

Article

Water Sources of Upland Swamps in Eastern Australia: Implications for System Integrity with Aquifer Interference and a Changing Climate

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Abstract: Temperate Highland Peat Swamps on Sandstone (THPSS) in Eastern Australia are Groundwater Dependent Terrestrial Ecosystems that occur in the headwaters of streams on low relief plateaus. Like upland swamps and peatlands globally, they provide base flow to downstream catchments. However, these swamps are subject to aquifer interference from mining and groundwater extraction and are threatened by urbanization and climate change. We collected winter and summer water samples from swamps in two highland regions of Eastern Australia. Water from the swamps was analyzed for hydrogen ($\delta^2\text{H}$) and oxygen ($\delta^{18}\text{O}$) isotopes and compared with rainwater, surface water and groundwater samples from the surrounding bedrock aquifers to identify likely swamp water sources. Radon (^{222}Rn) was used as an environmental tracer to determine whether the swamps were predominantly groundwater or rainwater fed. Four out of five swamps sampled in the Blue Mountains had greater than 30% of water derived from the surrounding bedrock aquifer, whereas swamps in the Southern Highlands received less than 15% of water from the surrounding aquifer. The water sources for swamps in both regions are controlled by catchment morphology, e.g., valley shape. Understanding water sources of these systems is critical for the determination of likely impacts on THPSS from aquifer interference activities and a changing climate.

Keywords: upland swamps; peatland; radon; isotopes; aquifer connectivity; water table; groundwater dependent terrestrial ecosystems

1. Introduction

Temperate Highland Peat Swamps on Sandstone (THPSS) are a type of peat forming wetland located on plateaus in the headwaters of streams that feed into major drinking water catchments of eastern Australian cities. They are valley bottom swamps similar to the ‘fen’ classification of Northern Hemisphere peatlands in terms of their landscape position, morphology and sedge dominated floristics [1,2]. THPSS are low energy, sediment accumulation systems that terminate downslope at a bedrock constriction or step, discharging at the downstream end to small bedrock streams [3–5]. Like their Northern Hemisphere counterparts, THPSS are late-Pleistocene to Holocene features that began forming when increased rainfall and higher temperatures facilitated plant growth which led to organic matter accumulation within the sediment matrix, allowing for the formation of peat [6–8].

THPSS function in ways similar to other upland swamps and peatlands, acting as water storage and delivery systems to downstream catchments and providing base flow in dry times [9–13].

The standing water level in the swamps is typically around 0.2 m below the soil surface [3] although the sediment column is typically saturated due to soil capillary forces [14]. There is almost no surface water within THPSS, except during rainfall events [15]. They are Groundwater Dependent Terrestrial Ecosystems where their high water tables are an essential requirement for the maintenance of their unique hydrophilic vegetation and for the storage of carbon [3,9,14,16,17].

THPSS and peatland systems globally are under considerable stress from anthropogenic activities operating at different spatial scales [18–20]. Degradation from swamp drainage, channelization and peat extraction is well documented [3,21–24]. However, impacts from indirect, catchment-scale activities such as underground (longwall) mining and groundwater extraction have not been widely studied [25]. Activities that interfere with local and regional aquifers can have catastrophic consequences for groundwater dependent ecosystems such as peatlands and swamps [26–28]. Understanding where these swamps source their water is essential, not only for the appropriate management of downstream water resources, but also for the conservation of these ecosystems.

The water budgets of peatland systems typically consist of precipitation, evapotranspiration and interactions with surface and regional groundwaters [29,30]. The extent to which regional groundwater influences peatland hydrology is often constrained by geology and geomorphic setting [31–34], while the precipitation and evapotranspiration components are largely a function of climate and altitude [35–37].

Peatlands in the northern hemisphere have been classified according to their hydrological and geomorphic structure [2]. Blanket bogs and raised mires are largely rainwater fed systems located in undulating to flat catchments. They rely on high precipitation and low evaporation rates to maintain their water tables [2]. Valley or basin fens source a significant component of their water from the surrounding groundwater aquifers [33,38,39]. These peatlands are moderately steep and found in low points or valleys within high altitude areas [2]. Thus, the geomorphic structure of these systems plays a significant role in whether they have hydrological connectivity with the surrounding aquifer. Despite the similarities in the geomorphology of Northern Hemisphere fens and THPSS, no work has been undertaken, to date, to determine whether, like fens, THPSS are groundwater fed.

The aims of this paper are to:

- (1) investigate the structural attributes that may play a role in determining the hydraulic connectivity of THPSS swamp water to local bedrock aquifers (henceforth called groundwater);
- (2) identify the extent to which the swamp aquifer (henceforth called swamp water) contributes to downstream surface waters; and
- (3) discuss implications of how groundwater interference and climate change disturbances will impact on the water storage capacity of these systems with knock-on effects to other functions such as carbon storage.

We used oxygen ($\delta^{18}\text{O}$) and hydrogen ($\delta^2\text{H}$) isotopes, and ^{222}Rn as environmental tracers of rainwater and groundwater contributions to determine the relative sources of water within 17 swamps in the Blue Mountains and Southern Highlands regions of NSW, Australia. Swamp/catchment morphometrics were analyzed using GIS. We hypothesized that the geomorphic structure of swamps and their catchments are a key control on where swamps source their water from and that swamp water makes a significant contribution to downstream surface water flow.

2. Regional Setting

2.1. Blue Mountains Study Area and Hydrogeology

The study area is located within the Blue Mountains World Heritage Area (Katoomba 33°42'51" S; 150°18'36" E), approximately 100 km west of Sydney (Figures 1 and 2a). The geology of the Blue Mountains plateau consists of low relief Triassic quartz sandstones inter-bedded with claystones which are dissected by steep dendritic gorges [40,41]. Elevation extends to over 1000 m above sea level (asl)

at Blackheath. Rainfall for the region falls primarily in the summer months with mean annual rainfall at Katoomba of 1400 mm/year [42]. Snowfalls in the upper Blue Mountains can occur during winter with Blackheath receiving 15–20 cm in July 2015 during the study period [43]. The average maximum air temperature for Katoomba in summer is 23 °C while the mean minimum is 13 °C. The average maximum for winter is 9 °C while mean minimum is 3 °C. Relative humidity averages 74% [42].

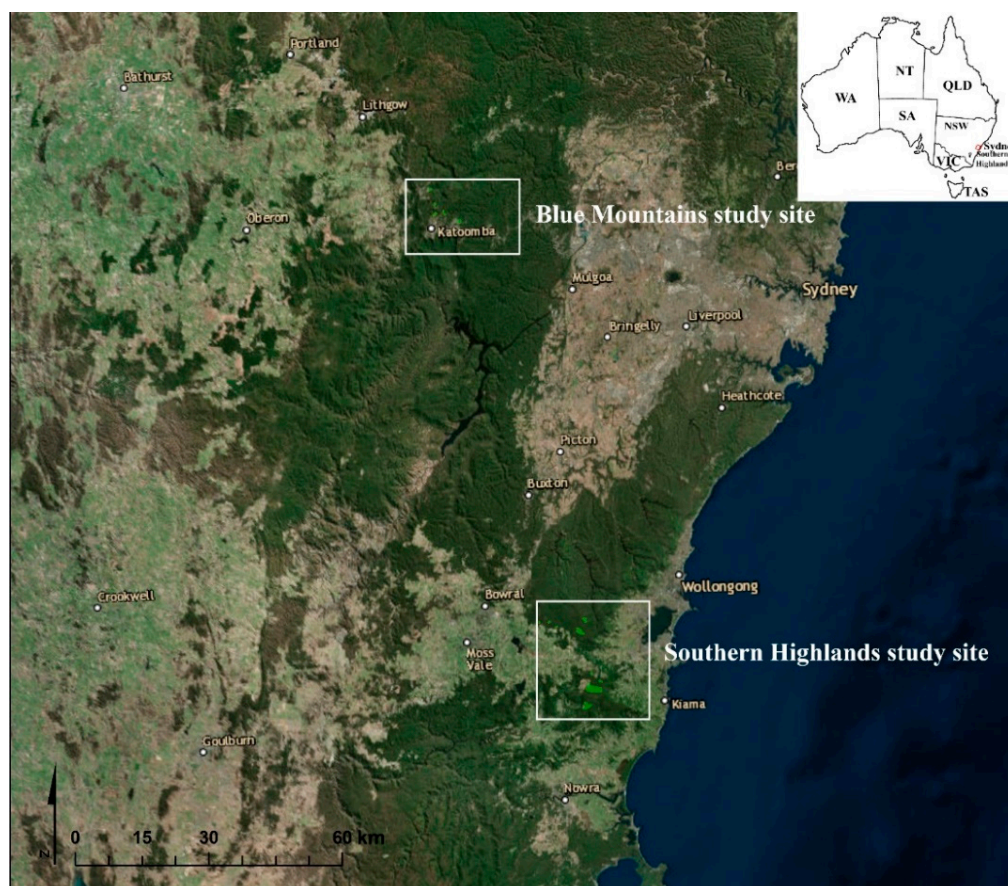


Figure 1. Location map of the study regions.

The hydrogeology of the upper Blue Mountains sandstones is complex with both primary and secondary permeability occurring within four geological formations: Hawkesbury Sandstone dominates the ridges of the lower Blue Mountains consisting of cross-bedded medium to coarse quartzose sandstone, 1–10 m thick with lenses of laminate shale up to 3 m thick. The upper 30 m of this formation is poorly cemented west of Hazelbrook. The Narrabeen Group underlies the Hawkesbury Sandstone and consists of three formations: the Burrellow Formation, an interbedded shale, laminate, fine quartz lithic sandstone and medium to coarse quartzose sandstone and conglomerate that is coarser and interbedded with more fine conglomerates in the western Blue Mountains: Wentworth Falls Claystones are red to grey kaolinite, illite and quartz claystone interbedded with sandstone 2 m thick at Katoomba: Banks Wall Sandstone, a coarse to very coarse quartzose sandstone with frequent claystone layers and iron cemented zones, 100 to 300 m thick [44]. Within the Hawkesbury Sandstone, primary permeability occurs west of Hazelbrook particularly within the sandstone overlying the Wentworth Falls claystone in the upper Blue Mountains [44]. Primary water bearing zones are between 2.5 and 185 m below ground level (bgl) with an average depth of 34.5 m. THPSS are located within these claystone/sandstone geological units [45].

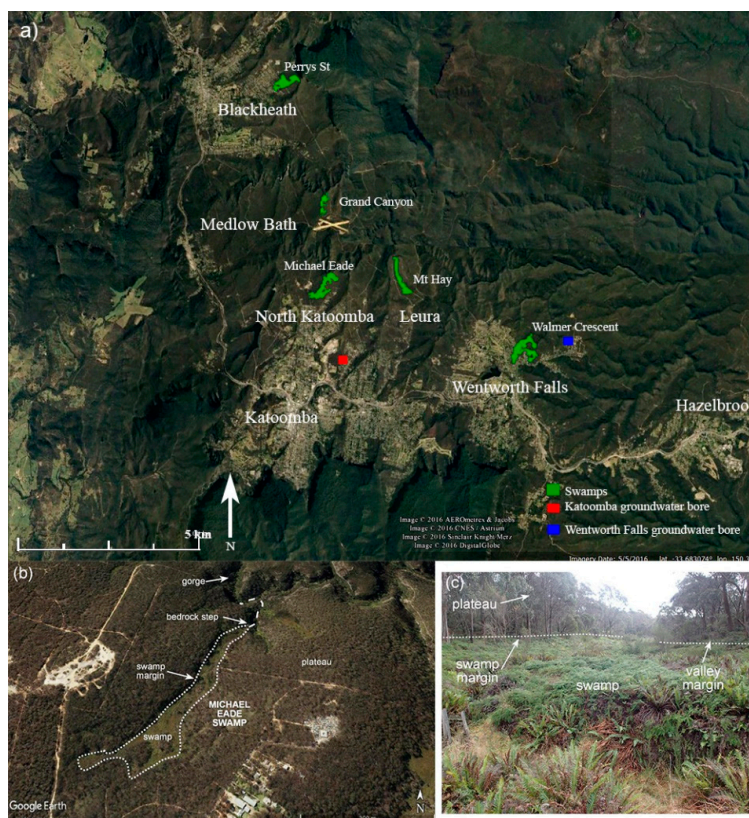


Figure 2. Blue Mountains swamps. (a) swamp and groundwater bore locations (b) tilted Google Earth image showing swamp morphology for Michael Eade swamp; (c) on-ground shot of Marmion swamp, photo source: K. Fryirs. Note steep-sided V-shaped valley and elongate swamp morphology.

The sedimentology of intact Blue Mountains THPSS consists of four distinct units [3,9,46,47]. The surficial organic fines (SOF) is a surface layer to a maximum depth of 0.7 m. This layer is highly porous consisting of red-brown fine sands and silts with living organic matter within the sediment matrix [3]. Relatively low carbon to nitrogen ratios indicate high rates of organic decomposition [48]. Moisture content within this unit is high, however the water table only reaches this layer during or after rainfall [9]. Underlying the SOF is the alternating organic sands (AOS) which are black, highly organic, alternating sandy loams and loamy sands. High carbon to nitrogen ratios in this unit indicate high carbon storage [3]. Water tables generally sit within this layer [9].

Five THPSS in the Blue Mountains were chosen from the database reported in Fryirs and Hose [4] and Fryirs, et al. [49]. The swamps are located in Wentworth Falls, Leura, North Katoomba, Medlow Bath and Blackheath (Figure 2a). The swamps range in elevation from 836 m asl for the Wentworth Falls Site to 983 m asl for Blackheath. The swamps are located within small steep sided elongate V-shaped valleys at the top of the Blue Mountains plateau with a generally north-easterly aspect. Downslope, the swamps discharge into small bedrock streams from a knickpoint or bedrock step [49] (Figure 2b,c). Sclerophyll forest or woodland vegetation communities border the swamps with sedge, grass, heath and shrub communities occupying the swamp center [50] (Figure 2c). Dominant species includes *Carex* spp., *Lepidosperma limicolum*, *Dichelachne inaequalis*, *Poa labillardieri* var. *labillardieri*, *Epacris microphylla*, *Epacris paludosa* and shrubs; *Grevillea acanthifolia*, *Hakea* spp., *Leptospermum* spp. [20].

2.2. Southern Highlands Study Area and Hydrogeology

The Southern Highlands study area is located approximately 100 km southwest of Sydney on the Illawarra Escarpment, an undulating, low relief plateau of Hawkesbury sandstone lying at approximately 600–800 m asl [51] (Figures 1 and 3a). The geology consists of horizontally bedded

Triassic sandstone with basalt capping in localized areas [52]. Hawkesbury Sandstone is the surficial geological unit in the area [53]. The study area can be divided into two subregions: the East Kangaloon area, located within the Nepean River catchment and the Budderoo area, located within the Kangaroo River catchment (Figure 3a). The East Kangaloon area falls within Sydney's drinking water catchment. The Budderoo area, 16 km west of Kiama, falls within Budderoo National Park and drains into the Kangaroo River, which is part of the Shoalhaven River catchment. Average annual rainfall is 1600 mm/year at Robertson to the northwest of both subregions [42], however a rainfall gradient occurs on the plateau, increasing in the east at approximately 50 mm/km, largely due to orographic precipitation [51]. Evaporation is lower than precipitation inputs, creating a positive precipitation to evaporation ratio that is most apparent in winter [54]. Mean minimum and maximum summer temperatures are 12 and 26 °C respectively, and mean winter minimum and maximums are 2 and 13 °C, respectively. Relative humidity averages 75% [42].

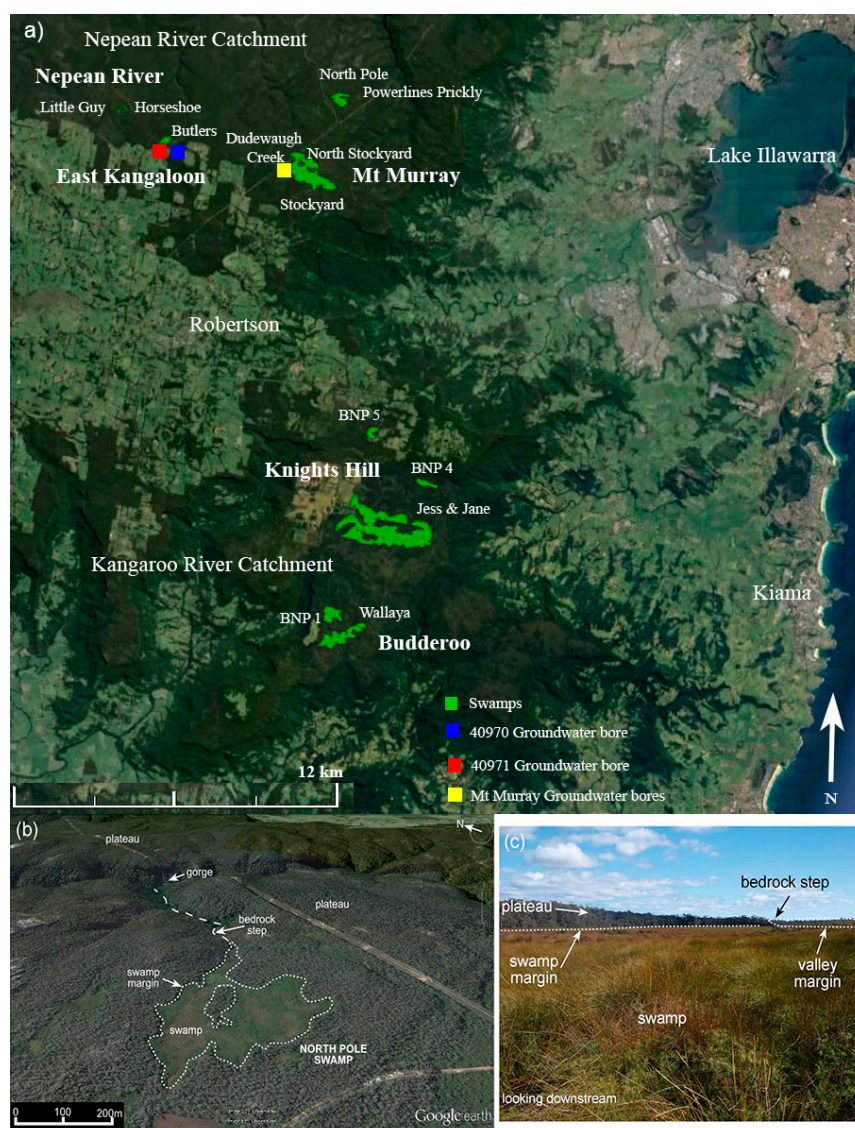


Figure 3. Southern Highlands swamps. (a) swamp and groundwater bore locations (b) tilted Google Earth image showing swamp morphology (modified from Fryirs et al., 2018 [50]); (c) on-ground shot of Jess and Jane swamp, photo source: K. Fryirs. Note low-lying plateau, shallow U-shaped valley and rounded swamp morphology.

The Hawkesbury Sandstone unit in this region is considered the primary water bearing geological unit. It is a layered aquifer with multiple groundwater bearing zones within vertically discrete horizons of varying connectivity. Groundwater occurs as both primary (through sandstone pore space) and secondary fracture flows. The East Kangaloon area is considered the primary recharge area for the regional aquifer [53]. Distinct water bearing zones occur within secondary porosity fractures that have considerable lateral variability [55]. There are two major aquifer zones in the upper part of the Hawkesbury Sandstone; the upper aquifer lies at depths of 15–40 m and the lower aquifer occurs between 40 and 60 m although a shallow water bearing zone occurs at 5–7 m bgl [56]. The sedimentology of the Southern Highlands THPSS is similar to that of the Blue Mountains swamps with the four previously described sedimentary units overlying bedrock or saprolite [47].

Seven THPSS in the East Kangaloon sub-region and five in the Budderoo sub-region were selected for sampling based on previous investigations [47] (Figure 3a). Elevation ranges from 580 m to 640 m asl across the two subregions. These swamps are relatively large, flat basins located within round, low relief valleys (Figure 3b,c). Vegetation is dominated by *Gymnoschoenus sphaerocephalus*, *Drosera binata*, *Baumea articulate*, *Leptospermum juniperinum*, *Gleichenia dicarpa* and *Xyris operculata* [14].

3. Materials and Methods

3.1. Swamp Morphometry

Mapping of THPSS catchment areas was undertaken using hydrologically enforced SRTM Digital Elevation Models (DEM) sourced from Geoscience Australia's Elevation Information System in ARCGIS 10.3. Swamps and their associated catchments were mapped as discrete polygons for attribute analysis. Physical attributes such as swamp and catchment area, slope and elevation were measured using GIS automation tools. Statistical analysis of physical attributes and water sources and storage times was undertaken using Principal Component Analysis, 1-way analysis of variance (ANOVA) and a linear regression model in Minitab® (version 17.3.1). Assumptions of normality and homogeneity of variance were assessed using Q-Q plots and plots of residuals. The significance level (α) for all tests was 0.05.

3.2. Water Sample Collection

3.2.1. Isotopes

Stable isotopes of oxygen ($\delta^{18}\text{O}$) and hydrogen ($\delta^2\text{H}$) are widely used in hydrological investigations because kinetic changes that produce fractionation and mixing of $\delta^{18}\text{O}$ and $\delta^2\text{H}$ isotopes from differing sources can provide valuable information on water residence times, sources and climate sensitivity [57]. In this study, $\delta^2\text{H}$ and $\delta^{18}\text{O}$ isotope values were used to establish mixing lines to ascertain whether regional groundwater is an endmember of swamp water.

Sampling within the Blue Mountains and Southern Highlands took place between July 2015 and February 2016. Samples for isotope analysis from both swamp water and surface water of bedrock streams located downstream of the swamps were collected in two rounds; July–August 2015 and January–February 2016. Rainwater samples for isotope analysis were collected in each region from rain events either prior to, or during sampling events. Additional rainwater $\delta^{18}\text{O}$ and $\delta^2\text{H}$ isotope values from samples were collected as part of a study by Hose, et al. [58].

Swamp water was collected from piezometers installed within the swamps. Each piezometer was constructed of 50 mm diameter PVC pipe, slotted (1 mm width) along its entirety, with a basal cap. The piezometers extended through the alluvial sediment to saprolite or bedrock and were installed using a Russian D-corer to maximum depth of 2.81 m. The depth of swamp sediments ranged from 0.75 to 2.81 m.

The piezometers were purged prior to sampling by removing three well-volumes of water using a bailer. Physico-chemical parameters of temperature, dissolved oxygen, pH, and electrical conductivity

were measured using a YSI Pro Plus multi-parameter meter (YSI Inc., Yellow Springs, OH, USA) and sampling was undertaken after these parameters had stabilized. Samples were collected in 30 mL HDPE bottles, ensuring no headspace. Lids of the bottles were sealed with tape to prevent evaporation and were stored away from direct sunlight until analysis. Surface water samples were collected from small bedrock streams downstream of the swamps at the same time as swamp water sampling. Physico-chemical parameters were measured during sample collection. Groundwater samples were collected from existing groundwater bores in each region with physico-chemical parameters measured prior to sampling.

The depth of the Wentworth Falls and Katoomba groundwater bores in the Blue Mountains were 50 m and 19 m below ground level (bgl) respectively with static water levels in the Katoomba bore between 3.4 and 4.4 m bgl. Groundwater bores in the Southern Highlands were at depths of 7 m and 90 m bgl with static water levels between 1.05 and 2.5 and 1.7 and 3.12 m bgl respectively. Three well volumes were purged using a peristaltic pump (Geotech Geopump™ Peristaltic Pump Series II). Samples were analyzed at the Environmental Isotope Laboratory at Australian Nuclear Science and Technology (ANSTO).

The stable isotope ratios of $\delta^{18/16}\text{O}\text{‰}$ and $\delta^{2/1}\text{H}\text{‰}$ were obtained via isotope ratio infrared spectroscopy (IRIS) [59,60] using a Picarro™ L2130i cavity ring down spectrometer. Instrument calibration and quality control is achieved by utilizing secondary standards that have been accurately calibrated against IAEA primary standards VSMOW2, SLAP2 and GISP. Multiple sets of standards are analyzed throughout the analytical run to enable instrument drift correction. Each standard and sample are injected six times into the instrument, the first injection is used to flush the system to remove memory effects; the remaining five injections are used to generate analytical data with small standard deviations. Raw data analysis and reduction are undertaken using the IAEA's SICalb software, version 2.14j. Stable isotope data are reported as δ -values relative to VSMOW.

3.2.2. Radon (^{222}Rn)

Radon (^{222}Rn) is an inert gas with a half-life of 3.8 days that has been used as an environmental tracer of groundwater for well over 20 years [61,62]. It is produced by the radioactive decay of ^{226}Ra and emanates from mineral grains by α -recoil which dissolves in the aqueous phase making it an ideal conservative tracer for groundwater [62–64].

Sample collection for ^{222}Rn took place in October 2015 in the Blue Mountains and in December 2015 in the Southern Highlands. Samples were collected from the swamp water within the fully screened piezometers installed within the swamps. Three well volumes were purged prior to sampling using a peristaltic pump (Geotech Geopump™ Peristaltic Pump Series II). Temperature, dissolved oxygen, pH, and electrical conductivity were measured using handheld meters and water sampling for ^{222}Rn analysis was undertaken after these parameters had stabilized.

Samples were collected in 1.25 L PET bottles using the peristaltic pump. The bottles were filled to three times overflowing to ensure no headspace remained in the bottle. Surface water samples were collected from the small bedrock streams, below each swamp. The PET bottles were then placed within an insulated container heated to 25 °C prior to extraction.

Extraction took place within 4 h of sampling. Fifty milliliters of water was removed from the bottles using a syringe and then 25 mL of mineral scintillant was injected into the bottles. The bottle was then shaken for 4 min prior to scintillant aqueous phase extraction into a 20 mL PTFE scintillation vial [65]. Samples were transported within 2 h of extraction to the Radon Analytical Laboratory at Australian Nuclear Science and Technology Organisation (ANSTO).

Sediment emanation incubation was undertaken using 350 g of sediment from cores collected during the water sampling rounds. The sediment was placed in 50 μm filter bags within PVC containers 300 mm high and 100 mm diameter. The containers were then filled with 2.4 L deionized water ensuring no headspace and sealed. The containers were then left to incubate for six weeks. The incubated water was then removed from the containers using a peristaltic pump connected to HDPE tubing (sealed

within the PVC container) into 1.25 L PET bottles. Extraction methods then followed the field-based extraction methodology.

The ^{222}Rn samples were analyzed via liquid scintillation counting on a PerkinElmerTM Quantulus 1220 ultra-low background liquid scintillation counter. Samples were allowed to thermally stabilize inside the counter for several hours before being assayed. A standardized solution of ^{226}Ra , which was sealed inside an air-tight glass Schott bottle with no headspace for 2 months, was used as the analytical standard. The ^{222}Rn from this solution was extracted from the solution in the same way as the samples. An analytical blank was also created by utilizing RO water in place of sample/standard solutions, hence eliminating matrix effects. All samples/standards/blanks were counted under identical conditions using a PSA value of 58 to discriminate between alpha and beta decay. Quantification of the ^{222}Rn activity in the samples was completed using first principles including blank subtraction and decay correction back to the sampling date/time.

3.3. Calculating Water Sources

Radon is conventionally used as an environmental tracer to quantify groundwater inputs in surface waters. This study attempts to determine if groundwater is a significant swamp water source. This means that conventional mixing equations require some modification to suit the examination of a receiving body that is a shallow groundwater aquifer rather than a surface water body.

To estimate ^{222}Rn activity in the swamp water that can be explained by groundwater sources, ^{222}Rn emanation from the sediment incubation was subtracted from the radon activity derived from the swamp water samples, as modified from Santos and Eyre [66]:

$$^{222}\text{Rn}_{\text{ex}} = ^{222}\text{Rn}_{\text{sw}} - ^{222}\text{Rn}_{\text{em}} \quad (1)$$

where $^{222}\text{Rn}_{\text{ex}}$ is the ^{222}Rn activity in swamp water that can be explained by groundwater sources, $^{222}\text{Rn}_{\text{sw}}$ is the ^{222}Rn activity in the swamp water at the time of measurement and $^{222}\text{Rn}_{\text{em}}$ is the ^{222}Rn emanation from the sediment incubation.

Outgassing of ^{222}Rn to atmosphere was not considered to be important for the calculation of groundwater contribution to the swamp water, however radioactive decay of groundwater derived ^{222}Rn was considered in the mixing model. The calculation of radioactive decay for groundwater derived ^{222}Rn was modified from Burnett, et al. [67] such that:

$$^{222}\text{Rn}_{\text{dec}} = ^{222}\text{Rn}_{\text{gw}} - ([\text{Ln}(^{222}\text{Rn}_{\text{ex}}/^{222}\text{Rn}_{\text{gw}})] / -\lambda) \times \lambda \quad (2)$$

where $^{222}\text{Rn}_{\text{dec}}$ is the actual groundwater derived ^{222}Rn activity after radioactive decay has been accounted for, $^{222}\text{Rn}_{\text{gw}}$ is the ^{222}Rn activity in the groundwater at the time of measurement and λ is the radon decay constant (0.181 day^{-1}).

To calculate the relative ratio of groundwater to other water inputs, a simple mixing ratio, modified from Santos and Eyre [66], was used:

$$\text{GW}_{\text{ra}} = (^{222}\text{Rn}_{\text{ex}} / ^{222}\text{Rn}_{\text{gwdec}}) \times 100 \quad (3)$$

where: GW_{ra} is the percentage of groundwater passing through the vertical plane of the swamp at the point of measurement and $^{222}\text{Rn}_{\text{gwdec}}$ is the ^{222}Rn concentration in the groundwater end member after radioactive decay has been accounted for.

To calculate the minimum percentage of water from the swamp water that contributes to downstream surface waters, Equation (3) was modified such that:

$$\text{SW}_{\text{rn}} = (\text{Rn}_{\text{sur}} / \text{Rn}_{\text{sw}}) \times 100 \quad (4)$$

where SW_{rn} is the percentage of water derived from the swamp water, Rn_{sur} is the ^{222}Rn concentration in surface waters and Rn_{sw} is the ^{222}Rn concentration in the swamp water. As evasion to atmosphere has not been accounted for in this equation, it can only provide an estimate of the minimum contribution of the swamp water to surface waters.

Uncertainty analysis was undertaken for the radon mixing model to confirm their validity. Uncertainty was calculated from an error propagation equation [68] such that:

$$\gamma Q/Q = [\sqrt{(\gamma^{222}Rn_{sw}/^{222}Rn_{sw})^2 + (\gamma^{222}Rn_{gw}/^{222}Rn_{gw})^2}] \times GW_r \quad (5)$$

where γQ is the uncertainty of groundwater derived swamp water, Q is the calculated groundwater derived swamp water, $\gamma^{222}Rn_{sw}$ is the uncertainty of ^{222}Rn activity in the swamp water at the time of measurement and $\gamma^{222}Rn_{gw}$ is the uncertainty of ^{222}Rn activity in the groundwater at the time of measurement.

Defining endmembers of hydrological systems can be difficult due to spatial and temporal variability as well as errors in mixing models [69]. Determining endmembers from mixing lines can be useful in determining water sources, particularly for the identification of groundwater recharge [69]. Endmembers of mixed water samples should fall along the mixing line with the mixed waters within the interval defined by the endmembers [69]. Mixing lines for each swamp were developed from isotope ratios of the summer and winter groundwater and swamp water to validate whether groundwater was an endmember of the swamp water.

4. Results

4.1. Regional Differences in Swamp Morphometry

There were significant differences in swamp and catchment morphometry between the two regions. Mean swamp slope in the Blue Mountains ranged from 28° to 45° while swamps in the Southern Highlands ranged from 2.2° to 7° (Table 1). Minimum swamp slope differences were also significant ($p < 0.05$) with Blue Mountains mean minimum slopes, on average, 0.9° less than Southern Highlands' minimums. Catchment slope between the two regions was also significantly different ($p < 0.5$). Blue Mountains mean catchment slopes were between 5.3° and 9.9° , while Southern Highlands' catchment slopes were between 1.9° and 6.5° (Table 1). Catchment slope variability or range was also significantly different in the two regions, with slope ranges showing 55% more variation in the Blue Mountains (Table 1).

Table 1. Statistics for geomorphic attributes of swamps in the two regions.

Geomorphic Attribute of Swamp	Region	Min	Max	Mean (\pm SD)	ANOVA <i>p</i> -Value
Swamp area (m^2)	Blue Mountains	69,468	146,179	98,792 (\pm 31,946)	0.3
	Southern Highlands	12,913	1,794,440	275,337 (\pm 504,070)	
Swamp length (m)	Blue Mountains	652	1,086.6	845 (\pm 171)	0.7
	Southern Highlands	259	3373	987 (\pm 938)	
Minimum swamp slope ($^\circ$)	Blue Mountains	0	1.3	0.3 (\pm 0.6)	0 *
	Southern Highlands	0.2	3.1	1.2 (\pm 0.73)	
Mean swamp slope ($^\circ$)	Blue Mountains	28	45	36 (\pm 7)	0 *
	Southern Highlands	2.2	7	4.5 (\pm 1.5)	
Swamp elongation ratio	Blue Mountains	0.3	0.4	0.4 (\pm 0.08)	0.2
	Southern Highlands	0.3	0.6	0.4 (\pm 0.1)	
Aspect ($^\circ$)	Blue Mountains	114	234	176 (\pm 51)	0.3
	Southern Highlands	103	292	212 (\pm 62)	
Catchment area (m^2)	Blue Mountains	404,568	707,840	580,168 (\pm 131,493)	0.4
	Southern Highlands	159,345	4,557,040	925,632 (\pm 1,332,324)	
Catchment length (m)	Blue Mountains	1000	1393	1217 (\pm 171)	0.7
	Southern Highlands	515	3854	1410 (\pm 984)	

Table 1. Cont.

Geomorphic Attribute of Swamp	Region	Min	Max	Mean (\pm SD)	ANOVA <i>p</i> -Value
Min catchment slope ($^{\circ}$)	Blue Mountains	0	1.2	0.5 (\pm 0.5)	0.1
	Southern Highlands	0	0.4	0.06 (\pm 0.13)	
Max catchment slope ($^{\circ}$)	Blue Mountains	18.4	33.4	25 (\pm 6.2)	0 *
	Southern Highlands	7.4	30	14 (\pm 6.5)	
Mean catchment slope ($^{\circ}$)	Blue Mountains	5.3	10	8 (\pm 2)	0 *
	Southern Highlands	1.9	6.5	4 \pm 1.2	
Catchment slope range	Blue Mountains	18.4	33	25 \pm 6.3	0 *
	Southern Highlands	7.1	30	14 \pm 6.6	
Catchment elongation ratio	Blue Mountains	0.6	0.7	0.7 \pm 0.05	0.6
	Southern Highlands	0.5	0.8	0.6 \pm 0.1	
Min elevation (m asl)	Blue Mountains	823	946	906 \pm 52	0 *
	Southern Highlands	565	639	594 \pm 27	
Max elevation (m asl)	Blue Mountains	911	1038	984 \pm 50	0 *
	Southern Highlands	607	789	663 \pm 60	
Mean elevation (m asl)	Blue Mountains	876	1,002	953 \pm 51	0 *
	Southern Highlands	587	671	619 \pm 27	
Elevation range (m asl)	Blue Mountains	64	94	78 \pm 13	0.7
	Southern Highlands	19	210	64 \pm 59	

* statistically significant difference ($p < 0.05$) between regions.

There were clear differences in swamp morphometry between the two regions as apparent from cross-sectional profiles in Figures 4 and 5. THPSS of the Blue Mountains are set within V-shaped valleys with increasing gradients toward the swamp termination point or foot, located at downstream bedrock steps or valley constrictions. The swamps are narrow, steep-sided and elongate [49]. Southern Highlands' swamps are set within broad U-shaped valleys and have gentler gradients toward the swamp outlet. Elevation differences were also significantly different between the two regions. On average, the Blue Mountains swamps were 953 m asl while Southern Highlands swamps were 619 m asl (Table 1). Other physical attributes of these systems such as swamp and catchment area, and aspect were not significantly different.

4.2. Swamp Water Sources

Radon concentrations in the swamp water of Blue Mountains THPSS ranged from 1 Bq/L to 4.3 Bq/L in the swamp water and between 2.4 and 5.3 Bq/L in the groundwater (Table S1). Southern Highlands' ^{222}Rn concentrations ranged from 1.1 Bq/L to 9.3 Bq/L in the swamp water. ^{222}Rn concentrations in groundwater were 69.3 Bq/L for shallow groundwater (7 m bgl) and 17.7 Bq/L for the deep groundwater (90 m bgl) (Table S1).

The Radon mixing ratio for the Blue Mountains' swamps indicated relatively high contributions from groundwater to the swamp water. Groundwater contributions ranged from 28% to 82%, with an average of 51% (Table 2 and Figure 6a). Except for Walmer Crescent swamp in Wentworth Falls, the degree of uncertainty for the Radon mixing model was less than 5% (Table S2). Four out of the five swamps had contributions from groundwater of greater than 30% (Table S2 and Figure 6a). Mixing lines of groundwater and swamp water isotope ratios (Figure 7a–e) show groundwater isotope ratios for three of the five swamps, Walmer Cres at Wentworth Falls, Mt Hay at Leura and Perrys St at Blackheath sitting at one end, along the mixing line, indicating that groundwater was one endmember of the swamp water.

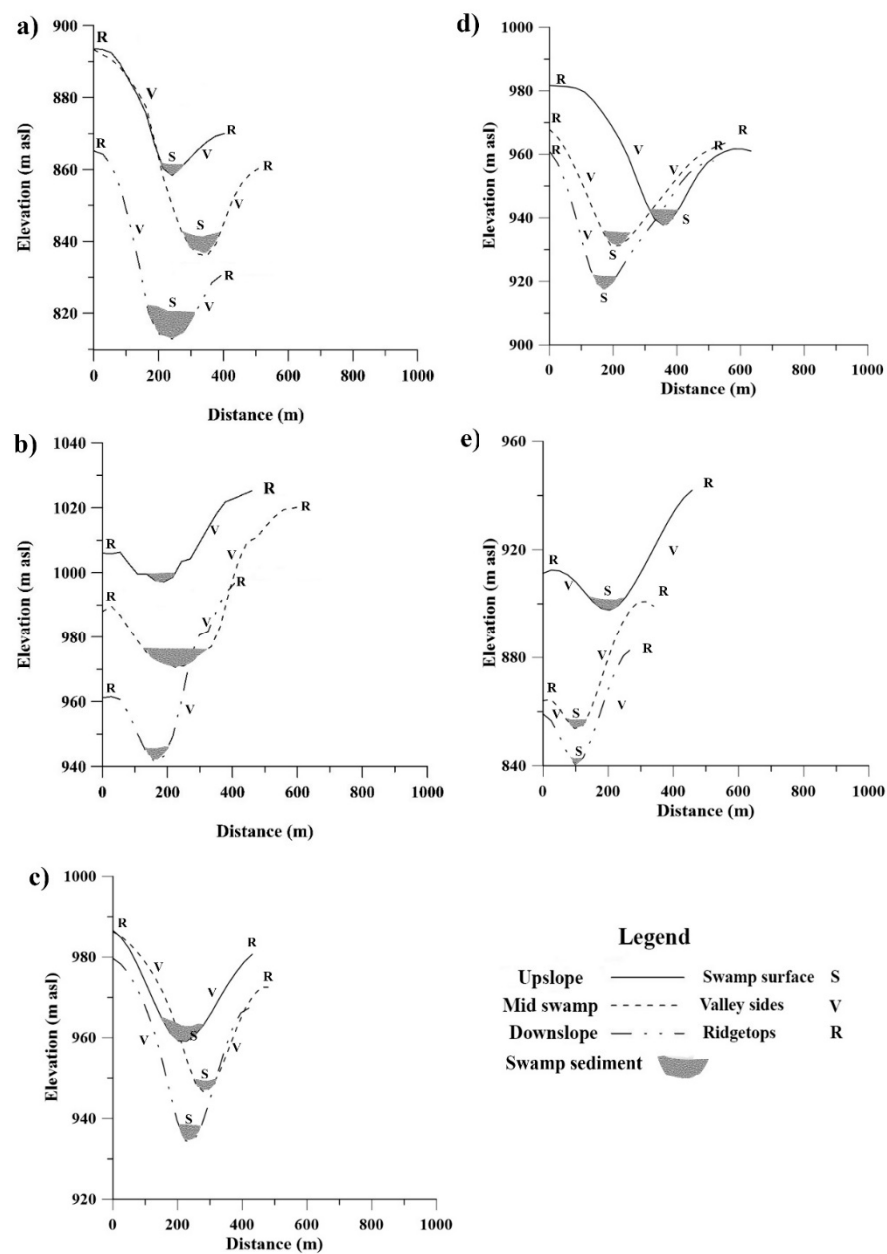


Figure 4. Swamp profiles for Blue Mountains swamps showing swamp positions within valley settings: (a) Walmer Cres, Wentworth Falls (b) Perrys St, Blackheath (c) Grand Canyon, Medlow Bath (d) Michael Eade, North Katoomba (e) Mt Hay, Leura.

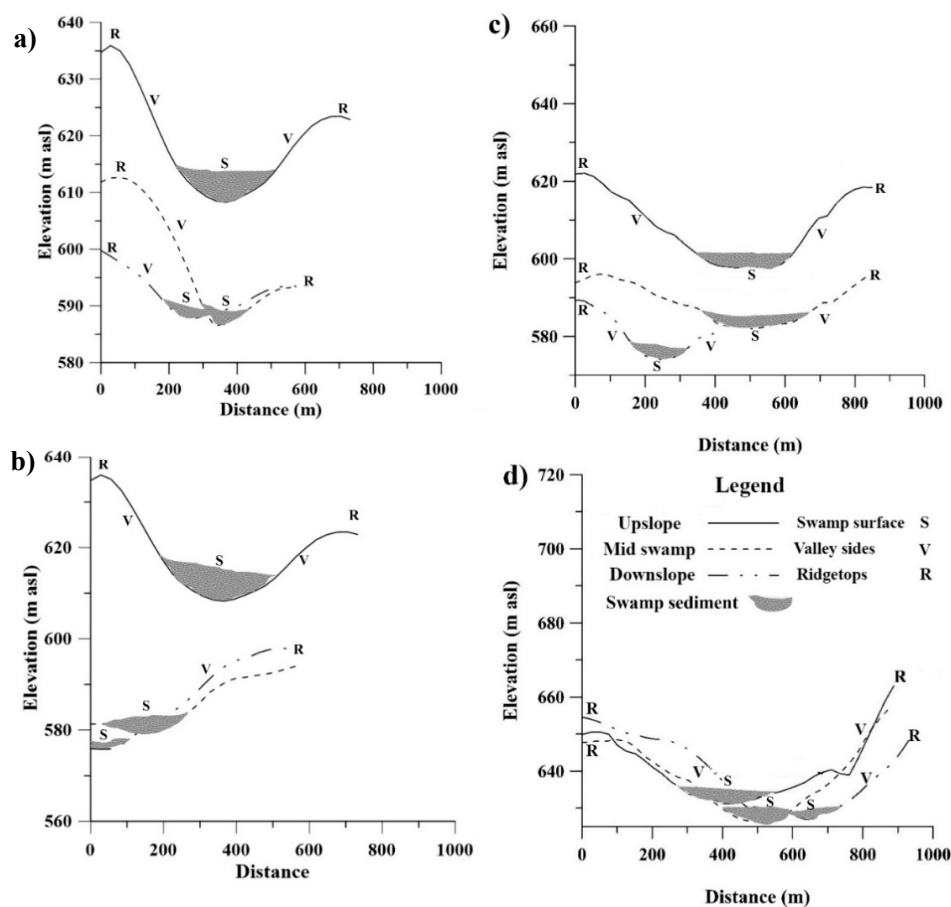


Figure 5. Swamp profiles for Southern Highlands' swamps showing swamp positions within valley settings: (a) BNP2, Budderoo (b) North Stockyard, Mt Murray (c) Butlers swamp, East Kangaloon (d) Jess & Jane, Knights Hill.

Table 2. Statistics for swamp and surface water mixing models and mean residence times for swamps in the two regions.

Water Source and Storage	Region	Min	Max	Mean (\pm SD)	ANOVA p -Value
Groundwater contribution to swamp water (%)	Blue Mountains	28	82	51 (\pm 22)	0 *
	Southern Highlands	7	14	10 (\pm 3)	
Swamp water contribution to downstream surface water (%)	Blue Mountains	0.6	51	21 (\pm 20)	0.2
	Southern Highlands	10	92	44 (\pm 35)	

* statistically significant difference ($p < 0.05$) between regions.

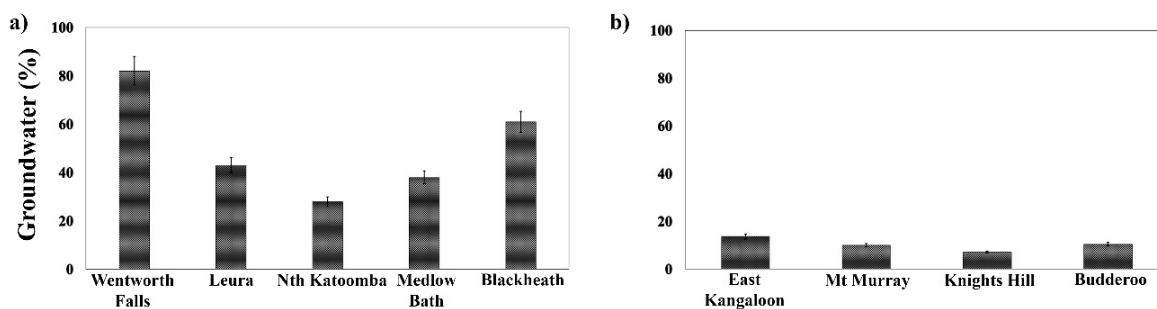


Figure 6. The percentage of swamp water derived from groundwater sources for (a) Blue Mountains and (b) Southern Highlands swamps. Error bars derived from uncertainty analysis.

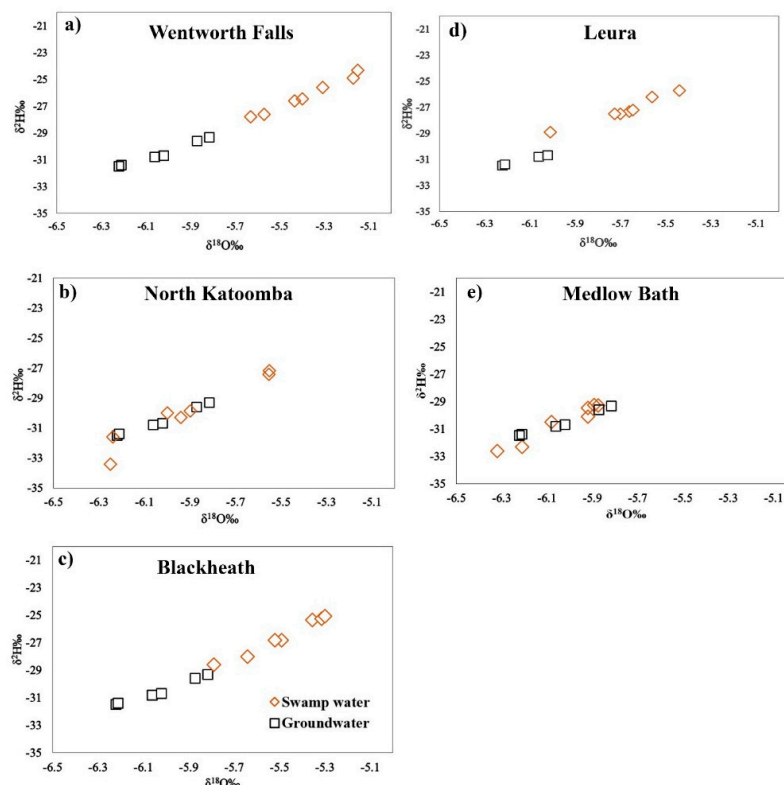


Figure 7. Mixing lines comprised from oxygen and deuterium isotope ratios for groundwater endmembers and swamp water in Blue Mountains (a) Walmer Cres, Wentworth Falls; (b) Michael Eade, North Katoomba; (c) Perrys St, Blackheath; (d) Mt Hay, Leura; (e) Grand Canyon, Medlow Bath.

In the Southern Highlands, the radon mixing ratios from groundwater to the swamp water ranged from 7% to 14%, with an overall average of 10%, significantly lower than that of the Blue Mountains (Table 2 and Figure 6b). The uncertainty for the Southern Highlands Radon mixing models were either equal to, or below 1% (Table S2). Isotope mixing lines (Figure 8a–d) for the southern highlands indicated that, with the exception of the Budderoo swamp (Jess and Jane), groundwater was not an endmember of these swamps.

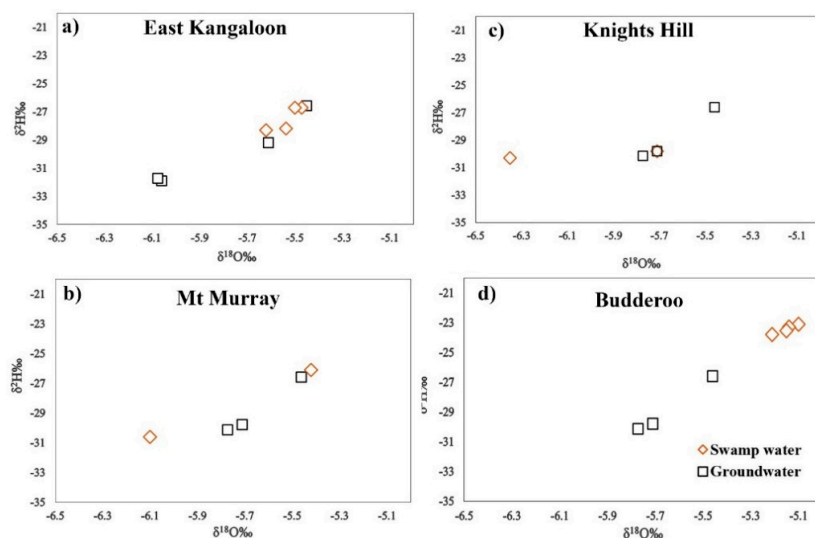


Figure 8. Mixing lines comprised from oxygen and deuterium isotope ratios for groundwater endmembers and swamp water in Southern Highlands (a) Butlers, East Kangaloon; (b) North Stockyard, Mt Murray; (c) Jess & Jane, Knights Hill (d) BNP2, Budderoo.

Principal component analysis of swamp water sources and swamp/catchment morphometrics indicated a positive correlation between elevation, swamp and catchment slope, and catchment elongation and percentage of swamp water sourced from groundwater. These variables account for around 54% of the variation in swamp water sources. There was also a weak negative correlation between swamp and catchment area and length, swamp elongation and aspect (Figure 9). Regression for swamp and catchment slope, catchment elongation and elevation also showed a strong correlation ($p < 0.05$) between these swamp/catchment attributes and groundwater connectivity (Table 3 and Figure S1). In general, steeper swamps in rounder catchments with steeper more variable slopes at higher, more variable elevations had greater groundwater connectivity than did swamps with lower gradients in flatter, more elongate catchments at lower, less variable elevations.

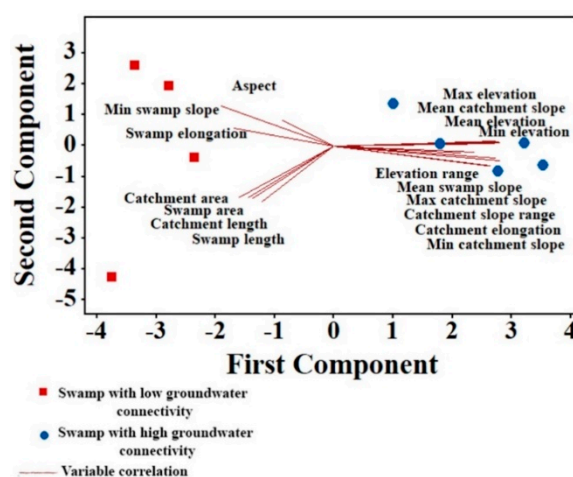


Figure 9. Principle components analysis biplot of 17 swamp/catchment morphometric variables and percentage of swamp water derived from groundwater sources.

Table 3. Regression analysis of swamp water - groundwater connectivity (from Radon mixing model) and a range of geomorphic attributes of the swamps. Shaded cells are statistically significant differences ($p < 0.05$) between regions.

Response	Continuous Predictor	p-Value	R ²	Random Residual
Groundwater contribution to swamp water (%) (²²² Rn mixing model)	Swamp area	0.3	0.1	
	Swamp length	0.3	0.1	
	Minimum swamp slope	0.1	0.2	
	Mean swamp slope	0 *	0.6	Yes
	Swamp elongation ratio	1	0	
	Aspect	0 *	0.5	Yes
	Catchment area	0.2	0.2	
	Catchment length	0.2	0.2	
	Minimum catchment slope	0 *	0.5	No
	Maximum catchment slope	0 *	0.6	Yes
	Mean catchment slope	0 *	0.8	Yes
	Catchment slope range	0 *	0.6	Yes
	Catchment elongation	0 *	0.8	Yes
	Minimum elevation	0 *	0.5	No
	Maximum elevation	0 *	0.5	No
	Mean elevation	0 *	0.5	No
	Elevation range	0 *	0.7	Yes

* statistically significant difference ($p < 0.05$) between morphometric attribute and groundwater contribution.

4.3. Swamp Water Contributions to Downstream Surface Waters

^{222}Rn concentrations in Blue Mountains surface waters ranged from 0.03 to 0.5 Bq/L with a mean of 0.3 Bq/L (Table S3). Radon mixing ratios for surface waters downstream of Blue Mountains' swamps indicated that an average of 21% of surface water was derived from swamp water within a range of 0.6 and 51% for the study swamps. ^{222}Rn concentrations in Southern Highlands' surface waters ranged from 0.16 to 3.4 Bq/L with a mean of 1.4 Bq/L (Table S3). Contributions from the swamp water to downstream surface waters were somewhat higher than those of the Blue Mountains and ranged between 9.7 and 92% with a mean of 44%, however mean contributions in each region were not significantly different ($p > 0.05$, Table 2 and Figure 10).

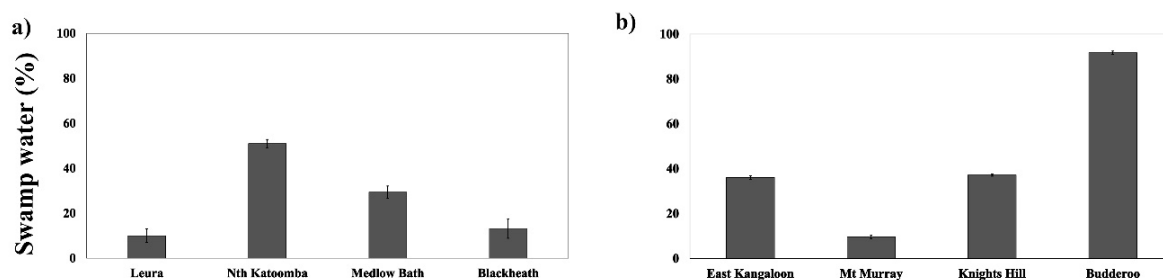


Figure 10. The minimum percentage of surface water derived from swamp water sources for (a) Blue Mountains; (b) Southern Highlands. Error bars derived from uncertainty analysis.

5. Discussion

5.1. Structural Controls on Water Sources of THPSS

The connectivity of upland swamps and peatlands to aquifers has been well documented in the Northern Hemisphere [2,70,71] with slope and catchment morphology being key controls on water sources (surface water or groundwater) [72–74]. The results of this study indicate that, like Northern Hemisphere peatlands and other Groundwater Dependent Terrestrial Ecosystems, morphometric characteristics of THPSS valleys and their catchments are also key controls on water sources. The Blue Mountains swamps are set within steep sided v-shaped valleys at elevations between 820 and 1000 m asl as Figure 5 and Table 2 shows. These swamps source between 28% and 82% of their water from groundwater. In contrast, the Southern Highlands' swamps set within more rounded, gentler valleys at lower elevations with more uniform relief. These swamps source between 7% and 14% of their water from groundwater (Figure 5, Table 2).

The extent to which a swamp is sourcing water from groundwater or surface water has implications for the extent to which key swamp functions (water storage and carbon storage in particular) can be affected by different disturbances [9,10,14,75–77]. Here we consider the dual role of groundwater interference and a changing climate on swamp function, disturbances that are particular threats to THPSS [25].

5.2. Sensitivity of THPSS to Groundwater Interference

THPSS that receive a high proportion of water from groundwater are particularly vulnerable to groundwater interference or extraction. These swamps have more stable water tables than those that are surface water fed, therefore maintaining the permanently saturated sediments required for primary functions such as carbon storage and peat formation [3,13,15,78]. More stable water levels also help maintain biotic composition and function [14]. Differences in the water table response of groundwater fed swamps to low rainfall periods differs markedly from that of primarily rainwater fed swamps where water table drawdowns frequently occur during dry periods. Figure 11a shows two Blue Mountains swamps, Grand Canyon and Walmer Cres which source 38% and 82% of their water from groundwater, respectively with stable water tables during a month without significant

rainfall, while Figure 11b shows Butlers and North Stockyard swamps in the Southern Highlands (13.7% and 10% of water sourced from groundwater, respectively), with drawdowns of up to 0.6 m. Fryirs, et al. [9] found similar drawdowns occurred during dry times at Jess and Jane swamp in the Southern Highlands where this study found only 7% of swamp water was derived from groundwater.

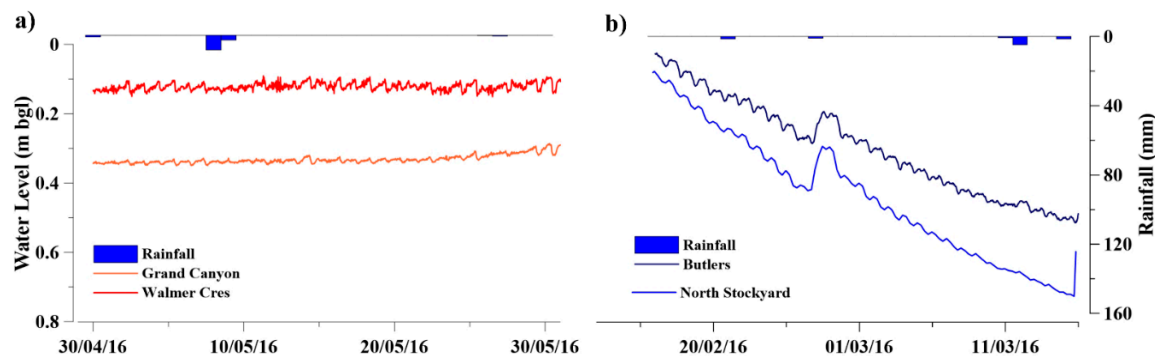


Figure 11. Water table levels for (a) Blue Mountains and (b) for Southern Highlands' swamps during a dry period. Source: (a) unpublished data from Cowley, et al. [15]; (b) WaterNSW unpublished data.

Changes in the hydrological connectivity of swamps to groundwater sources is likely to lead to changes in water levels with knock-on effects on other important swamp functions. Lower, more variable water tables, have the potential to reduce the water and carbon storage capacities of these systems and increase the rate of organic matter decomposition [5,15]. With lower water tables, the swamps retain less water and the aeration of upper layers of sediment increases the filtration of oxic water to the deeper layers [79]. This in turn lowers organic matter content within swamp sediments, thus reducing their water holding capacity [79,80]. Increased primary productivity within the sediments leads to CO₂ emission to the atmosphere as well as the export of dissolved organic carbon (DOC) and particulate organic carbon (POC) downstream [81]. Loss of these crucial swamp functions can, in turn lead to structural changes to the swamp sediments themselves, thus initiating a positive feedback loop that further reduces the carbon and water storage function of these systems [3,22,82].

While we have highlighted the importance of groundwater to upland swamps, we can only speculate on how they respond to changing groundwater inputs. Given the considerable capillary fringe (potentially several meters [14] in the THPSS sediments), sediments remain saturated well above the water table. Minor changes in groundwater input may have little effect on the swamp structure and function, suggesting a staged response [83] with effects occurring after a critical threshold is reached, although inevitably swamp discharge will be reduced. However, given the often dramatic water table drawdowns in swamps and peatlands as a result of aquifer interference from mining, water extraction and tunneling [26,28,84], the buffering capacity of the system will be quickly exceeded. The consequences of water table drawdown on swamp desiccation, channelization, carbon emissions and export, and vegetation changes, even leading to swamp destruction, have also been documented [25,80,84–86]. Thus consideration of impacts on Groundwater Dependent Terrestrial Ecosystems such as THPSS, of aquifer interference at a regional scale should be undertaken [17].

Although swamps may tolerate small changes to groundwater input, swamps provide 0.6% and 92% of downstream surface waters. Any significant change in the water balance of the swamps will have serious implications for downstream water supply and provision of base flow to lower catchment streams during relatively short dry periods [87].

It is essential that swamps vulnerable to water table drawdowns from aquifer interference be identified prior to the commencement of any aquifer interference activity within these hydrologically connected zones. Once swamps have experienced significant drawdowns, the re-instatement of their former structure and function is virtually impossible [25,26]. By understanding the structural controls on the hydrological connectivity of THPSS, appropriate planning controls can be employed to identify

the swamps that may be sensitive to aquifer interference, to prevent aquifer interference where impacts on swamp water tables are likely, and better inform management and rehabilitation activities [88].

5.3. Sensitivity of THPSS to a Changing Climate

THPSS that are primarily rainwater fed are particularly vulnerable to a changing climate. The high water tables that are a feature of THPSS and upland swamps more generally, are dependent on a climate regime where evaporation rates are lower than precipitation [89]. Diurnal patterns of water table fluctuation during periods of low rainfall have been observed in Northern Hemisphere peatlands [2,90] but evaporation rates are generally low [91,92]. In Australia, average annual evaporation rates are expected to increase by approximately 5.6% between 2030–2050 [93] and rainfall is expected to become more variable with longer duration droughts punctuated by more intense rainfall and flooding events [94]. The proportion of THPSS that source a majority of their water from rainfall, such as the Southern Highlands' swamps will, under predicted climate warming scenarios, be placed under significant water stress. Given that these swamps are located at lower elevations than other THPSS, these swamps are likely to be impacted by increased temperatures and evaporation earlier than those found at higher elevations (Table 1). Lowered water tables within THPSS in the upper catchments as a result of climate change will produce changes to geomorphic structure and function of the primary water storage and carbon storage sedimentary unit, the alternating organic sands [3,95]. Increased temperature and evaporation rates will also affect organic matter supply and decomposition, leading to decreased water storage and increased carbon emission and export [96,97]. Nichols, et al. [98] found higher temperatures and evaporation during the mid-Holocene led to much lower carbon accumulation rates as a result of vegetation changes at an ecosystem scale. Jassey, et al. [99] found increases in warming lead to changes in the microbial food web which destabilizes carbon and nitrogen cycling in peatlands, leading to significant climate feedbacks.

Any disturbance that affects the water holding capacity of THPSS will decrease base flows to lower catchment streams. Given that THPSS occupy a significant area of the drinking water supply catchments for Sydney, Australia's largest city, a management focus aimed at minimizing disturbance to their water sources and maintenance of their water storage function is imperative for safe guarding future water supplies, particularly in times of drought [100,101].

6. Conclusions

This study has been the first to investigate the water sources of THPSS and to identify the structural features that control where these swamps source their water. THPSS that are found at high elevations within steep sloped V-shaped valleys are more likely to be groundwater fed than those at lower elevations in more U-shaped valleys with gentler slopes. THPSS provides up to 92% of the water in downstream water courses, confirming their importance in the water supply of downstream catchments. Changes in water table levels in THPSS as a result of aquifer interference within hydrologically connected swamp catchments or increases in temperature and evaporation from a warming climate in rainwater fed systems, will likely result in losses of organic matter within the sediment with concomitant decreases in carbon accumulation and increases in carbon exports. By understanding the water source and storage dynamics of these systems, and their sensitivity to groundwater interference and climate change, it is vital that THPSS are protected, particularly in regions where they make an important contribution to water supply catchments and ecosystem services.

Supplementary Materials: The following are available online at <http://www.mdpi.com/2073-4441/11/1/102/s1>, Figure S1: Regression plots showing correlations between groundwater connectivity and a subset of swamp-catchment morphometrics such as (a) Mean swamp slope, (b) Mean catchment slope, (c) Maximum catchment slope (d) Catchment slope range, (e) Catchment elongation, (f) Swamp elevation range, Table S1: Individual Radon and isotope sampling results for swamp water, groundwater, surface waters and rainwater, Table S2: Groundwater mixing model results for swamp waters and surface waters for all swamps within the two

study regions, Table S3. Statistics for $\delta^2\text{H}\text{‰}$, $\delta^{18}\text{O}\text{‰}$ and ^{222}Rn for swamp water, groundwater and surface water in the two regions.

Author Contributions: Conceptualization, K.L.C., K.A.F. and G.C.H.; Methodology, K.L.C. and R.C.; Formal analysis, K.L.C. and R.C.; Validation, R.C.; Writing—original draft preparation, K.L.C.; Writing—review and editing, K.A.F., G.C.H. and R.C.; Visualization, K.L.C., K.A.F. and R.C.; Supervision, K.A.F.; Investigation, K.L.C.; Project administration, K.A.F.; Funding acquisition, K.A.F. and G.C.H.

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