Ecohydrological analysis of a South African through-flow mire: Vankervelsvlei revisited

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SUMMARY

The Vankervelsvlei mire has one of the thickest peat deposits (more than 10 m) in South Africa, which started accumulating before 7000 BP. Two previous studies on the hydrological system that sustains the wetland reached inconsistent conclusions and disagreed strongly on the main sources of water feeding the wetland. One suggested that the wetland is fed by groundwater discharging from the underlying Table Mountain Group Aquifer, while the other proposed that the wetland is a perched system fed only by precipitation water. We tried to reconcile these discrepancies by measuring water table, hydraulic pressure and temperature in the peat profile and analysing the ionic composition of the groundwater. We also carried out radiocarbon dating (^{14}C) of groundwater and surface water. Our results showed that both groundwater and surface water are relatively young (<50 years) and that Vankervelsvlei is hydrologically a through-flow system with (local) mineral-poor groundwater entering the mire, possibly from a catchment located in the dunes that lie to the south-east. The groundwater exits the mire at the opposite (northern) side. Our findings do not support either the hypothesis that the mire is fed by groundwater from a deep regional aquifer, or the notion that it is sustained exclusively by precipitation water.

KEY WORDS: groundwater, peatland, radiocarbon dating, water composition, wetland

INTRODUCTION

Compared to countries like Canada and the Russian Federation with their extensive mire areas (Joosten 2010), South Africa hosts relatively few and small mires, occurring mostly in the high-rainfall eastern part of the country (Grundling & Grobler 2005). The Vankervelsvlei mire is located near the southern coastline of South Africa. It is one of the few almost pristine mires in the country and has an exceptionally thick peat layer (almost 11 metres; Irving & Meadows 1997, Grundling *et al*. 2017). For that reason, the mire has attracted much attention from scientists who were interested in how the mire survived the very pronounced environmental changes during the Quaternary period (Irving & Meadows 1997, Irving 1998, Grundling & Grobler 2005, Roets *et al*. 2008, Parsons 2009) and how the mire was able to keep its good condition despite intensive afforestation in the surrounding dune areas.

Roets *et al.* (2008) studied the geo-hydrological surroundings of Vankervelsvlei and Groenvlei Lake and suggested that both wetlands are fed directly or indirectly by discharging groundwater from the deep Table Mountain Group Aquifer. The groundwater from this fractured aquifer is supposed to have entered the dunes through an opening in the overlying impervious shale aquitard. Due to the high pressure the water would rise about 150 m, reaching the Vankervelsvlei. Finally, Vankervelsvlei would partly discharge southwards to the Groenvlei Lake. This conceptual model was based on water chemistry data, which showed resemblance between the groundwater in Vankervelsvlei, Groenvlei Lake and the Table Mountain Group Aquifer.

Parsons (2009) published several objections to the conceptual model of Roets *et al.* (2008). He was not convinced that the geological situation would allow sufficient hydraulic pressure for groundwater from the Table Mountain Group Aquifer to reach Vankervelsvlei. Although no detailed information on the geological strata below the study area was available, he concluded that the high water table in the wetland found by Roets *et al.* (2008) corresponded to perched water above an impervious layer and that the regional water table was much lower (between 1.4 and 3.7 m a.m.s.l.). Therefore, he argued that the mire must be sustained by precipitation only and that there was no hydraulic link to either the Table Mountain Group Aquifer or Groenvlei Lake. He did not present evidence to show that the wetland is fed exclusively by precipitation. The occurrence of a *Sphagnum* layer in the vegetation (observed in our study) may be an indication for that, but the analyses of water samples by Roets *et al*. (2008) indicate that there is input of base-rich groundwater, at least locally.

In the present study we aimed to improve our understanding of the hydrological system that controls and sustains the Vankervelsvlei. For this purpose we used a quick-scan ecohydrological analysis (van Wirdum 1991, Grootjans *et al*. 2006, Grootjans & Jansen 2012) combining quantitative aspects of hydrology (such as water levels and hydraulic pressures) with qualitative aspects such as ionic composition, ^{14}C in groundwater and temperature profiles in the peat (van Wirdum 1991, Schot & Molenaar 1992, Mitsch & Gosselink 2000, Joosten & Clarke 2002, Appelo & Postma 2005, Miller *et al*. 2017).

Temperature measurements in the soil profile have been used to provide information on the origin of water flows in South African peatlands (Grundling 2014). Groundwater profiles directly fed by precipitation water or influenced by local hydrological systems still reflect the temperature conditions relating to the most recent weather conditions (day and night regimes or hot or cold periods in recent time frames; Martin & Dean 1999). Deep groundwater from regional systems has a very constant temperature, since temperatures are not influenced by daily or even annual fluctuations in temperature (Rose 1966, van Wirdum 1991).

Radiocarbon dating of groundwater provides insights on the origin and time dependence of the aquifer. Establishing the absolute age of the water is a complex and controversial matter (Geyh 2000), but one can assess the relative ages of different groundwater flows.

This article addresses the following scientific questions: (i) is the Vankervelsvlei mire fed by regional (old) groundwater from the Table Mountain Group Aquifer, or by relatively young groundwater from local hydrological systems; and (ii) is the occurrence of base-rich groundwater in the mire associated with old groundwater?

STUDY AREA

The Vankervelsvlei mire (coordinates 34° 0' 71" S, 22° 54' 22" E) is located in Western Cape Province about 400 km east of Cape Town, approximately 8 km north-east of the town Sedgefield and just 5 km from the coast (Figure 1). It is an inter-dune wetland with a surface area of about 25 ha and no visible

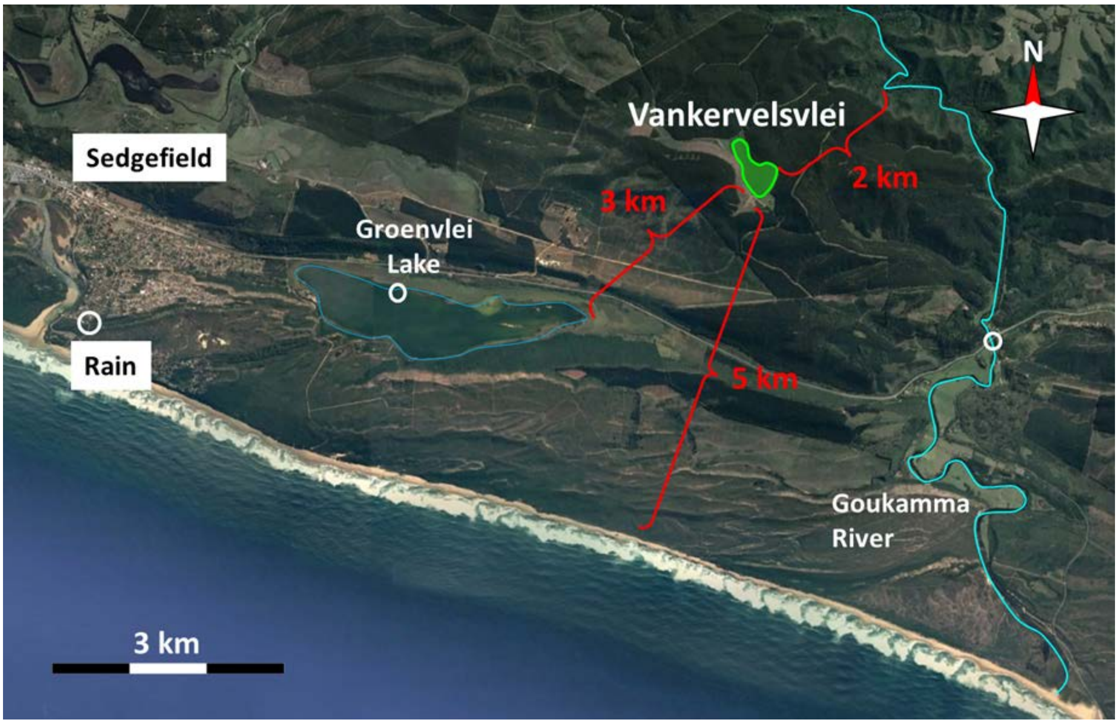

Figure 1. Location of the Vankervelsvlei study area. White circles show the locations of surface water (Goukamma River, Groenvlei Lake) and rainwater (Sedgefield) samples.

surface-water inflow (Figure 2), situated at a mean altitude of 153 m a.s.l. on the edge of the landward Wilderness embayment (Illenberger 1996, Quick *et al*. 2016). Currently, the wetland is surrounded by a commercial *Pinus* plantation owned by the company PG Bison Southern Cape Forests.

The mean annual precipitation recorded over the last ten years by a weather station (30734 George-Outeniqua) located 40 km west of Vankervelsvlei was 803 mm $year^{-1}$, with annual evapotranspiration averaging 1039 mm $year^{-1}$ (ARC-ISCW 2016). The mean annual temperature is 16.1 °C, with mean monthly maximum 25.1 °C in February and mean monthly minimum 7.5 °C in July (ARC-ISCW 2016).

Radiocarbon analyses by Irving (1998) dated the peat layers between 3000 and 7000 years BP. The deeper clay layers underneath the peat (Irving 1998, Grundling *et al*. 2017, Elshehawi *et al*. 2018) were dated as > 40,000 years BP (Irving & Meadows 1997), near the background limit of the ^{14}C dating method.

The closest water bodies, lying more than 120 m lower than the wetland, are the Goukamma River (approximately 2 km to the north-east) and the Groenvlei Lake (approximately 3 km to the south-west; see Figure 1). The dunes surrounding the Vankervelsvlei wetland have steep slopes (varying between 11 % and 33 %) and consist of deeply leached sandy soils (Illenberger 1996, Grundling *et al*. 2017). The surrounding relief of the depression containing the peatland corresponds to aeolian stabilised dunes composed of cross bedded aeolianite, which belong to the 'landward barrier

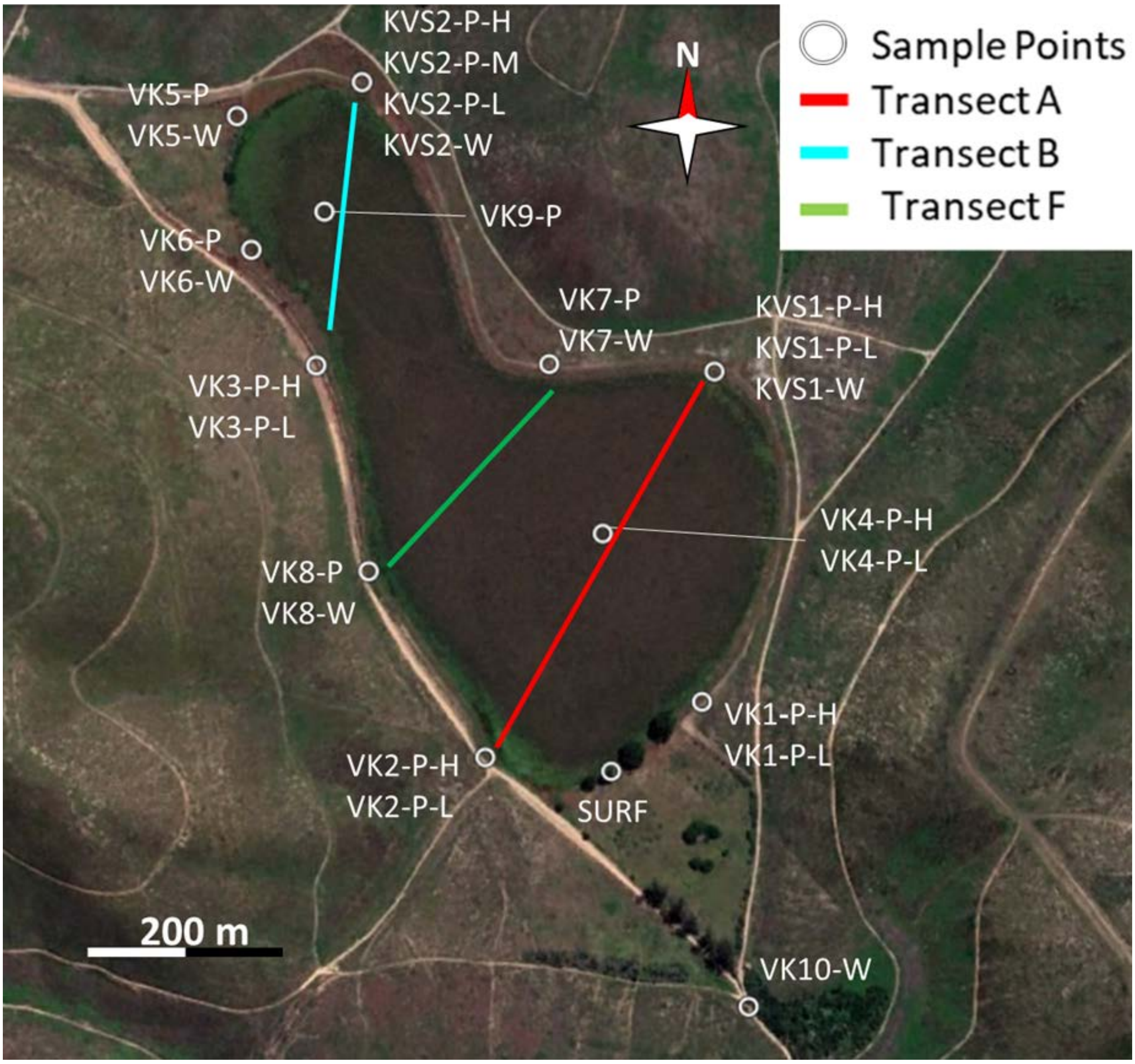

Figure 2. Aerial view of Vankervelsvlei (Google Earth, 18 Dec 2019), showing temperature and water level transects (A, B, F) plus locations of boreholes (e.g. VK1 - piezometer (P) or well (W) - relative height of piezometer in nest (H=high, M=medium, L=low)) and surface water sampling points.

dune' (Illenberger 1996, Bateman *et al*. 2011, Quick *et al*. 2016). The age of these lithified aeolian dunes is estimated to be between 205 and 250 ka with a core possibly dating to ~330 ka (Lisiecki & Raymo 2005, Bateman *et al.* 2011). The wetland and the fossilised dunes most likely overlie the Peninsula Formation sandstones and quartzites of the Table Mountain Group of the Cape Supergroup. The depth to the Table Mountain Group Aquifer is unknown (Coetzee 1979, Parsons 2009, Bateman *et al*. 2011).

It is likely that the Vankervelsvlei originated as a coastal open water body within the 'landward barrier' and started to fill up with sediments (leached clay, silt and later organic matter) during the past ~40,000 years (Irving & Meadows 1997, Irving 1998, Quick *et al*. 2016). The stratigraphic analysis made by Irving (1998) suggested two major depositional phases; an earlier phase characterised by fine inwashed material in the form of clays, and a more recent phase dominated by peaty sediments rich in organic matter.

This region is known for its indigenous forest, comprising also the Knysna and Fynbos vegetation types (Mucina & Rutherford 2006). Nevertheless, the surrounding stabilised aeolian dunes are currently covered by mature *Pinus* plantations and some *Eucalyptus.* Some areas have already been harvested (Figure 2). Within the edges of the wetland no open water is currently visible, except for an artificial opening in the southern side which was formerly used for water extraction. The dense vegetation cover consists of mixed sedge and wetland herbaceous vegetation. Dominant plant species are *Capeochloa cincta*, *Cladium mariscus* (saw-sedge), *Sphagnum* sp., *Phragmites australis* (common reed) and *Thelypteris palustris* (marsh fern).

Due to its particular features the Vankervelsvlei has been earmarked in the 2015 CapeNature Protected Area Expansion Strategy for inclusion as a potential future Protected Area or consideration for Formal Stewardship status (Turner 2012, Grundling *et al*. 2017).

METHODS

Water levels, hydraulic pressures and rainfall

An initial analysis and estimation of the topography of the area was done using Google Earth (version 7.1.8.3036). This information was plotted in the final diagrams of the geomorphology of the area.

A groundwater monitoring network consisting of wells and piezometers was installed in 2015 and 2016 (Figure 2, Table A1 in the Appendix). Wells, giving information about water table depth, consisted of fully perforated (slotted) PVC pipes 2 m long and 50 mm in diameter which were covered with geotextile screening. Piezometers, giving information on hydraulic pressures at specific depths, had a 0.2 m long slotted filter at the bottom of each pipe, which was again covered with geotextile screening. Some piezometers were grouped (located within 1–4 m of each other) in measuring sites (piezometer nests). All measuring points and surface water levels in three transects (A, B and F) were accurately levelled (~1mm error) by FJ Loock Land Surveyors Inc. using a differential GPS on 25th June 2016. The accuracy in the mire itself could be less (about 5 mm) due to the soft peat surface. Water levels and hydraulic pressures were recorded three times between May and June 2016 (second week of May, second and last weeks of June). The water table measurements had an accuracy of ~5 mm.

Rainfall was measured using a manual raingauge (installed at Sedgefield; see Figure 1), from which water was collected for chemical analyses after a rainfall event on 21 June 2016.

Peat temperatures and water level measurements

Peat temperature profiles were measured along three transects across the wetland (Figure 2). Temperatures were measured every 20 cm directly in the peat using a 2 m metal probe (van Wirdum 1991). Water levels, hydraulic pressures and peat temperatures were measured during three periods: the second week of May 2016, when air temperatures ranged from 10 °C to 25 °C (May averages for the city of George: 10 °C min/22 °C max; ARC-ISCW 2016); the second week of June 2016 with air temperature 5–28 °C and the last week of June 2016 with air temperature 4– 22 °C (June averages for George: 8 °C min/19 °C max).

Ionic composition

Groundwater (from piezometers) and surface water were sampled with a PVC sampling bailer in Vankervelsvlei, Goukamma River and Groenvlei Lake during the second week of June 2016. Rainwater was sampled in Sedgefield (Figure 1). Samples were stored in 250 ml polyethylene terephthalate (PTET) bottles which were filled to the brim and transported in a coolbox. The water was analysed at the Agricultural Research Council Institute for Soil, Climate and Water in Pretoria. The concentrations of Na^{+}, K^{+}, Ca^{2+}, Mg^{2+}, NO_3^{-}, PO_4^{3-} and $Fe^{II(III)}$ plus Si were analysed by emission spectroscopy using an inductively coupled plasma source (ICP; APHA *et al*. 1985a). The main anion concentrations (HCO_3^{-}, SO_4^{2-} and Cl^{-}) were determined by ion chromatography (APHA *et al*. 1985b).

Radiocarbon dating

Water samples for ^{14}C analysis originated from eleven different sites in and around the mire (sites VK1−VK9, KVS1 and KVS2; Figure 2). All water samples were stored in 300 ml brown glass bottles filled to the brim and kept in a cool box and analysed at the Centre for Isotope Research of the University of Groningen, the Netherlands. Phosphoric acid (H_3PO_4) was used to react with the dissolved inorganic carbon (DIC) in the water samples forming CO_2. This carbon dioxide was cryogenically trapped using liquid nitrogen and graphitised by reduction with H_2 to pure graphite (Aerts-Bijma *et al*. 2001). Finally, the carbon isotope ratios $^{14}C/^{12}C$ and $^{13}C/^{12}C$ of the graphite were measured by Accelerator Mass Spectrometry (AMS; van der Plicht *et al*. 2000). The ^{14}C contents were expressed as activity ratios (^{14}a) relative to the international reference material, corresponding to the natural activity of 1950 (Mook & van der Plicht 1999). For terrestrial samples, these relative activities can be converted into conventional radiocarbon ages in BP. However, for water, straightforward interpretation of the measured ^{14}a concentrations (for instance in terms of dates) is problematic because this depends on the origin of the carbon (Mook & van der Plicht 1999, Mook 2006). This origin can be CO_2 exchanged with the atmosphere (having modern ^{14}C concentrations), or geological (not containing ^{14}C; Geyh 2000). Usually there is an offset, called the ‘reservoir effect’, between atmospheric and hydrological ^{14}C dates which are contemporaneous. Quantification of this offset is difficult for hydrological systems, and depends on a variety of geochemical factors (Geyh 2000, Mook 2006). Because of these uncertainties, dates in hydrology have not been corrected for isotope effects as is the convention. Hence, the ^{14}C activity ratios are presented as ‘uncorrected’ (Mook & van der Plicht 1999). Radiocarbon ages can be calculated when the activities are less than 100 %. These ages are represented in ‘not corrected ^{14}C years’ rather than in BP.

Data analyses

All data were analysed using the software R-statistics (version 3.2.0). Averages for groups or transects were compared by ANOVA followed by Tukey’s HSD to find means that were different from each other. Water level transects were analysed by OLS linear regressions in order identify significant slopes. Peat temperature profiles were plotted as isotherm maps with the help of the software 3DField (version 4.3.1.0).

RESULTS

Water levels

Water level measurements within the wetland (A, B and F; Figure 2) indicated no significant differences in the water table gradients along transects at 95 % confidence level. Also, the calculated hydraulic gradient across the 500 m interval between transects A and B (south–north direction) was only 0.00014.

The water levels measured in the external wells surrounding the wetland on 01 June 2016 are shown in Figure 3. The lowest levels were observed at the northern side of the wetland, and the highest levels to the south (blue series in Figure 3). The northernmost measuring point consisted of a deep piezometer located at 145.066 m a.s.l. (KVS2-P-L). This piezometer was dry in all three surveys. Since there was no evidence of a perched water table at this location, we assumed the water table to be below the base of this piezometer, indicating a steep decrease in water table towards the north. The southernmost well (VK10-W; (Figure 2) shows a water level of 172.651 m a.s.l., indicating an abrupt rise in the water table towards the south. Within the wetland, the water table measured with a differential GPS on 24 June shows a rather flat surface which is only slightly higher than in all wells directly surrounding the mire.

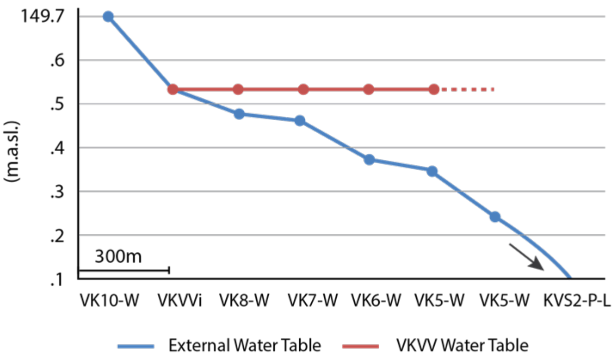

Figure 3. Water table measurements (m a.s.l.) measured in wells surrounding the wetland on 21 June 2016 are presented in blue. Surface water levels on the mire measured by FJ Loock Surveyors Inc. on 24 June are presented in red. The Y-axis corresponds to the water table and the X-axis corresponds to the straight-line distance from the southernmost measuring point VK10-W to the northernmost piezometer nest KVS2-P, which was dry throughout the observation period. The black arrow indicates that the water table at KVS2-P-L was deeper than 149.1 m a.s.l.

Hydraulic head

The average hydraulic head of the three surveys was calculated for the six piezometer nests (sites VK1, VK2, VK3, VK4, KVS1 and KVS2) installed in the wetland, and then the corresponding hydraulic gradients were calculated (Table 1).

Piezometer nests set up for vertical hydraulic gradient calculations (sites VK1, VK2, VK4) showed infiltration in the centre and on the south-west tip of the mire (Table 1). At the southern point VK1, the piezometers showed clear exfiltration. VK4 had only one measurement.

For the horizontal gradient sites (VK3, KVS1, KVS2) the directions of the gradients pointed towards the wetland from its east and west sides and away from the wetland at the northern point KVS2.

Temperature profiles

Compared to the annual average (air) temperature of the region, which is 16.1 °C (ARC-ISCW 2016) and ranges from 8 °C to 14.1 °C, the temperatures measured within the peat layer during the three surveys were low. Figure 4 shows the variation in temperature with depth for three transects (B, F and A). These temperature profiles indicate that relatively cold water occurs in the upper peat layers in the north and east, while relatively warm water occurs in deeper layers more to the south (transects A and F).

Ionic composition of groundwater

The concentrations of the ions Cl^-, Ca^{2+} and HCO_3^- were plotted in a Cartesian plane (Figure 5). It can be seen that higher concentrations were found in the south and north-west of the Vankervelsvlei (sites VK1, VK2 and VK6).

Chloride concentrations were high in most all of the water samples (Figure 5), compared to inland wetlands (Stuyfzand 1993, Appelo & Postma 2005, van Wyk *et al*. 2011).

Finally, it can be seen from Table A2 that all sulphate concentrations were low (<10 mg L^{-1}), pointing to anoxic conditions (Stuyfzand 1993).

Radiocarbon dating

Shallower samples, from depths less than 250 cm below ground surface, showed ^{14}C activities ranging from ~98 % to ~110 %, indicating that most of them (8 out of 11) were recent water. Activities higher than 100 % correspond to ages more recent than 1950 AD. The two samples from deep piezometers in the middle of the wetland (VK4-P-L and VK9-P) showed lower values than the rest of the samples (Table 2).

Table 1. Elevation of the filters of the piezometers (bottom of the screen) and average hydraulic heads over the three measuring periods between May and June 2016.

	pipe ID	elevation of filter (m a.s.l.)	average head (m a.s.l.)	average hydraulic gradient	standard deviation	n	
nest configuration vertical hydraulic gradients	VK1-P-L	148.709	149.539	-0.057	0.019	2	exfiltration
	VK1-P-H	149.466	149.496				
	VK2-P-L	148.231	149.301	0.155	0.063	3	infiltration
	VK2-P-H	148.953	149.413				
	VK4-P-L	144.008	149.388	0.045	-	1	infiltration
	VK4-P-H	146.763	149.513				
nest configuration horizontal hydraulic gradients	VK3-P-H	148.793	149.456	0.005	0.002	3	in wetland
	VK3-P-L	148.630	149.470				
	KVS1-P-L	148.534	149.517	0.011	0.002	3	in wetland
	KVS1-P-H	148.555	149.475				
	KVS2-P-L	145.066	dry	<-0.104	0.002	3	outside wetland
	KVS2-P-M	148.472	149.242	-0.018	0.003	3	outside wetland
	KVS2-P-H	149.110	149.452				

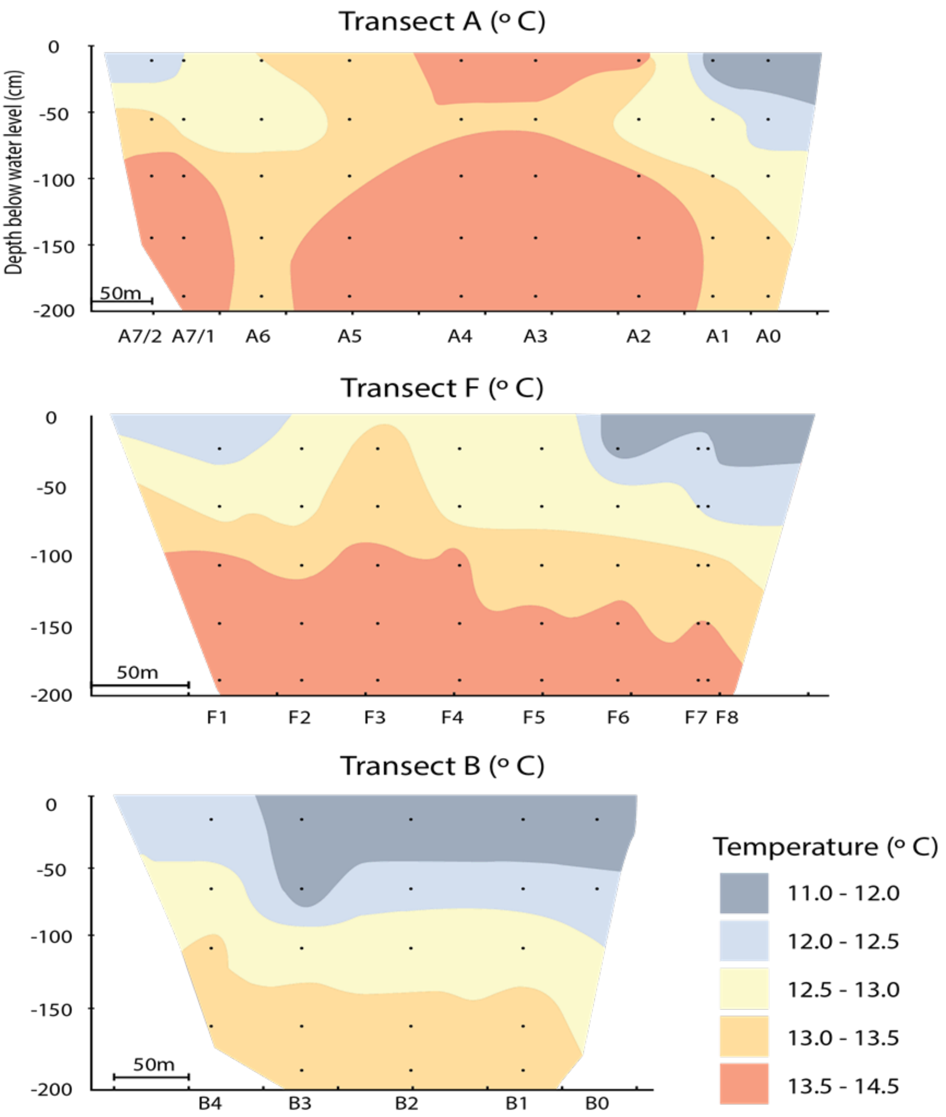

Figure 4. Temperature profiles in °C for three transects (A,B and F) measured on 11–13 May 2016. Transect B is situated in the North, while transect A is situated in the South, with transect F in the middle. Black dots represent the measuring depths.

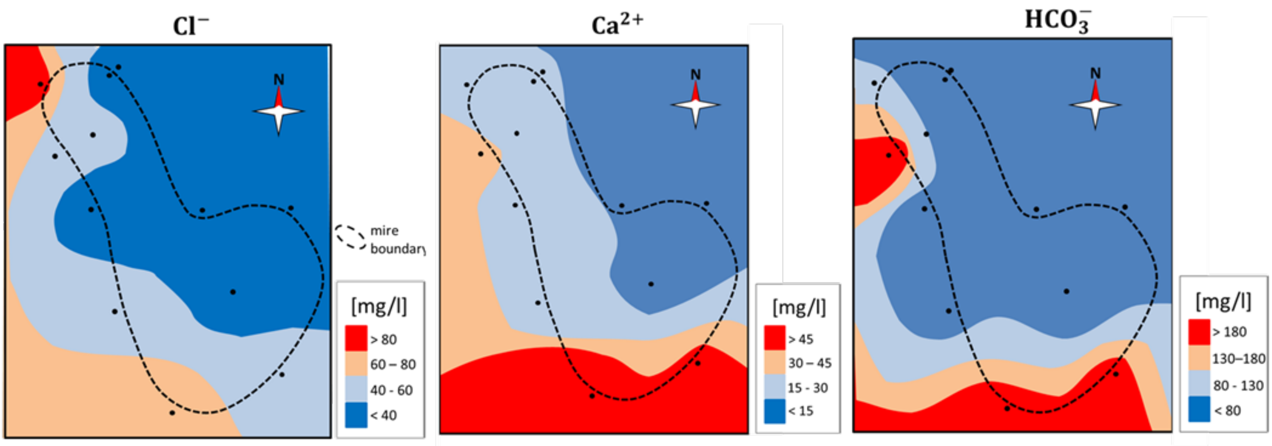

Figure 5. Cl^-, Ca^{2+} and HCO_3^- concentrations of groundwater measured in piezometers in and around Vankervelsvlei.

Table 2. Radiocarbon activities for groundwater samples in Vankervelsvlei.

GrA	sample	depth (cm)	uncorrected ^{14}a (%)
66976	VK1/1	221	100.27 ± 0.34
66977	VK2-a	234	109.68 ± 0.35
66985	VK3-b	176	107.36 ± 0.35
66978	VK4-a	552	96.41 ± 0.60
66979	VK5/1	215	98.44 ± 0.33
66981	VK6/1	232	104.76 ± 0.35
66899	VK7/1	246	99.98 ± 0.34
66984	VK8/1	197	107.98 ± 0.35
66986	VK9	629	92.04 ± 0.31
66900	KVS1/2	124	101.98 ± 0.40
66901	KVS2/2	145	104.64 ± 0.42

DISCUSSION

Hydrological system of Vankervelsvlei

Precipitation and evapotranspiration

Given that the evapotranspiration of the zone exceeds the total precipitation by 236 mm year^{-1} (ARC-ISCW 2016), it seems impossible that the wetland could be fed by precipitation only, and a second source of water must exist.

Water levels

The water level measurements from wells outside the mire clearly indicate a rather steep hydraulic gradient with water table levels decreasing from south to north (Figure 3). The two most extreme measuring points (KVS2-W to the north and VK10-W to the south) show a difference in water level of slightly more than 23 m. Within the mire itself the water table gradient is extremely small (around 0.00014), with water levels decreasing from south to north. Therefore, water level differences measured within the mire itself are insignificant; the water table within the mire can be considered to be flat. Surprisingly, the water table was higher within the mire than in most of the northern surrounding dunes (Figure 3). It is possible but unlikely that this could have been caused by clay layers being penetrated during coring, resulting in incorrect (lower) water level measurements in wells and piezometers located in the immediate surroundings of the mire.

The measurements from piezometers to the south and south-east (VK1-P-L, VK1-P-H, KVS1-P-H) in May and June 2016 consistently showed modest groundwater exfiltration (site VK1) and also water movement towards the wetland (site KVS1). This implies that the dunes located at the south side of the wetland, which belong to the 'landward barrier' (Illenberger 1996), feed the mire with groundwater. Site VK3, located at the western edge of the wetland, also showed some exfiltration of groundwater. This indicates that the western dune also supplies the wetland with groundwater, at least seasonally.

On the basis of these measurements, we suggest that Vankervelsvlei is indeed not fed solely by precipitation water, and that groundwater from a local aquifer is important in maintaining high water levels in the mire.

Radiocarbon dating

The results of the radiocarbon dating show that all of the groundwater and surface water sampled in Vankervelsvlei was relatively recent. All radiocarbon activity ratios are larger than 90 %, implying that any reservoir effects are insignificant (Mook 2006). Most of the younger samples show ^{14}a activity ratios greater than 100 %, indicating that the ^{14}C concentration is influenced by the 1960s anthropogenic 'bomb peak' so the samples must be younger than ~50 years (Hua *et al.* 2013). These results partly confirm the interpretation of Parsons (2009), who suggested that the mire was not fed by deep groundwater from the Table Mountain Group Aquifer (estimated age 880–2600 years; Wu 2005) and must, therefore, be fed by precipitation only. However, our results from water level measurements and radiocarbon dating suggest that the mire is fed by a local hydrological system which sustains a flow of recent groundwater with low concentrations of dissolved minerals, in addition to precipitation.

Temperature profiles

The temperature measurements in the peat profiles gave further insights about the possible groundwater movement through deeper layers of the mire. In deeper (>100 cm) layers, temperature was hardly influenced by short-term changes in weather. On the other hand, the temperature of shallow (<50 cm) groundwater was closer to the June average (weather station 30734 George-Outeniqua, ARC-ISCW 2016) and clearly reflected the influence of forest shading and tall vegetation along the edges of the mire (Figure 4).

Compared to the annual average temperature of the region (16.1 °C in the city of George; ARC-ISCW 2016), the groundwater of the Vankervelsvlei was significantly colder, especially in the upper layers of peat. Therefore, input of local groundwater is very likely. The temperature profiles of transects B and F showed a stratified pattern of temperature and the upper layer was rather cold (<12 °C) over almost the whole top layer, clearly indicating infiltration conditions. Due to these conditions the mire system loses water to the north (and east), causing cold water from the top layer to sink into deeper layers.

The deeper layers showed a general trend towards higher temperatures, closer to the mean annual temperature of the region. Cooler winter air temperatures result in cooler near-surface mire temperatures and cooler local groundwater in the dunes that discharge to the edge of the mire.

Ionic composition

The ionic composition of the groundwater in the mire revealed that it is poor in dissolved minerals. This is because the surrounding dunes are old and most minerals that dissolve readily in water have been leached already. The very low sulphate concentrations reflect the anoxic nature of the peat layers and the lack of oxidising processes such as pyrite oxidation (Stuyfzand 1993). This anoxic groundwater allowed the formation and conservation of peat (Parish *et al.* 2008).

Significantly higher concentrations of calcium and carbonate were found at four points located near the grasslands to the north and south of the Vankervelsvlei. All of the pertinent samples originated from rather shallow piezometers and wells (1–2 m below surface). In the southern grasslands we found remains of concrete constructions associated with houses that were once located there, so it is possible that the high concentrations of calcium and bicarbonate in the groundwater originated from buried remnants of old buildings. This could explain why Roets *et al.* (2008) found relatively calcareous groundwater around the mire. High calcium and bicarbonate concentrations do not necessarily point to inputs of old groundwater from the deep regional aquifer (Schot & Molenaar 1992). Our radiocarbon dating of water samples also supports the idea of inflow of local groundwater polluted by local sources of carbonate and calcium.

The source of chloride in rainwater is the sea, therefore coastal areas have significantly higher concentrations of sodium and chloride than inland areas (Stuyfzand 1993, Appelo & Postma 2005, van Wyk *et al*. 2011). For a similar coastal region (Cape Town), van Wyk *et al*. (2011) reported an average chloride concentration of 2.67 mg L^{-1}. For Dysseldorp (Southern Cape) and Cape Town the values were 1.9 mg L^{-1} and 13 mg L^{-1} respectively (van Wyk *et al*. 2011). The rainwater sampled in the present study was within the range presented above, with chloride concentrations of 6.17 mg L^{-1} for Sedgefield (7 km seaward from the Vankervelsvlei). Dry deposition in forested areas is significantly higher than in other land types due to interception by the trees and even more when the chloride concentration in rainwater is more than 50 µmol L^{-1} (1.77 mg L^{-1}) (Stuyfzand 1993, Appelo & Postma 2005). The pine plantation generates significant evapotranspiration, increasing the Cl^- concentration even more (Stuyfzand 1993). These phenomena also explain why groundwater inflow can have chloride concentrations of 30 mg L^{-1} or higher, similar to the case of the Mfabeni mire in a similar environment (Grundling 2014).

Summarising, we could say that the relatively high chloride and low sulphate concentrations found in all of our water samples indicate that the water source of the wetland is groundwater - probably infiltrated precipitation water coming from sand dunes in the immediate vicinity.

Conceptual model

The findings of the present study mainly support the hypothesis of Parsons (2009) that Vankervelsvlei is not fed by groundwater originating from the deep Table Mountain Group Aquifer, as was previously suggested by Roets *et al.* (2008). However, the hypothesis of Parsons (2009) that the mire is fed by precipitation water alone is also incorrect. Besides the direct rainwater input to the Vankervelsvlei, an inflow from a local groundwater system also exists, probably originating mainly from the south-eastern side of the wetland. The (topographically defined) catchment area of this groundwater system is about 150 ha. The mire receives direct rainfall on its 25 ha area, which is less than 20 % of the total catchment area. Therefore, the dunes belonging to the ‘landward barrier’ located on the southern side of the wetland probably make up the local groundwater system that is providing the mire with additional groundwater, explaining the stable water levels in the mire, even during drier periods. The local groundwater system is sustained by the multiple thin clay and loamy-sand layers located in the surrounding dunes.

As already pointed out by Irving (1998) and Parsons (2009), there is a thick clay layer underneath the mire which keeps a rather stable water level within the wetland boundaries. Furthermore, the work of Grundling *et al*. (2017) in Vankervelsvlei revealed the occurrence of numerous (very) thin clay or loamy sand layers in the dunes surrounding the mire. We also found such layers during drilling of the boreholes in the areas surrounding the wetland. The presence of these thick and thin clay layers slows the downward movement of groundwater and directs it into the mire, which it crosses before infiltrating again into deeper sand layers mainly on the northern side (Figure 6).

Due to the localised inflow and outflow areas, the wetland can be defined as a through-flow system (Stuyfzand 1993, Adema *et al*. 2002, Grootjans *et al*. 2006). This conceptual model should be further tested with a more focused borehole network, which would require the addition of shallow piezometers in the southern and northern surroundings of the wetland - as well as within its borders - in order to study the direction of groundwater flow. In addition, some deep piezometers under the Vankervelsvlei could deliver valuable information about the regional groundwater table, and further prove that the wetland has its own hydrological system.

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AUTHOR CONTRIBUTIONS

Hydrological field data were collected by SRM, P-LG and BCWvdW. SRM, APG and P-LG were the main authors of the manuscript. APG, JvdP and ATG supervised the project.

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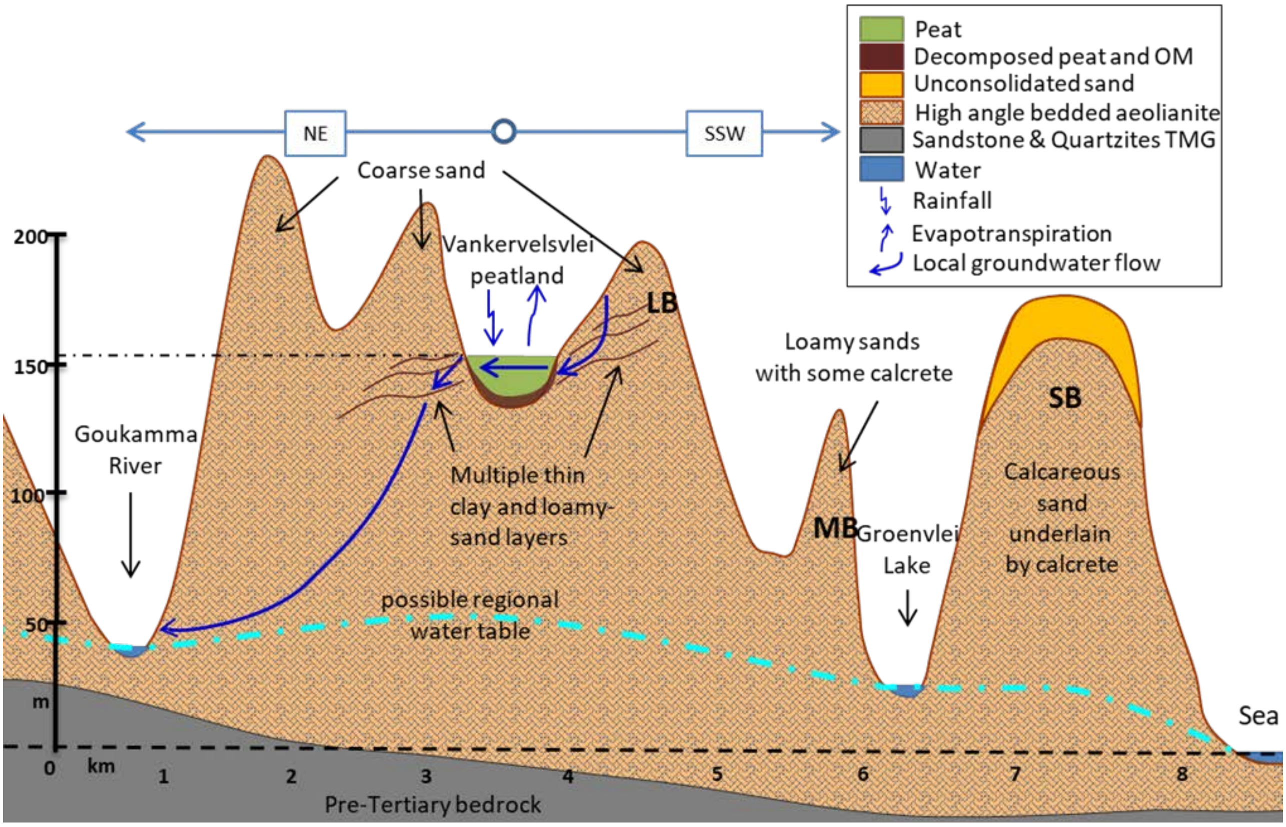

Figure 6. Conceptual model of the hydrological system (main water flows) supporting the Vankervelsvlei mire superposed on the geo(morpho)logical model of the barrier dune landscape proposed by Bateman *et al*. (2011) for the Kosi Bay area of the Maputaland Coastal Plain (see also Botha & Potrat 2007, Grundling *et al*. 2014, Kelbe *et al*. 2016). LB: landward barrier; MB: middle barrier; SB: seaward barrier (Bateman *et al*. 2011, Illenberger 1996).

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Appendix

Table A1. Setup of the network of piezometers and wells in the research area. Types: P=piezometer, W=well. Piezometer elevations: H=high, M=medium, L=low.

site	type	piezometer elevation	pipe ID	ground surface elevation (m a.s.l.)	elevation of filter (m a.s.l.)	latitude	longitude
VK1	P	L	VK1-P-L	150.862	148.709	34° 0.840' S	22° 54.331' E
	P	H	VK1-P-H	150.862	149.466	34° 0.841' S	22° 54.330' E
VK2	P	L	VK2-P-L	150.552	148.231	34° 0.875' S	22° 54.170' E
	P	H	VK2-P-H	150.223	148.953	34° 0.875' S	22° 54.170' E
VK3	P	H	VK3-P-H	151.375	148.793	34° 0.637' S	22° 54.051' E
	P	L	VK3-P-L	150.393	148.630	34° 0.637' S	22° 54.051' E
VK4	P	L	VK4-P-L	149.523	144.008	34° 0.737' S	22° 54.257' E
	P	H	VK4-P-H	149.523	146.763	34° 0.737' S	22° 54.257' E
KVS1	P	L	KVS1-P-L	150.216	148.534	34° 0.637' S	22° 54.342' E
	P	H	KVS1-P-H	149.756	148.555	34° 0.638' S	22° 54.340' E
	W	n/a	KVS1-W	149.587	-	34° 0.639' S	22° 54.339' E
KVS2	P	L	KVS2-P-L	151.901	145.066	34° 0.448' S	22° 54.096' E
	P	M	KVS2-P-M	NA	148.472	34° 0.466' S	22° 54.084' E
	P	H	KVS2-P-H	149.599	149.110	34° 0.471' S	22° 54.081' E
	W	n/a	KVS2-W	150.623	-	34° 0.463' S	22° 54.090' E
VK5	P	n/a	VK5-P	150.213	148.088	34° 0.489' S	22° 53.995' E
	W	n/a	VK5-W	150.220	-	34° 0.489' S	22° 53.995' E
VK6	P	n/a	VK6-P	150.310	147.902	34° 0.569' S	22° 54.006' E
	W	n/a	VK6-W	151.329	-	34° 0.569' S	22° 54.006' E
VK7	P	n/a	VK7-P	150.608	148.231	34° 0.634' S	22° 54.218' E
	W	n/a	VK7-W	150.608	-	34° 0.634' S	22° 54.218' E
VK8	P	n/a	VK8-P	149.660	147.684	34° 0.761' S	22° 54.088' E
	W	n/a	VK8-W	149.671	-	34° 0.761' S	22° 54.088' E
VK9	P	n/a	VK9-P	149.518	143.233	34° 0.545' S	22° 54.057' E
VK10	W	n/a	VK10-W	172.741	-	34° 1.027' S	22° 54.365' E

Table A2. pH, EC, ions and nutrients (in mg L^{-1}).

pipe ID	pH	EC	NO_3^-	Cl^-	SO_4^{2-}	PO_4^{3-}	HCO_3^-	Na^+	K^+	Ca^{2+}	Mg^{2+}	$Fe^{II(III)}$	Si
VK1-P-L	5.49	470	0.18	43.29	1.12	27.25	195.81	28.54	11.01	51.63	8.29	20.09	115.01
VK2-P-L	7.09	490	0.05	71.48	1.01	4.93	183.61	36.24	7.65	58.23	9.50	33.32	107.17
VK2-P-H	7.28	510	1.05	68.00	2.09	2.94	197.64	35.18	5.26	62.40	10.81	1.71	7.49
VK3-P-H	6.75	230	6.27	44.05	0.56	0.49	50.02	26.11	3.95	19.90	8.54	29.82	117.24
VK3-P-L	6.35	160	0.43	22.32	1.03	0.79	56.73	17.05	2.49	11.59	4.86	35.46	70.58
VK4-P-L	5.59	160	0.39	41.23	0.35	0.91	28.67	30.47	1.35	2.59	2.41	5.94	136. 20
VK4-P-H	6.16	140	0.60	28.14	2.90	1.12	29.89	14.10	1.29	10.97	3.88	12.09	37.51
VK5-P	6.20	390	0.07	86.42	1.81	2.29	82.96	23.14	1.39	22.76	9.17	23.19	212.48
VK6-P	6.04	530	0.18	48.81	0.76	1.06	237.90	39.74	13.74	40.51	20.02	56.24	437.82
VK7-P	5.83	120	0.39	24.31	0.45	0.49	27.45	12.52	3.72	11.10	5.00	20.99	106.51
VK8-P	6.26	220	0.13	46.59	0.74	0.82	63.44	19.60	4.92	18.59	5.54	16.78	221.74
VK9-P	6.63	210	0.51	44.89	2.88	6.56	53.68	23.29	3.23	21.77	7.48	11.76	127.75
KVS1-P-L	5.72	130	0.40	31.11	1.21	0.51	25.62	16.76	4.16	10.83	5.17	18.25	138.47
KVS1-P-H	6.22	130	0.15	26.46	0.95	0.53	32.94	16.18	3.97	11.32	5.85	21.48	182.37
KVS2-P-M	5.62	140	0.48	30.30	1.46	0.81	25.62	15.83	4.19	13.02	7.20	19.30	152.37
KVS2-P-H	5.90	140	0.14	22.30	0.65	0.68	47.58	16.89	4.17	14.61	7.26	13.10	88.12
SURFACE	5.19	100	0.16	26.04	0.56	0.97	20.74	14.00	4.48	10.35	4.47	11.62	10.22
GROENVLEI	8.81	3720	4.77	1051.96	146.26	21.13	344.65	640.46	19.83	47.43	94.73	1.09	0.07
GOUKAMA	7.58	29440	101.27	5352.00	1591.62	119.05	122.61	2295.01	251.12	247.72	719.76	1.23	1.74
RAIN	7.14	50	0.23	6.17	1.73	1.02	15.86	6.60	0.90	4.46	1.25	1.09	0.75