Groundwater monitoring, geophysical and hydrochemical assessment of highly disturbed peat deposits at Badas, Brunei Darussalam

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SUMMARY

While a few tropical peatlands remain in pristine condition, many of them, especially in Southeast Asia, have been degraded and have been subjected to drainage, deforestation or fires. At the largest peat deposit in Brunei Darussalam, the Badas peat dome, anthropogenic disturbances arising from urbanisation and land use changes in the past decades have resulted in deforestation, peat subsidence and groundwater drainage. We investigated these disturbances along two transects established at the Badas peat dome via a combination of approaches: (1) topographic survey, (2) seismic refraction survey, (3) rain gauge monitoring and (4) groundwater monitoring via piezometers and slug testing. In addition, groundwater samples were taken from piezometers for water chemistry analysis. This research demonstrated how excavations have led to the creation of lagoons, resulting in changes to the structure of the peat dome, leading to groundwater drainage. The drainage has caused 15 cm to 45 cm of peat thickness to dry out. In addition, with the removal of the peat layer and the establishment of artificial lagoons, surface water can now directly infiltrate into the sand layer, causing the second transect to have a lower groundwater level. Finally, groundwater drainage, evapotranspiration from the lagoons, and possibly tidal influence as the peatland is draining towards the South China Sea less than 3 km away, caused changes to the groundwater chemistry, causing increased salinity and Dissolved Organic Carbon (DOC), showing that peat degradation has been occurring in both transects.

KEY WORDS: peat degradation, seismic refraction, slug test, tidal influence, tropical peatland

INTRODUCTION

Peatlands are the largest natural terrestrial organic carbon store. Tropical peatlands sequester around twice as much carbon per unit area per year as boreal peatlands and more than four times as much carbon per unit area per year as terrestrial forests or oceans (Temmink *et al.* 2022). They cover an estimated area of 58.7 million hectares worldwide, storing 75–119 Gt of carbon (Warren *et al.* 2017, Leifeld & Menichetti 2018). Pristine peatlands are typically waterlogged, resulting in the formation of anoxic conditions that reduce the rate of decomposition (Joosten & Clarke 2002, Posa *et al.* 2011) and promote significant organic matter accumulation when organic carbon production exceeds depth-integrated decay. Tropical peatlands are generally ombrogenous, typically forested with a dome-shaped structure (Posa *et al.* 2011, Jauhiainen *et al.* 2016). A large portion of these tropical peatlands are in South-East Asia (SEA; Omar *et al.* 2022), with an estimated size of around 25,000 km^2 and 67 Gt C stored (Page *et al.* 2011, Chin & Parish 2013, Dohong *et al.* 2017). Recent studies estimated that the tropical peatlands of the central Congo basin holds as much as 29 Gt C alone (Crezee *et al.* 2022).

For the past several decades SEA peatlands have been under threat from logging, agriculture and urban development, affecting around 129,000 km^2 (Becek & Odihi 2008, Hooijer *et al.* 2010, Leng *et al.* 2018). These disturbances from the creation of ditches and canals (see Figures 1 and A1) resulted in a drawdown of the water table in the peat, leading to oxidation causing further degradation. However, when peat fires occur, especially during dry periods, a rapid loss of peat (Usup *et al.* 2004, Saputra 2019) takes place. This in turn has led to the emission of large amounts of greenhouse gases (e.g., CO_2, CH_4, N_2O) into the atmosphere, estimated to be in the order of 1.48 Gt CO_2e annually (Leifeld & Menichetti 2018). One of the most significant indications of peat degradation is the release of Dissolved Organic Carbon (DOC), which has previously been observed to be significantly greater at sites affected by deforestation (Gandois *et al.* 2013). The DOC will drain from the peatland via rivers (Müller *et al.* 2015) or drainage canals to the sea.

Brunei Darussalam has still well-preserved peat deposits which cover around 18 % of its total land area, but from 1980 to 2000 it was observed that 5 % of the total peat swamp forest had been disturbed (Becek & Odihi 2008). One of the areas that has been affected by humans can be seen on a section of the largest peat dome in Brunei, called the Badas peat dome (Suhip *et al.* 2020). Disturbance started in the late 1960s with the construction of a road leading to the Badas water pumping station. However, in 2006, at the northwestern side of the dome adjacent to the Seria bypass highway, noticeable land excavation and deforestation can be observed through Google Earth imagery (Appendix) over a period of six years, resulting in the formation of large lagoons from excavation of peat and sand for road construction (Figure 1). In addition, fires occurred surrounding the

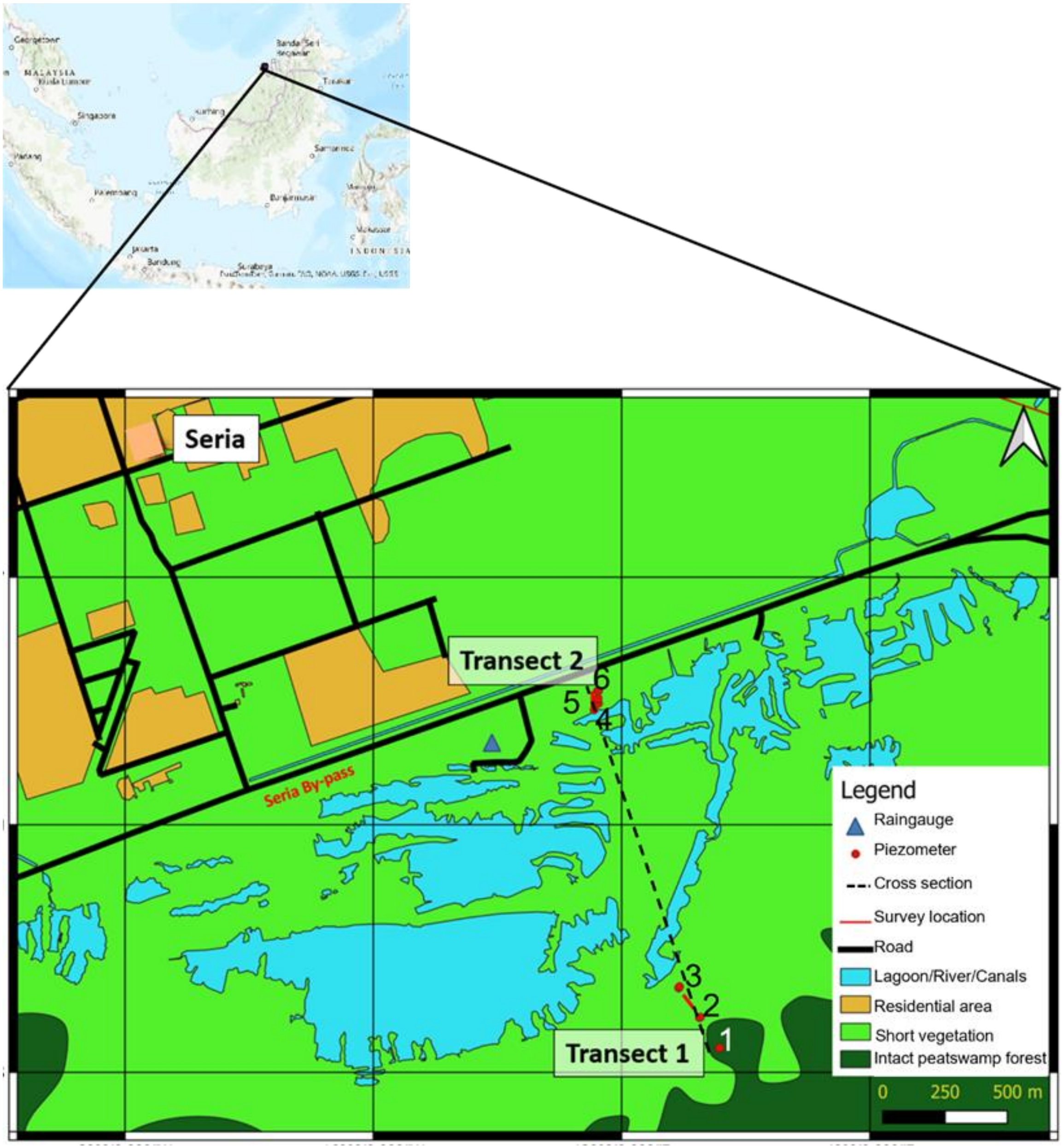


Figure 1. Map showing land coverage of the study site with monitoring well locations and well numbers, based on Google Earth Landsat satellite imagery from 2019.

lagoons extending towards the forest edge. This peat swamp forest is unique as it is populated by *Shorea albida* trees, which only flower around once in a decade (Becek *et al.* 2022). Fire events at the Badas peat dome have been mapped previously using satellite imagery (Addly *et al.* 2022). A direct connection between dry seasons and the occurrence of fire around the area of the lagoons has been observed in previous studies (Hasan *et al.* 2017). Thus, without sufficient supply of precipitation and vegetation cover the peat can dry out leading to peat fires. The peat degradation at this location was previously studied by Suhip *et al.* (2020), and it was estimated that the groundwater level was able to fall into the sand layer found beneath the peat to a depth of around 4 m below the surface.

The northern side of the peat dome has not been investigated before. To study the effects of peat degradation in this area several factors were investigated. These factors are: (1) the thickness of peat sediments removed, (2) groundwater behaviour in the sediments and (3) changes in the groundwater chemistry along two transects.

METHODS

Study site

The study site is in the Belait district of Brunei Darussalam. The annual rainfall from a rainfall station in Seria exceeds 2,300 mm (Sandal 1996). There are two dry seasons: from February to March as well as June to August; and two wet seasons from October to January and May to June. The lagoons mentioned are situated around 1.5 km from the Seria town centre (4° 35.675' N, 114° 20.950' E). Prior to equipment installation a site survey was performed in the study area finding that the lagoons were connected to four culverts running under the Seria highway, allowing the water to flow towards the South China Sea (Figure 1).

The stratigraphy of the peat dome is primarily composed of recent sediments of peat, as well as sand and clay layers below the peat, with older Pleistocene sand sediments exposed at the southeastern side near the Belait river (Sandal 1996, Techno Advance Laboratory 2009, Suhip *et al.* 2020).

It was decided to perform the investigation using transects. This decision was made after investigations found a sand horizon below the peat layer in the vicinity of one of the transects, which was interesting since clay was also found as a base layer below the peat (Suhip *et al.* 2020). To investigate further, assuming the sand layer could be an ancient buried beach dune system, two transects were selected for the study. The first transect was around 300 m long, the second transect was located closer to the forest at the southern part of the lagoons and was only accessible by boat (Figure 1) through lagoonal channels.

During the early site assessment, the area of the second transect was observed to be in the direct vicinity of tall *Shorea albida* trees, which are common in the area, but some had burn marks caused by recent peat fires. However, areas closer to the lagoons began to show greater signs of degradation, with an increase in the presence of charred fallen trees and ferns, indicating post-fire recovery (Hirano *et al.* 2014, Suhip *et al.* 2020). Directly next to the lagoons, it was also noticed that fast moving water close to the surface was flowing into the lagoons, indicating drainage.

The second transect, located around 1.5 km away from the forest edge, close to the highway, had a shorter length of around 82 m. It had similar conditions to the degraded portion of the first transect, but it was less waterlogged, showing it had experienced greater peat deterioration with an increased number of *Acacia* trees, an invasive plant able to grow very fast after a fire event (Tuah *et al*. 2020). This initial site assessment demonstrated an opportunity to study the hydrology of both transects.

Investigation strategy

The depth of the lagoons was measured using a weighted nylon rope marked with a flagging tape at 1 m intervals. The area of the lagoons was estimated using QGIS. After the initial site survey, piezometer installations were undertaken, and topographic and geophysical surveys were performed at the transects.

In addition, a tipping bucket rain gauge (Texas Instruments, USA) with a pendant data logger (Hobo Onset, USA) was installed at the site. Lastly, hydraulic testing was performed followed by water sampling to evaluate the flow behaviour and chemistry within the peat and underlying sand layer.

Piezometer installation and monitoring

For this study, 13 piezometers were installed to monitor hydraulic head fluctuations in the peat and sand layers over a period of six months (August 2020 – January 2021) covering a dry and wet season. These data were recorded using pressure transducers (Levelogger, Solinst, Canada) inserted in all piezometers. Only one barometric pressure logger (Barologger Gold, Solinst, Canada) was used, as it can be accurate up to a radius of 30 km (Solinst 2020). The piezometers were made of 3.81 cm inner diameter Polyvinyl Chloride (PVC) (Figure 2), all

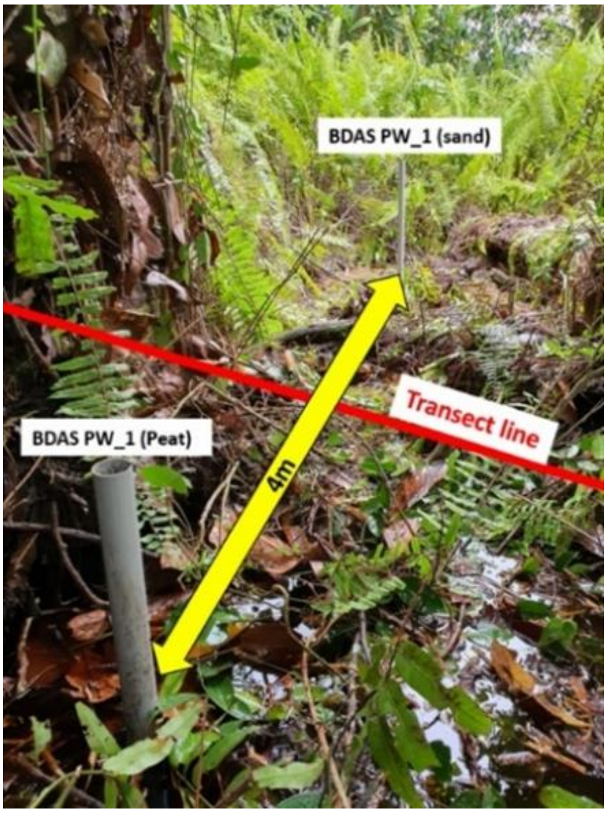


Figure 2. Example of piezometer placement at Transect 1. The water at the surface is not moving noticeably.

having a single closed bottom end cap and well screens with 5 mm size holes drilled to allow fluid to enter. The well screens varied in length and were 0.90 m for piezometers installed in peat and 0.20–0.30 m for piezometers installed in sand. Each piezometer was installed by hand-drilling with a Dutch auger. During the drilling process, soil samples were collected and recorded until drilling reached the target depth. At this point the piezometer was inserted. During augering, once the sand horizon was reached, hand augering became significantly harder, making progress deep into the sand layer difficult. Also, the water saturated sand kept falling back into the hand augered hole, slowing down the augering process. Therefore, smaller screen lengths were chosen for the sand layer. To develop the piezometer, a 2 cm diameter PVC slug was inserted into the well and manually pushed up and down into the water to flush out any debris and to prevent blockages at the well screen. For a properly developed piezometer one could hear the surging water moving up and down and into the wellbore from the movement of the PVC slug in the well. If any issues were encountered during this stage, either the development was extended until the piezometer was properly developed or the piezometer was re-installed. Once the piezometers had been installed and developed, the leveloggers were suspended by Kevlar cord and submerged in the wells, whilst the barologger was suspended above the water level and tied securely from the top of the pipe with a Kevlar cord. Before the loggers were deployed, they were set to record at 20-minute intervals and synchronised to start recording at the same time.

Six piezometers were installed for each transect, in pairs at approximately 4 m spacing (Figure 2) at three different locations on the transect (Figure 3). An additional piezometer was installed on Transect 2, with the goal of collecting information on the hydraulic head of the lagoon.

The levelogger and barologger data were downloaded on site every three months to make sure the loggers were recording properly. Before the data were collected, the groundwater level was measured from the top of the pipe at a known GPS time using a Solinst dipmeter (Model 102M). With this information, including the topographic levelling information described in the next paragraph, and after barometric compensation was performed, the hydraulic heads were calculated.

Topographic levelling and monitoring

An optical level instrument (Bosch GOL 26D) mounted on an aluminum tripod with a surveying staff to measure height was utilised for this survey. Great care was taken to not have the mounted tripod subside into the peat due to the weight of the observer standing next to the tripod while readings were taken. Due to dissimilar transect distances, the topographic survey plan was different for each site and mapped out carefully before levelling was done (Figure 3). The accuracy of the optical level alone without considering human error is around ± 1.6 mm over 30 m (Bosch 2010). Care was taken when placing the tripod and surveying staff in order not to disturb the natural topography of the peatland. Before both surveys were carried out, two Garmin 64s outdoor GPS were placed on the surface at the reference point (RP Transect 2) for 30 minutes to obtain the surface elevation. The obtained topography data from levelling was found to compare well with a high-quality digital terrain model (DTM) representing the bare-earth surface at a spatial resolution of 20 m, which became available after the study was conducted. The DTM was produced from a light detection and ranging (LiDAR) survey carried out in 2009 by the Survey Department, Ministry of Development, Brunei Darussalam (Figure 4).

The topographic levelling was necessary for the calculation of the hydraulic head.

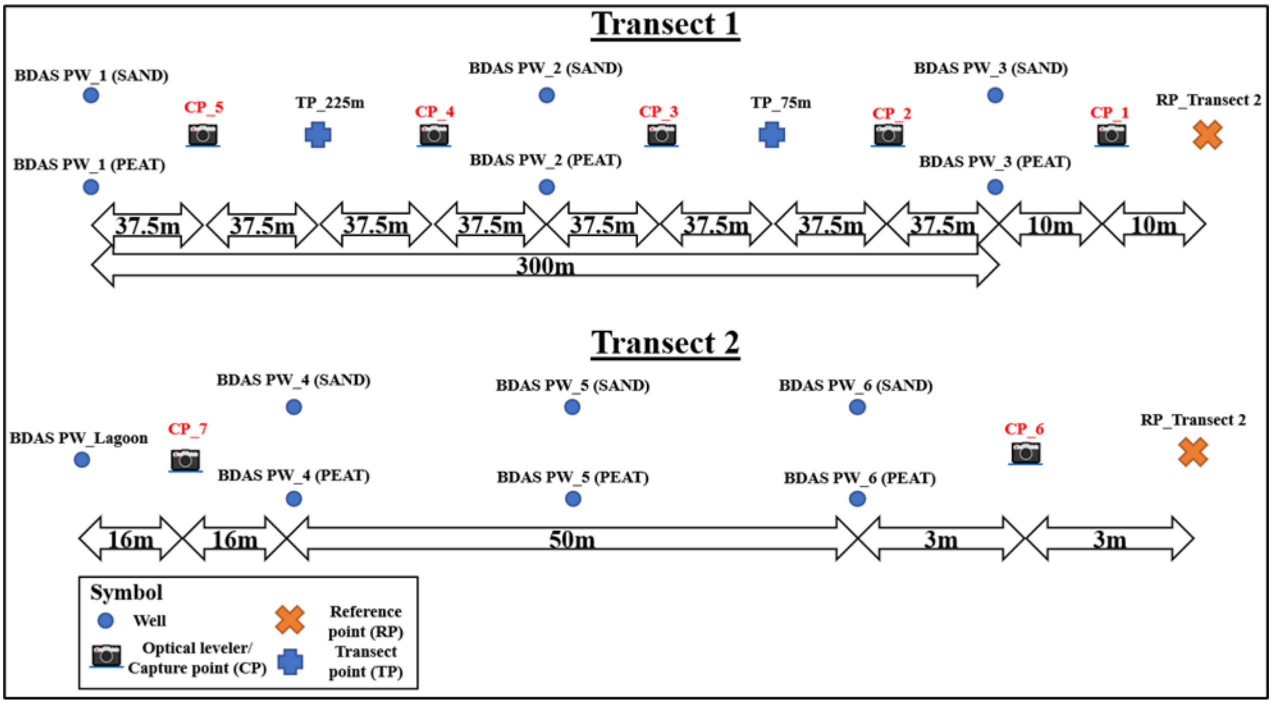


Figure 3. Topographic survey plan for both transects.

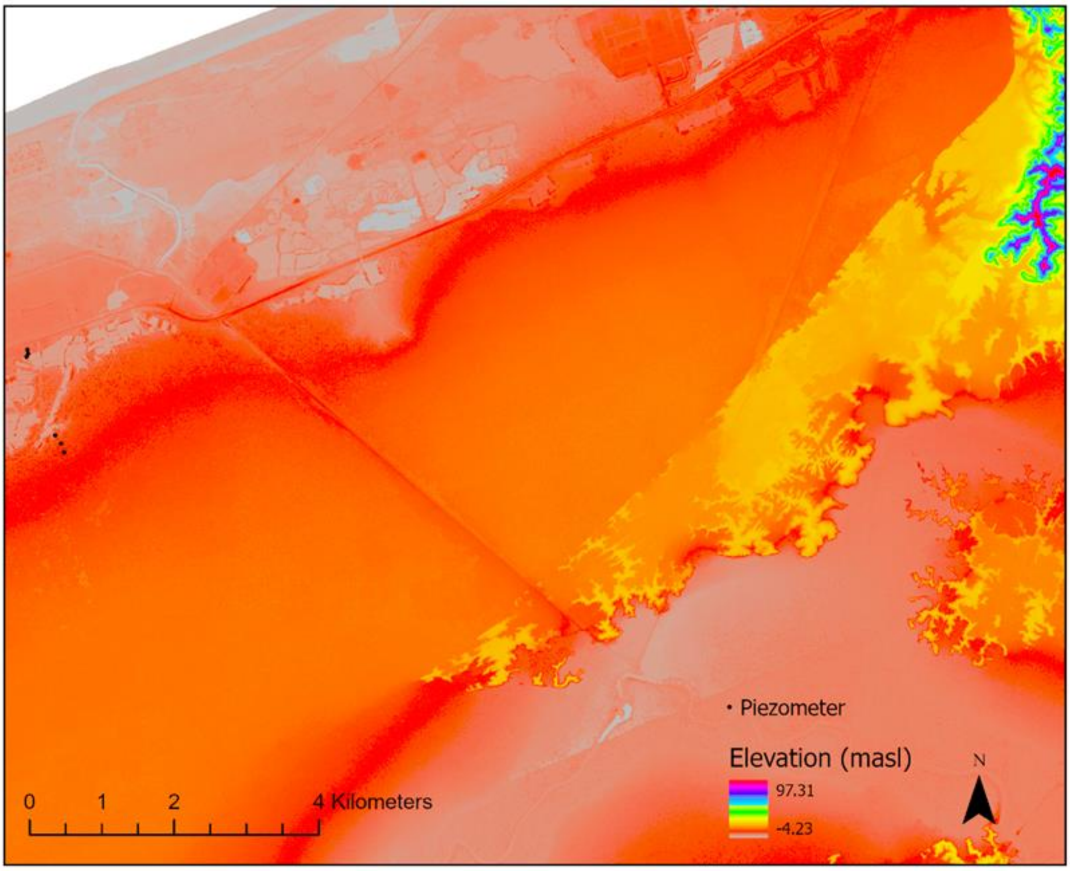


Figure 4. Topography of the Badas peat dome from LiDAR data. The white area in the top left corner represents the South China Sea. The yellow/orange colours coincide with sand ridges at the surface. The elevation in these areas is around 15 m a.s.l. The similarity in directional trends of the outcropping sand (yellow and orange colours) and the coastline suggests that this sand could be an ancient beach dune deposit.

Seismic refraction

For the seismic refraction survey, a *Geometrics SmartSeis* 24 channel portable seismograph was used, powered by a 12 Volt battery. A detailed method description can be found in Suhip *et al.* (2020). The seismograph was connected to 24 vertical geophones (10 Hz) to obtain p-wave data, sourced from a 5 kg sledgehammer struck onto a metal strike plate, causing seismic vibrations. For the survey, 24 geophones were placed on the ground surface in a line. All the configurations for the acquisition on both transects were identical (Table 1), having a total of three stacks for each of the 13 shot locations to improve the signal to noise ratio, as well as to obtain more data for ease of interpretation.

For subsequent data comparison purposes, p-wave velocities were compiled from different studies, as shown in Table 2.

Once the seismic data had been acquired from the field, they were processed using the *Seisimager 2D*^{TM} suite of software (Geometrics 2009) for seismic interpretation, as also explained in Suhip *et al.* (2020). In brief, the data were first opened in *Pickwin* to pick the individual first arrivals of the 13 individual raw datasets, which were then compiled into a single file. This file was then transferred into *Plotrefa* software for layer interpretation, in which 2D images of the subsurface were generated showing the layer p-wave velocities as well as the thicknesses.

Table 1. Seismic survey configuration and details.

Component	Details
Data recorder	Geometrics SmartSeis 24 channels
Seismic source	5 kg sledgehammer
Geophone type	10 Hz vertical geophone
Number of geophones	24
Sampling interval	0.25 ms
Recording length	0.25 s
Geophone spacing	2 m
Total survey length	48 m
Total geophone length	46 m
Offset distance	2 m
Stacking	3
Shot intervals	4 m
Shot location (m)	2, 6, 10, 14, 18, 26, 30, 34, 38, 42, 46, 48

Table 2. Primary wave velocity of earth materials (after Bourbie *et al.* 1987; Said *et al.* 2015 and Fkirin *et al.* 2016).

Material	P-wave velocities (m s^{-1})
Air	300
Tropical peat soil	200–700
Unsaturated soil	400–1200
Clay	1000–2500
Saturated clays	1100–2500
Oil	1200–1250
Saturated soil	1500–2000
Saturated sandstones	2000–3000
Sandstone	2000–6000
Coal	2200–2700
Limestone	2500–6000
Ice	3400–3800
Granite	5500–6000

Hydraulic testing

In this project, all the existing piezometers (excluding the lagoon piezometer) were tested to obtain estimated hydraulic conductivity values via slug testing. During this test a 1.9 cm diameter PVC slug T-pipe was introduced into the piezometer (Figure 5) to induce a hydraulic gradient.

Before the test was conducted, the initial water level was measured. The slug was then instantaneously inserted into the piezometer, displacing water inside the piezometer and causing the water level to rise (falling head test). The slug remained submerged and was left undisturbed for 4 minutes or until the water equilibrated, then it was removed as quickly as possible (rising head test). During these tests, water level values were recorded using a Solinst levelogger and barologger, which were set to record at one second intervals. To analyse the slug test data, the software Slugin (Martos-Rosillo *et al.* 2018) was used. For this study, the data were analysed using the method of Cooper *et al.* (1967), with the equation expressed below:

$$F(\alpha,\beta) = \frac{8\alpha}{\pi^2}\int_0^\infty \frac{e^{\left(-\frac{\beta u^2}{\alpha}\right)}}{u\Delta u}\,\mathrm{d}u \qquad [1]$$

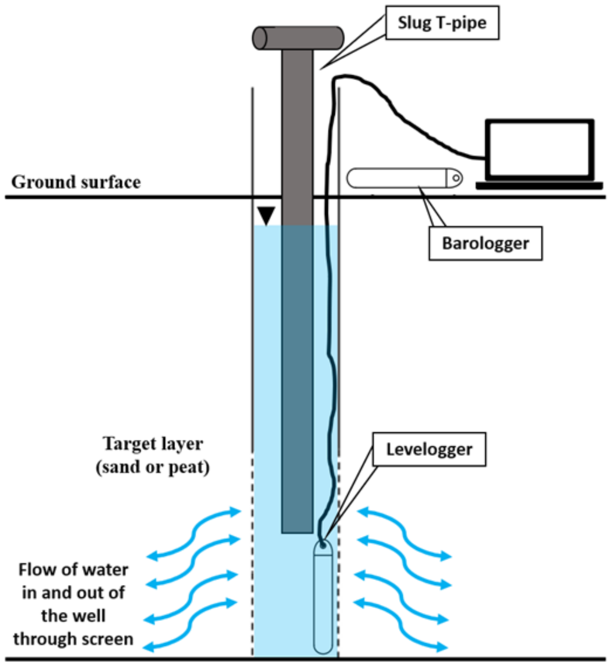


Figure 5. Slug testing illustration.

where:

α = integration parameter: $\alpha = \frac{R_W^2 S}{R_C^2}$;

β = integration parameter: $\beta = \frac{Tt}{R_C^2}$;

R_C = effective well casing radius (m);

R_w = effective filtering zone radius (m);

T = time since the injection or withdrawal (s);

S = storativity of the aquifer;

t = transmissivity of the aquifer (m^2 s^{-1});

u = integration variable;

Δu = a complex function:

$$\Delta u = [uJ_0(u) - 2\alpha J_1(u)^2 + uY_0(u)]^2 + [uY_0(u) - 2\alpha Y_1(u)]^2 \quad [2];$$

J_0, J_1 = Bessel functions of the first kind and zero and first order; and

Y_0, Y_1 = Bessel functions of the second kind and zero and first order.

The Cooper *et al.* method is recommended for application in confined aquifers, but previous investigations have found that its use should not be generally rejected for unconfined aquifers (Weeber & Narasimhan 1997). Unlike in the Cooper *et al.* method, compressive storage is neglected in the Hvorslev (1951) and Bouwer & Rice (1976) methods. In addition, the Cooper *et al.* method is mathematically rigorous and provides estimates of storage coefficients. Thus, this method was chosen for this study, since compression as well as storativity - that were regarded as important to consider for peatlands - are taken into consideration (Freeze & Cherry 1979, Chirlin 1989).

Groundwater sampling and rainfall monitoring

Water sampling in this study was done using a Geopump peristaltic pump connected to a silicone rubber hose that was inserted directly into the piezometers. In total, 9 piezometers were sampled. These wells were located at the edges of each transect. Sampling was undertaken to distinguish the hydrochemistry of the sand and peat layers. For each well, water samples were collected and poured into 100 ml polyethylene bottles to analyse major anions and cations, as well as Dissolved Organic Carbon (DOC). The samples were sent to the Eawag research facility in Switzerland, where the samples were analysed for major anions and cations using ion chromatography (Metrohm, 930 Compact IC Flex, Switzerland) with a Metrohm Metrosep C 6 column. For DOC analysis the samples were analysed via catalytic combustion at 720 °C using a Shimadzu, TOC-L, CSH, Japan.

Rainfall was monitored using a tipping bucket rain gauge (Texas Electronics Inc TR-525S, USA) connected to a pendant data logger (Hobo, Onset Computer Corp UA-003-64) which was calibrated in the field prior to use. The equipment was installed around 2 m above ground in an open area on a 5.08 cm diameter PVC pipe anchored 2 m into the ground. Bird spikes were wrapped around the crown of the gauge to prevent birds from perching.

RESULTS

The rainfall data collected at Badas showed a total of 3878 mm of rain from February 2020 to January 2021 with the highest monthly rainfall recorded in November 2020, followed by September 2020 and January 2021, whilst the lowest was recorded in February 2020 up until March 2020. From the daily rainfall data collected, one can distinguish three clusters of heavy rainfall events (September 2020, November 2020, January 2021) causing a rise in groundwater levels.

The subsurface data obtained from field measurements showed that the peat thickness was lower towards the edge of the Badas peat dome at the Seria Bypass highway in the south (Table 3). In addition, during the coring of the lagoon groundwater monitoring piezometer, a mixture of peat and sand was found, indicating that peat and sand were extracted during excavation and disposed towards the sides of the lagoon, resulting in amalgamation. The area of the lagoon after analysis in QGIS was determined to be 0.63 km^2. The depth of the lagoon reached up to 10 m. A schematic geological cross-section through the area is shown in Figure 6.

The rapid water level rise in the peatland due to rainfall followed by a more gradual decline in water levels after rainfall becomes apparent in the Figures. Unfortunately, due to low battery power on several of the leveloggers (piezometers 1, 3 and 6), some of the monitoring data were not usable (Figures 7 and 8) resulting in data gaps. An analysis of the hydraulic head data showed that Transect 2, which can be regarded as more degraded compared to Transect 1, showed the strongest rises as well as the steepest drops in hydraulic head in the peat. Overall hydraulic heads in the peat were lower in Transect 2 compared to Transect 1. Hydraulic heads in the sand in Transect 2 were overall also lower than in Transect 1 (Tables 4 and 5). Compared to the peat surface the hydraulic head was on average 10 cm lower at Transect 2 compared to Transect 1. Transect 2 showed larger variations (rise and fall) in hydraulic head compared to Transect 1.

Table 3. Piezometer well details with well ID numbers increasing from N to S.

Well ID	Well dimensions				Max. peat depth (m)	Elevation data (m.a.s.l)		
	Total well length (m)	Stickout height (m)	Distance from surface to well screen (m)	Well screen length (m)		Surface elevation (m.a.s.l)	Well bottom elevation (m.a.s.l)	Peat bottom elevation (m.a.s.l)
BDAS PW_1 sand	5.83	1.20	4.63	0.3	4.57	6.250	1.620	1.680
BDAS PW_1 peat	2.04	0.50	1.54	0.9	-	6.249	4.709	-
BDAS PW_2 sand	4.68	0.90	3.78	0.3	3.35	5.454	1.674	2.104
BDAS PW_2 peat	2.04	0.50	1.54	0.9	-	5.53	3.990	-
BDAS PW_3 sand	4.21	1.39	2.82	0.3	2.66	2.699	-0.121	0.039
BDAS PW_3 peat	2.04	0.5	1.54	0.9	-	2.662	1.122	-
BDAS PW_4 sand	2.33	1.00	1.33	0.2	1.25	3.936	2.606	2.686
BDAS PW_4 peat	2.04	0.99	1.05	0.9	-	3.846	2.796	-
BDAS PW_5 sand	2.63	1.40	1.23	0.2	1.00	3.763	2.533	2.736
BDAS PW_5 peat	2.00	0.96	1.04	0.9	1.10	4.176	3.136	3.076
BDAS PW_6 sand	2.42	1.07	1.35	0.2	1.10	4.029	2.679	2.929
BDAS PW_6 peat	2.03	1.00	1.03	0.9	1.20	4.113	3.083	2.913
BDAS PW Lagoon	3.03	0.57	2.46	0.9	-	3.353	0.893	-

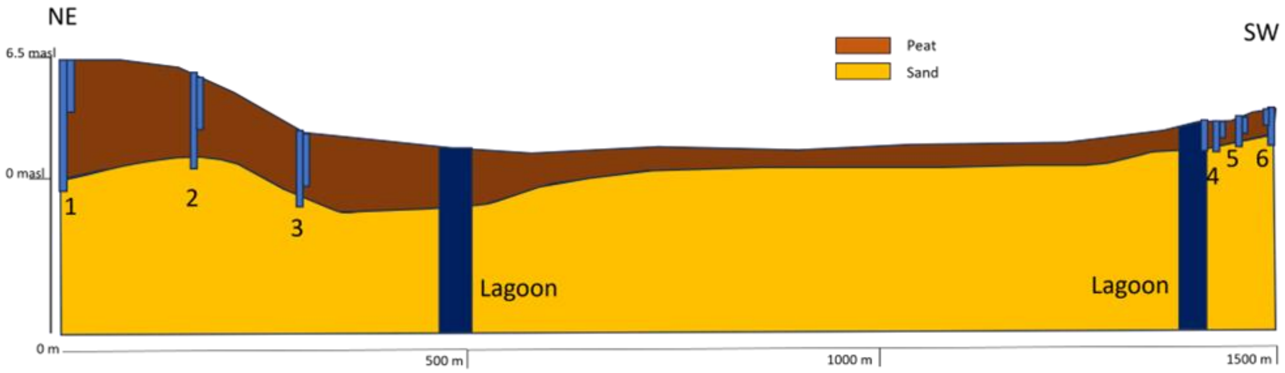


Figure 6. Schematic geological cross-section extending from NE to SW over a length of 1.5 km. Sand thickness was assumed to be a minimum of 4 m (Techno Advanced Laboratory 2009).

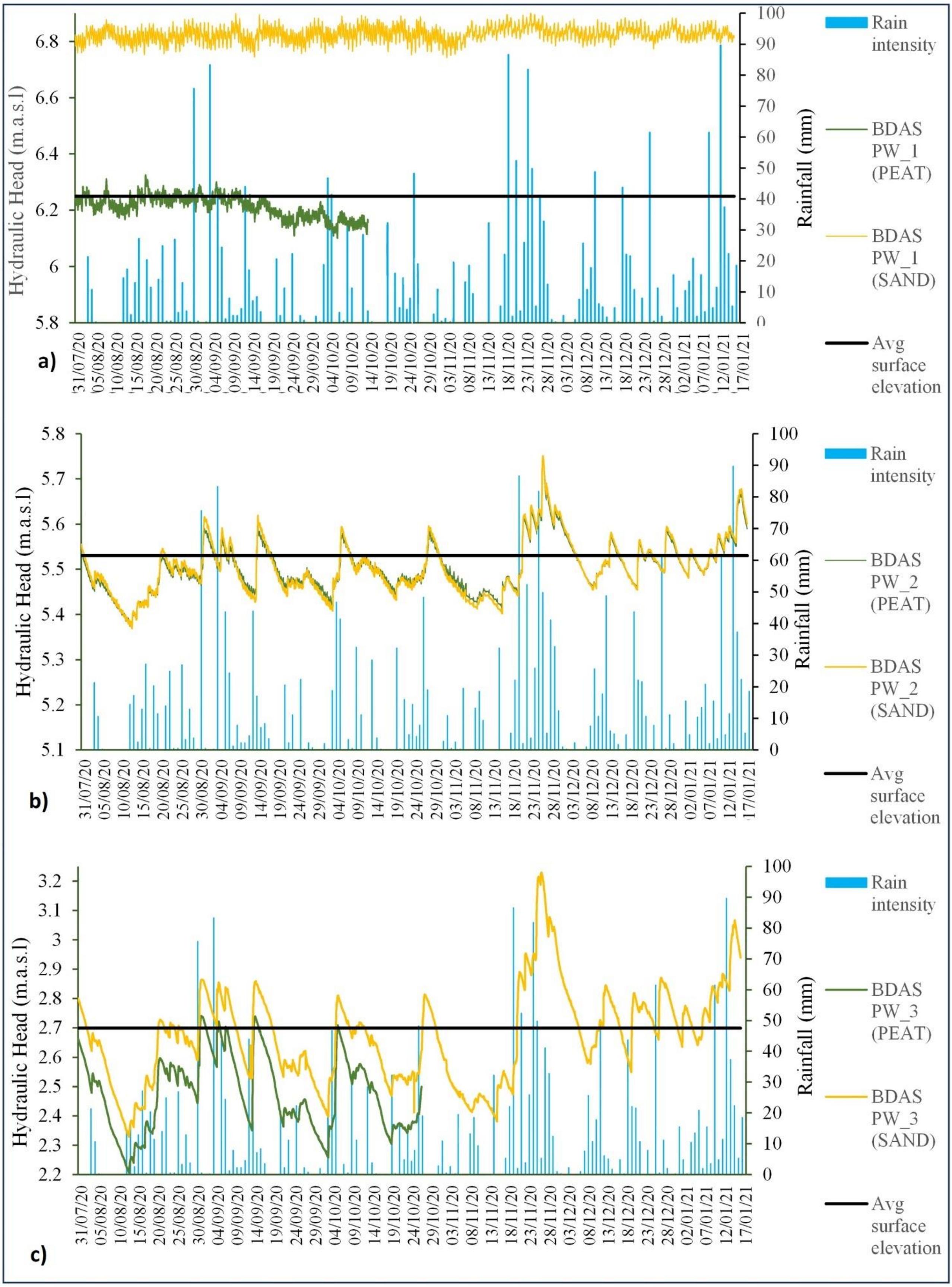


Figure 7. Groundwater monitoring and rainfall data for Transect 1: a) piezometer 1; b) piezometer 2; and c) piezometer 3.

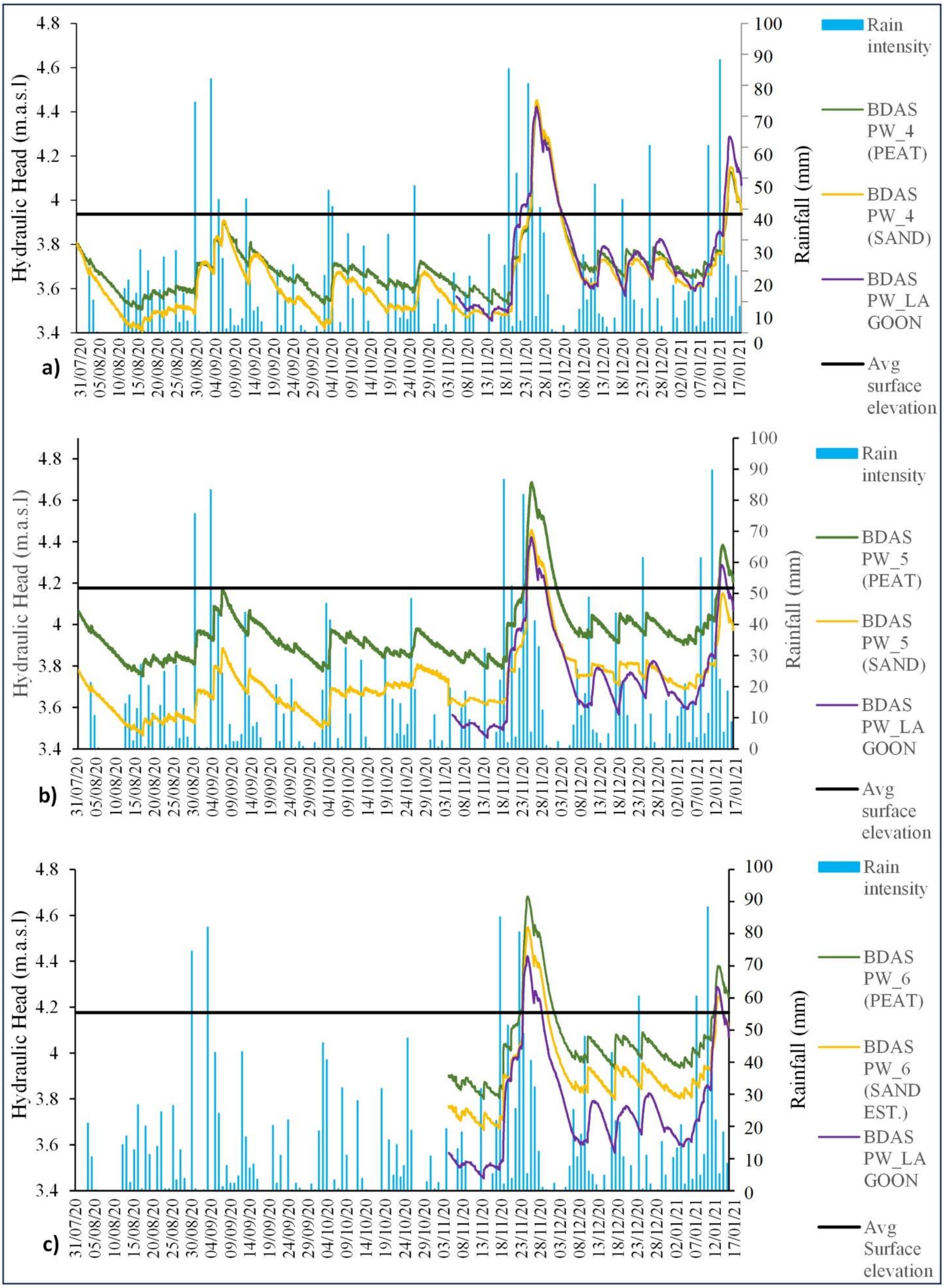


Figure 8. Groundwater monitoring and rainfall data for Transect 2: a) piezometer 4; b) piezometer 5; and c) piezometer 6.

Table 4. Transect 1: hydraulic head details.

Well ID	Date	Hydraulic head (m)		Height difference to surface (m)
BDAS PW_1 PEAT	18 Aug 2020	Max	6.325	0.076
	05 Nov 2020	Min	6.100	-0.395
		Median	6.218	-0.053
BDAS PW_1 SAND	24 Nov 2020	Max	6.907	0.657
	03 Nov 2020	Min	6.742	0.492
		Median	6.827	0.577
BDAS PW_2 PEAT	25 Nov 2020	Max	5.747	0.217
	13 Aug 2020	Min	5.373	-0.157
		Median	5.496	-0.034
BDAS PW_2 SAND	25 Nov 2020	Max	5.751	0.297
	13 Aug 2020	Min	5.369	-0.085
		Median	5.496	0.042
BDAS PW_3 PEAT	31 Aug 2020	Max	2.740	0.078
	13 Aug 2020	Min	2.206	-0.456
		Median	2.474	-0.188
BDAS PW_3 SAND	26 Nov 2020	Max	3.229	0.530
	13 Aug 2020	Min	2.329	-0.370
		Median	2.673	-0.026

Table 5. Transect 2: hydraulic head details.

Well ID	Date	Hydraulic head (m)		Height difference to surface (m)
BDAS PW_LAGOON	26 Nov 2020	Max	4.422	1.069
	14 Nov 2020	Min	3.453	0.100
		Median	3.721	0.368
BDAS PW_4 PEAT	26 Nov 2020	Max	4.431	0.585
	17 Aug 2020	Min	3.504	-0.342
		Median	3.682	-0.164
BDAS PW_4 SAND	26 Nov 2020	Max	4.452	0.516
	17 Aug 2020	Min	3.404	-0.532
		Median	3.624	-0.312
BDAS PW_5 PEAT	26 Nov 2020	Max	4.686	0.510
	17 Aug 2020	Min	3.753	-0.423
		Median	3.937	-0.239
BDAS PW_5 SAND	26 Nov 20	Max	4.457	0.694
	17 Aug 2020	Min	3.468	-0.295
		Median	3.703	-0.060
BDAS PW_6 PEAT	26 Nov 2020	Max	4.682	0.506
	14 Nov 2020	Min	3.800	-0.376
		Median	4.017	-0.159
BDAS PW_6 SAND	Data unavailable due to malfunctioning logger near the end of its battery life.			

A more detailed view of hydraulic heads with time revealed a tidal pattern (Figure 9). This was confirmed when comparing with the tidal inflection points from Seria which varies on an around 6 h basis. This tidal influence is unexpected considering that Piezometer 5 of Transect 1 is around 4 km distant from the South China Sea (Figure 4). It can be seen that the amplitude of the tidal pattern is less than 2 cm, which is also in the range of atmospheric tides. Further analysis showed that the tidal pattern became more diminished in the wet season and did not show during the heavy storm events in December. Further research is planned to investigate the influence of tides on the hydrology of this coastal peatland. Tidal influence was found in both the peat and the sand layer.

The results of the slug test analysis are shown in Table 6. The hydraulic conductivity analysis showed that hydraulic conductivities in the peat were higher with 5.75×10^{-4} m s^{-1} for peat compared to 1.9×10^{-5} m s^{-1} for sand. The several orders of magnitude higher hydraulic conductivities that were observed for two rising head tests were not included in calculation of this average. In addition, hydraulic conductivities for peat in the second transect were generally lower compared to the first transect with average hydraulic conductivities of 1.48×10^{-5} m s^{-1} for Transect 1 compared to 1.32×10^{-6} m s^{-1} for Transect 2. An example of a slug test is shown in Figure 10.

The results from the seismic refraction surveys for Transect 1 and Transect 2 show that, overall, p-wave velocities were lower at Transect 2 than at Transect 1 (Figures 11 and 12). Peat is shown in brown while sand is shown in yellow. The p-wave velocities for the peat layer at Transect 2 were significantly lower than at Transect 1.

The results from the hydrochemical analysis are shown in Figure 13. It becomes obvious from Figure 13 that DOC, as well as Na^+ and Cl^- concentrations, are elevated in Transect 2 compared to Transect 1.

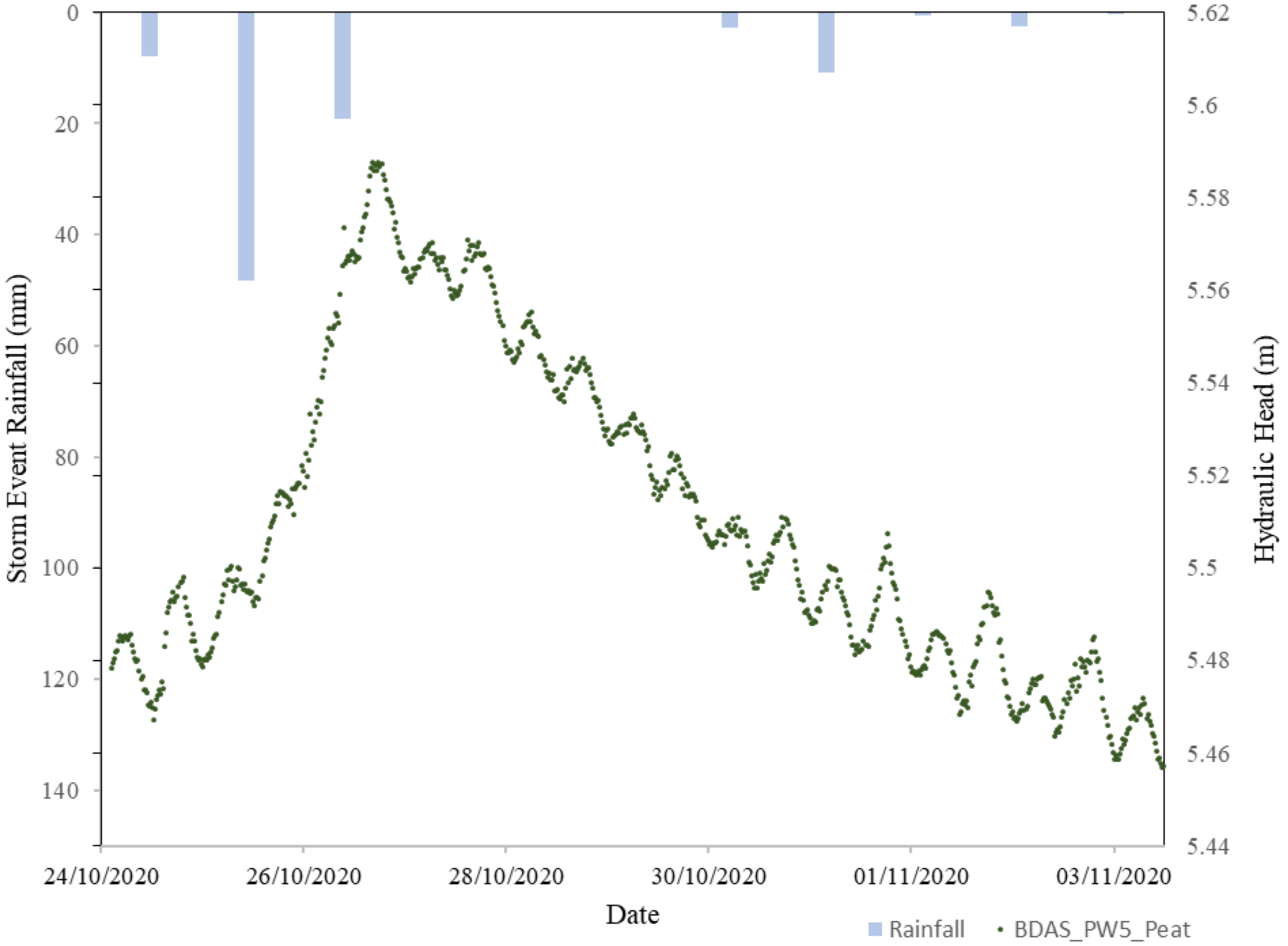


Figure 9. Peat piezometer 5 hydraulic head data revealing tidal influence, in the range of atmospheric tides.

Table 6. Hydraulic conductivities (K) and storage coefficients (S) from slug tests.

Well ID	Cooper-Bredehoeft-Papadopulos method			
	Falling head		Rising head	
	K (m s^{-1})	S	K (m s^{-1})	S
BDAS PW_1 sand	9E-06	0.06	1.5E-06	0.13
BDAS PW_1 peat	2.2E-06	0.27	2.8E-06	0.70
BDAS PW_2 sand	3E-06	0.06	6E-05	0.17
BDAS PW_2 peat	1E-05	0.18	4.4E-05	0.57
BDAS PW_3 sand	5E-06	0.08	2E-07	0.02
BDAS PW_3 peat	-	-	-	-
BDAS PW_4 sand	1E-05	0.21	3E-05	0.02
BDAS PW_4 peat	3.1E-06	0.31	5.5E-03	0.59
BDAS PW_5 sand	2.3E-05	0.48	1.3E-02	0.12
BDAS PW_5 peat	2.9E-07	0.43	1.1E-04	0.73
BDAS PW_6 sand	7.5E-06	0.07	5.5E-07	0.01
BDAS PW_6 peat	4.9E-07	0.43	1.4E-06	0.23

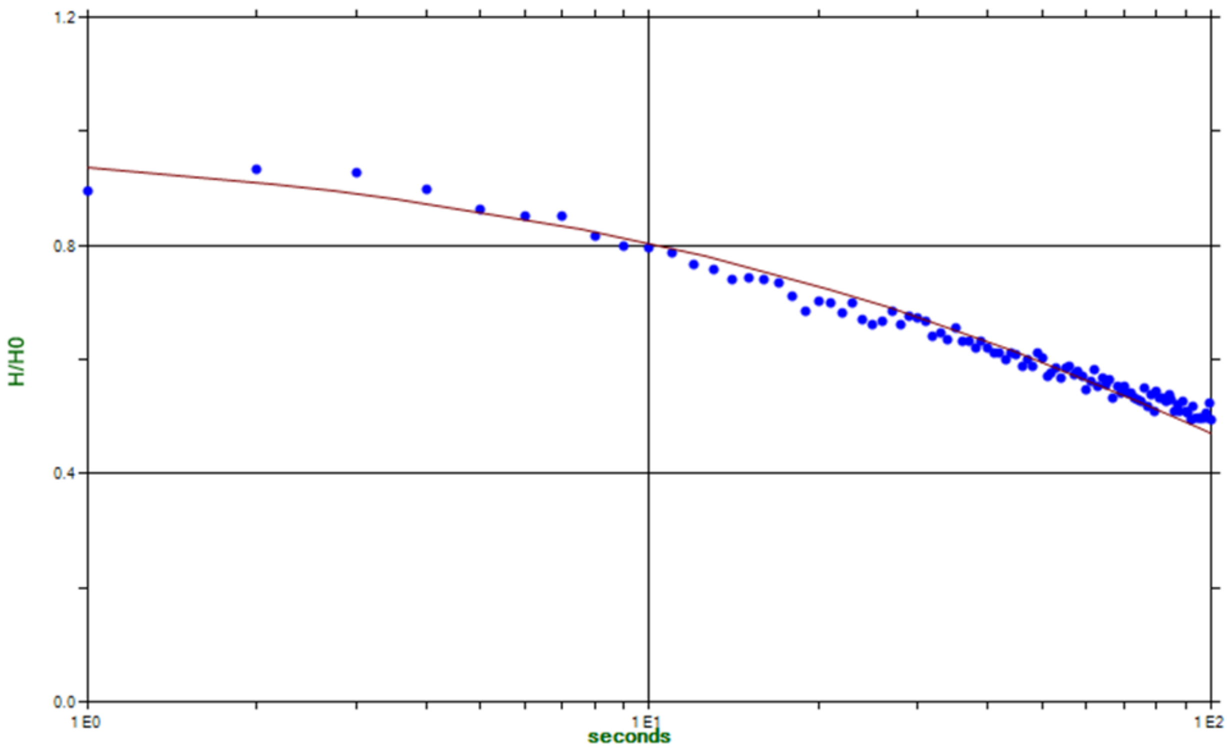


Figure 10. BDAS PW_6(PEAT) Falling Head Test, simulated and observed curves using the Cooper *et al.* (1967) method.

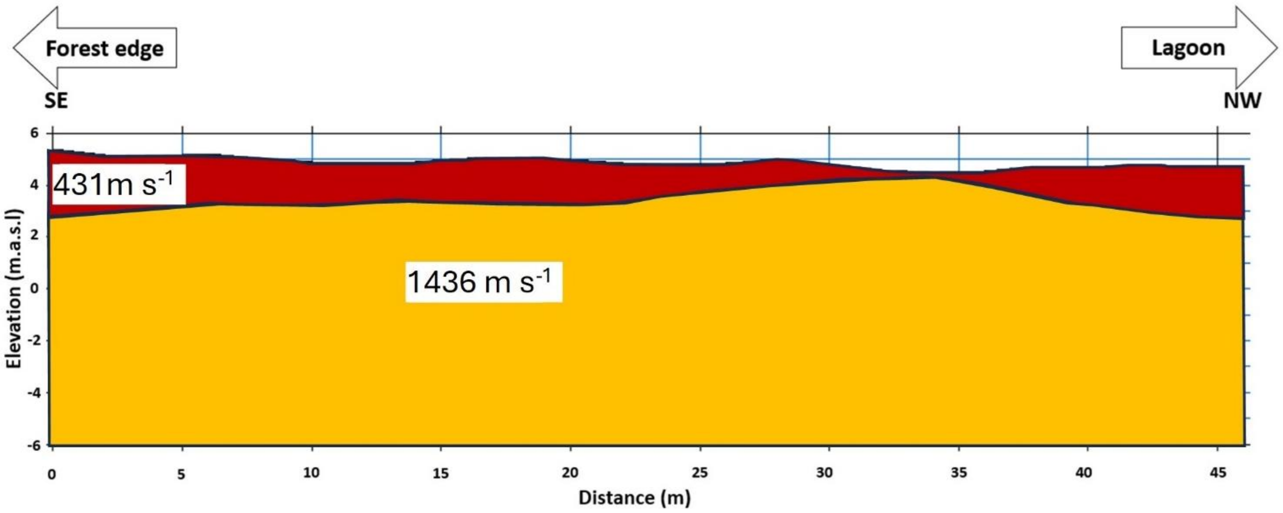


Figure 11. Transect 1 p-wave seismic velocity profile with peat shown in brown and sand in orange.

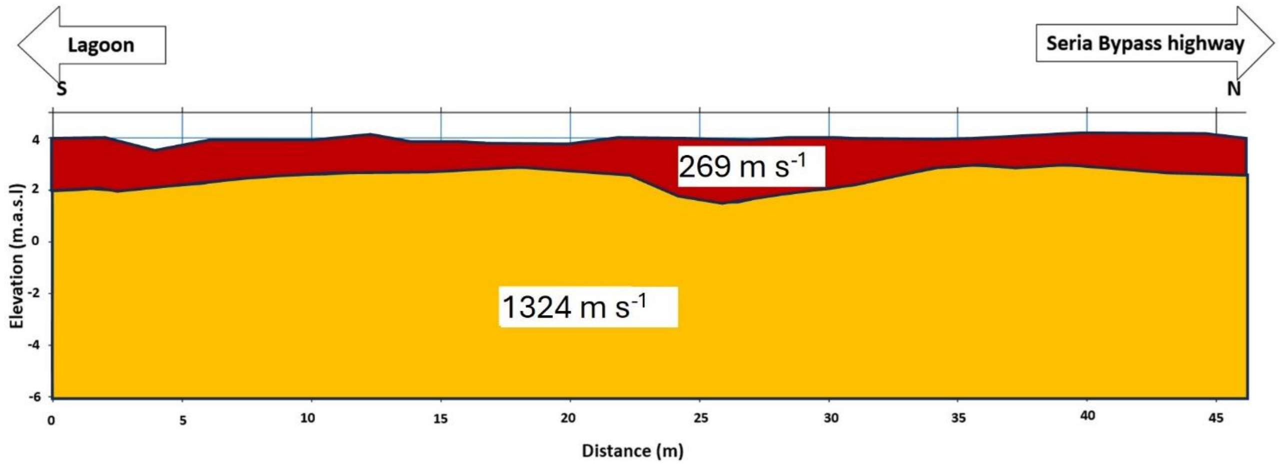
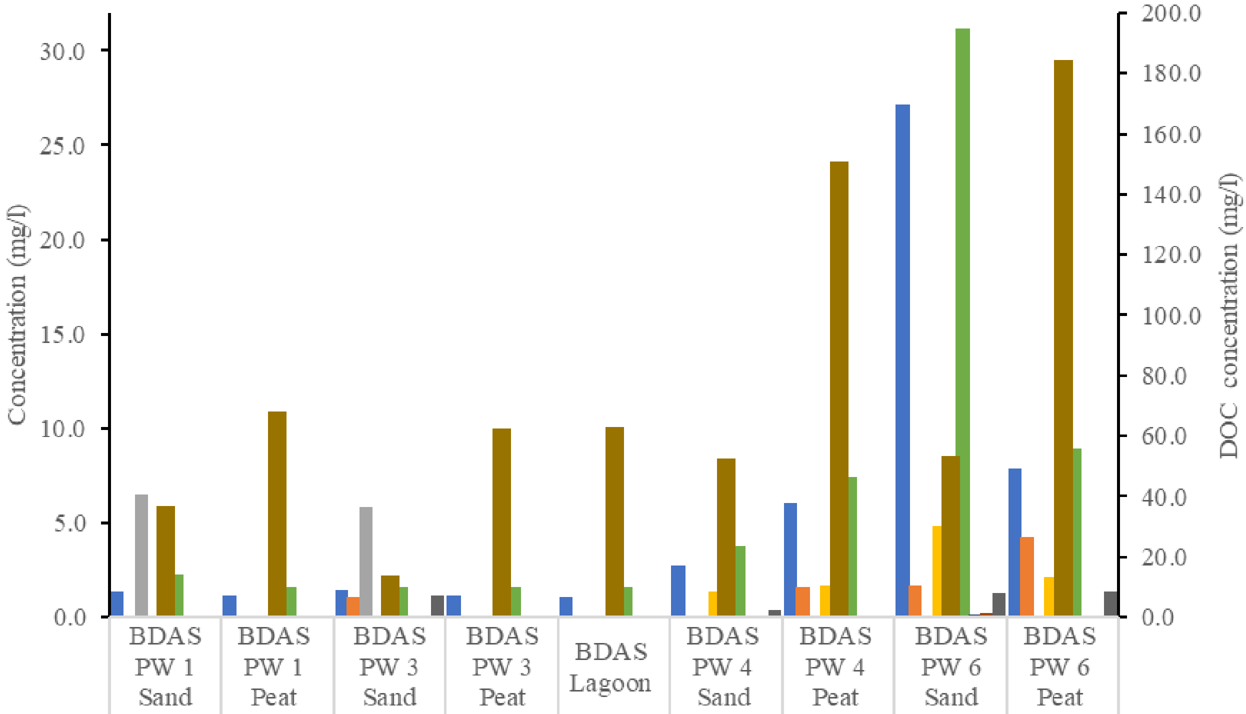


Figure 12. Transect 2 p-wave seismic velocity profile with peat shown in red and sand in orange.

DISCUSSION

Seismic refraction as well as resistivity surveys have been used successfully in the past in Brunei to investigate coastal aquifers (Azhar *et al.* 2019, Azffri *et al.* 2022). From the seismic refraction survey results it becomes obvious that the lower p-wave velocities provide evidence of the drier peat conditions at Transect 2, since it is known that dry sediments or rocks result in lower p-wave velocities than wet sediments or rocks (Kahraman 2007).

Information on hydraulic conductivities in tropical peatlands is generally rare. To our knowledge, only six studies in the peer-reviewed literature provide data on hydraulic conductivity or transmissivity in tropical peatlands (Takahashi & Yonetani 1997, Kelly *et al.* 2014, Baird *et al.* 2017, Cobb *et al.* 2017, Cobb & Harvey 2019, Putra *et al.* 2023). The hydraulic conductivities of tropical peatlands can be difficult to parameterise (Hogan *et al.* 2006) because of the significant contrasts in hydraulic conductivity with very high hydraulic conductivities near the surface. Thus, piezometer slug tests could be affected if the water table is moved into a very high permeability zone through the insertion of a slug. This could have been the reason why the slug test for the peat monitoring well at location 3 failed. However, the obtained average hydraulic conductivity of 5.7×10^{-4} m s^{-1} for the slug tests in peat monitoring wells is similar to reported literature values and higher than the values of 6×10^{-5} m s^{-1} at a depth of 29.1 cm reported by Cobb & Harvey (2019) and 4.64×10^{-5} m s^{-1} at a depth of 50 cm reported by Kelly *et al.* (2014). Our slug tests were performed at depths between 4.5 m and 0.6 m below the surface, depending on the depth and screen intervals of the piezometers (Table 3). The obtained storativity results ranged from 0.01 to 0.73. This range



	BDAS PW 1 Sand	BDAS PW 1 Peat	BDAS PW 3 Sand	BDAS PW 3 Peat	BDAS Lagoon	BDAS PW 4 Sand	BDAS PW 4 Peat	BDAS PW 6 Sand	BDAS PW 6 Peat
Na+	1.3	1.1	1.4	1.2	1.0	2.7	6.1	27.2	7.9
Mg2+	0.0	0.0	1.1	0.0	0.0	0.0	1.6	1.6	4.2
Ca2+	6.5	0.0	5.8	0.0	0.0	0.0	0.0	0.0	0.0
K+	0.0	0.0	0.0	0.0	0.0	1.3	1.7	4.9	2.1
F-	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.05
Cl-	2.3	1.6	1.6	1.6	1.6	3.8	7.4	31.1	8.9
Br-	0.07	0.00	0.00	0.00	0.00	0.00	0.06	0.13	0.08
NO3--N	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.2	0.0
SO42-	0.00	0.00	1.10	0.00	0.00	0.38	0.00	1.29	1.35
DOC	36.7	68.2	13.7	62.4	62.7	52.5	151.0	53.6	184.5

Figure 13. Hydrochemistry of Transect 1 and Transect 2 water samples.

in values should not be surprising given that previous research has shown that specific yield varies with depth and spatially within peat soil (Schut & Westbrook 2022).

The response of groundwater levels due to rainfall events demonstrate that the vadose zone is thin, and that water easily percolates to the groundwater table within the time frame of a storm event resulting in the sharp rise in groundwater levels from storm events as can be seen in Figures 7 and 8. The heavy storm events during December caused a rise in hydraulic head of around 0.7 m (Figure 8b) in the peat piezometer 2 in Transect 2, while for the peat piezometer 5 (Transect 1) the rise was only around 0.4 m. Research has shown that the response to storm events in tropical peatlands varies spatially and can differ between peatland types e.g. drained and forested peatland (Putra *et al.* 2023). Transect 1 can be considered less degraded compared to Transect 2, resulting in the more "muted" response to storm events at Transect 1 compared to Transect 2. The results from groundwater monitoring indicate that in certain areas, such as piezometer locations 1 and 3, flow is occurring from the sand layer into the peat layer, whereas at the other locations the flow is mostly from the peat layer into the sand layer since the hydraulic heads in the peat are higher than in the sand. While for piezometer 1 the overall hydraulic head values make sense, it is clearly noticeable that at this location there is almost no response of the groundwater table to rainfall, which is unusual. While this location is closer to the forest and the vegetation there is taller with trees close to the piezometer, the absence of a clear response to rainfall is difficult to explain because earlier measurements in nearby intact forest invariably showed a clear response of the water table to rainfall (Cobb *et al*. 2017). For this location, part of the data from the peat piezometer was removed because the data showed an unexplainable drop in hydraulic head. The authors have noted that in certain cases at the end and close to the end of the battery life of these loggers sometimes data is still recorded but does not represent actual, true and correct measurements. Thus, the hydraulic head data for Piezometer 1 should be treated with caution.

A flow from the sand into the peat is possible if the sand has a higher hydraulic head than the peat (e.g., Freeze & Witherspoon 1967, Tóth 1963, Siegel 1983, Siegel & Glaser 1987). The sand lies in the form of sand ridges towards the north of the peat dome at a higher elevation than the peat, also facilitating flow from the sand into the peat. Here the sand is present at an elevation of between around 14.5 and 15.5 m a.s.l. at the surface (Figure 4). Our previous investigations showed that the sand layer does not have a constant thickness throughout the area (Suhip *et al*. 2020). The undulating topography of the sand layer (Figures 11 and 12) and its variable thickness could facilitate flow from the sand into the peat layer. Thus, the flow from the sand into the peat could resemble a more local flow system due to localised highs and lows of the peat and sand surfaces compared to the overall regional flow system (Tóth 1963). Tracer experiments could help to better understand the local flow system (Gödeke *et al.* 2008). The sand layer below the peat could resemble an ancient, buried beach dune system that due to its relatively high permeability can be seen as an important component of the peatland water balance. The presence of beach sand in inland Brunei, such as the white sands of Tutong, are evidence of changing sea levels and changing coastlines.

The groundwater monitoring results also show that some of the flow is directed toward the lagoons. Thus, the establishment of the lagoons when the highway was constructed altered the groundwater flow system, which was previously to the margins of the peatland as expected. These margins once extended farther north towards the South China Sea, but now coincide with the Seria by-pass road (Figures 1 and 4). The second transect also shows higher sodium chloride concentrations likely due to marine (tidal) influence and evaporation from the lagoons. An additional reason for lower water tables with respect to the peat surface at Transect 2 compared to Transect 1 could be due to the decrease in vegetation cover at Transect 2 compared to Transect 1 leading to lower groundwater tables due to the decreased effect of shading (Limpens *et al.* 2014) since Transect 1 is within the direct vicinity of dense vegetation and *Shorea albida* trees. The higher DOC concentrations in the second transect compared to the first transect can be explained by increased aerobic oxidation of peat leading to higher DOC concentrations, since the water table is lower in Transect 2 and not at the ground surface anymore. The reported DOC concentrations in the pore-water with over 100 mg L^{-1} at Transect 2 were higher than the DOC concentrations reported for a deforested site with 79.9 mg L^{-1} (Gandois *et al.* 2013).

The results from groundwater monitoring showed that a tidal influence was observed which was unexpected considering the established transects are more than 3.5 km from the South China Sea, Hydraulic testing revealed hydraulic conductivities for the sand layer to be similar to the surface peat, thus the sand aquifer could be an important aquifer when considering the overall peatland water balance. Peat degradation was more advanced at Transect 2 evident from lower groundwater tables and higher DOC concentrations. The results from seismic refraction also showed lower p-wave velocities for Transect 2 indicating a lower peat water saturation than at Transect 1. This result corresponds well with our findings that the groundwater table relative to the peat surface in Transect 2 is overall lower than in Transect 1. The construction of the lagoons has likely impacted the groundwater flow field as potential evaporation can take place over the lagoon area, as well as drainage from the lagoons via culverts towards the South China Sea. Ideally, they should be backfilled for peatland restoration purposes. The combination of different methods with geophysical survey, groundwater monitoring, hydraulic testing and water sampling proved useful in addressing the anthropogenic impact on a tropical peatland. Long term monitoring is required to quantify the anthropogenic impacts on these precious ecosystems. Further research is planned to investigate the tidal influence on the Badas peatland.

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AUTHOR CONTRIBUTIONS

SHG and ARC conceptualised the study; ARC, RSS, SHG, MAAS and MS developed the methodology of the research; MAAS, SHG, ARC collected the data; MAAS, ARC, MS, SHG and RSS analysed the data; MAAS wrote the first draft of the manuscript and all authors revised, reviewed and gave critical feedback. All authors contributed to the final editing of the manuscript and approved the final version.

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Appendix

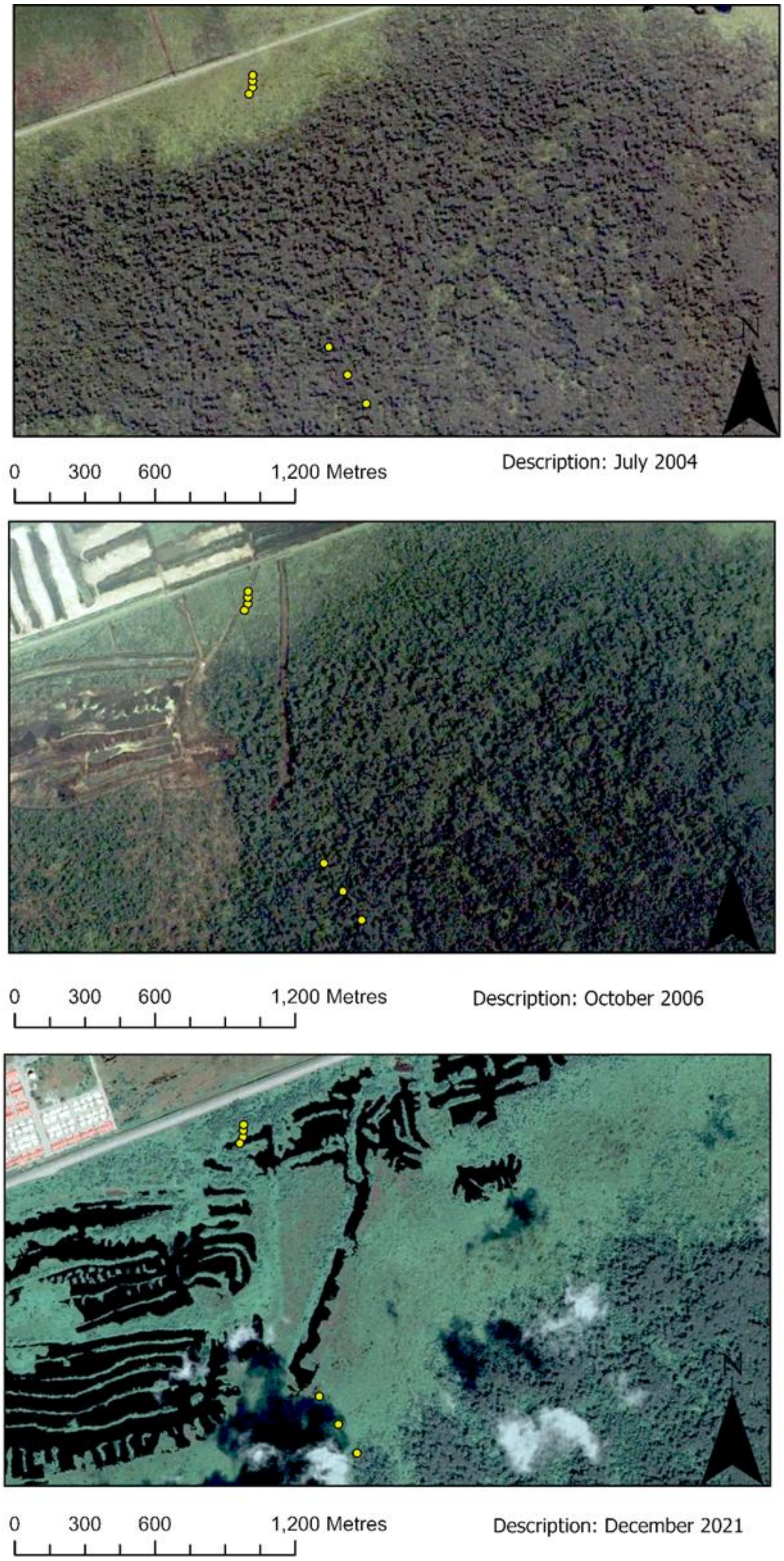

Figure A1. Selected Google Earth Landsat/Copernicus images illustrating the dramatic land cover changes, in particular peat swamp forest loss, that has occurred due to the excavation of lagoons at the study site. Piezometer locations are shown in yellow.