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A nested hierarchical perspective to enhance interpretations and communication in fluvial geomorphology for use in water resources management: Lessons from the Okavango Delta, Botswana.

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Abstract

A key skill that geomorphologists possess is the ability to use multi-scale perspectives in their interpretations of landscapes. One way to gain these perspectives is with the use of nested hierarchical frameworks. In fluvial geomorphology, such frameworks help with assessment of large-scale controls (e.g. tectonic activity, climate change) on the pattern and dynamics of smaller scale physical features (e.g. channels, floodplains, bars), and conversely illustrate how these smaller scale features provide the building blocks from which to make interpretations of fluvial processes and dynamics over larger spatial and temporal scales. Given the rapid pace of technological developments, the range of relatively inexpensive tools available for visualising and mapping landscapes at different spatial scales is expanding exponentially. In this paper, which focuses on the World Heritage-listed Okavango Delta in Botswana, we demonstrate how various visualisations generated by different technologies at different spatial scales (catchment, landscape unit, reach, site, and geomorphic unit) are providing critical baseline information to enhance interpretation and communication of fluvial geomorphology, with potential application in water resources management. In particular, our nested hierarchical approach could be used as an interactive communication tool for non-specialists and embedded within existing and future management plans for the Delta. The construction of nested hierarchies that synthesise information and analyses can be a valuable addition to the environmental manager's toolkit.

Keywords: reading the landscape, geographical context, communicating geomorphology, geomorphic mapping, spatial analysis

Introduction

Geomorphology is the scientific study of the characteristics, origin and development of landscapes. Geomorphic enquiry thus entails the description and explanation of earth surface processes, landforms and the broader landscape (Fryirs and Brierley, 2013). One of the fundamental skills of the geomorphologist lies in field interpretation of processes, process histories and landscape evolution (Thornbush et al 2014), and in the capacity to place site-specific perspectives and interpretations in their broader landscape context (Brierley et al 2013; Gurnell et al 2016). Consequently, geomorphology can be seen as an innately geographical science (Baker and Twidale 1991; Church 2010).

In recent years, there has been widening recognition that both global environmental change and human activities are increasing the magnitude and frequency of geomorphological hazards and placing increasing pressure on many aspects of ecosystem service delivery. This has led to a growing demand for geomorphology in many environmental management contexts, particularly river and water resources management (Du Toit et al 2003; Brierley and Fryirs 2008; Ralph et al 2016). Among many issues, improved management of transboundary rivers in drylands has been identified as a key global challenge (Turton et al 2003; Varis et al 2008; Harris and Alatout 2010). In the past, many such rivers have been mismanaged because decisions about channel management or water resource allocations have commonly been made in a piecemeal, isolated manner without considering the broader catchment perspective. Commonly, the lower parts of catchments are most impacted, such as where the construction of dams, sediment mining or land degradation in the upper reaches leads to alterations in downstream flow availability and quality, and sediment supply (Mueller and Marsh 2002; Kgathi et al 2006; Varis 2008). Ongoing climate and land use changes may well exacerbate such problems (Turton et al 2003; Pröpper and Gröngröft 2015). Effective, sustainable management of such rivers thus demands the application of geographical knowledge and reasoning, particularly by adopting multi-scale perspectives.

In this paper, we focus on the Okavango Delta, located in the northern Kalahari Desert of Botswana (**Figure 1**). The Delta is southern Africa's largest and most ecologically significant freshwater wetland (McCarthy 2013), and in 2014 was inscribed as the 1000th World Heritage site, partly because of its outstanding ecological diversity and hydrological characteristics. The Delta is supplied with water by the Okavango River, a transboundary river that arises in central Angola, crosses the narrow Caprivi Strip in Namibia, and then enters northwest Botswana where flow disperses along a network of anabranches and distributaries (**Figure 1**). Flow in the Okavango River is perennial but highly seasonal, largely being dependent on the intensity of summer rainfall in the headwaters (Government of Denmark and Republic of Botswana 2006). The river is important for all three countries for there are few other permanent surface water resources in these parts of their territories. In particular, Botswana's tourism industry has grown substantially to become the country's second largest economic sector (~5% GDP) and is largely based around the Okavango Delta (BTDP 1999; Mbaiwa 2002; Rahm et al 2006). However, the upstream countries of Namibia and Angola are reliant on the Okavango River for proposed irrigation agriculture and hydropower developments. In recent years, for instance, Namibia has developed plans for a pipeline to divert water for drought relief, and for a hydropower dam upstream of the Delta (Mbaiwa 2004; Kgathi et al 2006; Mendelsohn 2010). Prolonged civil war in Angola, which ended in 2002, has prevented significant water resources developments in the uppermost catchment, but continued agricultural expansion and potential hydropower generation are likely to impact on the river into the future (Mbaiwa 2004; Kgathi et al 2005; Pröpper and Gröngröft 2015). Given these competing demands, management of the water resources in the Okavango catchment has had a long and contested history (Jansen and Madzwaamuse 2003; Turton et al 2003; Mbaiwa 2004; Rahm et al 2006). The

Permanent Okavango River Basin Water Commission (OKACOM) is the authority established in 1994 by Angola, Namibia and Botswana to manage the river basin (Mendelsohn 2010; OKACOM 2017).

Against this backdrop, the aims of this paper are to: 1) outline the importance of perspectives and visualisation in geomorphic interpretations of landscape, and in particular the value of a nested hierarchical perspective for gaining geographical context and communicating geomorphology; 2) document the range of data collection, visualisation and mapping tools used by our research team to build our nested hierarchy for study of the Okavango Delta; 3) demonstrate how this hierarchical approach can be used to enhance geomorphic interpretations in the Panhandle region of the Delta; 4) discuss how the resulting multi-scale perspective can provide a useful tool for communicating geomorphology to non-specialists, potentially including practitioners and policy makers who work in water resources management in the Delta; and 5) outline the broader implications and potential developments of our research approach in transboundary river catchments and other environmental management contexts.

Perspectives and visualisation in geomorphic interpretations of landscape

A key aim of the geomorphologist is to ‘read the landscape’, namely by using field and other spatial datasets in order to build a picture and interpret the system under investigation (Fryirs and Brierley, 2013). This requires landscape observation from different perspectives and at different spatial scales, and the use of theory and concepts in spatial and temporal context (Phillips 1998; Bishop et al 2012; Gregory and Lewin 2015). Field scientists in particular often develop an intuitive feel for landscape that may sit outside, but that may certainly overlap with and complement, formal abductive, inductive and deductive reasoning. These three routes to scientific explanation are essentially what geomorphologists aspire to do as part of more “mature explanation” in geosciences (Kleinhans 2010, p290).

The spatial scale at which observations are made not only constrains what is seen, but dictates how and what is interpreted (Bishop et al 2012). Maximising the range and number of perspectives on the landscape before going to the field, and more importantly while in the field, is therefore critical for providing geographical context for subsequent interpretations (Thornbush et al 2014). For example, measuring the grain size characteristics of sand on a point bar provides a very different perspective from an aerial view of a sequence of meander bends from a helicopter, but both are necessary for a comprehensive, holistic interpretation of fluvial morphodynamics. Clearly, the lens through which we view a landscape is critical for understanding and interpreting it (Tooth et al 2016)

With rapid technological advances, the range of tools for visualising and mapping the landscape, and for gaining multiple perspectives in the field, is expanding exponentially (e.g. Tooth 2015; Williams et al 2016) (**Table 1**). In many ways there has been a revolution in the way that geomorphological research is conducted (Bishop et al 2012; Tooth et al 2016). Whereas early geomorphologists might have headed out into the field with a map, a compass and a shovel, the backpack of the modern geomorphologist may be filled with a much greater range of technology. Commonly, Google Earth or other software with high resolution satellite imagery is used on a tablet or mobile phone, unmanned aerial vehicles (UAVs) with cameras and other sensors are deployed at field sites to produce imagery and digital terrain models (DTMs), terrestrial laser scanners (TLSs) survey millions of points in minutes, and cameras with panoramic and 360^{o} recording capabilities provide wide-angle digital images and video footage (**Table 1**).

Nonetheless, there is still a real need for ‘old-fashioned’ techniques that can be used to complement or enhance data gathered using new technology (**Table 1**). It is critical that the modern geomorphologist maintains an innate geographic ability to interpret the landscape by gathering new data and generating new visualisations, and supplements these with on-the-ground evidence from soil profiles or bank exposures dug with shovels, cores recovered with drill rigs or augers, and cross sections surveyed with total stations or automatic levels (Thornbush et al 2014). The traditional way of doing things is often the only available option in remote or difficult terrain (e.g. densely vegetated or areas with no signal reception). Most importantly, we must remember that no new technology will do the geomorphic interpretation (Tooth 2015).

Nested hierarchical perspectives on landscape and use in communicating geomorphology

One way to gain various perspectives is with the use of nested hierarchical frameworks (e.g. Poole 2002; Brierley and Fryirs 2000; Dollar et al 2007; Frissell 1986; Gurnell et al 2016). Nested hierarchies provide a framework with which data can be synthesised, managed and used for targeted sampling and data collection at various spatial scales. In fluvial geomorphology, such frameworks have been used for decades and facilitate the assessment of large-scale controls on the pattern and dynamics of smaller scale channel features, while also illustrating how smaller scale features provide the building blocks from which to make interpretations of fluvial processes and changes over larger scales (Brierley and Fryirs 2000, 2005; Fryirs and Brierley 2013; Gurnell et al 2016). Nested hierarchical frameworks are scaffolded such that structures and processes that operate over small spatial and temporal scales are constrained by, or nested within, boundaries set by structures and processes that operate over larger spatial and temporal scales (Schumm and Lichty 1965; de Boer 1992; Phillips 1998; Gumbricht and McCarthy 2003). These frameworks provide the means for making bottom-up, constructivist interpretations of forms and processes, while also enabling top-down analyses of their controls (Brierley 1996; Brierley and Fryirs 2005).

When used effectively, nested hierarchical frameworks provide an elegant way to frame geographical perspectives, organise scientific data and information, and make more insightful and sophisticated interpretations of landscape that are placed within appropriate spatial context (Dollar et al 2007). Possibly more important, and less well explored to date, is the potential use of nested hierarchies as conceptual and visualisation tools for communicating geomorphology to non-specialist audiences, whether they be school children, landowners, practitioners or policy makers (Brierley 2009; Vervoort et al 2014; Gregory and Lewin 2015). Such perspectives, interpretations, and communication approaches can thus feed into river and water resources management (Du Toit et al 2003; Brierley and Fryirs 2005, 2008). In the sections below, we document the range of data collection, visualisation and mapping tools used by our research team in constructing the nested hierarchy and producing a visual product for use in the Okavango Delta.

Study area

Geomorphologically, the Okavango Delta (**Figure 1**) is a large alluvial fan (c. 12 000km^2) comprised of two main geomorphic domains: 1) the relatively confined (up to 12 km wide) depression known as the Panhandle, where the Okavango River and its anabranches meander through permanent swamps; and 2) the broader (up to 120 km wide) Fan, where water and sediment is dispersed through several large stable sinuous to straight distributary channels that feed both permanent and seasonal swamps (Tooth and McCarthy 2004). In the southern, peripheral region of the Delta, periodic high discharges enter the Boteti River, with flow sometimes continuing as far as the Makgadikgadi depression with its lacustrine basins (see Gumbricht et al 2001).

Through the Panhandle, the Okavango River declines in size from ~90 m to ~50 m wide, owing to water loss to surrounding swamps and to evapotranspiration (Tooth and McCarthy 2004; McCarthy

2013). The channel is highly sinuous, and characterised by regular and irregular meanders, scroll bars, cutoffs and point bars. Dense vegetation (principally *Cyperus papyrus* and *Phragmites* spp.) lines the main channel and its anabranches, and plays a significant role in stabilising banks and regulating lateral flow losses from the channels. Bank erosion is most pronounced in the upper Panhandle where the river intersects an elevated (~5-10 m) scarp overlain by Kalahari sand. The river is anastomosing in the central Panhandle, where the Filipo channel breaks from the eastern bank of the Okavango River to create a branch that eventually rejoins the Okavango ~26 km downstream. Avulsion is common in this reach (Smith et al 1997). Our overall research project is focusing in particular on characterising the avulsion dynamics in this reach, as well as the processes driving channel abandonment and failure, but here we focus more on the methodological and applied aspects of our project.

Approach and results

The various techniques available to geomorphologists (**Table 1**) and the images or data they produce, can be arranged in a hierarchical manner to capture and display the range of geographical perspectives for any given system. In our study of the Okavango Delta, we used the techniques and technology outlined in **Table 2** to build a hierarchy of geomorphic information with five nested spatial scales (**Figure 2**): 1) catchment; 2) landscape unit; 3) reach; 4) site (sub-reach); and 5) geomorphic unit (landform). Our hierarchical framework differs slightly from existing frameworks (e.g. Brierley and Fryirs 2005) in that we focus more on the site (sub-reach) scale and eliminate the smaller hydraulic unit (habitat) scale. This is because our research in the Okavango aims to analyse, interpret and communicate geomorphology mainly at the geographical scales of reaches and sites, and the analytical techniques we employed were chosen specifically to capture data and information most relevant to these scales. While the structure of the nested hierarchy nonetheless remains similar to the published examples from other geographical contexts (e.g. Frissell et al 1986;

Brierley and Fryirs 2000, 2005), we have compiled the datasets and images in such a way that the content of each ‘box’ is a visual illustrating the types of outputs produced from the mix of traditional and newer technologies (**Figure 2**). As addressed in the following sections, the resulting multi-scale perspectives are allowing us to enhance interpretations of the fluvial geomorphology of the Okavango Panhandle, and to communicate the insights to non-specialists, potentially including practitioners and policy makers in water resources management. To aid with the communication aspects, we have constructed an interactive version of **Figure 2** using the online presentation software suite, *Prezi*; this can be viewed at https://prezi.com/view/51UpgNhfKS1unm2NOM1L/ and in **Supplementary Information**.

An outline of the five nested spatial scales in our hierarchy and the main resulting visual products is presented in the following sections.

Catchment scale

Catchments (also called drainage basins or watersheds) are topographic and hydrological entities that have been described as the fundamental geomorphic unit (Chorley 1969). Catchments can be divided into sub-catchments. Analyses at the (sub)catchment scale set the context for smaller scale investigations, particularly by providing valuable insights into the boundary conditions within which rivers operate (Brierley and Fryirs 2005). For example, (sub)catchment geology is a key control on sediment transport regime, and (sub)catchment morphometry (including size, shape, relief, drainage density and pattern, and connectivity) is a key control on the hydrological regime. When combined with analyses of regional climate, these (sub)catchment-scale controls influence the flow-sediment-vegetation morphodynamics of rivers operating at finer scales in the hierarchy.

At the catchment scale, catchment maps were compiled and combined to produce **Figure 2A** and gain perspective on the size of the Okavango catchment (~156 250 km^2), the arrangement and shape of the sub-catchments (elongate in both the north and west), the drainage pattern (parallel and trellis-like in the upper catchment, transitioning to dendritic and distributary in the Delta), the geological structure (e.g. position of faults), and the drainage density (higher upstream, lower downstream) (McCarthy 2013). This perspective places the Okavango Delta in context, both in terms of position in the catchment and the morphometrics of the contributing (sub)catchments.

Landscape unit scale

Landscape units are sometimes called physiographic compartments or land systems units (Cooke and Dornkamp 1990). They are areas of relatively homogenous topography, morphology and relief. Examples of landscape units are plateaus, escarpments, rounded hills, lowland plains, and deltas. They are macro landscape features that control, amongst other things, the slope and lateral confinement of rivers. Their position and pattern within a catchment dictates the sequencing of process zones (i.e. production, transfer and deposition zones; Schumm 1977) and the pattern of valley settings within which river reaches occur at the next finer scale in the hierarchy (Fryirs et al 2016).

At the landscape unit scale, several types of visual outputs were produced. Five different landscape units were identified based on their topography and morphometry (**Figure 2A**). These include highlands that extend up to 1800 m above sea level, sand dunefields, alluvial plains, alluvial fan and swamps at around 1000 m above sea level, and pans and lakes. This map provides a basis from which spatial terrain analysis could be undertaken to extract and analyse quantitative geomorphic metrics such as slope, valley confinement, and profile concavity (Partridge et al 2010; Perron and Royden 2013; Fryirs et al 2016). This map provides additional context for placing the Okavango

Panhandle and Delta in topographic and landscape position. Google Earth and Garmin Birds Eye satellite imagery provide a spectacular perspective of the alluvial swamps and fans in the Okavango Delta and neighbouring Kwando system, the adjacent alluvial plain and Kalahari sand dunefields, and various pans and lakes that dot the region (**Figure 2B**). NASA Shuttle Radar Topography Mission (SRTM) data was used to derive a Digital Elevation Model (DEM) which highlights the morphology of the Panhandle, the pattern of ridges and depressions on the Delta surface, and sand dunes in the west (**Figure 2C**; McCarthy 2013). A map of flow inundation (**Figure 2D**), produced from NOAA AVHRR satellite data (1 km^2 resolution) and ERS-ATSR and composite Landsat MSS/TM data, depicts the flooding frequency (in %) for different areas of the Panhandle and Fan. On this map, black areas are near-permanently inundated, with seasonal and quasi-seasonal flooding occurring in areas depicted in shades of grey (McCarthy et al 2003). Landsat satellite imagery was also used to map the distribution of landcover and ecoregions (**Figure 2E**), as derived from a combined statistical and contextual rule-based post-classification (McCarthy et al 2005).

Reach scale

Reaches are sections of river along which flow and sediment load are sufficiently uniform to enable maintenance of near-consistent or characteristic forms and associated processes (Brierley and Fryirs 2005; Kellerhals et al 1976). Alternating patterns of reaches are referred to as segments (Frissell et al 1976). For rivers, reaches are often differentiated by channel planform and the assemblages (packages) of finer scale geomorphic units (landforms) that comprise them.

At the reach scale in the Panhandle, Google Earth and Garmin Birds Eye satellite imagery (along with aerial photographs, not shown) were the primary means of visualisation (**Figure 2F**). Other pre-existing geomorphic maps of the Panhandle were also used (not shown, but for examples see Smith et al 1997 and McCarthy 2013). These maps are invaluable as tools for analysing the morphology of the Panhandle relative to adjacent landscape units, channel planform attributes, and the relative extent of channels and floodplains, and also provide insight into the distribution and morphology of palaeochannels, permanent swamps, and various active channels. When accompanied with air photograph sets or a temporal sequence of Google Earth images, analyses of historical channel avulsion and migration can be undertaken.

Site and geomorphic unit scales

In our study, sites were defined at the sub-reach scale and may occur along river channels and on floodplains. To capture the range of geomorphic units that make up river reaches requires analysis of numerous sites. Selecting the correct sites to undertake more detailed analysis, that are representative, or that capture the range of variability, is critical if interpretations are to adequately reflect the morphodynamics occurring in the system.

Geomorphic units, also called landforms, are the building blocks of rivers and the surrounding landscapes. Each geomorphic unit is created by certain process-form interactions at particular positions in landscapes, and units may have differing material properties (Brierley and Fryirs 2005; Fryirs and Brierley 2013). Units may comprise erosional or depositional forms, and the mix of geomorphic units (called an assemblage) that occurs along a river reach is dictated by the range of processes occurring along that reach. This range of processes determines river behaviour. When considering the global diversity of rivers, there is a spectrum of in-stream and floodplain geomorphic units that occur in different types of river reaches and valley settings. Channel geomorphic units range from bedrock-influenced features such as cascades and rapids, through to mid-channel depositional features such as longitudinal bars, to bank-attached depositional features such as benches or point bars, to fine-grained sculpted features such as scour pools and planar riffles (see Fryirs and Brierley 2013; Wheaton et al 2015). Floodplain geomorphic units also span a spectrum from homogenous, discontinuous pockets with limited relief, to complex, more continuous surfaces that may comprise landforms such as levees, backswamps, chute channels, and crevasse splays.

At the site and geomorphic unit scale in the Okavango Panhandle, the set of techniques and methods used was the most extensive. At the site scale, the most impressive and transformative perspectives were those gained from the air. Aerial surveys from a helicopter (**Figure 2G** and **H**) provided an unparalleled perspective of individual sites and their geomorphic unit assemblages, as well as their position relative to other sites, reaches and landscape units. Additional perspectives were gained from UAV-derived data and analysis using Structure from Motion (SfM), which allows for 3D digital terrain analysis at a much greater level of detail than manual topographic surveys (**Figure 2I**). At these scales, we also utilised a range of other visualisation techniques, including panoramic and 360^0 cameras mounted to boats to gain live video and still images of the trunk stream and tributary networks (**Figure 2J** and **K**). These videos were calibrated against GPS and topographic survey data to gain insights into downstream changes in channel width along the Panhandle. By capturing continuous video footage from a helicopter, a longitudinal perspective of floodplain and channel/palaeochannel character across the Panhandle was gained and was used to place still, oblique aerial photography in context. Floodplain transects were surveyed using tape and clinometer survey techniques (**Figure 2L**), but alternatively could have been completed using a digital theodolite, automatic level or terrestrial laser scanner.

The perspectives gained and mapping undertaken at coarser scales in the nested hierarchy were used to select locations in the Panhandle for more detailed geomorphic unit analysis. At this scale, more traditional techniques complement analyses undertaken using new technology, both in the field and in the laboratory. Standard sediment analysis were used to document the sedimentology of floodplains from pit and bank exposures. These data are visualised by constructing sediment columns (logs) (**Figure 2M**). Sediment samples were collected for treatments including bulk density and grain sizing. Samples for Optically Stimulated Luminescence (OSL) dating were extracted using coring and augering equipment (**Figure 2M**). When analyses are completed, these data will be added to the sediment columns to assess vertical trends in sedimentology, quantify sedimentation rates in different parts of the Okavango Panhandle, and interpret overall geomorphic development. At numerous locations along the Okavango River and its anabranches, channel cross sections were surveyed and a velocity meter used to determine flow characteristics (**Figure 2N**). Velocity data are presented as isovel maps (**Figure 2O**) and are used to calculate relative discharges through different channels. Bed load sampling was undertaken in each channel to assess sediment transport characteristics (**Figure 2P**). A Trimble GPS Pathfinder ProXRT Receiver connected to a dual frequency GNSS antenna was used at multiple sites in the Panhandle to determine channel water levels (**Figure 2Q**). When compared to historical water levels and calibrated against gauged discharge data, water level changes will be mapped and used to aid interpretations of geomorphic adjustments.

Interpretations and discussion

Using the hierarchical approach to enhance geomorphic interpretations in the Okavango Panhandle

One challenge for the modern day geomorphologist is to know where to focus data collection to address the right questions (Lisenby and Fryirs, 2017). Vast amounts of data can now be easily generated using new technologies, but the risk is that data are gathered in the absence of a fundamental research question or hypothesis. Without careful consideration of what data are being collected, and at what scale and resolution, the problem of extracting information that captures the essence of character or functionality of a landscape is thus simply transferred from the field to the computer laboratory. This runs the risk of vital parts of the puzzle being missed or misinterpreted, without any new insights being generated. In our study, we have developed an organisational framework (the nested hierarchy) for the Okavango Delta that contains essential data and information for undertaking more detailed interpretations and explanations of the fluvial geomorphology. Using our interactive version of **Figure 2** in *Prezi*, we can dynamically visualise the Okavango from a range of different geographical perspectives, and at different scales in the hierarchy. Here we briefly discuss an application of this approach to assess patterns and processes of channel change that are a critical part of the fluvial geomorphology of the Panhandle, including those changes occurring at the landscape scale and at the finer scales of reaches and sites.

Previous on-the-ground observations and measurements have shown that there is a significant overall downstream decrease in the size of the Okavango River and its distributaries through the Panhandle and Fan (Tooth and McCarthy 2004). To date, however, it has been unclear whether the channel decreases in size in a predictable manner downstream or whether there are variations in channel size at a finer scale. With the use of our hierarchical framework and additional high-resolution data gathered using new technology, we can enhance our insights and interpretations. At the landscape unit scale, the Okavango River trunk stream has a nearly constant longitudinal gradient in the Panhandle (**Figure 3A**). Relatively coarse-resolution channel width analyses derived from field measurements by Tooth and McCarthy (2004) show that the river has a broadly uniform downstream decrease in width over an ~85 km long reach (**Figure 3B**). Higher resolution measurements in the same reach using 2004 Google Earth imagery, however, show that channel width is highly variable, both decreasing and increasing, while the overall downstream width decrease is still observed (**Figure 3C**). The overall downstream channel width decrease is therefore not a simple linear relationship, but shows a step change from 1.2 m/km to 0.26 m/km at 70 km downstream from Shakawe. The step-like manner in which channel width changes in this reach is due to finer scale reach or site controls, including losses or gains of water at channel bifurcations of confluences (**Figure 2H**), development of point bars (**Figure 3D** and **3E**), and low levees that flank parts of the channel that do not have floating aquatic vegetation along their margins (**Figure 3F**).

At the reach scale (**Figure 2F**), some channels in the Panhandle are more sinuous than others and it is clear that some channel sections have become connected or disconnected due to meander bend cutoff (**Figure 3G**) and avulsion. Techniques employed at reach and site scales, including oblique aerial photography and video footage, reveal that vegetation (e.g. *Vossia cuspidata*) encroaches far into the channels in certain locations. Confirmation is provided by UAV-derived 3D terrain data using SfM (**Figure 2I**), which shows vegetation bordering and encroaching into the channel on the inside of some bends, and in straight reaches downstream of major bifurcation points where flow has divided between two channels. Boat-level observations of channel form, and cross-section measurements of channel width, flow velocity and discharge provide additional data to confirm the patterns and processes of channel size change (**Figure 2J**). At the geomorphic unit scale, channel cross-sectional area, flow velocity and bedload measurements can be compared, highlighting the links between channel size, flow and sediment transport (**Figure 2N, O, P**). For instance, downstream channel size changes are largely the result of increases or decreases in channel width, with depth and velocity showing fewer changes (Tooth and McCarthy 2004). In markedly narrowing channels, however, sediment transport rates decrease, which leads to partial infilling. This promotes increasing diversion of flow through the porous, vegetated channel margins, leading to decreases in flow velocity and further vegetation encroachment. Ultimately, this can lead to channel abandonment and avulsion (McCarthy 2013). In summary, for this reach in the Panhandle, a multi-scale perspective has provided a higher resolution dataset that can be used to enrich previous interpretations into downstream channel size changes and their role in avulsion.

Using the hierarchical approach to communicate geomorphology and better inform water resources management in the Okavango Delta

One overarching benefit of adopting a multi-scale perspective through the development of a nested hierarchical framework is to help non-specialists and decision makers understand more fully how various parts of the system fit together and interact across scales, thereby enhancing insight into the functionality of the system as a whole (Brierley 2009; Vervoort et al 2014; Gregory and Lewin 2015). In the Okavango catchment, for instance, there is a current, pressing need to understand the impacts of climate change, land use changes and water resource developments (e.g. dams, weirs, extensive extraction) in Angola, Namibia, and Botswana on total annual flow volumes, seasonal flow variability, water quality, and sediment and nutrient loads in the Delta (Government of Denmark and Republic of Botswana 2006; Kagathi et al 2006; Pröpper and Gröngröft 2015). These natural and human drivers, operating in large part at the catchment and landscape unit scales, influence the reach, site and geomorphic unit scale relationships between flow, sediment, vegetation and other biota that underpin the ecological diversity and other ecosystem services in the Delta (Jansen and Madzwamuse 2003; Hamandawana and Chanda 2010; Mendelsohn 2010). Analyses by Andersson et al (2006) and Pröpper and Gröngröft (2015) of the impacts of climate change and development scenarios on the Okavango catchment indicate that in the long term, climate change will considerably reduce mean annual flow and increase flow variability, but in the short-to-medium-term, the impacts of potential increases in irrigated agriculture, hydropower dam building, and flow diversion are likely to be much more marked. An obvious impact of dam building and large irrigation diversions will be reduced peak flooding in the Okavango Panhandle and Fan, thereby threatening the maintenance of complex wetland ecosystems. Due to the pronounced dry season experienced in the south of the catchment during winter, such developments may also exacerbate natural seasonal variability, which may have ramifications for wetland ecosystems and human communities in an already water-stressed environment (Jansen and Madzwamuse 2003; Kagathi et al 2006;

Pröpper and Gröngröft 2015). A less obvious, but no less insidious, impact of dam or weir building is a reduction in downstream sediment flux. As noted above, sedimentation within channels in the Delta plays a role in channel avulsion, for this promotes loss of water from the channel to the surrounding swamps, facilitating a decrease in flow velocity, vegetation encroachment, and ultimately channel failure (Government of Denmark and Republic of Botswana 2006). Avulsion leads to water, sediment and nutrient dispersal, rejuvenating parts of the wetlands and promoting biodiversity (McCarthy and Ellery 1998; Kagathi et al 2006; McCarthy 2012). Other abandoned channels may become filled with fine sediment to create topographically elevated ridges that often give rise to tree-covered islands, and these also play a fundamental role in the functioning of the Okavango through their influence on water salinity, nutrient concentrations and habitat diversity (McCarthy et al 2012). Overall, a significant change in sediment flux from the upstream catchment may translate to changes in sedimentation rates linked to avulsion processes in the Delta.

At reach, site and geomorphic unit scales, therefore, it is important to recognise that the relationships between flow, sedimentation and vegetation growth that underpin processes such as avulsion ultimately create a complex mosaic of landforms within a broader context, and so cannot be assessed and managed in isolation or without spatial context (Kagathi et al 2006; Mendelsohn 2010). In transboundary rivers in particular, recognition and accommodation of these multi-scale linkages in catchment development planning is thus essential to avoid cross-border and within-country conflicts (Turton et al 2003; Harris and Alatout 2010; Mendelsohn 2010). Throughout the Delta in Botswana, for instance, many local communities and tour companies site their accommodation on river frontages and require access to the channels for transport (Jansen and Madzwamuse 2003; Pröpper and Gröngröft 2015). Any potential changes to channel location that may result from avulsion are seen as a threat, and so efforts are commonly made to clear channels and keep them ‘locked’ in position, without any consideration of the potential consequences for reaches downstream where similarly close relationships between channel position, local communities and tourism companies may exist (Kagathi et al 2006; Mendelsohn 2010). Adopting a multi-scale perspective and constructing nested hierarchies may help people to recognise that local (e.g. site and short reach scale) geomorphological processes can thus have important effects at the longer reach or landscape unit scale. Attempts to restrict the movement of avulsion-prone channels may succeed in the short term, but are likely to fail in the medium to long term and also risk imposing 'unnatural' flow regimes in parts of the wetlands. While this is generally recognised in regional and national management plans for the Delta, there tends to be only tacit acknowledgement of the importance of adopting such perspectives at the local scale (Jansen and Madzwamuse 2003; Turton et al 2003; Mendelsohn et al 2010; Pröpper and Gröngröft 2015). Formal use of hierarchical frameworks potentially can help such multi-scale, geographical perspectives to be embedded more fully in decision making and planning, including projects, monitoring and management plans developed under OKACOM (Mendelsohn 2010).

Possible developments of the hierarchical approach for communicating geomorphology and using scientific insights in management

We recognise that **Figure 2** is a static characterisation of the Okavango at each scale, but our interactive version using *Prezi* introduces a new element of dynamic observation through a flexible and navigable system of multimedia files (maps, photographs and videos). In an era of rapid technological developments, such approaches and syntheses provide new and exciting ways of contextualising and visualising landscapes, and communicating geomorphology (Tooth et al 2016). Within and beyond the Okavango catchment, this has many potential benefits for end user engagement and other outreach activities (Vervoort et al 2014). For instance, while new technology allows faster data capture over larger areas and with greater precision than ever before, the use of a nested hierarchy provides the framework for synthesising and visualising pre-existing and new datasets in an integrated, coherent manner. This opens up great opportunities for public communication of geomorphology, such as how river systems are structured and function at, and across, different spatial scales (c.f. Vervoort et al 2014). In addition, these technologies are helping to democratise parts of the research process through citizen science, particularly by allowing people to generate their own place-based knowledge and engage more fully in environmental management practice (Brierley et al 2006; Brierley 2009; Vervoort et al 2014; Haywood et al 2016).

In the Okavango Delta, the intent is for **Figure 2** to provide geographical and geomorphological context for the various datasets, but we envisage that it could also be used as a template upon which temporal analyses are added as we gather additional data regarding the timeframes of adjustments. Indeed, detailed 3D hierarchies could be produced for each of the catchment, landscape unit, reach, site and geomorphic unit scales to visualise geomorphic changes over time, as well as the varying timeframes (millions of years to days) over which these changes occur. This approach could complement and extend previous approaches adopted by studies in and around the Delta that have investigated landscape and landcover dynamics but by necessity have had to rely on static imagery at a restricted range of spatial scales for temporal analysis (e.g. Hamandawana and Chanda 2010).

While beyond the scope of this paper, and well beyond the extent of the data and information currently available for the Okavango, in other landscapes where high resolution and extensive databases and resources already exist, there is significant potential for even more sophisticated multi-media, nested hierarchy visualisations to be produced. In these situations, a user would be able to zoom into the figure and access images, videos, animations, and models showing different features at different scales and resolutions. Such technology can be used to provide not only geographical context across spatial scales but also context over time (Montgomery 2007; Brierley et al 2013; Phillips 2015). Such approaches that synthesise existing and new datasets into an interactive and visual product, have the potential to be highly effective in communicating geomorphology as part of more sustainable environmental management practices, particularly for transboundary rivers (c.f. Armitage et al 2015).

Conclusion

This paper has demonstrated how at different scales in a nested hierarchy, various data collection, visualisation and mapping techniques have been used to gain geographical perspective and build a comprehensive picture of the Okavango catchment and Delta, and the Panhandle in particular. While the reality of most fieldwork is a focus on conducting relatively detailed analyses at finer scales in the hierarchy (reach, site and geomorphic unit scales), we found it invaluable to gain a much broader perspective (catchment to reach scales) both prior to, and during, fieldwork. In particular, obtaining a large-scale aerial perspective, whether derived from air photographs, remotely piloted aircraft or a helicopter, provides the context for making better informed and more insightful geomorphic interpretations of the landscape. Constraining analyses to too fine a scale, and/or failing to gain a broader perspective, runs the risk of misinterpretations. Our use of a nested hierarchical framework is certainly enhancing our ongoing analyses and interpretations of the fluvial geomorphology of the Okavango Delta, and also has potential to improve communication of geomorphology and engagement in water resources management. Moreover, given the rapid pace of technological advances that are enabling ever more detailed geographical and geomorphological data acquisition, multi-media nested hierarchical visualisations have significant potential for further developments, both within the Okavango Delta and beyond. Such developments are not only important scientifically but also provide a critical geographical perspective with which to engage a broader community and manage the environment.

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Figures

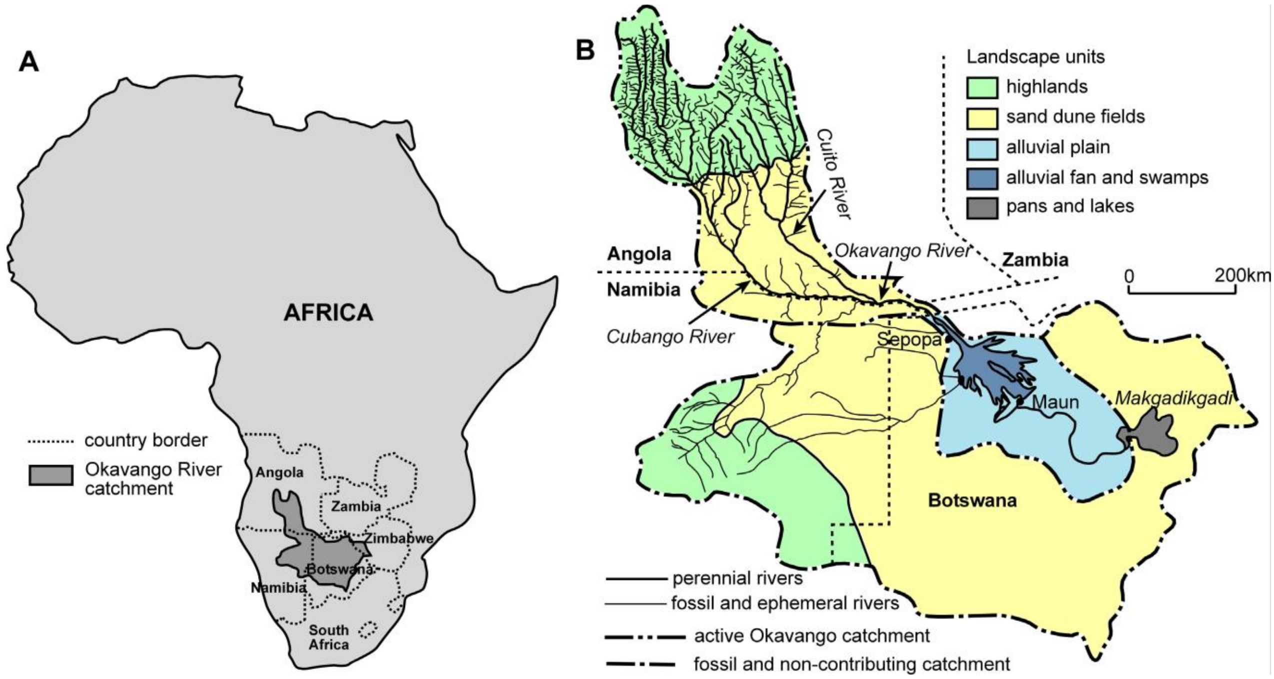


Figure 1 (A) Location of Botswana and the Okavango River catchment in southern Africa. (B) Okavango River catchment showing the drainage network that includes the Okavango Delta. Landscape units are also depicted. Basemap modified from Figure 4 in Mendelsohn et al (2010).

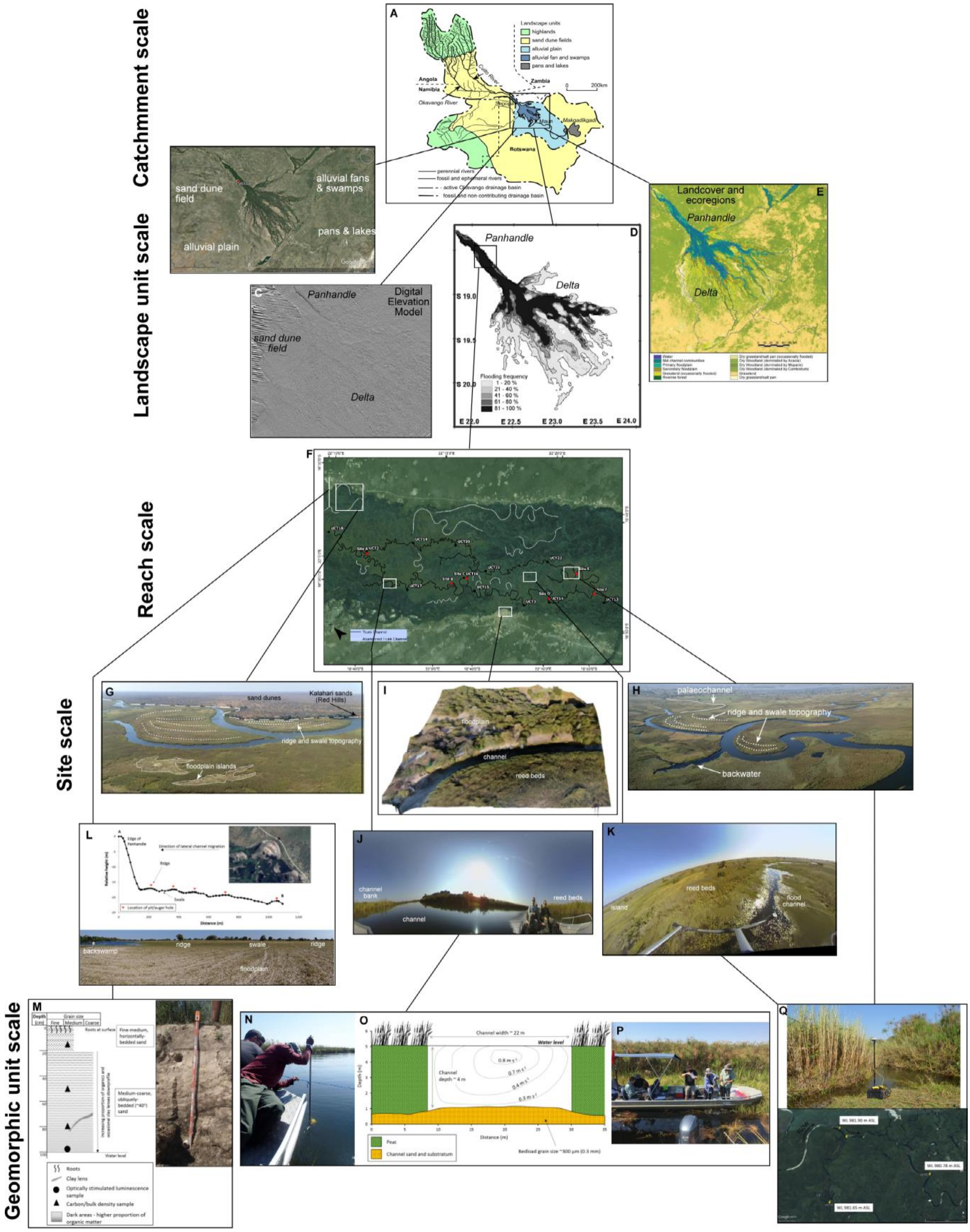


Figure 2 A nested hierarchical perspective for use in interpretation and communication of the fluvial geomorphology of the Okavango Delta. Sources of each visualisation are noted in **Table 2**.

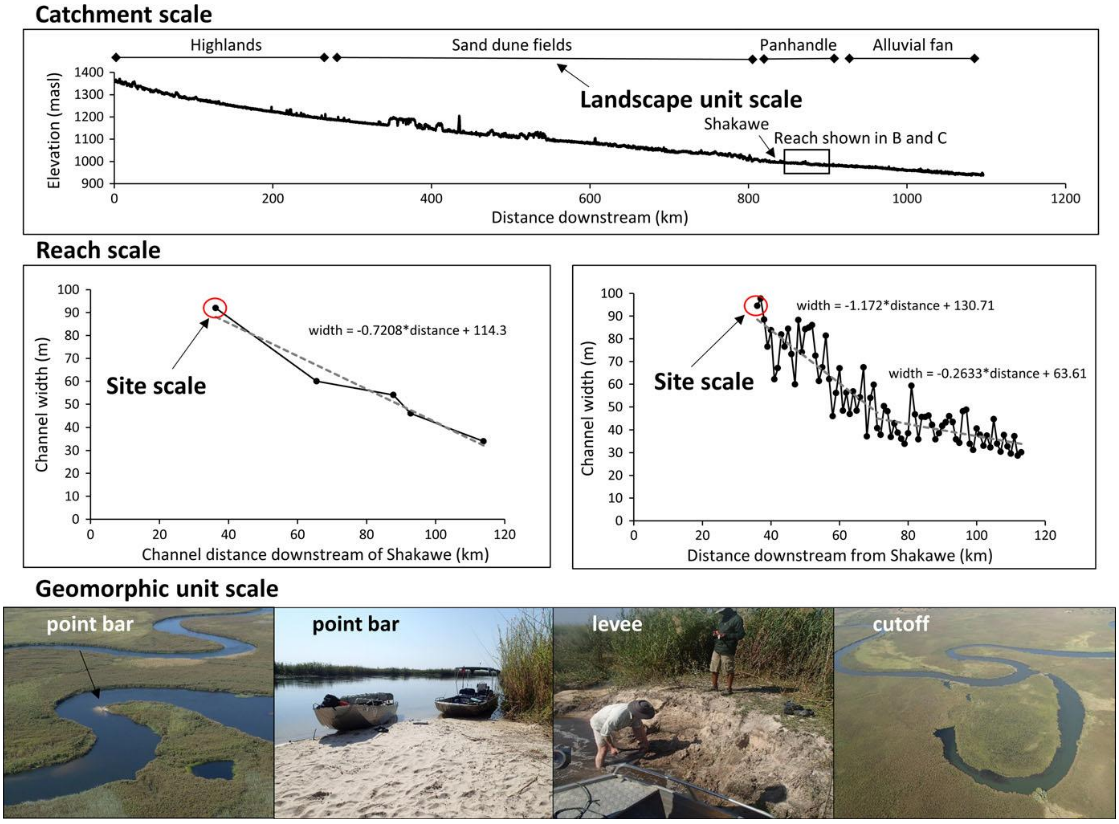


Figure 3 Hierarchical framework highlighting how the use of new technology can enhance our understanding of the Okavango River in the Panhandle. (A) Longitudinal profile of the Okavango River extracted from SRTM data (30 cm cell size). B) Reach scale pattern of downstream decrease in channel width as measured by Tooth and McCarthy (2004). Note the approximately constant rate of overall width decrease. (C) High resolution channel width data from the same reach as (B), obtained using Google Earth satellite imagery from the year 2004. Note the high level of variability in channel width and the step change in the rate of overall width decrease that is not apparent in Tooth and McCarthy’s (2004) coarser resolution data. (D) Image of a point bar from the air. Flow direction is from middle right to lower left. (E) Image of a point bar on the ground, looking downstream. (F) Image of a breached levee on the main channel. During floods, flow direction is away from the camera. (G) Image of a meander cutoff from the air. Flow direction is from left to right.

Table 1 Examples of the range of techniques available to visualise and map landscapes across spatial scales.

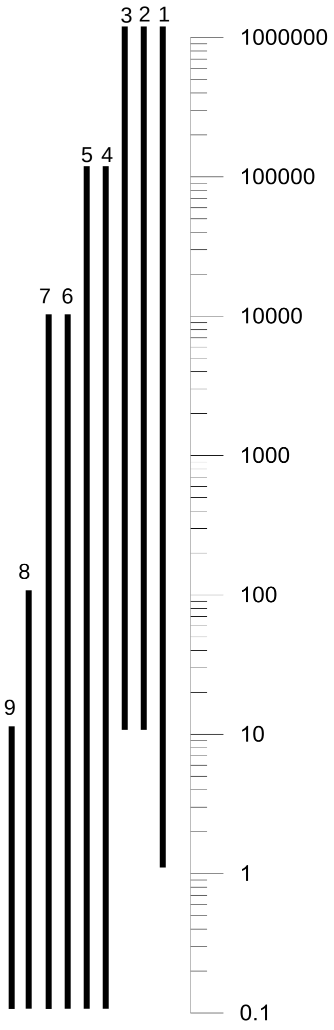
	Technique	System component	Utility	Scale of observation	Observation extent (km^2)	Graphic key of observation extent (km^2)
1	Satellite imagery	Catchments, landscape units, reaches	Inundation, land cover	1:1,000,000 to 1:100	1,000,000 to 1 km^2	
2	Aerial photographs and orthophoto mosaics	Catchments, landscape units, reaches, sites	Inundation, land cover, topography	1:1,000,000 to 1:1000	1,000,000 to 10 km^2	
3	Topographic maps	Catchments, landscape units, reaches, sites	Land cover, topography	1:1,000,000 to 1:1000	1,000,000 to 10 km^2	
4	Geomorphic maps	Reaches, sites, geomorphic units	Land cover, topography, geomorphic units	1:100,000 to 1:10	100,000 to 0.1 km^2	
5	River and wetland maps	Reaches, sites, geomorphic units	Geomorphic units, hydraulic units	1:100,000 to 1:10	100,000 to 0.1 km^2	
6	DGPS	Reaches, sites, geomorphic units	Topography, longitudinal profiles, cross sections, surface samples	1:100,000 to 1:10	10,000 to 0.1 km^2	
7	Aerial laser and optical surveys	Reaches, sites, geomorphic units	Topography, longitudinal profiles, cross sections, surface samples	1:100,000 to 1:10	10,000 to 0.1 km^2	
8	Terrestrial laser and optical surveys	Reaches, sites, geomorphic units	Topography, longitudinal profiles, cross sections, surface samples	1:1000 to 1:10	100 to 0.1 km^2	
9	Site maps	Sites, geomorphic units	Surface samples, profiles (pits, bank exposures and cores)	1:100 to 1:10	10 to 0.1 km^2	

Table 2 Technique, technology and software used to capture data and thus visualise the landscape at different spatial scales in the nested hierarchy for the Okavango Delta.

Spatial scale Image/data	Technique or technology used to produce image/data (brand, edition etc.)	Software used to process image/data
Catchment scale		
A) Catchment map	Compiled from Landsat imagery in conjunction with a low resolution differential GPS survey. (30 m cell size)	Original: ESRI software Compilation and addition of landscape units: Macromedia Freehand MX
Landscape unit scale		
B) Imagery	Google Earth (2.5 m cell size), Garmin BirdsEye satellite imagery (sub-metre cell size)	Original: Google Earth Compilation: Macromedia Freehand MX
C) Topography/Digital Elevation Model	NASA Shuttle Radar Topography Mission (SRTM) 90 m data set	ESRI software
D) Flow inundation map	NOAA AVHRR satellite data (1 km^2 resolution), ERS-ATSR and composite Landsat MSS/TM data	ESRI software
E) Land cover classification	Landsat TM/MSS and MODIS imagery (30 m cell size)	ESRI software
Reach scale		
F) Reach map with sites	Garmin BirdsEye satellite imagery (as above), ESRI Basemap satellite imagery, Google Earth (2.5 m cell size), aerial photographs 1:40,000	ArcMap
Site scale		
G) & H) Panoramic photographs	Digital camera still photographs (12 megapixel)	Photoshop CS5 and Kolor Autopano Giga 3.5
I) 3D digital elevation model using Structure from Motion	Phantom 2 RPA, oblique RGB images	Agisoft PhotoScan Professional 1.2.6

(SfM)		
J) & K) 360^0 panoramic photos and video	360fly camera with 8 element glass ultra-fisheye lens (aperture: F2.5; field of View: 240°; focal length: 0.88 mm; video resolution: 1504 x 1504 @ 29.97fps)	360fly Desktop Director
L) Cross sections	100 m measuring tape and clinometer, Garmin BirdsEye satellite imagery (as above)	Microsoft Excel, Microsoft Powerpoint
Geomorphic unit scale		
M) Sediment column	Geoscience Australia field texture guide	Microsoft Powerpoint
N) Channel velocity profiles	Universal Current Meter F1 with 4 m pole extension (measuring range: 0.025 – 10 m/s)	Microsoft Excel, Microsoft Powerpoint
O) Channel cross sections	Sonar depth reader, Bushnell Laser 450 range finder (range: 5-999 m; accuracy: ±1 m)	Microsoft Excel, Microsoft Powerpoint
P) Bedload sampling	Van Veen Grab bedload sampler	Microsoft Powerpoint
Q) Water levels	Trimble GPS Pathfinder ProXRT Receiver connected to a dual frequency GNSS antenna (accuracy: ± 3-10 cm)	Trimble TerraSync software, Microsoft Excel
M) Bank exposure and pit sediment sampling (OSL, bulk density, sedimentology)	Spade, Dormer push-tube sampler, mallet and anvil	Microsoft Powerpoint