Could alluvial knickpoint retreat rather than fire drive the loss of alluvial wet monsoon forest, tropical northern Australia?

Annegret Larsen (Corresponding author)[1,2]; Jan-Hendrik May[3,4], Patrick Moss[2], Jorg Hacker[5]

[1]Institute of Earth Surface Dynamics, University of Lausanne, 1015 Lausanne, Switzerland. Email: annegret.larsen@unil.ch. Phone: +41216924431; [2]School of Geography, Planning, and Environmental Management, The University of Queensland, Brisbane, 4072, Queensland, Australia; [3]GeoQuest Research Center, School of Earth and Environmental Sciences, University of Wollongong, Wollongong, 5000, New South Wales, Australia; [4]Institute of Earth and Environmental Sciences - Geology, University of Freiburg, 79104 Freiburg, Germany; [5]ARA - Airborne Research Australia, School of the Environment, Flinders University, Adelaide, 5106, South Australia, Australia

Abstract

Drainage rejuvenation through headward migration of alluvial knickpoints is common in ephemeral semi-arid streams, but has not yet been described for tropical rivers. In the Australian monsoon tropics (AMT), wet monsoon forests have an important ecological function, and are present along many alluvial valleys and springs within a eucalypt-savanna dominated landscape. Using a combination of lidar, remote sensing and field evidence, we observe the ongoing destruction of wet monsoon forest through hydro-geomorphic feedbacks, along with the headward retreat of an alluvial knickpoint at Wangi Creek in Litchfield National Park, Northern Territory. Due to the highly transmissive shallow aquifer along the lower Wangi Creek, this knickpoint retreat leads to a downstream drop in in-channel water level, which in turn drives a decrease in the local groundwater table. The lowered groundwater level causes the shallow anabranches and formerly water saturated peaty floodplain soil to desiccate, which results in a reduction of vegetation density. The resulting dry surface conditions allow annual to bi-annual high frequency low-intensity fires to affect the monsoon forest, while wet rainforest upstream of the knickpoint remains intact. In this paper, we argue that such hydro-geomorphic feedbacks may cause the initial destabilization of the forest, which then provides the necessary conditions for the impact of fire. This scenario thus challenges the prevalent view that fire is a first order control on the spatial extent of wet monsoonal rainforest in the study area, and provides a new and testable hypothesis for further studies in the AMT.

Keywords Australia, alluvial knickpoint, destabilisation, fire, hydrogeomorphic feedbacks, Northern Territory, savannah, tipping point, tropical ecosystem, wet monsoon rainforest, airborne lidar

1. INTRODUCTION

Alluvial knickpoints are locations on the long profile with an abrupt change of elevation and slope, and they migrate up valley floors (Schumm *et al.*, 1984). They cause geomorphic instability, are major sediment producers and are typically found in semi-arid, ephemeral and/or discontinuous streams (Bull, 1997, Cooke and Reeves, 1976), but are also described for headwater catchments in swampy environments in South East Australia (Brierley and Fryirs, 1999, Prosser *et al.*, 1994, Young, 1986), and for tropical and subtropical southern Africa (Mäckel, 1973, Whitlow, 1994). Alluvial knickpoints create landforms termed arroyo, wadi or gully, are highly dynamic and can thus have large impacts on natural resources and infrastructure (Schumm *et al.*, 1984). This is not only because of the often deep channel incision downstream of the knickpoint that poses obvious challenges for land-use, but also because of the immediate impact knickpoints have on the riparian vegetation (Schumm *et al.*, 1984). Degradation and/or death of vegetation associated with knickpoint migration, even if not directly impacted by erosional processes, has been widely noted (Hastings and Turner, 1965, Webb and Leake, 2006). It is also well known that vegetation plays an important role regarding the aggradation and surface stability of valley floors before and after knickpoint erosion (Hupp, 1992, Prosser *et al.*, 1995). Surface stability and aggradation may eventually lead to renewed knickpoint incision, representing cyclical behavior of systems exhibiting these features (Schumm *et al.*, 1984). Up to present, however, the feedbacks between hydrology, geomorphology and ecology have only rarely been addressed in the context of detailed field observations or other geomorphic data (Webb and Leake, 2006).

Vegetation strongly influences sediment transport processes, including hillslope and fluvial processes (summarized in Gurnell (2014)). In turn, vegetation is also significantly influenced by local hydrological conditions, most prominently in water-limited and water-logged conditions, but also in areas with variable water table fluctuations (Bätz *et al.*, 2015, Corenblit *et al.*, 2007). However, this reciprocity between hydrologic, geomorphic and ecologic processes often prohibits the distinction between the three factors. It has been shown, that largely undisturbed catchments with a strong inter-annual and annual repetitive nature are likely to exhibit a stronger deterministic control of hydro-geomorphic processes over the ecosystem (Lewis *et al.*, 2000). Such hydrologic conditions are prevalent in the landscapes of the Australian Monsoon Tropics (AMT), which are characterized by strong seasonal contrasts in climate and hydrology (McDonald and McAlpine, 1991, Taylor and Tulloch, 1985). In particular, these landscapes observe large flood magnitudes and high water tables during the wet summer months, and a long period of reduced water availability (Moliere et al., 2009), as well as managed and natural fires associated with the winter dry season. In such extreme conditions, the hydrological, geomorphic and ecological drivers of vegetation dynamics are closely coupled, and small changes in one of these factors has the potential to destabilize the local environmental system. Across the AMT, however, there have been very few detailed studies on hydrology and geomorphology (Hamilton and Gehrke, 2005), limiting the available data on possible hydrogeomorphic feedbacks between vegetation, ecology and fire (Jansen and Nanson, 2004, Tooth *et al.*, 2008). Moreover, the insufficient understanding of the involved physical processes also means that fire has become a prominent explanatory driver of ecosystem dynamics in the AMT (Banfai and Bowman, 2006, Bowman, 2000). As a result, conservation and management measures are more likely to ignore the integration of hydrological and geomorphic aspects, ultimately limiting their effectiveness.

Wet monsoon forests (WMF) in alluvial river valleys and springs along escarpment margins are discrete and insular rainforest pockets within the otherwise savannah-dominated AMT landscapes (Bowman *et al.*, 2010). WMF communities provide important ecological functions; they serve as habitat for species sensitive to the more restricted water supply during the dry season (Russell-Smith and Bowman, 1992), are characterized by increased regional biodiversity, and form natural barriers to low intensity fire propagation. However, they are also vulnerable to environmental change because they have i) small patch sizes, ii) a fragmented distribution, iii) sensitivity to high intensity fires, and iv) large patch margin to internal vegetation ratios (Russell-Smith and Bowman, 1992). Additionally, they are often assumed to be a relic of wetter past climates, and have supposedly fragmented into small patches due to increasing aridity of the Australian continent since the Pliocene (Greenwood *et al.*, 2005, Moss, 2008, Webb and Tracey, 1981).

In this paper, we aim to document and understand the complicated feedbacks between hydrology, geomorphology and ecology within the alluvial valley WMF along Wangi Creek, Northern Territory, Australia - an ecosystem of large ecological, cultural, and economic value; and explain its ongoing destruction associated with the headward retreat of an alluvial knickpoint. We use aerial photography and landsat imagery to document the history of rainforest destruction and airborne lidar to quantify changes in vegetation and surface processes. Field investigations provide evidence on the local hydrologic, geomorphologic and ecologic conditions. We argue that a process-based perspective is essential to improve the protection of these unique ecosystems.

2. Site selection

We selected a tropical river catchment, in which wet monsoon forest is partially intact along the stream, and partially degraded and/or removed. Wangi Creek is an accessible, right-bank tributary of the Reynolds River in Litchfield National Park in the Northern Territory of Australia (Figure 1 a). The majority of its catchment is located on the Litchfield plateau, which is mostly built from quartzites and Neoproterozic sandstone (Ahmad *et al.*, 1993). Here, Wangi Creek forms a shallow bedrock channel with isolated pockets of alluvium. The study reach comprises the lower part of Wangi Creek, in which the creek flows across a slightly inclined pediment plain (~ 2.7 mkm^{-1}), built up by fine grained sediments. The study reach is located between a sandstone escarpment, where Wangi Creek forms a ~70 m high waterfall with an associated plunge pool immediately downstream, and its confluence with several small tributaries shortly before entering the Reynolds River (Figure 1 b, c). Within the studied reach, Wangi Creek is characterised by a well-developed WMF, but this ecotone is only partially intact, and in other parts destroyed. This riparian forest is typical for the AMT ecosystems, which occur as small, distinct patches along rivers and springs, are not affected by fires (Bowman, 1992, Russell-Smith, 1991), and exhibit a sharp boundary to the adjacent ecotone, the tropical mesic, eucalypt dominated savannah (Griffiths *et al.*, 1997, Williams *et al.*, 2003). Savannahs in the region are burnt annually or biannually, mostly by low-intensity anthropogenic fires. Average annual rainfall in tropical Australia is 2000 mm, with more than 90 % of precipitation falling in the six-month summer period between October and March. Rainfall data (Intensity-frequency-duration and daily rainfall) for a ~32 km distant location (Batchelor, NT) also show this strong seasonality and highly repetitive annual nature of high-intensity precipitation events for the area (Supplement Figure 1). Consequently, hydrographs in northern Australia, including the study area are characterized by short-duration and high-magnitude flood events, and large intra- and interannual variability (Moliere *et al.*, 2009). In the study reach, the dry season low flow has been estimated to ~2 m^3s^{-1} (Soper, 2014). Based on flood debris, flood marks and the presence of well-developed flood levees alongside the channel (Nott *et al.*, 1996), the maximum flow depths during the wet season can reach ~3-4 m in exceptional years. This large seasonal contrast is geomorphologically expressed in a channel-in-channel-morphology (Figure 2). The macro-channel varies between 140 and 320 m in width (Figure

2), and is incised into the surrounding gently westward dipping surface, which is partly comprised of deeply weathered bedrock and older sandy alluvial deposits (Ahmad *et al.*, 1993). The elevation difference between this higher surface and the inner-floodplain and channel is ~5 m in the upstream part of the reach and declines downstream to 1.5 m ~6 km away from the escarpment. Dry season channels are incised into the inner-floodplain to variable depths of between a few centimetres to several meters. Enlarged channel sections (waterholes or billabongs) can be up to several meters deep with comparatively low flow velocities. The overall dry season channel pattern is anabranching with the number of parallel anabranches increasing with distance downstream (Figure 3). Fresh sand deposits locally cover small patches of the inner-floodplain surface and confirm its regular inundation.

2. METHODS

In order to analyse and quantify the degree of spatial change in surface topography and associated vegetation disturbance in the WMF covering the floodplain area of the study reach, we performed a detailed spatial analysis of the Wangi Creek channel, floodplain topography, and vegetation cover. This was done on basis of an airborne lidar survey, flown over a ~500 m wide and 4 km long reach (Figure 1) under low flow conditions in June 2013. The lidar was a Riegl Q560 small footprint full waveform resolving scanner mounted on a Flinders University's research aircraft. The lidar was flown at approximately 300 m above the terrain along parallel lines spaced 125 m apart. The lidar point cloud was extracted and geo-referenced from the full waveform data using Riegl's and Flinders University software with an ensuing accuracy of approximately 0.5m horizontally and 0.1m vertically. Using the open source LAStools software (www.rapidlasso.com), the point cloud was then classed into ground and non-ground returns, from which a DTM ("surface-lidar" from ground returns) and a DSM ("canopy-lidar" from first return non-ground returns) at 0.5 m pixel size was derived. Furthermore, canopy density (CD) was derived using non-ground return points (Fieber *et al.*, 2015). Spatial changes in canopy density were calculated using ESRI ArcGis 10.1, and the Geomorphic Change Detection (GCD) add-in (gcd.joewheaton.org/). The calculation describes the net volume between canopy and surface (VCS), and is interpreted as a proxy for vegetation intactness, as CD reduces with increasing disturbance (Fieber *et al.*, 2015). The minimum level of detection threshold was determined to 0.5 m in order to distinguish actual change from inherent noise (Wheaton, 2008). Spatially uniform errors were created and propagated for the channel area, and for three zones within the channel separately (Table 1). All results were clipped to the floodplain area, which was mapped along the flood levees visible on the lidar DEM and verified during the field surveys. Channel centrelines were determined to map the channel pattern. The ARCHydro Toolbox was used to create long profiles along floodplain and longest flow path. In order to derive height differences between floodplain and channel, the closest points on the floodplain and longest flow path were selected using the near-function, and then subtracted.

To assess the longer-term historical evolution of the WMF at Wangi Creek, we visually analysed multi-temporal remote sensing data including historical aerial photography (1941; www.nla.gov.au), CORONA satellite photographs (1966; USGS 2008), atmospherically corrected LANDSAT TM surface reflectance data (1987-2011; www.earthexplorer.com), and high-resolution satellite imagery provided by Bing (September 2012; mvexel.dev.openstreetmap .org/bing) and Google Earth (July 2013; maps.google.com). LANDSAT TM data was visualized in 4-3-1 band combinations allowing for maximized visibility of wetland vegetation (Lillesand *et al.*, 2008). All other images were contrast-sharpened and georeferenced in ArcGIS 10.1.

To verify and complete findings derived from remote sensing, vegetation and geomorphology of the study area was mapped during two field campaigns in October 2013 and May 2014. This mapping included: i) type and condition of the vegetation ii) geomorphic characterization of channel and floodplain, iii) in-channel water level height, and iv) estimated moisture content of the surface soil was mapped. Also, erosional scars and the extent of exposed roots on burnt stems were recorded in order to identify tree damage due to either post- or pre-fire erosion (Table 1). Where possible, channel depth relative to the water surface was also measured.

All field findings were recorded with a hand-held global positioning system (GPS) with a typical horizontal accuracy of ~ 3 m in latitude and longitude. Where possible, a Trimble RTK differential GPS was used in combination with the online post-processing and correction service AUSPOS on the static base station. Catchment-wide spatial analysis such as watershed delineation were processed using the one arc-second SRTM derived Digital Elevation Model (DEM) (resolution 30 m) (Gallant, 2011). In the absence of stream flow data, we used the Australian Bureau of Meteorology`s intensity-frequency-duration (IFD) design rainfall data to show the high intensity of rainfall events in the area, and the available daily rainfall data for the time period between 01.07.2013 – 30.06.2014 to indicate the large differences in rainfall between dry and wet season (Supplement-Figure 1).

4. Results

A single ~1.5 m high, abrupt and well defined step in channel bed elevation divides the study reach into an area with dense, intact WMF and thinned, disturbed and destroyed WMF (Figure 4). This step was observed in October 2013 (Figure 3) at the same location as in the DEM (June 2013), and identified as an alluvial knickpoint. During the dry season, the knickpoint forms a natural divide with regard to the dry season channel morphology and hydrology, as well as the ecology of morphology of the inner-floodplain (Table 1). In order to assess geomorphic, hydrological and ecological variation associated with the knickpoint location, we describe the dominant vegetation, soil characteristics, and geomorphic changes upstream (Zone I) and downstream (Zone III) of the knickpoint (Figures 4 – 6), and within a transition zone surrounding the knickpoints of 2013 and 2014 (Zone II) (Figure 3). To provide longer-term spatial context for our observations, we then document historical changes along Wangi Creek as deduced from remote sensing imagery (Figure 7).

4.1 Variation in hydrology

Within Zone I, the groundwater level was found between 0 and 15 cm below the surface within the inner-floodplain, resulting in waterlogged and anoxic subsurface conditions, and creating ideal environmental conditions for peat development (Figure 5 b). Subtle topographic depressions of ~20 - 30 cm depth within the undulating inner-floodplain surface allow groundwater to intersect the surface, creating areas with shallow water on the inner-floodplain (Figure 5 b). Immediately adjacent to the knickpoint, (Zone II) and further downstream (Zone III) (Figure 3), the inner-floodplain surface is dry. The in-channel water table of all anabranches has dropped significantly by more than one meter, which is approximately the same height as the knickpoint. This also means that shallow anabranches in Zone II and III with a depth of less than 1 meter have fallen entirely dry (Figure 5 c).

4.2 Variation in geomorphology

Within Zone I, Wangi Creek consists of two parallel channel anabranches (Figure 3), along with several billabong-type expanded channel sections. Lidar measurements indicate that the channel width fluctuates between 28 and 80 m (average ~38 m) (Figure 6 c). Field evidence suggests dry season channel widths of ~ 3- 36 m. Upstream of the 2014 knickpoint location, dry-season-and macro-channels seem to have the same extension (~40 – 80 m) (Figure 3, 5 b). However, field evidence suggests several meters wide and only a few centimetres incised anabranches within this area, with the high water floodplain table likely being the reason for these contrasting observations. Between October 2013 and May 2014 the knickpoint location had migrated 337 m upstream (Figure 3). We observed a consistent ~1.5 m offset within the long profile at the 2013 and 2014 knickpoint locations (Figure 1 c). The same height difference is also recorded in the lidar derived elevation difference between the in-channel low flow water level and the channel bank height (Figure 5 a). Upstream of the knickpoint (Zone I), this height difference is between 0- 1.5 m (often close to bankfull), while downstream of the knickpoint Zone II and III) the height difference increases abruptly to between 1.5-3.6 m (Figure 6 a). Lidar derived channel width also undergoes significant change at the knickpoint location (Figure 6 b). In Zone I, lidar derived channel width is between 3 and 36 m width, but highly variable. In contrast, channel width immediately contracts to 9.4 m on average with the transition into Zone II. The channel starts to progressively widen further downstream and settles between 10 and 25 m (average ~16 m) (Figure 6 b).

4.3 Variation in vegetation and soil

Along the entire study reach the WMF is restricted to the macro-channel area. Within zone I, the dominant vegetation community is consistently tropical moist mesophyll forest (Table 1). Dominant canopy tree species are: *Carpentaria acuminata, Calophyllum soulattri, Carallia brachiata, Eleocarpus arnhemicus, Xanthostemon eucalyptoides,* while in the understory tree species are: *Pandanus spiralis, Pandanus aquaticus, Hyriastele Wendlandiana, Helicia australasica. Pandanus spiralis* and *Pandanus aquaticus* were observed preferentially along the channel margins, forming a riparian community distinct from the surrounding plant communities (Griffiths *et al.*, 1997). No obvious fire marks were identified within the WMF, even though the adjacent higher elevation surfaces (savannah) had recently burnt. Flood marks and recent flood debris in trees were very common. The soil type in the inner-floodplain is a histosol characterized by a ~0.5 – 1.5 m thick organic A-horizon with occasional sand-lenses (WRB, 2014), overlying fluvial sands, and water saturated up to the surface. The A-horizon is composed of a dense, fibrous root mass of low bulk density (i.e. peat). CD percentage is 76 %, and VCS reaches values of 4.7 ± 0.4 m (Table 2).

Within the transition zone (Zone II) immediately downstream of the 2013 knickpoint, the vegetation was recently burnt to variable extents (Figure 5 b-c). The large canopy trees were mostly intact and showed signs of recovery from the recent fire by re-sprouting and flowering, as did *Pandanus aquaticus* where adjacent to or within the dry season channels (Figure 5 c). Other understorey plants, except from (invasive) grass species, such as Gamba Grass (*Andropogon gayanus*) exhibited no obvious signs of re-establishment. Interestingly, exposed and burnt tree roots indicate that the peaty soil had lost ~30 cm of surface elevation (Figure 5 d) even though there were no signs of physical (fluvial) erosion of the top soil (Figure 5 c, 5 d). Given the very low bulk density of peat, this suggests that the soil had compacted prior to the fire. VCS values were calculated to be 3.6 ± 0.4 m, and CD drops to 72 % (Table 2).

Zone III starts ~500 m downstream from the 2013 knickpoint location (Figure 3), where much of the peaty soil is physically eroded, rather than compacted, and exposes the underlying alluvial sands

(Table 1). In addition, many WMF canopy trees have toppled, leaving mainly *Melaleuca* and *Eucalyptus* trees in place, albeit severely burnt (Figure 5 f). Some channel sections are completely covered with toppled trees. In situ tree stumps with exposed and burnt roots are scattered over the inner-floodplain. Grasses, sedges and seedlings grow mainly along the riparian channel margins and in isolated patches on the inner-floodplain (Figure 5 h). Their density, size, and biomass volume increase with distance downstream (Figure 6 b). VCS values drop to the lowest recorded values of 2.6 ± 0.3 m, as does CD (59 %) (Table 2).

The most obvious and marked changes to the soil and ground surface between the 2013 and 2014 field surveys were observed immediately downstream of the 2013 knickpoint location (Table 1). Here, in 2013 the peaty soil had been compacted by ~30 cm, but was otherwise intact, and signs for physical erosion were absent. In 2014 however, the top horizon in the same area was heavily fractured, without significant internal structure, and in many places fragmented by physical erosion. In addition, a substantial amount of vegetation, especially *Pandanus aquaticus* growing adjacent to dried out dry season channels, had died.

4.4 Long-term changes in rainforest extent

The visual interpretation of remote sensing imagery shows that the WMF within the entire alluvial section of our Wangi Creek study reach was intact between 1941 and ~1990 (Figure 7). The first signs of disruption appears in the early 1990s (1989 - 1995) landsat TM imagery as a ~100 m long interruption of vegetation (red in false-colour imagery) 5 km downstream from the plunge pool (Figure 7). In the following ~5 years, vegetation cover along a ~350 m reach immediately upstream of the point of initial disruption is characterized by low surface reflectance (blue-cyan) indicating continued fragmentation and decline of vegetation cover in this area. By ~2002, the rainforest vegetation had fragmented into disconnected patches of forest extending ~1 km upstream of the initial disruption, and had reached the limit of the Litchfield National Park (marked by a fence line) in 2006. By 2012, the rainforest fragmentation along Wangi Creek had migrated ~1.9 km upstream of the initial disruption. Along the entire area of disruption, the rainforest only persists in ~50-100 m small and disconnected patches and pre-existing billabongs had disappeared (Figure 7). On average the knickpoint migrated 116 m yr^{-1}, but accelerated (to ~370 m yr^{-1}) during the wet season 2013/2014 (Figure 3).

5. Discussion

5.1 First order control of the Alluvial Knickpoint

Our results show that the dry season channels and the inner-floodplain of the alluvial reaches at Wangi Creek experience major and sudden hydrologic, geomorphic and ecological disturbance. We suggest that the simplest explanation for a common first order control on all these changes is the presence and headward retreat of an observed alluvial knickpoint with time.

To our knowledge, alluvial knickpoints have not yet been described for tropical rivers. The processes related to knickpoints described here are different from those described by Brooks *et al.* (2009) where gullies dissecting older alluvial sediments of major Australian tropical river systems are typically constructing dendritic drainage patterns. Globally, alluvial knickpoints are common geomorphic features in discontinuous ephemeral streams in semi-arid areas, and have been studied in detail in the southwestern USA (Bull, 1997, Schumm and Hadley, 1957). In South East Australia, alluvial knickpoints were also observed to be the erosional mechanism of cut- and fill cycles in swampy headwater catchments (Fryirs and Brierley, 1998, Prosser *et al.*, 1994), peatland bogs (Nanson, 2009) and in the chain-of-ponds systems (Eyles, 1977, Eyles, 2007). When comparing the physical characteristics of catchments exhibiting alluvial knickpoint retreat (including this study) common characteristics include, i) high flow variability, ii) a resistant layer, either related to a dense vegetation cover or a cohesive sediment or soil, overlying an erodible substrate, iii) high volume fraction of fine-grained erodible material and iv) a flat valley-fill shape with unchannelized sections.

5.2 Mechanisms and feedback between geomorphology and hydrology

Even though precipitation is highly seasonal, stream flow within the study reach persists throughout the dry season, which is very likely favoured by a widespread shallow aquifer within the inner-floodplain, which creates the very high groundwater level upstream of the knickpoint. In turn, the perennial flow and maintenance of a relatively shallow ground water table are likely the result of a combination of processes. Firstly, the water storage within the highly fractured upper catchment sandstone escarpment (Lau *et al.*, 1987) effectively provides a stable upper boundary condition for the downstream alluvial aquifer enabling perennial flow conditions, as well as shallow water tables in the dry winter months (Dunne, 1990). This hypothesis is also supported by the observation of numerous pockets of WMF unrelated to any obvious drainage lines along the lower slopes of the sandstone escarpment (Figure 1 a), which are likely sustained by groundwater springs at the break in slope (Dunne, 1990). Secondly, along the alluvial reaches of Wangi Creek downstream of the escarpment, groundwater flow in the highly transmissive sand and peat alluvial aquifer within the inner-floodplain is likely laterally confined by the deeply weathered and clayey meta-sediments which form the macro-channel boundary (Ahmad *et al.*, 1993). The resulting limited storage and continuous replenishing from the upstream fractured sandstone aquifer potentially explain the very shallow water table in the inner-floodplain, which sets the conditions for perennial flow within the low flow (dry season) channel aquifer.

Approximately 350 m upstream of the knickpoint, Wangi Creek flows in several shallow anabranches, which become increasingly constricted in a downstream direction, and are then abruptly channelized into a 3 m wide channel just downstream of the 1.5 m vertical drop of the low-flow water table (knickpoint) (Figure 6). This results in much greater exposure of the downstream channel banks (Figure 6), which leads to undercutting and decreasing bank stability. This then promotes bank failure including the destruction of the riparian vegetation and their protecting root systems (Figure 8 b), and subsequent widening of the channel farther downstream of the knickpoint. This first contraction of sheet flow to a single and narrow channel and subsequent widening of the channel seems to be fairly typical for alluvial knickpoint incision in semi-arid regions (Webb and Leake, 2006). Further downstream, entire sections of the inner-floodplain were subject to floodplain stripping during the wet season 2013/2014 (Figure 4 g-h). This process eroded the topmost sediments across the full floodplain width and exposing an uneven sandy surface. Dry season channels became wider and shallower due to bank instability and subsequent aggradation of the channel bed (Figure 4 h, 5 b). Even though a complete quantification of sediment flux is beyond the scope of this paper, there are strong signs that there is a net erosion of sediment in Zone III within the dry season channel and inner-floodplain area (Figure 6).

The described contrast in channel water elevation upstream and downstream of the knickpoint results in a locally increased groundwater gradient or 'drawdown' towards the downstream channel. This causes a relative drop in the water table within the entire inner-floodplain downstream of the knickpoint, enabled by the highly porous nature of the sandy but laterally confined aquifer (Figure 8). This drawdown of the shallow ground water table has also been described by Webb and Leake (2006), and provides a powerful explanation for the widespread observation of vegetation death surrounding alluvial knickpoints.

5.3 Mechanisms and feedback between hydro-geomorphology and ecology

Even though any dense WMF vegetation has high water demand that might present a physiological challenge given the highly seasonal climate (Griffiths *et al.*, 1997), it was found that the WMF upstream of the knickpoint persists throughout the dry season because of the perennial streamflow and the shallow floodplain ground-water level. In combination, these conditions provide the basis for the accumulation of organic material, and ultimately the development of histosols and thick peat deposits (Figure 4 e). These environmental conditions are likely to be representative of the entire inner-floodplain prior to the initial disturbance in 1990, and the subsequent knickpoint retreat.

The WMF is well adapted to local hydro-geomorphic conditions, including species tolerating permanently water-logged conditions and annual large flood events (Griffiths *et al.*, 1997). This results in the development of dense root networks, peat soils and a stable and resistant floodplain surface (Figure 4 a-b, e). Additionally, the very dense root network of the riparian vegetation, dominated by *Pandanus aquaticus* and *Pandanus spiralis,* stabilizes channel banks and thus likely controls the position of major anabranch channels (billabongs) for decades (Figure 7). As a result, no signs of bank slumping or erosion along the channels were found in Zone I, and the billabong channel sections have very steep channels banks and the typical low width/depth ratio. This physical integrity/stability combined with the recent deposition of sand lenses on the inner-floodplain surface indicates that Zone I is currently a depositional environment, in which the dense vegetation effectively stabilizes the surface, protecting the sediment against erosion in areas with unchannelized low-flow and during the very high flow events experienced in the wet season. This also means that under intact conditions, the inner-floodplain is likely to accrete through time.

The knickpoint causes a relative drop in the water table within the inner-floodplain, especially during the dry season which in turn results in a more limited water supply for vegetation, especially impacting the understorey component (Figure 4 c), and is reflected in the drop in VCS (Figure 5 c). Riparian *Pandanus* trees are particularly affected, as they must source their water directly from shallow anabranches, which become dry as the knickpoint advances (Figure 4 c). Larger trees within the inner-floodplain are not immediately impacted, likely because their root systems are still able to reach the lowered aquifer. However, as the peat horizon begins to decompose and subside due to oxidization under drier conditions, tree roots are exposed, ultimately decreasing the stability of the taller vegetation and making the WMF more vulnerable to regularly occurring flood events (Figure 4 d). Under these circumstances, the decomposition of the peat soil and the destruction of the WMF vegetation can potentially be accelerated by fires within the inner-floodplain (Figure 4 c-f).

In Zone III, the peaty surface soils have been mostly eroded (Figure 4 g,h), the WMF is largely degraded (Figure 4 g), and partially replaced by small sclerophyll shrubs (Figure 8 c, Table 1). Some *Melaleuca* and eucalypts remain scattered across the inner-floodplain, with all the larger WMF trees toppled. These trees (especially in the riparian zone) are then a source of the large logjams, which appear further downstream and promote backwater effects, overbank flow and floodplain erosion. This causes the distance between floodplain and in-channel water table to decrease (Figure 6) and potentially leads to hydrological conditions comparable to those upstream of the knickpoint, re-establishing a high water table in the floodplain and returning to conditions favourable for the establishment of WMF. This would suggests that the hydro-geomorphic processes and feedbacks destabilizing and destroying the rainforest pockets at Wangi Creek may be cyclical rather than irreversible. This ultimately depends on the applied temporal perspective and time frame. Further investigation into the late Quaternary dynamics is therefore needed in order to clarify the cyclicity of erosion and deposition in this river system, and with it the resilience and recovery of the rainforest ecosystems over longer time scales.

5.4 Timescales of ecosystem destruction

In the years between 1994 and 2006 the formerly continuous cover of WMF along Wangi Creek shows a clear tendency towards fragmentation (Figure 7). We hypothesize that the onset of this destabilisation is caused by the initiation and upstream migration of the knickpoint, and the associated hydrological and ecological feedbacks are impacting the WMF in a spatially heterogeneous way. Knickpoint retreat rates mainly depend on stream power and erodibility of the substrate (Schumm *et al.*, 1984), and therefore are likely to be relatively constant with the annual occurrence of high discharge events within the relatively homogeneous peaty and sandy alluvium along Wangi Creek. If this is the case, then we can use the timing and rough location of the forest disturbance in the years between 1994 and 2014, and the lidar survey in 2013, to estimate rates of knickpoint retreat. According to these data, the knickpoint has migrated with an average rate of ~116 m yr^{-1} over the last 24 years (Figure 9). By association, these results therefore also represent the significant pace with which hydro-geomorphic feedbacks proceed to destabilize the WMF pockets in the AMT.

Mechanisms triggering the initiation of alluvial knickpoints are widely discussed throughout the literature, and possibilities given are i) climate variability (Bull, 1997, Tucker *et al.*, 2006), ii) land-use change (Eyles, 2007, Fryirs and Brierley, 1998) or iii) base-level drop caused by the incision of the tributary, or the steepening of the gradient through accumulation (Schumm *et al.*, 1984), or some combination of the three. Even though our data does not allow the unambiguous identification of the triggering mechanism of the alluvial knickpoint at Wangi Creek, one possible scenario could be that increasing/continued aggradation over time along the lower study reach overcame a topographic threshold enabling a minor alluvial knickpoint, which could have migrated upstream with a relatively stable retreat rate of 116 m yr^{-1} (Figure 9). Also, enhanced wet season precipitation since the 1990s could have led to increased wet season stream flow in the region, for which there is evidence from the Daly River (~ 50 km SW of the study area) (Jolly, 2001, Wasson *et al.*, 2014, Wasson *et al.*, 2010). As land-use is extensive or not existent in the study area, and no signs for intensive fire were detected on satellite imagery since the 1990s, we hypothesize that a combination of enhanced wet season stream flow and the overcoming of a topographic threshold might be the trigger mechanisms for knickpoint initiation. Clearly, further research is required to clarify the initiation of the knickpoint in more detail.

5.5 The role of fire

Low intensity fires only very rarely impact intact WMFs in the AMT (Bowman, 2000). This notion is supported by the lack of field evidence for fire impacts within the intact WMF zone at Wangi Creek. The reason for this low impact of fire likely relates to the waterlogged surface, and the resulting minimal availability of any dry biomass or fuel load.

From remote sensing and field observation, it became clear that fire affects the floodplain only downstream of the knickpoint (section 5.4). Our observations suggest that this is likely related to the significant drop in groundwater table. As a result, i) many previously open surface water features, particularly the anabranch channels, are without water in the dry season, ii) the surface is not waterlogged, and iii) the dry peat provides abundant fuel. In tropical rainforests with shallow groundwater and peat development in Indonesia, the incursions of forest fires are attributed almost exclusively to human impact (Siegert *et al.*, 2001), and more specifically to the artificial drainage of the peat for logging (Page *et al.*, 2009, Wösten *et al.*, 2008). In contrast, intact Indonesian peat swamp forests appear to be little impacted by fire (Page *et al.*, 2002). Even though these Indonesian peat swamp forests are much larger in extent than the WMF in Northern Australia, our observations suggest by analogy that the drainage and drying of the peat surface and subsequent burning are broadly the same processes, only at Wangi Creek - and possibly in many other, similar rainforest pockets in the AMT - they are achieved via different pathways/triggering mechanisms (anthropogenic draining vs hydro-geomorphic feedbacks). More specifically, it appears that low-intensity fires can only affect the inner-floodplain vegetation following initial disturbance amplified by subsequent hydro-geomorphic feedbacks such as those related to an alluvial knickpoint (Figure 9). This role of fire within the feedback loop between hydrology, geomorphology and ecology clearly needs further testing, instead of assuming its dominance within all ecotones. Additionally, it is unknown how widespread alluvial knickpoints in rivers within the AMT are, but there is a chance that they may represent an important erosional mechanism within low-order streams. If this is true, then understanding the exact feedbacks, and especially exploring the triggering mechanism is of large importance for the management of the affected streams.

CONCLUSIONS

Our findings and the resulting interpretation shows that wet monsoonal forest loss and extension at Wangi Creek is the result of peat development and highly localized geomorphic, hydrological and ecological feedbacks. This differs from the widely published view that fire controls the extension and loss of rainforest in the AMT (Banfai and Bowman, 2006, Bowman, 2000). Further work, including more detailed monitoring is required to understand the detailed mechanisms and feedbacks leading to the destruction of the monsoonal forest, and test the wider applicability of the conceptual model developed in this study. Our results have shown average knickpoint migration rates of 116 m yr^{-1}, which can accelerate up to 370 m yr^{-1} in years of large flood events. These rapid rates seem to herald the potentially ongoing destruction of the WMF at Wangi Creek over the next few decades. While the exact causes of knickpoint initiation and upstream migration remain unclear, the effects on floodplain geomorphology and ecology are remarkably visible and are most likely subject to complex feedback mechanisms, such as i) groundwater table lowering resulting from the headward migrating knickpoint and the highly transmissive shallow and confined aquifer, ii) followed by drying and subsidence of the surface peat, and iii) potential burning of the dry peat and vegetation, eventually leading to the loss of channel bank and floodplain stability, subsequent slumping, lateral erosion, and channel widening.

ACKNOWLEDGEMENTS

The authors thank the Australian Research Council (ARC) for funding, Litchfield National Park for access and support, and Aidan Soper for field support. We also thank Joshua Larsen, Stuart Lane and two anonymous reviewers for their critical review of the manuscript, which greatly improved it.

FIGURE CAPTIONS

Figure 1: The Wangi Creek catchment

a) Field area location, including adjacent creeks and wet monsoon forest distribution, and the seasonal wetlands, estimated on base of Landsat 7, band-combination 5-4-3. The inset highlights the Litchfield Plateau region in Northern Australia.

b) Wangi creek long profile, derived from SRTM data, and continued through to sea level. The study reach is marked as a box.

d) Study reach long profile (derived from high resolution lidar data), from Wangi plunge pool (downstream of the Wangi waterfall from Litchfield Plateau), to the confluence with the trunk stream.

Figure 2: The geomorphology of Wangi Creek exhibits macro- and dry season channels, and two floodplains. The surface of the macro channel, the floodplain and the in-channel water table (dry season channels) is derived from a high-resolution DEM, the dry season channel dimensions are estimated from field measurements.

Figure 3: Wangi creek flow pattern and disturbance. Foreground: Flow pattern of Wangi Creek within the study reach and cross-sections through the channel area (A – F). Note: Cross sections display the height of the in-channel water levels, as they are derived from lidar data. Background: Wangi creek valley with indication of vegetation density (VCS) (white = low, black = high) from lidar.

Zone I is undisturbed wet monsoon forest, Zone II of moderate disturbance and migrating with the position of the knickpoint in 2013 and 2014, and Zone III is burnt and heavily disturbed.

Figure 4: Photographs of different parts of the research area, from upstream (a) to downstream (h). (a) intact wet monsoon forest; (b) high ground water level in the inset-floodplain during dry season, including the top of a ~ 1 m thick peat horizon covered by a sand deposit; (c) the drying up of shallow anabranches followed by a fire affects riparian vegetation. Note: no physical surface erosion can be found; (d) 30 cm exposed and burnt roots, and no signs of physical erosion indicate the compaction of the peat due to drainage. Roots were burnt after compaction; (e) a ~ 1 m thick peat horizon overlying fluvial sands; (f) knickpoint in 2013, with unbunt riparian vegetation upstream (background), and burnt riparian vegetation downstream (foreground). Note: the tree on the right side has fallen over because of a stability loss due to the erosion of the near-surface layers; (g) Residual patch of dries out peat within a heavily eroded and burnt channel area; (h) sandy, heavily eroded channel area with successional vegetation in the background.

Figure 5: Lidar data derived graphs showing the impact of the knickpoint in 2013, following distance downstream (x-axis). (a) Volume between canopy and surface (m^3/m^2) along the channel long profile (0.5 m pixel size); (b) channel width (m) measured at the height of the in-channel water table; (c) height difference (m) between in-channel water table and inner-floodplain. Data displaying negative values in (a) were deleted, which is reflected in smaller point density in areas with lower values.

Figure 6: Long profile of Wangi Creek and vegetation (both based on high resolution lidar data). The dashed line indicates an estimation of the Wangi crook long profile before the knickpoint started to retreat.

Figure 7: Satellite imagery. Visually analysed multi-temporal remote sensing data including historical aerial photography (1941), declassified intelligence CORONA satellite photographs (1966), atmospherically corrected Landsat TM surface reflectance data (1989-2007), and high-resolution satellite imagery provided by Bing (2012).

Figure 8: Schematic model of destabilisation of the channel area of Wangi creek. (a) intact inset-floodplain upstream of knickpoint. The in-channel and ground water table is permanently high in the subsurface of the inset-floodplain, and a histosol with a ~ 1 m thick peat horizon is developed; (b) the knickpoint has caused a drop of in-channel and ground water table. This initiated the contraction of the peat horizon (dashed line indicates surface during intact conditions) and channel banks to become instable. Shallow anabranches fall dry and vegetation with shallow roots die because of an interrupted water supply during the dry season; (c) the entire peat horizon is eroded, the surface rugged, trees were destabilized and have fallen over. The surface lowering relative to the surface under intact conditions (dashed line) has causes again a relative high in-channel water and ground water table. Question marks indicate that the exact boundaries between the shallow aquifer and the less permeable layers are unknown.

Figure 9: Knickpoint retreat rate between estimated year of initiation (1990) and last field investigation 2014. Circles represent estimation of knickpoint location made from remote sensing (RS), boxes from field measurements. The overall knickpoint retreat rate is 116 m $yr^{-1,}$ (the negative slope originate in the distance being measured downstream from the plunge pool).

Supplement Figure 1: Rainfall intensity chart (a), and annual distribution of daily rainfall (b) in Litchfield National Park. a) The rainfall intensity for each standard ARI is plotted on a graph of intensity versus duration. Colourful lines represent analysis near the study area (13.175°S;

130.675°E). The grey area indicates the range of ARIs between 1 and 100 year from a temperate region in SE Australia (35.657°S, 149.254°E) for comparison. The range of duration on the x-axis is from 5 minutes to 72 hours. The seven curves: for 1, 2, 5, 10, 20, 50 and 100 year ARIs have a negative gradient, consistent with experience that heavier rainfall occurs over shorter durations. This graph indicates the high probability (63.2 %) of rainfall events delivering more than 40 mm hr^{-1} to occur annually. Data download: 09/10/2015. B) Daily rainfall data and cumulative rainfall from Batchelor, NT (weather station directory number 014233, coordinates: 13.05°S, 131.03°E, and elevation: 104 m) shows the strong seasonality of rainfall between 1/7/2013 and 30/6/2014, with nil daily rainfall values during the dry season (April – September) and up to 92.2 mm d^{-1} during the wet season (October – March).

TABLES

Table 1: Field observations within the area close to an alluvial knickpoint (Surveys in October 2013, and May 2014)

Year AD	2013				2014			
Channel length[1] (GPS coordinates)	Geomorphology and Hydrology	Ecology	Fire	Figure	Geomorphology and Hydrology	Ecology	Fire	Figure
1432 m (681507/8543567/20)	Two channels, water table ~ 20 cm underneath surface, peaty subsurface	Gallery Rainforest	no	4 a,b	Same as 2013	Same as 2013	same	same
2534 m (681046/8542845/17)	Two channels, one of which is a billabong, high water table in floodplain	See above	no	4 a, b, c	Knickpoint, watertable in waterhole has dropped ~ 1.5 m, exposed banks, downstream of knickpoint dry floodplain surface, upstream wet floodplain surface.	Same as 2013	no	4 d
2601 (681045/8542814/17)	n/a	n/a			Channel bank slumping creating log jams, dry floodplain surface, ~ 30 cm of tree roots exposed	Degraded Gallery Rainforest with ferns	no	4 e, g
2965 m (680977/8542518/16)	1.5 m high knickpoint, surface dry, 30 cm of tree roots exposed, no	Burnt *Pandanus* and *Melaleuca* forest	yes	4 c, d, e	Heavily eroded floodplain, soil unstable, roots of all	Degraded *Pandanus* and *Melaleuca forest*	yes	4 f

	signs for surface erosion				trees exposed			
4430 m (680662/8542408/14)	Heavily eroded and dry floodplain, shallow and wide channel, floodplain stripping, some patches of dried peat left	Savanna	yes	4 g	Heavily eroded and dry floodplain, shallow and wide channel, floodplain stripping, small patches of dried peat left	Savanna	yes	
3676 m (680612/8542207/14)	Heavily eroded and dry floodplain, shallow and wide channel, no soil left	Grass and young *Pandanus*	yes	4 h	Heavily eroded and dry floodplain, shallow and wide channel, no soil left	Grass and young *Pandanus*	yes	4 h

[1]measured from plunge pool in downstream direction

Table 2: Results of GCD estimate

	Area (m²)	% vegetation cover	Net difference between canopy and surface (m³)	Mean distance between canopy and surface (m)	Mean distance between canopy and surface (m), including only pixels with detectable change
Zone1	616145.7	76	2874790.3 ± 234278.6	4.7 ± 0.4	6.1 ± 0.5
Zone2	66151	72	238671.8484 ± 23673.4	3.6 ± 0.4	5.0 ± 0.5
Zone3	429287	59	1132701.236 ± 127439.4	2.6 ± 0.3	4.4 ± 0.5
Total	769963.3	69	4248203.4 ± 384981.6	5.5 ± 0.5	5.5 ± 0.5

Rounded to one decimal point

References

Ahmad M, Wygralak AS, Ferenczi PA, Bajwah ZU. 1993. Explanatory Notes and Mineral Deposit Data Sheets - Pine Creek SD 52-8. In *1:250.000 Metallogenic Map Series*, Survey NTG (ed): Darwin.

Banfai DS, Bowman DMJS. 2006. Forty years of lowland monsoon rainforest expansion in Kakadu National Park, Northern Australia. Biological Conservation **131**: 553-565. DOI: http://dx.doi.org/10.1016/j.biocon.2006.03.002

Bätz N, Verrecchia EP, Lane SN. 2015. The role of soil in vegetated gravelly river braid plains: more than just a passive response? Earth Surface Processes and Landforms **40**: 143-156. DOI: 10.1002/esp.3631

Bowman D. 1992. Monsoon Forests in North-Western Australia. II. Forest-Savanna Transitions. Australian Journal of Botany **40**: 89-102. DOI: http://dx.doi.org/10.1071/BT9920089

Bowman DMJS. 2000. Australian rainforests: islands of green in a land of fire. Cambridge University Press: Cambridge

Bowman DMJS, Brown GK, Braby MF, Brown JR, Cook LG, Crisp MD, Ford F, Haberle S, Hughes J, Isagi Y, Joseph L, McBride J, Nelson G, Ladiges PY. 2010. Biogeography of the Australian monsoon tropics. Journal of Biogeography **37**: 201-216. DOI: 10.1111/j.1365-2699.2009.02210.x

Brierley GJ, Fryirs K. 1999. Tributary–trunk stream relations in a cut-and-fill landscape: a case study from Wolumla catchment, New South Wales, Australia. Geomorphology **28**: 61-73. DOI: http://dx.doi.org/10.1016/S0169-555X(98)00103-2

Bull WB. 1997. Discontinuous ephemeral streams. Geomorphology **19**: 227-276. DOI: http://dx.doi.org/10.1016/S0169-555X(97)00016-0

Cooke RU, Reeves RW. 1976. Arroyos and environmental change in the American South-West. Clarendon Press: Oxford
Corenblit D, Tabacchi E, Steiger J, Gurnell AM. 2007. Reciprocal interactions and adjustments between fluvial landforms and vegetation dynamics in river corridors: A review of complementary approaches. Earth-Science Reviews **84**: 56-86. DOI: http://dx.doi.org/10.1016/j.earscirev.2007.05.004
Dunne T. 1990. Hydrology, mechanics, and geomorphic implications of erosion by subsurface flow. In *Groundwater Geomorphology*, Higgins CG, Coates DR (eds). The Geological Society of America: Boulder, Co; 367.
Eyles RJ. 1977. Birchams Creek: the transition from a chain of ponds to a gully. Australian Geographical Studies **15**: 146-157. DOI: 10.1111/j.1467-8470.1977.tb00094.x
Eyles RJ. 2007. Changes in drainage networks since 1820, Southern Tablelands, N.S.W. Australian Geogrpaher **13**: 377-386
Fieber KD, Davenport IJ, Tanase MA, Ferryman JM, Gurney RJ, Becerra VM, Walker JP, Hacker JM. 2015. Validation of Canopy Height Profile methodology for small-footprint full-waveform airborne LiDAR data in a discontinuous canopy environment. ISPRS Journal of Photogrammetry and Remote Sensing **104**: 144-157. DOI: http://dx.doi.org/10.1016/j.isprsjprs.2015.03.001
Fryirs K, Brierley G. 1998. The character and age structure of valley fills in upper Wolumla Creek catchment, south coast, New South Wales, Australia. Earth Surface Processes and Landforms **23**: 271-287. DOI: 10.1002/(sici)1096-9837(199803)23:3<271::aid-esp867>3.0.co;2-5
Gallant JC, Dowling, T.I., Read, A.M., Wilson, N., Tickle, P., Inskeep, C. 2011. 1 second SRTM Derived Digital Elevation Models User Guide. Australia G (ed). Geoscience Australia: Canberra; 106.
Greenwood DR, Christophel DC, Bermingham E, Dick CW, Moritz C. 2005. The origins and tertiary history of Australian" tropical" rainforests. . In *Tropical rainforests: past, present and future*; 336-373.
Griffiths AD, Parks NT, Commission W, Parks, Territory WCotN. 1997. Biological Survey of Litchfield National Park. Parks and Wildlife Commission of the Northern Territory
Gurnell A. 2014. Plants as river system engineers. Earth Surface Processes and Landforms **39**: 4-25. DOI: 10.1002/esp.3397
Hamilton SK, Gehrke PC. 2005. Australia's tropical river systems: current scientific understanding and critical knowledge gaps for sustainable management. Marine and Freshwater Research **56**: 243-252. DOI: http://dx.doi.org/10.1071/MF05063
Hastings JR, Turner RM. 1965. The Changing Mile. The University Of Arizona Press: Tucson, Arizona
Hupp CR. 1992. Riparian Vegetation Recovery Patterns Following Stream Channelization: A Geomorphic Perspective. Ecology **73**: 1209-1226. DOI: 10.2307/1940670
Jansen JD, Nanson GC. 2004. Anabranching and maximum flow efficiency in Magela Creek, northern Australia. Water Resources Research **40**: W04503. DOI: 10.1029/2003wr002408
Jolly P. 2001. Daly River Catchment Water Balance. Natural Resources Division; 41.
Lau JE, Commander DP, Jacobson G. 1987. Hydrogeology of Australia. In *Bureau of Mineral Resources, Geology and Geophysics Bulletin*, Energy DoRa (ed). Australian Government Publishing Service: Canberra; 23.
Lewis WM, Hamilton SK, Lasi MA, Rodríguez M, Saunders JF. 2000. Ecological Determinism on the Orinoco Floodplain: A 15-year study of the Orinoco floodplain shows that this productive and biotically diverse ecosystem is functionally less complex than it appears. Hydrographic and geomorphic controls induce a high degree of determinism in biogeochemical and biotic processes. BioScience **50**: 681-692. DOI: 10.1641/0006-3568(2000)050[0681:edotof]2.0.co;2

Lillesand T, Kiefer RW, Chipman J. 2008. Remote Sensing and Image Interpretation, 6th Edition. Wiley: New York

Mäckel R. 1973. Dambos: A study in morphodynamic activity on the plateau regions of Zambia. CATENA **1**: 327-365. DOI: http://dx.doi.org/10.1016/S0341-8162(73)80018-9

McDonald NS, McAlpine J. 1991. Floods and droughts: the northern climate. In *Monsoonal Australia: landscape, ecology and man in the northern lowlands*. AA Balkema: Rotterdam, Netherlands 41-62.

Moliere DR, Lowry JBC, Humphrey CL. 2009. Classifying the flow regime of data-limited streams in the wet-dry tropical region of Australia. Journal of Hydrology **367**: 1-13. DOI: http://dx.doi.org/10.1016/j.jhydrol.2008.12.015

Moss PT. 2008. An Island of Green in the Sunburnt Country: The Rainforest of the Humid Tropics of Northeastern Australia and Their Response to Quaternary Environmental Change. Geography Compass **2**: 1777-1797. DOI: 10.1111/j.1749-8198.2008.00185.x

Nanson RA. 2009. The Evolution of Peat-Swamp Channels and Organic Floodplains, Barrington Tops, New South Wales, Australia. Geographical Research **47**: 434-448. DOI: 10.1111/j.1745-5871.2009.00596.x

Nott JF, Price DM, Bryant EA. 1996. A 30,000 year record of extreme floods in tropical Australia from relict plunge-pool deposits: Implications for future climate change. Geophysical Research Letters **23**: 379-382. DOI: 10.1029/96gl00262

Page S, Hoscilo A, Langner A, Tansey K, Siegert F, Limin S, Rieley J. 2009. Tropical peatland fires in Southeast Asia. In *Tropical Fire Ecology*, Cochrane MA (ed). Springer: Heidelberg; 263-287.

Page SE, Siegert F, Rieley JO, Boehm H-DV, Jaya A, Limin S. 2002. The amount of carbon released from peat and forest fires in Indonesia during 1997. Nature **420**: 61-65

Prosser IP, Chappell J, Gillespie R. 1994. Holocene valley aggradation and gully erosion in headwater catchments, south-eastern highlands of Australia. Earth Surface Processes and Landforms **19**: 465-480. DOI: 10.1002/esp.3290190507

Prosser IP, Dietrich WE, Stevenson J. 1995. Flow resistance and sediment transport by concentrated overland flow in a grassland valley. Geomorphology **13**: 71-86. DOI: http://dx.doi.org/10.1016/0169-555X(95)00020-6

Russell-Smith J. 1991. Classification, species richness, and environmental relations of monsoon rain forest in northern Australia. Journal of Vegetation Science **2**: 259-278. DOI: 10.2307/3235959

Russell-Smith J, Bowman DMJS. 1992. Conservation of monsoon rainforest isolates in the Northern Territory, Australia. Biological Conservation **59**: 51-63. DOI: http://dx.doi.org/10.1016/0006-3207(92)90713-W

Schumm SA, Hadley RF. 1957. Arroyos and the semiarid cycle of erosion [Wyoming and New Mexico]. American Journal of Science **255**: 161-174. DOI: 10.2475/ajs.255.3.161

Schumm SA, Harvey MD, Watson CC. 1984. Incised Channels. Morphology, Dynamics and Control. Water Resources Publications: Littleton, CO, USA

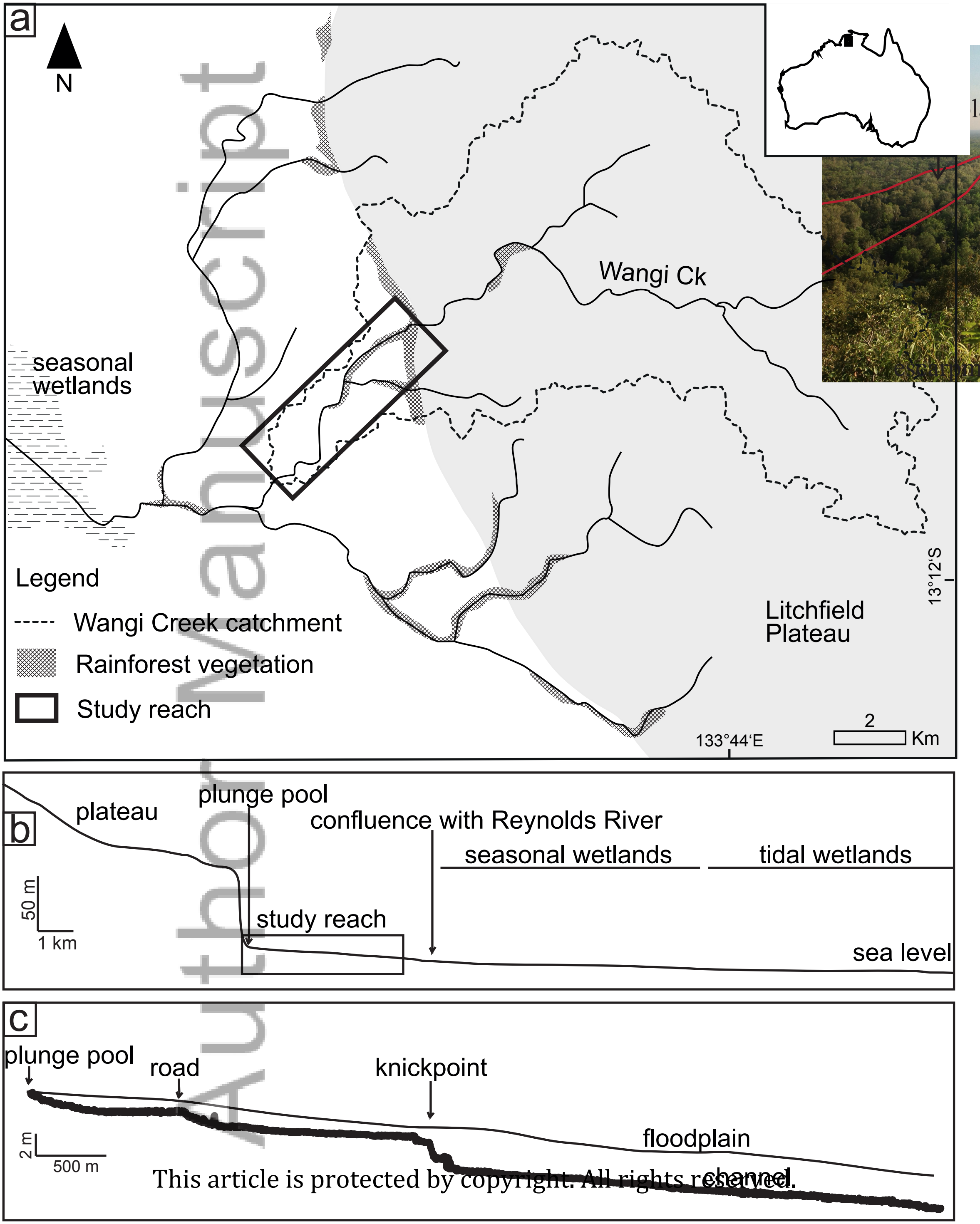
Siegert F, Ruecker G, Hinrichs A, Hoffmann AA. 2001. Increased damage from fires in logged forests during droughts caused by El Nino. Nature **414**: 437-440

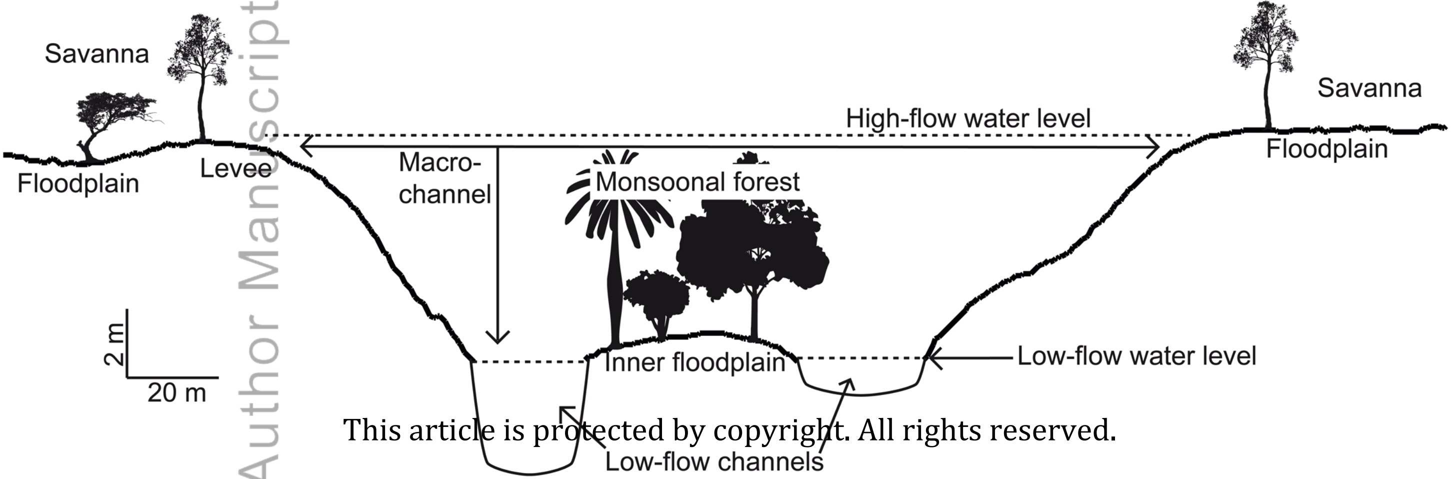
Soper A. 2014. From past to present: hydrological and morphological characteristics of Wangi Creek, Northern Territory. In *Earth and Environmental Science*. University of Wollongong: Unpublished; 91.

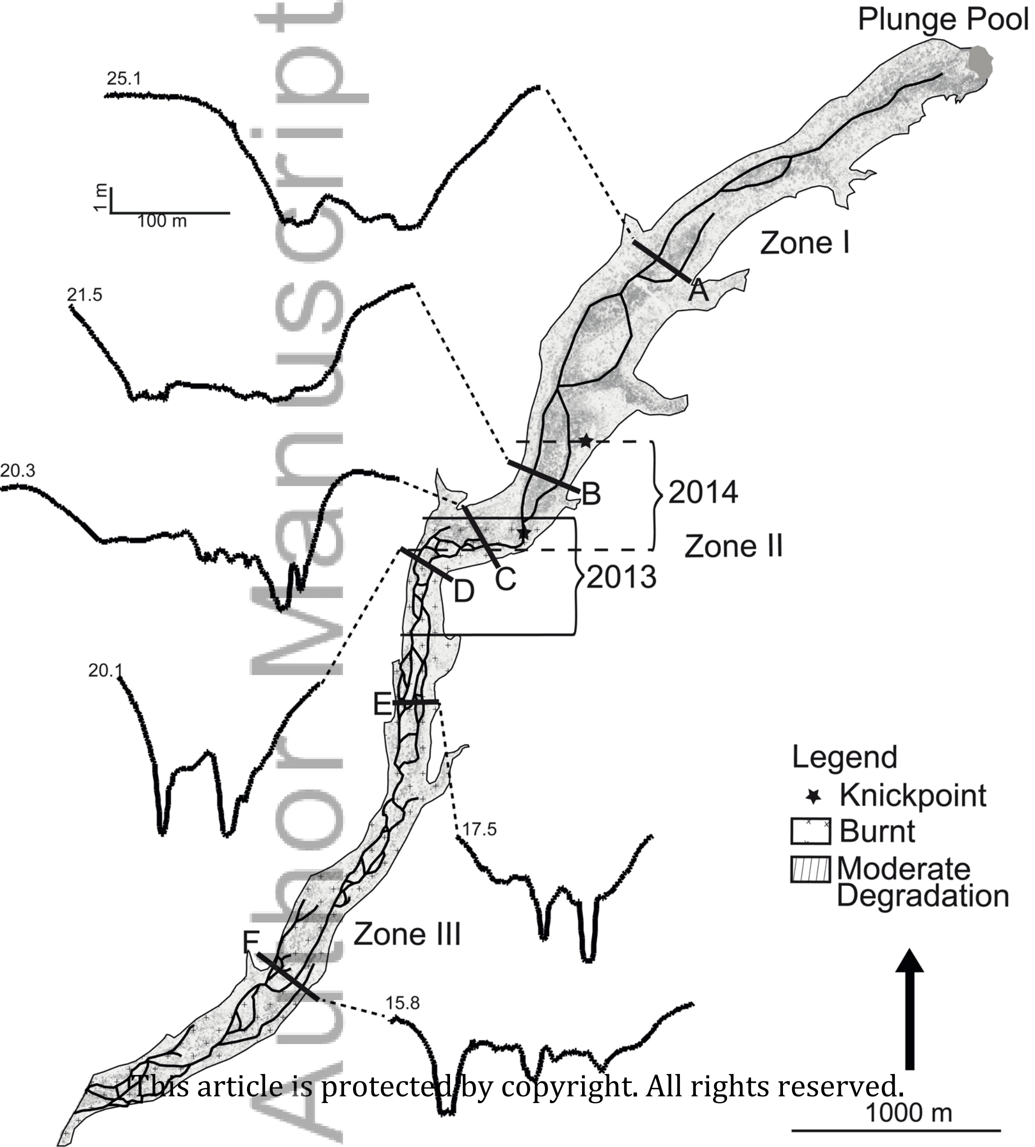
Taylor JA, Tulloch D. 1985. Rainfall in the wet-dry tropics: extreme events at Darwin and similarities between years during the period 1870–1983 inclusive. . Australian Journal of Ecology **10**: 281-295

Tooth S, Jansen JD, Nanson GC, Coulthard TJ, Pietsch T. 2008. Riparian vegetation and the late Holocene development of an anabranching river: Magela Creek, northern Australia. Geological Society of America Bulletin **120**: 1021-1035. DOI: 10.1130/b26165.1

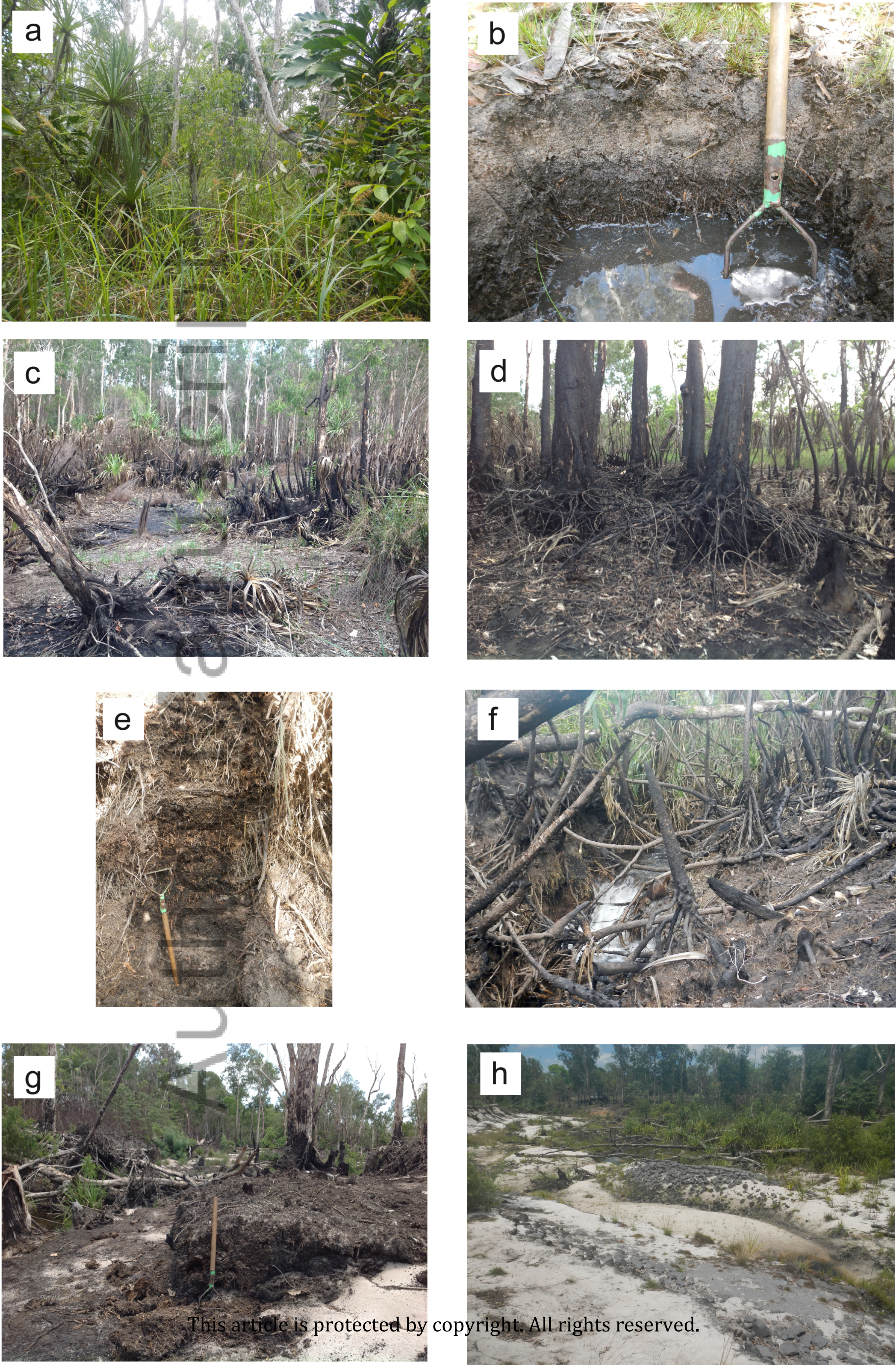
Tucker GE, Arnold L, Bras RL, Flores H, Istanbulluoglu E, Sólyom P. 2006. Headwater channel dynamics in semiarid rangelands, Colorado high plains, USA. Geological Society of America Bulletin **118**: 959-974. DOI: 10.1130/b25928.1
Wasson RJ, Brooks AP, Olley JM, Knight J, Rustomji P. 2014. Erosion, sediment transport and deposition in the Daly River catchment: Implications for catchment management. In *TRaCK*. Charles Darwin University: Darwin; 20.
Wasson RJ, Furlonger L, Parry D, Pietsch T, Valentine E, Williams D. 2010. Sediment sources and channel dynamics, Daly River, Northern Australia. Geomorphology **114**: 161-174. DOI: http://dx.doi.org/10.1016/j.geomorph.2009.06.022
Webb LJ, Tracey JG. 1981. Australian rainforests: patterns and change. In *Ecological Biogeography of Australia*, Keast A (ed). Hague: Boston; 607-694.
Webb RH, Leake SA. 2006. Ground-water surface-water interactions and long-term change in riverine riparian vegetation in the southwestern United States. Journal of Hydrology **320**: 302-323. DOI: http://dx.doi.org/10.1016/j.jhydrol.2005.07.022
Wheaton JM. 2008. Uncertainty in Morphological Sediment Budgeting of Rivers. University of Southampton; 412.
Whitlow R. 1994. Gullying within wetlands in Zimbabwe: Morphological Characteristics of Gullies. South African Geographical Journal **76**: 11-19
Williams RJ, Woinarski JCZ, Andersen AN. 2003. Fire experiments in northern Australia: contributions to ecological understanding and biodiversity conservation in tropical savannas. International Journal of Wildland Fire **12**: 391-402. DOI: http://dx.doi.org/10.1071/WF03025
Wösten JHM, Clymans E, Page SE, Rieley JO, Limin SH. 2008. Peat–water interrelationships in a tropical peatland ecosystem in Southeast Asia. CATENA **73**: 212-224. DOI: http://dx.doi.org/10.1016/j.catena.2007.07.010
WRB IWG. 2014. World Reference Base for Soil Resources 2014. International soil classification system for naming soils and creating legends for soil maps. . FAO: Rome
Young A. 1982. Upland swamps (dells) on the Woronara Plateau, N.S.W. *Department of Geography*. Universiyt of Wollongong, Australia: Wollongong; 169.

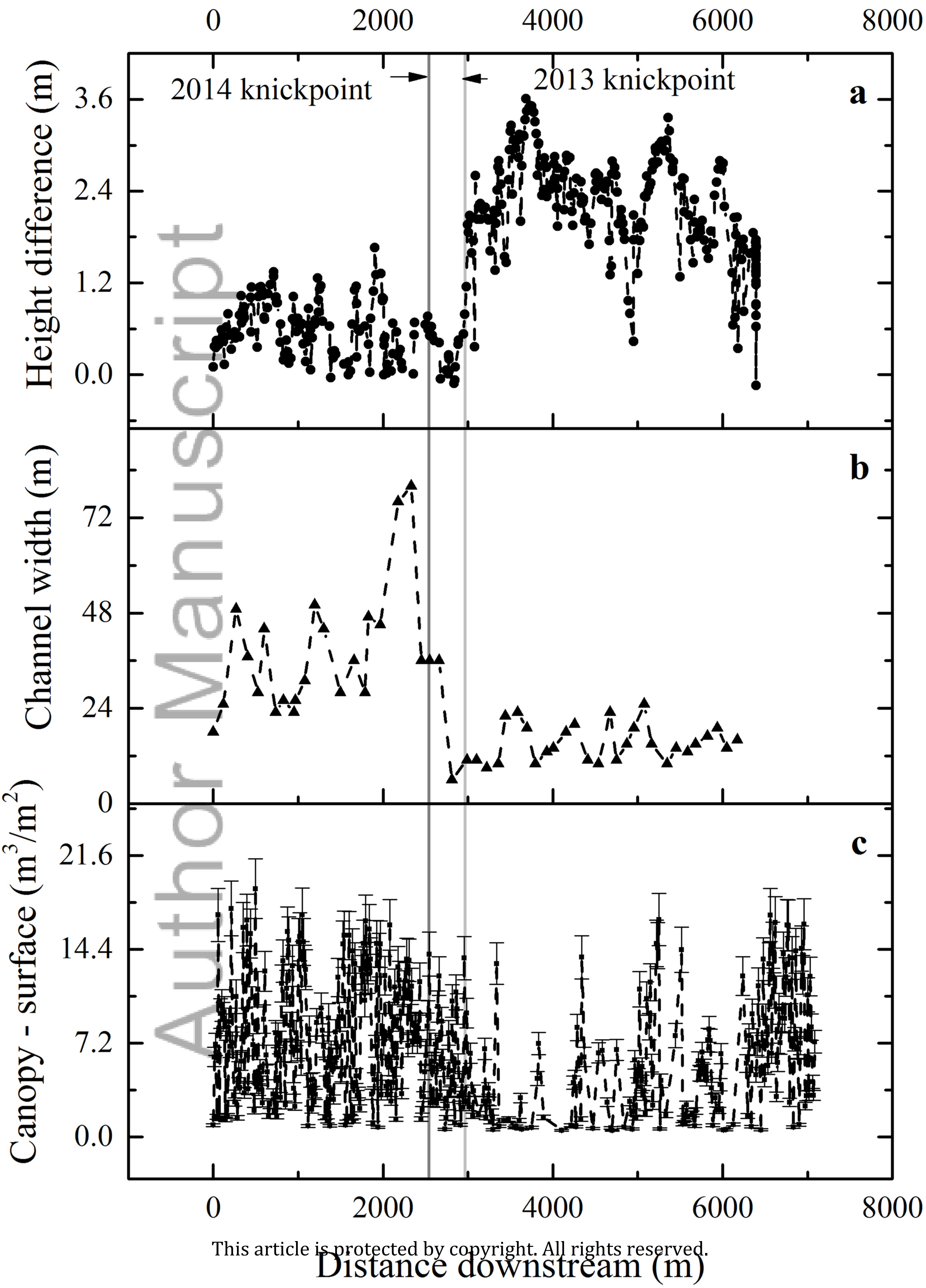

a
N
seasonal
wetlands
Wangi Ck
Litchfield
Plateau
Legend
Wangi Creek catchment
Rainforest vegetation
Study reach
13°12'S
133°44'E
2
Km
b
plateau
plunge pool
confluence with Reynolds River
seasonal wetlands
tidal wetlands
50 m
1 km
study reach
sea level
c
plunge pool
road
knickpoint
floodplain
2 m
500 m
channel


Savanna
Floodplain
Levee
Macro-
channel
Monsoonal forest
High-flow water level
Savanna
Floodplain
2 m
20 m
Inner floodplain
Low-flow water level
Low-flow channels

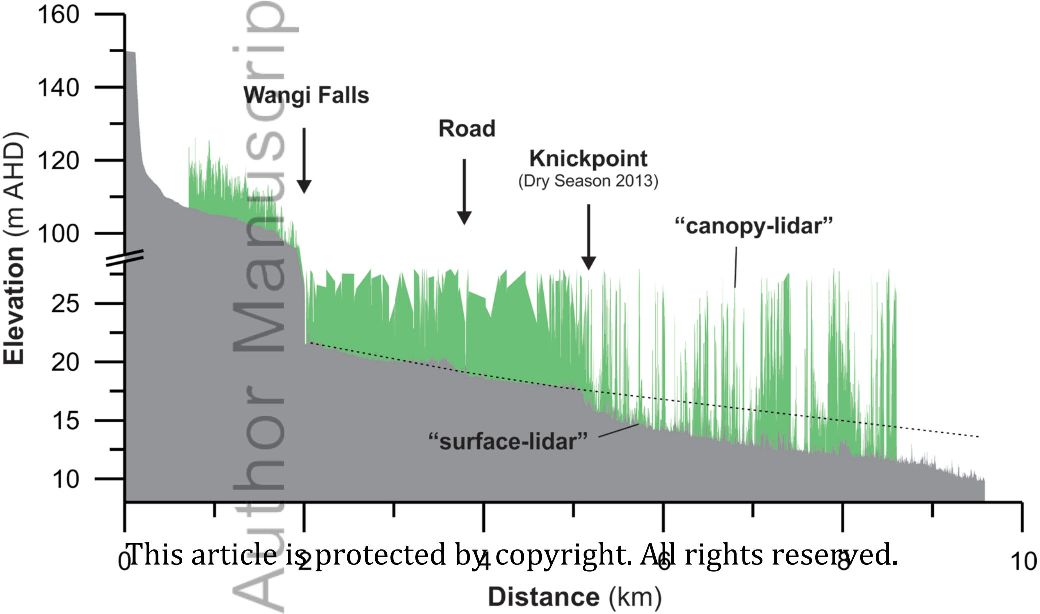


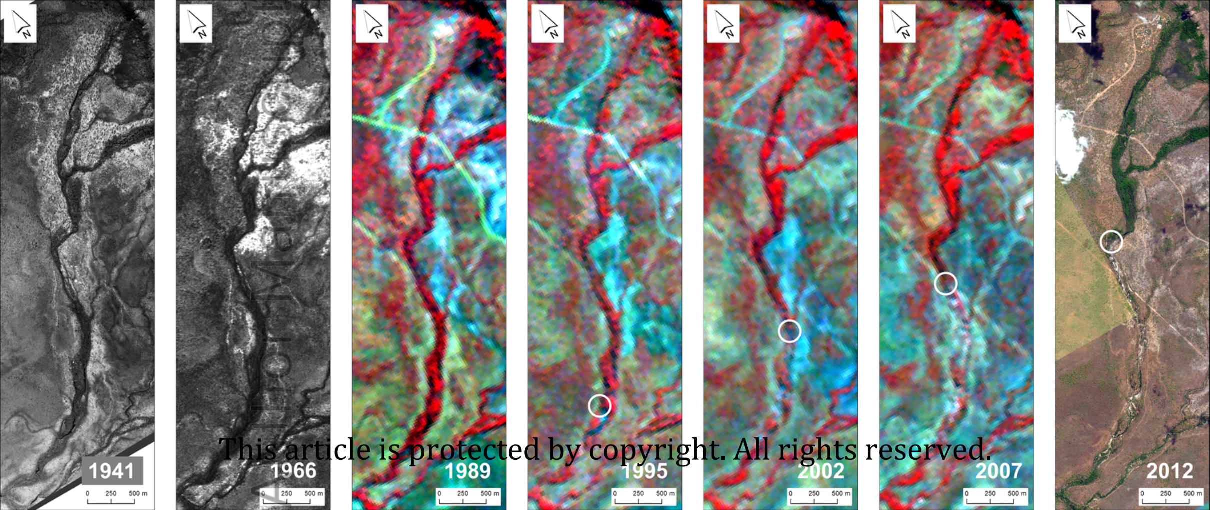
Plunge Pool
25.1
1 m
100 m
Zone I
A
21.5
20.3
B
2014
Zone II
C
D
2013
20.1
E
17.5
Legend
Knickpoint
Burnt
Moderate Degradation
F
Zone III
15.8
1000 m

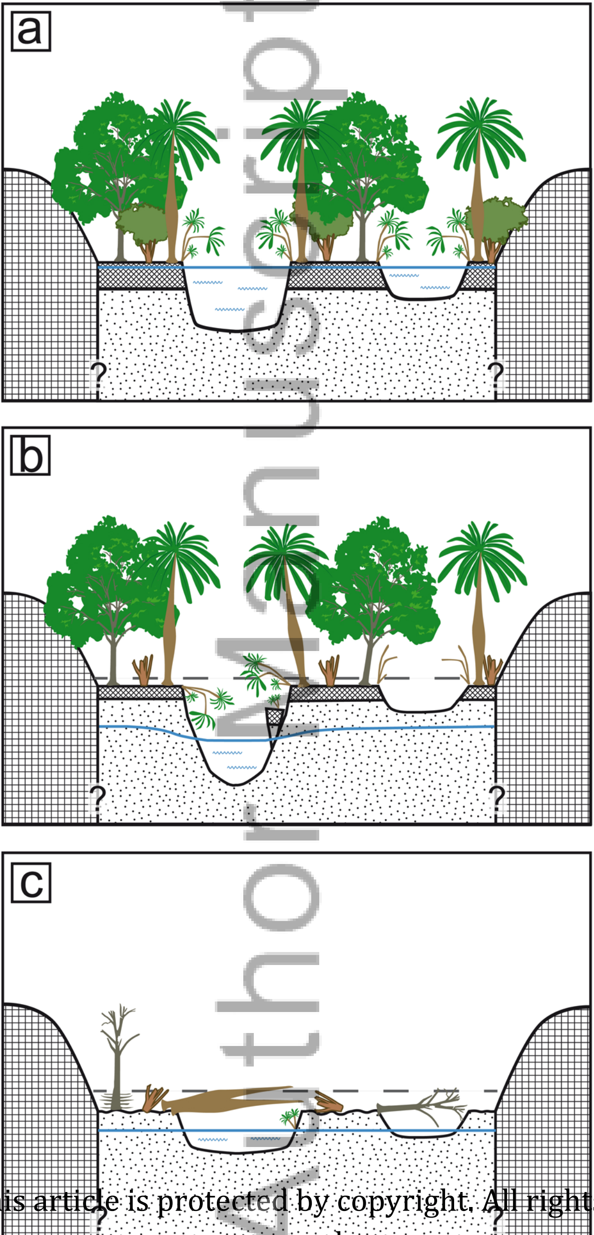

a
b
c
d
e
f
g
h

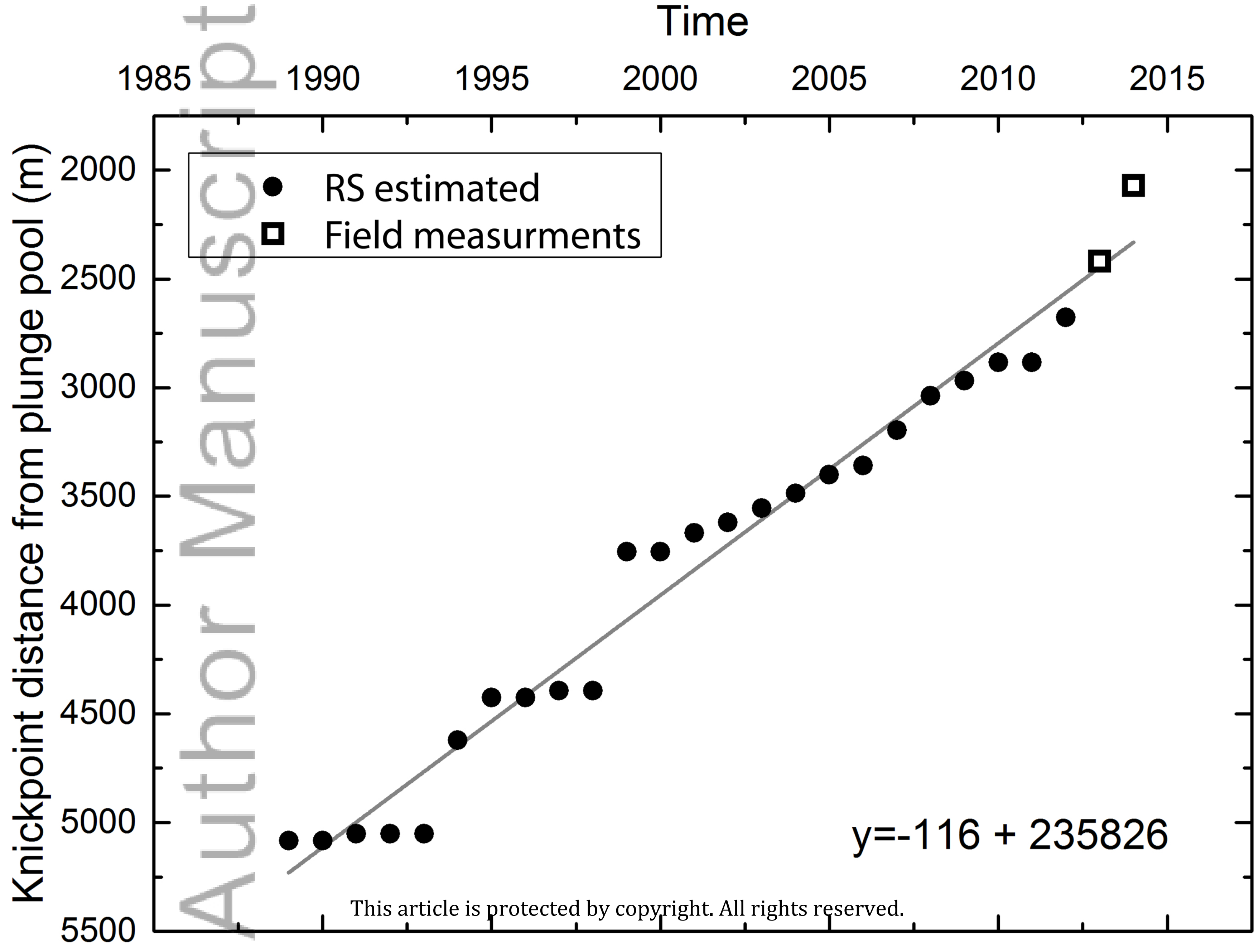


2014 knickpoint
2013 knickpoint
a
b
c
Height difference (m)
Channel width (m)
Canopy - surface (m^3/m^2)
Distance downstream (m)
0
2000
4000
6000
8000
3.6
2.4
1.2
0.0
72
48
24
0
21.6
14.4
7.2
0.0


160
140
120
100
25
20
15
10
Elevation (m AHD)
Wangi Falls
Road
Knickpoint
(Dry Season 2013)
"canopy-lidar"
"surface-lidar"
0
2
4
6
8
10
Distance (km)


N
1941
0 250 500 m
1966
1989
1995
2002
2007
2012


a
?
?
b
?
?
c
?
?


Time
1985
1990
1995
2000
2005
2010
2015
Knickpoint distance from plunge pool (m)
2000
2500
3000
3500
4000
4500
5000
5500
RS estimated
Field measurments
y=-116 + 235826