia* seedlings should be planted immediately following the construction of the weirs. This will allow them time to establish and fast track the production of recalcitrant organic matter. However, to prevent their large size from further destabilising banks, they should be planted at least two metres away from the banks.

As water and nutrients begin to be held back by these weirs, potential primary productivity in the surrounding area will increase. This will leave the areas vulnerable to weed (King and Buckney 2000). To preempt this, fast growing shrubs such as *Leptospermum polygalifolium* (tantoon) should be planted along the banks. These should be interplanted with slower growing climax shrubs (such as *Melaleuca citrina* (crimson bottlebrush) and *Callicoma serratifolia* (black wattle)), sedges and ferns.

In consultation with other branches of council, additional weirs could be constructed at the same time along Cripple Creek between the downstream end of BWMF and the Yellow Rock Fault (see figure 5.1). Although this land is not managed by BWMF, the damage caused to the creek in this area has been primarily caused by sand mining and landfilling activities that have occurred on BWMF land. This makes the restoration of this land, our moral responsibility.

- **Halting of upstream movement of incised area into Winnicoopa Swamp** within one year.
- **Leachate impacted groundwater is treated and returned to the old channel in the Western area of Main Swamp** within three years.

The leachate captured by the groundwater cutoff wall is sourced from cell A, the only unlined landfill cell. This cell has been closed for almost three decades. Readily leached chemicals have long since been leached. The remaining leachate, while still relatively nutrient rich, has a lower EC than the darkly stained water currently being discharged from Main Swamp into Cripple Creek.

At present, this leachate is being pumped to sewer. Fundamentally, this is not solving the pollution problem caused by the landfill, it is merely exporting it off site. Further, by exporting this pollution we also export the water carrying it, upsetting the natural hydrology of the site.

The leachate collected by the cutoff wall should be pumped to a sub-surface flow artificial wetland (based on the design of Bolton and Bolton (2013)) which should be constructed in the old night soil area (figure 5.1). The output of this should then be passively piped to the Western most edge of the *Melaleuca* forest, and discharged from the end of the old diversion pipe. From here the water will join the old channel, however the series of wood mulch mounds will sufficiently slow its downstream movement that most of it will seep into the underlying sediment.

There are three advantages of releasing it directly into the old channel rather than constructing a drainage ditch. Firstly, the wood mulch will act as a secondary filter of the treated leachate, acting as a final polishing stage. Secondly, it will keep the wood mulch permanently wet, speeding up the transformation of this into a peat-like material. And finally, it will create a series of permanent ponds which will increase the habitat for frogs and other aquatic animals.

Based on monitoring of the effectiveness of this treatment process, leachate collected from the lined landfill cells should also be added to the constructed wetland. The treatment of all leachate on site will lead to a cost saving of around $50,000 per year in trade waste disposal fees. Given that BWMF only has space to accommodate ten to fifteen more years of waste, even if on-site treatment of all leachate tuns out to be impractical at present, with the cessation of landfilling, leachate quality will improve markedly making treatment practicable.

Treating leachate on site will not only have financial and hydrological payoffs. It will also allow for the cessation of ammonia volatilisation in the leachate pond. This will stop the unintended addition of basicity to the Western end of the swamp. The return to a more natural pH will work synergistically with reductions in nutrient inputs to the swamp to lower nutrient availability within the swamp. This should make the conditions within the swamp less conducive to weed growth.

Once all leachate is treated on site, the Main Dam (a holding pond for leachate before it is pumped to sewer) should be converted to a detention basin for Attunga Creek. This should be used to harvest water during large flow events. This water should then be slowly released to provide a steady inflow of water to the swamp, mimicking the natural role of throughflow.

- **Infiltration of most runon from Attunga catchment within Main Swamp** within two years.

  At present, discharge from Attunga catchment enters Main Swamp through an unplanned eroded channel to the South. Instead, a short pipe should be installed underneath the fire trail to deliver the flow into the planned discharge point which currently only receives overflow from Attunga Creek drain during very large rain events.

  Where this water enters Main Swamp it is held behind a berm. This was presumably originally designed to encourage infiltration. Unfortunately the large hydraulic gradient created by this wall was sufficient to cause pipe erosion, undermining the berm. The point where the berm has been breached should be converted into an armoured riprap overflow point. This should maintain a small lip to encourage infiltration in the area South of the berm while not producing a hydraulic gradient large enough to cause the berm to become undermined in other areas.

  Down gradient of the riprap, a series of contour banks should be created using coir logs to encourage non-channelised overland flow through the swamp. These contour banks should join up along the Southern edge of Cripple Creek to prevent this flow from entering the channel and destabilising the channel banks. At the point where a leaky weir has been installed in the channel, any remaining overland flow that has not infiltrated, should be directed into the channel with the weir's geofabric lining protecting the entry point.

- **Average standing water level in Main Swamp measurement bores returned to at least 1.5 metres** within three years.

  In addition to treated leachate, water from low flow rain events should be directed to the Western portion of Main Swamp. This could be achieved by installing a small lip where the channel from the diversion pipe splits in two. The lip should be approximately ten centimetres high and prevent low flows from entering Spurwood Creek. This will encourage increased levels of infiltration within the Western portion of Main Swamp.

Initially, the wood mulch placed in Main Swamp will have a high hydraulic conductivity allowing water to move through it relatively quickly. However, over several years the hydraulic conductivity of the wood mulch will be diminished as the wood settles and starts to humify and as clay and silt sized particles accumulate creating a blocking layer. This will slow the lateral movement of water increasing the volume of water permanently stored within the swamp.

- **Net loss of carbon from Main Swamp halted** within three years.
- **Natural filtering of low flow water moving through the swamps re-established** within three years.
- **The water in Cripple Creek leaving BWMF is clean and clear with low nutrient, organic carbon and sediment loads** within five years.

Structures built within Main Swamp and Winnicoopa Swamp should be planned so as to not only slow the flow of water, but also maximise denitrification, nutrient complexation by peat and/or uptake into plants, and sediment settlement. Designing to reduce nutrient loads will reduce the competitiveness of weeds within downstream areas while reduced bed loads will improve bank stability (Fryirs and Brierley 2013).

Improvements in the dissolved organic carbon (DOC) load may not be realised immediately. Wallage, Holden, and McDonald (2006) found that drain blocking of peat swamps was highly effective in reducing the quantity of DOC export. However, over the short period of their study, the colour of the DOC remained darker (on a per carbon atom basis) than the DOC of a reference peatland. They suggested that this may be related to a phenol oxidase 'enzyme-latch' which continued to cause peat degradation even after watertables were restored. While it is likely that any such effect would not be permanent, it is not clear how long the effect would last.

- **Downstream Cripple Creek rated as in good health based on macroinvertebrate community** within five years.
- **Significant flattening of unit hydrograph for runon entering swamp system from urban and operational areas** within 5 years

As shown in section 3.2.3, flashy rainfall passes straight through the swamps rather than recharging the groundwater. By slowing the rate at which water enters the swamps, more of the water can be absorbed by the swamp, maintaining a high watertable.

Winnicoopa Creek

In collaboration with other areas of council and Sydney Water, funding should be sought for the construction of a stormwater quality improvement device (SQID) at the end of Winnicoopa Road. Stormwater outlets into other, smaller tributaries of Cripple Creek should also be investigated as potential locations for SQIDs.

Attunga Creek

The feasibility of diverting some of the water currently directed down Attunga Road into natural flow lines within the bushland of Railway catchment should be considered. However, care should be taken, not to overload these flow lines and thereby creating new incised channels.

A series of simple leaky weirs should be installed along the rock drain through which Attunga Creek flows along the Southern edge of the operational area. If spaced at a distance of 5 metres around 70 weirs will be required. These can be constructed by placing small rectangular hay bales upstream of large sandstone rocks. The validity of this design has already been demonstrated by the three existing weirs currently placed along this drain (figure 5.2). These have proved successful at slowing water and trapping sediment. Indeed one such weir has trapped sufficient sediment to create a small vegetated area[1].

The rocks can be sourced from on site for free. If bought in bulk the bales should cost less than $15 each. Not including labour, these weirs should cost approximately $2000. If each weir were to be filled to its maximum extent, at least 100,000 litres could be temporarily held in the rock channel. In a rain event where water enters BWMF along Attunga creek at a rate of one litre per second (similar to the moderate rain event reported in section 4.2.3), this quantity amounts to over a full day's runon.

Once the hay bales have started to weather and they have been well saturated after a substantial rain event, holes should be dug into the bales and filled with soil. Into these holes a diversity of sedges (see fig:flora) should be planted.

In addition to these small weirs, consideration should be given to the construction of a more substantial structure immediately downstream of the flat area two thirds of the way down the drain where a small drainage line enters the drain (marked on figure 5.1). Assuming storage in only the first metre of soil, this small area has the potential to store over 300,000 litres of water, equivalent to four days of input at one litre per second[2].

[1] Some of the weirs have proved less stable with the rocks being moved by large flow events. By installing more weirs water movement will be slowed and so movement of the weirs will be less likely. Nevertheless, consideration should be given to cementing at least some of the upstream weirs in place.

[2] Note that this assumes that storage is not infiltration limited. To maintain reasonable hydraulic conductivity the settling of clay and silt particles on the surface must be effectively limited by upstream structures.

This area is already colonised by sedges. Relatively dense *Melaleuca linariifolia* and *M. citrina*, along with scattered *Gahnia clarkei*, should be planted throughout this area. The sedges already in place should be monitored to assess their response to more frequent inundation. If they show signs of stress *Schoenus melanostachys* should be planted in their place.

Internal catchment

Drainage from the stormwater dam should be modified so that the dam can empty entirely, while the rate of discharge should be reduced. Inflows larger than the capacity of the dam would still be able to overflow via the existing spillway. At a conservative estimate, this would open up at least three million litres of storage. From empty, this dam would be able to hold 35 days of constant inflow at one litre per second, while from full, with a constant output of two hundred millilitres per second, the dam would take close to six months to empty.

The current environmental consent conditions for this dam require water sampling during any flow event. If the dam was modified to be flowing almost continuously, these consent conditions would need to be modified. Weekly sampling of discharge would fit with the current water sampling schedules and would likely be acceptable to the EPA.

Railway catchment

A detailed survey of the flow of water from non-vegetated areas of site that are part of Railway catchment should be conducted. This should identify potential retention areas before its entry into the diversion pipe or alternatively, rerouting of runoff into the internal catchment and downstream stormwater dam. Thought should be given to expanding the size of the existing upstream sedimentation basin as well as reduction of its discharge rate.

Where the diversion pipe discharges into Main Swamp, a shallow rock-lined channel should be built connecting to the series of three depression in the grassy area of Main Swamp. These depressions have the capacity to hold approximately 200,000 litres of water. This is slightly more than two days flow at one litre per second. Beyond adding a relatively modest amount of extra storage to the system, the creation of a backswamp in this area will increase infiltration into the clayey sands underlining the grassy area. As argued in section 4.2.3, maintaining the watertable in the areas surrounding a peaty drainage line is vital for the maintenance of the watertable within the drainage line itself.

- **Higher and more stable baseflow in downstream Cripple Creek** within five years.
- **Significant reduction in sediment and nutrient load of water entering the swamp systems from urban and operational areas**

Figure 5.2: **Leaky weir in Attunga Creek rock drain.** *Note the deeper water upstream of the weir.*

within five years.

Kang, Kayhanian, and Stenstrom (2008) classifies urban pollution as either short-term, which accumulates over a period of dry weather (eg. oil on a road), or long-term, which is the constant background pollution of an area (eg. lead in soil). The first flush of a rain event can be defined as the quantity of discharge required to remove most short-term pollution from an area (Bach, McCarthy, and Deletic 2010).

To maximise the ecological utility of the SQIDs, they should be designed to be able to retain and treat the first flush of runoff. This will maximally protect the downstream areas from nutrient pollution.

5.3 Ecosystem composition and structure

- **All *Ligustrum sinense* (narrow leaf privet) and *Zantedeschia aethiopica* (arum lily) removed from swamp areas of BWMF** within ten years.

  Methods of weed removal within Main Swamp appear to have been largely successful and should be applied within downstream Cripple Creek and Winnicoopa Creek. In addition to active removal, emphasis should be placed on modifying the environment to make it less hospitable to weed species. This can be achieved by pre-treating runon using SQIDs and planting a dense herbaceous stratum using allelopathic species such as *Gleichenia dicarpa*.

- ***L. sinense* and *Z. aethiopica* (arum lily) removed from drainage lines throughout the Cripple Creek catchment** within fifteen years.

This will require cooperation with other areas of council as well as Sydney Water, however without action upstream it will be difficult to maintain the BWMF section of Winnicoopa Creek weed free in the long term. The formation of a local bushcare group, demonstrating community concern about the health of Winnicoopa Creek, may help to secure cooperation from Sydney Water.

- **A tall herbaceous stratum and scattered shrub stratum underneath all areas of *Melaleuca* swamp forest within BWMF** within ten years.

  In the BWMF section of Winnicoopa Swamp, active revegetation is probably unnecessary within all but the most weedy areas. However, a planting programme will be required in the incised area below the current swamp.

  In the Southern and Western portions of Main Swamp, which are at the greatest risk of further erosion, plantings of the herbaceous stratum should concentrate on sedges, especially *Schoenus melanostachys* (black bog rush), rather than ferns due to their graminoid morphology which allows them to trap sediment and debris (Isselin-Nondedeu and Bédécarrats 2007) and fibrous root systems which binds the soil reducing erosion (Barrett 2013).

  Throughout Main Swamp, *Melaleuca citrina* and *Callicoma serratifolia* should be planted to create an open to sparse shrub stratum. Although *Acacia* are also typical components of Paperbark Swamp Forest communities (figure 3.2), they should not be planted because the urban runoff and landfill leachate already provide elevated levels of nitrogen.

- **The conversion of the grassy area in Main Swamp into an area of native open Bench Woodland** within five years.

  The grassy area in Main Swamp provides a valuable food resource for herbivores. As noted in section 3.1.2, flat open grassy areas in valley bottoms have likely been reduced since the British invasion. As such this area should be retained as a fairly open area with only a sparse shrub stratum and occasional emergent *Eucalyptus sclerophylla*. Species such as *Entolasia spp.* (panic grasses), *Microlaena stipoides* (weeping grass) and *Themeda triandra* (kangaroo grass) should be encouraged in the herbaceous stratum. In selecting appropriate endemic grass and forb species, palatability should be considered as a desirable characteristic.

- **A number of trial plantings of dense *Melaleuca citrina* (crimson bottlebrush) in between the existing *M. linariifolia* swamp forest and surrounding wet heath** within three years.

  In Warrimoo Swamp, the *M. citrina* community (Cyperoid heath in the scheme of Keith and Myerscough (1993)) is not evident along the entire length of the swamp. A possible explanation for this patchy distribution is the interaction of hydrology and disturbance regime (see section 3.7.1). If this is correct, the necessary conditions for this community may not currently exist in Main Swamp. However, even if the trail plantings are not successful, provided that some *M. citrina* survive as a shrub species underneath *M. linariifolia*, there will be a seed bank for this community to develop after a future disturbance event.

- **Mature invasion resistant vegetation in all vegetation strata along drainage lines in BWMF** within twenty years.

- **New swamp forests within the currently incised area of Winnicoopa and Cripple Creeks** within the medium term.

- **Monitoring of the vegetation community around Spurwood Creek** over the medium term.

  As noted in section 4.3.1, historical imagery shows that an unidentified non-*Melaleuca* tree species dominated lower Spurwood Creek until the installation of the cutoff wall. This area now contains an open wet heath shrub stratum with a sedge or fern herbaceous stratum. Because this area is geomorphologically stable and hosts few weeds, this area should be left to continue developing along its current succession trajectory. However it should be regularly monitored to ensure that it remains stable and weed free. If, in the future, this situation changes active revegetation or other interventions may be required.

- **No more planting of *Melaleuca styphelioides* (prickly-leaved tea tree) within swamp areas**

  Several years ago, five *M. styphelioides* were planted within Main Swamp on a trial basis. Figure 3.2 indicates that *M. styphelioides* are rare inhabitants of Paperbark Swamp Forests, and that they are not present within either Warrimoo Swamp or Glenbrook Lagoon. While the trial plantings show that they are clearly better competitors against grass than *M. linariifolia*, within the better drained grassy areas, Bench Woodland species are more appropriate than *Melaleuca*. Patches of young *M. linariifolia* in both Main Swamp and Winnicoopa Swamp demonstrate that where hydrological conditions are appropriate, *M. linariifolia* regenerates profusely and so there is no need to replace it with a different *Melaleuca* species.

- **Where practicable, *Melaleuca* seedlings used in plantings should be sourced from local genetic stock**

  The secondary metabolites expressed by many *Melaleuca*, including *M. linariifolia*, differ by region (Brophy, Craven, and Doran 2013). These differences, known as chemotypes, appear to be at least partly related to geographically variable herbivores (Bustos-Segura, Külheim, and Foley 2015). To ensure that plantings have resistance to locally abundant herbivores, local seeds should be utilised where possible.

- **A diverse range of permanent and seasonal birds and mammals utilising swamp areas** within ten years.

- **A healthy aquatic macroinvertebrate community along the length of Cripple Creek** with ten years.

  Over the two decades that the aquatic macroinvertebrate composition of Cripple Creek has been recorded, the health of the creek has only been rated as 'good' once. Increasing baseflow, repairing upstream channelisation, reversing peat oxidation and reducing nutrient and sediment inputs should lead to improvements of macroinvertebrate composition within a relatively short period. If the macroinvertebrate community fails to respond within five years the design of the restoration interventions should be reassessed.

- **Development of a policy regarding the management of wild dogs/dingoes within BWMF** within three years.

  A new family of wild dogs/dingoes are likely to eventually re-establish within the Cripple Creek catchment some time in the future. Before this occurs, a policy addressing safety concerns around their interactions with both the council staff as well as the public using BWMF should be developed. This policy should balance evidence based conservation concerns with input from front line council staff. An education programme about the actual risks from wild dogs/dingoes may help reduce some of the more unrealistic fears of staff.

- **Review of control options of foxes and wild cats within BWMF** within three years.

- **Review of the use of, and location of, baiting within the BWMF operational area** within three years.

5.4 Ecosystem function

- **Dramatic improvement in water quality immediately downstream of Main Swamp** within two years.

- **Peat production re-established in both Main Swamp and Winnicoopa Swamp** within three years.

  Together, slowing the movement of water, raising the watertable, removing *Ligustrum sinense* (narrow leaf privet), reducing nutrient inputs, and increasing the density of the herbaceous stratum should slow the breakdown of organic matter and reduce its export off site.

- **Natural aggradation of Main Swamp, downstream Cripple Creek and Winnicoopa Creek reinstated** over the medium term.

- **Substantial reduction in external nutrient cycling in swamp areas of BWMF** within ten years.

- **A continuous dense herbaceous stratum underneath *Melaleuca linariifolia* providing habitat for a range of mammals** within ten years.

  It is likely that herbaceous species differ in their provision of habitat niches. While a general toposequence of herbaceous species is obvious within Warrimoo Swamp (see section 3.4.2), detailed ecological work would be required to delineate the exact niches of each species. A more realistic and natural approach is to plant a range of herbaceous species in each area requiring revegetation and allow natural selection to determine the eventual composition.

  In doing so, except where specifically required for other purposes, seedlings should be planted at a reasonable distance from each other to allow for individual plants to establish before they are exposed to competition. This will prevent the fastest growing, early succession plants immediately dominating.

- **Provision of nectar and other services from *M. linariifolia* over an expanded range** within ten years.

- **Effective dispersal of fungi throughout Cripple Creek catchment by mycophagous mammals utilising the swamp as habitat** over the medium term.

  While fungi dispersal is difficult to measure directly, the abundance and diversity of mycophagous mammals is likely to be an acceptable proxy measurement.

- **A resilient swamp community** over the medium term.

  From the reference model, the central tenets of resilient swamps appear to be increased throughflow entering the swamps over longer periods, decreased nutrient flows entering the swamps, slower nutrient cycling within the swamps, reduced organic matter exports from the swamps and an abundant herbivore community.

  When implemented together, the installation of upstream works to slow the movement of water within the catchment and to reduce its nutrient content; the cessation of the unintentional addition of carbonate to Main Swamp through volatilisation of ammonia in the leachate dam; the installation of leaky weirs within the swamps to increase groundwater height and prevent the loss of organic matter; the removal of weeds to slow nutrient cycling and the planting of a dense herbaceous stratum to provide habitat for herbivores should lead to resilient swamp ecosystems re-asserting themselves.

- **Improved aesthetic and educational ecosystem services provided outside of operational areas** within five years.

As well as their inherent environmental functions ecosystems can also produce various cultural services. These should not be seen as mere add-ons to the central ecosystem functions of the Paperbark Swamp Forests. Because the BWMF swamps exist on the urban fringe the production of cultural services are vital to their restoration and ongoing protection (Baker and Eckerberg 2013).

The removal of weeds, repair of channelisation, installation of interpretive signage along existing paths, development of a Bushcare group and publicising of the unique properties of the vegetation community through council publications will help to develop the cultural services of the swamps.

5.5 External exchanges

- **Capture, and effective treatment, of runoff from non-vegetated upstream areas** within five years.

  To reduce the nutrient load of the first flush of captured runoff, SQIDs are often designed with detention basins where trapped water infiltrates through a filter medium into a sub-surface drainage pipe (Rossmiller 2014). Although following a different design, the proposed weirs along the Attunga Creek rock drain will fulfil a similar goal by filtering water through straw bales and the sediment and organic matter trapped up gradient of them. By contrast, the existing storm water dam and upstream retention basin do not follow this pattern. The possibility of modifying these existing structures to increase nutrient removal should be investigated.

  At present, discharge from the storm water dam is trickled over a short bed of limestone rocks with the aim of increasing the pH of water to promote the conversion of ${NH_4}^+$ to NH_3 and its subsequent volatilisation. Given the small size of the limestone bed, it is unclear how effective this process is. If it does, in fact, increase volatilisation, like the NH_3 from the leachate pond, a substantial amount of this NH_3 is likely re-precipitated on the tall vegetation in Main Swamp.

  Even if this process is effective in removing ${NH_4}^+$ from the swamp system, any environmental benefits from this are likely to be negated by the increased pH of discharge water. As such, the effectiveness of this limestone bed should be studied and, if it is, in fact, effective, consideration should be given to its removal.

- **Complete cessation of the export of sand-sized sediment from BWMF** within 5 years.

  The construction of weirs and bank stabilisation work in the incised area of Winnicoopa Creek are the most important actions to achieve this goal. Also important will be minor works along the fire trail to reduce sediment mobilisation in this area, and the installation of SQIDs at the urban-bush interface.

- **Substantial reduction in the export of sediment from the BWMF operational area to Main Swamp** within two years.

  Although there are various engineering solutions, such as sedimentation ponds, used around the BWMF area, there is a poor erosion minimisation culture. The use of temporary sediment fencing is insufficient and often poorly implemented. To rectify this, an educational programme about erosion control should be carried out for the operational staff, and a system for monitoring rates of sediment export should be implemented.

- **Complete cessation of water-driven export of weed propagules from BWMF** within 10 years.

  The installation of leaky weirs should capture any weed propagules entering Main Swamp, preventing their downstream export.

- **Increased habitat connectivity between Main Swamp, Winnicoopa Creek and downstream Cripple Creek** over the medium term.

- **Regular propagule dispersal within and between swamps of the Cripple Creek catchment** within ten years.

  This will be almost impossible to measure directly, however the presence of important animal vectors visiting the swamps is likely to be an appropriate proxy. Further work will be required to develop a list of indicator species, but local bush regeneration practitioners (pers comm) suggest that swamp wallabies, currawongs and fruit bats are likely to be particularly important.

  It should be noted, however, that species transporting endemic propagules are also likely to be vectors for the transport of weed vectors. This underlies the importance of maintaining the geophysical and ecological underpinnings of a resilient ecosystem that is able to resist invasion from the inevitable spread of weed propagules.

5.6 Disturbance regime

- **Reduction in the frequency of pulse disturbance events** within five years.

  The increased peakiness of the hydrograph, due to land clearing on the ridges and within the BWMF operational area, is not a disturbing process, *per se*, but significantly changes the flood regime of the catchment making flooding disturbance events much more common. This more frequent flooding regime mirrors the more frequent fire regime that has prevailed in the BWMF catchment due to prescribed burning and anthropogenic wildfires (figure 4.14).

The installation of SQIDs to slow water before it enters swamps will reduce the frequency of flood events within the BWMF swamps. Modifying the fire regime is likely to be more difficult. As an initial step, the Rural Fire Service (RFS) should be contacted, and a discussion about the current fire regime begun. How successful this discussion will be is unclear since conservation of the natural environment is just one of the many competing priorities that the RFS must balance in its management of the local fire regime.

- **Removal of press disturbing processes in both Main and Winnicoopa Swamps** within five years.

  The lowering of watertables, due to the installation of the groundwater cutoff wall in Main Swamp, and due to the loss of peaty sediment in the incised area of Winnicoopa Creek, can be viewed as an ongoing press disturbance. As Tomkins and Humphreys (2005) note, it appears that two or more simultaneous disturbances are required to initiate channelisation of a healthy swamp. The continuing nature of this disturbed groundwater regime makes the swamps highly vulnerable to any pulse disturbances caused by the accelerated flood and fire regimes.

- **Development of a major disturbance preparation and response plan** within three years.

  As noted, in section 3.7.2, Kurrajong Fault swamps are adapted to regular disturbances and many plants, especially the wet heath species, require particular disturbance regimes to allow for their continued presence within the swamps. Nevertheless, it is likely that the BWMF swamps are subject to both more frequent disturbances and are less resilient to these disturbances due to their degraded state.

  As such, plans should be developed for both preparation and response to the two most important pulse disturbances events: floods and fires. At a minimum these plans should include the visual inspection of the swamps before a major predicted event and in the immediate aftermath of an event. Basic supplies such as coir logs and geofabric should be kept on hand to allow for the temporary protection of areas identified as vulnerable to erosion before longer term measures can be enacted.

- **Improved resilience through promotion of natural repair processes** over the medium term.

- **Incorporate the swamps into a whole of site rehabilitation plan** within ten years.

  Landfilling at BWMF is expected to cease in approximately one decade. Once landfilling has ceased, a rehabilitation plan will be required for the whole site. Initial planning was carried out by BMCC (1985), however community and regulator expectations have shifted in the time since this report was produced.

As argued by BMCC (1985), BWMF is owned by the local community and its rehabilitation should be designed with the local community in mind. There is already demonstrated community demand for pedestrian and bicycle access through the site. This could be achieved by dividing the dirt road running along the Southern edge of the operational site down its centre. Water trapping structures could be installed on the half of this road next to the Attunga Creek rock drain, enlarging the nascent swamp running along this drain, while the other half could be retained as a walking/cycling track through the site.

Alternatively, a similar development could convert the Northern dirt road around the current operational area into a walking track next to a swampy area, leaving the Southern road for management use. Either way, additional fencing would likely be required to separate public access from areas that continue to be used for waste transfer and recovery.

Improving public access to swamp areas will be vital to increasing public connection and concern for the endangered ecological community on their doorsteps. This social buy-in will be necessary for the long term success of the restoration project.

- **Incorporate future changes in climate into planning decisions** over the next year.

  Over the coming decades, the Cripple Creek catchment is projected to receive lower winter rainfall but more intense rainfall year round, higher temperatures, reduced soil moisture and harsher fire weather (Dowdy et al. 2015). For the swamps this will mean that inputs from the catchment will become more uneven and throughflow between events will be reduced. When designing water slowing or detaining structures, this increase in rainfall variability needs to be considered, with structures designed to accommodate larger levels of runoff than may presently be required.

  There will also be more frequent disturbances in the catchment due to fires. This underlies the importance of building a relationship with the Rural Fire Service now, so that BWMF can become involved in planning for the fire regime of the Cripple Creek catchment into the future.

6 | Research requirements and monitoring plan

Along Winnicoopa Creek three transects should be established in each of the three sections of the swamp distinguished in figure 4.10. These transects should be marked with star pickets and used for long term monitoring. Three similar transects marked with star pickets should be established in Warrimoo Swamp to act as a control. Because of the more complicated geography of Main Swamp, transects are less appropriate. Instead, a grid aligned to the compass points and containing forty metre by forty metre squares should be established. The vertices of this grid should be marked by star pickets. These points should be used as the centre points for a series of quadrats for long term monitoring. Finally, three monitoring points along downstream Cripple Creek should also be established.

Monitoring along these transects and quadrats should be conducted immediately to determine pre-intervention baselines, and then repeated once every five years, in line with, and feeding into, the BWMF vegetation management plan cycle. Extra monitoring should be conducted after any large disturbance event such as a fire. To prevent the swamps being 'monitored into extinction' (Lindenmayer and Likens 2018) trigger points for action should be established following the baseline survey.

To reduce the cost and time burden of this monitoring, contact should be made with the Western Sydney University Hawkesbury Institute for the Environment or Macquarie University's Department of Environmental Sciences to find students who may be interested in assisting with the monitoring.

6.1 Geophysical conditions

Baseline measurements of basic soil properties including texture, colour, structure, fragments, bulk density, pH, EC, and single ring infiltration, should be recorded following the methods in soil and terrain (2009) and Rayment and Lyons (2011). These measurements should be taken for the soil surface along the transects and in Main Swamp's quadrats. These will allow for the assessment of the degree and extent of eutrophication of swamp sediments and the degree to which SQIDs, weed removal and other interventions are effective.

The existing in-house water monitoring programme measuring pH, EC and NH_3 should be expanded to include apparent colour measured on the Hazen scale. Water colour acts as a cheap proxy for dissolved organic carbon in water (Wallage, Holden, and McDonald 2006). The geographic scope of the water monitoring programme should also be increased with new measurement points created as indicated in figure 6.1. This will allow for monitoring of the effectiveness of SQIDs in improving the quality of the water entering the swamps and the effectiveness of leaky weirs in improving the quality of the water exiting the swamps. Macroinvertebrate surveys should also be reinstated at the downstream end of Main Swamp allowing for the effect of Main Swamp on creek health to be disentangled from the effect of the downstream area.

The regular weekly monitoring programme should be expanded to include the standing water level of the three groundwater wells in Main Swamp. This will allow for the impact of hydrological interventions on groundwater height to be assessed. It will also allow modelling of the sensitivity of groundwater levels to rainfall.

A synthetic precipitation record should be constructed for BWMF using the short interval of weather data from the on site automatic weather station to hindcast past precipitation using correlations with longer running rainfall records from surrounding BOM weather stations. This will allow the production of more accurate recurrence interval data for storm events, a necessary pre-requisite for most hydrological modelling.

Recent technological advances have allowed for the development of low cost stream gauges using digital cameras and image processing software (Lee et al. 2010; Zhang et al. 2019). While less accurate than traditional gauges, these gauges are much cheaper, easier to install and easier to maintain than traditional gauges. Digital camera stream gauges should be installed as shown in figure 6.1.

These gauges will be able to determine both the size and shape of the hydrographs produced by each sub-catchment. This data will allow for the prioritisation of hydrological interventions as well as the quantification of their impact once constructed. In combination with the synthetic precipitation record, discharge data will allow for the creation of recurrence intervals for flood events. This will be useful not only for protection of the swamp, but also for management of the wider site.

Surface water flows within the operational zone of Railway Creek catchment are complex and are not correctly represented by the current digital elevation model used by council. The location and direction of these flows should be ground truthed during a rain event so that modelling of the catchment can be broken up into relatively uniform sub-catchments. This will allow for appropriate changes to existing water infrastructure in this area to be designed.

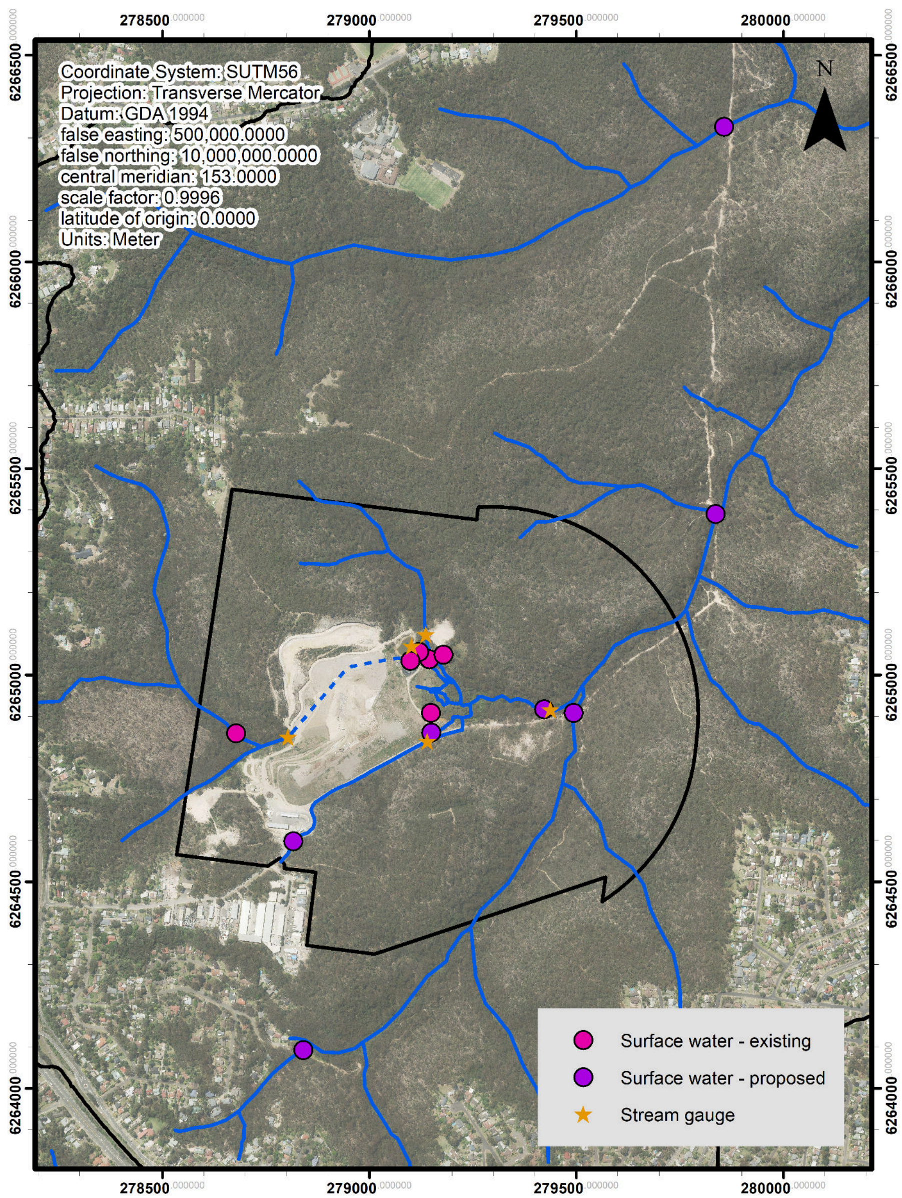


Figure 6.1: **Existing and proposed locations for surface water monitoring.**

6.2 Ecosystem composition

A checklist of plant species likely to be encountered in each strata of the swamps should be constructed based on figure 3.2. This should be used to conduct a survey of the abundance of each species following the method from Bayley and Brouwer (2014), using larger search distances for higher strata than lower strata.

At present, robust fauna monitoring that is able to generate useful data requires a large time investment from appropriately skilled individuals (Lindenmayer et al. 2016). Unfortunately, this would be too expensive and time consuming to be able to be justified for the current project. However, recent advances in bio-acoustics using cheap recording devices and machine learning have substantially reduced the time, cost and expertise required to run a successful monitoring programme (Gibb et al. 2019; Stowell et al. 2019). While these tools are not yet off-the-shelf solutions, they are likely to become more readily available over the coming years. As such, their potential should be re-assessed with each five year monitoring cycle.

For the moment, the only direct measurement of faunal abundance, (other than the ongoing aquatic macro-invertebrate surveys), should be the noting of scats during soil surface assessments. A series of easily identifiable classes should be developed based on initial trial surveys. At a minimum, scat classes should include foxes, wombats, large macropods, small macropods, rodents and other.

6.3 Ecosystem structure

Vegetation structure along the transects and quadrats should be assessed following the standards set out in McKenzie et al. (2019). Of particular concern should be the monitoring of the structure of the herbaceous stratum since the reference model showed this to provide important habitat and to be involved in geomorphological repair processes.

6.4 Ecosystem function

To measure the effectiveness of the interventions in promoting aggradation, the volume and composition of any sediment or organic matter slug held behind weirs should be estimated once per year for the first five years after a weir is installed. After this time, ongoing measurements should be included as part of the five yearly monitoring cycle

6.5 External exchanges

At the three monitoring points along downstream Cripple Creek, bank and bed sediment, morphology and vegetation should be assessed using the standard method described in Thorne (1998). This will allow for the assessment of the downstream impact of interventions in the swamps.

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