Quantifying and contextualising cyclone-driven, extreme flood magnitudes in bedrock-influenced dryland rivers

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Abstract

In many drylands worldwide, rivers are subjected to episodic, extreme flood events and associated sediment stripping. These events may trigger transformations from mixed bedrock-alluvial channels characterised by high geomorphic and ecological diversity towards more dominantly bedrock channels with lower diversity. To date, hydrological and hydraulic data has tended to be limited for these bedrock-influenced dryland rivers, but recent advances in high-resolution data capture are enabling greater integration of different investigative approaches, which is helping to inform assessment of river response to changing hydroclimatic extremes. Here, we use field and remotely sensed data along with a novel 2D hydrodynamic modelling approach to estimate, for the first time, peak discharges that occurred during cyclone-driven floods in the Kruger National Park, eastern South Africa, in January 2012. We estimate peak discharges in the range of 4470 to 5630 m3s-1 for the Sabie River (upstream catchment area 5715 km2) and 14 407 to 16 772 m3s-1 for the Olifants River (upstream catchment area 53 820 km2). These estimates place both floods in the extreme category for each river, with the Olifants peak discharge ranking among the largest recorded or estimated for any southern African river in the last couple of hundred years. On both rivers, the floods resulted in significant changes to dryland river morphology, sediment flux and vegetation communities. Our modelling approach may be transferable to other sparsely gauged or ungauged rivers, and to sites where palaeoflood evidence is preserved. Against a backdrop of mounting evidence for global increases in hydroclimatic extremes, additional studies will help to refine our understanding of the relative and synergistic impacts of high-magnitude flood events on dryland river development.

Key words: dryland river, 2D hydraulic modelling, extreme flood, flood estimation, palaeoflood, Sabie River, Olifants River

INTRODUCTION

Drylands (hyperarid, arid, semiarid and dry-subhumid regions) cover 50% of the Earth's surface and sustain 20% of the world's population (United Nations, 2016). Many drylands are characterised by strong climatic variations, with extended dry periods interspersed with short, intense rainfall events, and are widely considered to be among the regions most vulnerable to future climate change (Obasi 2005; IPCC 2007; Wang et al., 2012). Many dryland river flow regimes are similarly variable (McMahon et al., 1992), with long periods of very low or no flow being followed by infrequent, short-lived, large or extreme flood events (see Tooth, 2013). This variable flow regime is one of the primary controls on dryland river process and form, commonly resulting in channel-floodplain morphologies and dynamics that differ markedly from many humid temperate rivers (Tooth, 2000; 2013; Jaeger et al., 2017). In particular, the role of extreme events in the episodic 'stripping' of unconsolidated sediment from alluvial fills on an underlying bedrock template has been reported as a key control on the long-term development of many southern African, Australian, Indian and North American dryland river systems (e.g. Womack and Schumm 1977; Baker 1977; Kale et al. 1996; Bourke and Pickup 1999; Wende 1999; Rountree et al. 2000; Tooth and McCarthy 2004; Milan et al., 2018a, Milan et al., 2018b). These stripping events limit long-term sediment build-up and contribute to incremental channel incision over geological time.

Over the last few decades, research into bedrock-influenced dryland rivers has increased (e.g. Heritage et al., 1999; 2001; Tooth et al., 2002; 2013; Meshkova and Carling, 2012; Keen-Zebert et al., 2013), but hydrological and hydraulic data remain limited owing to the difficulty in collecting information in these typically harsh environments with their relatively infrequent channel-shaping flows. In particular, gauging stations commonly fail to accurately record flow data during large or extreme flood events, as the structures are commonly drowned out and/or suffer physical damage. This paucity of data hampers efforts to develop conceptual and quantitative models of the response of these types of dryland rivers to past, present and future climatic changes, impacting on our understanding and subsequent management of such systems.

Similarly, while computational modelling has led to significant insights into the flow hydraulics, sediment dynamics and morphological responses of fully alluvial rivers (e.g. Nicholas et al., 1995; Nicholas, 2005; Milan and Heritage, 2012; Thompson and Croke, 2013), to date there have not been similar advances in our understanding of bedrock-influenced dryland river dynamics. For instance, owing to the paucity of channel roughness information available for these morphologically-diverse river types, past experience has shown that modelling and indirect estimation of extreme discharges commonly has proved problematic and may generate unreliable data (Broadhurst et al., 1997).

Despite these limitations, improved remote survey technologies and more sophisticated hydraulic modelling software now enhance the possibility of capturing and processing high-resolution topographic data to generate improved estimates of flood hydraulics and magnitudes in bedrock-influenced dryland systems. Against this backdrop, this paper demonstrates how a combination of remotely sensed and field data has been used to apply a 2D hydraulic model for the bedrock-influenced Sabie and Olifants rivers in the Kruger National Park (KNP), South Africa (Fig. 1), where Cyclone Dando generated high-magnitude floods in 2012. Our approach utilised improved data collection, and DEM processing alongside more sophisticated hydraulic modelling and represents a step forward from previous flood modelling estimation work on these rivers that employed 1D modelling (Heritage et al., 2004). The aims are to: 1) use this model to estimate the peak discharges for the floods on these two rivers; 2) compare these estimates with those generated by other commonly-used flood estimation approaches; and 3) compare the estimates with the peak discharges of large or extreme floods recorded or estimated on other southern African rivers. Our approach may be transferable to other sparsely gauged or ungauged rivers that are subject to high-magnitude flood events, and to sites where palaeoflood evidence is preserved, and so may help to refine our understanding of the magnitude, frequency and impacts of such events on river development.

STUDY SITES

The Sabie and Olifants rivers are located in the southern and central part of the KNP in the Mpumalanga and Limpopo provinces of northeastern South Africa (Fig. 1). The 54 570 km^2 Olifants catchment incorporates parts of the Highveld Plateau (2000-1500 m), the Drakensberg Escarpment, and the Lowveld (400-250 m). The 6320 km^2 Sabie River covers part of the Drakensberg Mountains (1600 m), the low-relief Lowveld (400 m), and the Lebombo zone (200 m). Rainfall in both catchments is greater in the headwaters (2000 mm yr^{-1}) and declines rapidly eastwards towards the South Africa–Mozambique border (450 mm yr^{-1}). Within the middle reaches, sediment is dominantly sand and fine gravel (median grain size 1-2 mm) (Broadhurst et al. 1997). Although water abstractions have altered the low flows (generally below 50 m^{3}s^{-1}) along both rivers, intermittent cyclone-driven flood flows are unaffected, and the channels remain unimpacted by engineering structures or other human activities over considerable lengths within the KNP. Thus, both rivers represent excellent, near-pristine sites for investigating bedrock-influenced dryland river dynamics.

Fig. 1.

In the KNP, both rivers are characterised by a bedrock ‘macrochannel’, which extends across the floor of a 10-20 m deep, incised valley. The macrochannel hosts one or more narrower channels, bars, islands and floodplains (Fig. 2A-C). Outside of the macrochannel, floods have a very infrequent and limited influence. These rivers are characterised by a high degree of bedrock influence, and the diverse underlying geology results in frequent, abrupt changes in macrochannel slope and associated sediment deposition patterns. Locally, bedrock may be buried by alluvial sediments of varying thickness, resulting in diverse channel types that range from fully alluvial (Fig. 2A) to more bedrock-influenced (Fig. 2B-C) (van Niekerk et al. 1995).

Fig. 2

In mid-January 2012, Cyclone Dando impacted on eastern southern Africa. Widespread heavy rainfall (450-500 mm in 48 hours) led to high-magnitude floods along many of the rivers that drain into and through the KNP. Preliminary 2D hydraulic modelling of the Sabie River flood shows that local velocities peaked at 4 ms^{-1}, resulting in extensive erosion and sedimentation along many reaches (Heritage et al. 2014; Milan et al. 2018b). Here, we extend our analyses of the 2012 floods, focusing on the use of a 2D hydrodynamic modelling approach to estimate peak discharges along both the Sabie and Olifants Rivers.

METHODS

Application of a 2D hydrodynamic model requires baseline data on channel topography in the form of a Digital Elevation Model (DEM). Following the Cyclone Dando floods in January 2012, aerial LiDAR and photography (Milan et al., 2018c) were obtained on 30th May 2012 for 50 km reaches of both the Sabie and Olifants rivers in the KNP (Fig. 1). Southern Mapping Geospatial surveyed the rivers using an Opetch Orion 206 LiDAR, flown from a Cessna 206 at 1100 m altitude. Average point density was 409 318 points/km^2. The root mean squared error for z was 0.04 m, and for x and y was 0.06 m. Standard deviation for x and y were 0.05 and 0.06 m respectively, based on 5 ground survey points. These data effectively represent the post-flood condition of the rivers, both of which had suffered considerable vegetation and soft sediment stripping. It is argued that this stripping would have occurred up to the peak flood flow and as such this surface would be representative of that which experienced the maximum discharge being estimated in this study.

Strandline elevations

At selected sites along the Sabie and Olifants rivers, the flow levels associated with the Cyclone Dando floods were surveyed using a Leica 500 RTK GPS in May 2012 (Fig. 1B-C). Despite the four months that had elapsed between the January floods and the surveys (a time gap imposed by the availability of funding), strandlines of organic debris (e.g. branches, twigs, reeds) were very well preserved along significant lengths of each survey reach (Fig. 2E-G). The fresh condition of the debris and occasional 'best before' dates on embedded plastic bottles showed clearly that these strandlines were from the January 2012 floods (Fig. 2H).

Fig. 3.

Previous work (Heritage et al., 2004; Fisher, 2005) has shown that receding floods can leave several strandlines depending on local conditions. Furthermore, elevation differences of 3 m were often evident between the base and top of individual strandlines, and some strandlines were measured in locations where debris was less abundant than the locations illustrated in Figure 2F-G. Nevertheless, surveys focused on finer organic material such as that showed in Figure 2G, taking the highest elevation debris line as the datum within a given reach, and therefore provide an indication of the highest stage reached by the 2012 floods. Survey of larger woody debris (e.g. Figure 2E) was avoided due to difficulties in determining actual water level given superelevation issues and the flexible nature of the wood.

Hydrodynamic modelling

Post flood LiDAR data (Milan et al., 2018c) for the Sabie and Olifants rivers were used to provide the physical boundary conditions for hydraulic modelling of the 2012 floods. The models represent the longest and most detailed flow simulations conducted on rivers in the region generating hydraulic parameter estimates for the floods at 2 m scale along the 50 km reaches covering a variety of channel types in single integrated models for each river. Flow resistance parameters are also required to represent many sources of energy loss (Lane and Hardy 2002). A Mannings ‘n’ or Darcy Weisbach *f* flow resistance value is most often used to represent grain roughness. Previous research protocols have used both a uniform parameter and spatially distributed parameterisation (Legleiter et al. 2011, Logan et al. 2011). Werner et al. 2005 demonstrate that spatially-distributed floodplain roughness failed to improve flood model performance when compared to use of a single roughness class. Horrit and Bates (2002) and Bates et al. (2006) also found that utilisation of a constant channel and floodplain roughness value provided a pragmatic approach to flood modelling. They also note that many of the roughness factors represented by the roughness coefficient in 1D models are integrated into the modelling process in 2D models, most notably form roughness, including the effects of the projection morphological units such as bars and bedrock islands into the flow, which is represented by topographic variation in the DTM and implicitly includes changes in channel type along each 50 km modelled reach. As such, no attempt was made to incorporate sophisticated representations of spatial roughness pattern based on factors such as sediment size variation feature types and vegetation community patterns for the study reaches, with a nominal Manning’s ‘n’ roughness value of 0.04 used, in the simulations to represent model skin resistance (see Broadhurst et al., 1997).

JFlow, a 2-D depth-averaged flow model is a commercial 2-D flow modeling tool noted for its ability to handle large data sets through the use of a graphics processing unit-based computation. JFlow was developed as a solution to harness the full detail of available topographic data sets such as those available from LiDAR, and to investigate overland flow paths (Bradbrook, 2006). Simplified forms of the full 2-D hydrodynamic equations are used in the model, but the main controls on flood routing for shallow, topographically driven flow are captured (Bradbrook, 2006). As such JFlow simulations must be regarded as only a first approximation of 2D flow but its ability to handle topographically induced form roughness (a major resistance component on the systems being studied) and its relatively rapid run time and robustness on long complex reaches makes it ideal for the proposed modelling .The model also performed well compared to other shallow water simulations in a benchmarking exercise by the EA (Néelz, & Pender, 2013). Bates et al. (2010) and Neal et al. (2010) demonstrated that the model was capable of simulating flow depths and velocities within 10% of a range of industry full shallow water codes such as TuFlow and InfoWorks. Their simulations of gradually varying flows, revealed that velocity predictions were 'surprisingly similar' between the models and they suggest that JFlow model may be appropriate for velocity simulation across a range of gradually varied subcritical flow conditions.

The DEMs of each study reach were degraded to uniform 1 m data grids and input into the JFlow software to generate 2 m resolution surface meshes using a uniform triangulation algorithm. Morphologic scale form roughness variation (and by definition channel type) was defined using the local bed level variation derived from the original survey data (see Entwistle et al., 2014). It was assumed that at the flow peak the majority of the soft sediment and vegetation in the two rivers had been eroded, as such their impacts on flow resistance were not considered.

Inflow and outflow discharges and flow stage boundaries were set during hydraulic model runs, based on low flow survey data and high flow approximations (these were refined within the program during model runs to satisfy the conservation of mass and momentum equations). Flow simulations were conducted up to 5000 m^3s^{-1} on the Sabie River and 15 000 m^3s^{-1} on the Olifants River. These upper values were chosen based on a continuity equation estimate of peak flows, which was undertaken whilst in the field. These data were used to develop simulated rating curves for each of the study sites.

Flood estimation

Simulated water surface elevation versus simulated discharge rating curves were derived for the upstream and downstream parts of each of the sites shown in Fig. 1. These values were used to estimate peak flows using the surveyed RTK GPS strandline elevations.

RESULTS

Model validation

Comparisons were made between the simulated water surface elevations and the RTK GPS surveyed strandlines (Fig. 3). For the Sabie (Fig. 3A), very close matches were found at sites 1, 2, 4 and 6, with RTK elevations mostly within 0.3 m of the simulated water elevations. Simulated water elevations are over-predicted by 0.5-1.5 m for sites 3 and 5, whereas simulated water elevations were under-predicted by 1.0-1.5 m at sites 7 and 8 farther downstream. For the Olifants (Fig. 3B), simulated water surfaces show much more variability but surveyed strandline elevations are generally within 1 m of the simulated elevations The water surface simulation data suggest that the assumptions of gradually varied flow and subcritical flow are not always satisfied along the model reaches (Coulthard et al., 2013) and this will introduce a degree of error in the calculated discharges. For both rivers, the deviation between simulated and measured elevations was in the same order as the vertical variation (± 3 m) evident for the strandlines (Fig. 2). Some parts of the surveyed elevations along the strandlines matched simulated water elevations better than others, suggesting the possibility of multiple strandlines having been surveyed. Although we are unable to substantiate, this may result from pulsing or recession of flood peaks. This could not be verified due to a lack of gauge data for the flood. Modelled and surveyed flood inundation extents are also plotted in Fig. 4. For the Sabie River, there is a very close match between modelled and surveyed inundation extents (Fig. 4A), whereas for the Olifants River, simulated flood extent appears to be slightly under-predicted (Fig. 4B).

Fig. 4.

Extreme flood estimation

The highest simulated flood stage of 5000 m^3s^{-1} for the sites along the Sabie River is lower in elevation than the majority of strandline measurements and does not exceed the surveyed limits of the flood extents (Fig. 4A). This suggests that during the 2012 floods, peak discharges were slightly in excess of this simulated flow. Regression analysis-derived rating equations for each study site along the Sabie study reach (Fig. 1B) allowed estimation of the peak flood magnitude, which ranges from 4470 m^3s^{-1} to 5630 m^3s^{-1} (Table 1, Fig. 5). For the Sabie River, these results suggest that 2012 flood did not exceed the peak stage or extent of the 2000 Cyclone Eline floods, which ranged between 6000 and 7000 m^3s^{-1} towards the lower end of the Sabie study reach (Heritage et al., 2003). This conclusion is supported by field observations from the Sabie River. At the Low Level Bridge crossing near Skukuza (Fig. 1A), a roadside marker indicates the limit of the 2000 floods. This marker stands at a higher elevation than the strandlines from the 2012 floods, indicating that at this location, the 2012 floods were not as large as the 2000 flood event. The anecdotal accounts of park rangers suggest that this finding also applies more widely along the Sabie study reach, and is supported by the absence of any damage during the 2012 floods to the tarred road that runs adjacent to the macrochannel margins along the right bank, where comparatively this road had been extensively damaged during the 2000 event.

Table 1.

Fig. 5.

The 15 000 m^3s^{-1} flood simulation for the sites along the Olifants River exceeds some of the surveyed strandline elevations but remains within the limits of the surveyed flood extents (Fig. 3). This suggests that during the 2012 floods, peak discharges approached or slightly exceeded this simulated flow. Regression analysis derived rating equations for each study site allowed estimation of the peak flood magnitude, which ranges from 14 407 m^3s^{-1} to 16 772 m^3s^{-1} depending on location (Table 1, Fig. 5).

DISCUSSION

Comparisons between flood estimation methods

The method used in this paper to estimate flood magnitudes along the Sabie and Olifants rivers can be compared to other published methods for estimating (palaeo) flood velocities and discharges. These range from the use of regime type equations (e.g. Wohl and David, 2008), maximum transported grain size and/or bedform dimensions (e.g. Costa, 1983; Williams, 1983; Wohl and Merritt, 2008) and friction based approaches (e.g. Kochel and Baker, 1982; Heritage et al., 1997; Broadhurst et al., 1997; Birkhead et al., 2000).

Wohl and David's (2008) width–discharge relationship for bedrock-influenced channels is statistically significant, but the r^2 value for the regime equation was low at 0.59, principally due to variation in rock strength. This relationship was applied to the study sites on the Sabie and Olifants rivers (Fig. 2) and generated peak flows of between 25 000 to 50 000 m^3s^{-1} for the Sabie (macrochannel width 250-500 m), and 75 000 m^3s^{-1} in wider reaches on the Olifants (macrochannel width 700 m). All but the lower values are outside the range of data used by Wohl and David (2008) to generate the original width–discharge relationship. As such, little confidence can be placed in the application of this regime type approach to estimating flood magnitude on the KNP rivers.

Application of the maximum transported grain size to derive an average flood velocity estimate (Costa, 1983; Williams, 1983) is also difficult to apply in the case of the Sabie and Olifants rivers. In both catchments, the metamorphic and igneous bedrock weathers to supply mainly sand and fine gravel (granules, minor pebbles) to the rivers. Consequently, cobble- or boulder-sized sediment is supply limited and any use of the empirical relationships would lead to a gross underestimation of peak discharges.

Application of the slope-area method to the downstream parts of the study reaches of both rivers using an estimated Darcy-Weisbach friction factor of 0.125 and a strandline-derived macrochannel water surface slope generated peak discharge estimates of between 3112 m^3s^{-1} and 3558 m^3s^{-1} for the Sabie River and between 12 923 m^3s^{-1} and 13 417 m^3s^{-1} for the Olifants River. These estimates are lower than the peak discharge predicted using the 2D modelling approach and are likely to be less accurate as the technique utilises an average reach slope and estimated roughness coefficients derived from the strandline data and previously published research (Broadhurst et al., 1997; Birkhead et al., 2000). This contrasts with the 2D approach adopted here where the form roughness and water surface slope are intrinsically linked to the detailed local topographic variation captured in the baseline digital elevation model.

In summary, these alternative approaches to flood discharge estimation along the Sabie and Olifants rivers yield a wide variety of values, with some approaches clearly inapplicable or inappropriate given the context of the study sites. Even the more sophisticated approaches that utilise slope, area and friction data require many of these parameters to be estimated or are limited by difficulty in accurately measuring strandlines in the field.

The simplified 2D JFlow method applied in this study does not require such data and can estimate flood discharge from a detailed topographic model alone (e.g. a LiDAR-derived DEM). This model contains ‘effective’ parameters that are related to aggregated hydraulic processes, which cannot, in general, be determined from the physical characteristics of the reach under consideration (Hunter et al., 2007). Channel form roughness, capturing protrusion into the flow at the morphological unit scale (including sand bars, bedrock islands etc. which when aggregated also represent channel type differences), is explicitly integrated into the modelling approach through the detailed LiDAR DEM and, as outlined earlier, for our study a single representative grain and hydraulic flow resistance value was input to the model as this represents only a minor component of flow resistance. Stripping of vegetation and soft sediment was also likely to have occurred up to the peak discharge and as such the stripped DEM surveyed after the floods was assumed to adequately represent the overall form resistance operating at the flood peak.

Previous research (e.g. Werner et al., 2005) supports this approach, demonstrating that spatially-distributed floodplain roughness based on land-use mapping failed to improve flood model performance when compared to use of a single floodplain roughness class. Horrit and Bates (2002) and Bates et al. (2006) also found that utilisation of a constant channel and floodplain roughness value provided a pragmatic approach to flood modelling. Such an approach is also justified on the premise that the approach is primarily for use in estimating palaeofloods. As such, in these previous studies no attempt was made to incorporate more sophisticated representations of spatial roughness pattern based on factors such as sediment size variation and vegetation community patterns, as these data are typically not available in palaeocontexts.

Comparisons with extreme floods on other southern African rivers

Based on the historic flow record (Fig. 6A), the 2012 Cyclone Dando flood on the Sabie River can be classed as ‘extreme’. As noted, however, this was a smaller magnitude flood than the 2000 flood event (Heritage et al., 2004) and a detailed comparison shows that the 2012 event overall had a more subdued morphological impact (Milan et al., 2018b). Based on the historic record (Fig. 6B), the 14 407 m^3s^{-1} to 16 772 m^3s^{-1} flood estimate for the Olifants River appears to be more extreme. Indeed, in comparison with the catalogue of maximum peak discharges compiled by Kovacs (1988) and other related studies, this 2012 event ranks among some of the most extreme floods recorded for any southern African river in the last couple of hundred years (Fig. 7). For instance, the 2012 Olifants River flood far exceeds the well-documented 1981 Buffels River flood of up to 8000 m^3s^{-1} (Stear, 1985; Zawada, 1994), the 1987 lower uMgeni River flood of 5000-10 000 m^3s^{-1} (Cooper et al., 1990; Smith, 1992) and the 1974 and 1988 discharges of 8000-9000 m^3s^{-1} that occurred along the much larger middle Orange River (du Plessis et al., 1989; Bremner et al., 1990; Zawada and Smith, 1992; Zawada, 2000). The 2012 Olifants River flood is even comparable in magnitude to the extreme floods that occurred along rivers draining to the KwaZulu-Natal coast during Cyclone Domoina in January 1984 (Kovacs et al., 1985; Kovacs, 1988). Higher discharges have almost undoubtedly occurred along much larger rivers such as the Orange earlier in the Holocene; for example, 13 palaeofloods with discharges in the range of 10 000-15 000 m^3s^{-1} occurred along the lower Orange River during the last 5500 years and were exceeded by one catastrophic discharge of around 28 000 m^3s^{-1} sometime between AD 1453 and AD 1785 (Zawada 1996; 2000; Zawada et al., 1996). Nevertheless, the Olifants River flood remains notable on an historic timescale, particularly given the associated geomorphological impacts, which involved widespread stripping of alluvium along extensive reaches of the river in the KNP (Fig. 2D).

Fig. 6.

Fig. 7.

CONCLUSION

In this paper, a simplified 2D modelling approach has been used to estimate the magnitudes of the cyclone-driven, flood events on the Sabie and Olifants rivers in January 2012. The method relies on an accurate LiDAR-derived DEM of a river to account for form roughness assuming that vegetation and soft sediment stripping had occurred prior to the flood peak, and applies a uniform additional roughness factor to account for grain and hydraulic flow resistance components. The use of a simplified 2D code allows for more rapid simulations, modelling very large areas in detail and provides a robust modelling framework that can generate hydraulic estimates for a range of flows. Comparison of field surveyed and simulated water surface slope and inundation patterns for the peak flows suggests that the model performs well overall.

On both rivers, the flood flows can be described as ‘extreme’, with the discharge on the Olifants being among one of the largest ever recorded or estimated for any southern African river in the late Holocene. Given the documented changes in rainfall patterns in the Kruger National Park since the 1980’s (MacFadyen et al., 2018) whereby seasonal patterns appear to be attenuating and rainfall extremes on both ends of the spectrum appear to be extending it is possible that flood extremes on the two study rivers and other systems on the region are becoming increasingly likely. On systems where such extremes are known to drive geomorphic change (Milan et al., 2018b) this may trigger a state change towards bedrock-dominated systems, illustrating the impact of climate change on the region.

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Zawada, P.K., Smith, A.M., 1991. The 1988 Orange River flood, Upington region, Northwestern Cape Province, RSA. Terra Nova 3, 317–324.Table 1. Rating equations and discharge range estimates for the Cyclone Dando floods in January 2012.

Table 1. Rating equations and discharge range estimates for the Cyclone Dando floods in January 2012.

River	**Site**	**Rating equation**	**R^2**	**Mean (m^3s^{-1})**	**Min (m^3s^{-1})**	**Max (m^3s^{-1})**
Sabie upstream	S1	994.17 x - 252681	0.89	5423	5322	5474
	S2	799.15 x - 196814	0.88	5291	5072	5426
	S3	718.00 x - 162309	0.89	5129	5021	5236
	S4	807.62 x - 174412	0.87	5041	4959	5199
	S5	1414.60 x - 285616	0.99	5096	4649	5237
	S6	860.55 x - 157470	0.92	5174	5045	5258
	S7	708.16 x - 113191	0.94	4470	4364	4644
	S8	721.61 x - 106722	0.91	4550	4262	4764
Sabie downstream	S1	1051.30 x - 265900	0.94	5366	5298	5504
	S2	728.49 x -178469	0.98	5484	5378	5519
	S3	785.25 x - 176913	0.86	5352	5295	5465
	S4	1131.50 x - 244936	0.81	5237	5102	5372
	S5	1414.60 x - 285616	0.99	5630	5372	5709
	S6	896.86 x - 163283	0.88	5237	5156	5506
	S7	706.59 x - 112199	0.96	5095	5024	5236
	S8	686.98 x - 101047	0.86	4611	4404	4714
Olifants upstream	O1	1908.90 x - 378047	1	14423	14041	14614
	O2	2453.20 x - 507757	0.94	14407	13548	15020
	O3	2473.70 x - 450161	1	15637	13905	16379
	O4	3526.90 x - 619833	0.97	16772	16067	17478
	O5	1984.50 x - 297692	0.97	15859	15462	16454
Olifants downstream	O1	2118.50 x - 419168	0.99	15125	14701	15336
	O2	2726.30 x - 561512	0.94	15264	14010	15809
	O3	2819.00 x - 513987	0.98	14576	13166	15985
	O4	2950.10 x - 511883	1	16185	15595	16480
	O5	1766.60 x - 260630	0.98	16726	15843	17963

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Fig. 1. A) Location of the Sabie and Olifants rivers and the Kruger National Park (KNP) in northeastern South Africa. Red boxes indicate the extent of the study reaches inside the KNP, B) Flood strandline survey sites on the Sabie River; and C) Olifants Rivers. The coordinate system in B) and C) is WGS84 UTM36S.

Fig. 2. Photographs from sites on the Sabie and Olifants rivers. Examples of the diverse channel types found in the KNP, A) mixed braided (Sabie River, flow direction from top to bottom), B) cohesive mixed anastomosed (Sabie River, flow direction from bottom to top), C) bedrock anastomosed (Olifants River, flow direction from top to bottom), D) Extent of stripped channel on the Olifants river. Typical strandline evidence recorded on the Sabie and Olifants rivers in the Kruger National Park: E)–G) examples of organic debris accumulations (flow direction is from left to right on image E), and bottom to top (images F and G); H) plastic drinks bottle embedded within a strandline, showing a 'Best Before' (BB) date of 4th July 2012. Given the limited shelf life of such products, this BB date implies that strandline would have been formed in the months preceding the survey (i.e. during the January 2012 floods) and not in earlier (pre-2011/2012) flood events. In G), note the considerable distance and elevation of the strandline from the low flow discharge (just visible on far middle right). In general we surveyed finer material such as that showed in G, taking the highest elevation debris line as the datum.

Fig. 3. Flood strandline and water surface elevations for the survey sites on the: A) Sabie River, for the high flow simulations of 5000 m^3s^{-1}; and B) Olifants River, for the high flow simulations of 15000 m^3s^{-1}.

Fig. 4. Flood strandline position (red dots) and modelled flow extent on the: A) Sabie River, for the high flow simulations of 5000 m^3s^{-1}; and B) Olifants River, for the high flow simulations of 15000 m^3s^{-1}. The greyscale indicates water elevation for the flood peak simulations.

Fig. 5. Modelled discharge variation for the Cyclone Dando floods in January 2012 along the: A) Sabie River; and B) Olifants River. Data for S5 on the Sabie River has been omitted due to the poor rating relation. Error bars indicate maximum and minimum discharge estimates.

Fig. 6. Annual maximum flows on the: A) Sabie River at Lower Sabie Rest Camp (Station X3H015); and B) Olifants Rivers at Mamba (Station B7H015) (source: Department of Water Affairs and Forestry). It should be noted that some of the peaks are estimates rather than actual gauge records, as gauges are often damaged during the extreme flows, and the 2000 flood for the Sabie River was estimated at 9400 $m^3 s^{-1}$ by the Department of Water Affairs and Forestry, larger than the Heritage et al. (2004) estimate. M = missing data, Q = data not audited, A = above rating.

Fig. 7. A) Extreme flood estimates for southern African rivers (after Kovacs 1988), incorporating the estimates for the Sabie and Olifants river floods of January 2012, as derived from the results of this study; B) Example of an extensively stripped reach along the Olifants River (flow direction from bottom left to top right). During the 2012 flood, up to several metres of alluvium was eroded along tens of kilometres of the river in the Kruger National Park, leading to widespread exposure of the underlying bedrock template.

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Table 1. Rating equations and discharge range estimates for the Cyclone Dando floods in January

2012.