Research Article

Dynamics of groundwater flow and upwelling pressure heads at a wetland zone in a headwater catchment

George W. Waswa[1] · **Simon A. Lorentz**[2]

Abstract

The rate and direction of groundwater flow are a function of the gradient of the hydraulic head, whose components are gravity head and pressure head. This paper presents results and analyses of field observations of pressure head responses to some rainfall events of 2000/2001 summer season in a headwater catchment in South Africa. A transect spanning from a steep hillslope zone, through a transition zone and a flat low-lying wetland zone, to a stream channel zone was instrumented with tensiometers to monitor the responses of pore-water pressure to rainfall. The season's late rainfall events simultaneously caused the pressurized pore-air driven Lisse effect water table response at the transition zone, and the capillary fringe-assisted groundwater ridging water table response at the wetland zone. During the events, the Lisse effect dissipated, but followed by sequences of stepped increases in pressure head in the deep soil profile at the transition zone. These stepped increases in pressure head, whose magnitudes increased with depth, were caused by the upwelling pressure heads induced by rainfall spike intensities at the wetland zone. These upwelling pressure heads could have major and disproportionate influence on the dynamics of groundwater flow.

Keywords Capillary fringe · Groundwater ridging · Lisse effect · Upwelling pressure heads · Wetland zone

1 Introduction

The rate and direction of groundwater flow are a function of the gradient of the hydraulic head, whose components are gravity head and pressure head. Gravity head is with reference to elevation datum, and pressure head, part of which is a water table, is with reference to atmospheric pressure. Groundwater below a water table can flow by gravity. Therefore, a water table configuration and response have a pronounced effect on the direction and rate of groundwater flow. Heliotis and DeWitt [1] recognized three types of water table responses to rain, namely groundwater ridging, the Lisse effect and the storage type, which is due to rain infiltration and recharge of groundwater.

Groundwater ridging is the rapid water table rise during a rainfall event, in an environment where, in the pre-event period, a capillary fringe extends to or intersects the ground surface [2]. Gillham [3] was among the first researchers to explain the physical processes involved in this phenomenon. Based on the Young–Laplace concept of capillarity, Gillham [3] explained that an addition of a very small amount of water at the ground surface fills the capillary meniscus and relieves the capillary tension, resulting in an almost instantaneous rise of the water table to the ground surface. This explanation was supported by subsequent studies of laboratory experiments [4], field experiments [1, 5] and numerical simulations [6]. Furthermore, some researchers [7, 8] have attempted to describe the phenomenon using mass balance equations. However, it is worth noting that in the capillary fringe, which is also

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descriptively referred to as the zone of *tension saturation*, every pore is fully occupied with water (*saturated*) whose pressure head is below atmospheric pressure (in *tension*). In terms of energy, therefore, the capillary fringe is part, and at the bottom, of the vadose zone. A water table, which is the boundary between the vadose zone and phreatic zone, is also defined in terms of energy as the locus of points along which pressure head is zero [9]. Therefore, the difference between the capillary fringe and the phreatic zone is only in the energy content; otherwise, both zones are ideally saturated. It follows that the conversion of the capillary fringe into phreatic water requires only an addition of pressure head (energy), a process that will automatically elevate the water table, not necessarily to the ground surface but, to a position that will depend on the amount of pressure energy added. Certainly, results of field observations in the Weatherley Research Catchment in South Africa [10] and other study sites [11] found a direct relationship between the intensity of rainfall and the water table rise in groundwater ridging.

The Lisse effect is the rapid response of a water table due to pressurized pore air ahead of a wetting front. Freeze and Cherry [12] explained that in the Lisse effect, the compressed pore air pressure acts directly on a water table, resulting in an equivalent rise in the groundwater level in a well. Weeks [13] considered the Lisse effect and the associated water table as a material phenomenon, and explained that the pressurized air pushes the water from the aquifer into the well to produce a water-level rise to compensate for the pressure difference between the confined air pressure and the atmospheric pressure; and that a minor drawdown of the water table may be induced as water flows from the aquifer into the well as its water level rises. However, recent laboratory and theoretical investigations [10, 14] revealed that the Lisse effect is an energy phenomenon, in that the rapidly pressurized pore air induces an additional pressure head into the aquifer, resulting in a rapid rise of the water table that is properly indicated by the rapid rise of the water level in an observation well [15].

Localized water table responses might result in changes in the water table configuration and, hence, changes in the rate and/or direction of groundwater flow. Gillham [3] gave some hypothetical field illustrations of how the groundwater ridging rapid water table response, in an undulating topography, might promote a highly transient and complex groundwater flow such as the rapid delivery of pre-event groundwater into a nearby stream channel and unexpected reverse flow into a hillslope. Novakowski and Gilham [5] used simulated rainfall experiments on a field plot to demonstrate that under shallow water table conditions, the presence of the capillary fringe can induce a rapid and disproportionate response to precipitation and that in areas of rolling and undulating topography a disproportionate water table response can result in highly transient and complex hydraulic head distributions. Abdul and Gilham [4] used a laboratory physical model to demonstrate that the rapid rise of the water table in groundwater ridging phenomenon can result in the rapid delivery of pre-event groundwater into a nearby stream channel. More recently, Zang et al. [8] used a numerical two (water–air) phase flow mass balance model to demonstrate that Lisse effect pressurized airflow in the upslope mitigates the dissipation of groundwater ridging into a hillslope. They also demonstrated that groundwater ridging can also be observed where an unsaturated zone is above the capillary fringe with a subsurface lateral flow.

The objectives of this paper are (1) to present results of field observations of water table responses due to normal infiltration process, the pressurized pore air-driven Lisse effect and the capillary fringe-driven groundwater ridging, at a wetland zone of a headwater catchment and under natural rainfall events, and (2) to present interesting observations of intense rainfall-induced pressure heads generated at the wetland zone, where the water table was at the ground surface, and their subsequent upwelling in the neighbouring zone where the water table was deep, and causing it (the water table) to rise.

2 Materials and methods

2.1 Study area

Field observations were carried out in the Weatherley Research Catchment, located in the uMzimvubu Water Management Area in the northern Eastern Cape Province in South Africa (Fig. 1). The catchment, which covers 1.5 km^2, is located at 31° 06′ 00″ South, 28° 20′ 10″ East and approximately 1300 m above mean sea level.

The catchment drains in a northerly direction, and the contributing hillslopes are generally steep. The wetland zone, which seasonally expands and contracts, exists along the entire reach of the stream. The Mean Annual Precipitation is 740 mm, of which over 70% is concentrated in the summer months of November to March.

The land cover at Weatherley is predominantly Highlands Sourveld grassland, and typical grass species include *Themeda triandra* and *Tristachya leucothrix*. Succulent species of the genera *Aloe* and *Crassula* are also common on shallow slopes.

The soils at the catchment display a varying degree of wetness and colour and include red and yellow apedal

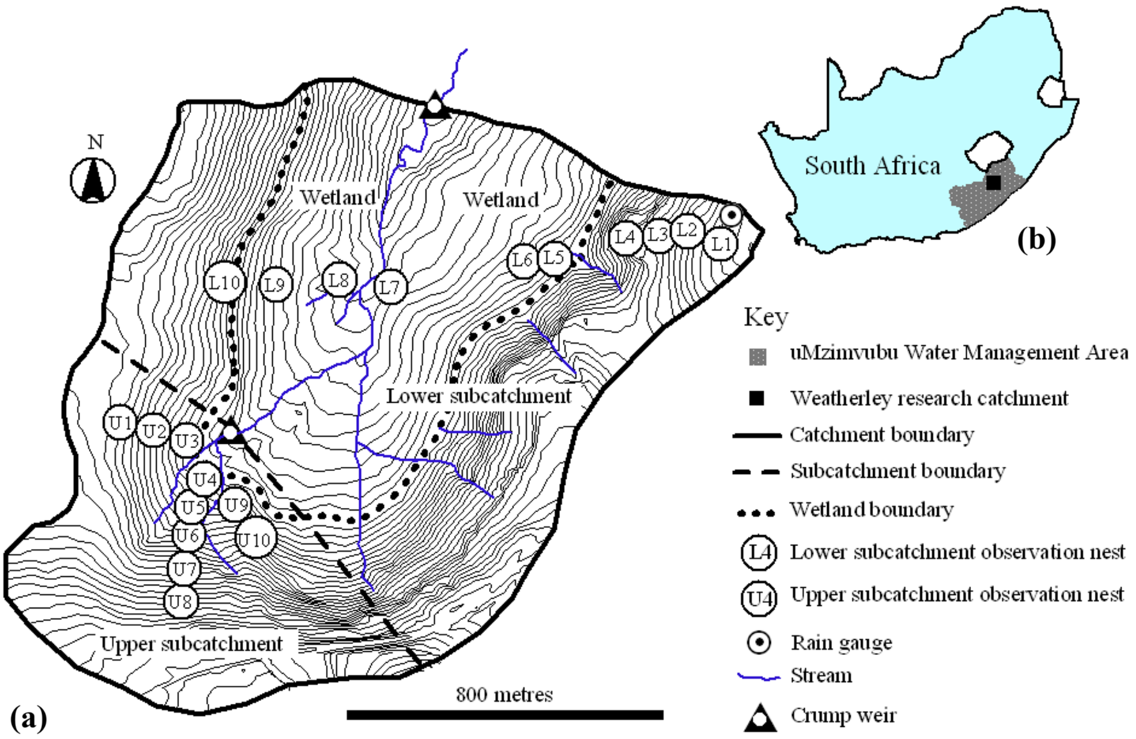

Fig. 1 Study site (adopted from [17]), **a** Weatherley Research Catchment and **b** its location in South Africa

mesotrophic soils as well as neocutanic and hydromorphic soils. The western slope of the catchment, from where the results presented in this study were obtained, is dominated by brown to dark reddish brown Hutton form with sandy loam soils at the surface and sandy clay loam subsurface soil. The Clovelly form is also encountered with bleached loamy sand and sandy loam top soils on brown sandy loam subsoil. Laboratory tests of hydraulic properties of the soils near the wetland zone indicated values of pore air entry pressure head of about 45 cm H_2O and saturated hydraulic conductivity of between 2.35 and 11.32 cm/h [10, 16].

2.2 Experimental set-up

Weatherley Research Catchment was established in 1995 with the aim of assessing the impact of afforestation on water resources. Afforestation of the catchment, however, was done in January 2002 [17].

The catchment was divided into two sub-catchments: the upper sub-catchment (in the south) and the lower sub-catchment (in the north). The stream channel was installed with two weirs to gauge the flows from each sub-catchment. Full weather stations were located near the upper and lower weirs, and there is an additional tipping bucket rain gauge on the crest of the eastern hillslope in the north-eastern corner of the catchment.

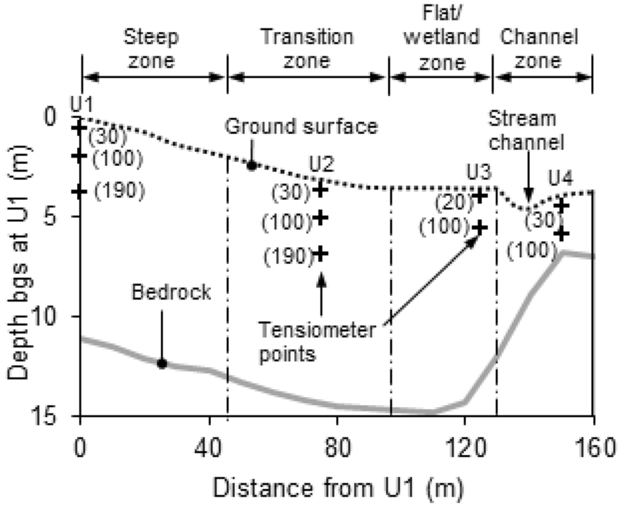

Fig. 2 A transect showing the positions of tensiometers (the values in parenthesis are depth in cm below ground surface at the respective nests). The depth below ground surface (bgs) at U1 is exaggerated two times

Each sub-catchment was installed with a transect of observation nests (Fig. 1) that consisted of instruments to monitor shallow groundwater levels and pore-water pressure heads.

The results reported in this paper are from subtransect of the observation nests in the upper

Table 1 Characteristics of the rainfall events

Event no	Date	Duration (h)	Amount (mm)	Average intensity (mm/h)	12-min max intensity (mm/h)
2	15 Sep 2000	2.5	8	2.3	8
3	17–20 Sep 2000	81	49.8	0.6	7
70	10 Mar 2001	7	47.2	6.7	75
75	17 Mar 2001	5	26.6	5.3	89

sub-catchment, namely U1, U2, U3 and U4, which represent four hillslope zones: the steep hillslope zone, the transition (from steep to flat) zone, the low-lying flat zone (also called the wetland zone) and the stream channel zone (Fig. 2). Each of the four observation nests was installed with two or three ceramic cup tensiometers, in a vertical alignment and at depths indicated in Fig. 2.

2.3 Rainfall events

Observations of the responses reported in this study are of representative rainfall events that occurred during the summer season of 2000/2001 (September 2000–April 2001). Ninety-six rainfall events were recorded in the catchment during the season [10, 16]. Four representative rainfall events, Events 2, 3, 70 and 75, will be used in this paper. Events 2 and 3 represent the season's early rainfall events, and Events 70 and 75 represent the season's late rainfall events. These events, whose characteristics are summarized in Table 1, were selected in order to understand the responses of the catchment in those two parts of the season. Generally, the season's late rainfall events were heavy with spike intensities and occurred when the soil profile at the study site was pretty wet.

3 Results and discussions

3.1 Rainfall infiltration

The responses of the pore-water pressure head to rainfall Events 2 and 3 are presented in Fig. 3. The results show that prior to the rainfall Event 2 the pressure heads at the shallower depths at U2 and U3 were significantly negative (in tension/suction), indicating that the soil profiles at these nests were in very dry conditions and the water table was deep. For instance, at U3, prior to the rainfall Event 2, the pressure heads at 20 cm and 100 cm depths were – 110 cm H_2O and – 10 cm H_2O, respectively. Assuming a profile of uniform soil, whose value of pore air entry pressure head was – 45 cm H_2O [10], these observed results indicate that the water table was about 110 cm below ground surface and the unsaturated zone extended to 65 cm from the ground surface. Similar conditions existed at U2.

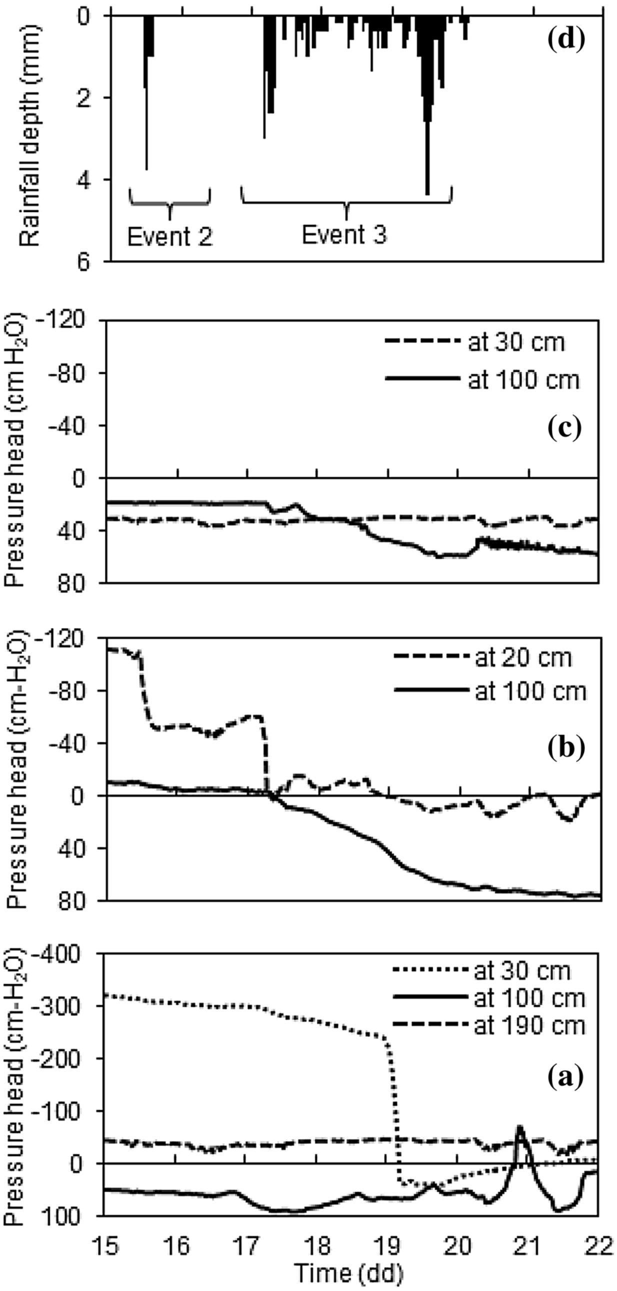

Fig. 3 Pore-water pressure head responses at observations point **a** U2, **b** U3 and **c** U4 to **d** rainfall Events 2 and 3

At U4, prior to rainfall Event 2, the pressure heads at 30 cm and 100 cm depths were 30 cm H_2O and 20 cm

H_2O, respectively. These results indicate the presence of two phreatic zones and water tables at this nest, that is perched water table above the 30 cm depth and another deep water table at 20 cm above 100 cm depth (and 80 cm below ground surface). A laboratory test of the soil from this nest [17] indicated the presence of clay soil. The perched water table, therefore, could be a result of some lenses of clay.

With the above initial conditions, the pressure heads at all depths at U2 and U4 did not respond to the rainfall Event 2. The unresponsiveness of pressure head at U4 could be explained by the presence of the clay loamy soil which does not easily allow infiltration. The unresponsiveness of the pressure heads at U2 could be due to the steep terrain of the site which did not allow sufficient concentration of rainwater for infiltration to take place. Additionally, rainfall Event 2 was generally of very light intensity and small amount (Table 1) to cause an appreciable infiltration of a dry soil.

Nevertheless, rainfall Event 2 caused the pressure head at 20 cm depth at U3 to increase by 60 cm H_2O, i.e. from – 110 cm H_2O to about – 50 cm H_2O, within 10 h. The pressure head at 100 cm depth, however, showed only slight response. These results indicate normal infiltration process at U3, of which the infiltrated rainfall substantially increased the water content at 20 cm depth, but the wetting front did not reach the 100 cm depth. The pressure head at 20 cm depth remained nearly constant at – 50 cm H_2O for 36 h, up to the initial period (first 2.5 h) of the rainfall Event 3, during which the pressure head at this depth again significantly increased to around 0 cm H_2O. During this initial period of Event 3, the response in pressure head at 100 cm depth, again, was insignificant. Similar results were observed at U2, where the pressure heads at 30 cm depth significantly increased, while the responses in pressure heads at 100 cm and 190 cm depths were generally negligible. This behaviour of the significant response in the pressure heads at shallower depths and non-responsiveness or very slight responses in deep soil profile indicate a normal infiltration process, where the wetting front does not reach the deep soil profile.

3.2 Groundwater mound and reverse flow

At U4 (Fig. 3c), the pressure head at 100 cm depth (deep soil profile) continuously responded throughout the rainfall Event 3, while the pressure head at 30 cm depth (shallow soil profile) did not respond at all (i.e. remained constant at around 30 cm H_2O). These results are unexpected, and contrary to observations made at other nests, i.e. U2 and U3 where, as expected and already explained, the pressure head at shallower depths responded to rainfall events and ahead of the pressure head at deeper soil profile, clearly indicating direct infiltration process. Therefore, at U4, infiltration appears not to have taken place to account for the observed pressure head responses at 100 cm depth. A consideration of the neighbouring nests reveals that during Event 3 the pressure head at 100 cm depth at U4 responded in a similar pattern as the pressure head at 100 cm depth at U3. These results indicate that the pressure head at 100 cm depth at U4 responded to the recharge of the groundwater (at U4) from U3, in a process that is illustrated in Fig. 4. The water table configurations in Fig. 4 were derived from the results of pressure head responses at the respective nests and times (presented in Fig. 3).

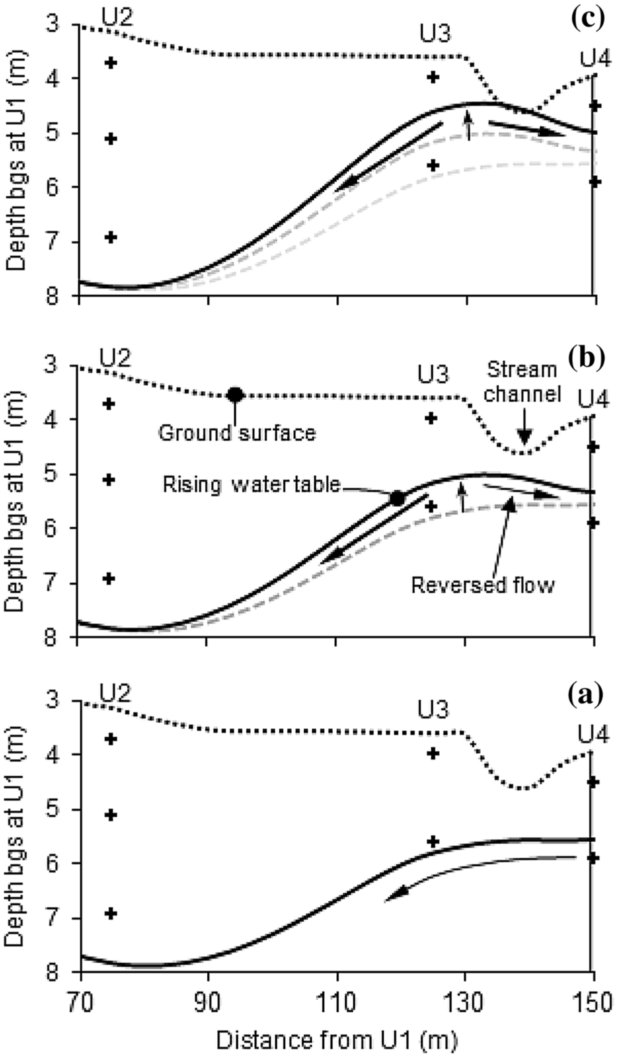

Fig. 4 Water table configurations at the study site **a** prior to rainfall Event 2: 15th September 2000 at 00:00H; **b** during rainfall Event 3 on 18th September 2000 at 00:00H; and **c** during Event 3 on 19th September at 00:00H. The position of the water table is based on pressure head value of the deeper/deepest tensiometer in Fig. 3. The depth below ground surface (bgs) at U1 is exaggerated two times

Initially, prior to rainfall Event 2, the water table (hydraulic gradient) between U4 and U3 was tilted towards U3 and, consequently, the direction of groundwater flow was from U4 to U3 as indicated in Fig. 4a. During Event 3, due to a relatively flat terrain and a more porous sandy loamy soil at U3, infiltration at this nest was faster than at nest U4. This resulted in a rapid recharge of the groundwater and rapid elevation of the water table at U3, forming a water table mound at this zone (Fig. 4b and c), which reversed the direction of flow of groundwater towards U4 and enhanced the rate of flow of groundwater into the hillslope. The reversed flow to U4 resulted in recharge of deep groundwater table at U4 and caused the observed increase in pressure head in the deep soil profile (including 100 cm depth), without the process of direct rainfall recharge at nest U4 (Fig. 4b and c). Similar observations of the formation of water table mounds and reversals of direction of flow were reported by Rosenberry and Winter [18].

3.3 Rapid response of a shallow water table and the role of a capillary fringe

Results of the pressure head responses to rainfall Events 70 and 75 are presented in Figs. 5 and 6, respectively. Event 70 had three spike intensities (Fig. 5d), and Event 75 had four spike intensities (Fig. 6d). From the results in Fig. 5c, it can be noted that prior to Event 70, at U4, the pressure heads at 30 cm and 100 cm depths were 20 cm H_2O and 100 cm H_2O, respectively. These indicated a single water table that was at 10 cm below ground surface and, since the soil at this site had a pore entry pressure head of 45 cm H_2O [10], the capillary fringe intersected the ground surface. At U3 (Fig. 5b), prior to rainfall Event 70, the pressure heads at 20 cm depth and 100 cm depth were − 10 cm H_2O (tension condition) and 65 cm H_2O (phreatic conditions), respectively. These results indicate that the water table was at 30 cm below ground surface and the capillary fringe intersected the ground surface.

It can be seen from Fig. 5 that the rainfall Event 70 caused the pressure heads at all depths at both U3 and U4 to respond simultaneously. At U4, the pressure head at 30 cm depth increased by about 15 cm H_2O, while at U3 the pressure head at 20 cm depth increased by about 30 cm H_2O, in a process that rapidly converted the capillary fringe into phreatic conditions and hence elevated the water table to the ground surface at both nests. Note that the increases in pressure heads at the shallow depths were about the same magnitudes as the depth of the capillary fringes prior to the event. At both nests, the pressure head at 100 cm depth responded in the same pattern as at shallow depths, but the responses were translated in time and attenuated in magnitude.

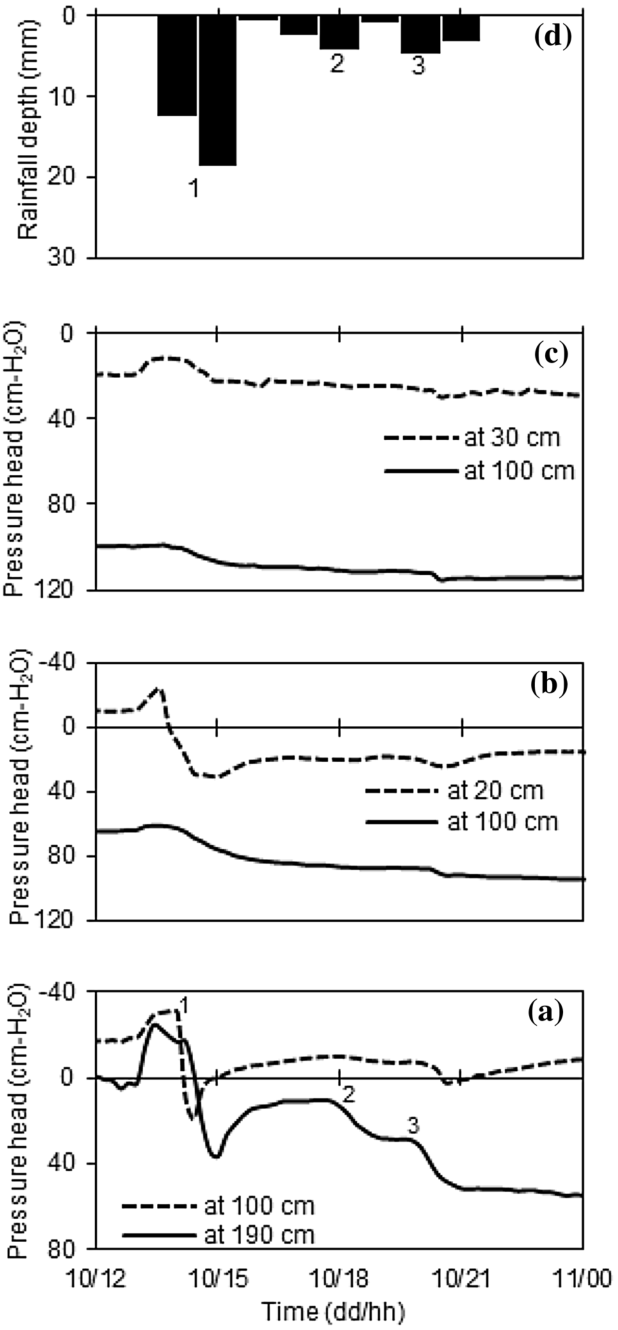

Fig. 5 Pore-water pressure head responses at observations nest **a** U2, **b** U3 and **c** U4 to **d** rainfall Event 70 (that occurred on 10th–11th March)

Results in Fig. 6c show that prior to rainfall Event 75 at U4 the pressure heads at 30 cm and 100 cm depths were 30 H_2O and 110 cm H_2O, respectively. At U3 (Fig. 6b), the pressure heads at 20 cm and 100 cm depths were 20 cm H_2O and 95 cm H_2O, respectively. These results indicate that at both nests the water table was already at the

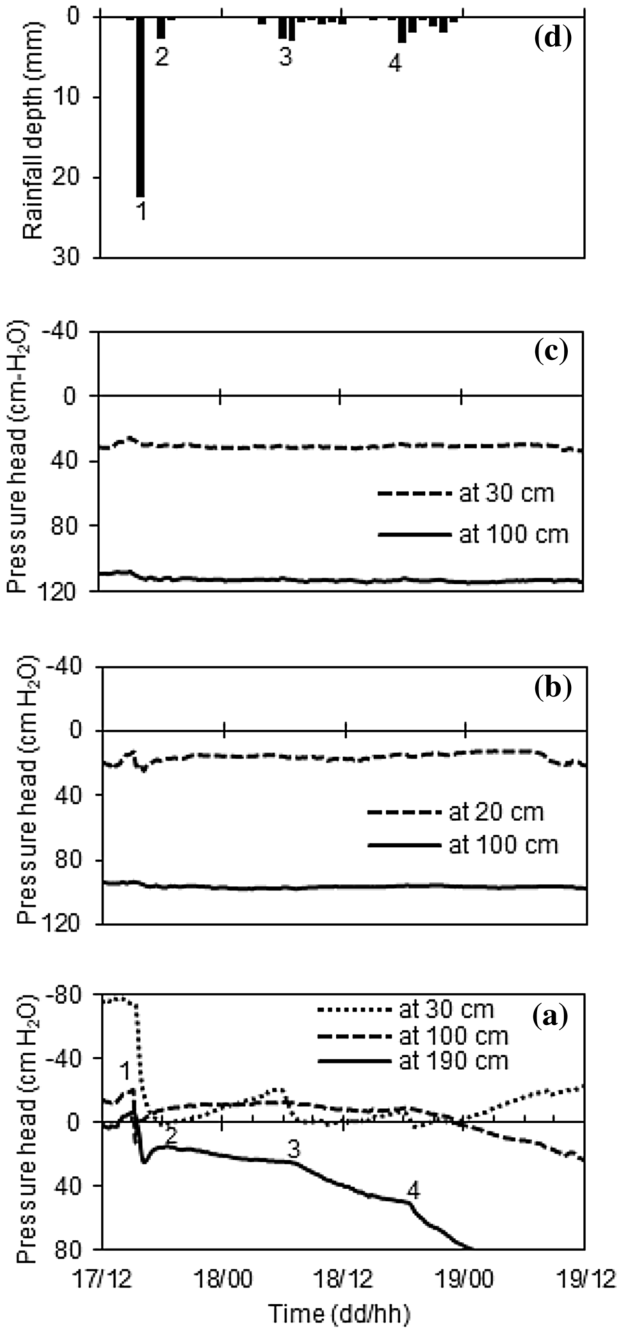

Fig. 6 Pore-water pressure head responses at observations nest **a** U2, **b** U3 and **c** U4 to **d** rainfall Event 75 (that occurred on 17th–19th March 2001)

ground surface and the capillary fringe was absent. On these conditions, it can be noted that rainfall Event 75, which was more intense than Event 70 (Table 1), did not cause any appreciable response in pressure heads at both U3 and U4.

A comparison of the observed results from U4 and U3, i.e. the initial conditions prior to the rainfall events and the responses of the pressure heads at these nests, clearly reveals the role of a capillary fringe in groundwater ridging rapid water table response.

Prior to rainfall Event 2, the water table at U3 was deep below the ground surface and so was the capillary fringe (Figs. 3b and 4a). A very dry unsaturated zone existed between the ground surface and the top of the capillary fringe. On these initial conditions, it was noted that the rainwater (from Events 2 and 3) infiltrated and recharged the deep groundwater, hence causing the water table to gradually rise towards the ground surface (Figs. 3b and 4c).

Prior to rainfall Event 70, the water table at U3 was shallow (at 30 cm below ground surface: Fig. 5b) and the capillary fringe intersected the ground surface. It is worth noting here that in the capillary fringe, also known as the zone of *tension saturation*, every pore space is fully occupied (*saturated*) with water that is in *tension*. Within this definition, therefore, at U3, prior to Event 70, due to the presence and position of the capillary fringe, the ground surface was saturated with (pore) water that was in tension. On these initial conditions, it was noted that the intense rainfall at the ground surface caused a rapid response of pressure head throughout the soil profile, converted the capillary fringe into phreatic water and raised the water table to the ground surface. Since at U3 the ground surface was already saturated, the intense rainfall could not infiltrate the soil profile to cause the observed rapid responses in pressure head. Note that the difference between a capillary fringe and a phreatic zone is only in the pressure energy content, and the conversion of the former into the later requires only an additional energy, although some researchers [7, 8] have used mass-based models to simulate the phenomenon. In the groundwater ridging phenomenon, the kinetic energy-laden intense rainfall induces additional pressure head into the pressure energy-deficient capillary fringe (tension pore water) at the ground surface. The induced pressure head is diffusively transmitted down through the pore water, elevating the pressure head at every depth of the soil profile. Prior to Event 75, at U3 (Fig. 6b), the water table was already at the ground surface, and therefore, the capillary fringe was absent. Results showed that an intense rainfall at the ground surface only caused a pressure pulse through the soil profile without elevating the pressure heads.

From the above discussion, it is clear that for groundwater ridging rapid water table response to occur, first, the capillary fringe should be present and extend to, or intersect, the ground surface. It is for this reason that groundwater ridging rapid water table response was not observed during Events 2, 3 and 75. Second, there should be an intense rainfall at the ground surface. The extension of the capillary fringe to the ground surface provides the necessary contact between the kinetic energy-laden raindrops of the intense rainfall and the tension (pressure energy deficient) pore water, so that the kinetic energy from the raindrops can be rapidly induced, as additional pressure energy, into the tension (pressure energy deficient) pore water. This view of the role of the capillary fringe in groundwater ridging is in agreement with those of Marui et al. [19] who concluded from field observations that the rapid response of pore-water pressure in the deep soil profile was assisted by pressure transmission through pore spaces occupied by a relatively continuous water phase. Similarly, the tension saturation (near-saturation)-assisted transmission of intense rainfall-induced pressure head was also observed in field experiments by Torres et al. [20] and column experiments by Rasmussen et al. [21]. Therefore, for capillary fringe-assisted groundwater rapid water table response to occur, there should be sufficient (tension-saturated or near-saturated) continuous pore-water phase from the ground surface to the water table below.

3.4 Upwelling pressure heads and rapid response of a deep water table

Results in Fig. 5a show that at U2, prior to Event 70, the pressure heads at 100 cm and 190 cm depth were − 20 cm H_2O and 0 cm H_2O, respectively. This implied that the water table was at 190 cm depth below ground surface and the tensiometer at 100 cm was within the zone of tension saturation/near saturation. The first spike intensity of rainfall Event 70 (Fig. 5d) caused the pressure head at both depths to simultaneously and rapidly increase by a similar magnitude into phreatic conditions. The pressure heads at both depths then recovered uniformly up to the time of the second spike intensity, when the pressure heads at both depths suddenly increased, but pressure heads at 190 cm depth increased more rapidly and significantly than the pressure head at 100 cm depth. The third spike intensity caused further stepped increase in pressure head at both depths, and again with the increase at 190 cm depth being higher than that at 100 cm depth. After the rainfall event, the pressure head at 190 cm depth continued to increase steadily, while the pressure head at 100 cm depth steadily recovered into vadose conditions. Similar observations were recorded during Event 75.

From the results in Fig. 6a, it can be seen that at nest U2 and prior to Event 75, the pressure heads at 30 cm, 100 cm and 190 cm depths were − 80 cm H_2O, − 10 cm H_2O and 0 cm H_2O, respectively. These indicated that the water table was at 190 cm depth, the capillary fringe or near-saturated conditions extended just above the 100 cm depth, and the unsaturated zone extended to the ground surface. The first rainfall spike intensity caused a steep increase in pressure head at all depths, but the pressure head at 30 cm depth (which was in unsaturated zone with continuous pore air) increased more significantly than at both 100 cm and 190 cm depths (which were in tension saturation/near saturation conditions). However, just like in Event 70, the pressure heads at 100 cm and 190 cm depths (which were initially in saturated/near-saturated conditions) responded and recovered uniformly up to the second rainfall spike intensity, which caused the pressure heads at both depths to increase, but 190 cm depth recorded a more significant increase than the 100 cm depth. In summary, the spike intensities of rainfall Event 75 also caused stepped increases in pressure head at all depths. The pressure head at the shallower (30 cm) depth, however, responded more rapidly and immediately started recovering, indicating a passing wetting front/infiltration profile. On the other hand, the pressure head at 100 cm and 190 cm depth displayed a relatively delayed and slow response, but with the pressure head response at 190 cm depth always being higher than at 100 cm depth.

These stepped increases in pressure head at U2 (transition zone) during Events 70 and 75 can be interpreted with respect to the pressure head responses at the adjacent wetland zone (nest U3) and with the aid of a pictorial illustration in Fig. 7. Prior to rainfall Event 70, at U3 (Figs. 5b and 7a), the water table is shallow and the capillary fringe extends to the ground surface. At U2, the water table/phreatic zone (zone A in Fig. 7a) is deep, the zone of tension saturation (near saturation) extends just above 100 cm depth (zone B in Fig. 7a), and the unsaturated zone (zone C in Fig. 7a) extends to the ground surface. The first spike intensity of Event 70 (arrow *a* in Fig. 7b) induces an additional pressure head into the capillary fringe at U3 (arrow c in Fig. 7b), which elevates the water table (arrow f in Fig. 7b) to the ground surface. At U2, the first spike intensity of Event 70 infiltrates the soil (arrow b in Fig. 7b), generating a strong infiltration profile (Zone D in Fig. 7b), which entraps and pressurizes the pore air (arrow d in Fig. 7b) in the unsaturated zone. The pressurized pore air induces an additional pressure head (arrow e in Fig. 7b) in the saturated zone below, resulting in a simultaneous response of pressure head at all depths, including the elevation of the water table (arrow h in Fig. 7b). Dissipation of pore air pressure results in a uniform recovery of pressure head at all depths and the fall of the water table (arrow j in Fig. 7c). Subsequent spike rainfall intensities (arrow a in Fig. 7d) induce an additional pressure head (arrow c in Fig. 7d) into the aquifer at U3. However, since the water table is now at the ground surface at U3, this additional pressure head does not result in a significant increase in pressure head here at U3 but is registered as a

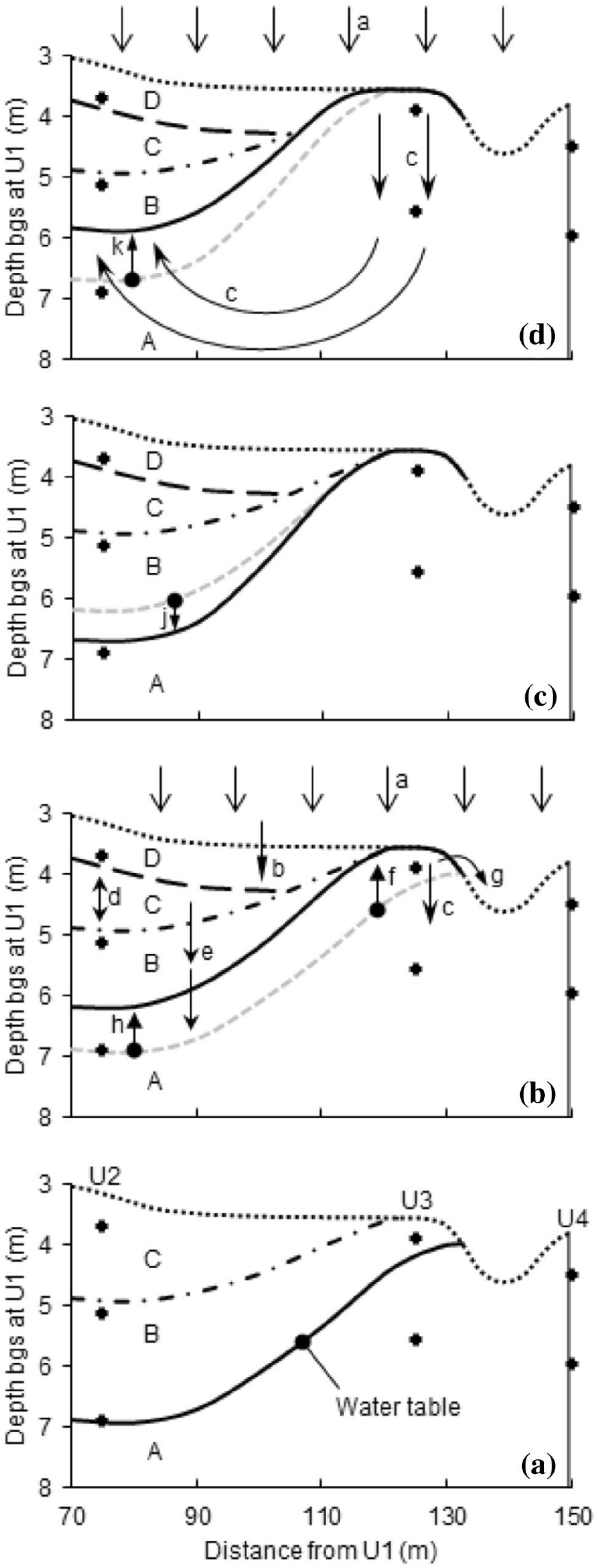

Fig. 7 A model of groundwater ridging and the Lisse effect rapid water table responses, and the upwelling pressure heads at the wetland zone in the weatherly Research Catchment, South Africa: **a** the initial water table with capillary fringe extended to ground surface at U3, **b** the Lisse effect type rapid water table response at U2 and the groundwater ridging rapid water table response at U3, **c** the receding water table at U2 due to dissipation of entrapped pressurized pore air, **d** intense rainfall-induced pressure heads at U3 and their upwelling at U2, causing an increase in pressure head at U2. The depth below ground surface (bgs) at U1 is exaggerated two times. *Groundwater Zones*: A: Phreatic zone; B: the tension saturation/near-saturation zone; C: unsaturated zone with continuous pore air; D: infiltration profile. *Key to arrows*: a: intense rainfall (e.g. Event 70); b: infiltration in the unsaturated zone; c: intense rainfall-induced pressure head; d: compressed pore air between the wetting front and the top boundary of the capillary fringe (zone B); e: pressurized pore air-induced pressure head; f: rising water table due to intense-rainfall induced pressure head; g: gravity flow of groundwater into the stream channel from the converted capillary fringe; h: the Lisse effect water table rise; j: falling water table due to dissipation of pressurized pore air; k: rising water table (pressure head) at U2 due to upwelling of intense rainfall-induced pressure head

pressure pulse (Fig. 6b). Much of the additional pressure head is transmitted downwards and upwells in the nearby neighbourhood (U2), where the water table is deep. The upwelling pressure heads result in elevated pressure heads in this neighbouring zone (U2) including the elevation of the water table (arrow k in Fig. 7d). This explains the more rapid and high responses of pressure heads in the deep soil profile (e.g. 190 cm depth) than in the shallower soil profile (e.g. 100 cm depth) recorded at U2 during Events 70 and 75 (Figs. 5a, 6a).

It should be noted that in groundwater ridging the source of pressure head is at the ground surface and the pressure head diffuses downward through the pore water [10, 11]. Inversely, at U2, it appears that the source of pressure head is from below and the pressure head diffuses upwards through pore water. From this analysis, it can be stated, therefore, that the intense rainfall-induced pressure head (observed as pressure pulses) at the wetland zone (when the water table is at the ground surface, e.g. in the later part of Event 70: Fig. 5b and in the entire Event 75: Fig. 6b) is upwelled as a rising pressure wave at U2, thereby causing the observed elevated pressure heads and water table at U2.

4 Conclusion

Localized recharge can result in groundwater mound which can change the direction and rate of groundwater flow. For a capillary fringe-assisted groundwater ridging rapid water table response to occur, a sufficient (tension-saturated/near-saturated) continuous water phase from the ground surface to the water table and intense rainfall at the ground surface are necessary. At the sites with undulating topography and wetland conditions, intense rainfall might result in an unexpected and disproportionate transient pressure heads, and therefore groundwater flow dynamics. Intense rainfall-induced pressure heads, at a zone with the water table at the ground surface, can be diffusively transmitted down through pore water, and upwelled and elevate the pressure heads (and water table) in the neighbouring zone.

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Compliance with ethical standards

Conflict of interest On behalf of all authors, the corresponding author states that there is no conflict of interest.

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