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

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

3

4

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14

15 **Abstract**

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

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

38

39

40 INTRODUCTION

41 Drylands (hyperarid, arid, semiarid and dry-subhumid regions) cover 50% of the Earth's surface and
42 sustain 20% of the world's population (United Nations, 2016). Many drylands are characterised by
43 strong climatic variations, with extended dry periods interspersed with short, intense rainfall events,
44 and are widely considered to be among the regions most vulnerable to future climate change (Obasi
45 2005; IPCC 2007; Wang et al., 2012). Many dryland river flow regimes are similarly variable
46 (McMahon et al., 1992), with long periods of very low or no flow being followed by infrequent, short-
47 lived, large or extreme flood events (see Tooth, 2013). This variable flow regime is one of the primary
48 controls on dryland river process and form, commonly resulting in channel-floodplain morphologies
49 and dynamics that differ markedly from many humid temperate rivers (Tooth, 2000; 2013; Jaeger et
50 al., 2017). In particular, the role of extreme events in the episodic 'stripping' of unconsolidated
51 sediment from alluvial fills on an underlying bedrock template has been reported as a key control on
52 the long-term development of many southern African, Australian, Indian and North American dryland
53 river systems (e.g. Womack and Schumm 1977; Baker 1977; Kale et al. 1996; Bourke and Pickup
54 1999; Wende 1999; Rountree et al. 2000; Tooth and McCarthy 2004; Milan et al., 2018a, Milan et
55 al., 2018b). These stripping events limit long-term sediment build-up and contribute to incremental
56 channel incision over geological time.

57
58 Over the last few decades, research into bedrock-influenced dryland rivers has increased (e.g.
59 Heritage et al., 1999; 2001; Tooth et al., 2002; 2013; Meshkova and Carling, 2012; Keen-Zebert et
60 al., 2013), but hydrological and hydraulic data remain limited owing to the difficulty in collecting
61 information in these typically harsh environments with their relatively infrequent channel-shaping
62 flows. In particular, gauging stations commonly fail to accurately record flow data during large or
63 extreme flood events, as the structures are commonly drowned out and/or suffer physical damage.
64 This paucity of data hampers efforts to develop conceptual and quantitative models of the response
65 of these types of dryland rivers to past, present and future climatic changes, impacting on our

66 understanding and subsequent management of such systems.

67

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

75

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

91 understanding of the magnitude, frequency and impacts of such events on river development.

92

93 **STUDY SITES**

94 The Sabie and Olifants rivers are located in the southern and central part of the KNP in the
95 Mpumalanga and Limpopo provinces of northeastern South Africa (Fig. 1). The 54 570 km² Olifants
96 catchment incorporates parts of the Highveld Plateau (2000-1500 m), the Drakensberg Escarpment,
97 and the Lowveld (400-250 m). The 6320 km² Sabie River covers part of the Drakensberg Mountains
98 (1600 m), the low-relief Lowveld (400 m), and the Lebombo zone (200 m). Rainfall in both
99 catchments is greater in the headwaters (2000 mm yr⁻¹) and declines rapidly eastwards towards the
100 South Africa–Mozambique border (450 mm yr⁻¹). Within the middle reaches, sediment is dominantly
101 sand and fine gravel (median grain size 1-2 mm) (Broadhurst et al. 1997). Although water
102 abstractions have altered the low flows (generally below 50 m³s⁻¹) along both rivers, intermittent
103 cyclone-driven flood flows are unaffected, and the channels remain unimpacted by engineering
104 structures or other human activities over considerable lengths within the KNP. Thus, both rivers
105 represent excellent, near-pristine sites for investigating bedrock-influenced dryland river dynamics.

106

107 **Fig. 1.**

108

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

117

118 **Fig. 2**

119

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

127

128 **METHODS**

129 Application of a 2D hydrodynamic model requires baseline data on channel topography in the form
130 of a Digital Elevation Model (DEM). Following the Cyclone Dando floods in January 2012, aerial
131 LiDAR and photography (Milan et al., 2018c) were obtained on 30th May 2012 for 50 km reaches of
132 both the Sabie and Olifants rivers in the KNP (Fig. 1). Southern Mapping Geospatial surveyed the
133 rivers using an Opetch Orion 206 LiDAR, flown from a Cessna 206 at 1100 m altitude. Average
134 point density was 409 318 points/km². The root mean squared error for z was 0.04 m, and for x and
135 y was 0.06 m. Standard deviation for x and y were 0.05 and 0.06 m respectively, based on 5 ground
136 survey points. These data effectively represent the post-flood condition of the rivers, both of which
137 had suffered considerable vegetation and soft sediment stripping. It is argued that this stripping would
138 have occurred up to the peak flood flow and as such this surface would be representative of that which
139 experienced the maximum discharge being estimated in this study.

140

141 **Strandline elevations**

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

149

150 **Fig. 3.**

151

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

161

162 **Hydrodynamic modelling**

163 Post flood LiDAR data (Milan et al., 2018c) for the Sabie and Olifants rivers were used to provide
164 the physical boundary conditions for hydraulic modelling of the 2012 floods. The models represent
165 the longest and most detailed flow simulations conducted on rivers in the region generating hydraulic
166 parameter estimates for the floods at 2 m scale along the 50 km reaches covering a variety of channel

167 types in single integrated models for each river. Flow resistance parameters are also required to
168 represent many sources of energy loss (Lane and Hardy 2002). A Mannings 'n' or Darcy Weisbach f
169 flow resistance value is most often used to represent grain roughness. Previous research protocols
170 have used both a uniform parameter and spatially distributed parameterisation (Legleiter et al. 2011,
171 Logan et al. 2011). Werner et al. 2005 demonstrate that spatially-distributed floodplain roughness
172 failed to improve flood model performance when compared to use of a single roughness class. Horrit
173 and Bates (2002) and Bates et al. (2006) also found that utilisation of a constant channel and
174 floodplain roughness value provided a pragmatic approach to flood modelling. They also note that
175 many of the roughness factors represented by the roughness coefficient in 1D models are integrated
176 into the modelling process in 2D models, most notably form roughness, including the effects of the
177 projection morphological units such as bars and bedrock islands into the flow, which is represented
178 by topographic variation in the DTM and implicitly includes changes in channel type along each 50
179 km modelled reach. As such, no attempt was made to incorporate sophisticated representations of
180 spatial roughness pattern based on factors such as sediment size variation feature types and vegetation
181 community patterns for the study reaches, with a nominal Manning's 'n' roughness value of 0.04
182 used, in the simulations to represent model skin resistance (see Broadhurst et al., 1997).

183

184 JFlow, a 2-D depth-averaged flow model is a commercial 2-D flow modeling tool noted for its ability
185 to handle large data sets through the use of a graphics processing unit-based computation. JFlow was
186 developed as a solution to harness the full detail of available topographic data sets such as those
187 available from LiDAR, and to investigate overland flow paths (Bradbrook, 2006). Simplified forms
188 of the full 2-D hydrodynamic equations are used in the model, but the main controls on flood routing
189 for shallow, topographically driven flow are captured (Bradbrook, 2006). As such JFlow simulations
190 must be regarded as only a first approximation of 2D flow but its ability to handle topographically
191 induced form roughness (a major resistance component on the systems being studied) and its

192 relatively rapid run time and robustness on long complex reaches makes it ideal for the proposed
193 modelling .The model also performed well compared to other shallow water simulations in a
194 benchmarking exercise by the EA (Néelz, & Pender, 2013). Bates et al. (2010) and Neal et al. (2010)
195 demonstrated that the model was capable of simulating flow depths and velocities within 10% of a
196 range of industry full shallow water codes such as TuFlow and InfoWorks. Their simulations of
197 gradually varying flows, revealed that velocity predictions were ‘surprisingly similar’ between the
198 models and they suggest that JFlow model may be appropriate for velocity simulation across a range
199 of gradually varied subcritical flow conditions.

200

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

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

214

215 **Flood estimation**

216 Simulated water surface elevation versus simulated discharge rating curves were derived for the
217 upstream and downstream parts of each of the sites shown in Fig. 1. These values were used to

218 estimate peak flows using the surveyed RTK GPS strandline elevations.

219

220 **RESULTS**

221 **Model validation**

222 Comparisons were made between the simulated water surface elevations and the RTK GPS surveyed
223 strandlines (Fig. 3). For the Sabie (Fig. 3A), very close matches were found at sites 1, 2, 4 and 6,
224 with RTK elevations mostly within 0.3 m of the simulated water elevations. Simulated water
225 elevations are over-predicted by 0.5-1.5 m for sites 3 and 5, whereas simulated water elevations were
226 under-predicted by 1.0-1.5 m at sites 7 and 8 farther downstream. For the Olifants (Fig. 3B),
227 simulated water surfaces show much more variability but surveyed strandline elevations are generally
228 within 1 m of the simulated elevations. The water surface simulation data suggest that the assumptions
229 of gradually varied flow and subcritical flow are not always satisfied along the model reaches
230 (Coulthard et al., 2013) and this will introduce a degree of error in the calculated discharges. For
231 both rivers, the deviation between simulated and measured elevations was in the same order as the
232 vertical variation (± 3 m) evident for the strandlines (Fig. 2). Some parts of the surveyed elevations
233 along the strandlines matched simulated water elevations better than others, suggesting the possibility
234 of multiple strandlines having been surveyed. Although we are unable to substantiate, this may result
235 from pulsing or recession of flood peaks. This could not be verified due to a lack of gauge data for
236 the flood. Modelled and surveyed flood inundation extents are also plotted in Fig. 4. For the Sabie
237 River, there is a very close match between modelled and surveyed inundation extents (Fig. 4A),
238 whereas for the Olifants River, simulated flood extent appears to be slightly under-predicted (Fig.
239 4B).

240

241 **Fig. 4.**

242

243 **Extreme flood estimation**

244 The highest simulated flood stage of $5000 \text{ m}^3\text{s}^{-1}$ for the sites along the Sabie River is lower in
245 elevation than the majority of strandline measurements and does not exceed the surveyed limits of
246 the flood extents (Fig. 4A). This suggests that during the 2012 floods, peak discharges were slightly
247 in excess of this simulated flow. Regression analysis-derived rating equations for each study site
248 along the Sabie study reach (Fig. 1B) allowed estimation of the peak flood magnitude, which ranges
249 from $4470 \text{ m}^3\text{s}^{-1}$ to $5630 \text{ m}^3\text{s}^{-1}$ (Table 1, Fig. 5). For the Sabie River, these results suggest that 2012
250 flood did not exceed the peak stage or extent of the 2000 Cyclone Eline floods, which ranged between
251 6000 and $7000 \text{ m}^3\text{s}^{-1}$ towards the lower end of the Sabie study reach (Heritage et al., 2003). This
252 conclusion is supported by field observations from the Sabie River. At the Low Level Bridge crossing
253 near Skukuza (Fig. 1A), a roadside marker indicates the limit of the 2000 floods. This marker stands
254 at a higher elevation than the strandlines from the 2012 floods, indicating that at this location, the
255 2012 floods were not as large as the 2000 flood event. The anecdotal accounts of park rangers suggest
256 that this finding also applies more widely along the Sabie study reach, and is supported by the absence
257 of any damage during the 2012 floods to the tarred road that runs adjacent to the macrochannel
258 margins along the right bank, where comparatively this road had been extensively damaged during
259 the 2000 event.

260

261 **Table 1.**

262

263 **Fig. 5.**

264

265 The $15\,000 \text{ m}^3\text{s}^{-1}$ flood simulation for the sites along the Olifants River exceeds some of the surveyed
266 strandline elevations but remains within the limits of the surveyed flood extents (Fig. 3). This
267 suggests that during the 2012 floods, peak discharges approached or slightly exceeded this simulated
268 flow. Regression analysis derived rating equations for each study site allowed estimation of the peak

269 flood magnitude, which ranges from 14 407 m³s⁻¹ to 16 772 m³s⁻¹ depending on location (Table 1,
270 Fig. 5).

271

272 **DISCUSSION**

273 **Comparisons between flood estimation methods**

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

280

281 Wohl and David's (2008) width–discharge relationship for bedrock-influenced channels is
282 statistically significant, but the r² value for the regime equation was low at 0.59, principally due to
283 variation in rock strength. This relationship was applied to the study sites on the Sabie and Olifants
284 rivers (Fig. 2) and generated peak flows of between 25 000 to 50 000 m³s⁻¹ for the Sabie
285 (macrochannel width 250-500 m), and 75 000 m³s⁻¹ in wider reaches on the Olifants (macrochannel
286 width 700 m). All but the lower values are outside the range of data used by Wohl and David (2008)
287 to generate the original width–discharge relationship. As such, little confidence can be placed in the
288 application of this regime type approach to estimating flood magnitude on the KNP rivers.

289

290 Application of the maximum transported grain size to derive an average flood velocity estimate
291 (Costa, 1983; Williams, 1983) is also difficult to apply in the case of the Sabie and Olifants rivers.
292 In both catchments, the metamorphic and igneous bedrock weathers to supply mainly sand and fine
293 gravel (granules, minor pebbles) to the rivers. Consequently, cobble- or boulder-sized sediment is

294 supply limited and any use of the empirical relationships would lead to a gross underestimation of
295 peak discharges.

296

297 Application of the slope-area method to the downstream parts of the study reaches of both rivers using
298 an estimated Darcy-Weisbach friction factor of 0.125 and a strandline-derived macrochannel water
299 surface slope generated peak discharge estimates of between 3112 m³s⁻¹ and 3558 m³s⁻¹ for the Sabie
300 River and between 12 923 m³s⁻¹ and 13 417 m³s⁻¹ for the Olifants River. These estimates are lower
301 than the peak discharge predicted using the 2D modelling approach and are likely to be less accurate
302 as the technique utilises an average reach slope and estimated roughness coefficients derived from
303 the strandline data and previously published research (Broadhurst et al., 1997; Birkhead et al., 2000).
304 This contrasts with the 2D approach adopted here where the form roughness and water surface slope
305 are intrinsically linked to the detailed local topographic variation captured in the baseline digital
306 elevation model.

307

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

313

314 The simplified 2D JFlow method applied in this study does not require such data and can estimate
315 flood discharge from a detailed topographic model alone (e.g. a LiDAR-derived DEM). This model
316 contains 'effective' parameters that are related to aggregated hydraulic processes, which cannot, in
317 general, be determined from the physical characteristics of the reach under consideration (Hunter et
318 al., 2007). Channel form roughness, capturing protrusion into the flow at the morphological unit scale
319 (including sand bars, bedrock islands etc. which when aggregated also represent channel type

320 differences), is explicitly integrated into the modelling approach through the detailed LiDAR DEM
321 and, as outlined earlier, for our study a single representative grain and hydraulic flow resistance value
322 was input to the model as this represents only a minor component of flow resistance. Stripping of
323 vegetation and soft sediment was also likely to have occurred up to the peak discharge and as such
324 the stripped DEM surveyed after the floods was assumed to adequately represent the overall form
325 resistance operating at the flood peak.

326

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

336

337 **Comparisons with extreme floods on other southern African rivers**

338 Based on the historic flow record (Fig. 6A), the 2012 Cyclone Dando flood on the Sabie River can
339 be classed as ‘extreme’. As noted, however, this was a smaller magnitude flood than the 2000 flood
340 event (Heritage et al., 2004) and a detailed comparison shows that the 2012 event overall had a more
341 subdued morphological impact (Milan et al., 2018b). Based on the historic record (Fig. 6B), the 14
342 $407 \text{ m}^3\text{s}^{-1}$ to $16\,772 \text{ m}^3\text{s}^{-1}$ flood estimate for the Olifants River appears to be more extreme. Indeed,
343 in comparison with the catalogue of maximum peak discharges compiled by Kovacs (1988) and other
344 related studies, this 2012 event ranks among some of the most extreme floods recorded for any

345 southern African river in the last couple of hundred years (Fig. 7). For instance, the 2012 Olifants
346 River flood far exceeds the well-documented 1981 Buffels River flood of up to $8000 \text{ m}^3\text{s}^{-1}$ (Stear,
347 1985; Zawada, 1994), the 1987 lower uMgeni River flood of $5000\text{-}10\,000 \text{ m}^3\text{s}^{-1}$ (Cooper et al., 1990;
348 Smith, 1992) and the 1974 and 1988 discharges of $8000\text{-}9000 \text{ m}^3\text{s}^{-1}$ that occurred along the much
349 larger middle Orange River (du Plessis et al., 1989; Bremner et al., 1990; Zawada and Smith, 1992;
350 Zawada, 2000). The 2012 Olifants River flood is even comparable in magnitude to the extreme floods
351 that occurred along rivers draining to the KwaZulu-Natal coast during Cyclone Domoina in January
352 1984 (Kovacs et al., 1985; Kovacs, 1988). Higher discharges have almost undoubtedly occurred
353 along much larger rivers such as the Orange earlier in the Holocene; for example, 13 palaeofloods
354 with discharges in the range of $10\,000\text{-}15\,000 \text{ m}^3\text{s}^{-1}$ occurred along the lower Orange River during
355 the last 5500 years and were exceeded by one catastrophic discharge of around $28\,000 \text{ m}^3\text{s}^{-1}$
356 sometime between AD 1453 and AD 1785 (Zawada 1996; 2000; Zawada et al., 1996). Nevertheless,
357 the Olifants River flood remains notable on an historic timescale, particularly given the associated
358 geomorphological impacts, which involved widespread stripping of alluvium along extensive reaches
359 of the river in the KNP (Fig. 2D).

360

361 **Fig. 6.**

362

363 **Fig. 7.**

364

365

366 **CONCLUSION**

367 In this paper, a simplified 2D modelling approach has been used to estimate the magnitudes of the
368 cyclone-driven, flood events on the Sabie and Olifants rivers in January 2012. The method relies on
369 an accurate LiDAR-derived DEM of a river to account for form roughness assuming that vegetation
370 and soft sediment stripping had occurred prior to the flood peak, and applies a uniform additional

371 roughness factor to account for grain and hydraulic flow resistance components. The use of a
372 simplified 2D code allows for more rapid simulations, modelling very large areas in detail and
373 provides a robust modelling framework that can generate hydraulic estimates for a range of flows.
374 Comparison of field surveyed and simulated water surface slope and inundation patterns for the peak
375 flows suggests that the model performs well overall.

376

377 On both rivers, the flood flows can be described as ‘extreme’, with the discharge on the Olifants being
378 among one of the largest ever recorded or estimated for any southern African river in the late
379 Holocene. Given the documented changes in rainfall patterns in the Kruger National Park since the
380 1980’s (MacFadyen et al., 2018) whereby seasonal patterns appear to be attenuating and rainfall
381 extremes on both ends of the spectrum appear to be extending it is possible that flood extremes on
382 the two study rivers and other systems on the region are becoming increasingly likely. On systems
383 where such extremes are known to drive geomorphic change (Milan et al., 2018b) this may trigger a
384 state change towards bedrock-dominated systems, illustrating the impact of climate change on the
385 region.

386

387

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391

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

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

River	Site	Rating equation	R ²	Mean (m ³ s ⁻¹)	Min (m ³ s ⁻¹)	Max (m ³ s ⁻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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567 **List of Figures**

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

572
573 **Fig. 2.** Photographs from sites on the Sabie and Olifants rivers. Examples of the diverse channel
574 types found in the KNP, A) mixed braided (Sabie River, flow direction from top to bottom), B)
575 cohesive mixed anastomosed (Sabie River, flow direction from bottom to top), C) bedrock
576 anastomosed (Olifants River, flow direction from top to bottom), D) Extent of stripped channel on
577 the Olifants river. Typical strandline evidence recorded on the Sabie and Olifants rivers in the
578 Kruger National Park: E)–G) examples of organic debris accumulations (flow direction is from left
579 to right on image E), and bottom to top (images F and G); H) plastic drinks bottle embedded within
580 a strandline, showing a ‘Best Before’ (BB) date of 4th July 2012. Given the limited shelf life of
581 such products, this BB date implies that strandline would have been formed in the months preceding
582 the survey (i.e. during the January 2012 floods) and not in earlier (pre-2011/2012) flood events. In
583 G), note the considerable distance and elevation of the strandline from the low flow discharge (just
584 visible on far middle right). In general we surveyed finer material such as that showed in G, taking
585 the highest elevation debris line as the datum.

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588

589 **Fig. 3.** Flood strandline and water surface elevations for the survey sites on the: A) Sabie River, for
590 the high flow simulations of 5000 m³s⁻¹; and B) Olifants River, for the high flow simulations of 15000
591 m³s⁻¹.

592

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

596

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

600

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

607

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

614

615 **List of Tables**

616

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

618 2012.

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