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A review of the impacts of pumped hydro energy storage construction on subalpine and alpine biodiversity: lessons for the Snowy Mountains pumped hydro expansion project

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ABSTRACT

The Australian government's proposal to expand the Snowy Hydro Scheme to include a second pumped hydro energy storage (PHES) system, and support for feasibility studies for PHES in Tasmania, offer an opportunity to incorporate more intermittent renewable energy generation into the National Energy Market. However, the infrastructure construction required for PHES expansion may have negative effects for biodiversity in subalpine and alpine areas. To identify the potential effects of PHES on biodiversity in Kosciuszko National Park (KNP), this systematic literature review assesses: (i) the key environmental disturbances likely to arise from PHES construction; and (ii) the specific impacts of these construction processes on biodiversity in subalpine and alpine environments. We find that the effects of PHES construction-related disturbances are likely to be negative for subalpine and alpine biodiversity, with impacts including the proliferation of exotic flora, habitat loss resulting from vegetation clearing, altered landscape hydrology and reduced water quality. Management recommendations to limit these impacts are provided and further research is recommended to assess: (i) the effects of PHES on fish populations in alpine reservoirs; (ii) the utility of spoil as artificial habitat for endemic fauna; and (iii) the chemical and physical impacts of spoil dumping in alpine reservoirs.

KEYWORDS

Australian Alps; biodiversity; energy storage; environmental impacts; invasive species; Kosciuszko National Park; pumped storage hydropower

Introduction

Located in Australia's Southern Alps, the Snowy Mountains Scheme is an integrated water and hydro-electric power utility that was constructed in the 1950s to divert water into Australia's agricultural regions and assist in delivering peak-load electricity to meet demand in the eastern states (Snowy Hydro Limited 2017). In 2017, the Australian government released a proposal to expand the Snowy Hydro Scheme to include, at the time of writing, a \$2 billion pumped storage 'battery' system (Prime Minister of Australia 2017). Further, in 2018, the Australian and Tasmanian governments announced feasibility studies for 14 pumped hydro energy storage (PHES) systems in that state, with additional schemes being considered in Victoria, South Australia and Queensland (ARENA 2018;

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Pittock 2019). Proponents highlight PHES's ability to enable electricity generation to meet demand through storage, allowing increased inclusion of solar and wind technologies in electricity grids (Lu et al. 2018). Indeed, internationally in the U.S.A., Europe, Japan and China, PHES systems have been implemented as a cost-effective alternative to oil for shaving peak electricity demand since the 1890s, due to the efficiency of recycling of water over a large hydraulic head (Barbour et al. 2016).

Closed-loop PHES systems such as the proposed Snowy 2.0 expansion may have few environmental impacts once active, due to their conservation and recycling of water (Hearps et al. 2014). However, the large-scale construction processes required to install the scheme's infrastructure will impact on the biodiversity of the alpine and subalpine regions of the Australian Alps and Tasmania. The Snowy 2.0 project's feasibility study outlines plans to construct 27 km of underground tunnels to link the existing Talbingo and Tantangara reservoirs (Figure 1), allowing water to be recycled across the ~ 600-m hydraulic head between the dams. The construction would take place within the borders of Kosciuszko National Park (KNP), using sites disturbed previously by mining and the original Snowy Hydro Scheme, as well as new areas of land (Snowy Hydro Limited 2017). Like other alpine and subalpine areas around the world, the intended construction sites are important for biodiversity (Pickering and Hill 2007) and form the catchment for major river systems, including the Murray–Darling (Worboys, Good, and Spate 2011). Thus, maintenance of the area's ecological health is of vital importance to secure food and water supplies for south-eastern Australia.

Conservation of biodiversity and catchment health in KNP is at risk from human interactions in the park and climate change (Briceño, Hoyle, and Nicotra 2015; McDougall 2001). European livestock grazing in the Australian Alps prior to the area's protection in 1967 and construction of the original Snowy Hydro Scheme substantially damaged KNP's ecosystems, including soil destabilisation, wetland destruction and the introduction of alien plant species as a result of clearing, road construction and the dumping of leftover rock and soil (Johnston and Johnston 2004; Schulz and Wilks 2017). Despite control programs over the past two decades, feral animals and invasive flora have damaged wetland and streamside vegetation and caused substantial erosion to fragile humus and peat soils (McDougall 2001). The impacts of climate change, including drying conditions, extreme weather events, and more frequent and extreme fires are likely to exacerbate these disturbances and threaten the long-term sustainability of water supplied from these catchments (Worboys 2016).

Careful consideration of these issues is critical when assessing the construction impacts of Snowy 2.0. To ensure a better understanding of the potential biodiversity conservation challenges in KNP if the PHES project is approved, this paper systematically reviews the literature to assess: (i) the key environmental disturbances likely to arise from PHES construction; and (ii) the specific impacts of these construction processes on biodiversity in subalpine and alpine environments. Based on these findings, recommendations are provided to ensure new disturbances are minimised.

Methodology

Common disturbances of PHES construction to biodiversity and the environment were identified through a review of publicly available environmental impact assessments

Figure 1. The Snowy Hydro Scheme and proposed Snowy 2.0 expansion plans are situated in the northern area of KNP. © Snowy Hydro Limited 2018.

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(EIAs), technical reports and briefing documents from projects globally. Further, peer-reviewed literature appearing in scientific journal databases related to PHES projects was reviewed for commentary on environmental impacts. These records were sourced using search strings including (PHES OR Pumped hydro electric storage OR pumped battery storage OR pumped storage) AND (construction OR environmental statement OR environmental assessment OR technical report OR impacts OR environmental disturbances OR costs). Data were catalogued according to common environmental disturbances discussed.

The environmental disturbances of PHES construction identified were then systematically reviewed to quantify their potential impacts on alpine and subalpine biodiversity following the procedure developed by the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) Statement (Moher et al. 2009) (Figure 2). Research papers were collected from databases, including Science Direct, Scopus, Google Scholar, Web of Science, Trove and JSTORE during April and May 2018. Keywords used for the searches included (road OR construction OR habitat modification OR habitat fragmentation OR clearing OR spoil OR drilling OR tunnelling OR infrastructure development OR disturbance OR camps OR impact OR trampling OR dumping OR vehicle) OR (biodiversity OR environment OR flora OR fauna OR exotic OR weeds OR wildlife) AND (alpine OR subalpine OR Alps OR Snowy Mountains OR Kosciuszko National Park).

Given indicative plans for Snowy 2.0 to dump spoil generated from construction activities into fresh water reservoirs in KNP (Snowy Hydro Limited 2017), an independent search string was also employed to assess the potential impact of spoil on freshwater environments: (fresh water OR reservoir OR lake OR river OR dam OR aquaculture) AND (spoil OR acid rock drainage OR sediment OR mine waste OR tailings). Additional academic papers were sourced using the reference lists of articles, and personal communication was sought with other researchers who provided commentary on related topics.

Articles were screened at two levels for their inclusion in the study's database. First, titles and abstracts were analysed and excluded if they did not address two or more of the following criteria: (i) focus on subalpine, alpine or freshwater environments; (ii)

Figure 2. PRISMA literature search flow diagram.

mention an environmental disturbance related to road construction, land clearing, spoil dumping, human presence, infrastructure development, drilling, tunnelling and/or water quality; and (iii) concentrate on flora, fauna or aquaculture. Articles that satisfied these requirements were read in full and excluded if they did not provide a specific focus on effects of construction-related disturbances on alpine or subalpine flora, fauna or aquaculture, or focus on the impact of spoil dumping on freshwater environments.

A database of the publications retrieved was compiled to determine: (i) what methods have been used to determine the environmental impact of each construction process; (ii) what are the common impacts to biodiversity and environmental responses reported; (iii) where has the research been conducted; and (iv) what management recommendations have been suggested.

Results

Fifteen papers were reviewed from keyword searches related to 'PHES environmental impact'. These included six environmental impact statements, five technical reports and four project briefing documents. The relevant literature identified is given in the online Supplemental material. All papers reported environmental disturbances arising from the construction phase of PHES implementation (Table 1), with vegetation clearing the most common concern (13 articles), followed by altered water quality (11), access road construction (11), spoil disposal (10), human presence (8), dam construction (8), land inundation (7) and transmission line infrastructure (5). The articles discussed 17 currently operating or proposed PHES facilities spanning nine countries, including the U.S.A. (7 facilities), Europe (4), South Africa (2), China (2), Indonesia (1) and Australia (1). All articles were published between 1974 and 2018, with the majority (11) published after 2000.

Environmental disturbances associated with PHES construction (road construction, land clearing, spoil dumping, human presence and altered water quality) were then assessed for their specific impacts on subalpine, alpine and freshwater biodiversity. The relevant literature identified is given in the online Supplemental material. Fifty-seven papers were identified, of which 42 used observational methods, 8 used an experimental methodology and 7 were review papers (Table 2). Twenty-four of the papers reviewed focused on the Australian Alps, with additional papers from Europe (17), the U.S.A. (8), South America (3), Japan (1) and New Zealand (1). Thirty-nine papers reported impacts to flora, of which 26 explicitly identified negative impacts. Eleven papers discussed impacts to fauna, of which five explicitly identified negative impacts. A further nine papers discussed impacts to aquaculture, of which five explicitly identified negative impacts.

Road construction was the most commonly reported environmental disturbance impacting biodiversity in subalpine and alpine environments (19 papers), with other processes reported including vegetation clearing (17), spoil disposal (16) and human disturbance (12). The negative impacts to biodiversity identified from these disturbances were classified into five primary categories, namely the: (i) proliferation of exotic flora; (ii) reduction in native vegetation coverage; (iii) impacts to endemic fauna; (iv) altered landscape hydrology; and (v) reduced water quality in reservoirs connected to PHES systems. Of these, proliferation of exotic flora was discussed most commonly (22 papers), followed by reduced native vegetation coverage (16), altered water quality (12),

Table 1. Literature reporting on environmental disturbances from PHES construction processes.

Paper	Year	Country	PHES project	Environmental disturbances ^a							
				DC	RC	HP	VC	TL	SD	WQ	LI
ADB	2002	China	Guangzhou Pumped Storage							•	
ADB	2002	China	Zhanghewan Pumped Storage	•		•		•	•	•	•
Cavazzini & Pérez-Díaz	2014	Germany	Goldisthal Pumped-Storage Plant		•	•	•			•	
Dames & Moore	1981	U.S.A.	Northfield Mountain Pumped Storage		•		•		•		
Dames & Moore	1981	U.S.A.	Helms Pumped Storage Project	•	•		•	•	•	•	•
Federal Energy Regulatory Commission	1979	U.S.A.	Prattville Pumped Storage Project	•	•	•	•			•	•
Federal Energy Regulatory Commission	2007	U.S.A.	Lake Elsinore Advanced Pumped Storage Project	•			•		•	•	
Robbins & Mathur	1976	U.S.A.	Muddy Run Pumped Storage Project							•	
Roberts & Erasmus	1982	South Africa	Drakensberg Pumped Storage	•	•	•	•	•	•		•
Savannah Environmental Pty Ltd	2008	South Africa	Ingula Integration Project		•	•	•	•			
Snowy Hydro	2017	Australia	Snowy Hydro 2.0		•	•	•		•	•	
State Water Resources Control Board	2012	U.S.A.	Eagle Mountain Pumped Storage			•	•	•	•		
Tennessee Valley Authority	1974	U.S.A.	Raccoon Mountain Pumped-Storage Plant	•	•		•		•		•
Tjomsland & Haakon Bakken	2012	Norway	Tonstad pumping plant						•	•	
Wänn et al.	2012	Greece	Thissavros PHES Scheme	•	•		•			•	•
Wänn et al.	2012	Ireland	Turlough Hill Pumped-Storage Plant		•		•			•	
World Bank	2010	Indonesia	Upper Cisokan Pumped-Storage Plant	•	•	•	•		•		•

^aDC, dam construction; RC, road construction; HP, human presence; VC, vegetation clearing; TL, transmission lines; SD, spoil disposal; WQ, water quality; LI, land inundation.

impacts to endemic fauna (8) and changes to hydrology (8). The two papers reporting positive impacts to fauna (Table 2) discussed habitat creation from land-based spoil disposal for the species mountain pygmy-possum (*Burramys parvus*) and smoky mouse (*Pseudomys fumeus*).

Table 2. Number of published studies (1973–2017) that examined the impacts of disturbance (vegetation clearing, road construction, human disturbance, spoil disposal) on subalpine, alpine and freshwater biodiversity.

Category	Total	Negative Impact	No Impact	Positive Impact
All Studies	57	35	20	2
Method					
Observational	42	30	10	2
Experimental	8	2	6
Review	7	3	4
Disturbance Reported					
Vegetation Clearing	17	11	6
Road Construction	19	15	4
Human Disturbance	12	7	5
Spoil Disposal (land)	4	1	1	2
Spoil Disposal (water)	12	6	6
Environmental Impact Type					
Proliferation of exotic flora	22	16	6
Reduced Native Coverage	16	7	9
Impacts to endemic fauna	8	4	2	2
Changes to hydrology	8	5	3
Reduced water quality	12	8	4
Impacted Taxa					
Flora (Terrestrial)	39	26	13
Fauna (Terrestrial)	11	5	4	2
Aquaculture	9	5	4

Discussion

Environmental disturbances arising from PHES construction

The reviewed EIAs, technical reports and policy documents identified several environmental disturbances associated with PHES construction, including vegetation clearing, access road construction, spoil disposal, increased human presence, transmission line infrastructure, land inundation and altered water quality in associated reservoirs and catchment areas. This result was anticipated, as these concerns match those of similar large-scale infrastructure processes such as dam-building, road and tunnel construction (Steffen 2012). Although PHES systems have been implemented globally since the 1890s (Yang and Jackson 2011), an increase in reporting on their environmental risks in the literature since 2000 (Table 1) likely reflects increased scrutiny on the environmental costs of energy generation, as well as requirements for mandatory EIAs in many jurisdictions (Jay et al. 2007).

While the majority of papers reviewed (~ 80%) identified common environmental disturbances such as vegetation clearing and access road construction arising from PHES construction, concerns associated with land inundation, human presence and spoil disposal appeared to be largely determined by the environmental context of the project under assessment. Projects on already degraded land, such as the Zhanghewan Pumped Storage Project near Beijing, for example, anticipated less impact on the habitat of endemic species than projects in protected or high-biodiversity designated areas (ADB 2002; Roberts and Erasmus 1982). Likewise, projects utilising existing reservoirs to create close-looped pumped storage systems did not identify the same concerns of land inundation as those projects requiring large-scale damming of rivers or streams (Robbins and Mathur 1976;

Wänn et al. 2012). When considering the environmental disturbances likely to arise from PHES in KNP, this review therefore accounted for Snowy 2.0's specific context as a closed-loop PHES system in a protected area.

Impacts on alpine and subalpine biodiversity

The environmental disturbances of PHES construction identified from the literature are likely to have a range of negative effects for biodiversity in KNP. These impacts, including the proliferation of exotic flora, habitat loss resulting from vegetation clearing, altered landscape hydrology and reduced water quality in reservoirs connected to PHES systems, are now described and management strategies to minimise disturbance are provided.

Proliferation of exotic flora

Although inaccessibility has historically protected mountain systems from wide-scale disturbance, increased human activity over the last century has corresponded with a rise in exotic plant richness in mountains globally (Pyšek et al. 2011). Several studies in the U.S.A., Europe, Japan and South America have cited road construction as a primary contributor to the presence and proliferation of exotic species (Alexander et al. 2009; Arroyo et al. 2000; Becker et al. 2005; Bell and Bliss 1973; Takahashi and Miyajima 2010). Literature reviews discussing ecological impacts of road presence have highlighted vehicles as key dispersal agents of alien plants (Spellerberg 1998), while the role of roadsides as dispersal corridors and potential habitat for exotic plant species has also been well covered (Andrews 1990; Pauchard and Alaback 2004).

The literature reviewed on the Australian Alps shares this trend, classifying the region as highly susceptible to exotic plant invasions (Pickering and Growcock 2009). Vegetation clearing for infrastructure enables introduced weeds, such as orange hawkweed (*Pilosella aurantiaca*), yarrow (*Achillea millefolium*) and sheep sorrel (*Rumex acetosella*), to establish and spread into adjacent native vegetation, where they often outcompete native taxa (Pickering and Hill 2007). Indeed, multiple studies focused on KNP have identified increased occurrences of alien flora on and adjacent to access roads, human settlements, infrastructure (such as ski resorts) and discarded spoil heaps (Godfree, Lepschi, and Malinson 2004; Johnston 2005; McDougall et al. 2005). This exotic species spread is likely to be further exacerbated by the warming temperatures resulting from global climate change (Worboys, Good, and Spate 2011). For example, warmer soil conditions may facilitate increased weed dispersal, while at the same time impacting the regeneration of native seeds (Briceño, Hoyle, and Nicotra 2015). However, with an incomplete understanding of many exotic species in alpine areas, predicting the long-term impact of their dispersal on native flora remains challenging (Johnston and Pickering 2001). Because the construction of roads and infrastructure for Snowy 2.0 has a high likelihood of contributing to introduced species dispersal, it will be necessary to have management programs to minimise disturbances and promote effective monitoring and revegetation strategies to reduce negative impacts of exotic species.

Habitat loss resulting from vegetation clearing

The impacts of habitat clearing to facilitate infrastructure for recreational activities such as skiing have been well-documented globally. According to a review on the topic by Sato,

Wood, and Lindenmayer (2013), habitat destruction resulting from winter recreation infrastructure can negatively impact species richness in mammals, arthropods and birds, as the quality of the environment between populations is altered. For example, in their study of arthropod diversity in the European Alps, Wettstein and Schmid (1999) concluded that habitat fragmentation resulting from anthropogenic disturbances negatively affected the species richness of butterfly populations in montane wetlands. Lower landscape connectivity has also been found to decrease gene flow in fauna populations, with the resulting effects of inbreeding depression and genetic drift enhancing extinction risk (Emaresi et al. 2011). However, the geographical spread of these fauna studies is dominated by North America and the European Alps, with little research relating to taxa outside these areas. One exception to this, an analysis by Sato et al. (2014), found clearing for ski runs in KNP had negative effects on the population richness of endemic reptile species.

The large-scale disposal of spoil generated from construction activities has also been identified as a concern for habitat preservation, due to its disruption to native vegetation and ecosystem services (Johnson 1987; Walker and Everett 1987). Successful revegetation of remnant spoil dump sites has been estimated to require a minimum of 35 years (Rydgren et al. 2011), leaving a long interim period in which spoil heaps hold minimal ecological value. Hence, the discovery by Schulz, Wilks, and Broome (2012), of the use of the original Snowy Hydro Scheme's remnant spoil as habitat by threatened species was surprising. These species, including the flame robin (*Petroica phoenicea*), smoky mouse (*Pseudomys fumeus*) and mountain pygmy-possum (*Burramys parvus*), were observed using the spoil heaps and adjacent vegetation as foraging habitat, indicating the possibility that dump sites may have the capacity to support vulnerable endemic populations (Schulz and Wilks 2017).

Altered hydrology in construction areas

Alpine soils play an integral role in the hydrological cycle of the catchment, influencing subsurface water movement, volume and quality (Graham-Higgs et al. 2006; McDougall 2001). Modification of the environment through exotic plant introductions or soil removal for infrastructure may therefore alter the movement of subsurface water, increasing rates of erosion and sedimentation within the catchment (MacPhee and Wilks 2013). For example, Lee's (1979) assessment of the impacts of hydroelectric construction activities on Victoria's Bogong High Plains, found that construction disturbance had increased the formation of erosion pavements and soil exposure. This, in turn, dried out bog complexes and other wetland vegetation in some areas, while other areas received increasingly turbid run-off, with sediment filling ponds and impacting stream flow (Lawrence 2001). With indications that the drying conditions associated with climate change in the Australian Alps will lead to further damage to wetlands and moisture-holding peat soils (Worboys, Good, and Spate 2011), strategies are needed to ensure erosion resulting from construction processes is minimised and catchment health can be maintained.

Compromised water quality in PHES reservoirs

Johnson (1987) identified the risks associated with remnant gravel pits following extraction for roads and other construction projects. As gravel has low moisture-holding capacity, heavy rain produces increased surface run-off, heightening soil erosion within

the catchment. The resulting sedimentation in waterways can impair ecosystem productivity and kill aquatic organisms by smothering eggs and altering aquatic habitats (Trombulak and Frissell 2000). Sedimentation may also increase in Australia's alpine catchment, with plans to dispose Snowy 2.0 construction spoil within freshwater reservoirs. Analysis by van den Berg et al. (2001) on the construction of a spoil storage depot in Lake Ketel, the Netherlands in 1996, reported that the sediment dynamics of the lake were substantially altered by the spoil's presence, with toxic contaminant accumulation usually occurring in sedimentation areas. Similarly, Lubke, Raynham, and Reavell (1981) reported a positive relationship between increased turbidity and lower levels of colonisation by native plant species following spoil disposal in the Doro River, Botswana.

The disposal of spoil in reservoirs will be additionally concerning if the spoil material contains metal toxins. When 'reactive' sulphur-containing spoil is exposed to air and water it can form acid rock drainage through redox reactions (Hoke et al. 1990), with acidic run-off risking negative effects on biodiversity. Indeed, studies from the U.S.A., Europe and Australia have indicated a negative relationship between dissolved metals and taxa richness in lakes, rivers and streams, as high concentrations of sulphide ions can kill fish and alter growth rates of algae and other microorganisms (Flint 1979; Liess, Gerner, and Kefford 2017; Orem et al. 2006). Since Snowy Hydro Limited's (2017) feasibility study has considered that spoil obtained from its tunnelling processes may be reactive, the spoil's disposal within Talbingo and Tantangara reservoirs may pose risks to freshwater biodiversity. Disposal plans focus on the reservoirs' 'dead water' zones (DWZ) to limit the oxygen available to react with metal toxins in the spoil (Snowy Hydro Limited 2017). However, few studies have been undertaken to assess the ability of DWZs to contain toxic elements or sediment over many decades or centuries. Brookes et al. (2008), for example, warn that changes to a reservoir's thermal stratification as a result of fluctuating inflows, may alter the hydrodynamic processes within the reservoir, including in the DWZ. If climatic or water-level changes were to result in previously stored spoil escaping from the DWZ in Talbingo or Tantangara reservoir, this may harm flora and fauna, and diminish the water quality of the major catchment of south-eastern Australia.

Management implications

Long-term management strategies are necessary to reduce the impacts of PHES construction on subalpine and alpine biodiversity in KNP, particularly in the context of climate change. Management strategies emphasised in the literature include the minimisation of disturbance, revegetation of disturbed areas and the implementation of appropriate disposal mechanisms for construction waste materials. The potential value of these strategies to minimise risk to alpine, subalpine and freshwater biodiversity is now discussed.

Minimise disturbance

Because the spread of exotic plant species is closely linked to disturbances from infrastructure, vehicles, roads and human activity, minimisation of disturbance provides the simplest means to limit their establishment (Johnston and Johnston 2004; Pickering, Bear, and Hill 2007). Project planning for Snowy 2.0 should aim to maximise use of existing access roads and previously disturbed locations (such as Lob's Hole and the historic Kiandra goldfields) as epicentres for construction camps, reducing instances of large-

scale impact to areas of undisturbed vegetation. Worker activities and facilities should likewise be designed to minimise the inadvertent transfer of alien species into KNP via clothing and vehicles (Pickering, Bear, and Hill 2007). This could be achieved by restricting access to KNP areas not required by the construction process and workplace practices that reduce the risks of seed dispersal (e.g. wheel and footwear washing). Locating high-traffic areas within vegetation least susceptible to introduced species invasion (such as dense grassland) could help, while regular monitoring of newly disturbed sites for introduced species would increase the effectiveness of early eradication programs (Pauchard and Alaback 2004; Schroder 2014).

Revegetation programs

In areas where disturbance is unavoidable, rehabilitation of native vegetation will be crucial. Revegetation approaches should incorporate active and ongoing monitoring of vegetation in construction-affected areas to prevent the intrusion of new alien species. Measures to contain existing weeds, stabilise soil on road verges and in spoil dumps, and re-establish vegetation cover to protect endemic fauna are needed (Pickering, Bear, and Hill 2007). Restoring alpine wetlands is also highly important to conserve catchments in the context of climate change. The risk that drier conditions may compromise the water-holding capacities of the region's humus and peat soils means that urgent regeneration works are required to re-establish wetland vegetation and stabilise streambeds to prevent further erosion (Worboys, Good, and Spate 2011).

It is recommended that revegetation strategies follow the principles outlined by Kent et al. (2002), prioritising the retaining and regenerating of existing native vegetation ahead of reseeded and replanting. Because fertilisers tend to favour exotic species (Hagen et al. 2014), their use is not recommended, unless research is carried out demonstrating their ability to significantly and selectively benefit native species. Likewise, mulches and seed mixes containing alien species should be avoided during revegetation programs, due to the tendency for exotics to outcompete native species (Lugo and Gucinski 2000; Parendes and Jones 2000).

With long-term commitment and monitoring, there is high potential for effective revegetation works in the Alps. Previous successes in the revegetation of alpine wetlands following prolonged cattle grazing prior to the 1970s demonstrated that with sufficient investment, works can restore soils and increase the water-holding capacity of the catchments. Further, the Restoration of Former Snowy Sites Project that commenced in KNP in 2003 has had considerable success in using region-specific strategies to stabilise landforms and promote regrowth of locally dominant species at over 200 of 400 degraded sites (MacPhee and Wilks 2013): expansion of this program is recommended.

Spoil disposal

The disposal of spoil generated from tunnelling requires careful management to reduce impacts on biodiversity. While PHES projects overseas have advocated for the re-use of spoil in the construction process (Roberts and Erasmus 1982), without large-scale road or dam construction this is unlikely to be feasible for Snowy 2.0. Terrestrial spoil disposal has previously posed challenges in KNP due to the slow timescale for vegetation re-establishment on spoil heaps (Rydgren et al. 2011). For example, the 2003 Restoration of

Former Snowy Scheme Sites Project tasked with rehabilitating the original Snowy Hydro spoil heaps, identified key barriers arising from: (i) a lack of established techniques to facilitate restoration works in steep, high-altitude valleys; and (ii) the absence of any substantial soil and organic matter in spoil disposal areas (MacPhee and Wilks 2013). Countering these difficulties will require long-term, secure funding and skilled staff to increase the establishment of native vegetation.

If the spoil generated from Snowy 2.0 is found to be reactive, impacts of potentially contaminated run-off require careful consideration. Disposal of reactive spoil should be limited to areas where impacts of turbidity, siltation and acid rock drainage can be minimised to reduce the impact on water quality (Orem et al. 2006). This could include disposal in disused quarries, mining or landfill sites outside KNP boundaries. Containment methods for spoil disposed of inside waterways must have enough capacity and be sufficiently robust to work under worst-case scenario conditions, with consistent monitoring required to ensure long-term recovery of biota and to test for recontamination (DER 2015).

Recommendations for future work

Review of the processes that have impacted biodiversity in KNP has highlighted key gaps in the literature where further research is recommended. These include:

- Assessment of the influence of PHES operations (including water recycling between Talbingo and Tantangara reservoirs) on native fish populations, particularly the risks associated with introducing redbfin perch (*Perca fluviatilis*) into Tantangara Reservoir (Snowy Hydro Limited 2017).
- Additional studies of the ecology of alpine alien plants to ensure any long-term impacts to the catchment's hydrology can be minimised.
- Research on the impacts of vegetation clearing and artificial boulder-field creation on the habitat of native fauna would be useful to determine the benefits of long-term revegetation in the park for endemic fauna, given the mixed results of previous studies in KNP (Sato et al. 2014; Schulz, Wilks, and Broome 2012).
- Research to determine the long-term viability of dead water storage as a disposal option for reactive spoil in the Talbingo and Tantangara reservoirs.

This recommended research will be particularly important in the context of climate change, which is predicted to decrease precipitation in the Australian alpine region by up to 20% over the coming century (Nicotra et al. 2017). These changes will increase the vulnerability of key mountain ecosystems to disturbances such as weed invasions, disease outbreaks and vegetation loss associated with increased soil temperatures (Worboys, Good, and Spate 2011).

The issue of feral animals, particularly horses in the Australian Alps also warrants close attention. The presence of feral horses in KNP since the 1820s has demonstrably impacted water catchment wetlands, as heavy trampling and grazing contribute to large-scale erosion of fragile peat-soils (OEH 2016). However, there are still substantial knowledge gaps regarding horse impacts on biodiversity in KNP, reflected in the NSW government's 2018 decision to cancel its culling program (Parliament of NSW 2018). Ideally, the Snowy 2.0 EIA will incorporate analysis of the long-term threats of both climate change and

environmental degradation resulting from horse trampling, to ensure their impacts do not jeopardise the health of the alpine catchment and hence the long-term success of the PHES expansion project.

Conclusion

Review of the literature has identified the key environmental disturbances associated with the construction of a PHES system to be vegetation clearing, access road construction, spoil disposal and altered water quality. These disturbances are likely to have negative effects for the subalpine and alpine biodiversity of KNP, including increasing the proliferation of exotic vegetation, damaging habitat crucial to endemic fauna and altering the hydrological cycle and water quality in the alpine catchment. Management strategies that minimise disturbances, assure revegetation of disturbed areas with native vegetation and dispose of spoil away from fragile areas are recommended to limit impacts to subalpine and alpine biodiversity. These management strategies should be accompanied by further research on the vulnerabilities of KNP to feral animals, weed invasions and climate change, to ensure the strategies implemented are adaptable to likely long-term changes in the alpine region.

It is likely that with the final investment decision for Snowy Hydro 2.0 in the coming year and PHES feasibility studies currently being undertaken in Tasmania (Commonwealth of Australia 2018), new technical documents, EIAs and review papers will be released as the projects progress towards final approval. Continued review is recommended to ensure a broad, up-to-date view of the overall costs and benefits of Snowy Hydro 2.0 and other PHES expansion projects. These findings will be valuable for informing decisions on the potential of PHES both in Australia and internationally.

Disclosure statement

No potential conflict of interest was reported by the authors.

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Anna Normyle graduated from The Australian National University with a Bachelors of Development Studies. She is currently completing a research-based Master of Environment at ANU, with areas of interest in geography, environmental management, GIS and environmental accounting. She has a keen interest in the Australian alpine region and the complex socio-ecological dimensions to the region's management.

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