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ORIGINAL PAPER

Variation in soil water content and groundwater levels across three land cover types in a floodplain of the Kromme catchment, South Africa

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Abstract Invasions of floodplains and riparian areas by alien woody species replacing predominantly herbaceous indigenous vegetation have altered the hydrological and ecosystem functioning in catchments. Although existing studies have examined changes in river flows following the establishment or clearing of alien woody vegetation, our understanding of impacts on soil water content and groundwater remains poor. Limited process knowledge restricts our capacity to reliably model and predict the impacts of land cover changes. As such, this work compared temporal variations in soil water content (SWC) and groundwater levels at three locations with different vegetation types: black wattle (*Acacia mearnsii*) trees, palmiet (*Prionium serratum*), and grass (dominated by *Pennisetum clandestinum spp*), within a floodplain site in the Kromme Catchment in the Eastern Cape Province of South Africa. Soil water content and shallow groundwater levels ($<$ 4 m below ground) were monitored from August 2017 to December 2019 using soil moisture probes and piezometers. Rainfall, vegetation type and antecedent conditions were identified as the major factors controlling observed responses. On average, soil water content and water retention were significantly higher ($p < 0.05$) at the palmiet site, whilst the wattle site had the lowest SWC among the three sites. Shallow groundwater levels were also higher at the palmiet and grass sites and lowest at the wattle site. Results showed the negative impacts of black wattle trees on SWC and groundwater levels. These results are crucial for improved quantitative predictive capacity which would allow for better catchment management, for example, informing water supply planning and guiding restoration programs focusing on alien plant clearing.

Keywords Palmiet wetland · Grass · Floodplain · Semi-arid · Alien plants · Groundwater · Soil water content

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Introduction

Water scarcity is a global phenomenon that is projected to increase, particularly in arid and semi-arid regions (Boretti and Rosa 2019). Therefore, considerable efforts to improve water supply continue to be made worldwide. Land use and land cover types, their location within a catchment and changes thereof are some of the factors that control and alter hydrological responses of catchments (Awotwi et al. 2015; Berihun et al. 2019). One major issue in many countries is the invasion of riparian zones by alien woody species. Some of the problematic species are willows (*Salix spp*) in Australia, salt cedar (*Tamarix spp*) in America, and the black wattle (*Acacia mearnsii*) in South Africa (Doody et al. 2011; Gwate et al. 2021; Huxman et al. 2005; Rebelo et al. 2015). The Working for Water Programme in South Africa has been clearing invasive alien plant species (IAPs) since 1995 to reduce their adverse effects on water resources (Galatowitsch and Richardson 2005; McConnachie et al. 2012). Woody trees typically use more water than herbaceous plants and seasonally dormant grasses (Calder and Dye 2001; Rossatto et al. 2014). Several studies have quantified reductions in river flows from areas with woody invasive alien plants and/or changes in streamflow patterns after clearing (Doody et al. 2011; Dye and Jarmain 2004; Görgens and Van Wilgen 2004; Le Maitre et al. 2015; Le Maitre et al. 2020; Scott-Shaw et al. 2017; Versfeld and Versfeld 2011; Warburton 2012). Other studies have focused on variations in soil water conditions under different land cover types (She et al. 2010; Yang et al. 2019). However, there are few studies characterizing the dynamic variations in both soil water content and/or groundwater levels in areas with contrasting vegetation types, particularly in semi-arid areas (Albhaisi et al. 2013; Jacobs et al. 2013; Niu et al. 2015).

Characterizing available soil water, offers unique insights into soil water status, depletion and recharge (Hou et al. 2018; Ries et al. 2015). Such knowledge is essential for understanding vegetation impacts on hydrological processes in a catchment particularly during low flow periods. Vegetation alters soil properties such as the organic matter content and soil texture whilst soil water content is controlled by infiltration and evapotranspiration rates among other factors (Dai et al. 2022; Zhu et al. 2022). Consequently, when transpiration rates increase, river levels decrease (Le Maitre et al. 2020). Processes like surface flow and interflow generation may be reduced and groundwater contributions to streamflow may also decline due to increased transpiration rates. Therefore, knowledge of spatial and temporal variations in soil water content and groundwater levels helps to better understand the processes influencing observed streamflow responses. This can lead to improved process modelling and predictive capacity, and ultimately more informed catchment management.

In South Africa, the Australian black wattle predominantly invades riparian areas where water is readily available (Dye and Jarmain 2004) and competes aggressively with the native plants such as grass and palmiet. Black wattle can alter a catchment's hydrological regime and ecosystem function by increasing rates of transpiration, resulting in reduced streamflows (Dye and Jarmain 2004; Galatowitsch and Richardson 2005; Görgens and Van Wilgen 2004; Le Maitre et al. 1999). Field measurements from previous work and estimates of transpiration rates for black wattle ranges from 740 to 1500 mm/year (Clulow et al. 2011; Dye and Jarmain 2004; Meijninger and Jarmain 2014), 600–900 mm/year for grassland (Calder and Dye 2001; Dye and Jarmain 2004), and ~695 mm/year for palmiet (Rebelo 2012a). Therefore, clearing of alien woody species will likely result in an increase in river flows (Le Maitre et al. 2015; Le Maitre et al. 2020) and groundwater levels (Albhaisi et al. 2013; Everson and Kelbe 2019; Moyo et al. 2009; Scanlon et al. 2005).

The impacts of black wattle invasion on soil water dynamics are determined in relation to the fluxes that would occur under the vegetation type it has replaced. In the eastern and southern parts of South Africa, black wattle replaces a range of different vegetation types including the rare palmiet plants (Crous et al. 2019; Railoun 2018). Palmiet is a wetland plant endemic to South Africa, often found in valley bottom areas. It is regarded as an ecosystem engineer due to its extensive, fibrous, and thick root system (can grow up to 2 m) that traps sediment and slows down the velocity of flow during flood events, thereby stabilizing and filling in channels (Rebelo et al. 2015, 2019; Sieben 2012). However, palmiet does not survive competition when invaded by woody species because of its intolerance to full shade from the dense tree cover (Boucher and Withers 2004; Rebelo 2012a). Rebelo (2012) analysed long-term streamflow in the Kromme catchment, as estimated from a downstream reservoir, and found evidence of a decline in the runoff ratio correlating with increased coverage of black wattle replacing palmiet wetlands.

Water use of a vegetation type can vary considerably with its setting (soil, climate conditions, landscape position) and, therefore it can be difficult to compare findings for vegetation types across different individual studies. This work therefore, compared soil water content and groundwater across three different vegetation types all located in the same setting: side by side in a floodplain area where a wattle invasion was partially cleared and adjacent areas where palmiet and grass have re-established on cleared portions in the middle of a meso-scale mountainous catchment. The study compared responses under invasive wattle cover to those under two different veg types (palmiet and grassland) that exist in different parts of the floodplain when not invaded. This was done because no prior studies had observed soil water and groundwater processes in palmiet, wattle, and grass in the same conditions. Furthermore, studying soil water content and groundwater variation under different land cover types in this setting adds to the knowledge and foundation for effective water resource management and ecological restoration in semi-arid floodplain areas where woody alien species have invaded. This is also locally important as the study catchment, the Kromme, is an important water source area, supplying cities, towns, and agricultural areas (Nel et al. 2017; Le Maitre et al. 2018). Knowledge gathered in this work can also be used in other water source catchments in the larger Langkloof region that have similar invaded floodplains.

Materials and methods

Study area

The study was conducted in the Kromme River catchment in the Eastern Cape Province of South Africa (Fig. 1). Rainfall in the Kromme catchment is highly variable with no defined wet or dry season and a mean annual of approximately 600 mm/year (Rebelo et al. 2015). The Kromme has mean annual evaporative demand of approximately 1400–1800 mm/year and average minimum temperatures range from 4 to 16 °C whilst average maximum temperatures fluctuate between 22 °C and 29 °C throughout the year.

The Kromme catchment is made up of a few geologic formations collectively known as the Cape Supergroup which consists of quartzitic sandstones and shale (Rebelo et al. 2015). The Table Mountain Group (TMG) is a dominant formation within the Cape Supergroup (Diamond 2014). The topography in the catchment is extremely variable and altitude ranges from 1500 m.a.s.l to sea level over a distance of approximately 100 km. The Kromme comprises both steep areas and floodplains with significant alluvial deposits and alluvial aquifers.

The dominant vegetation type in the catchment is fynbos, found on mountainous areas and high plateaus (Mander et al., 2010; Mucina and Rutherford, 2006). Thickets of indigenous trees occupy small sections in the lower mountain slopes, narrow mountain kloofs and riparian areas where nutrient rich soils occur (Mucina and Rutherford, 2006). Other areas have shale renosterveld, grassland and forest (Mucina and Rutherford, 2006). Furthermore, the Kromme supports large permanent wetlands which are dominated by palmiet (*Prionium serratum*) with smaller patches of reeds, sedges, grasses, and ferns (Haigh, et al., 2002). Land uses in the catchment consist of intensive fruit, vegetable, and livestock farming including irrigated pasture for dairy cattle (Rebelo 2012b).

Land cover conversion in the catchment has mostly been floodplain cultivation as well as the growth of dense stands of invasive trees, predominantly in riparian areas (Mander et al., 2010; Rebelo, 2012). Dominant invasive alien trees in the catchment are black wattle (*Acacia mearnsii*) and pines (*Pinus pinaster*). The Working for Water Programme cleared IAPs in riparian zones in the catchment from upstream to downstream of the Kromme River. However, clearing of (IAPs) in the entire catchment was not completed. The work stopped at the Willowvale site, with the floodplain area to the west of a road crossing having been cleared in 2014 and the area to the east retaining solid black wattle cover (Fig. 1). The Willowvale site therefore presented an opportunity to monitor soil water content and shallow groundwater across multiple vegetation types in close spatial proximity to one another: a dense wattle stand and the palmiet and grassland that recovered after black wattle clearing. The different sub-sites can be assumed to experience similar rainfall and temperature as well as adjacent streamflow and groundwater inputs from the upper catchment and surrounding mountains due to their close proximity (approximately 150 m apart) (Fig. 1).

Monitoring and data collection procedures

Soil water content and shallow groundwater levels (<4 m) were monitored from August 2017 and is

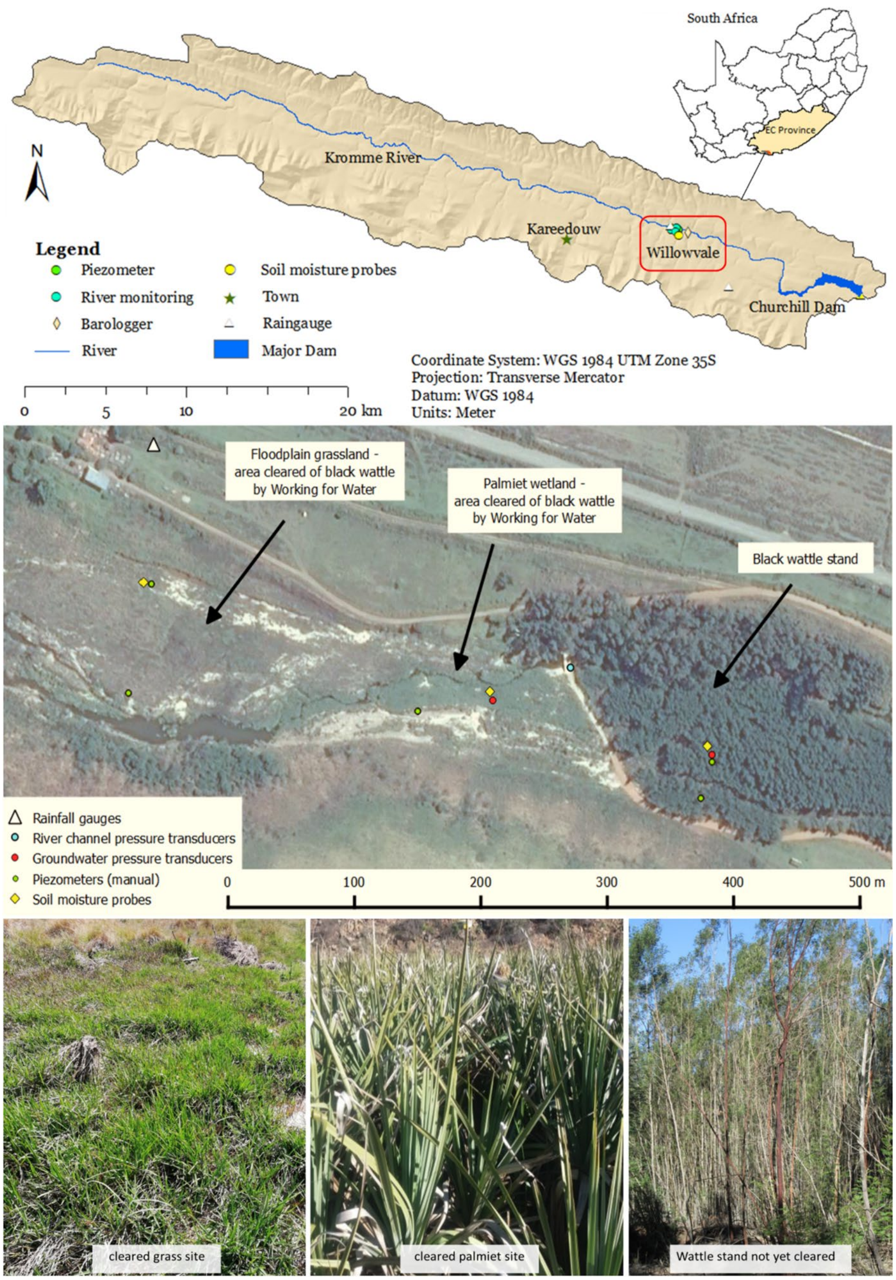

Fig. 1 Location of the study area and monitoring locations across the three vegetation types

still ongoing as part of South African Environmental Observation Network (SAEON) long term observations, but results presented here are from August 2017 to December 2019. To monitor variation in shallow groundwater levels, piezometers (PZ) were installed at the wattle, palmiet, and grass sites (Fig. 1). Two piezometers were installed at the wattle site (1.6 and 3.1 m depths) approximately 50 m apart. One piezometer was installed at the palmiet site (2.6 m). At the grass site, two piezometers (1.9 and 3.1 m) were installed approximately 100 m apart. Table 1 shows piezometer depths and elevations (m.a.s.l). The layout of piezometers was intended to give information regarding groundwater gradient across and down the floodplain. Two piezometers, one at the wattle site and one at the palmiet site, were equipped with pressure transducers (Solinst Levellogger) logging at 30 min intervals. Piezometers were augured to a depth

Table 1 Piezometer depths and mean elevations above sea level

Piezometer name	Site	Piezometer depth (m)	Surface elevation (m.a.s.l)	Bottom elevation (m.a.s.l)
WT PZ1	Wattle	3.1	179.2	176.1
WT PZ3	Wattle	1.6	178.2	176.6
PM PZ4	Palmiet	2.6	180.5	177.9
GS PZ6	Grass	2.0	181.2	179.3
GS PZ7	Grass	3.2	181.6	178.4

WT Wattle, *PM* Palmiet, *GS* Grass and *PZ* Piezometer

of refusal which was due to either reaching rock or a layer of dry, unconsolidated sand (repeated collapsing of soil inside the augured hole). Water levels in the river at a site between the palmiet and wattle monitoring points were also measured using a Solinst Levellogger logging at 30 min intervals to compare variations between the groundwater and surface water levels.

To investigate changes in soil water content, capacitance probes (DFM Technologies), were used which measure soil water content as a percentage of saturation. The probes were installed 2 m away from piezometers in the wattle, palmiet and grass sites (Fig. 1). The probes have six sensors at 100 mm intervals to a depth of 600 mm. Soil samples were collected at each horizon where piezometers were installed for texture and particle size analysis using standard sieving and sedimentation methods. Event-based rainfall was measured using a Davis tipping bucket rain gauge (calibrated to 0.2 mm) which was installed in the floodplain, approximately 100 m from the grass piezometer. Temperature was recorded hourly by a HOBO temperature-event logger at the rain gauge. Field visits were done every 2–3 months to download data and conduct manual sampling.

Data analysis

Calendar days were used to classify rainfall events and analyse responses over longer time periods (weeks, months, and seasons). For selected events, rainfall and responses were analysed over shorter time periods (<48 h) at an hourly timestep. In this case, the rainfall event was defined from the hour it started raining until the hour the rain stopped, without regard to a change in calendar date. Classes of daily rainfall event sizes used to assess soil water content and groundwater responses are presented in Table 2.

Table 2 Rainfall event size classification

	Event size (mm/day)
Light	<9.99
Moderate	10–19.99
Heavy	20–39.99
Very heavy	>40

Soil water content (SWC) responses at each depth were calculated using Eq. 1

$$\Delta SWC_{d,t} = SWC_{d,t} - SWC_{d,t-1} \quad (1)$$

$SWC_{d,\ t}$ is soil water content in percent saturation at depth *d*, for timestep *t* and $\Delta SWC_{d,\ t}$ is the change in soil water content between timestep t-1 and timestep t.

A notable SWC response in this work is defined as an increase in SWC of 10% (of saturation) or more over a 24 h period. For selected events, hourly time-series of SWC were analysed to better understand response patterns at smaller timescales. All increments of change described in the results are given as magnitude changes in units of percent of saturation (the unit measured by the probes). These percentage values do not refer to proportional changes (i.e. they are not values of change as a percent of the previous value). Large events in which the river flooded the monitoring points could be identified from the piezometer pressure transducer water level logs and this additional input was considered when interpreting the SWC responses.

To get insights on water retention with depth, exceedance probability percentages were calculated for each observed depth across the three sites to show the amount of time in which soil water content values were equalled or exceeded. Descriptive statistics were used to provide a quantitative summary of soil water content at the three sites. Analysis of variance (ANOVA) was used to test the influence of different vegetation types on mean soil water content (averaged over the 60 cm depth) over the sampled period, applying a threshold of $p < 0.05$ to determine statistical significance. Paired sample t-tests were performed to check for differences between means for vegetation type pairs. Furthermore, mean values of all data for each season during the monitoring period were calculated for each site (grass, palmiet and wattle). Seasons were split into: summer (December, January and February), autumn (March, April and May), winter (June, July and August) and spring (September, October and November).

Table 3 Soil textural classes by layer for the **a** wattle, **b** palmiet and **c** grass sites

Site	Depth (cm)	Sand (%)	Silt (%)	Clay (%)	Texture class
Wattle	0–20	89	6	5	Sand
	21–100	89	6	5	Sand
	101–160	87	8	5	Loamy sand
Grass	0–20	89	6	5	Sand
	21–70	83	10	7	Loamy sand
	71–180	87	6	7	Loamy sand
Palmiet	0–20	89	6	5	Sand
	21–160	89	6	5	Sand
	161–240	89	6	5	Sand

Results

Soil texture

The soil texture analyses showed that the three sites (grass, palmiet, wattle) have very similar, sandy soils. At all three sites (Table 3), soils are generally sands to loamy sands (83–89% sand, 6–10% silt and 5–7% clay). The horizons where soil moisture probes were installed (0–60 cm) were sandy across the three sites. Given the soils were generally sandy across the three sites; differences in soil water content between the sites can largely be attributed to the differences in vegetation cover.

Rainfall variation at Willowvale from 2017 to 2019

The distribution of rain events was characterised by many light to medium events and a few heavy events in the catchment (Fig. 2). Prolonged dry periods were experienced between May and July 2017. The wetter periods were in September to November 2018 after the high intensity rainfall events on the 07 and 08 September 2018 (134 mm total) and 12–14 November 2019 (62 mm total). Some events corresponded with surface flow peaks, and others resulted in both surface flow peaks and full inundation of the sites and notable groundwater table responses in the floodplain. The total amount of rainfall received at Willowvale site in 2017, 2018 and 2019 was 451, 555 and 416 mm/year respectively. The catchment was monitored during a relatively dry period except for the observed large

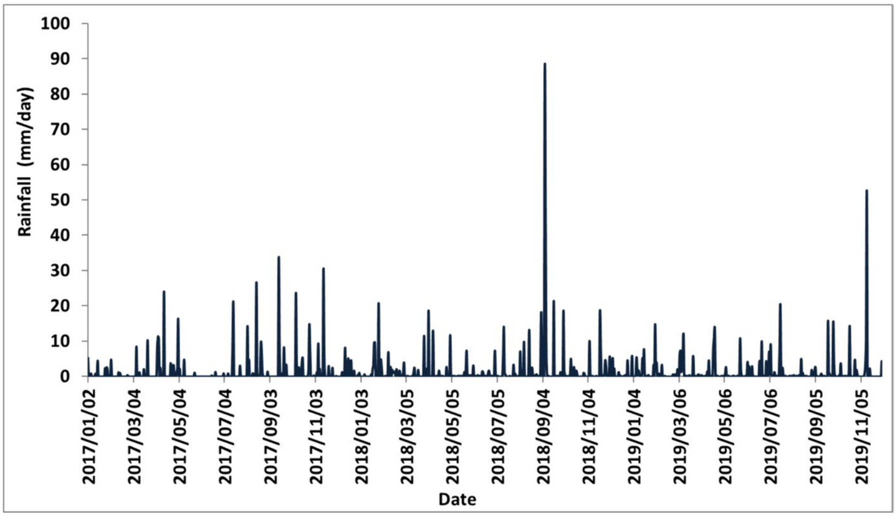

Fig. 2 Observed rainfall for the 2017–2019 period

September 2018 and November 2019 storms which triggered pronounced soil water and hydrometric responses (Fig. 2).

Water table responses in areas dominated by grass, palmiet and wattle vegetation types

Shallow groundwater levels showed notable differences across the three sites (Fig. 3). Important to note is that when monitoring began in April 2017, the water table was below all installed piezometer depths (depths varied from 1.6 to 3.2 m below ground).

The water table was found to be deeper below ground under the wattle than under either grass or palmiet, except during the largest storms. At the grassland sites, the water table was 2–3 m below ground for much of the sampling period only rising above 2 m after storm events (Fig. 3). At the palmiet site, water table depths typically ranged between 2.1 and 2.5 m below the ground surface from April 2017 to December 2019 except during and after large storm events. At the wattle site, the water table was below 3.2 m depth, (the installed piezometers at this site were dry for most of the monitoring period) (Fig. 3). The water table rose to within 2 m of the ground following the September 2018 rainstorm of 134 mm in 48 h, 28 mm in November 2018 and 62 mm in November 2019.

The major rainfall events in summer 2018 as well as across all seasons in 2019 showed notable peaks in groundwater levels, as detected by the pressure transducers at both the palmiet and wattle sites

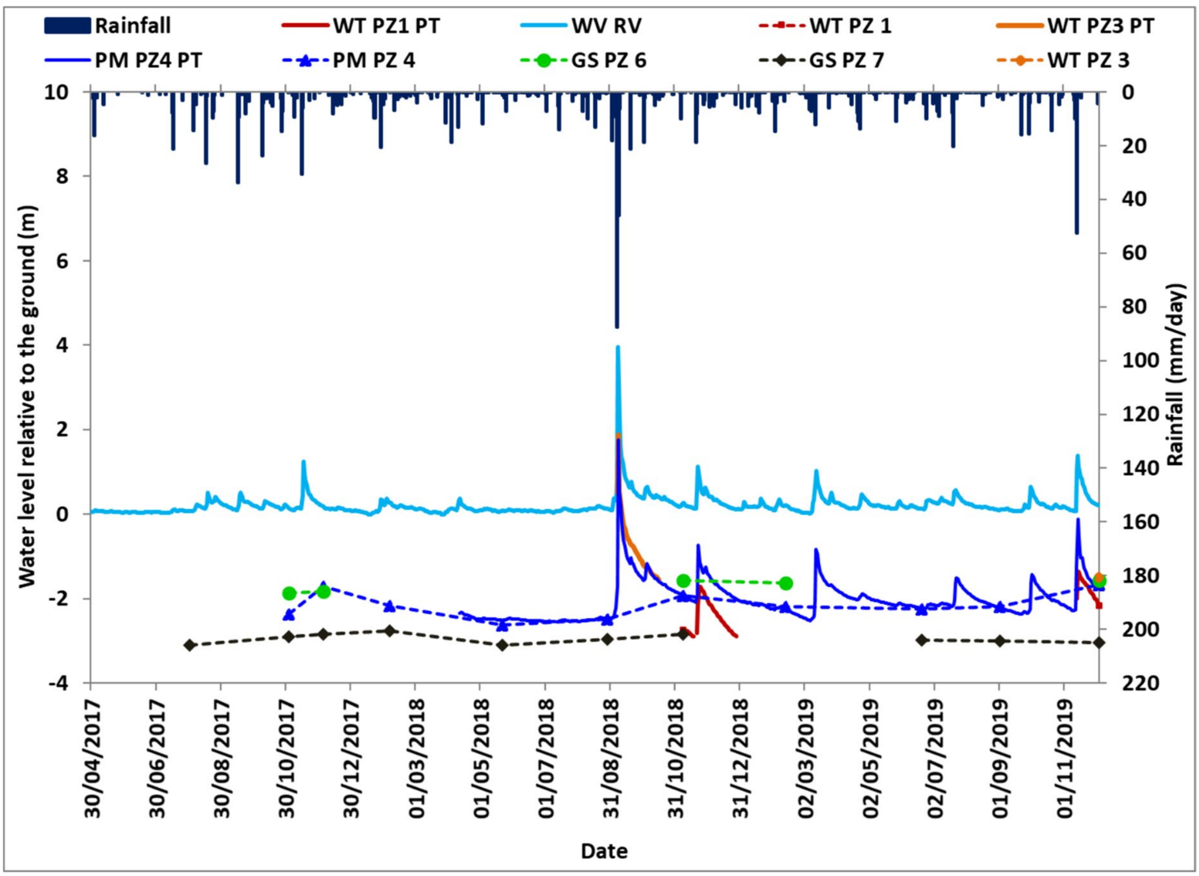

Fig. 3 Observed variation in water table depths from piezometers (PZ) at grass (GS), palmiet (PM) and wattle (WT) sites. WV RV is the observed water level in the river at Willowvale relative to the channel thalweg. Solid lines represent continuous data measured with pressure transducers (PT), whilst dotted lines are only for visualisation purposes for manual dip meter measurements taken during field trips. A missing manual measurement data point for a site when other sites have data indicates that the water level was below the bottom depth of the piezometer

(which coincided with river peaks (Fig. 3). The palmiet and wattle time series records were used to analyse floodplain groundwater response to the September 2018 event. After 62 mm of rainfall in 19 h, the water table rose from 2.2 m below ground level (m.b.g.l.) to 2.08 (m.b.g.l.) at the palmiet site showing an increase of 0.12 m. The water table at the wattle site rose to 1.9 m.b.g.l. All wattle piezometers were dry before the onset of this event, the deepest of which was 3 m.b.g.l. In the 20th hour since the onset of the event, after 54 mm of rainfall, the water level measured by the pressure transducer rose from 2.08 (m.b.g.l.) to 0.5 m above the ground level (m.a.g.l.) in one hour indicating inundation. This inundation was not a function of the vegetation or soil types but overland flow/flooding from the river inundating the site. The water level reached a maximum of 2.5 m above the ground. The overland flow lasted for at least 80 h (more than 3 days) at the palmiet and wattle sites. Sharp decreases were observed over four to five days after the storm for both the wattle and palmiet sites shown by steep receding slopes (Fig. 3). After the storm event, the water table remained at relatively higher levels than observed prior to the September 2018 rainstorm at the palmiet site. At the wattle site, the water table dropped to levels below the installed piezometer depths, as it had been prior to the event, so it is not known if the water table remained elevated compared to its pre-event level or not. In general, the groundwater table at this floodplain site only rose significantly across the area following the September 2018 and November 2019 rainstorms (Fig. 3).

Spatio-temporal variations of soil water content under three contrasting vegetation types

Notable differences were observed in soil water content responses to rainfall at different depths among the black wattle, palmiet and grassland sites. Marked fluctuations of soil water content were observed in response to rainfall events of ≥ 10 mm/day in general across all sites (Fig. 4).

Soil water content responses varied with depth at the grass site. Notable responses to some light events were only observed in shallow soils (0–20 cm); however, for some heavy events (> 20 mm/day), deeper soils responded more than shallow layers (Fig. 4). Deeper soils had larger soil water content changes compared to the shallow soils for some rainfall events i.e. on the 16th of August 2017 and 20th of July 2019, after events of 26 and 20 mm/day respectively. In general, soils between 40 and 60 cm had high SWC increases (> 15% saturation) whilst 20–30 cm had less than 2% saturation increase. This could have been due to a rise in the alluvial aquifer water table recharged by subsurface flow generated further up or around the contributing catchment, such that the lower soil layers at this site were influenced by the capillary fringe. For most rainfall events greater than 30 mm/day, SWC at all depths increased significantly (> 10% proportional increase) except for the soils at 30 cm depth which seldom responded at this grass site due to active root water uptake at this depth by *Pennisetum clandestinum* (Kikuyu) grass.

At the palmiet site, only shallow soils (0–10 cm) were responsive to light rainfall events (< 10 mm/day) for most of the observation period. Notable soil water content changes were observed down the profile at 10–30 cm soil layers in response to moderate rainfall events (Fig. 4). For some events, i.e. after an event of 19 mm on the 20th of November 2018, the 40, 50 and 60 cm soils had the most significant change in water content (increases in % saturation of 25, 73 and 74% respectively). In general, the soils at 50 and 60 cm depths had higher SWC compared to the soils and 30 and 40 cm suggesting close proximity to the capillary fringe or lateral contributions in the deeper layers.

Soil water content responses at the wattle site varied greatly with responses observed at the grass and palmiet sites. Pronounced changes were observed at 10–20 cm soils following some light events at the wattle site (Fig. 4). For most moderate to heavy rainfall events, notable soil water content responses were also observed in the 20–30 cm soil layers particularly in 2017 (i.e. 33.8 mm and 23 mm on 15 September and 8 October respectively). In the early part of the observation period, the 40–60 cm soils only responded to events over 10 mm/day (Fig. 4). After the September 2018 storm (134 mm in 48 h), the SWC in these deep layers did rise and then maintained a constant elevated water content through 2019, only showing notable responses to rainfall events greater than 20 mm/day. This could be the field capacity for this layer (between 15 and 25% saturation) and/or there is enough water in other layers such that the ET demand does not deplete soil water in this layer over time. Events of 25 mm/day or more resulted in full profile response likely indicating local recharge particularly

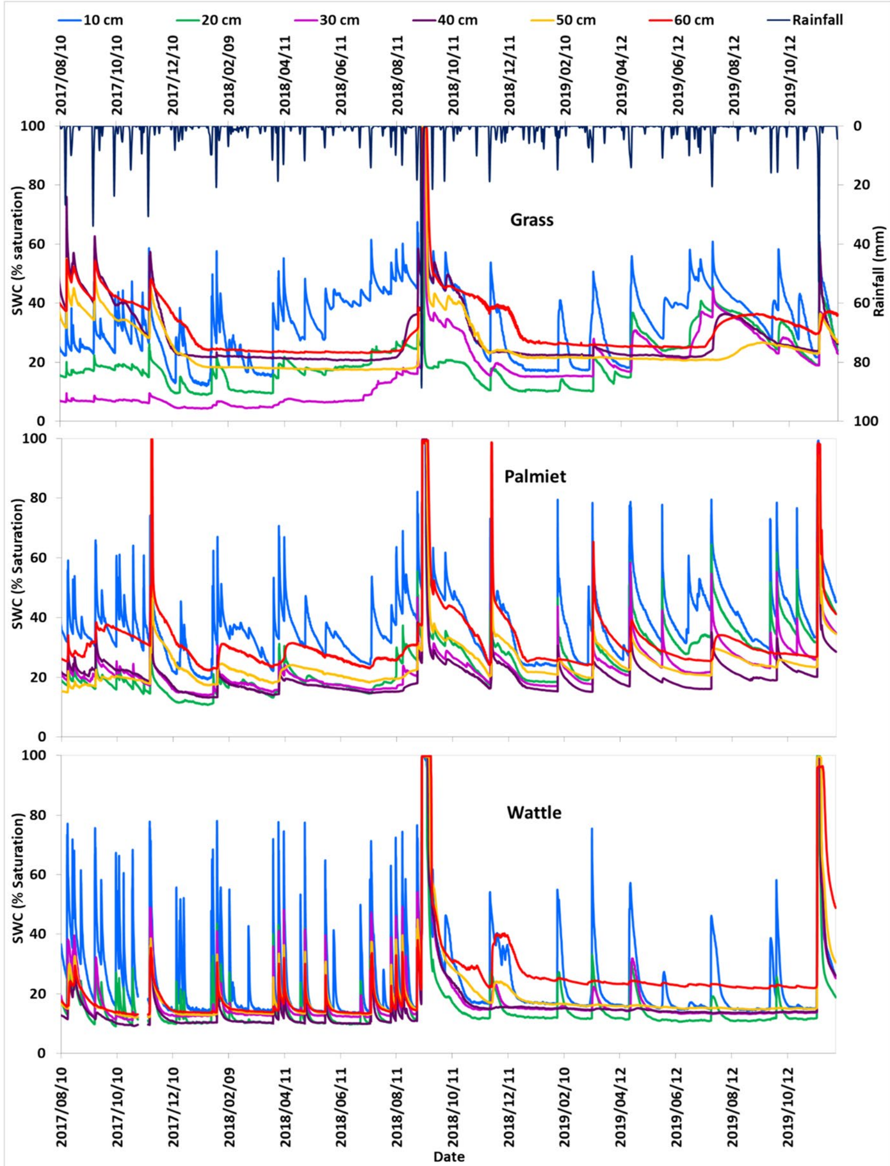

Fig. 4 Observed temporal variation of soil water content under grass, palmiet and wattle from August 2017 to December 2019. 10 to 60 cm show SWC at the respective depths

when the 60 cm depth water content stayed elevated (at 25% saturation on average) assuming that the groundwater table was close enough to impact the capillary fringe which is also shown by peak responses in groundwater levels (Fig. 3). In the second half of the time series, after the large September 2018 rain event and groundwater table rise, the wattle soils became much less responsive to events of up to 20 mm/day than they had been before. This was not seen at the palmiet site and was seen to a far lesser degree at the grass site (Fig. 3). Some of the larger rain events early in the observation period caused a quick responses and peaks in the deeper soils at the same time as the peaks in the shallower layers due to streamflow pulses or a quick wetting front.

Comparison of the advance of the wetting front in response to moderate and heavy storm events

Moderate events which occurred on 20–21 November 2018 (26 mm) and on 19–20 July 2019 (28 mm) (Fig. 5) and heavy storm events which occurred 7–8 September 2018 (134 mm) and the 12–13 November 2019 (62 mm) (Fig. 6), were used to analyse the

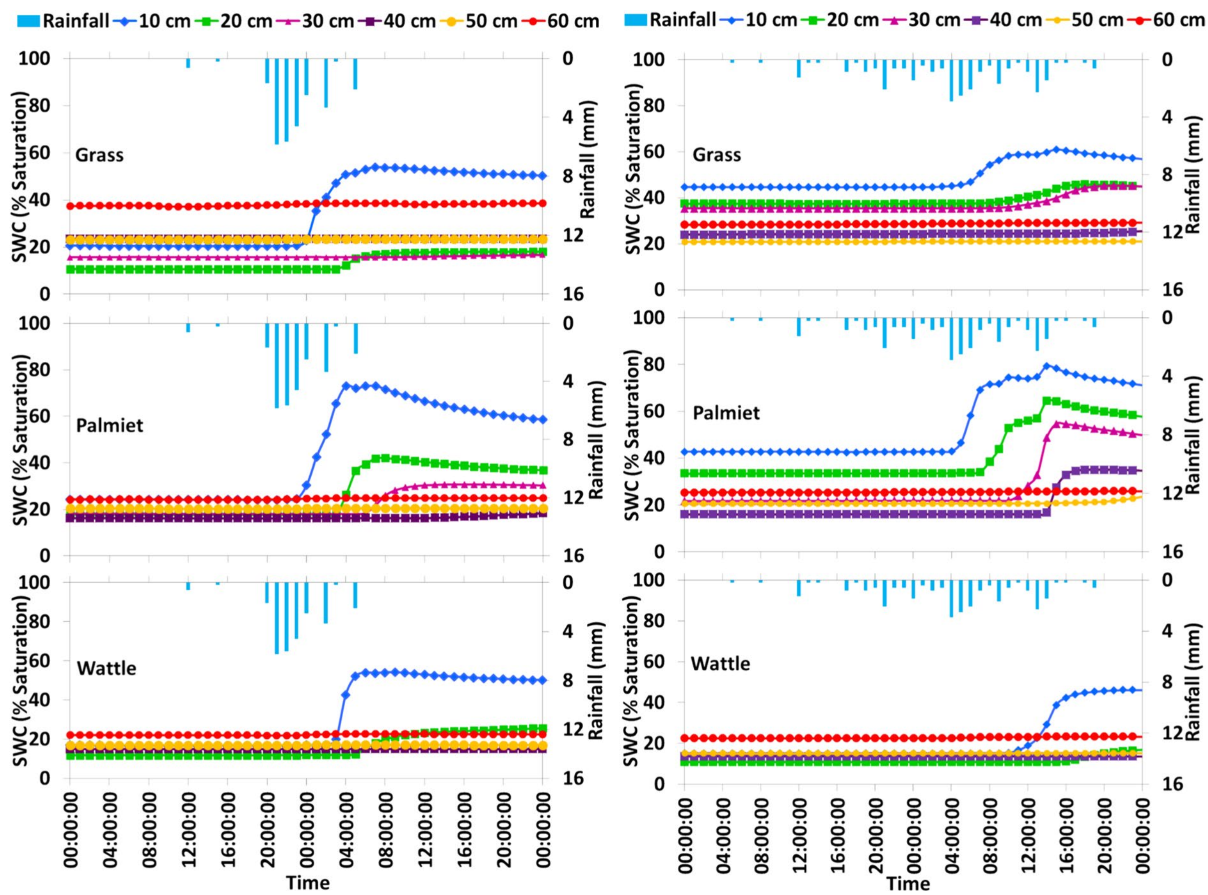

Fig. 5 Hourly soil water content at 10–60 cm depths over 48 h periods with moderate rainfall events, 26 mm on 20–21/11/2018 (left) and 28 mm on 19–20/07/2019 (right)

advance of the wetting front. Larger SWC increase and deeper percolation was observed in the palmiet compared to the other vegetation types in response to the moderate events (Fig. 5). Antecedent moisture tended to be higher in the palmiet which would contribute to percolation to deeper layers. After the July 2019 event, marked SWC responses were also observed at the palmiet site, with the 10–40 cm soils responding and a small and delayed increase at 50 cm soils (Fig. 5). At the grass site, SWC responses were observed in the 10–30 cm soils (Fig. 5). At the wattle site, only the shallow 10 cm soils showed a marked response whilst the underlying 20 cm soils showed a small and delayed response (Fig. 5). For these two moderate events, the data shows water moving down the profile but generally not reaching depths beyond 30 cm (Fig. 5). The higher antecedent wetness in the July 2019 event likely contributed to the depth reached by the wetting front compared to November 2018. Results suggest larger rainfall events would be needed for percolation to the deeper layers.

During the September 2018 storm event, the wetting front took approximately 5 h from the onset of precipitation, amounting to 5 mm of cumulative rainfall, to reach the 10 cm sensor across all three sites (Fig. 6). As the storm continued, the profiles reached saturation 23 h after the onset of the rainfall, after 89 mm of cumulative rainfall. The data shows the downward progression of the wetting front. However, at the palmiet and wattle sites, the deeper 60 cm soils reached saturation before some of the upper layers (Fig. 6). This suggests the floodplain groundwater, recharged by lateral subsurface flows, rose and saturated the deeper soils before the wetting front reached that soil layer. All soils reached and maintained

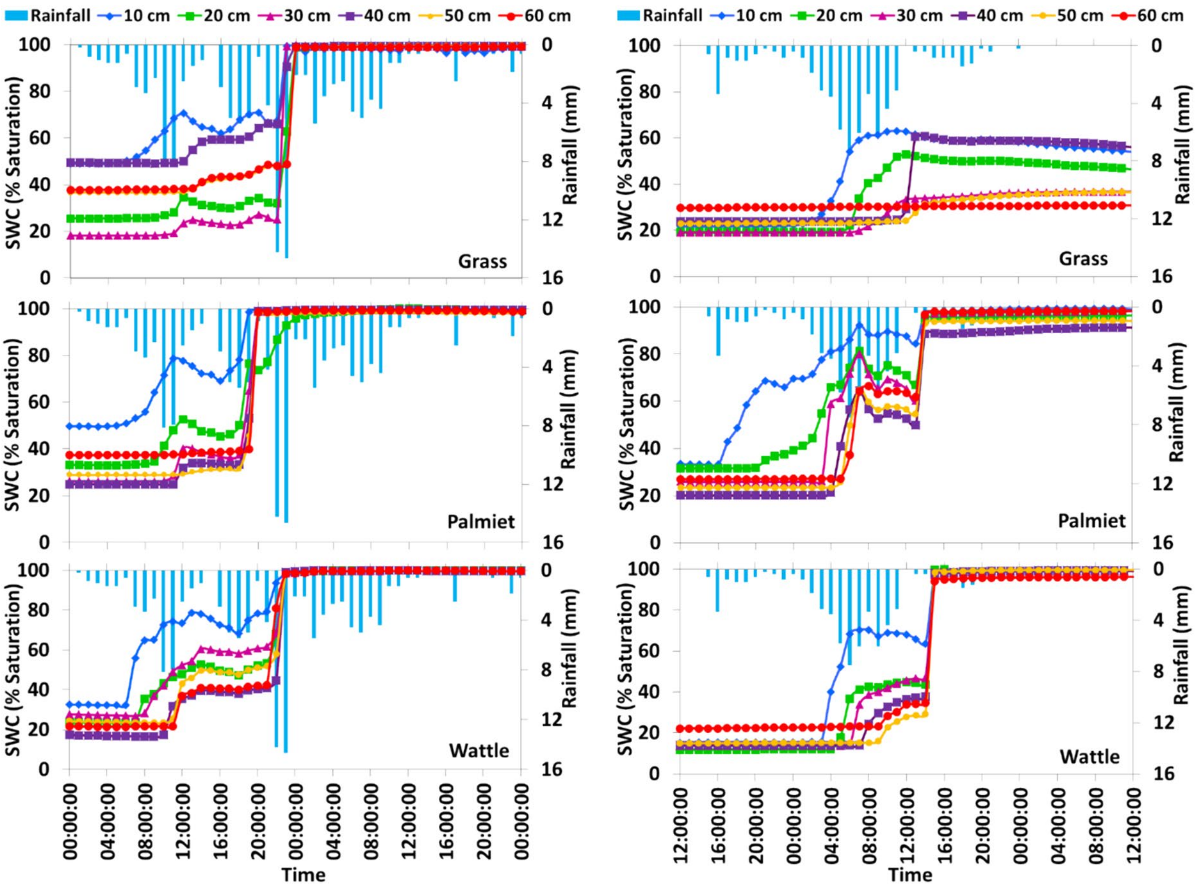

Fig. 6 Soil water content responses to storm events on 07–08 September 2018 (134 mm) (left) and 12–13 November 2019 (62 mm) (right) at Willowvale site. 10 to 60 cm show SWC at the respective depths

saturation for several days across the three sites which was due to overbank flooding shown by high river stage (Fig. 3).

In response to the 62 mm storm event on the 12th to the 13th of November 2019 (Fig. 6), the palmiet site responded within three hours from the onset of the rainfall and 4 mm of cumulative rainfall. The wetting front at the grass and wattle sites progressed much slower (Fig. 6). Grass and wattle sites had lower antecedent soil water content in the upper profile compared to soils at the palmiet wetland which would contribute to the delay. At the grass site, soils at 60 cm showed less than 1% saturation increase. At the palmiet site, SWC at all measured depths responded significantly within 6–18 h, reaching SWC values of 40–85%. The wattle and palmiet soils reached saturation 11 h from the onset of the rainfall event but the soils at the grassland site did not reach saturation in response to this storm event (Fig. 6). The saturation at the palmiet and wattle sites was linked to alluvial aquifer rise as shown by in Fig. 3. At the palmiet site, the shallow groundwater level rose to 11 cm below the ground surface. The soil water content had actually started declining at most depths and sites, before the sharp increase to saturation at the palmiet and wattle sites. There was very little rain by this time therefore, river and alluvial aquifer contributions could be probable factors associated with this final increase.

Seasonal variations in soil water content with depth at the different sites

Distinct seasonal variation in patterns of soil water content for the sampling period were observed across the three sites (Fig. 7). Given the lack of rainfall

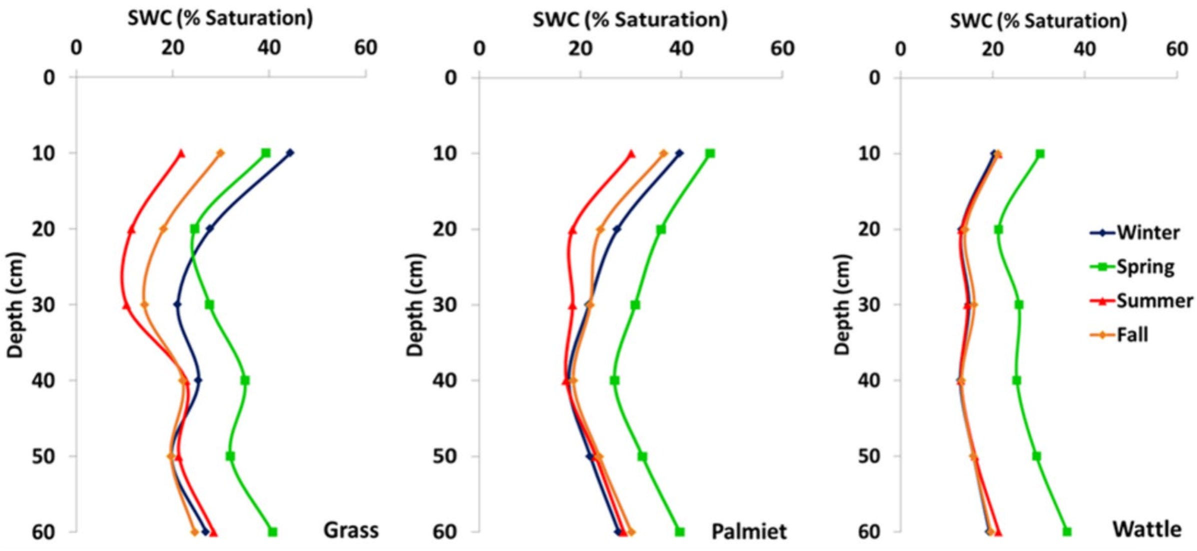

Fig. 7 Seasonal variations in soil water content at the grass, palmiet and wattle sites

seasonality and the high inter-annual variability, different patterns may be observed in a longer term average. The lowest SWC values were observed in summer at all sites. At the wattle site, no notable differences were observed between the average SWC profiles for winter, summer and fall of the sampling period (Fig. 7). At the palmiet site, there were no significant differences in SWC averages for the deep (40–60 cm) soil layers across these three seasons. During summer and spring, 0–40 cm soils at the palmiet site had higher average SWC compared to the grass site, but the deep (50–60 cm) soils had relatively similar SWC at the two sites (Fig. 7). The highest water contents were observed across all sites in spring due to the large September 2018 event.

Frequency analysis of soil water content at the three sites

Exceedance probability curves for the observed soil water content showed significant differences in soil water retention capacity among the three sites under different vegetation communities (Fig. 8). Each exceedance curve shows the frequency of different soil water content levels at each depth per site during the sampled period (August 2017–December 2019). The distribution of soil water content across the sampling period was a result of multiple factors; rain events (assumed to be the same at all sites), canopy interception (assumed to be different across all sites), infiltration and percolation rates, ET rates, and the depth of the water table, and capillary fringe. The amount available to infiltrate was assumed to differ due to canopy interception. ET rates were assumed to differ across all sites with an expected difference in the distribution of withdrawals with depth.

All three sites exceeded or equalled 100% saturation for less than 2% of the sampled period (Fig. 8). This was obtained after an 88 mm/day storm in September 2018. The wetting pattern suggested that the whole floodplain became flooded with water flowing from upstream of the river which is also shown by river stage of up to 4 m above ground (Fig. 3). The 50% exceedance SWC value for the shallow soils was approximately 40% saturation at the grass and palmiet, while it was much lower, under 20% saturation, at the wattle site (Fig. 8). This could be an indication that the wattle trees were intercepting more water thereby reducing the amount infiltrating, and/or were drawing the soil water below field capacity more quickly and more regularly at 10–20 cm depths than the other vegetation types. No significant variation was shown for the deeper soils' 50% exceedance SWC between grass and palmiet. Intermediate soils (30–40 cm), however showed relatively similar 50% exceedance SWC

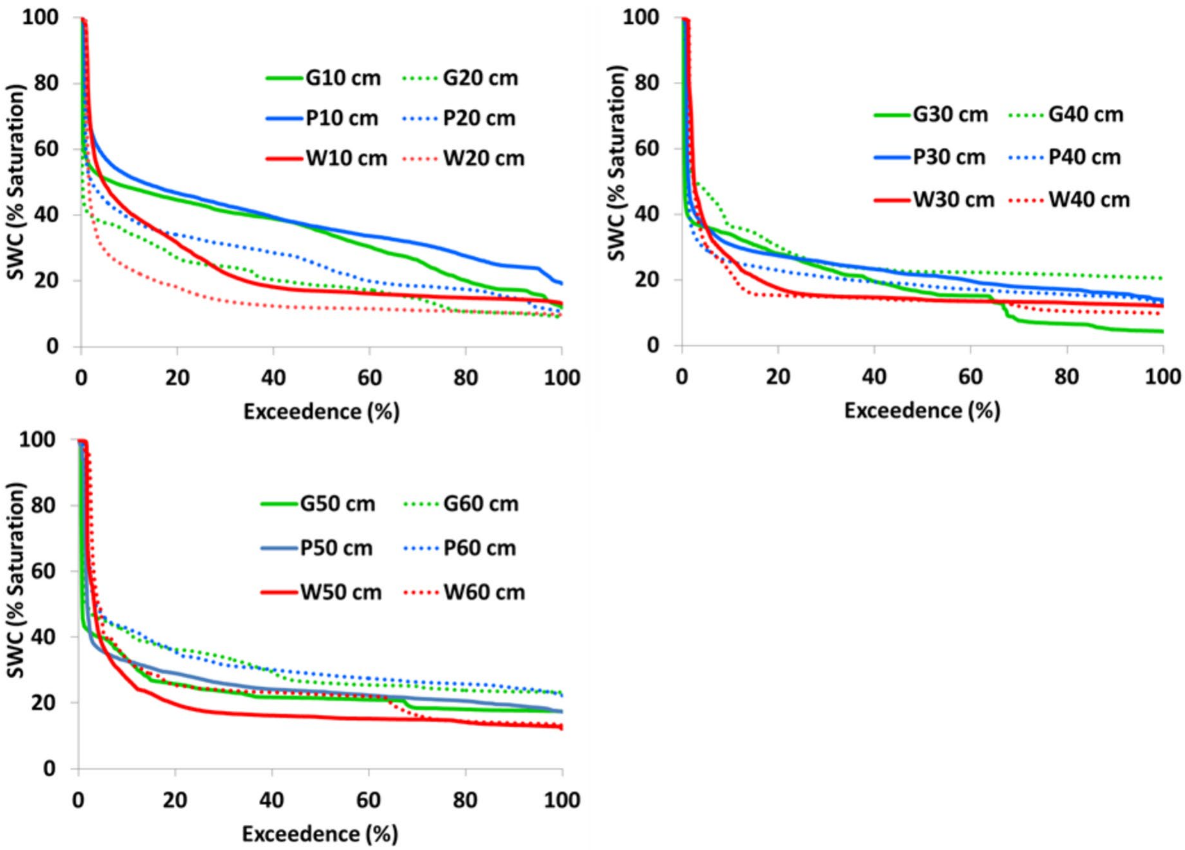

Fig. 8 Soil water content exceedance probability for shallow (10–20 cm) intermediate (30–40 cm) and deeper (50–60 cm) layers at the grass (G), palmiet (P) and wattle (W) sites

for wattle and grass, while the palmiet was higher (Fig. 8).

Overall mean soil water content over the monitoring period

The mean soil water content over the full 60 cm profile for the sampled period is shown for each site in Fig. 9. The palmiet site had the highest profile SWC values ranging from 20 to 38% saturation with an average of 27%. The grass site had a profile SWC range of 16–33% saturation and an average of 25%. The wattle site had the lowest profile SWC values and the least variation over the period, with values ranging from 15 to 24% and an average of 19%. Paired t-tests comparing the series of profile SWC

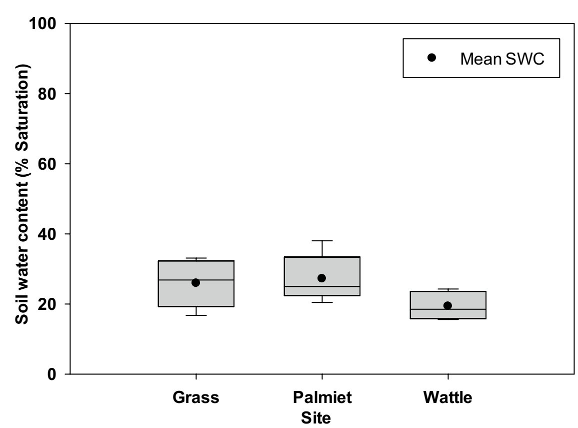

Fig. 9 Variation in full profile (0–60 cm) mean soil water content across the three sites

values across the sites showed that the palmiet site had a significantly ($p < 0.05$) higher water content than the wattle site.

Discussion

The study described variability in water table responses under the three contrasting vegetation types, and facilitated the description of subsurface flow regime at the floodplain site. The land cover types at the study site were observed to influence soil water content and shallow groundwater dynamics. Similar to other studies in semi-arid environments, the magnitudes soil water content changes varied depending on differences in magnitudes of precipitation events, antecedent conditions (Gao et al. 2014), duration of dry interval preceding each rainfall event (He et al. 2012; Heisler-White et al. 2008; Wilcox 2010), and vegetation cover type (Niu et al. 2015; Wang et al. 2013; Yang et al. 2019). Variation of groundwater levels were also influenced by land cover types, similar to the findings of other studies (Mohan et al., 2017; Muriuki et al. 2023), These studies showed that changes in land use and land cover had significant impacts on water balance components such as groundwater levels and recharge.

Effective rainfall for the replenishment of soil water content

The observed results suggested that events greater than 30 mm/day played a key role in increasing soil water storage at all sites. Similar to other semi-arid landscapes, precipitation (light to medium rainfall events) was the main source of replenishment in the shallow soils (0–20 cm) however, recharge and storage in deeper 50–60 cm soils required continuous rainfall (high antecedent soil water) or heavy rainfall (Berihun et al. 2019; Hou et al. 2018; Yang and Shang 2012). This has also been shown in other studies where smaller events merely caused fluctuations in the topsoil due to wetting and drying by evaporation (Berihun et al. 2019; Heisler-White et al. 2008). Events equal or greater than 25 mm/day were needed to get through canopy and litter interception and for a wetting front to move down the profile to the deep 60 cm soil layers. Furthermore, periods of dry spells also affected recharge of soils at greater depths as more precipitation was required to replenish the soils (Niu et al. 2015). Similar observations were made by He et al. (2012) in the Qilian Mountains in northern China where soils at 50–60 cm depths were effectively recharged by continuous (increasing antecedent conditions) and/or larger amounts of precipitation.

Variation in soil water content and infiltration among land cover types

Soil water content responses varied across sites due to the different vegetation types. At the grassland site, on average, the water table at this site was approximately ≥ 1.8 m below ground surface or lower when the 40–60 cm soils had relatively constant values therefore the capillary fringe could not have influenced the soil water content during these periods. Soils at 30 cm depth seldom responded at this grass site. The site is dominated by *Pennisetum clandestinum* (Kikuyu) grass with root depths between 20 and 40 cm (Heuzé et al., 2015), therefore the lower SWC and small responses at 30 cm may be attributed to active root water uptake at this depth. At the palmiet site, soil water content responses were highly dynamic with depth. The soils at 60 cm show high soil water content which rose during the sampling period from August 2017 to December 2019. This was attributed to increased local recharge shown by the wetting front moving down the profile to deep layers in response to most rainfall events compared to the grass and wattle sites. Palmiet plants promote recharge due to their fibrous root system (Rebelo et al. 2015). Regeneration of palmiet after wattle clearing may, therefore, be dependent on groundwater levels. The root systems influences the movement of water down the profile probably through the creation of preferential flowpaths from the root structures (Wahren et al. 2009). Pronounced fluctuations at the palmiet site were not as quick as the wattle site as there was a lag in responses after rainfall events and water content decline after peak responses was gradual. Soil water content gradually increased at deeper layers and in some cases without direct rainfall inputs which could have been an indication of localized contributions from subsurface soil water or capillary rise. Another potential factor was the general rise of the water table in the alluvial aquifer in response to rainfall events and subsurface inputs at the floodplain margin and main river bed. Palmiet traps sediment and reduces water velocity in channels due to the clonal nature of its extensive root system (Job, 2014; Rebelo et al. 2015), therefore, subsurface water was retained for longer periods in palmiet dominated areas and recharge of deeper soil horizons was promoted (Crous et al. 2019; Railoun 2018; Rebelo et al. 2019; Sieben 2012). These results highlight the importance of the indigenous herbaceous palmiet plants in promoting groundwater recharge through its fibrous root system (Rebelo 2012a). At the wattle site, the responses of soil water content after rainfall events were quick (reaching peak water content in one or two hours on average after the onset of events). The wattle site had sharp soil water content decrease after peak responses resulting in the least water retention across the three sites. This was an indication of rapid water use by the black wattle trees. Wattles have coarse and shallow roots that may influence preferential flow (Wahren et al. 2009) hence the sharp peaks after rainfall events and wattles are also capable of accessing soil water in both shallow and deep soils depending on its accessibility.

Seasonal patterns in soil water content for the different vegetation cover types showed notable differences in soil water content between spring and other seasons across all sites. All the large storm events occurred in spring thereby increasing the mean soil water content at all sites compared to other seasons. All sites had low mean soil water content in summer, compared to spring and winter indicating the importance of ET in summer (drying out soils and lowering water tables) such that little recharge occurs. Water levels under wattle vegetation cover remained below piezometer depths only to respond to high intensity events (> 40 mm/day). In areas without black wattle trees (palmiet and grassland), shallow groundwater levels remained within 2 m of the ground surface for prolonged periods. A possible explanation was the difference in root distribution and evapotranspiration rates of the different vegetation types (Li et al. 2017), particularly due to greater transpiration by the wattle trees as reported by other studies (Bulcock and Jewitt 2012; Clulow et al. 2011; Dye and Jarmain 2004). Soils at the black wattle site were drier and the alluvial groundwater table was also lower at this site as expected given differences in transpiration rates for these species measured elsewhere in the literature (i.e. Calder and Dye 2001; Doody et al. 2011; Le Maitre et al. 2015; Rebelo, 2012).

Implications for soil and water conservation in semi-arid landscapes

The spatial and temporal variation of soil water content were significantly influenced by rainfall event size and intensity (Fan et al. 2016), as well as by the above ground structure of the land cover types (Molina et al. 2007; Niu et al. 2015). Temporal variations of soil water content in different land cover types were not always consistent with rainfall event sizes due to differences in the dry sequence duration preceding events (Gao et al. 2014; Niu et al. 2015). In many semi-arid landscapes, alien invading woody species have been shown to have increased transpiration rates particularly in riparian areas where water is readily available consequently reducing river flows and groundwater levels in the floodplain (Doody et al. 2011). All piezometers were dry when they were installed as it was during a dry period but shallow groundwater levels rose in areas with palmiet and grass but remained below piezometer depths under the wattle invaded site. Removal of invading species and replacing or allowing the regrowth of native herbaceous species may result in improved subsurface hydraulic processes (i.e. water retention and infiltration rate), reduced ET rates and consequent increase in groundwater recharge (Doody et al. 2011; Kellner and Hubbart 2016; Niu et al. 2015; Wahren et al. 2009) as shown by the results of this study. Rainfall that could recharge the floodplain alluvial aquifer may be lost to ET by the alien vegetation. The floodplain alluvial water table can have an impact on catchment outflow and water yield particularly in large catchments, therefore alien invasion in floodplains can have detrimental effects on overall outflow and catchment water yield particularly in catchments that have sizeable floodplains such as the Kromme.

Conclusion

This study characterized spatial and temporal soil water content dynamics and shallow groundwater levels across three sites under contrasting vegetation types (black wattle, grass and palmiet) at a floodplain site in a semi-arid catchment. Rainfall event magnitude, antecedent wetness and vegetation type were identified as the major factors controlling soil water content dynamics and shallow groundwater levels. Deep 50–60 cm soils were generally recharged by rainfall of magnitudes 30 mm/day or higher. On average, soil water content was higher at the palmiet and grass sites compared to the wattle invaded site possibly due to higher transpiration rates by the woody alien species. The groundwater table at the palmiet and grass sites was sometimes observed to rise without local recharge. Contributions were possibly from mountain runoff infiltrating and coming through the subsurface or lateral or groundwater flow down the valley elevation gradient. However, following some heavy events, groundwater was observed to rise to levels within the root zone at the palmiet and wattle sites affecting the soil water content directly from the capillary fringe. In general, the water table at the wattle site was below the depth of installed piezometers (3 m) for more than 90% of the time only responding to rainstorms greater than 40 mm/day.

Given the relative importance of floodplain landscapes particularly in arid and semi-arid catchments, as well as the global increase in land use and land cover changes particularly alien invasions in riparian landscapes, quantitative studies of this kind are therefore imperative on the subject of impacts of contrasting land cover types on floodplain hydrology as well as to guide vegetation recovery and restoration efforts (Gao et al. 2014; Ziadat and Taimeh, 2013). Soil water varies at both spatial and temporal scales, therefore understanding these variations becomes critical particularly in arid and semi-arid landscapes for water resource management and vegetation restoration (He et al. 2012; Wang et al. 2013; Ziadat and Taimeh, 2013).

The results of this study can therefore guide restoration works as well as to build capacity through science communication regarding the impacts of black wattle on subsurface processes as well as the ecological and hydrological importance of palmiet in river systems. Soil moisture plays a very important role on water cycling and vegetation growth in arid and semi-arid catchments. Furthermore, studying soil water content variation under different land cover types adds to the knowledge and foundation of effective water resource management and ecological restoration in semi-arid systems particularly in areas where woody alien species have invaded.

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Author contributions FJ and JG collected the data. FJ, JG and DM analyzed the data. FJ wrote the manuscript, JG and DM contributed to all written sections of the manuscript.

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Data availability Data was collected and analysed. It is availble if needed.

Declarations

Competing interests The authors declare no competing interests.

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