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RESEARCH ARTICLE
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Key Points:

- The net ecosystem water balance of an Australian mountain peatland was determined over a 4-year period
- Groundwater made the highest contribution to peatland water inputs, and the vast majority of water left the peatland as streamflow
- High groundwater contributions suggest the peatland can cope with periods of low rain/snowfall

Supporting Information:

Supporting Information may be found in the online version of this article.

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Sphagnum Peatland Hydrological Balance Shows High Groundwater Dependence and Resilience to Short-Term Dry Periods

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Abstract Quantifying the hydrological connectivity of wetland ecosystems is crucial for their sustainable management and conservation. Australian mountain peatlands typically form and persist on sloping terrain downstream of groundwater springs. This suggests that they depend heavily on groundwater inputs. The relative contributions of groundwater, surface runoff, rainfall and snow to these ecosystems have, however, not yet been quantified. This study calculated the water balance of an Australian *Sphagnum* peatland by continuously monitoring key hydrological parameters over 4 years (2017–2021). Precipitation (including rain and snowfall, and snowmelt), evapotranspiration, changes in peat water storage (soil moisture and water table depth), and stream outflows were monitored using an eddy covariance system with ancillary soil sensors, a piezometer array, and externally sourced precipitation data. Groundwater contributions were calculated, and baseflow separation was performed using two publicly available tools. The results showed a substantial contribution of groundwater to the ecosystem, accounting for approximately 65% of total annual inputs. Groundwater inputs sustained stream outflows of 1.5 mm per day during periods without precipitation (i.e., summer dry periods), providing persistent surface wetness in this critical growing period. A total of 94% of the peatland water balance (70% from groundwater) was lost as streamflow, thereby maintaining essential summer flows in downstream catchments. These substantial groundwater contributions may thus provide greater resilience to dry periods in hydrologically intact peatlands in Australia than previously thought.

1. Introduction

Hydrological processes fundamentally control the formation, persistence, and function of peatlands. Peatlands occur where high rainfall and/or impeded drainage cause waterlogging, and primary productivity exceeds decomposition rates (Joosten and Clarke, 2002; Treat et al., 2019). Water supply variability can lower the peat water table, increasing the depth of the unsaturated peat surface layer, thereby enhancing heterotrophic respiration through oxidation activities (Labadz et al., 2010). Unsaturated peat soils release carbon through decomposition, contributing to atmospheric greenhouse gas emissions (Dinsmore et al., 2010). Peatland functioning is also strongly influenced by water quality, including the concentration of nutrients and minerals in the incoming water, which affects the growth and development of peat vegetation (Labadz et al., 2010). The biophysical characteristics of undisturbed peatlands stabilize internal hydrological functions and are thought to provide some capacity to buffer against changes in climate (Mercer, 2018; Siegela and Glaser, 2006). However, long-term alterations to peat hydrology can impact peatland hydrological function, and, if sustained over time, can lead to peat loss, contraction, and ecosystem transformation (Holden et al., 2003).

Mountain (i.e., alpine, subalpine, and montane) peatlands are hydrologically complex due to the interconnectedness of internal and external hydrological processes that occur at different spatial and temporal scales (Mercer, 2018). For example, peatland topography is generally considered a first-order hydrological control factor, and upslope geography creates flow paths that influence both incoming and outgoing water (Valois

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et al., 2020). Further interactions between flow paths and peat properties, such as drainable soil porosity, moisture content, specific yield, and hydraulic conductivity, drive groundwater storage below peats (Xiao et al., 2019). Underlying impermeable bedrock ensures sufficient water retention on the below–land surface of hillslope and valley–bottom peatlands as confined/non–confined aquifers (Gorham, 1957).

Mountain peatland catchments contribute to the seasonal redistribution of water via three functions; they collect, store, and discharge water into stream flows (Branfireun and Roulet, 1998; Roulet, 1990, 1991; Siegela and Glaser, 2006). Previous studies have investigated peatland hydrological connectivity, water storage properties, and the slowing of precipitation release into streamflow (i.e., the concept of peatlands acting as "sponges") (Nijp et al., 2017; Price et al., 2003; Rutherfurd et al., 2009; Valois et al., 2020; Western et al., 2008), although comprehensive peatland water balance studies remain rare (Brust et al., 2018; Lhosmot et al., 2025; Thompson et al., 2014).

Mountain peatland hydrological recharge occurs under saturated conditions following snowmelt or rainfall (Siegela, 1988). Water discharge from peatlands contributes water to small bedrock streams, thus helping maintain baseflow to lower parts of the catchment (Western et al., 2008). Groundwater hydrology and water balance studies in boreal regions have revealed the dynamics of groundwater in these areas (Bourgault et al., 2017; Branfireun and Roulet, 1998; Brannen et al., 2015; Cooper et al., 2010; Cowley et al., 2020). However, direct groundwater observations are often lacking in other wetland ecosystems due to difficulties in obtaining the required data (Hunt et al., 1996; Ramesh et al., 2020). As such, indirect approaches, such as modeling, are often applied (Hood and Hayashi, 2015; Somers and McKenzie, 2020) to interrogate relationships between ground and surface water at an ecosystem- and catchment-wide scale.

The alpine, subalpine, and montane *Sphagnum* peatlands of southeastern Australia are geographically constrained to poorly drained areas (Pemberton, 2005; Whinam et al., 2003b) and, critically, contribute to the broader hydrology of the region (Lawrence et al., 2009; Rutherfurd et al., 2009; Western et al., 2008). The biogeochemical characteristics of these ecosystems provide valuable environmental services on local, regional, and global scales in terms of the provisioning of materials, hydrological regulation, environmental/ecological support and cultural services (DEWHA, 2009; Ramsar Convention Secretariat, 2013). When intact, Australian *Sphagnum* peatlands sequester and store significant amounts of carbon from the atmosphere, playing a critical role in global carbon cycling (Gunawardhana et al., 2025; Hope & Nanson, 2015; Treby & Grover, 2023, 2024). Despite their environmental value, these ecosystems are threatened by a range of disturbances, with an estimated 50% of *Sphagnum* peatlands lost in Australia since the continent's colonization (Threatened Species Scientific Committee, 2009). Consequently, the protection and restoration of Australian peatlands is a national government priority (DEWHA, 2009).

The present study is the first to evaluate the complete water balance of a *Sphagnum* peatland in an Australian mountain region. Understanding the hydrological components of peatlands is essential for determining how different inputs and outflows influence, and are influenced by, environmental conditions and disturbances. Furthermore, exploring the hydrological functioning of a reference peatland (i.e., intact, or in near-pristine condition) enables restoration targets to be set for similar ecosystems which have been disturbed or degraded. This study, therefore, aimed to (a) quantify the net ecosystem water balance of an intact *Sphagnum* peatland over a 4-year period; (b) compare net ecosystem water balance between snow-free and snow-covered periods; and (c) determine the groundwater dependency of the peatland, including during dry periods. Using these data, a conceptual diagram of the magnitude, direction, and connectivity between each of the peatland hydrological components was developed to demonstrate the net ecosystem water balance of the site. The results of the study are discussed in the context of setting meaningful benchmarks for the hydrological restoration of Australian mountain peatlands.

2. Materials and Methods

2.1. Study Area

The study was conducted over 4 years (June 2017 to May 2021) at Watchbed Creek, Heathy Spur–1 (HS–1), a sloped *Sphagnum* peatland in the valley of a small mountainous headwater catchment of the Bogong High Plains, Victoria (Figure 1). The surrounding catchment comprises hillslopes and valleys, with elevations ranging from 1,680 to 1,790 m. The peatland area is 5 ha, of a total 25.8 ha catchment. Several previous hydrogeological and

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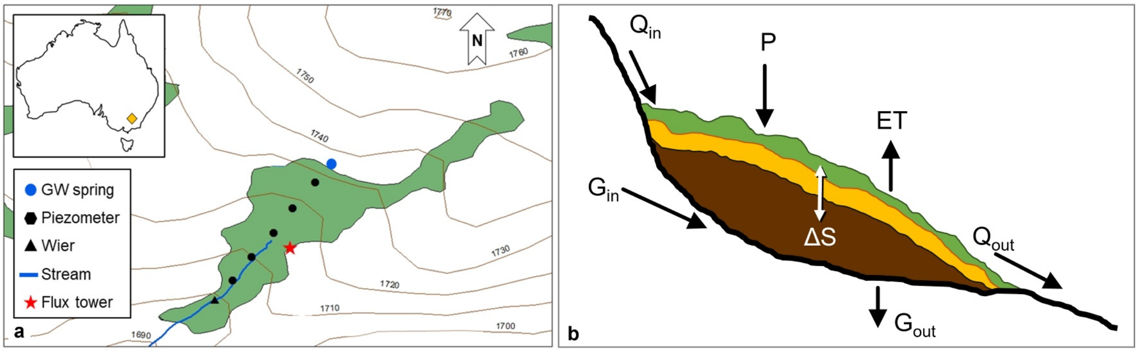

Figure 1. Study site and water balance conceptual approach: (a) map of Watchbed Creek headwater catchment (HS-1) showing the area of the *Sphagnum* peatland (shaded green) and hydrological measurement locations (adapted from Gunawardhana et al., 2021 with permission from Elsevier under license 6030510276554); and (b) schematic diagram of the water balance components of the peatland, where: P = precipitation (including rainfall, snowfall, and snow water equivalents); ET = evapotranspiration; Q_{in} = incoming surface runoff from surrounding hillslopes; G_{in} = incoming groundwater flow from underlying aquifers; G_{out} = groundwater leaving by infiltration or deep percolation to the underlying aquifer; Q_{out} = streamflow leaving the peatland; and ΔS = the change in peat water storage (water table depth and soil moisture) over time.

ecological investigations have been conducted at this site (Gunawardhana et al., 2021; Karis et al., 2016; Silvester, 2009; Silvester et al., 2021; Western et al., 2008). The vegetation of adjacent ecosystems comprises snow gum (*Eucalyptus pauciflora*) woodland, grassland (*Poa spp.* dominated) and open heathland. The peatland contains many small ponds, and the primary streamline forms near the peatland center (Figure 1; Gunawardhana et al., 2021).

The climate in the study region is subpolar oceanic (Köppen-Geiger classification Cfc) (Beck et al., 2018), with mean annual temperatures of 9.4°C, and maximum and minimum temperatures of 6.1°C and 13.1°C, respectively (reference period 1990–2021; BOM, 2021). Mean annual precipitation is 2346 mm yr^{-1} (reference period: 1951–2021; BOM, 2021), and snow typically falls between June and October. The watershed is usually snow-covered for around 3 months per year, with snowmelt typically occurring between late September and October.

The peatland vegetation community at the study site is dominated by *Sphagnum* mosses (*Sphagnum cristatum*) with shrub species (*Dracophyllum continentis, Epacris paludosa*, *Baeckea gunniana, Callistemon pityoides,* and *Grevillea australis*) interspersed through the *Sphagnum*, on both hummock and hollow areas. The bedrock geology comprises sedimentary rocks, and the underlying soil is a paralithic, acidic-sapric organosol (McKenzie et al., 2004). Peatland depth varies across the peatlands, with peat soils greater than 1 m deep in the lower depressions and shallower peat depths on the valley sides of less than 0.3 m.

2.2. Application of the Water Balance Concept

Direct measurements at the Heathy Spur-1 peatland enabled quantification of P, ET, Q_{out} and ΔS, aggregated to daily values over the 4-year study period. Parameters not directly measured were $Q_{\text{in},}$ $G_{\text{in},}$ and G_{out}. The water balance concept is valuable in explaining the hydrological connectivity, movement, and the origins of different hydrological components in headwater catchments (Brannen et al., 2015). The peatland water balance is the net sum of inflows and outflows of water from a peatland (Figures 1b and 2), and, according to Ingram (1983), the long-term water balance for a wetland can be determined using Equation 1:

$$P + Q_{\text{in}} + G_{\text{in}} = G_{\text{out}} + \text{ET} + Q_{\text{out}} \pm \Delta S \tag{1}$$

where P = precipitation; Q_{in} = surface water inflows; G_{in} = groundwater inflows; ET = evapotranspiration; G_{out} = groundwater outflows; Q_{out} = surface water outflows; and ΔS = the change in water storage between the beginning and the end of the selected time period (soil moisture changes in the unsaturated zone and water table depth changes in the saturated zone).

In applying the water balance concept to the study site, G_{in} and G_{out} were combined and considered as net groundwater recharge (G_{net}), shown in Equation 2:

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$$G_{in} + G_{out} = G_{net} \tag{2}$$

G_{net} is an unknown parameter in the water balance concept. However, we expected that G_{out} is negligible due to well–humidified lower peat layers at the site. As such, for calculating the water balance, it was assumed that $G_{out} = 0$. For this study, the water balance equation's overall residual component is R, which is the sum of G_{in} and Q_{in} (not directly measured, see further below) shown in Equation 3:

$$R = G_{in} + Q_{in} \tag{3}$$

Equation 1 was modified by use of the assumptions and relationships in Equations 2 and 3, enabling quantification of the water balance using the simplified Equation 4, adapted from Lhosmot et al. (2025):

$$R = \mathrm{ET} + Q_{out} + \Delta S - P \tag{4}$$

The water balance components were expressed as an equivalent peatland–water depth (millimeters; mm). In this work, the peatland water balance was quantified for the snow-covered and snow–free periods. The snow-free period is defined as the time between the end of the snowmelt and the beginning of snow accumulation each year. Water balance variables were calculated daily for the snow-free period, and an aggregated water balance for the snow period was calculated for each study year, because daily snowfall records were not available (see further below).

An equation was developed using measured snow density data to build a relationship with the number of days since the first day of snow accumulation (>1 cm), in order to include density changes with snow compaction after snowfall following Jonas et al. (2009) (Equation 5). Calculated snow densities were then used to derive the SWE (snow water equivalent) from snow depth data using Equation 6 (Hill et al., 2019; Winkler et al., 2021).

$$P_b = 0.00269x + 0.25 \tag{5}$$

where P_b = snow density; and x = days snow accumulated.

$$\mathrm{SWE} = hs\,\frac{p_b}{p_w} \tag{6}$$

where h_s = snow depth (cm); p_b = snow density (g cm^{-3}); and p_w = density of water (g cm^{-3}).

The change in water stored in the peat profile (ΔS) between the beginning and the end of each time period was calculated from the change in water table depth in the saturated zone, plus the change in soil moisture content in the unsaturated zone, shown in Equation 7:

$$\Delta S = \Delta \mathrm{SWC}\ \mathrm{x}\ \mathrm{WTD} + \Delta \mathrm{WTD}\ \mathrm{x}\ \theta_d \tag{7}$$

where ΔSWC = the change in average soil water content in the unsaturated zone; WTD = average water table depth; ΔWTD = change in water table depth between one day and the next; and θ_d = drainable soil porosity.

Measured stream-flow data was partitioned into the quick flow from precipitation and baseflow from groundwater, by applying the baseflow separation technique to the stream hydrograph. Here, the baseflow is considered to be the component of streamflow that originates from a non-point source, as distributed flow path groundwater input (Partington et al., 2012), shown in Equation 8:

$$Q_{out} = \mathrm{BF} + Qf \tag{8}$$

where Q_{out} = stream outflow; BF = baseflow or groundwater contribution to the stream outflow; and Q_f = quick flow or surface water contribution to the stream outflow.

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2.3. Evaluation of Net Groundwater and Surface Water Inflow

Net groundwater was calculated by adding the ET contribution to baseflow groundwater. The rationale for this approach is as follows. Following Cochand et al. (2019), it is assumed that some of the groundwater entering the peatland is lost via ET and therefore is not measured at the downstream weir as streamflow (Kitlasten & Fogg, 2015; Li et al., 2019; Millar et al., 2018). As such, the net groundwater contribution was calculated using the streamflow hydrograph separation approach, combined with measured ET data, to evaluate net groundwater for the peatland as per Equation 9:

$$G_{\text{net}} = \text{BF} + \text{ET} \tag{9}$$

where BF = baseflow; and ET = evapotranspiration. This method assumes that there is no ET associated with quick flow.

Baseflow separation was performed to gain additional insights into the contribution of groundwater to peatland ecohydrology by estimating the site's Baseflow Index (BFI; BFI+ 3.0; Gregor, 2010) using the local minimum method, and by using the Web-based Hydrograph Analysis Tool (WHAT; Lim et al., 2005). Both tools estimate how much streamflow is comprised of baseflow, and were selected on the basis that both are well-established, readily available, and robust tools for this purpose, when compared to other available methods (Chen and Teegavarapu, 2020; Combalicer et al., 2008). While the two methods produced similar results in terms of the timing and magnitude of peak stream flows (with output data strongly correlated), the WHAT method was more sensitive. As a result, the WHAT method was chosen to determine the net water balance of the site. A comparison of the two methods is provided in the Figure S2 in Supporting Information S1.

Once G_{net} is determined using Equation 9, there is only one unknown parameter remaining in Equation 3, enabling the modified water balance equation to be solved to calculate incoming surface water (Q_{in}).

2.4. Data Acquisition and Instrumentation

A summary of the method used to derive each component of the peatland water balance is provided in Table 1. Further details are included below.

2.4.1. Precipitation and Snow Water Contribution (P)

Precipitation was quantified from combined rainfall, snowfall, and snow water inflows to the peatland. Long-term data from Rocky Valley (BOM station no. 83043) shows that >30% of annual incoming precipitation falls as snow. Daily precipitation data were obtained from the Australian Bureau of Meteorology (Site 83043), a monitoring station located ~4 km from the study site and at a similar altitude (BOM, 2021). During the snow-free period, rainfall input was calculated daily. During the snow-covered period, precipitation was calculated as an aggregate over the entire period, described in detail below.

The contribution from snow water was quantified for each snow season during the 4-year study period. Snowmelt is generally expected to either directly infiltrate into the soil or move across the landscape into wetlands, and some snow is lost through sublimation (Hood and Hayashi, 2015). The latent energy requirement that drives snow sublimation and fluxes related to the sublimation can be captured by eddy covariance vapor analysis (Stigter et al., 2018). Therefore, the sublimation component of snow loss was accounted for in the ET component of Equation 4 and is not included in Equation 6. The approach used in this study quantified the amount of water stored in the snow on the day of maximum snow height, according to Equations 6 and 7. The liquid water contained within the snowpack was measured as the snow water equivalent (SWE), as outlined in Swenson et al. (2019). SWE is the product of snow density (relative to water) and snow depth, as described in Holbrook et al. (2016). Snow depth was continuously recorded at the flux tower (AU-APL) with a Sonic Distance Sensor (SR50A–L, Campbell Scientific, USA). In addition, snow height data records were obtained from manual measurements recorded by Falls Creek Alpine Resort staff.

Stratified snow density surveys were conducted within the catchment from 2015 to 2018 on random days within the snow-covered period by collaborator Dr Susanna Venn (Deakin University). An averaged snow column density was then calculated to incorporate snow density variations along the snow profile depth.

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Table 1

Summary of Data Collection Method for Water Balance Components of the Heathy Spur-1 (AU-APL) Peatland

Component	Abbreviation	Method	Instrumentation	Source
Precipitation (rainfall)	P	Direct measurement	NA	Bureau of Meteorology (BOM, 2021)
Precipitation (snowfall)	P	Direct measurement	Snow depth: Sonic Distance Sensor (SR50A–L, Campbell Scientific, USA).	Snow height: Falls Creek Resort
Precipitation (snow water equivalents)	P/SWE	Direct measurement & calculation	Snow depth: Sonic Distance Sensor (SR50A–L, Campbell Scientific, USA). Snow density: Snow density cutter	NA
Evapotranspiration	ET	Measured by EC	IRGASON; CR3000 (Campbell Scientific, USA); CNR1 (Kipp & Zonen, Netherlands)	NA
Incoming surface water	Q_{in}	Calculated by solving the water balance equation	NA	NA
Stream outflow	Q_{out}	Direct flow measurement and volume calculation	V-notch weir; WT-HR 500 piezometer (Trutrack, New Zealand)	NA
Groundwater inflows	G_{in}	Calculated using WHAT baseflow separation tool	NA	NA
Groundwater outflows	G_{out}	Assumed negligible	NA	NA
Change in water storage	ΔS	Direct measurement of SWC and WTD & reference value for θ_d	4 × CS655 reflectometers + CR3000 logger (Campbell Scientific); 4 × WT-HR 500 piezometers (Trutrack, New Zealand)	Grover (2006)

Note. EC = eddy covariance.

2.4.2. Evapotranspiration (ET) Measured by Eddy Covariance

The eddy covariance (EC) method was applied to measure peatland evapotranspiration (ET) from fluxes of latent energy (LE). The EC system (a combined sonic anemometer and open-path infrared gas analyzer, IRGASON, Campbell Scientific, Logan, Utah, USA) was installed 2.4 m above the land surface. It sampled the turbulent environment at a frequency of 10 Hz, with the raw measurements stored in a data logger (CR3000, Campbell Scientific, USA). The tower was also equipped with a series of meteorological instruments to collect low–frequency environmental data, including a CNR1 radiometer (Kipp & Zonen, Delft, Netherlands). Using the Bowen ratio method, LE fluxes, measured using the net radiometer, were corrected for energy balance non-closure (e.g., Billesbach et al., 2024) and converted to ET in mm per unit time. The resulting data comprise 2 years (2017–2019) of ET data from the site previously published in Gunawardhana et al. (2021) and two additional years of data presented for the first time in the present study (2019–2021). Details of tower installation, data processing, QA/QC and ET calculations are described in Gunawardhana et al. (2021).

2.4.3. Soil Water Content

Soil water content (soil moisture) was measured with four sets of CS655–12 cm soil water content reflectometers buried at 10 and 20 cm depth in the unsaturated zone. Water table depth was measured with a transect of five piezometers installed at 50 m intervals down the center of the peatland from the top to the bottom of the slope (Figure 1). Water table depth was recorded at 30-min intervals using Trutrack water height loggers (WT–HR 1000, TruTrack Ltd, Christchurch, New Zealand), and manual measurements were taken every 2 months to calibrate the data (Karis et al., 2016). Drainable soil porosity (θ_d) is defined as the quantity of water that can be drained from a unit volume of peat soil when the water table is lowered (or raised), and a value of 0.87 was applied from data measured on a similar Australian *Sphagnum* peatland on the Wellington Plains, Victoria

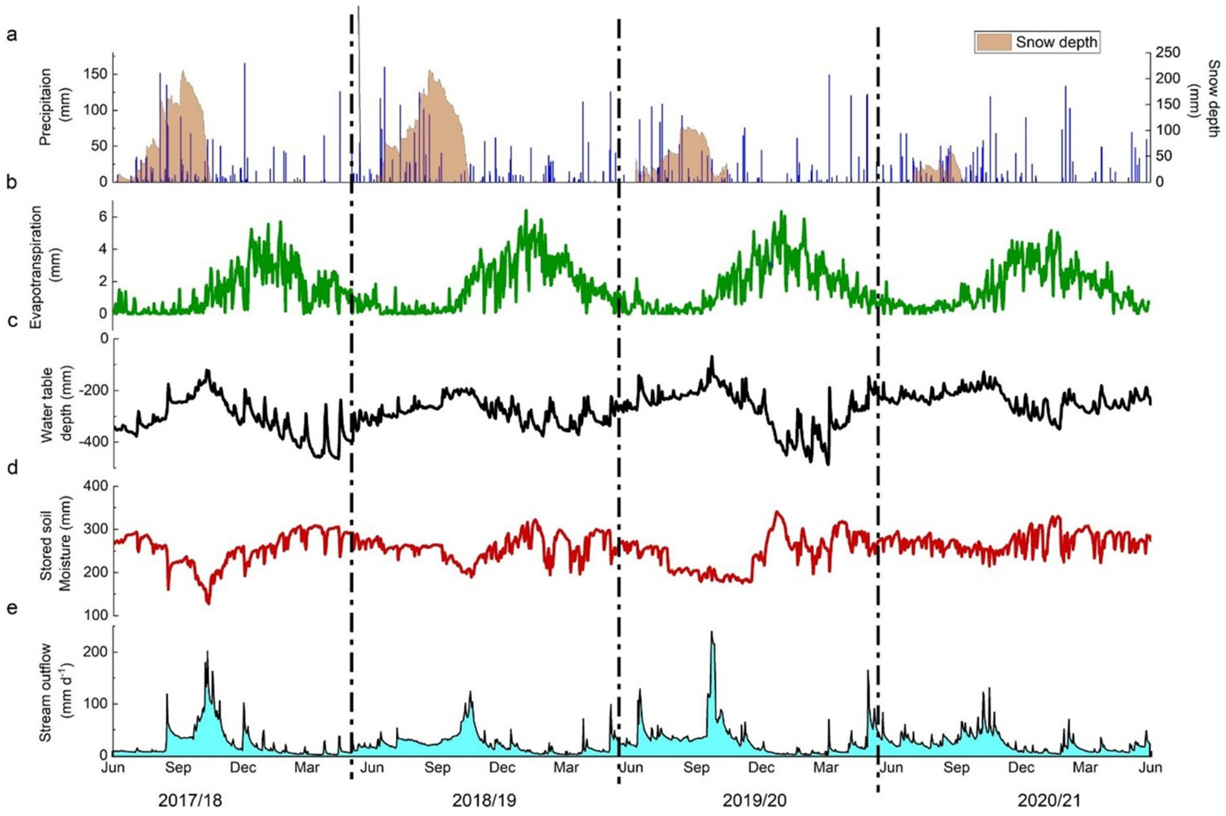

Figure 2. Peatland water balance components over the 4-year study period: (a) precipitation and snow depth; (b) evapotranspiration (ET); (c) average water table depth; (d) soil moisture (SWC) in the unsaturated peat surface zone; and (e) stream outflow. Dashed vertical lines show the start of each data year (1 June).

(Grover, 2006). This value was derived from dividing subsurface peat bulk density (dry mass × sample volume) by particle density, determined using a standard pycnometer method, to provide total porosity of the catotelm peat layer (Grover, 2006).

2.4.4. Stream Outflow (Q_{out})

Stream water outflow was monitored at 30-min intervals using a 300 mm high 90° V–notch weir, fabricated from a 15 mm recycled plastic board placed at the exit point of the peatland. The 30-min interval was selected to match the optimal eddy covariance data averaging interval, which increases effective data capture and enhances noise reduction (e.g., Loescher et al., 2006). Water height at the weir was recorded using a Trutrack water height logger (WT–HR 500; TruTrack Ltd). Casey (1992) introduced the sharp-edged weir discharge standard equation that was used to calculate stream discharge ($m^3\ d^{-1}$) derived from the weir's geometry. Finally, water volume was converted to water height by dividing water volume by the total peatland area.

3. Results

3.1. Components of the Peatland Water Balance

The hydrological components of the peatland, including daily P, snow depth, ET, WTD, soil moisture (SM), and Q_{out} are shown over the 4-year study period (June 2017–May 2021) in Figure 2. Over the 4-year study period, snowmelt generally started at the end of September and concluded by mid-October each year. Stream discharge peaks coincided with this period of snowmelt (Figure 2). Maximum stream outflow rates averaged 162 mm per day across the 4-year study period. After snowmelt, the stream outflow hydrograph shows a prolonged recession period interrupted by brief rainfall responses (Figure 2).

Considerable variation was observed in snow accumulation between the four study years, with markedly greater snow depth and duration in the first 2 years (2017–2018 and 2018–2019) compared to the last 2 years (2019–2020

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Table 2
Calculated Snow Water Equivalents (SWE) for Each Study Year and Measured Input Data Values

Year	Days with snow cover	Maximum snow depth (cm)	Days to maximum snow depth	Snow density (g cm^{-3})	SWE (cm)
2017/18	134	217	92	0.497	107.9
2018/19	134	217	75	0.451	98.1
2019/20	139	109	66	0.427	46.6
2020/21	94	60.5	52	0.389	23.6
	8	44	2	0.255	11.2

Note. The 2020–2021 season was a low-snow year, characterized by two small peaks in snow depth, with a winter melt event in between.

and 2020–2021). In 2020–2021, the lowest snowfall of the 4 years was observed, with the main snowmelt period starting at the beginning of September and concluding by 30 September. In each of the study years from 2017–2018 to 2019–2020, water table depth and stream outflows increased at the end of the snow-covered period, while soil moisture decreased. At this time, rates of ET began to increase (Figure 2). Following the snow-covered period of 2020–2021, no significant increase in stream flow or decrease in soil moisture was evident, in contrast to the previous 3 years. The water table depth remained relatively stable throughout the year (Figure 2). Further, summer maximum ET was lower in 2020–2021 than in the preceding 3 years, while rainfall during the latter part of the year was higher than in previous years (Figure 2).

Evapotranspiration exhibited clear annual patterns, increasing from September to December and then decreasing from March to June (Figure 2), which is consistent with the summer net radiation peaks observed in previous work (Gunawardhana et al., 2021). Annual maximum ET values averaged 5.2 mm day $^{-1}$ and across all years; ET was highest in mid-summer (January) and lowest in the winter months (June to August), with winter ET accounting for less than 10% of total annual ET.

The water table depth decreased (i.e., water height increased) at the end of the snow-covered period each year, suggesting that meltwater was infiltrating into the ground, groundwater inflows were increasing, and/or low or negligible rates of water loss through evapotranspiration (ET) during winter enabled the water table to rise (Figure 2). The water table was generally closer to the peat surface during spring and steadily decreased into summer and autumn (Figure 2). Water table drawdown occurred in the summer, with clear recession periods observed in 2017–2018 and 2019–2020 (Figure 2). Corresponding soil moisture in the unsaturated peat surface zone decreased when the water table level peaked and increased following snowmelt (Figure 2).

3.2. Snow Contributions to Peat Water Balance

Snow water equivalents (SWE) contributed between 34.8 and 107.9 cm of precipitation to the peatland annual water balance, equivalent to 53%, 48%, 30%, and 20% of total meteoritic water input in 2017–2018, 2018–2019, 2019–2020, and 2020–2021, respectively (Table 2). Snow densities ranged from 0.27 to 0.55 g cm^{-3} between June and October (Table 2). Snow density generally increased with time, with a strong correlation between snow density and days since snow accumulated ($R^2 = 0.89$; Figure S1 in Supporting Information S1).

3.3. Annual and Seasonal Peatland Water Balance Variations

Peatland water balances for each full year and the snow-covered and snow-free periods are shown in Figure 3. Water balance was comparable between 2017–2018 and 2018–2019, with snow water input, groundwater input, and stream-flow values similar to one another (Figure 3). During the 2019–2020 period, streamflow was higher than in other years during the snow-covered period and lower during the snow-free period (Figure 3). In 2020–2021, snowfall was lower than the preceding 3 years, and both Q_{out} and R were lower during the snow-covered period than the snow-free period (Figure 3).

3.4. Stream Water Baseflow Separation

Stream outflow and baseflow, modeled using two different baseflow separation methods, are shown in Figure S2 in Supporting Information S1. The baseflow separation outcomes of the WHAT and BFI methods differed minimally in terms of timing and magnitude of modeled peak stream flows, with the output data between the two

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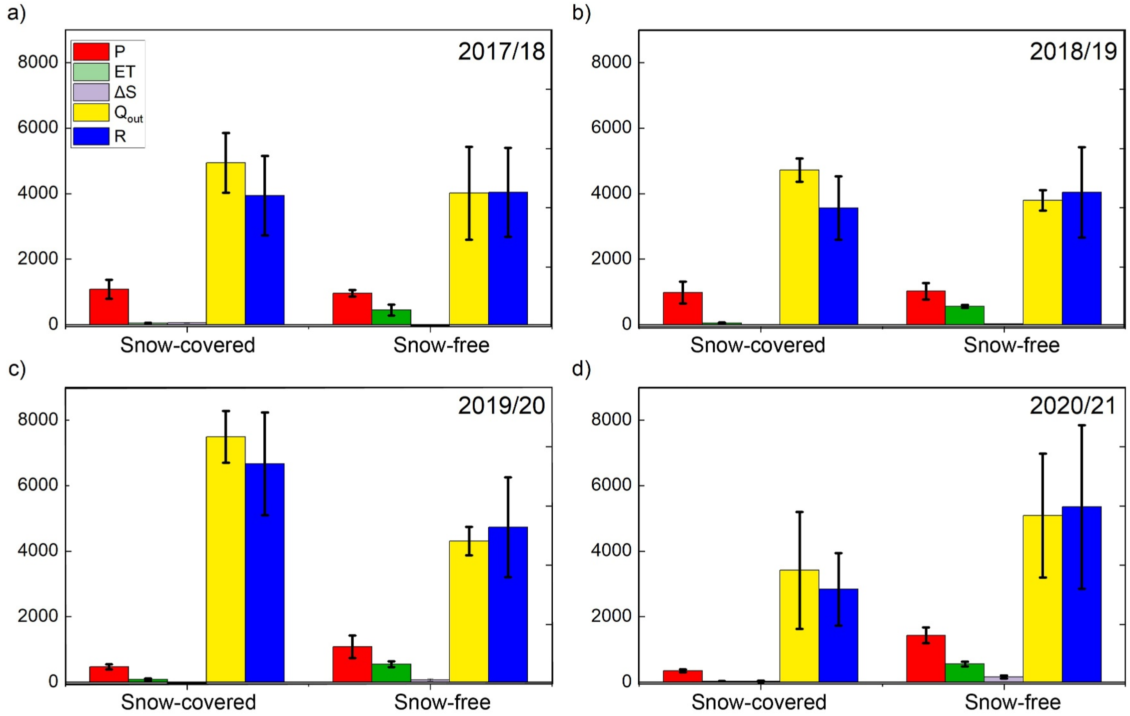

Figure 3. Water balance components (shown in mm) for the *Sphagnum* peatland site over the 4-year study period. Snow-covered period and snow-free period water balance components are shown for each year, including precipitation (P); evapotranspiration (ET); change in soil water storage from the beginning of the water year, that is, June 1st (ΔS); streamflow (Q_{out}); and the residual component (R, which comprises $G_{in} + Q_{in}$). Error bars represent standard deviation.

models showing strong correlation (Figure S3 in Supporting Information S1). The WHAT method was the more sensitive of the two and was therefore used to determine the net water balance of the site. The WHAT results suggest that baseflow comprised, on average, 64% of streamflow across the 4-year study period. During the snow-covered period, baseflow comprised an estimated 72% of streamflow, compared to 56% during the snow-free period.

3.5. Groundwater Contributions to Streamflow

The daily groundwater contribution (calculated from baseflow and evapotranspiration) to streamflow exiting the peatland exhibited considerable daily and seasonal variation, with values ranging from 1.5 to 85 mm d^{-1} (Figure 4). Water inflows to the peatland started to fall between mid-October and late December (Figure 4). This low-flow period extended from summer into autumn, with groundwater inflows averaging 6.5 ± 4.2 mm d^{-1} during the summer (Figure 4). Both the minimum and maximum contributions from groundwater to streamflow occurred during the 2019–2020 period. Calculated net groundwater inflow (G_{in}) over the 4-year study period was 6,602 mm, equivalent to 65% of inputs to the peatland annual water balance. During the snow-covered period, the groundwater contribution to the peatland water balance was 3,509 mm (72% of inputs), compared to 3,093 mm (59% of inputs) during the snow-free period. Overall, the maximum possible groundwater storage depletion (i.e., the amount of water storage availability in the peat) averaged 581 ± 58 mm across the 4-year study period.

3.6. Peatland Water Storage

The annual seasonal pattern of cumulative change in peatland water storage reflected the inputs of meteoric water from rain and snow (Figures 2 and 5). Snowmelt occurred at the beginning of spring (September and October), which coincided with shallow water table depths and peak water storage in the saturated zone. The lowest amount of water stored in the saturated zone was observed in the summer months when rainfall was less consistent (Figure 5). Significant water storage depletion in the saturated zone was observed in 2019–2020, with a maximum cumulative depletion of 204 mm from June 1st (Figure 5). An inverse relationship was evident between the amount of water stored in the saturated zone and the amount of water stored in the unsaturated zone, as the water

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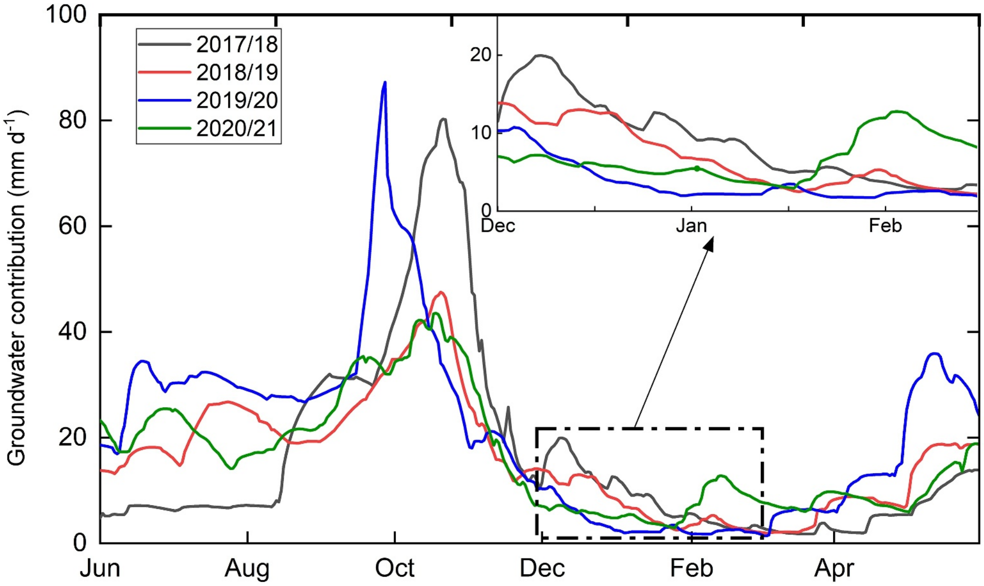

Figure 4. Groundwater contribution to streamflow exiting the *Sphagnum* peatland over the 4-year study period. Groundwater inflow calculation follows Equation 9 (see Methods).

table depth defines the boundary between the two. However, soil moisture in the unsaturated zone did not follow the same pattern as water table depth (Figure 2); soil moisture depletion was common in the summer, corresponding to increased water storage above the water table (Figure 5) and higher rates of water loss through evapotranspiration (ET).

In three of the study years, the total annual change in the amount of water stored in the peatland averaged <50 mm, that is, a very minor component (<1%) of the water balance (Figure S4 in Supporting Information S1). Annual storage change (Δ*S*) was positive in all 4 years, with the larger change in storage in 2020–2021 associated with more consistent rainfall that year (Figure 2; Figure S4 in Supporting Information S1). Changes in water storage in

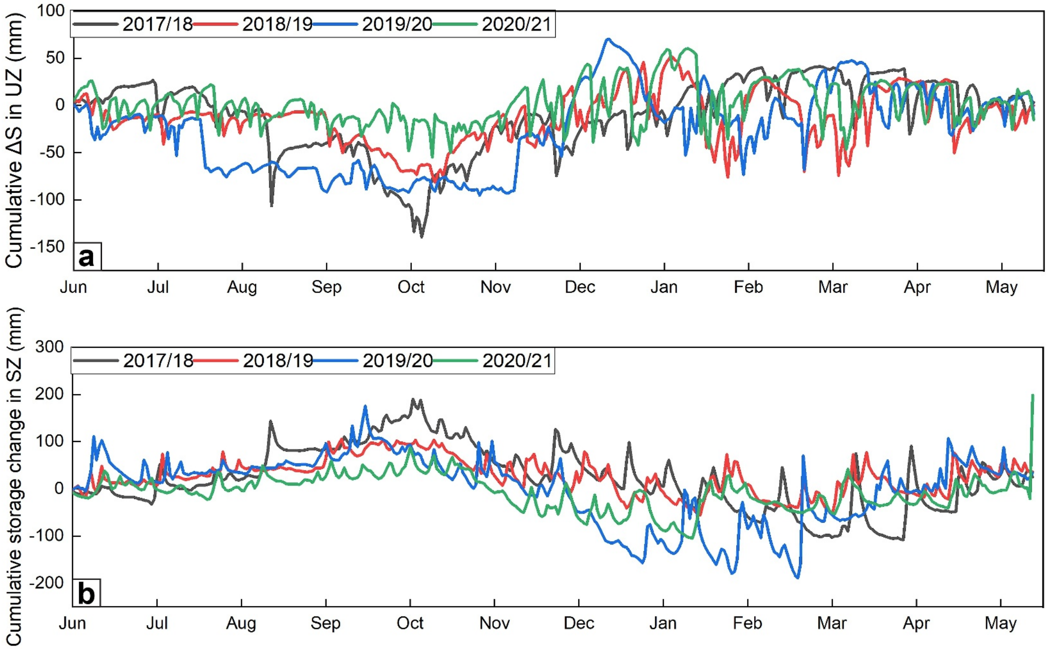

Figure 5. Cumulative change in water stored in the *Sphagnum* peatland during the 4-year study period: (a) above the water table in the unsaturated zone (UZ); and (b) below the water table in the saturated zone (SZ).

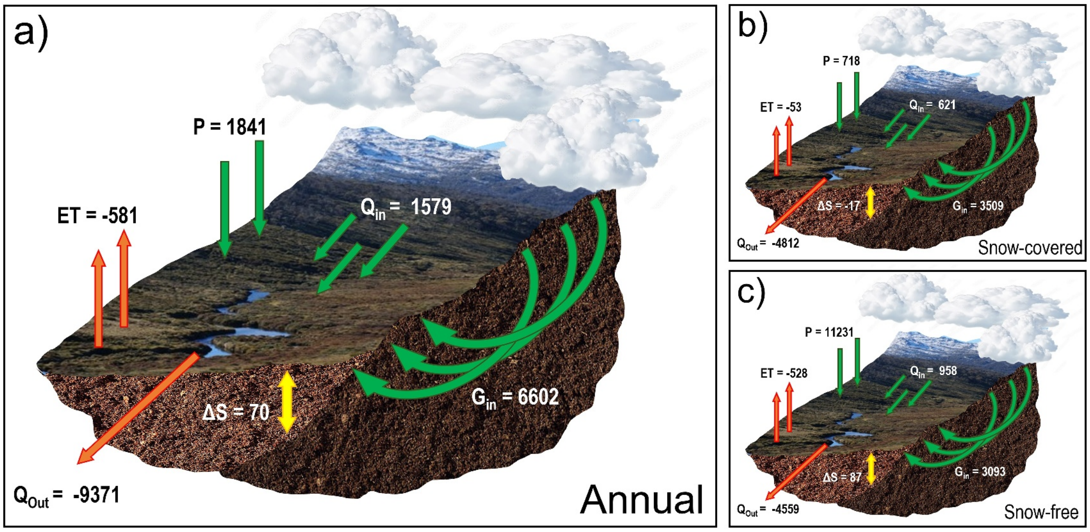

Figure 6. Conceptual diagram of the hydrology of an Australian *Sphagnum* peatland, shown as: (a) annual total; (b) snow-covered period; and (c) snow-free period water balances, averaged over the 4-year study period. All water fluxes are expressed as depth relative to the peatland area. Arrows indicate the hydrological connectivity between incoming water (Q_{in} = streamflow; P = precipitation from rainfall and snow; G_{in} = groundwater) and outgoing water (ET = evapotranspiration; and Q_{out} = streamflow) as well as the internal change in peatland water storage (ΔS).

the saturated zone, associated with changes in water table depth, were, overall, greater than those in the unsaturated zone (Figure S4 in Supporting Information S1).

3.7. Peatland Hydrology Conceptual Diagram

The peatland ecohydrology conceptual diagram illustrates the main water fluxes to and from the ecosystem over the 4-year study period (Figure 6). Groundwater inflow was the largest component of the annual water balance, accounting for 65% of inflows, and remained significant during both snow-covered and snow-free periods, at 72% and 59% of inflows, respectively. Precipitation from snow and rainfall comprised 18% of annual inputs and was 40% higher during the snow-free period than the snow-covered period. Surface runoff comprised 16% of annual inputs and was 21% lower during the snow-covered period. Streamflow comprised the major pathway for peatland outflows (94% annually) and was 253 mm higher during the snow-covered period (98% of outflows) than the snow-free period (90% of outflows). Evapotranspiration comprised only 6% of the overall outgoing water from the peatland (1% in the snow-covered period and 10% in the snow-free period). Changes in peatland water storage over the study period contributed only minimally to the overall water balance (<1% annually).

4. Discussion

This study presents the first comprehensive, multi-year water balance estimate of an Australian subalpine *Sphagnum* peatland, using data directly measured at the ecosystem scale. Hydrology is central to peatland function (Healy et al., 2007), underpinning biodiversity, carbon cycling, catchment regulation, and many other peatland ecosystem services (Waddington et al., 2014). A net positive water balance, which enables waterlogged conditions within the peat to be maintained, is critical for ensuring that peatlands continue to persist and accumulate peat, rather than retracting and/or transitioning to drier ecosystems (Evans, 2013; Roulet, 1990). By understanding how each component of the peatland water balance is affected by seasonality and other drivers, as shown here, more targeted management and peatland conservation approaches can be applied both now and in the future. Groundwater contributions accounted for the majority of water inputs to the peatland over the 4-year study period, while stream outflows represented the primary pathway for water outputs. Precipitation and surface runoff were important contributors to peat water inputs, but contributed only 25%–30% as much water to the peatland as groundwater. Changes in peat water storage over time were negligible, indicating that the system's capacity for additional water storage is limited. Although year-to-year variations in water balance components were evident, most parameters showed similar annual patterns and strong connectivity among hydrological components. The

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high groundwater dependence of this peatland has several important implications for ecosystem resilience in a changing climate, discussed further below.

4.1. Groundwater Inputs

Groundwater inputs made up approximately 65% of the annual ecosystem water balance at the *Sphagnum* peatland study site (Figure 6). This high contribution of groundwater inputs highlights the potential of high mountain aquifers to redistribute water seasonally, providing consistency in peat water over periods of both high and low rainfall, and thus resilience in dry periods/drought. The findings of this study also suggest that the mountain catchment surrounding the peatland has a substantial capacity to temporarily store incoming precipitation as groundwater in soils and bedrock and discharge this water into peatlands. For example, low rainfall periods persisting into the summer months were buffered by a minimum groundwater contribution of 1.5 mm d^{-1} during this time, which served to maintain the peat water table and soil moisture through a critical summer dry period. The strong connection of the site to the groundwater source, and the availability of groundwater feed into the peatland (via one primary source and several minor sources or seepages), indicates that this site can be defined, according to the classification scheme proposed by Mitsch & Gosselink (2007), as a geogenous peatland, or as a minerotrophic fen.

High groundwater transmissivity to the peatland is likely enhanced by both the topography of the site, that is, the hillslope site location providing a favorable gravitational gradient, and by highly porous soils in the adjacent catchment hillslopes (Chunfeng et al., 2021). Indeed, recent research has shown that Australian alpine humus soils (i.e., those surrounding the peatland study site) are highly porous, with a porosity of ~80%, suggesting high water permeability (Treby et al., 2024). Current theory suggests that groundwater recharge increases during the snow season, with peak storage likely reached before the end of the snowmelt period (Hood and Hayashi, 2015). However, the mechanism and location of groundwater storage for the study catchment both remain uncertain. This is likely because groundwater storage characterization is expensive, time-consuming and challenging (Cochand et al., 2019; Combalicer et al., 2008; Hood and Hayashi, 2015). Investigations at this site would add valuable insight into our understanding of peatland hydrological connectivity.

4.1.1. Precipitation and Snowmelt

Precipitation contributed 18% of the total water input to the peatland over the 4 years, with a higher proportion of snowfall contributing to total precipitation in the first 2 years of the study (Figure 3). However, despite a marked reduction in snowfall in 2019–2020 and 2020–2021, contributing much lower SWE to the peatland, total precipitation inputs were not lower than the previous 2 years, as higher rainfall in these years offset low snowfall. The water balance of the site was significantly influenced by snowmelt in the first two study years, when snowfall of 217 cm yr^{-1} was well above the long-term average for the area (135 cm yr^{-1}; Falls Creek Resort Management, 2019). Accumulated snow, both in and around the peatland, contributes to the water balance in two ways. Firstly, SWE on the hillslope contributes to surface inflows (Q_{in}) to the peatland, and secondly, SWE on the peat surface infiltrates the peat. The relative contributions of each SWE supply are influenced by multiple factors, including precipitation intensity and duration, site topography, antecedent soil moisture, soil infiltrability, hydraulic conductivity, preferential pathways, and groundwater table depth (Chen et al., 2014). During the snow-covered period, snowmelt runoff increases at times when the infiltration capacity of surface soils decreases due to soil water freezing (Iwata et al., 2010). The infiltration capacity of frozen soils depends on the partitioning of snowmelt into infiltration or runoff, as well as the depth and duration of soil freeze-thaw processes and site topographic variation (Bayard et al., 2005). Here, the depth and duration of soil freezing are both relatively shallow and short (lasting less than the snow-covered period). Overall precipitation inputs (from rain and snow) were 40% higher in the snow-free period, suggesting that frozen soils (reaching −1.5°C at 8 cm depth during the study period) may make a small contribution to lower infiltration into the peatland in the snow-covered period, although further research would be needed to confirm this.

4.2. Evapotranspiration

Evapotranspiration over the 4-year study period comprised only 6% of total water outputs from the peatland, indicating that ET is a minor pathway for water loss in this ecosystem. Precipitation consistently exceeded ET over the 4 years, with ET comprising 32% of annual precipitation inputs. This represents a relatively low ET/P fraction, given that ET accounts for approximately 65% of total precipitation at a global scale (Liu et al., 2019; Wang and Dickinson, 2012). Relatively low proportional ET losses at the peatland study site are likely driven, in part, by very low ET rates during the snow-covered period, comprising less than 1% of the total water balance. Furthermore, low annual temperatures and low net radiation at the peat surface (both strong drivers of ET at this site; Gunawardhana et al., 2021) presumably limit ET from the system, as has been reported across the Australian Alps (Australian Alps National Parks, 2024).

4.3. Stream Outflows

Stream outflow comprised the largest water balance output component, which has important implications both for downstream ecosystems and for human populations. The groundwater-fed streams of the Australian Alps contribute an estimated 29% of inflows to the Murray-Darling Basin (Worboys et al., 2015), an economically significant catchment that supports food production and domestic water use for millions of people (Murray-Darling Basin Authority, 2016; Thoms & Sheldon, 2000). Thus, flow rates high in the catchment can alter the habitat and water provisioning of a much larger river network. The stream at the peatland study site is a perennial first-order stream (Shreve, 1966), characterized by persistent but low flows during the dry season. The groundwater contribution to the peatland ecosystem comprised 70% of annual stream outflows, highlighting an important connection between groundwater and surface water at the site, consistent with peatland studies elsewhere (Ferone and Devito, 2004; Roulet, 1990; Siegela, 1988; Siegela and Glaser, 2006). In comparison, the contribution from surface runoff comprised only 17% of annual stream outflows. Additionally, groundwater contributions to streamflow were nearly two times greater than snowmelt, showing the importance of the groundwater reservoir for maintaining stream flows as well as peat water levels, as shown in wetlands in the northern hemisphere (Brannen et al., 2015; Cochand et al., 2019; Hood and Hayashi, 2015). Again, this suggests that the perennial incoming water supply from groundwater may provide some resilience to these ecosystems even under scenarios where rain and snow fall decrease in a warming climate.

4.4. Changes in Peat Water Storage

The annual sum of change to water stored in the peatland (ΔS) was positive and, in three of the four study years, was less than 50 mm, while the annual average storage change value was 70 mm, indicating that the long–term water balance was positive and that the peatland is hydrologically functioning well (Wang et al., 2017). The quantity of water storage in the unsaturated zone depends on the thickness of this peat layer, soil moisture levels, and soil hydraulic properties and gradients (Dietrich et al., 2019; Healy et al., 2007). The main governing factor for soil moisture depletion is ET (Dietrich et al., 2019), thus, low ET rates at the study site may explain, in part, how the peatland maintained a positive storage change over the study period. A moisture-depleted unsaturated zone can provide a large water storage capacity (Boelter, 1964). However, in the present study, soil moisture depletion (and therefore peat water storage capacity) was relatively low, averaging between 100 and 150 mm during the recession period and reaching a maximum of only 250 mm over the study period.

The water storage capacity of peatlands has been reported in few other studies. Valois et al. (2020) reported that peatlands in the arid Andes of north-central Chile have a storage capacity of 2 m in an 8 m peat profile. The literature indicates that water storage changes may result in volume changes in peats, which are subject to expansion and contraction with seasonal fluctuations in water content (Rezanezhad et al., 2016). Due to this storing and releasing potential, peatlands have gained a popular reputation as "sponges" that store rainwater and release it as baseflow (Western et al., 2008). In contrast, the present study suggests that intact Australian *Sphagnum* peatlands have limited temporary water storage potential, which is restrained to the shallow, unsaturated peat surface layer, challenging this previous assumption. Investigating peat water storage capacity in more degraded (i.e., hydrologically altered) peatlands may show that water storage potential varies with peatland condition and would be a valuable next step in this area of research.

4.5. Limitations

Uncertainty in our net ecosystem water balance estimation mainly depends on the largest component of the equation (Van Seters and Price, 2001), which here, was outgoing stream flows. Logger accuracy for the water height sensors used was ±1% of the measurement scale, with greater uncertainty in summer. However, a stage-discharge relationship was established based on manual discharge measurements, and the established correlation

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was applied to the data to minimize the error. Higher precision measurements of low summer flows were observed, and the weir was accurately calibrated and captured low-flow conditions. The SWE contribution to the annual average water balance was less than 10% (Figure 3) but may have been influenced by minor uncertainties associated with snow density calculations, due to spatial and temperature variability, that is, SWE can vary where there is substantial lateral variation in snow depth across the landscape (Holbrook et al., 2016). While SWE comprised only a small component of the water balance in the present study, methods to reduce uncertainty in its quantification, for example, using ground penetrating radar, could be explored in further research to refine estimates. Additionally, the method used to estimate Q_{in} and G_{in} is calculated rather than directly measured, introducing some associated, but unavoidable, uncertainty. Despite these uncertainties, the method used in the present study presents a narrow uncertainty range, even for heterogeneous mountainous peatland catchments with complex topography, and we consider the results presented to be reliable.

4.6. Environmental and Management Implications

The present study represents the longest and most comprehensive measurement of the net ecosystem water balance of an Australian *Sphagnum* peatland to date. The study site measured here has been previously recognized as a reference peatland, in intact, or near-pristine condition (Gunawardhana et al., 2021; Karis et al., 2016; Silvester, 2009; Whinam et al., 2003a). As such, this study provides two important contributions to peat hydrological management in this region. Firstly, the 4-year data derived from the present study site provides opportunity for long-term trends to be better understood with continued monitoring, for the influence of disturbances and sustained climate change to be determined. Secondly, the use of this reference site as one that represents a peatland in particularly good hydrological condition may serve as a benchmark for degraded or disturbed peatlands, for which restoration targets can be set and monitored against.

Managing the impacts of global change at a local scale presents a major challenge. Australia's mountain environments are likely more vulnerable to large temperature increases from anthropogenic climate warming than lowland areas (Bilish et al., 2020; Valois et al., 2020). In particular, predicted reductions in winter snowpack and earlier snowmelt, coinciding with increased air temperatures and rates of evapotranspiration, may reduce water inputs to the detriment of water-dependent mountain ecosystems such as peatlands (Bilish et al., 2020; IPCC, 2019; Reinfelds et al., 2014). Groundwater recharge in several mountain regions is also projected to decrease with reduced snowfall associated with climate change (Barnett et al., 2005; Somers and McKenzie, 2020). However, in the case of the peatland in the present study, our findings suggests that hill slope groundwater supply may provide some buffering, at least in the short term, against climate-driven hydrological changes in the study region.

5. Conclusion

The study assessed the water balance of a reference Australian *Sphagnum* peatland ecosystem over 4 years, quantifying each of the peatland hydrological components. The peatland is a groundwater-dependent ecosystem with a high dependency on localized, sustained groundwater flows. Even during a short dry period, groundwater exiting the peatland contributed 1.5 mm per day to streamflow. Regional aquifers provide groundwater recharge to the peatland during dry periods, particularly in summer, and substantial groundwater storage and discharge capacity in a peatland catchment may buffer summer outflows, potentially enhancing ecosystem resilience to climate change.

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Data Availability Statement

All data are available at https://figshare.com/s/a4129580ec378bb0fc9b.

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