BLUE MOUNTAINS WORLD HERITAGE INSTITUTE

The Blue Mountains Upland Swamps: A review of their ecological significance and outlook for future conservation and adaptive management

by

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Executive Summary

This review was conducted to bring together research on the function and significance of Blue Mountain Upland Swamps (BMUS), and to evaluate the role of Adaptive Management in their long-term conservation. Corresponding knowledge gaps were also identified.

The hydrological and carbon storage functions of BMUS have been identified as critical ecosystem services, which are threatened by environmental changes such as urban development, mining, and climate change. Because swamp function and management are highly complex, there is considerable uncertainty about how swamps will be impacted in the future and what the scale of those impacts will be.

It is argued that the collaborative project developed by the Blue Mountains World Heritage Institute and its investigative partners to assess the management and research needs in relation to BMUS will be beneficial for their long-term sustainability.

This review frames some critical questions that should be addressed within the project including:

- *How will swamps change in response to various threats and impacts acting together?*
- *What will be the spatial and temporal scales of such impacts?*
- *What is the best approach to restoration, management and conservation of BMUS in the face of uncertainty?*
- *How can the resilience of BMUS to environmental changes be improved?*

These questions are derived from issues that it is argued need to be considered to ensure that Blue Mountains Upland Swamps are managed effectively, and continue providing their important ecosystem services.

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1.0 Introduction

Wetlands provide valuable ecological services, yet despite their importance they are becoming increasingly degraded by anthropogenic activities (Russi et al. 2013). The Upland Swamps in the Blue Mountains region of New South Wales are no exception to this problem. Their role in sustaining water flow, enhancing water quality, storing carbon, and acting as a habitat for endangered animal and plant species has been well-documented as has their vulnerabilities to unnatural environmental changes (Hensen & Mahony 2010) (Young 2017). Further recognition of these complex wetland systems and their functional features is needed for continuous improvement to their management and adaptive capacity.

This literature review will start by providing background information on the Blue Mountain Upland Swamps (BMUS) followed by a summary of what is known about their geological structure, hydrological function, and carbon storage function. The various threats BMUS face will be discussed, along with the impacts that may follow their diminishing on either small or large scales. Current conservation, restoration and management approaches will be considered and analysed. Research that has been done on swamps with similar features in different regions will be used to provide additional knowledge that could be applicable to the BMUS. Together, these findings will show where there is uncertainty and gaps in knowledge about the BMUS, supporting an adaptive approach to their long-term management.

1. Background

Upland swamps, also known as Temperate Highland Peat Swamps on Sandstone (THPSS), are found throughout the Sydney Basin on the Hawksbury sandstone plateaus (Office of Environment & Heritage [OEH] 2016). As an ecological community they are listed as endangered under the *NSW Threatened Species Conservation Act 1995* and the *Commonwealth Environment Protection and Biodiversity Conservation Act 1999*. These listings include shrub and sedge swamps found on the Blue Mountain, Newnes, Woronora and Illawara plateaus (CoA 2014b). These upland swamps are abundant in the Greater Blue Mountains World Heritage Area where they are situated within an altitude range of 500-950m above sea level (OEH 2016). The Blue Mountains region (Figure 1) has a temperate climate which varies inter-annually and with altitude. The average temperature is 5 and 18 degrees Celsius during the winter and summer months, respectively, with an average annual rainfall of 1100 to 1600mm (OEH 2016). The swamps are densely vegetated with a mixture of shrubs and sedges typically 0.5-2.0 meters tall, as well as an abundance of endemic plant species, microorganisms, fungi, and diverse vertebrate and invertebrate fauna (OEH 2011) (OEH 2016). Approximately 3200ha of upland swamps are present in the Blue Mountains region (Hensen and Mahony 2010).

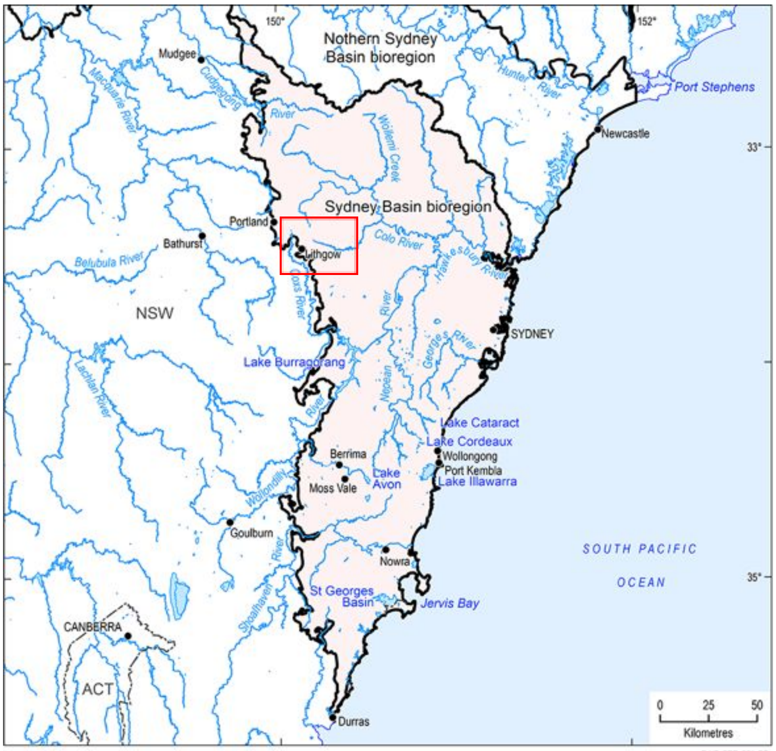

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Figure 1: Map of the study area (adapted from the Commonwealth of Australia bioregional assessments 2018)

Radiocarbon dating shows that sediment started accumulating in the BMUS during the late-Pleistocene to early Holocene making them at least 16,000 years old (Freidman & Fryirs 2015) (Fryirs et al. 2014).The Narrabeen sandstone plateaus on which the BMUS lie are Triassic in age (Young 2017) making them 251-205 million years old. The unique conditions necessary for swamp formation followed millions of years of tectonic evolution, uplift, erosion, and changing climatic conditions. Variation in stratigraphic age is found within individual swamps, meaning sediment was deposited in irregular phases and that their development was discontinuous (Freidman and Fryirs 2015).

Wetlands with similar characteristics to BMUS are found in different parts of the world, especially in the Northern hemisphere. They are referred to as peatlands, mire wetlands, topogenous mires, temperate fluviogenous mires, high altitude bogs, and valley mire fens. While research on the function and characteristics of these wetlands is certainly useful, the BMUS differ in their geomorphic landscape and environmental conditions making it difficult to apply knowledge transferred from different regions without significant uncertainty. Nonetheless, a lot of research has been done on European and North American peatlands as well as the Australian Snowy Mountain bogs which can be used to fill knowledge gaps and confirm findings on the BMUS. Therefore, research from different regions should be considered when additional upland swamp information is required like when management plans are being made, but should be done with caution.

2.0 Swamp Structure

BMUS are found in sequences of five distinct sediment units (Table 1). There is variability in the extent to which each unit is represented in different swamps as well as the variability within individual swamps (Fryirs et al. 2014). Swamps are 1 to 5 meters deep, with depth generally decreasing in the downstream direction (Glamore et al. 2016).

The Basal sands and gravels (BSG) unit sits on top of an impermeable sandstone unit which limits the loss of water through the swamp base (Labadz et al. 2010). The Surface Organic Fine (SOF) and Alternating Organic Sand (AOS) units are the most important units in terms of water and carbon storage, making them critical for the swamps overall function. The thickness of these important units can be altered as a result of unnatural change, particularly from urbanisation and mining within the water catchment area of a swamp (Cowley, Fryirs & Hose 2016a). In some cases, impacted swamps may show an additional layer of sediment at the surface or below the SOF unit referred to as the Contemporary Sands (CS) unit (Cowley, Fryirs & Hose 2016a).The processes that lead to these stratigraphical changes will be discussed in further detail as it is important to note the structural changes that can follow from human activity altering the natural conditions that the BMUS depend on.

Table 1: Soil profile of BMUS (Fryirs et al. 2014) (Freidman & Fryirs 2015) (Fryirs, Cowley & Hose, 2016a)

Unit	**Thickness**	**Max Depth**	**Sediment Characteristics**	**Organic Matter Content**	**Other notes**
Basal sands and gravels (BSG)	5-45cm	5.0m	Course-medium grain size, poorly sorted, rich in mineral sediment	2.6%- 3.7%	Base unit, sits above an impermeable sandstone
Fine cohesive sands (FCS)	5-35cm	4.5m	Sandy clay and or clayey sands with loamy texture	3.4%-7.6%	Marks the transition to ‘swamp’ conditions
Alternating organic sands (AOS)	Up to 2.0m (5-55cm sublayers)	3.8m	Sublayers of dark brown organic sands and light fine sands	10.7%-13.1%	Water table usually sits on top of this layer in intact swamps
Contemporary sands (CS)	Varies depending on degree of channelization, average 29cm	1.8m	Coarse, poorly sorted mineral sands and gravels	2.4-8.3%	Present in channelized swamps, absent in intact swamps
Surface organic fines (SOF)	20-100cm	0.7m	Plant debris, fine clays and silts	21-32%	The valley floor layer

2.1 Peat Formation

Peat forming units are those with a high Carbon to Nitrogen (C:N) ratio (~25 or higher) which reflects anaerobic and waterlogged conditions with low rates of organic matter decomposition (Rayment & Lyons 2010) (Labadz et al. 2010). Because organic breakdown is outpaced by organic matter production in these conditions, a layer of peat accumulates at the surface (Bonn et al. 2016). The units with the highest carbon content therefore have the highest peat-forming potential which decreases with depth. Most of the BMUS units have a low C:N ratio suggesting peat formation has only occurred for short periods of time during evolution of the swamp fill (Fryirs et al. 2014), alternating with periods of mineral sediment accumulation (Freidman & Fryirs 2015). The presence of vegetation during peat forming periods further increases waterlogging and therefore carbon accumulation, creating a positive feedback loop. This promotes further peat formation in the SOF unit. Because the BMUS are actively forming peat they are considered 'mires' by definition (Bonn et al. 2016), although BMUS are sometimes simply described as wetlands with peat forming potential. Regardless of what they are named it is important to note that the presence of peat in the BMUS is important for their overall function, including their ability to hold water and carbon.

2.2 Swamp Types

Upland swamps are sometimes further classified into 3 morphological types – hanging swamps, valley infill swamps, and headwater swamps (CoA 2014b) (Table 2).

Table 2: Morphological classification of upland swamps (CoA 2014b)

Type	**Hanging**	**Headwater**	**Valley Infill**
Gradient	Steep gradient	Shallow gradient	Medium gradient

Water Source	Groundwater connectivity; perched and regional aquifers are primary water sources, very reliant on groundwater discharge	Rainfall and runoff; limited groundwater connectivity	Rainfall and runoff; may intersect perched or regional aquifers, some groundwater connectivity
Topography	Occur on steep valley sides (where groundwater discharges directly to the surface)	Found on elevated topography high in catchments on relatively flat terrain	Found on incised topography, further down catchment than headwater swamps

Hanging swamps are predominantly found on the upper Blue Mountain plateaus. They form when groundwater moves laterally across an impermeable claystone layer beneath a permeable sandstone layer towards the valley side. The water then seeps out on the valley side, creating the waterlogged conditions necessary for swamp formation (Blue Mountains City Council [BMCC] 2018). This groundwater connection may be permanent or may only occur after rainfall (CoA 2014b). These swamps have a thin layer of sediment and peat deposition due to their steep terrain gradient. Headwater swamps are formed near catchment divides at the headwater of streams where topographic gradients are shallow. They are usually perched above the regional aquifer and source their water from rainfall and runoff with the possible exception of some groundwater interaction through fractures and joints (CoA 2014b). Valley infill swamps are found on gently sloping incised valleys or in natural depressions in the main drainage line of the valley. They source their water from rainfall and catchment runoff with some interaction with perched or regional aquifers (CoA 2014b). Compared to hanging swamps, headwater and valley infill swamps are structured for considerable sediment accumulation which further impedes drainage and results in waterlogged conditions and peat accumulation (BMCC 2011a). These morphological classifications should not be thought of as entirely separate systems; a swamp may actually be a mix of two or all three morphological types and headwater and hanging swamps may feed into and merge with valley infill swamps (Young 2017). While the degree of groundwater interaction varies significantly between swamps, their clear linkage to regional aquifer systems shows the connection that the BMUS have with other water systems in their catchment and therefore in the greater Sydney Basin.

3.0 Hydrologic Function

A swamps ability to store, hold and transmit water largely depends on the hydraulic conductivity and level of saturation of its units (Fryirs, Gough & Hose 2014). In literature, the BMUS are often described as acting like sponges. This behaviour occurs when swamps are not saturated prior to rainfall (water table is below the surface) which allows surface water to move vertically into the subsurface sediment, resulting in the storage of water before the swamps gradually release it back into the environment as baseflow, even during dry periods (Fryirs, Gough & Hose 2014) (Hensen & Mahony 2010). This water storage characteristic also moderates peak flows during storms, protecting downstream parts of the catchment from intense erosive flows (BMCC 2010a). If the subsurface layers are saturated prior to rainfall (water table is at the surface) the swamp will instead act as a rapid conduit for throughflow and overland flow transmitting water over the saturated layers parallel to the surface (Young 2017). The speed in which water moves through a swamp depends on the hydraulic conductivity of the sediment unit it is in as well as the hydraulic gradient. Hydraulic conductivity is determined by sediment properties such as porosity and permeability. Because sedimentary structure, gradient and hydrological conditions are not necessarily constant across a swamp, ‘sponge’ and ‘conduit’ behaviours can occur simultaneously (Fryirs, Gough & Hose 2014).

Water budgets are particularly useful in understanding storage capacity and water loss through swamps. Simply, the water balance may be expressed as: precipitation = evapotranspiration + discharge to stream + change in storage + error (Krogh 2015), although this formula does not account for any interaction with groundwater. The OEH (Krogh) and UNSW Water Research Lab (Glamore, Rayner & Anderson) have undertaken measurements of rainfall, evapotranspiration, outflow, soil moisture, and water levels to create preliminary water budget estimates. The measurements used for these estimates still have significant uncertainty and would benefit from additional research on runoff, canopy and leaf litter interception, infiltration, interflow and groundwater loss quantities (Glamore, Rayner & Anderson 2016). The large degree of heterogeneity in hydraulic properties within individual swamps also contributes to the complexity in finding appropriate water budget parameters. Although estimates of specific yield, porosity and hydraulic conductivity have been used, reducing the uncertainty in these parameters and additional research on groundwater connectivity could provide further insight to the water storage capacity of swamps (Glamore, Rayner & Anderson 2016) (Krogh 2015).

4.0 Carbon Storage Function

Peatlands are one of the world's most important terrestrial ecosystems with respect to gaseous and fluvial carbon storage, a function that often goes largely unrecognized (Page & Baird 2016). Peatlands can act as both sources and sinks of greenhouse gases (GHGs), with drained peatlands being responsible for 5-6% of anthropogenic carbon dioxide emissions globally (Joosten 2010)(IUCN 2017). Although peatlands in Australia account for a very small percentage of those total emissions, their role as carbon sequestration and storage systems should not be overlooked. The total carbon storage within the BMUS is unknown but quantitative estimates have been made for the peat bogs in the Snowy Mountains of Australia. These bogs are estimated to hold 3.55 million tonnes of carbon, although the rate of carbon accumulation is approximately half of what it has been historically (Hope, Nanson & Jones 2011). This is likely the result of swamp degradation from fires and agricultural grazing. The Snowy Mountain bogs share similar characteristics to the BMUS in terms of vegetation and sediment so their carbon accumulation rates may be comparable. However, location specific measurements of peat volume, water content, organic content and dry bulk density are needed to provide a more accurate carbon budget (Hope, Nanson & Jones 2011). There is still a lot of uncertainty surrounding peatland carbon dynamics globally (Limpens et al. 2008) and the BMUS are no exception to the knowledge gap.

5.0 Threats

Upland swamps are threatened by a number of anthropogenic influences including mining, urbanisation within their catchments, and climate change. Despite their ecologic value and endangered status under New South Wales (NSW) and Australia Commonwealth legislation, they have received very little real protection (Young 2017). The different threats acting together on the swamps create further complexity as each individual impact on a swamp cannot be understood on its own. Instead, a multitude of threats working in conjunction must be considered in swamp management.

5.1 Climate Change

There is significant uncertainty in how upland swamps will change in response to predicted changes in weather patterns. In NSW the average temperature is projected to rise by 0.4-1.0°C by 2030 and by 1.8-2.6°C by 2070 (OEH 2014). Changes in rainfall patterns are also forecasted; spring rainfall is projected to decrease and autumn rainfall to increase with a net decrease in annual rainfall (OEH 2014). These changes are large compared to historical variability in climate and will likely exacerbate other pressures on upland swamps (Finlayson et al. 2013).

Research done by Keith, Rodoreda and Bedward (2010) showed a strong correlation between mire wetland expansion/contraction and climatic moisture in NSW. They found that as climatic moisture increases, mires expand due to a decrease in net evapotranspiration. This suggests that mires will contract in response to increased evapotranspiration resulting from drying climatic conditions. While natural climatic cycles result in some swamp contraction and expansion, these patterns may be of a larger magnitude under climate change. Similar conclusions were drawn by Banaszuk and Kamocki (2008) from studying the hydrology of the undisturbed Narew mire in Poland. They found that as climate became drier, evapotranspiration increased, resulting in a lowered water table and decreased water storage in swamp sediment. These two studies together suggest that a net decrease in annual rainfall and increase in evapotranspiration would alter the swamps water balance and specific hydrological conditions which they are so dependent on. Therefore, projected climate change and preliminary observations raise concern about the stability of BMUS overall hydrological functioning and storage capacity in the near future (Keith, Rodoreda & Bedward 2010).

5.2 Mining

Few mines are still operating in the Blue Mountains World Heritage Area so the BMUS are not as threatened by coal mining as they once were. Nonetheless, monitoring the impacts of mining on other upland swamps in the greater Sydney Basin bioregion can provide further insight to their structure, function and response to environmental change. The Southern Highlands region is rich in coal resources and has a well-established mining industry. Disagreement over the benefits of underground coal mining versus the need for catchment protection has a long history in the region with proponents drawn to the economic benefits that mining brings and opponents concerned about the environmental impacts it has, particularly on freshwater resources (McNally & Evans 2007). While mining companies have disputed the environmental impacts (Centennial Coal 2013), a large body of research shows that longwall mining beneath swamps leads to erosion and subsidence (Young 2017) (Krogh 2015). This causes major changes in swamp structure, water retention characteristics, water quality, flow patterns, vegetation, and susceptibility to extreme weather events (CoA 2014c). Hydrograph measurements show that after rainfall, water levels in swamps that have been undermined spike and decline much faster than non-mined swamps (Glamore, Rayner & Anderson 2016). While periodic drying of swamps can occur naturally, it is unlikely that these responses are independent of mining impacts. Instead, these changes are likely the result of deep fracturing through the swamp base unit (BSG) leading to vertical drainage of water into a deep aquifer (CoA 2014a). Measurements showing a reduction in water volume at downstream reservoirs following mining supports this hypothesis (McNally & Evans 2007). Over time this mining-induced drainage can lead to desiccation which, along with significant structural changes, swamps are never able to fully recover from.

Under State legislation mining companies do have to obtain approval to operate and have a 'Subsidence Management Plan' because of the swamps protected status (CoA 2015). Trigger-action-response-plans (TARP's) are also commonly used by mining companies but they are increasingly recognized as an ineffective strategy because of the time lag between mining and swamp impacts (CoA 2014a). Swamp monitoring is a relatively new practice for mining companies so limited baseline information is available for reference. Monitoring is generally limited to piezometric water table measurements which does provide some general information but is often spatially and temporally insufficient to identify complex hydrological processes and provide quantitative data about mining impacts (CoA 2014c). Because groundwater movement is slow, a pressure disturbance can take as long as months or decades to propagate from a mine source to a swamp receptor, creating a time lag between mining and impacts (Glamore, Rayner & Anderson 2016). This is further evidence that the impacts of mining are not adequately shown with current monitoring practices. Hydrographs show that swamps respond inconsistently to undermining with some swamps showing more significant functional changes than others (Water NSW 2016).

Another problem with monitoring is that emergency mine water discharge points that sometimes exist at the head of swamps can add water volumes that dominate natural flows. This further complicates interpretation of piezometric data. For these reasons, any assessment of mining impacts should also include uncertainty analysis and scenario analysis (Glamore, Rayner & Anderson 2016). WaterNSW (2016) recommends improving monitoring by measuring flow volumes out of swamps and monitoring groundwater below swamps to better understand the relation between mining, swamps and shallow groundwater systems.

One proposed solution to mining induced subsidence is to change mine layouts which reduces resource recovery but could also reduce the environmental impact of mines (McNally & Evans 2007). Layouts can be modified by adjusting the length and width of longwall panels to change the magnitude and nature of surface movement (CoA 2014a). While this may seem like an obvious solution, it seems unlikely that the stricter provisions needed to implement these changes will be made in the current economic-driven context. Still, the current requirements for a Subsidence Management Plan are arguably inadequate in minimizing swamp damage and protecting water resources in catchments. Research consistently shows that monitoring techniques used by mining companies are not able to detect damaging impacts early enough, so although it may be met with political barriers, restricting mining in certain areas seems to be the only dependable way to prevent swamp subsidence and protect the surrounding ecosystem. Long-term planning that identifies high value swamps prior to mining and creates buffer zones around them should be included in a management plan (CoA 2014a).

5.3 Urban Development

Urban development within the water catchments of BMUS have been shown to damage swamps by altering their geomorphic structure, water chemistry, and overall function. The presence of impervious surfaces such as roads and roofs can block groundwater recharge and transport higher volumes of water to swamps, leading to the development of incised channels (BMCC 2011a). Because development in the Blue Mountains region is widespread and continuously expanding it is considered a major threat to swamps and should be a key consideration in swamp management.

5.3.1 Changes to Water Composition

Under natural conditions, swamps and the channels that flow from them are acidic (CoA 2014b). Research by Belmer, Wright and Tippler (2015) found that urban development within water catchments modifies swamp geochemistry, with the surface water of urbanised swamps being less acidic than swamps in unmodified catchments (mean pH of 6.6 and 4.7, respectively) and having 5 times higher salinity. This was found to be the result of stormwater infrastructure such as road gutters and drainage cannels diverting and increasing the magnitude of stormwater flows into swamps. These storm flows and urban runoff flows can carry contaminants such as dissolved concrete material and nutrient-rich residential pollution, that can change water chemistry and quality (Belmer, Wright & Tippler 2015).

5.3.2 Structural Changes

BMUS are often classified as either ‘intact’ or ‘channelized fills’ based on their geomorphic condition. The geomorphic condition of a swamp is not related to intrinsic properties such as catchment area or slope but is largely the result of urban development (Kohlhagen, Fryirs & Semple 2013). Table 3 summarizes some of the key differences between intact swamps and channelized fills. It is important to note that as BMUS are realistically found in a range of ecosystem states and geomorphic conditions they may be perceived as more of a spectrum than a binary classification.

The correlation between swamp condition and urbanisation is well documented. Swamps in highly urbanised catchments are subject to concentrated high velocity flows, which is what leads to incision and channelization. This results in erosion and the removal of fine sediment and organic matter from the SOF unit which affects a swamps ability to hold water and accumulate peat (Fryirs, Cowley & Hose 2016b). Research done by Kohlhagen, Fryirs and Semple (2013), Belmer, Wright and Tippler (2015), and Fryirs, Cowley and Hose (2016b) found that swamps in better condition are further away from urban development, have fewer stormwater release outlets, are further away from stormwater pipes, and have less of their catchment area covered by impervious surface. Despite the clear correlation, approximately 26% of BMUS have experienced incision or gullying (Cowley, Fryirs & Hose 2016b). This shows how widespread the impact of development is in the region.

Table 3: Key differences between intact swamp and channelized fills (Fryirs, Cowley & Hose 2016a) (Cowley, Fryirs & Hose 2016b)(Cowley, Fryirs & Hose 2018)

Intact Swamps	**Channelized Fills**

Good geomorphic condition	Poor geomorphic condition
No defined channel	Well defined and expanded channel
Unincised valley fill	Incised valley fill
Discontinuous drainage lines	Continuous drainage lines
High water table with little variability	High variability in water table
Presence of natural sediment units, including organic surface matter	Changes to sediment units, including the deposition of a Channelized Sands (CS) unit
Native vegetation	Little native vegetation, sometimes exotic vegetation and/or weed invasion
No visible surface disturbance	Knick points, sand splays, slumping, bank undercutting
Normal water flows	Signs of dewatering and desiccation

Cowley, Fryirs and Hose (2016a) found that the AOS and SOF units in intact swamps were almost double the mean thickness of the same units in channelized swamps. Because these are the main units in terms of water and carbon storage, moisture content was on average 30% higher and the C:N ratio 25% higher in intact swamps. The additional CS unit often found in channelized swamps has a higher degree of hydraulic conductivity, causing water to flow quickly across a swamp instead of percolating the subsurface units which can lead to swamp desiccation (Merson & Gold 2013). This changes the natural waterlogged anaerobic condition that the BMUS rely on, leading to organic matter decay and inhibiting peat formation.

5.3.3 Changes to Hydrologic Function

Hydrographs show that channelization changes the water level dynamics of swamps. Research done by Cowley, Fryirs and Hose (2018) found that channelized swamps have almost 3 times more water table variability than intact swamps (72% and 25%, respectively) with water tables rising quickly after rainfall and declining significantly during dry periods. Channelized swamps discharge more water than intact swamps after rainfall due to increased throughflow and a thinner SOF unit. They also discharge water sooner after rainfall and have higher discharge variability (Cowley, Fryirs & Hose 2016a) (Cowley, Fryirs & Hose 2018). These findings suggest that once channelized, swamps switch from being predominantly water storage systems to water transfer systems. Similar water table fluctuation patterns were found between drained and undisturbed peatlands in northern England by Holden et al. (2006) confirming that channelization leads to lowering and increased variation of the water level in swamps. They also found that even 6-7 years after restoration water level responses did not completely return to natural fluctuation levels. Even though channel blocking has shown some success in restoring water levels in the BMUS, the findings from Holden et al. (2006) suggest that protecting hydrologic function by minimizing urban impacts should be the first priority in BMUS management because rehabilitation efforts are limited in their ability to restore natural function.

5.3.4 Changes to Carbon Storage

While climate change will certainly contribute to swamp degradation research suggests that swamp degradation will also contribute to climate change. Cowley et al. (2018) found that channelized swamps export 18 times more fluvial carbon and emit up to 4 times more carbon dioxide than intact swamps showing that structural changes affect the BMUS carbon storage function. Research conducted in Southeast Asia and Europe confirms that peatland degradation increases both fluvial and gaseous carbon emissions although the magnitude of carbon exports differs between regions (Moore et al. 2013) (Billett et al. 2010). While degradation of peatlands in Europe is largely due to clearing for agriculture, their structural changes are similar to those in the Blue Mountains region. The emission of carbon dioxide from unnatural swamp channels makes them a net source of greenhouse gases, and the export of fluvial dissolved organic carbon alters downstream water chemistry and therefore quality. Cowley et al. (2018) also found that channelized swamps emit 5 times more methane than intact swamps. This is unlike the peatlands in the Northern hemisphere which have been found to decrease methane emissions once drained. Cowley et al. (2018) hypothesize that the BMUS differ due to the higher surface temperature and the short residence time of groundwater in the CS unit after channelization, which inhibits methanotroph (methane consuming) activity. This also serves as a reminder that knowledge transfer from international swamp systems must be done with caution, as the particular geomorphic and climatic conditions of the BMUS make their response to environmental change unique.

5.3.5 Vulnerability to Wildfires

Another reason that swamp restoration and conservation should be prioritized is that drained swamps become a wildfire hazard. Dry peat is highly flammable and peatland drainage has led to devastating fires internationally in Asia and Europe (Hooijer & Page 2016). Peat fires also release significant amounts of carbon, further contributing to GHG emissions (IUCN 2017). The Blue Mountains region is already a highly fire-prone area, so minimizing the hazard that results from swamp channelization and desiccation is important.

6.0 Conservation and Rehabilitation

The BMUS are listed as endangered ecological communities under the *Commonwealth Environment Protection and Biodiversity Conservation Act 1999* and the *NSW Threatened Species Conservation Act 1995*. Despite their status they continue to be threatened by mining, urban development, and climate change. Some conservation and restoration efforts are currently in place, particularly at the local scale. Researchers suggest that because restoration works can be costly the rehabilitation of certain swamps should be prioritized over others. Swamps that are not severely damaged and have a good chance of SOF and AOS unit re-establishment are most-likely to respond well to rehabilitation (Cowley, Fryirs & Hose 2018) (Kohlhagen, Fryirs & Semple 2013). On the other hand, it is unlikely that rehabilitation of severely damaged swamps with high energy channels will result in considerable improvement (Freidman & Fryirs 2015).

Restoration of swamps requires re-establishment of natural conditions, including high water table and natural vegetation. This creates the anaerobic environment needed to inhibit organic matter decomposition, promote carbon storage and support peat accumulation (Cowley, Fryirs & Hose 2016a). For swamps impacted by urban development this can be done with the help of various soft-engineering techniques such as channel blocking, coir log dams, sediment detention basins, wooden bed structures, and infiltration cells. These work by trapping sediment to prevent further erosion and slumping, re-establishing native vegetation and retaining water to reduce its velocity through swamps, and assisting with rehydration (Hensen & Mahony 2010). Some of these techniques are used by the 'Save our Swamps' (S.O.S.) program run by the BMCC and local volunteers. The S.O.S. program shows the local ambition for ecosystem rehabilitation and has been very successful in swamp management, receiving multiple awards for its innovative approach (BMCC 2018).

Banaszuk and Kamocki (2008), who studied evapotranspiration in Poland's Narew mire, propose that appropriate vegetation management within a water catchment could decrease evapotranspiration during times of exceptionally dry climate. This could minimize groundwater drawdowns and help maintain water levels during times of drought. Vegetation management is a relatively simple conservation strategy and could be particularly useful in NSW with predicted climate change impacts.

7.0 Outlooks for Adaptive Management

Ecosystem management is challenging because there are multiple internal and external influences acting together making it difficult to separate the impacts of one factor from all other potential factors. Climate change, for example, will interact with other drivers of change, such as mining, to create a response that is different than what it would be under one single threat. In addition to physical changes, social, political and economic factors play a role in ecosystem state. For example, legislation to protect an ecosystem might mitigate the impacts of climate change, while demand for further urban development might exacerbate it. For this reason, point solutions will be inadequate in swamp conservation and rehabilitation. Instead, a plan that can embrace the inherent uncertainty and complexity in these systems is needed to meet management objectives in the long run. Adaptive Management (AM) is a process that incorporates structured decision making and learning into a management plan (Allen et al. 2011). It can improve the ability of an ecosystem to adapt to change when uncertainty and controllability are both high (Birgé et al. 2016). While there are certainly uncontrollable factors acting on swamps, the biggest challenge in swamp management arises from uncertainty. AM is able to address such uncertainty whether it be from gaps in knowledge or the complex relations between the BMUS system components.

Adaptive Management is a cyclical process with the ultimate objective of learning through action and using that knowledge to inform future decisions. AM promotes proactive over reactive management, suggesting that addressing the sources as opposed to the consequences of degradation will be most effective in long-term swamp conservation. The use of an interdisciplinary and collaborative approach is an integral feature of AM. Geomorphic, structural and functional knowledge are all critical, but should be combined with stakeholder input, socio-economic values and community engagement (Kohlhagen, Fryirs & Semple 2013). Although environmental science seems to be the focus of management frameworks in the Blue Mountains World Heritage Area, including other sources of information can yield better results than relying on scientific input alone (Ashby, Fryirs & Howitt 2014). This ensures that social sources of uncertainty are accounted for and that knowledge and responsibility is shared between as many levels of management as possible. Stakeholders and key actors are defined as individuals or organizations that may affect swamps or be affected by the AM plan once it is implemented (Department of Agriculture, Fisheries and Forestry 2012). By this definition, the Commonwealth Government, the NSW Government, local councils (namely the Blue Mountains City Council, Lithgow City Council and Wingecarribee Shire Council), community members, landholders, volunteers (like those involved in the Save our Swamps program), urban developers, and mining companies are all stakeholders in BMUS management. With this many levels of management and involvement it is no surprise that there are different goals and values; some focus more on conservation and some focus more on restoration. Common ground can be found through transparency in decision-making and open communication to establish mutual goals. Furthermore, integration of knowledge from organizations, researchers, policy-makers and managers is increasingly needed to find solutions to environmental issues like swamp conservation (Dovers et al. 2017). A truly multi-disciplinary approach means ensuring there is collaboration between those who understand swamps, those who manage swamps, and those who are effected by swamp management. This kind of collaboration is what makes AM unique and useful in ecosystem management. The following sections outline some of the main components that should be considered in the design of an AM plan for BMUS.

7.1 Identifying Objectives

Identifying clear and specific objectives is a first step in AM. When many stakeholders are involved it is useful to find synergies in goals and plans. However, Ashby, Fryirs and Howitt (2014) found that there is currently a disconnect in priorities, strategies, and funding for the rehabilitation of BMUS between stakeholders at different levels. For example, at the local level the objectives of the 'Save our Swamps' program include raising awareness, community capacity building, and on-ground rehabilitation (BMCC 2018). At the Commonwealth level, the priority is creating protective legislation for certain ecosystems but with limited monitoring of success. Identifying a broad vision statement that all stakeholders can work towards, like to 'maintain biodiversity and geomorphological stability in order to maximise the resilience of the ecosystem' (Hope, Nanson & Jones 2011), can help guide decisions and actions. Knowledge and findings should be communicated between stakeholders at all scales so that they can use all available resources to manage swamps in the most efficient and effective way possible. This kind of collaboration requires strong leadership and engagement – something that is evident at the local scale, but not far beyond it. The existing collaborative management being done at the local scale should be used as a model to improve knowledge sharing and decision-making on a larger scale.

7.2 Monitoring

The importance of monitoring in AM is often overlooked but it is crucial for measuring progress towards objectives and improving management practices. In BMUS management, monitoring and evaluation is not well conducted beyond the local scale (Ashby, Fryirs & Howitt 2014). However, it is crucial that adequate monitoring and evaluation is done to feed information back into the AM cycle, which creates a base for continuous learning and improvement. Monitoring should be done by comparing indicators of change before and after intervention.

Brownstein et al. (2014) emphasize that careful consideration is needed when choosing sampling methods for monitoring. They suggest that sampling decisions should be based on clearly stated objectives, indicators of changes of concern, consideration of spatial scale, and trigger values (levels of unacceptable change). These recommendations are based on their assessment of a vegetation monitoring program for the Newnes plateau shrub swamps. They found that it was ineffective in reaching its objective due to its failure to state trigger values and failure to change the sampling design as objectives were modified. This highlights the important role of a well-informed and flexible monitoring program within an Adaptive Management framework.

The use of Thresholds of Concern (TPC) can be especially useful in ecosystem monitoring. TPC are monitoring endpoints which define the upper and lower levels of acceptable change in an ecosystem (Gillson & Duffin 2007), like trigger values. Because external influences like climate change will modify the relation between intrinsic factors, thresholds that allow for inevitable variability while setting limits for maximum variability are ideal in adaptive monitoring (Rogers & Biggs 1999). TPC should be developed for each parameter being monitored (Table 4). They will have an upper limit and a lower limit; the wider the TPC the more acceptable the variation. If a value falls outside the TPC limits, the cause must be assessed to determine what action should be taken. TPC should be chosen based on the best available knowledge because of the uncertainty in swamps, and they must be adapted as additional learning occurs. TPC should be chosen based on natural levels of variability as well as defined acceptable levels of impact which can be done with the help of quantitative risk assessment (CoA 2014b). The use of TPC in monitoring could help identify the impacts of mining, urban development and climate change before it is too late to make changes.

Table 4: Intrinsic and extrinsic parameters that may be included in a monitoring plan (Belmer, Wright & Tippler 2015)(Cowley, Fryirs & Hose 2016a) (Cowley, Fryirs & Hose 2018) (Belmer, Tippler & Wright 2018)

Intrinsic	**Extrinsic**
Water Chemistry – pH, ions and salinity	Urban development and plans for development
Water table level and variability	Climate – temperature, rainfall and humidity
Water discharge volumes and variability	Mining layouts
Moisture content	Water pollution in catchment
Organic matter content and C:N ratio	
Sedimentary unit presence and thickness, particularly SOF, AOF and CS	
Subsidence – amount and severity	
Abundance of aquatic macroinvertebrate	
Vegetation – types and abundance	

7.3 Evaluation and Feedback

Comparing the results of monitoring with the defined objectives will show if management practices need to be adjusted and may provide insight to how they should be adjusted. A management approach must be reliable at all scales for it to be sustainable in the long-term, so this evaluation and feedback should be done with input from all stakeholders. This is the ‘learning’ component of AM. Evaluation provides the information needed to modify objectives as needed which starts the cyclical AM process over again and informs subsequent actions.

Lessons from peatland restoration projects in Europe suggest that evaluation should be based on three assessment criteria – relevance, effectiveness and efficiency (UNDP-GEF 2010). Relevance assessment should determine if the outcomes of the management project are consistent with stakeholder priorities. Effectiveness assessment should determine if the project’s outcomes are meeting the stated objectives and expectations. Efficiency assessment should determine if the project is cost and time effective and evaluate any delays in the project.

8.0 Blue Mountains World Heritage Institute Upland Swamp Project

The Blue Mountains World Heritage Institute (BMWHI) and partners have initiated a project with the objective of evaluating the significance of the BMUS in maintaining water quality and quantity in the Greater Blue Mountains World Heritage Area, and monitoring their function under climate change. This project will use ongoing research to better understand the regional and large-scale significance of swamps as well as the potential consequences of their diminishing. This information will help inform management, rehabilitation and conservation plans.

The project will be undertaken with input from different teams at various institutions. Scott Mooney at the University of New South Wales (UNSW) will lead a team that focuses on quantifying water volume in BMUS(?) which will help inform water budget models and provide information on the complex water dynamics in swamp systems. Dr Ian Wright at Western Sydney University will lead a team that focuses on assessing water quality entering and leaving the BMUS(?). Dr Rachael Dudaniee at Macquarie University will lead a team focusing on the role of macro-invertebrates in providing ecosystem services and maintaining swamp function. Peter Dupen at WaterNSW will focus on understanding hydrological flow patterns between swamps, groundwater systems and surface water systems on a regional(?) scale. John Merson and the BMWHI team will integrate findings from the research and provide regular reporting on progress. Michael Hensen and Geoffrey Smith from the Environment division of Blue Mountains City Council will review the research and recommendations in these reports for possible integration into Upland Swamp management strategies.

The BMWHI Upland Swamp Project fits well into an adaptive management approach relevant to BMUS management needs. The collaborative research undertaken by the partner investigator teams will increase knowledge and provide additional baseline information for monitoring. The Upland Swamp Project will also assess the effectiveness of current restoration measures, which will help inform future decisions. This will create a foundation for continuous improvement to swamp management, rehabilitation and conservation.

9.0 Conclusions

In addition to summarizing the research that has been done on the BMUS this review identifies where there are gaps in the current knowledge; whether such gaps arise from insufficient research or the inherent uncertainty surrounding complex swamp systems. It is crucial that such knowledge gaps are acknowledged and addressed in plans of management. Firstly, more research on the dynamic relation between BMUS and other water systems could show how impaired hydrologic functioning in swamps will affect water systems on a large-scale beyond the Blue Mountains region. Secondly, quantitative estimates of the volume of carbon and water stored in swamps could show how valuable BMUS are in terms of climate change mitigation and providing freshwater resources. While research in these areas should be done to better inform managers, decisions must still be made in the face of uncertainty. Being able to make the BMUS resilient to a changing environment is crucial if they are to continue providing valuable ecosystem services. Adaptive management and collaborative research can build this resilience and ensure the long-term conservation of the Blue Mountain Upland Swamps.

10.0 Bibliography

Allen, CR, Fontaine, JJ, Pope, KL & Garmestani, AS 2011, 'Adaptive management for a turbulent future', *Journal of Environmental Management*, vol. 92, no. 5, pp. 1339-1345.

Ashby, N, Fryirs, K & Howitt, R 2014, 'Adaptive management of Temperate Highland Peat Swamps on Sandstone in the Blue Mountains: Is it occurring?', in G, Vietz, ID, Rutherford & R, Highes (eds), *Proceedings of the 7th Australian stream management conference,* pp. 378-384, Townsville, Queensland.

Banaszuk, P & Kamocki, A 2008, 'Effects of climatic fluctuations and land-use changes on the hydrology of temperate fluviogenous mire', *Ecological Engineering*, vol. 32, no. 2, pp. 133-146.

Belmer, N, Tippler, C & Wright, IA 2018, 'Aquatic ecosystem degradation of high conservation value upland swamps, Blue Mountains Australia', *Water, Air,* *and Soil Pollution*, vol. 229, no. 3, pp. 1-8.

Belmer, N, Wright, IA & Tippler, C 2015, 'Urban geochemical contamination of high conservation value upland swamps, Blue Mountains Australia', *Water, Air, and Soil Pollution*, vol. 226, no. 10, pp. 1-5.

Billet, MF, Charman, DJ, Clark, JM, Evans, CD, Evans, MG, Ostole, NJ, Worrall, F, Burden, A, Dinsmore, KJ, Jones, T, McNamara, NP, Parry, L, Rowson, JG & Rose, R 2010, 'Carbon balance of UK peatlands: Current state of knowledge and future research challenges', *Climate Research*,vol. 45, no.1, pp. 13-29.

Birgé, HE, Allen, CR, Garmestani, AS & Pope, KL 2016, 'Adaptive management for ecosystem services', *Journal of Environmental Management*, vol. 183, pp. 343-352.

Blue Mountains City Council 2010a, *Soft-engineering solutions for swamp remediation – a "how to" guide,* Section 1, BMCC, NSW.

Blue Mountains City Council 2010b, *Soft-engineering solutions for swamp remediation – a "how to" guide,* Section 2, BMCC, NSW.

Blue Mountains City Council 2018, *Waterways Swamps,* BMCC, NSW, viewed 19 September 2018,
<https://www.bmcc.nsw.gov.au/environment/waterways/swamps>.

Bonn, A, Allott, T, Evans, M, Joosten, H & Stoneman, R 2016, 'Peatland restoration and ecosystem services: an introduction', in A, Bonn, T, Allott, M, Evnas, H, Joosten & R, Stoneman (eds), *Peatland restoration and ecosystem services: Science, policy and practice*, Cambridge University Press, Cambridge, United Kingdom.

Brownstein, G, Blick, R, Johns, C, Bricher, P, Fletcher, A & Erskine, PD 2014, 'Optimising a sampling design for endangered wetland plant communities: Another call for adaptive management in monitoring', *Wetlands*, vol. 35, no. 1, pp. 105-113.

Centennial Coal 2013, *Temperate Highland Peat Swamps on Sandstone monitoring and management plan for LW's 415 - 417 Springvale Mine,* Toronto, NSW.

Commonwealth of Australia 2014a, *Temperate Highland Peat Swamps on*

Sandstone: longwall mining engineering design—subsidence prediction, buffer distances and mine design options, Knowledge Report, prepared by Coffey Geotechnics for the Department of the Environment, Commonwealth of Australia, Canberra.

Commonwealth of Australia 2014b, *Temperate Highland Peat Swamps on Sandstone: ecological characteristics, sensitivities to change, and monitoring and reporting techniques,* Knowledge Report, prepared by Jacobs SKM for the Department of the Environment, Commonwealth of Australia, Canberra.

Commonwealth of Australia 2014c, *Temperate Highland Peat Swamps on Sandstone: evaluation of mitigation and remediation techniques*, Knowledge Report, prepared by the Water Research Laboratory, University of New South Wales, for the Department of the Environment, Commonwealth of Australia, Canberra.

Commonwealth of Australia 2015, *Management and monitoring of subsidence induced by longwall coal mining activity*, prepared by Jacobs Group (Australia) for the Department of the Environment, Commonwealth of Australia, Canberra.

Cowley, K, Looman, A, Maher, DT & Fryirs, K 2018, Geomorphic controls on fluvial carbon exports and emissions from upland swamps in eastern Australia', *Science of the Total Environment*, vol. 618, pp. 765-776.

Cowley, KL, Fryirs, KA & Hose, GC 2016a, 'Identifying key sedimentary indicators of geomorphic structure and function of upland swamps in the Blue Mountains for use in condition assessment and monitoring', *Catena*, vol. 147, pp. 564-577.

Cowley, KL, Fryirs, KA & Hose, GC 2018, 'The hydrological function of upland swamps in eastern Australia: The role of geomorphic condition in regulating water storage and discharge', *Geomorphology*, vol. 310, pp. 29-44.

Department of Agriculture Fisheries and Forestry 2012*, Guidelines and template for preparing a wetland management plan*, prepared for primary producers (grazing, dryland cropping) in Queensland's inland catchments, Queensland Government, Brisbane.
Dovers, S, Whinman, J, Krogh, M, Young, A & Crawford, M 2017, 'Lessons for collaborative research in a changing operating environment', *Ecological Management & Restoration,* vol. 18, no. 2, pp. 120-124.

Finlayson, CM, Davis, JA, Gell, PA, Kingsford, RT & Parton KA 2013, 'The status of wetlands and the predicted effects of global climate change: The situation in Australia', *Aquatic Sciences*, vol. 75, no. 1, pp. 73-93.

Freidman, BL & Fryirs, KA 2015, 'Rehabilitating upland swamps using environmental histories: A case study of the Blue Mountains Peat Swamps, Eastern Australia', *Geografiska Annaler: Series A, Physical Geography*, vol. 97, no. 2, pp. 337-353.

Fryirs, K, Freidman, B, Williams, R & Geraldine, J 2014, 'Peatlands in eastern Australia? Sedimentology and age structure of Temperate Highland Peat Swamps on Sandstone (THPSS) in the Southern Highlands and Blue Mountains of NSW, Australia', *Holocene*, vol. 24, no. 11, pp. 1527-1538.

Fryirs, KA, Cowley, K & Hose GC 2016b, 'Intrinsic and extrinsic controls on the geomorphic condition of upland swamps in Eastern NSW', *Catena,* vol. 137, pp. 100-112.

Fryirs, K, Gough, J & Hose, GC 2014, 'The geomorphic character and hydrological function of an upland swamp, Budderoo plateau, southern highlands, NSW, Australia', *Physical Geography*, vol. 35, no. 4, pp. 313-334.

Gillson, K & Duffin, KI 2007, 'Thresholds of potential concern as benchmarks in the management of African savannahs', *Philosophical Transactions of the Royal Society B: Biological Sciences*, vol. 362, no. 1478, pp. 309-319.

Glamore, W, Rayner, D & Anderson, D 2016, *Upland Temperate Highland Peat Swamps on Sandstone hydrology investigations,* UNSW Water Research Laboratory, Sydney, NSW.

Hensen, M & Mahoney E 2010, 'Reversing drivers of degradation in Blue Mountains and Newnes Plateau Shrub Swamp endangered ecological communities', *Australasian Plant Conservation: Journal of the Australian Network for Plant Conservation*, vol. 18, no.4, pp. 5-6.

Holden, J, Evans, MG, Burt, TP, Horton, M 2006, 'Impact of land drainage on peatland hydrology', *Journal of Environment Quality*, vol. 35, no. 5, pp. 1764-1778.

Page, SE & Hooijer, A 2016, 'In the line of fire: The peatlands of Southeast Asia', *Philosophical Transactions of the Royal Society of London, Series B, Biological Sciences,* vol. 371, no. 1696.

Hope, G, Nanson, R & Jones P 2011, *The peat-forming bogs and fens of the Snowy Mountains of NSW,* Department of Archaeology and Natural History, Australian National University, Canberra, ACT.

IUCN 2017, *Peatlands and cilmate change,* International Union for Conservation of Nature, Gland, Switzerland.

Joosten, H 2010, 'The global peatland CO2 picture: Peatland status and emmissions in all countries of the world', *Greifswald University Wetlands International,* Wageningen, the Netherlands.

Keith, DA, Rodoreda, S & Bedward, M 2010, 'Decadal change in wetland-woodland boundaries during the late 20th century reflects climatic trends', *Global Change Biology*, vol. 16, no. 8, pp. 2300-2306.

Kohlhagen, T, Fryirs, K & Semple, AL 2013, 'Highlighting the need and potential for use of interdisciplinary science in adaptive environmental management: The case of endangered upland swamps in the Blue Mountains, NSW, Australia', *Geographical Research*, vol. 51, no. 4, pp. 439-453.

Krogh, M 2015, Environmental Trust Grant 2011/RD/0028: Hydrology of Upland Swamps on the Woronora Plateau Final Report, Office of Environment and Heritage Science Division.

Labadz, J, Allott, T, Evans, M, Butcher, D, Billett, M, Stainer, S, Yallop, A, Jones, P, Innerdale, M, Harmon, N, Maher, K, Bradbury, R, Mount, D, O'Brien, H & Hart, R 2010, *Peatland Hydrology,* IUCN UK Peatland Programme, Edinburgh, United Kingdom.

Limpens, J, Berendse, F, Blodau, C, Canadell, JG, Freeman, C, Holden, J, Roulet, N, Rydin, H & Schaenman-Strub, G 2008, 'Peatlands and the carbon cycle: from local processes to global implications - a synthesis', *Biogeosciences*, vol. 5, pp. 1475-1491.

McNally, G & Evans, R 2007, *Impacts of longwall mining on surface water and groundwater, Southern Coalfield NSW,* prepared by eWater CRC for NSW Department of Environment and Climate Change, Sydney, NSW.

Gold, A & Merson, J 2013, *The need for a strong Blue Mountain local environmental plan to safeguard the Greater Blue Mountains World Heritage Area,* Blue Mountains World Heritage Institute, Katoomba, NSW.

Moore, S, Evans, CD, Page, SE, Garnett, MH, Jones, TG, Freeman, C, Hooijer, A, Wiltshire, AJ, Limin, SH & Gauci, V 2013, 'Deep instability of deforested tropical peatlands revealed by fluvial organic carbon fluxes', *Nature,* vol. 493, no. 7434, pp. 660-663.

Office of Environment and Heritage 2011, *Blue Mountains Swamps in the Sydney Basin Bioregion - vulnerable ecological community listing*, Office of Environment and Heritage, NSW, viewed 1 October 2018, < file:///Users/alyssa/Desktop/Research%20Project/References/OEH%202011.webarchive>.

Office of Environment and Heritage 2014, *New South Wales climate change snapshot*, Office of Environment and Heritage & Adapt NSW.

Office of Environment and Heritage 2016, B*lue Mountains Swamps in the Sydney Basin Bioregion - vulnerable ecological community listing,* Office of Environment and Heritage, NSW, viewed 13 September 2018, <https://www.environment.nsw.gov.au/determinations/BlueMountainsSwampsVulnerableEcologicalCommunity.htm>

Page, SE & Baird, AJ 2016, 'Peatlands and global change: Response and resilience', *Annual Review of Environment and Resources,* vol. 41, pp. 35-57.

Rayment, G & Lyons, D 2010, *Soil chemical methods: Australasia*, CSIRO Publishing, Clayton, Victoria.

Rogers, K & Biggs, H 1999, 'Interacting indicators, endpoints and value systems in strategic management of the rivers of the Kruger National Park', *Freshwater Biology,* vol. 41, pp. 439-451.

Russi, D, ten Brink, P, Farmer, A, Badura, T, Coates, D, Förster, J, Kumar, R & Davidson, N 2013, *The economics of ecosystem and biodiversity for water and wetlands,* IEEP, London and Brussels; Ramsar Secretariat, Gland.

UNDP-GEF 2010, *Renaturalization and sustainable management of peatlands in Belarus to combat land degradation, ensure conservation of globally valuable biodiversity, and mitigate climate change,* Terminal Evaluation of GEF Peatland Project, Belarus.

Water NSW 2016, *Risk-Based Mining Assessment Framework – Phase 1 Literature Review*, Advisian WorleyParsons Group, Sydney, NSW.

Young, A 2017, *Upland Swamps in the Sydney Region*, Dr Ann Young, Marrickville, NSW.