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A Geomorphological Response Model for predicting sediment-related habitat change in ephemeral rivers

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Abstract Protection of aquatic ecosystems is a legal requirement emanating from the water laws of many countries globally. Methods to assess environmental flows are being developed and applied throughout the world, with an emphasis on perennial rivers. In South Africa, scientists are addressing environmental flow needs for ephemeral rivers by developing a Geomorphological Response Model that integrates expert knowledge into a decision support system, based on mathematically defined response curves. Geomorphologists play a key role in predicting the long-term change in ecosystem structure following water-related developments. In this paper we explain the process whereby we are developing geomorphic response curves that can be used to predict habitat related channel change in rivers for which there are limited hydrological or geomorphological data.

Key words Environmental flows; non-perennial rivers; sediment processes; habitat change; ecosystem structure; decision support system

INTRODUCTION

Water resources in many parts of South Africa are limited (King & Brown, 2006) and must be carefully managed in order to meet social and environmental needs. The South African National Water Act (1998) requires that an ecological Reserve be allocated in order to protect the integrity of each water resource. Setting the Reserve is part of a three-step process that involves classification of the water resource according to the desired level of protection, determining Resource Quality Objectives (RQOs) and setting the ecological Reserve (Rowntree & Du Preez, 2008). The protection class is used to guide RQOs for the resource in terms of the required in-stream and riparian conditions for habitat and flow. The ecological Reserve is required to meet quantity, timing and quality of streamflow objectives.

Environmental flow assessment methodologies have been developed in many countries, including Australia, Tanzania, the USA, UK and South Africa. Most methodologies involve a multi-disciplinary team of engineers, hydrologists, geomorphologists, ecologists, economists, lawyers, political scientists and communication specialists (Thoms & Sheldon, 2002; Dyson *et al*., 2003; Annear *et al*., 2004; Arthington *et al*., 2004; King & Brown, 2006; Tamatamah, 2007). The goal of maintaining environmental flows is to protect the river ecosystem. Thoms & Sheldon (2002) stress that sustainable environmental flow regimes are necessary to promote geomorphic processes that provide and maintain habitat. Geomorphologists have conducted environmental flow assessments for South African rivers to standardize methodology for the implementation of ecological reserves (Rowntree & Wadeson, 1998; Rowntree & Du Preez, 2008).

Major ecological Reserve determinations in South Africa have primarily focused on large perennial rivers. However, the majority of South African rivers are ephemeral (Rossouw *et al*., 2005) and there is a need to develop environmental flow assessment methodologies for these increasingly stressed systems (Bull & Kirkby, 2002). These systems are characterized by sand and gravels beds, variable flow regimes, extreme flood events (Thoms & Sheldon, 2002) and high sediment loads (Langbein & Schumm, 1958; Reid & Frostick, 1997; Beven, 2002). Accordingly, these distinctive hydro-geomorphic characteristics strongly influence ecosystem form and function.

Recognising the distinctive character and importance of ephemeral river ecosystems, a research project was initiated by the University of the Free State to develop an environmental flow assessment method for ephemeral rivers. This automated assessment model or Decision Support System (DSS) based on the ELOHA framework (Poff *et al*., 2010) has three assumptions:

(1) change in flow will change biophysical and socio-economic environments, (2) these changes can be predicted, and (3) they can be captured in the form of mathematical equations (response curves). Response curves are integrated into the DSS to evaluate ecological response to different water management scenarios by indicating deviation from present day flow conditions. The curves are used as input to a daily time series, simulating indicator change for a specific scenario over time. The average indicator change is calculated for the time series, resulting in a single value that can be compared to the present day or natural condition.

The DSS considers geomorphological change to be an important driver of ecosystem processes and special attention is given to floods and sediment fluxes. The aim of this paper is to explain the process of developing geomorphological response curves for the seasonal Mokolo River in Limpopo Province, South Africa.

The Mokolo River and catchment

The Mokolo River flows northwest to the Limpopo River in South Africa. The catchment area of 8395 km^2 is dominated by sandstone in the upper catchment and granite-gneiss covered by sandy alluvium in the lower catchment. The upper river reaches have steep stepped longitudinal profiles with very low to medium sediment storage potential (Partridge *et al.*, 2010). A narrow single channel that bifurcates around reed islands is common, with the bed material alternating between bedrock and fine sediment. In contrast, the lower catchment is characterised by a smooth longitudinal profile and a wide valley floor with high sediment storage potential (Partridge *et al.*, 2010). The channel widens and has a wandering or braided pattern. Bed material is predominantly coarse sand, with finer materials deposited on well-vegetated islands.

Mean annual precipitation decreases from 700 mm year^{-1} in the higher lying areas to 400 mm year^{-1} in the lowland, with mean annual potential evaporation ranging from 2200 mm year^{-1} in the higher areas to 2450 mm year^{-1} on the Limpopo Flats (DWA, 2010). Rainfall is highly seasonal, being concentrated in the summer season between October and March. The system can be described as intermittent, as surface flow stops during dry periods.

Fieldwork

In 2010, an ecological data set was collected for the various sites to provide a basic understanding of the functioning and diversity of the system. Four morphological levels were identified: the low-flow channel and three flood zones – Flood zones 1, 2 and 3 (Table 1). Following discussions with the vegetation specialist it was agreed that these were equivalent to the vegetation zones aquatic, marginal, lower and upper zone, respectively. A channel cross-section was surveyed using levelling to represent the general morphology in terms of the zones described above. High water levels prevented detailed surveys. One of the study sites (Site 4) is shown in Fig. 1 as an example to illustrate the different zones. Site 4 was a sand bed channel in the lowland reach of the river.

Table 1 Interpretation of geomorphological and vegetation zones.

Geomorph. zone	Veg. zone	Flood frequency, water availability and geomorphic process
Channel bed	Aquatic zone	Covered in water at low flows, main sediment transport zone during floods
Flood zone 1	Marginal zone	Covered in water during intermediate floods that would normally occur one or two times a year. High soil moisture status, but surface not saturated for long periods. Erosion or sediment deposition likely during floods.
Flood zone 2	Lower zone	Similar to marginal zone, but less likelihood of flooding and lower soil moisture status between flood events. Deposition may exceed erosion during floods.
Flood zone 3	Upper zone	Covered in water during flood events that have a frequency of 3 to 5 years. Floods deposit sediment and recharge deeper groundwater (±5 m). Main root zone unsaturated except during flood events.

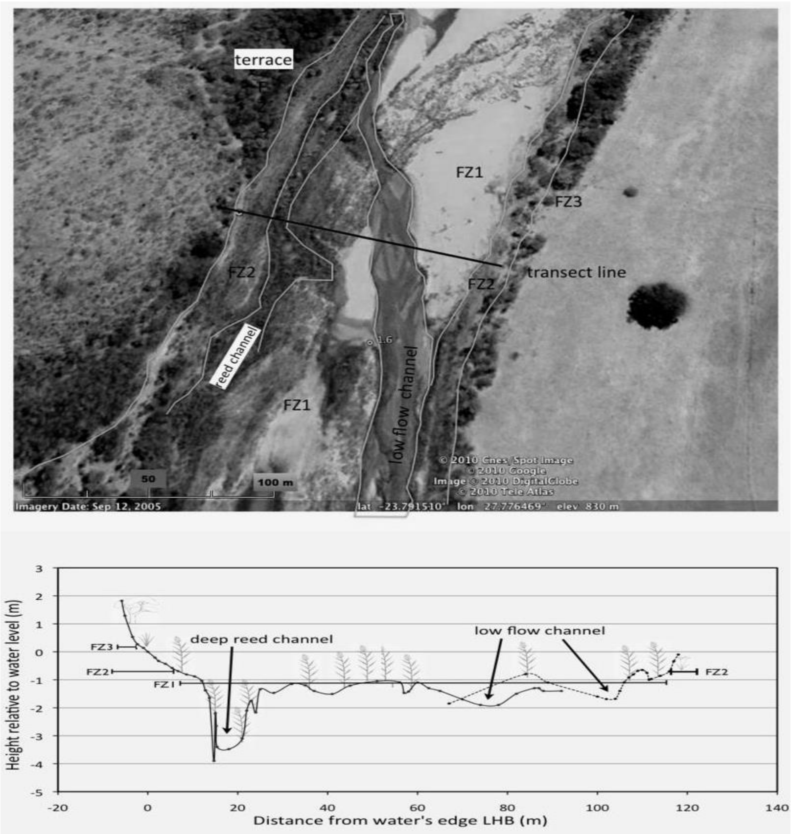

Fig. 1 Aerial view (Google Earth image) of Site 4 indicating flood zones 1, 2, 3 and low-flow channel (top). Cross-section of channel along transect line (bottom).

Geomorphological indicators

An indicator is a variable that can be quantified and is an expression of habitat availability or quality. The proposed geomorphological indicators are listed in Table 2. Change to channel width is linked to a number of indicators. The low flow channel is shaped by frequent low magnitude flows as well less frequent events that will be responsible for shaping flood zone 1. Together these two morphological units make up the active channel floor. If the low-flow channel widens it will

Table 2 Proposed geomorphological indicators.

No.	Indicator	Units	Ecological justification
G1	Percent of fines (sand and smaller) on bed	%	Important indicator of habitat quality in terms of sand bed *vs* gravel or cobble bed – has there been a loss of coarse substratum? Has coarse substratum become embedded?
G2	Width of low-flow channel	m	A measure of the amount of aquatic habitat potentially available.
G3	Low-flow channel depth	m	Shallow channels will overtop more readily in flood conditions and increase the potential of flood water reaching into flood zones 2 and 3.
G4	Geomorphic pool depth	m	Deeper pools should hold water for longer periods during no-flow periods.
G5	Length of pools	m/km of channel	An indicator of the extent of wetted habitat available during no-flow periods.
G6	Area of Flood Zone 1	m^2	Directly linked to the lower dynamic vegetation zone.
G7	Area of Flood Zone 2	m^2	Directly linked to the upper bank vegetation zone.
G8	Area of Flood Zone 3	m^2	Directly linked to the flood plain vegetation zone.
G9	Low-flow channel pattern	Number of channels	If the low-flow channel pattern changes it will indicate a significant system change, with resetting most habitat types.

do so at the expense of flood zone 1; the converse is true if it narrows. The edge of flood zone 2 is equivalent to normal bankfull, its extent will depend on lateral expansion or contraction of flood zone 1. Likewise, the boundary of flood zone 3 depends on change to flood zone 2. Although in theory the dimensions of each zone should be related to floods of a given frequency, in practice it may be difficult to separate these.

Developing response curves

Developing response curves means that we have to predict, to our best ability, the expected changes to channel morphology as a result of changes to the flow regime. Petts & Gurnell (2005) present a qualitative model of styles of channel adjustment below a dam in response to induced changes in discharge and sediment load. Their model indicates that if discharge stays the same but sediment load is markedly reduced, channel capacity, width, depth, bed roughness, channel slope and sediment conveyance will all increase. Conversely, if load stays the same but discharge decreases markedly, all variables other than slope decrease but slope increases.

Although useful in indicating the direction of change, this model does not provide a quantitative estimation. Given our limited understanding of river processes in the Mokolo system, the most practical way to develop a quantitative response curve was to use the principles of hydraulic geometry first developed by Leopold & Maddock (1953).

In South Africa the relationship between flood magnitude and frequency and channel form has been researched for Kruger Park rivers by Heritage *et al.* (2001), and for the Mkomazi, Mhlatuze and Olifants (Limpopo Province) by Dollar & Rowntree (2003). The hydraulic geometry of South African rivers has been described by Beck & Basson (2003).

Knighton & Nanson (1997) question the prevalence of equilibrium channel forms in dryland areas. They discuss the importance of high-magnitude, low-frequency events in controlling channel form in dryland rivers and show how the effects of individual events are preserved for longer in the landscape. Dryland rivers may therefore display transient states rather than equilibrium forms. This was in accordance with results found by Rountree *et al.* (2001), Heritage & van Niekerk (1995) and Heritage *et al.* (2004) for the Kruger Park rivers.

Disequilibrium in dryland river systems introduces further complexity to modelling channel change. The DSS works on a continuous time series, so it should be possible to introduce a time series of channel change into the model. How to do this is more problematic because channel change results from a continuous process of erosion and deposition, and channel form at any one point in time represents the combined effects of variable flows over the historic time period. A method to address this is described below.

Application of hydraulic geometry relationships to developing response curves

Hydraulic geometry has been used widely to describe the relationship between channel dimensions and some measure of the channel forming discharge. It is used here to develop response curves for width and depth.

Change in channel width According to the hydraulic geometry theory of Leopold & Maddock (1953), width is proportional to the square root of mean annual discharge, or:

$$W = aQ^b \tag{1}$$

with b varying for different dryland studies between 0.03 and 0.79 (Wolman, 1955; Scott, 1966; Merritt & Whol, 2003). Beck & Basson (2003) found that the average South African values for a and b are 4.417 and 0.485, respectively. These values were used to plot the response curve in Fig. 2, which displays estimated changes in the width of the main channel comprised of the low-flow channel and flood zone 1. The first step is to estimate the present day discharge that would just fill this channel and is assumed to be the effective flood to which the channel dimensions are adjusted. This is calculated using a hydraulic model. As a hypothetical example, an effective flood of 500 m^3/s was assumed for the present day. Applying equation (1) with the coefficient and exponent given by Beck & Basson (2003), the percentage change in channel width was calculated for given

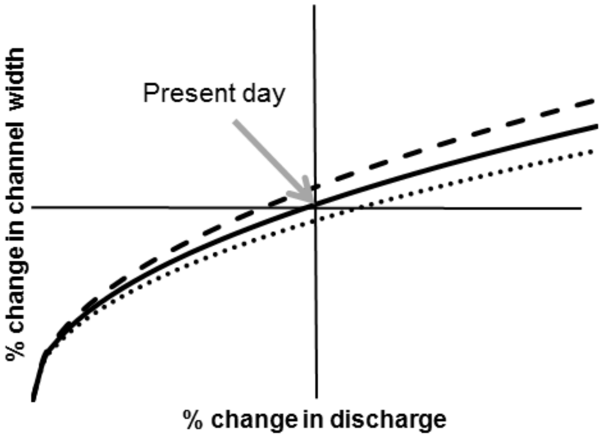

Fig. 2 The discharge–width response curve for non-perennial rivers. The broken line represents an increase in bed material and the dotted line represents an increase in suspended sediment.

percentage changes to the effective flood discharge. An example of the result is given by the solid line in Fig. 2.

A number of studies cover the influence of altered sediment loads on channel width, but due to high variability in response it is difficult to give a fixed ratio. The trend is that an increased suspended load will decrease width, but an increase in bed load will increase width (Leopold & Maddock, 1953; Dietrich *et al.*, 1989). In Fig. 2, hypothetical scenarios are given where coefficient a remains constant and b is increased from 0.485 to 0.495 for coarse sediment and decreased to 0.475 for suspended sediment. Figure 2 indicates that if the coarse sediment load increases, the predicted channel width increases in order to accommodate the load. The width curve will steepen as a result of the combined effect of coarse sediment and increased flow. If the suspended sediment load increases, the channel should narrow due to increased bank stability.

Change in channel depth Leopold & Maddock (1953) give the hydraulic geometry relationship for depth as:

$$d = cQ^f \tag{2}$$

where values for f can vary between 0.15 and 0.48 (Wolman, 1955; Scott, 1966; Merritt & Wohl, 2003). From field measurements in South Africa, Beck & Basson (2003) calculated that $c = 0.125$ and $f = 0.462$ (Table 1). The effect of changes in sediment load is the inverse of that for width (Leopold & Maddock, 1953). An increase in bed load will reduce the channel depth and an increase in suspended load will increase the depth.

Geomorphic pool depth and pool length While widely established hydraulic geometry relationships can be used to develop response curves for indicators linked to channel width and depth (G2, G3, G4, G6, G7, G8), equivalent empirical relationships appropriate to indicators G4 and G5 (geomorphic pool depth and length) are not available. Thompson (2002), using flume experiments, found a linear relationship between pool depth and discharge, but it is questionable whether this can be extrapolated directly to natural rivers.

Lisle (1986) studied the relationship between pool length and channel width. A permanent obstruction in a gravel/mixed bed river will scour a pool with a length equal to one bed width upstream of the obstruction and a pool with a length of three bed widths downstream of the obstruction (Lisle, 1986). For areas with no permanent obstructions, Clifford (1993) found that pool length equates to three channel widths. In mixed bed channels such as found in many reaches in the Mokolo, bedrock obstructions may have the same effect as the obstructions studied by Lisle (1986).

From aerial imagery of the Mokolo River, a pool length–channel width ratio of 2.63 ± 0.96 times the width of the channel was calculated. Thus we can derive a formula based on hydraulic geometry as follows:

$$\text{Pool length} = 2.63 \times \text{channel width} \tag{3}$$

Thus applying equation (1)

$$\text{Pool length} = 2.63 \times 4.417Q^{0.485} \tag{4}$$

Percentage fines on the bed and low-flow channel pattern

Changes to channel pattern and bed material represent the complex response to changes in flow, sediment supply and sediment calibre (Church, 2006), with a secondary response to vegetation encroachment (Shafroth *et al.*, 2002). Realistic quantitative models of channel pattern and bed material change are still to be developed; most change models are still qualitative descriptions based on expert judgement (Church, 2006). Expert opinion will be used to guide the possible direction of change in the DSS, but the process has not yet been formalised.

Converting the response curve into a time series of change

In order to evaluate the different flow scenarios in the DSS, it is necessary to create a time series based on measured flow data. Knighton & Nanson (1997) state that dryland rivers often retain the effect of a large flood for many years, indicating a long relaxation time. This effect of major flow events on the river channel can be explained through the catastrophe theory where we have space–time changes (Graf, 1988). In order to simulate the more catastrophic effect of extreme events such as those that caused stripping in the Kruger Park rivers, with the gradual build-up of sediment by smaller floods in intervening time periods, the following strategy was adopted. Channel dimensions were assumed to be proportional to the weighted mean of the maximum annual floods

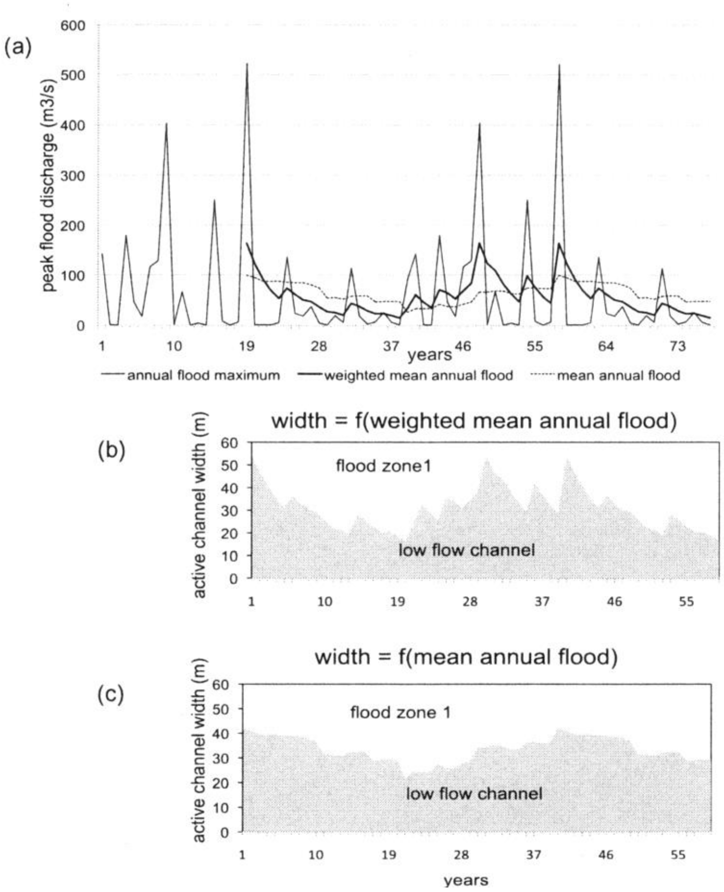

Fig. 3 Time series model of the effects of variable discharge on habitat change.

experienced during the last 20 years, where the maximum weight was ascribed to the most recent flood, the weight reducing over time so that the flood 20 years previously has a small impact on the present channel form. A weighting factor of 0.75 was used in this example. In this paper this is termed the effective flood.

For equilibrium channels, the moving mean annual flood can be used, with no weighting. Figure 3 presents a hypothetical time series showing the annual flood peaks, the mean annual flood and the weighted mean annual flood, derived as above (Fig. 3(a)). Figure 3((b) and (c)) also shows the predicted change in the relative extent of the low flow channel and the flood zone 1, assuming that the outer boundary of flood zone 1 remains static.

CONCLUSION

The DSS has the potential to be a helpful decision-making tool for water managers. These universal geomorphological models for highly variable systems might produce outcomes of low confidence. This is a first step for this model, but with testing and refining this model might produce outcomes with high confidence that will aid in allocating environmental flows.

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