Impact of urban development on endangered wetland ecological communities in the Greater Blue Mountains World Heritage Area

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Key Points

- Temperate Highland Peat Swamps on Sandstone (THPSS) are an 'endangered ecological community' found within the internationally significant Greater Blue Mountains World Heritage Area.
- Urban development poses a threat to THPSS communities along the urban-National Park interface, with urbanised swamp catchments exhibiting modified water chemistry.
- Urban swamps had elevated pH, electrical conductivity, calcium, bicarbonate, strontium and barium, and aluminium solubility is regulated by pH.
- These parameters can be monitored to establish changes from background levels over time in association with human impacts and urban development.
- There is increasing evidence that suggests that concrete surfaces in urban areas pose a potential source of geochemical contamination, which is of particular concern in fragile, poorly buffered environments such as THPSS.
- Identifying urban impacts on endangered communities within and along the World Heritage Area boundary through monitoring is crucial to ensure their ongoing management and conservation.

Abstract

The Greater Blue Mountains World Heritage Area contains outstanding natural values. However, its recent conservation outlook was downgraded from 'good with some concerns' to 'significant concern', with urban development identified as a high threat. Temperate Highland Peat Swamps on Sandstone (THPSS) are an endangered ecological community with exceptional biodiversity values. Within the Blue Mountains, many THPSS occur at the urban-National Park interface, and urban runoff modifying hydrology and water quality poses a risk. This work explored water quality in urban and naturally vegetated THPSS to determine key parameters for environmental monitoring. Urbanisation poses threats to THPSS along or outside the National Park boundary, leading to degraded water quality, erosion, modified hydrology and impaired biotic communities. These impacts pose risks to vulnerable downstream ecosystems within the World Heritage Area. The case of THPSS raises awareness of the importance of monitoring key parameters as part of an adaptive management approach that extends beyond National Park boundaries. This includes addressing regional and catchment-scale urban impacts (particularly stormwater, artificial impervious surfaces and concrete materials), ongoing monitoring, and stakeholder collaboration. The Blue Mountains has internationally recognised conservation values, making it imperative to reduce further degradation and ensure future conservation.

Keywords

Catchment urbanisation, swamps, water chemistry, sediment chemistry, urban stream syndrome, concrete water contamination

Introduction

The Greater Blue Mountains World Heritage Area (GBMWHA) covers over 1 million hectares in New South Wales (NSW) and is a place of outstanding natural beauty and unique biodiversity (UNESCO 2021). The region was listed as a World Heritage Area (WHA) in 2000 as it reflects post-Gondwana adaption and isolation in Australia, including significant evolutionary processes (criteria ix) and habitat values (criteria x) (UNESCO

2021). However, the establishment of the WHA boundary does not safeguard the environment against degradation. The recent IUCN Conservation Outlook for the GBMWHA (IUCN 2020) saw the region downgraded from 'good with some concerns' to 'significant concern'. The key threats that were identified included climate change and bushfires, pollution from residential and mining activities, invasive species, and pathogens (IUCN 2020). Additionally, urban development was recognised as posing a 'high threat' to the GBMWHA, particularly for ecosystems that rely on hydrology for natural functioning, such as wetlands.

Urban impacts on aquatic ecosystems have been characterised worldwide, referred to as 'urban stream syndrome' (Walsh et al. 2005). Catchment urbanisation is associated with increased cover of impervious surfaces, such as roads and concrete, and the introduction of stormwater infrastructure, which contributes to altered surface runoff, reduced infiltration and erosion (Walsh et al. 2005). Urban development is also linked with modified water quality, contributing to higher levels of nutrients, major ions and trace metals in runoff (Kaushal et al. 2017; Wright et al. 2018). The risk of urban degradation is of particular concern within poorly buffered, fragile environments within the GBMWHA, such as Temperate Highland Peat Swamps on Sandstone (THPSS).

THPSS were identified by the IUCN (2020) as a high biodiversity value community within the GBMWHA that is at risk of degradation from urban development. THPSS are a type of wetland community formed by peat accumulation on sandstone geology between 500 – 1000 m in elevation, that have specialised vegetation communities and are restricted to less than 3,000 hectares in the Blue Mountains, NSW (Belmer et al. 2018). They provide numerous valuable ecosystem services, including carbon sequestration and water regulation (Cowley & Fryirs 2020), and are home to many endangered species, such as the Blue Mountains Water Skink (*Eulamprus leuranensis*) and Giant Dragonfly (*Petalura gigangtea*) (Hensen & Mahony 2010). In addition to many swamps being located within the sensitive WHA, THPSS are also listed as 'endangered ecological communities' under the *Environment Protection and Biodiversity Conservation Act (1999)* (Commonwealth) and as 'vulnerable' in the Blue Mountains under the *Biodiversity Conservation Act (2016)* (NSW).

The Blue Mountains, approximately 100 km west of Sydney, has a population of approximately 80,000 people and is one of only two local government areas (LGA) worldwide that is encompassed within a WHA (BMCC 2020). Urban development occurs predominantly along the ridgeline following the Great Western Highway, with the GBMWHA occurring on either side (Figure 1). Within the Blue Mountains, many THPSS occur at the urban-National Park interface and are at high risk of degradation due to urban runoff impacts. Continued population growth, urban development and stormwater inputs poses a threat to this sensitive area due to the edge effects at the National Park boundary and potential downstream implications within the WHA.

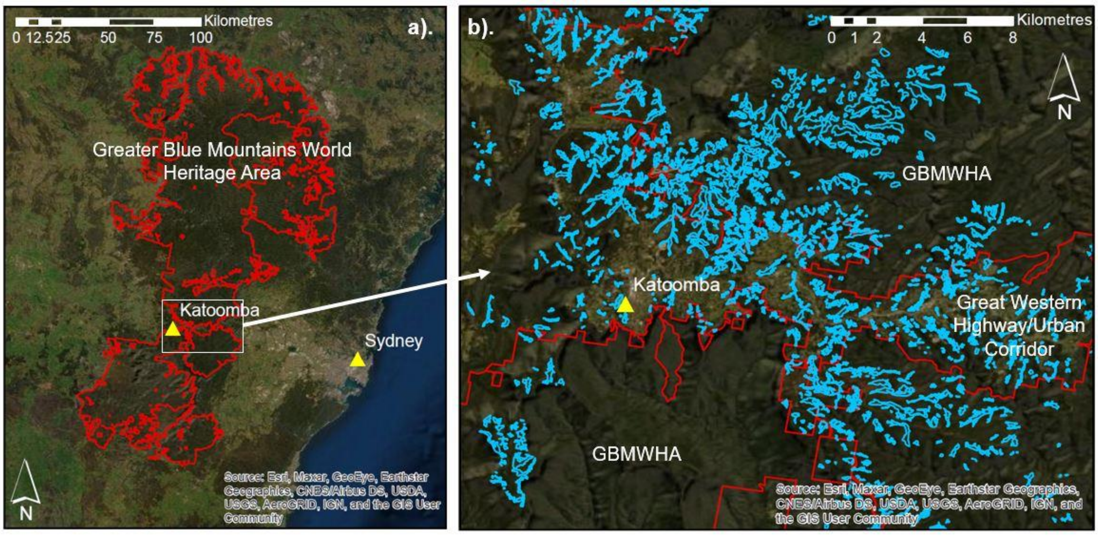

Figure 1. a). The boundary of the Greater Blue Mountains World Heritage Area (GBMWHA), NSW (shown in red; from the Department of the Environment 2013). b). The distribution of THPSS (shown in blue; from Commonwealth of Australia & Macquarie University 2019) at the urban-National Park boundary.

Study aims

Urban development places increasing pressure on vulnerable ecosystems within the GBMWHA, including THPSS, and continued degradation poses a potential risk to other sensitive environments located downstream within the WHA. Key to understanding and addressing this issue is monitoring these systems to establish and identify changes to background conditions that suggest potential urban degradation. This study explored the effects of urban development on fragile wetland communities in the Blue Mountains impacted by urbanisation. The aim was to evaluate key parameters that could be utilised as potential indicators within THPSS that reflect changes to the chemistry of swamps associated with urban development. It also aimed to explore the potential role of an emerging source of urban geochemical contamination, concrete materials, within fragile, poorly buffered environments such as THPSS.

Methodology

Eight THPSS sites were investigated in the Blue Mountains, including four urban and four naturally vegetated catchments (Table 1). Physiochemical properties and a suite of elements in surface water were assessed, with methods further outlined in Carroll et al. (2020) (which included two sampling events in 2017 at sites 1,3, 5 and 6) and Carroll (2018) (which included three sampling events at all eight sites in 2018). Briefly, in situ monitoring of pH and electrical conductivity was conducted using a calibrated TPS AQUA-Cond-pH meter. Duplicate surface water samples were collected, and elemental analyses were conducted by a NATA accredited laboratory. Data was analysed using IBM SPSS Statistics (version 25) using the independent samples Mann-Whitney U test, and key parameters that reflect potential indicators for monitoring swamp condition and the impacts of urban development were identified.

Table 1. Location of THPSS study sites in the Blue Mountains (from Carroll et al. 2019).

Swamp Location	Catchment Type	Latitude and Longitude	Altitude (m)	Impervious Area (%IA)	Directly Connected Impervious Area (DCIA%)
1. Bullaburra	Urban	-33.727319, 150.412928	755	25.0	9.5
2. Wentworth Falls	Urban	-33.707627, 150.361313	880	22.4	7.9
3. North Lawson	Urban	-33.713851, 150.427195	695	23.2	8.4
4. Popes Glen	Urban	-33.633639, 150.292336	1010	34.3	16.3
5. Mount Hay	Naturally vegetated	-33.668644, 150.346508	920	0.0	0.0
6. Hat Hill	Naturally vegetated	-33.599941, 150.328782	967	0.0	0.0
7. Lawson	Naturally vegetated	-33.696739, 150.444027	665	0.0	0.0
8. Kings Tableland	Naturally vegetated	-33.76210, 150.38373	780	0.2	0.002

Results

Surface water quality

Urban swamp catchments had modified water chemistry compared to the naturally vegetated swamps (Table 2; Figure 2). Calcium was almost 26 times higher in the urbanised catchments (p<0.001). Bicarbonate was below detection in the naturally vegetated swamps but averaged 27.3 mg/L in urban swamps (p<0.001). Strontium concentrations were over 11 times higher in urban swamps (mean 38.3 µg/L compared to 3.5 µg/L; p<0.001), and barium was more than three times greater in urban compared to naturally vegetated catchments (p<0.001; Table 2). Heavy metals, such as lead and cadmium, were not observed to differ significantly between catchment types, therefore were not identified as clear markers of urban impacts within THPSS in the Blue Mountains.

Table 2. Water physiochemical and elemental results. BD refers to below the detection limit (half of the detection limit was used for statistical analysis) and ns refers to not statistically significant.

Parameters	Urban			Naturally vegetated			U statistic (*p* value)
	Range	Mean	Median	Range	Mean	Median	
pH (pH units)	5.6 - 7.1	6.3	6.1	4.5 - 5.4	4.9	4.9	0.0 (p<0.001)
Electrical Conductivity (µS cm $^{-1}$)	45.1 - 164.9	119.2	137.5	23.2 - 79.1	40.3	31.3	375.0 (p<0.001)
Calcium (dissolved mg/L)	2.1 - 20.0	11.8	13.0	BD - 1.3	0.5	0.3	0.0 (p<0.001)
Bicarbonate Alkalinity as $CaCO_3$ (mg/L)	5.0 - 59.0	27.3	22.5	BD	BD	BD	0.0 (p<0.001)
Sodium (dissolved mg/L)	4.8 - 13.0	8.4	7.7	4.0 - 7.4	5.5	5.6	172.0 (p<0.001)
Potassium (dissolved mg/L)	BD - 2.8	1.3	1.1	BD	BD	BD	64.0 (p<0.001)
Magnesium (dissolved mg/L)	0.6 - 1.9	1.3	1.3	BD - 0.8	0.5	0.3	58.5 (p<0.001)
Chloride (mg/L)	6.0 - 36.0	17.7	13.5	6.0 - 11.0	8.5	8.0	154.5 (p<0.001)
Sulphate (mg/L)	BD - 14.0	5.3	3.0	BD - 6.0	1.8	0.5	211.0 (p<0.001)
Strontium (total µg/L)	11.0 - 75.0	38.3	38.0	1.3 - 7.9	3.5	2.5	0.0 (p<0.001)
Barium (total µg/L)	3.0 - 36.0	18.5	18.0	3.0 - 9.0	5.5	5.0	121.5 (p<0.001)
Iron (total µg/L)	120.0 - 7100.0	2017.4	1300.0	58.0 – 630.0	274.0	270.0	103.0 (p<0.001)
Aluminium (total µg/L)	BD -1200.0	188.7	20.0	80.0 – 290.0	156.0	120.0	526.0 (p<0.05)
Lead (total µg/L)	BD - 8.0	1.3	0.5	BD - 2.0	0.7	0.5	438.0 (ns)
Cadmium (total µg/L)	BD - 48.0	3.2	0.1	BD - 22.0	1.6	0.1	367.5 (ns)

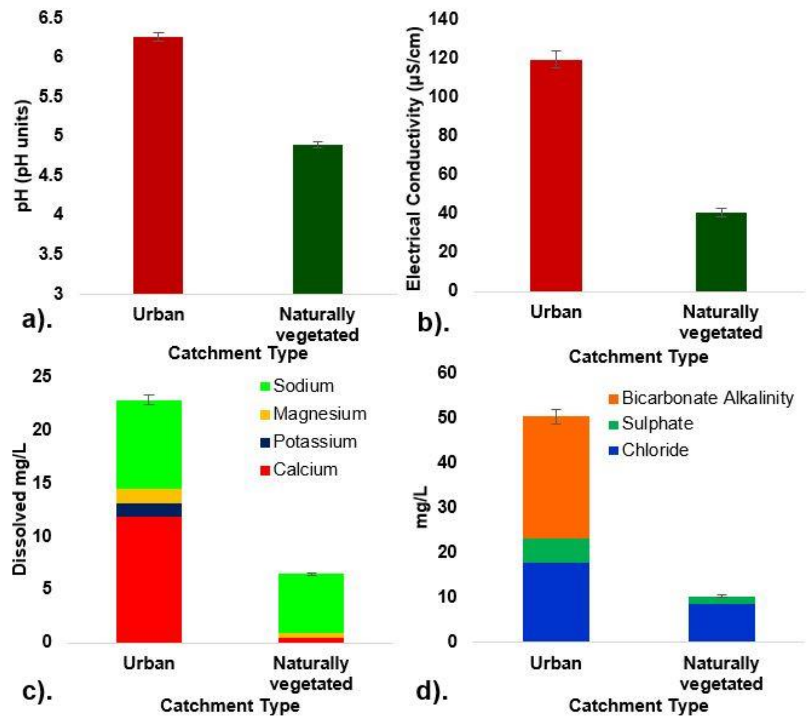

Figure 2. Urban swamps had modified physiochemical properties and elemental signatures in water compared to naturally vegetated swamps, for a). pH, b). electrical conductivity, c). major cations, and d). major anions.

Discussion

This study found that urbanised swamps had a modified elemental signature compared to naturally vegetated swamps. This is in line with previous research across urban catchments globally and within Australia (Tippler et al. 2014; Kaushal et al. 2017). THPSS provide a case study that represents the overlap of urban development with a high conservation value WHA. Results from this study highlight that changes to the elemental signature can be used to identify parameters which can be assessed over time to monitor changes in swamp condition associated with urban development. This includes monitoring pH, electrical conductivity, calcium, bicarbonate, strontium, barium, aluminium, and iron levels. The GBMWHA contains many valuable yet vulnerable ecosystems, and as many THPSS occur in the upper headwaters of this region, changes to swamp chemistry due to urban impacts has significant implications for downstream regions of the WHA.

Concrete as a suspected driver of elevated alkalinity and ionic change in swamps

Concrete is a chemically complex material commonly used in urban settings for stormwater infrastructure and gutters. A key component of concrete is lime ($Ca(OH)_2$), which can transform into calcite ($CaCO_3$) during the concrete ripening process. As concrete weathers over time or comes in contact with water, the lime can dissolve, leaching calcium (Ca^{2+}) and bicarbonate (HCO_3^-), making it a likely source of calcium and bicarbonate into natural ecosystems (Wright et al. 2018; Reaction 1).

$$Ca(OH)_{2(s)} + CO_{2(g)} + H_2O \rightarrow Ca^{2+} + HCO_3^- \qquad pK_{sp} = 5.3 \qquad [1]$$

A key consequence of higher calcium and bicarbonate levels is the associated increase in pH and alkalinity. The alkalinisation of urban aquatic ecosystems has been documented worldwide (such as Kaushal et al. 2017), and has widespread implications within natural ecosystems, through the alteration of background conditions and natural cycling. Modifying the pH of an ecosystems is also a key driver influencing the bioavailability and solubility of other elements. Using the solubility of Gibbsite ($AlOH_3$) as an example, the acidic naturally vegetated swamp catchments may have a higher concentration of the bioavailable $AlOH^{2+}$ and Al^{3+} in water (Figure 3). As the pH increases, this should lead to a reduction in $AlOH^{2+}$ as a precipitate is formed (e.g. $Al(OH)_3$). Whilst mean aluminium levels in urban swamps (188.7 µg/L) were similar to the naturally vegetated catchments (120 µg/L), the median values and range suggest an outlier aluminium value is present in the data. The median values for the urban swamps (20 µg/L) and naturally vegetated swamps (120 µg/L) are in line with the predicted trends for aluminium solubility (Table 2).

Concrete is a proposed source of alkalinity and ionic change in aquatic systems. Heavy metals, such as lead and cadmium, were naturally low, however concentrations of strontium and barium were higher in urban THPSS, which is in line with studies of urban aquatic systems (Kaushal et al. 2020). However, potential sources and the consequences of elevated metals within THPSS are not well-known. The dissolution of concrete has previously been suggested as a potential source of contamination to natural environments, due to the leaching of trace heavy metals (Tippler et al. 2014; Wright et al. 2018; Purdy, Reynolds & Wright 2020). For example, fly ash can be used in the production of concrete as an alternative to Portland cement, which can contain metals, such as strontium and barium (Christian et al. 2011; Vollpracht & Brameshuber 2016). Therefore, in addition to being associated with changes to natural hydrology and runoff from urban areas (Walsh et al. 2005), there is increasing evidence that suggests that concrete poses a potential source of modification to the elemental signature of freshwater systems.

This is of particular concern within sensitive ecosystems, such as THPSS, which are poorly buffered against changes in pH. For example, in systems where pH is naturally low (including contributions from rainfall and geology), runoff from urban concrete materials may impact water chemistry by increasing pH and calcium levels, which in turn modifies sediment chemistry (Figure 4). As these communities are adapted to acidic conditions, this may have significant consequences for the biotic community, such as modifying vegetation chemistry or biotic species. For example, Belmer et al. (2018) found that urban swamps had modified macroinvertebrate communities compared to naturally vegetated catchments.

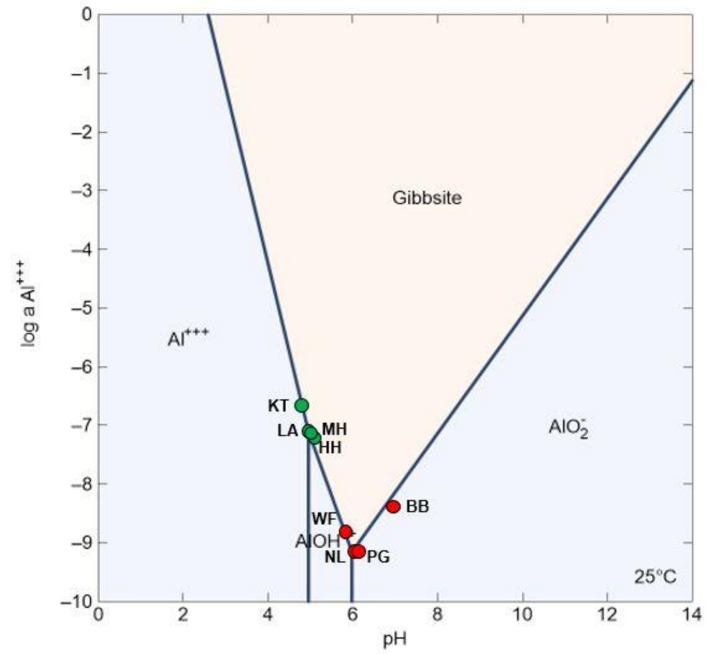

Figure 3. Aluminium solubility diagram, indicating aqueous (blue) and solid (orange) phases (conditions: T = 25 ̊C, P = 1 bars, a[H_2O] = 1; suppressed: 1123 species) with respect to the solubility of Gibbsite ($AlOH_3$). Mean pH per swamp is indicated as green for naturally vegetated (MH= Mt Hay, HH = Hat Hill, LA= Lawson and KT= Kings Tableland), and red for urban swamps (BB= Bullaburra, WF= Wentworth Falls, NL= North Lawson and PG=Popes Glen).

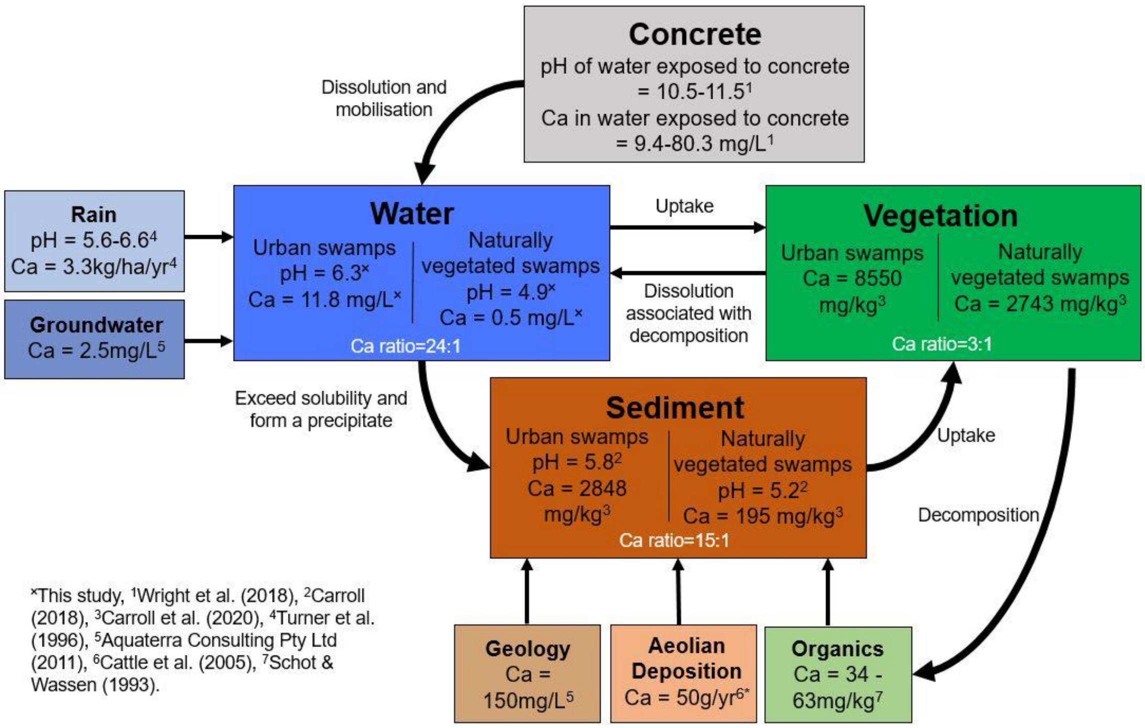

Figure 4. Conceptual model of changes in pH and calcium (Ca) in urban and naturally vegetated swamps. Approximate mean values of inputs entering the system were derived based on the current study, and previous Australian and international literature. pH of sediments from Carroll (2018) was based on the mean of surface (~0-5 cm) sediment samples. *Calcium in aeolian deposition was derived from the total salts value (500g/ha) given by Cattle et al. (2005), of which calcite ($CaCO_3$) type was assumed to represent 5% and the mean area of swamp catchments studied was estimated at 5 ha, which was converted to g/yr. Adapted from Carroll et al. (2019).

Management of THPSS within a fragile WHA

THPSS represent a fragile, poorly buffered system which highlights the effects of urban development from outside the WHA boundary on vulnerable natural environments. Without effective management to address these issues, there is a risk that the ecological condition of the GBMWHA may be further compromised. Therefore, adaptive management approaches that extend beyond National Park boundaries are required. Findings from this study suggest that key parameters to monitor in THPSS include pH, electrical conductivity, calcium, bicarbonate, strontium, barium, aluminium and iron. These parameters indicate changes to the alkalinity and bioavailability within the system that reflect potential urban inputs, and the modification of these key factors may result in impacts to THPSS and downstream communities. Monitoring of THPSS at risk of or subject to impacts from urban development could target these parameters (in conjunction with broader assessments of a suite of elements, physical and biological changes within swamps), as part of ongoing monitoring programs that seek to characterise the chemical fingerprint of THPSS. This would assist to establish background levels or the natural signature of swamps in order to identify changes or degradation over time that are linked with urban development. The calculation of ecological thresholds for key parameters linked with catchment urbanisation would also be aided by further research that seeks to enhance knowledge of baseline conditions, particularly within THPSS where threshold limits are not well-known.

Addressing urban inputs to sensitive wetland ecosystems requires consideration of regional and catchment-scale impacts, particularly stormwater and directly connected impervious surfaces. Impervious cover and urban runoff are important factors that influence water chemistry and ecosystem condition. Managing runoff in THPSS is key to reducing physical damage and erosion caused by high velocity stormwater damage, and limiting contaminants transported into swamps via stormwater. Managing stormwater, for example the use of stormwater detention basins and soft engineering works such as coir logs, can assist to improve swamp condition by reducing flows and erosion (Hensen & Mahony 2010). Aiming to understand and maintain natural flow regimes, through the reduction of impervious surfaces and incorporating water sensitive urban design principles within vulnerable catchment areas (Walsh et al. 2016; Li et al. 2017), is central to managing runoff into fragile THPSS. There is also a need to carefully consider the use of concrete surfaces within sensitive, acidic, poorly buffered catchments, such as THPSS in the Blue Mountains, as it poses a potential source of contaminants. Further research is required to verify this link and identify alternatives to concrete within sensitive environments. For example, this may include using alternative, local materials (such as sandstone), or exploring ways to reduce concrete weathering and leaching, such as through the sealing of concrete surfaces (Grella et al. 2014). Continued stakeholder collaboration, including between government agencies, volunteer organisations and the local community, is also essential to raise awareness of issues facing THPSS and promote the maintenance of these valuable ecosystems both within and outside the GBMWHA.

Conclusions

Urban development has a profound impact on the physical, chemical, and biological characteristics of THPSS and is recognised by the IUCN (2020) as a high threat contributing to degradation. In particular, concrete is suspected to play a key role in contributing to the modification of the natural elemental signature of urban swamps. The GBMWHA represents valuable environments that have high ecological, cultural, aesthetic and economic value. This study seeks to highlight potential impacts of urban development on a sensitive WHA, particularly at National Park boundaries. Key parameters that could be incorporated into monitoring programs to observe how the chemical condition of swamps is impacted by urban development include pH, electrical conductivity, calcium, bicarbonate, strontium, barium, aluminium and iron. This case study of THPSS emphasises the importance of reducing urban impacts to minimise the risk of further degradation to the GBMWHA and promote the future preservation of this high conservation value region.

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