Geomorphology 205 (2014) 142–154

Contents lists available at ScienceDirect

Geomorphology

journal homepage: www.elsevier.com/locate/geomorph

Fluvial connectivity and climate: A comparison of channel pattern and process in two climatically contrasting fluvial sedimentary systems in South Africa

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ARTICLE INFO

Article history:
Received 28 June 2011
Received in revised form 23 January 2012
Accepted 9 May 2012
Available online 18 May 2012

Keywords:
Hydrological variability
Floodplains and valley fills
Discontinuous channels
Climate change
Channel pattern

ABSTRACT

The aim of this research was to investigate the dynamics of valley formation, sediment delivery and channel pattern in two climatically contrasting fluvial sedimentary systems in South Africa. Each system comprised a network of headwater valley fills and floodplains underlain by sedimentary Karoo Supergroup rocks that are intersected by resistant dolerite dykes and sills. The Seekoei River Floodplain and Gordonville valley fill site in the Great Karoo, however, experience less than half the annual precipitation of the Nsonge River Floodplain and Hlatikhulu valley fill in the KwaZulu–Natal Drakensberg Foothills. Furthermore, rainfall is more variable in the Karoo. Despite climatic differences, headwater valley fills were geomorphically similar. In contrast, floodplains in the two regions were vastly different, even when the same downstream control (a resistant dolerite intrusion crossing the drainage line) was considered. Upstream of a dolerite dyke, the Nsonge River is highly sinuous and located in a wide floodplain that has been carved by lateral planation of the underlying bedrock. In comparison, the Seekoei River, located upstream of a dolerite sill, is discontinuous and characterized by floodouts and avulsing distributaries that undergo periods of bedrock incision, followed by infilling.
It is likely that this disparity is caused by the inability of infrequent, unsustained flows to develop meanders and, thus, adjust the channel planform to changes in discharge, sediment load and valley slope. Flow variability, thus, exercises a strong control on channel pattern and causes floodouts in headwater settings and the semi-arid Karoo floodplain. As a result, sediment transport in the Seekoei River is likely to be episodic, and net retention of sediment in the semi-arid floodplain is greater than in the sub-humid Nsonge River Floodplain, where sediment depth is limited.

1. Introduction

Field-based investigations of fluvial response to climate change lag behind all other fields of climate change research (Blum and Törnqvist, 2000). Whereas numerous studies have attempted to link phases of erosion and deposition to specific cold/warm climate phases (e.g. Penck and Brückner, 1909; Fisk, 1944; Peizhen et al., 2001; Driese et al., 2005; Benito et al., 2008), the complex nature of fluvial systems makes it difficult to predict how climate change will affect landscape processes and dynamics. This is largely because the landscape is not completely controlled by climate (Vandenberghe, 2002), and where climate is important, its effect may be variable, ranging from direct (e.g. peak precipitation) to indirect forcing (e.g. permafrost) (Vandenberghe, 2003).

Schumm (1977) and Begin and Schumm (1984) cautioned against generalizing fluvial response to climate change, as certain geomorphic systems are inherently more vulnerable to change because of differing thresholds. Climatic forcing may either be filtered, such that the impact is reduced downstream, or amplified, resulting in the effect being much larger than predicted (Phillips, 2010a). Furthermore, change can cascade through a system, and because of complex response, different regions may be out of phase even within a single drainage line (Schumm, 1973; Blum and Törnqvist, 2000). Thus, it is extremely important to consider the spatial and temporal scale of the geomorphic system under investigation (Schumm and Lichty, 1965).

Few studies have offered a comparison of fluvial styles, fluvial processes, and valley morphodynamics on equivalent lithologies, but in contrasting climatic settings. This research capitalizes on a rare opportunity to compare climatic controls on drainage basin processes. This paper considers two drainage basins in South Africa, from the scale of headwater valley fills near the drainage divide, to that of floodplains. The two drainage basins are similar with respect to elevation, vegetation, topography, geology and geomorphic history, but differ substantially in

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doi:10.1016/j.geomorph.2012.05.010

terms of climate. 'Headwater valley fills' are regions located close to the drainage divide where geomorphic and hydrologic factors prevent channeled flow in the form of a river and are consequently characterized by a valley of alluvial fill in which gully-floodout processes are the norm (for a review, see Brierley and Fryirs, 2005), and in which diffuse overland or groundwater flow is common. The term 'floodplain' includes the typical meandering floodplain, characterized by alluvial fill, alluvial ridges, scroll bars, and ox-bow lakes, as well as other floodplain types, as classified by Nanson and Croke (1992).

Climate is one of the main controlling factors in determining fluvial style, as it impacts upon vegetation and flow hydrology (Schumm, 2005; Goudie, 2006). The amount and timing of precipitation in a catchment most significantly influence whether a river is ephemeral or perennial, and as such, influence the manner in which sediment is transported from its source to the oceanic or continental sink. The nature of the hydrology of a drainage line, and the consequent sediment cascade, has direct geomorphic implications for the fluvial style of the drainage network. Considerable attention has been paid to understanding the relationship between channel slope, sediment supply, discharge and channel pattern, resulting in the development of empirically derived classification schemes (e.g. Leopold and Wolman, 1957; Ferguson, 1987; van den Berg, 1995; Eaton et al., 2010; Kleinhans and van den Berg, 2011). One outcome of these studies is that a change in either discharge or sediment load, both of which may be impacted by climate, results in adjustment of the energy available to perform geomorphological work, resulting in a change in channel pattern and/or process. These analyses, however, apply only to channels with relatively continuous flow (Eaton et al., 2010; Kleinhans, 2010). Discontinuous fluvial styles, such as gully-floodout networks, offer several challenges to traditional methods of discriminating channel types. Even by focusing only on the channel component, one faces the problem of quantifying bankfull discharge (and bankfull unit stream power) in an incisional, disequilibrium channel form, the geometry of which is rarely indicative of mean, or channel forming flow (Kirkby and Bracken, 2009). In addition, flow in discontinuous channels is rarely gauged, and because flow events are sporadic, field observations of gully flow are rare. Whereas it is beyond the scope of this paper to extend current planform discriminations to include discontinuous fluvial styles, observations are offered that may assist in developing discriminant functions.

The aim of this paper is to understand dynamics of valley formation and change, as well as styles of sediment delivery by examining catchments in different climatic settings, and to determine whether the response to different climatic conditions differs between floodplains and headwater valley fill settings. Through characterizing and contrasting the climate, geology and topography of a drainage basin in the semi-arid Karoo (Köppen climate Bskw — dry steppe climate with dry, cold winter; Köppen, 1923), to that of a drainage basin in the Foothills of the KwaZulu–Natal Drakensberg Mountains (Köppen climate Cw — temperate rain climate with dry winter; Köppen, 1923), and in comparing fluvial forms, processes, and valley morphometry, a conceptual model of valley morphodynamics and sediment delivery is presented. This comparison offers an opportunity to improve our understanding of geomorphic processes in environments with high variability in rainfall. The intention is not to suggest that in regions where rainfall becomes more variable or infrequent, that the current geomorphic regime will be completely replaced with the one described, but rather to highlight different fluvial processes that may become more common in some areas in the climate of the future. Our analysis cannot be used to investigate the processes and dynamics associated with rivers changing from one stable state to another.

2. Bioclimatic setting

Climatically, South Africa is located below the descending limb of the Hadley circulation, within the subtropical high-pressure belt. In the western regions, precipitation occurs predominantly through the passage of cold fronts associated with mid-latitude cyclones. In the east, in addition to cold fronts, disturbances in the tropical easterlies may be responsible for rain (Tyson and Preston-Whyte, 2000). In both regions, summer convection may produce rain during thunderstorms. Precipitation in southern Africa exhibits a strong east–west gradient, with regions on the eastern seaboard generally experiencing greater than 700 mm of precipitation each year (as shown in de Wit and Stankiewicz, 2006). The western South African hinterland, however, is semi-arid, and annual precipitation is between 100 and 500 mm. The most recent IPCC models of climate change for southern Africa suggest that rainfall is likely to decrease, or stay the same, concurring with earlier predictions (e.g. Hulme, 1996; Arnell, 1999). Irrespective of the actual amount of precipitation in both regions, it is clear that rainfall will become more variable, and the magnitude and incidence of large floods will increase (IPCC, 2007). More importantly, the duration and spatial occurrence of dry spells will increase.

The two systems selected for this study are located in contrasting climatic regions, with Gordonville and the Seekoei River Floodplain in the semi-arid Karoo, and Hlatikhulu and the Nsonge River Floodplain within the sub-humid Afromontane Foothills of the KwaZulu–Natal Drakensberg Mountains (Fig. 1). The annual water balance for Hlatikhulu and Gordonville, as calculated using Schulze's (1997) estimates of mean annual precipitation and mean annual potential evaporation for quaternary catchments, is −723 mm and −1946 mm, respectively.

The vegetation of Gordonville and surrounds is characterized by 'Eastern Upper Karoo nama-karoo' on the flats and gently sloping hills of the region, and is dominated by dwarf shrubs and 'white' grasses of the genera *Aristida* and *Eragrostis* (Mucina and Rutherford, 2006). The thin soils, boulders and stones of steeper slopes and dolerite ridges support dwarf Karoo shrubs and drought tolerant grasses (genera *Aristida*, *Eragrostis* and *Stipagrostis*) of the 'Upper Karoo Hardeveld'. The Hlatikhulu valley in KwaZulu–Natal is vegetated predominantly by 'Drakensberg Foothill moist grassland', while isolated patches of 'Northern Afrotemperate Forest' occur on steep south-facing slopes (Mucina and Rutherford, 2006). The floor of the Hlatikhulu valley comprises wetland vegetation, with grasses such as *Setaria sphacelata* and *Arundinella nepalensis* in temporary to seasonal wetland zones, and sedges and reeds (*Cyperus denudatus*, *Carex acutiformis*, *Carex cognata*, *Typha capensis* and *Phragmites australis*) in semi-permanently to permanently wet areas (Guthrie, 1996). Levee and channel-flanking vegetation at the Karoo and Drakensberg sites is essentially similar in structure, and predominantly comprises grasses with a maximum root-hold depth of ~0.5 m, although vegetation cover in the Karoo is slightly sparser than that in the Drakensberg Foothills.

3. Methods

Three main approaches are used to investigate the impact of climate change on fluvial processes; 1) reconstruction of past patterns of climate change and fluvial form and process using palaeoclimatic and sedimentological records (e.g. Prieto et al., 2004; Leigh, 2008; Nanson et al., 2008), 2) modeling change using current understanding of fluvial processes, often coupled with proxy records of past change (e.g. Coulthard and Macklin, 2001; Verhaar et al., 2008, 2010), or 3), studying geomorphic processes in regions where the climate is similar to what we might expect in the future, i.e. a 'space for time' substitution (Paine, 1985). This paper offers a variation on the latter approach, which is akin to the climosequence approach used in pedology and soil geography. For the purposes of comparison, this study involved characterizing the two study areas in terms of climate, geology and geomorphology. Southern Africa is extremely stable tectonically, and neither study area is adjusting to legacy conditions or recent glacial events. Geology for each study area was captured from 1:250 000 geology maps supplied by the Geological Survey of South Africa. The