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Water Table Dynamics of a Severely Eroded Wetland System, Prior to Rehabilitation, Sand River Catchment, South Africa.

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Water Table Dynamics of a Severely Eroded Wetland System, Prior to Rehabilitation, Sand River Catchment, South Africa.

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Abstract The severe degradation of the headwater wetlands of the Sand River, South Africa, by large erosion gullies has been a focus of a hydrological monitoring program in order to determine the hydrodynamic response of these wetlands to rehabilitation interventions. This paper presents the findings relating to the behaviour of a headwater wetlands groundwater phreatic surface prior to rehabilitation. The findings of hydrometric observations include the delineation of a stratified water table system and the behaviour of this suggests the occurrence of hydro-dynamically distinct regions within the wetland, and loss of groundwater through head-cut erosion. 2-Dimensional Electrical Resistivity Tomography (ERT) surveys identified a zone of finer sediment which is thought to act as a sub-surface flow buffer within this otherwise sandy wetland substrate. These findings suggest that these impacted wetlands need to be 'plugged' in order to restore their hydrological regime.

Keywords: wetlands; water table; erosion; gullies; South Africa

Introduction

'Hydrology is probably the single most important determinant of the establishment and maintenance of specific types of wetlands and wetland processes' (Mitsch & Gosselink, 1993). Furthermore, without the development of an understanding of how wetlands form from a hydrological and geomorphological perspective, the predicted function and wise management of such systems would prove difficult to achieve (Ellery *et al.,* 2005). It is generally accepted that wetlands at the headwaters of river systems act as regulators of flow by sustaining base-flows and attenuating peakflows. Although this is the subject of debate (e.g. Bullock & Acreman, 2003), it is only recently however that this presumption has begun to be tested in the southern African context (e.g. McCartney, 2000).Meanwhile these wetland hydrogeomorphic types do serve a purpose in the region in terms of food security through both wet and dry season subsistence cultivation. South Africa in particular experiences the continued conversion of these wetland systems for this very reason, with little or no control (Kotze & Silima, 2003).

The Sand River is the main tributary of the Sabie River, the last remaining perennial river to flow through the Kruger National Park and into Mozambique, although the Sand River itself was once considered a perennial river it is now considered as being severely degraded. The degradation of the Sand River is thought to be due to two principle factors; inappropriate forestry and commercial agriculture within the contributing catchment; and the degradation of the extensive wetlands at the headwaters of the river system through their conversion to agriculture for subsistence cultivation (Pollard *et al*., 2005), a situation that has arisen largely as a result of enforced settlement under the previous political regime of South Africa.

These wetland systems exist on a granitic geology in an area prone to large and intense rainfall events and these two factors contribute to the natural landscape scale erosional processes evident in the foothill zone of the Klein Drakensberg Escarpment. Meanwhile the recent population pressures have probably led to the degradation of the wetland environment and their contributing micro-catchments, such that it is postulated that excessive sediment delivery to and the mechanical modification of the wetland substrate have led to the over-steepening of the wetland surface topography and as a consequence made them extremely vulnerable to perturbation by rain events. As a result the initiation and rapid head-ward retreat of large erosion gullies now characterize these wetland systems leading to a significant loss of wetland sediment and severe desiccation of the wetland environment.

The aim of this study is to determine the present behaviour of the subsurface phreatic surface in one of these wetlands prior to technical rehabilitation, which ultimately seek to mimic the zones of finer sediments or ‘clay-plugs’ that are thought to have previously buffered the flows of sub-surface water in these very sandy (highly conductive) wetland soils. This forms part of a three year study examining the overall impacts of rehabilitation on the wetland’s hydrodynamics.

Method

The research site is located within the Manalana sub-catchment at the headwaters of the Sand River, approximately 300km East-North-East of Tshwane (Pretoria) (Figure 1), adjacent to the village of Craigieburn. This is one of many such headwater catchments containing riparian wetlands situated within a dry sub-humid belt on the periphery of the South African semi-arid lowveld savannah at the foothills of the Klein Drakensberg Escarpment. The Sand River is unusual in that its entire catchment is situated within this lowveld complex, meanwhile most other north-eastern South African river systems have their origins on the high altitude grasslands (highveld).

The relief of the long narrow basin of the Manalana catchment is relatively steep with an average 13% interfluve slope, whilst its altitude ranges from 744m asl at the highest point along the watershed to 654m asl at its confluence with Motlamogasana stream. The Manalana sub-catchment lies within a granitic geological zone and is underlain by medium to coarse grained porphyritic biotite granite, a dolerite dyke intersects this on its northern flank. Soils within the catchment are dominated with coarse to medium grained sand and are classified as being sandy-clays with a high plasticity. Significantly there appears to be higher clay content on the slopes, thus sand concentrations increase towards the valley bottom such that the wetland substrate itself is predominantly sand. Meanwhile gully erosion has been identified as being due in part to the exposure of the lower dispersive silt-clay horizon (>800mm deep) beneath a more stable sandy-clay A-horizon. The Manalana catchment is 2.61km² of which 2.5km² and 0.11km² (or 95.6% and 4.4%) make up the area of interfluve and wetland respectively. Rainfall is strongly seasonal in the Sand River catchment occurring during the summer months October to March. An MAP of 1075mm a^{-1} (1904-2000) for this area has been derived from the nearest long-term dataset at the Wales rain gauge, approximately 2.3km away, although the Manalana probably receives somewhat less than this since it is not in such close proximity to the Klein Drakensberg Escarpment.

Vegetation within the Manalana catchment is characterized by grassy shrubland communities on the interfluves to communities more suited to permanently flooded conditions within the wetlands (e.g. *Phragmites mauritianus*). Land use within the catchment comprises densely populated rural housing with dry crop smallholdings (e.g. maize), there is also a dense network of roads and pathways as well as heavy grazing by cattle and goats. Within the wetland itself there is a high density of plots with raised bed and furrow systems, cultivated predominantly with another regional staple, madumbe (*Colocasia esculenta*).

Instrumentation was installed during the latter half of the 2005 dry season (August-October) in order to determine the hydrological processes within the wetland catchment at the commencement of the first rains October-November. Hydrological monitoring stations with automated soil moisture tensiometers and shallow groundwater observation wells were installed along three transects that ran perpendicular to the longitudinal orientation of the catchment. In addition manual groundwater observation wells were replicated but at different depths at the wetland monitoring stations in order to account for possible water table stratification (see Figure 2). Further manual groundwater observation wells were installed at other relevant positions within the wetland.

Automated monitoring stations recorded soil moisture status and groundwater levels on a 12 minute time-step using a HOBO® 4-channel logger and University of KwaZulu-Natal (SBEEH) timing board system. Additional manual groundwater readings were made using a dip meter at least weekly and successively after rainfall events.

The longitudinal topography of the wetland was recorded using the dumpy level survey technique during September 2005.

A dry season Two-Dimensional Electrical Resistivity Tomography (ERT) survey was conducted during October 2006 when the water tables and soil moisture values were deemed to be at their lowest, this was necessary to delineate sub-surface materials in the absence of groundwater which encompasses the same resistivity range as clay materials (Loch, 1999).

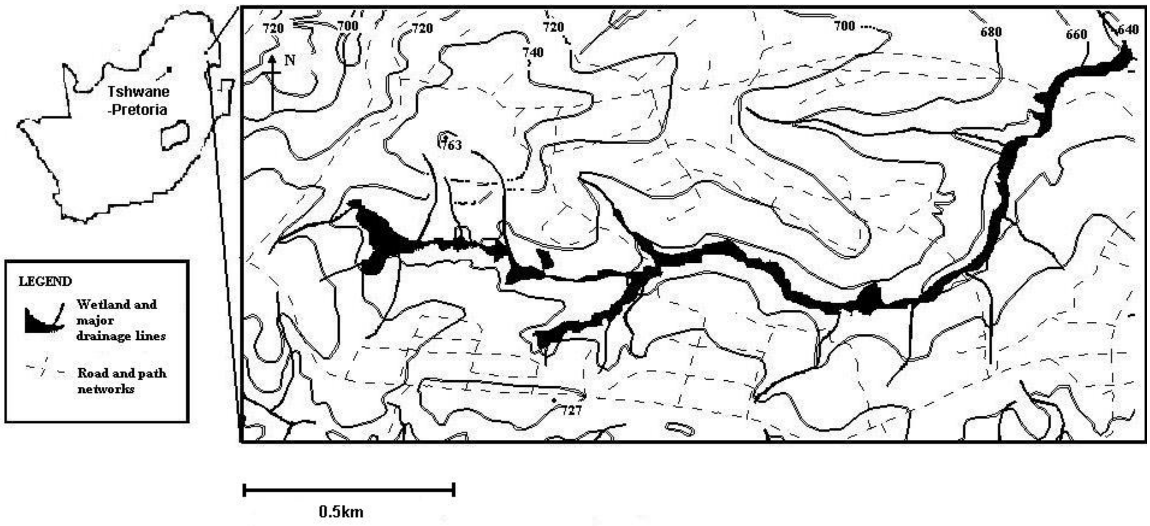

Figure 1. 1:15000 relief map of the Manalana catchment and its location within South Africa

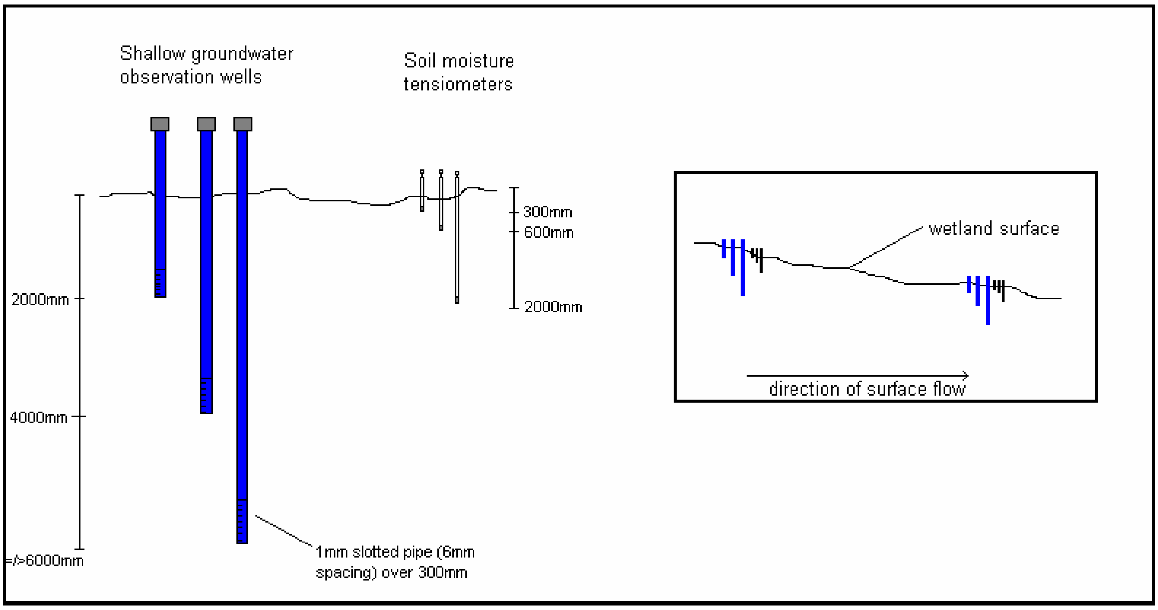

Figure 2. Schematic of groundwater well and tensiometer instrumentation (not to scale).

Results

Figure 3 displays the longitudinal profile of the Manalana wetland from its most head-ward position to just over 450m downstream. This illustrates the relatively steep gradient of the wetland in these headwater settings, with slopes ranging between 2.08% and 4.99%. This slope increases at sites of down-cutting erosion to 63.5%. Figure 3 also displays the gradient of the wetland prior to this down-cutting erosion through the mapping of the left and right walls (fills) of the gully, suggesting that the slope in this region would have been 1.67% in the past.

Figure 4 displays the locations of the hydrometry stations within the Manalana catchment of relevance to this paper. Figure 5 suggests that the phreatic surface of the wetland responds very rapidly to the rapid wetting of deep soils at the toe of the interfluves, since these hillslope toe positions experience a rapid wetting at >/= 2000mm soil depths following substantial rainfalls during the early part of the rainy season. This can be seen from Figure 5 where the 2040mm tensiometer at T1_2 (hillslope toe position) experiences a sharp fall of capillary pressure head moving into the positive pressure head range, hence a perched water table appears relatively quickly, as seen on the 8th of January 2006, consequently the water table at T1_3 (wetland position) rises very rapidly in response. The gaps in the data are due to sorting for unreliable readings and exceeding of transducer pressure range.

This rapid water table elevation was also observed at observation station T2_2, on the 8th January 2006 as shown by the 4000mm automated groundwater reading in Figure 6. The delineation of a stratified water table system is also displayed in Figure 6 whereby the perched water table observed in a 2000mm well appears quite far into the rainy season at 880mm below ground surface on 14th January 2006 rising to 410mm on 10th February 2006. Prior to this no water table was observed in the 6000mm observation well suggesting that the operative water table in this vicinity is within a 2000-4000mm depth. However following the substantial rains early (>368mm 26/10/05-14/01/06) in the season a much deeper water table appears from 3610mm below ground level on the 14th January 2006 rising up to 1150mm by 23rd March 2007.

Figure 7 displays the longevity of the existence of perched water tables as observed in 2000mm wells at four locations longitudinally downstream along the wetland, where well T3_2 is approximately 750m downstream. Here it is noted that the permanency of the perched water table increases downstream as one would expect since water will accumulate as one moves downstream. However the well at T2_3 does not satisfy this expectation, and indeed has the shortest duration, it is necessary to note here that hydrometry station T2_3 is adjacent to the site of active gully erosion (refer to Figure 4).

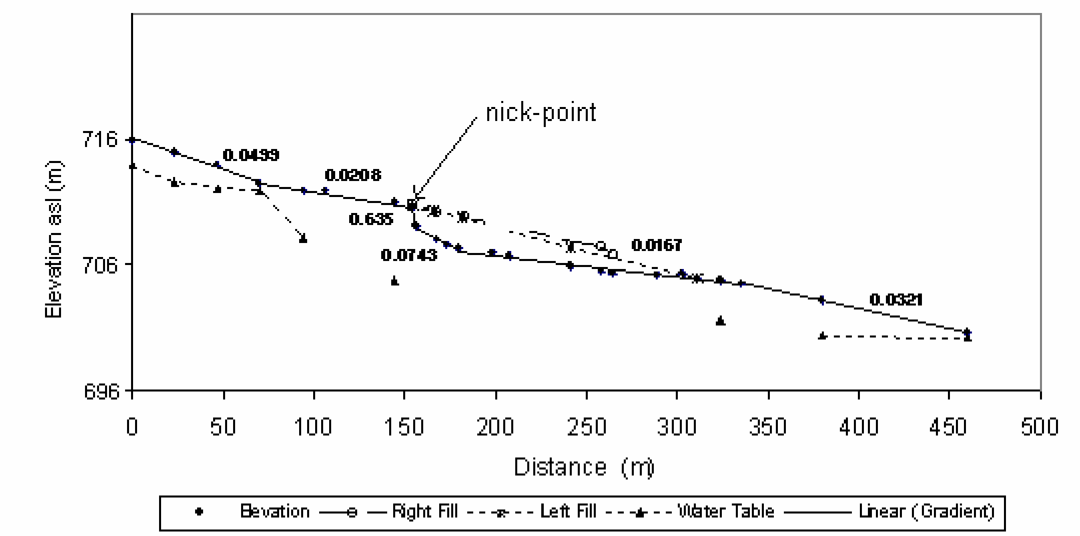

Figure 3. Longitudinal topographic profile of the Manalana wetland, numbers represent slope (c. 2005)

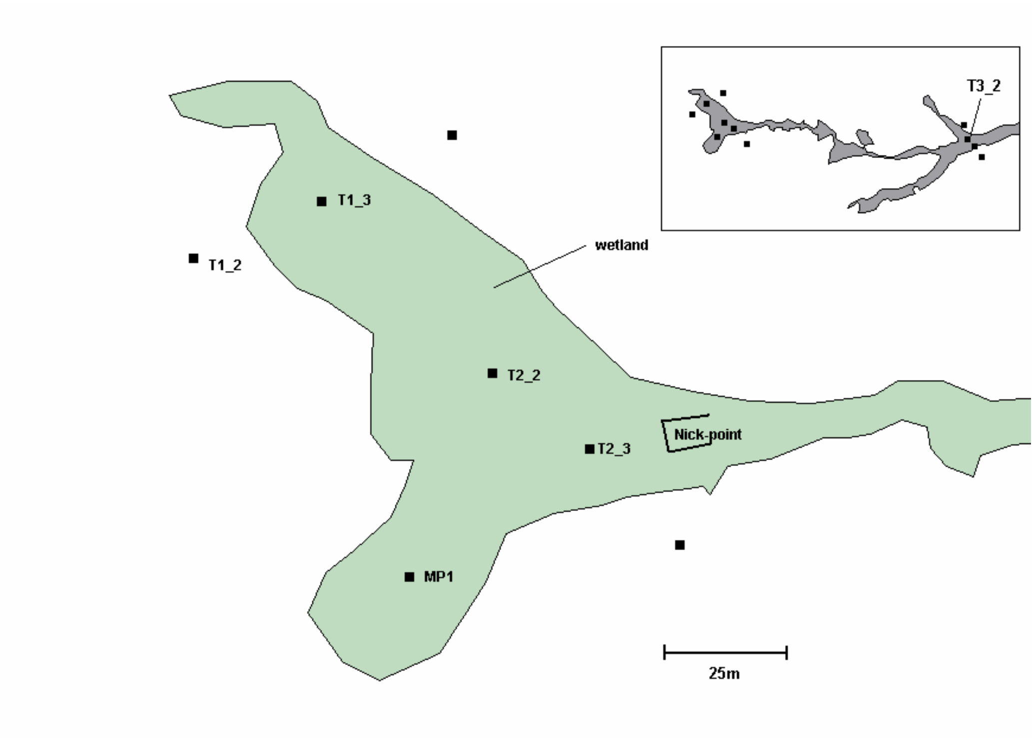

Figure 4. The most head-ward region of the Manalana wetland with hydrometric observation stations and site of active gully erosion (nick-point).

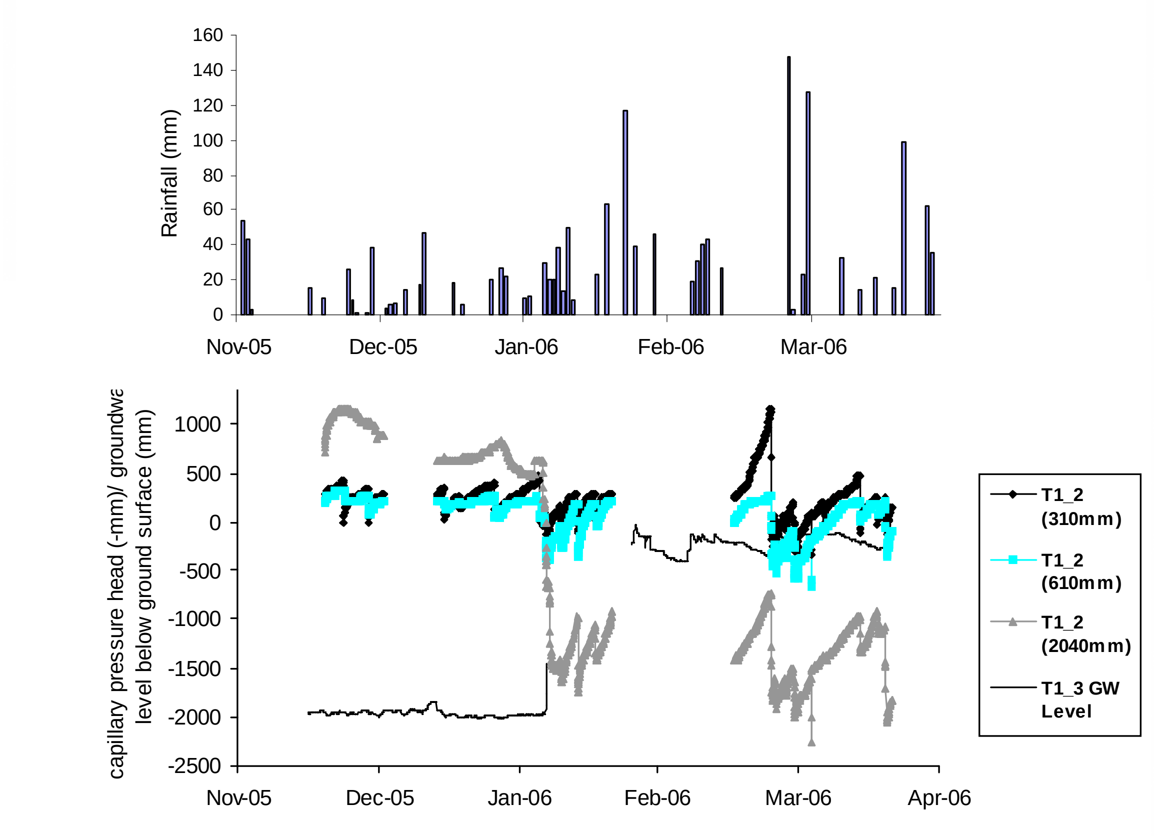

Figure 5. Soil moisture time series (hourly mean) at hillslope toe position (T1_2) at 310mm, 610mm and 2040mm depths, and water table elevation at T1_3. Rainfall data from the nearest accurate record, Hebron Forestry Station approximately 4.6km away.

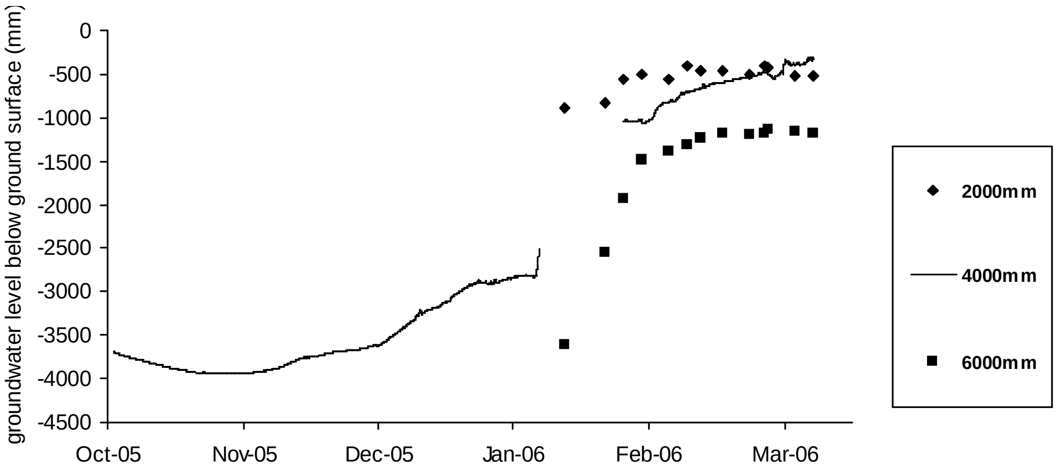

Figure 6. Differential water table levels at hydrometric observation station T2_2 (4000mm is automated).

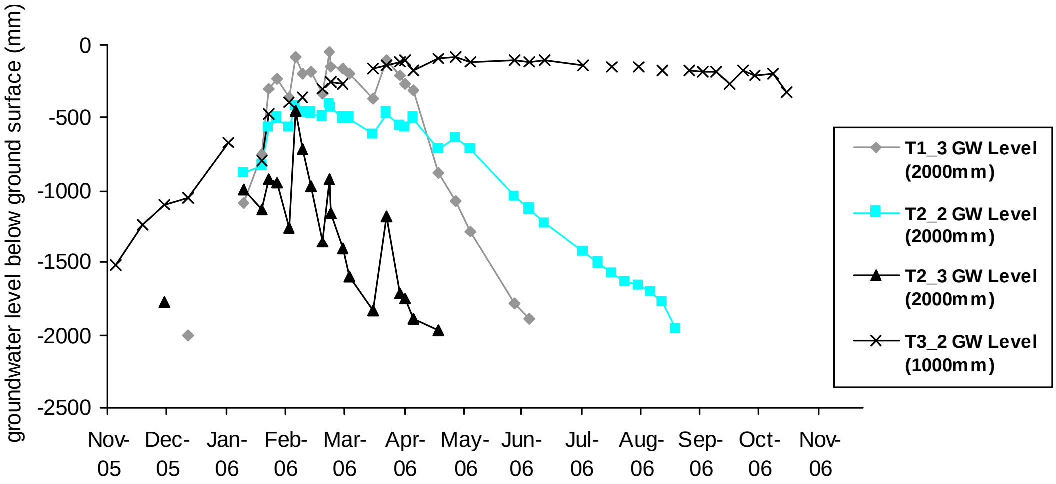

Figure 7. Perched water table permanency.

Figure 8 displays the positions of the perched and permanent water tables at three hydrometry stations in order to describe their longitudinal elevations. Here it is observed that throughout the rains of 2005-2006 the perched water table elevates toward the wetland surface meanwhile there is a deeper recharge to a permanent water table (as this water table was observed during the prior dry season) that also elevates during the rainy period. The significance of this display is the loss of groundwater elevation in the vicinity of active gully erosion for both the perched and deeper permanent water table systems at the site of erosion (nick-point).

Figure 9 documents the temporal fluctuation of the perched water table system at the three stations shown in Figure 8, but also at site MP1 (a stand-alone 6000mm observation well, refer to Figure 4). Here it is noted that all sites seem to experience water table fluctuations at the same time, obviously due to subsurface water inputs to the wetland. However the amplitude of these fluctuations suggests that different hydrodynamic conditions exist between two zones in this headward wetland region. Notably stations T1_3 and T2_2 exist in a larger distinct region were these fluctuations are dampened by some unknown cause, whilst MP1 and T2_3 exist in a smaller and narrower wetland zone with a much more pronounced water table fluctuation.

Figure 10 displays the sub-surface ERT survey conducted at the end of the dry season 2006, the upper image (A) is the initial image displayed without out topography, whilst the lower image (B) is the same survey displayed with topography at a greater number of model iterations. Here the zones of high resistivity indicated areas of substrate disturbance, such as altered wetland topography through subsistence cultivation practices (ridge and furrow systems and hoeing) against areas of undisturbed substrate further upstream. The notable finding from this image is what would appear to be two vertical, narrow bands of low resistance substrate, which are highly likely to be zones of finer sediment, delineated in the absence of groundwater (>3000mm) at the end of the dry season, since clays and groundwater have resistivity which ranges between 1-100 Ωm and 10-100 Ωm respectively.

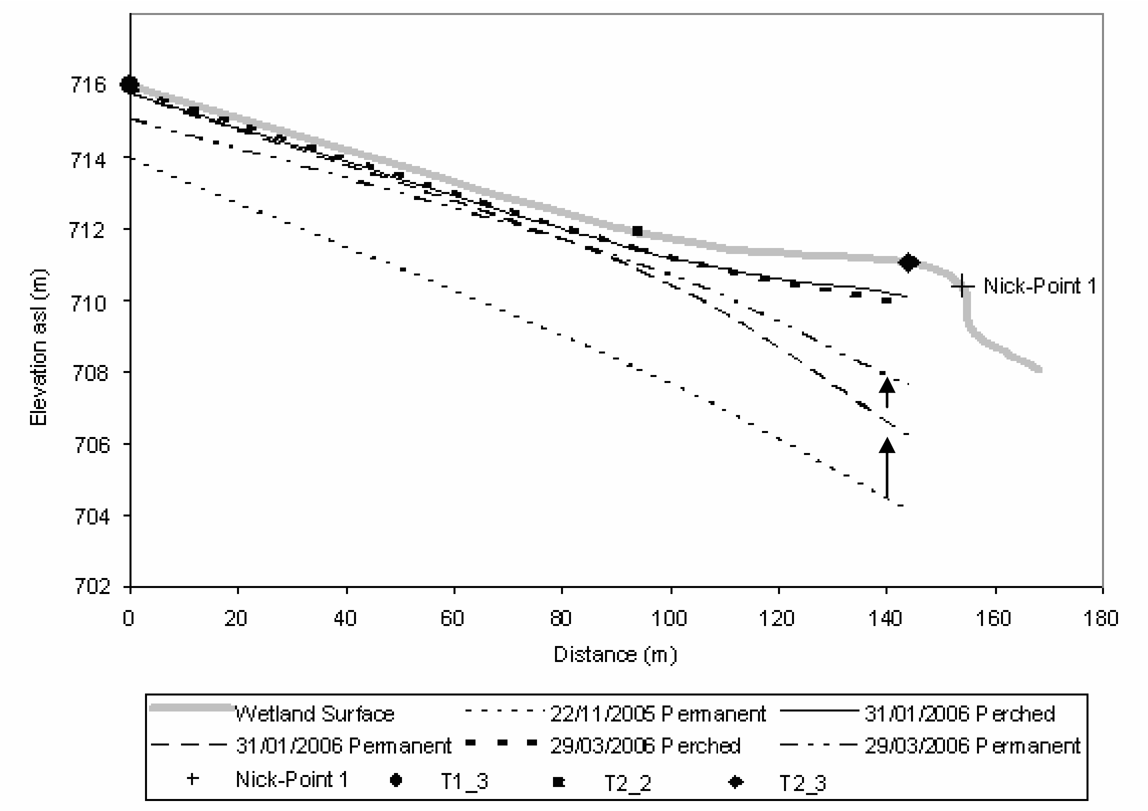

Figure 8. Longitudinal water table stratification during the 2005-2006 rains

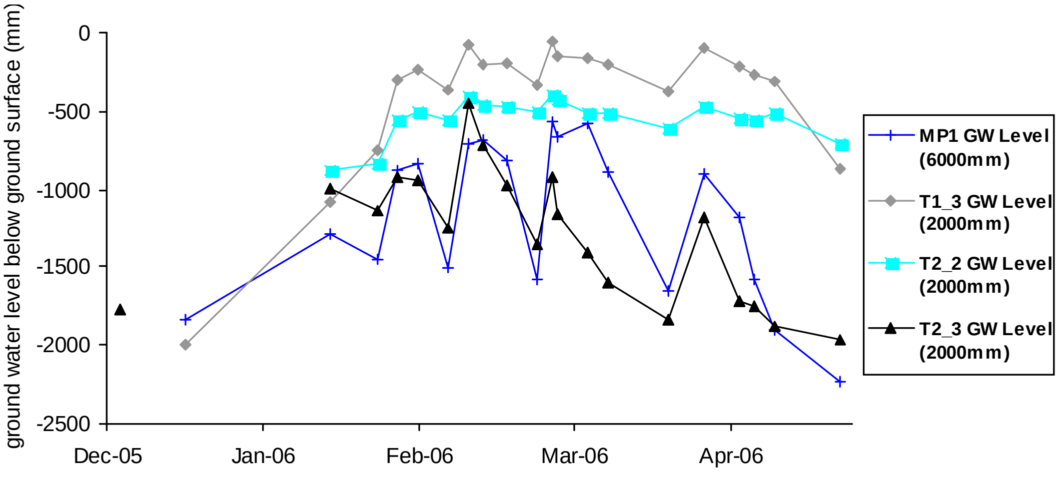

Figure 9. Perched water table behaviour during the 2005-2006 rains at each monitoring station.

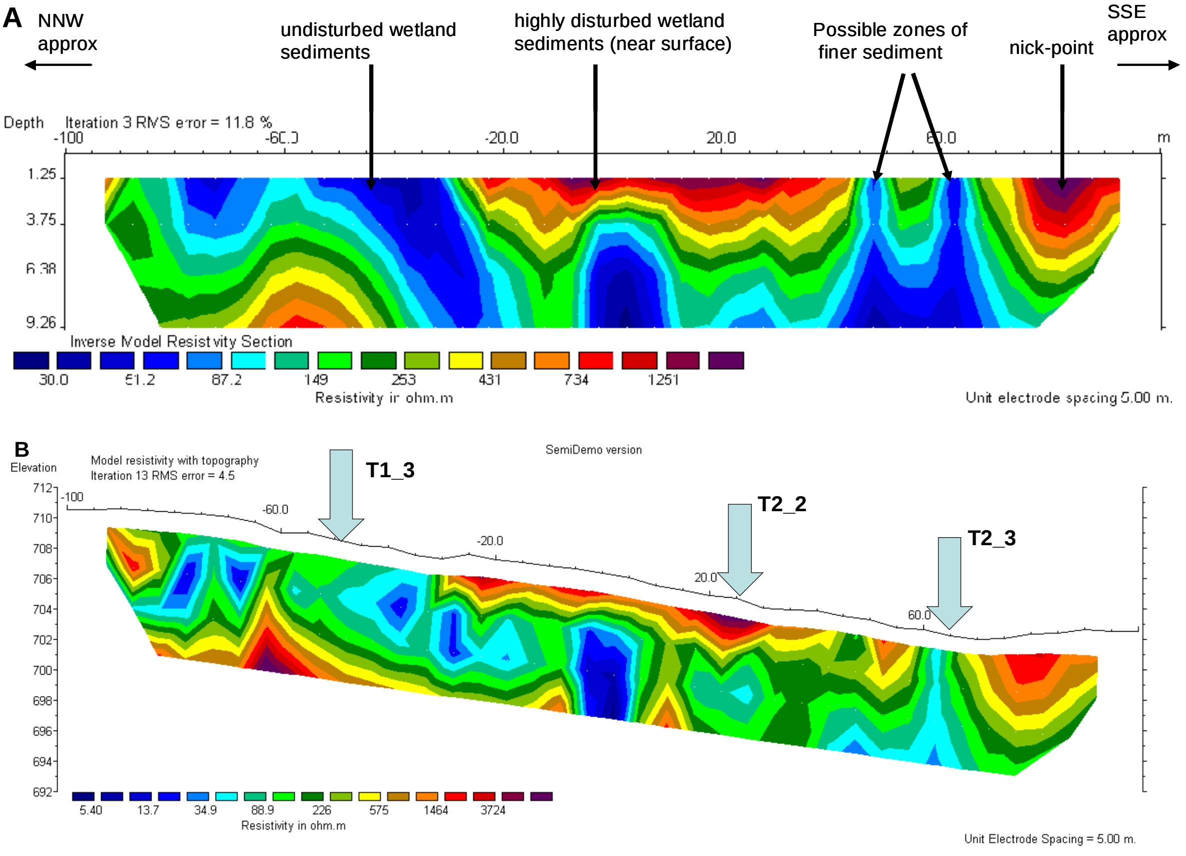

Figure 10. Dry season Two-Dimensional ERT survey longitudinally through headward zone of Manalana wetland (c. October 2006); A displays initial model output with interpretation; B displays model output with increased iteration, topography and relative positions of monitoring stations.

Discussion

Since the findings presented here were collated from the first year in a three year monitoring study their interpretation will be aided by successive hydrological sequences. Nevertheless some important interpretations can be made from them.

Firstly it was observed that the head-ward region of the Manalana wetland responds very quickly to the rapid saturation of deep substrate (2000mm) at the toes of the contributing catchment. It remains to be determined whether this input is caused by lateral through-flow resulting from excessive ponding of water at the soil bedrock interface, which is a distinct possibility as calcrete was observed within 500mm of the soil surface at these hillslope toe positions whilst conducting soil characterisation during the dry season of 2006.

The water table stratification observed is highly likely due to the stratification of different soil textural classes in the wetland substrate, with zones of more conductive coarser sandy materials overlying much less, near impermeable silt-clay bands. Initial soil characterisation in the wetland during the dry season of 2006 at site T1_3 revealed very thin layers of silt-clay, sometimes as narrow as 10mm within the predominantly sandy substrate and these were repeated successively up to a depth of 2000mm. This was the final depth of analysis and therefore these could perhaps exist at still greater depths. These clay bands have probably been created through leaching and capillary forces/vegetation hydraulic lift during the wet-dry cycles, acting to sort the finer sediments from the coarser sediments, this is of course speculative at present, it could also be an event driven phenomena. However this multiple stratification of soil textural classes would suggest that multiple perched water tables (temporally variable), exceeding those observed thus far, may exist in the wetland subsurface.

Furthermore, areas of substrate disturbance such as in the cultivated parts of the wetland may have reduced this stratification phenomenon somewhat to depths were the soil structure has not been artificially altered, in which case certain aspects of the wetlands hydraulic regime may have been irreversibly altered.

The appearance of a deep water table well into the rains, as highlighted by site T2_2 as depicted in Figure 6 also presents an intriguing observation. Since there is a shallower water table (i.e. within 4000mm of the surface) prior to the appearance of the deeper water table recorded in the 6000mm observation well, this would suggest one of two possibilities. First, either this deep zone is linked to a separate input, such as a deeper regional water table. Second, the hydrostatic pressure in the above perched water layer increases to a critical threshold level, such that the positive pressure head of this water induces a rapid infiltration of water through an otherwise low permeability silt-clay layer.

The fact that both permanent and perched water tables when presented longitudinally (Figure 8) seem to slope downward adjacent to site of active erosion suggest a loss of moisture from the wetland subsurface at this point, and this would be expected, especially in this highly conductive substrate. There appears to be some factor that causes a deflection in the hydraulic gradient of the water tables between sites T2_2 and T2_3, this would be a typical seepage zone with a rapid drawdown of subsurface water at the exit (nick-point). Interestingly this deflection is observed in both the perched and permanent water tables during the wet period, whilst at the end of the dry period (i.e. 22/11/2005) there is no deflection in the hydraulic gradient of the permanent water table suggesting much lower hydraulic conductivity of the wetland substrate at deeper depths, which could be inferred from the deeper low resistivity soils in Figure 10, underlying the modified, high resistant soils nearer the wetland surface.

As a 2-Dimensional ERT survey revealed what would appear to be zones of finer sediments between the two hydrometry stations T2_2 and T2_3, the assumption is that this is a controlling factor in the behaviour of the water tables in two regions of the wetland (Figure 9), between the first larger area upstream containing sites T1_3 and T2_2 and a smaller region with sites T2_3 and MP1. Since the water tables in these two regions fluctuate accordingly but with differing amplitudes, and we have seen a loss of water table elevation adjacent to the site of active gully erosion, we can confidently assume that these zones of finer sediments have a retaining influence on the sub-surface hydrodynamics in this wetland.

Conclusion

The first year of hydrometric observation and geophysical analysis of the Manalana wetland has revealed some important observations regarding the hydrodynamic processes in the headwaters of the Sand River system. The fact that zones of finer sediment were found to exist supports the original hypothesis that this is how moisture in the highly conductive sub-surface is retained. This has consequences for further rehabilitation of similarly degraded headwater wetlands in this river system that seek not only to halt the mass removal of wetland sediment but also restore to more natural hydrological regimes in the wetlands and consequently for crucial river system processes. The research however still requires considerable investment to determine the impact of rehabilitation on the wetland water balance, specifically inputs to this and the geomorphic controls existing in these headwater settings.

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