

Alternative stable river bed states at high flow

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Key Points:

- River dunes exhibit bimodal height distributions at high transport stages, caused by rapid shifts between dunes and Upper Stage Plane Bed.
- This can be interpreted as tipping behavior, i.e. flickering between two stable states.
- Tipping behavior in geomorphology calls for experimental designs with replication and reinterpretation of classical equilibrium relations.

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Abstract

River bedforms influence fluvial hydraulics by altering bed roughness. With increasing flow velocity, subaqueous bedforms transition from flat beds to ripples, dunes, and an Upper Stage Plane Bed. Although prior research notes increased bedform height variation with flow strength and rapid shifts between bed configurations, the latter remains understudied. This study reanalyzes data from earlier experiments, and reveals a bimodal distribution of dune heights emerges beyond a transport stage of 18. Dune heights flicker between a low and high alternative state, indicating critical transitions. Potentially triggered by local sediment outbursts, these shifts lead to dune formation before returning to an Upper Stage Plane Bed. This flickering behavior challenges the adequacy of a single snapshot to capture the system's state, impacting field measurements and experimental designs, and questions the classical equilibrium equations. This study calls for further research to understand and quantify flickering behavior in sediment beds at high transport stages.

Plain Language Summary

As the flow velocity of a river increases, the riverbed changes from being flat to having ripples, which develop into larger dunes and flat bed conditions. At high flow velocities, these observed bedforms become more variable, and bedforms can alternate between different shapes in a short time. Surprisingly, not much attention has been paid to understanding how these dunes behave when the river flows increase, which is crucial for predicting floods. This study re-examines data from previous experiments to better understand ambiguity in the relation. We found that as the flow increases, the riverbed does not settle into one stable bedform state, but instead keeps switching between two forms. This behavior can be attributed to flickering, which are repeated critical transitions between alternative stable states. This flickering behavior has large implications for how we measure rivers in the field and design experiments in the laboratory. The study suggests there is a need for more research to consider ambiguous relations in geomorphology.

1 Introduction

Subaqueous river bedforms are ubiquitous in low-land rivers, and they are known to impact the river by altering its hydraulics, ecology, and sediment balance. In this way, the geometry of river bedforms impacts the fairway depth (ASCE Task Force, 2002; Best, 2005) and impacts dredging requirements, they add to the form roughness of the river bed (Warmink et al., 2013; Venditti and Bradley, 2022) impacting the water level, and determine suitable foraging places for fish (Greene et al., 2020). In the lower flow regime (Froude number lower than one), and for a given grain size, various types of river bedforms can form, depending on the strength of the flow (e.g. Gilbert, 1914; Guy et al., 1966). Below the threshold of sediment motion, the river bed can be flat, but as the flow increases, a continuum of bedforms evolves, consisting of ripples, followed by dunes, and eventually the dunes may wash out to an Upper Stage Plane Bed. This sequence is generally summarized in phase diagrams (Berg and Gelder, 1993; Southard and Boguchwal, 1990) which correlate a measure of flow strength and a measure of grain size to various bedform planforms.

The height of the dunes, which increases with increasing flow strength and subsequently decays into Upper Stage Plane Bed, can be estimated using bedform predictors. For this purpose, Venditti and Bradley (2022) developed empirical equations for dune height prediction based on transport stage T , which is a measure of relative flow strength. T is defined as the ratio of the Shields stress θ and the critical Shields stress θ_c . The empirical equation for dune height Δ (m) as described below is obtained from laboratory studies (i.e. flows with a water depth h less than 0.25 m), and yields a parabolic relation between dune height Δ and transport stage T :

$$\frac{\Delta}{h} = -0.00100 \left(\frac{\theta}{\theta_c} - 17.7 \right)^2 + 0.417 \quad (1)$$

62 Large scatter was observed when comparing the results from bedform height predictors
 63 to actual measurements (Bradley and Venditti, 2017), and various researchers describe an
 64 increased variability in bed geometry with increasing transport stage (Venditti et al., 2016;
 65 Bradley and Venditti, 2019; Saunderson and Lockett, 1983) (Figure 1). The large vari-
 66 ability at high transport stages might be the reason that not many measurements and lab
 67 experiments are done in the regime where dunes transition into a flat bed (Karim, 1995).
 68 Despite the importance of dune behavior at high flow stages for, e.g., flood prediction (Julien
 69 and Klaassen, 1995) and infrastructure stability (Amsler and Schreider, 1999; Amsler and
 70 Garcia, 1997), not much attention has been given to this phenomenon.

71 The increased variability in bedform height with increasing transport stage is visual-
 72 ized using the data of Venditti et al. (2016) and Bradley and Venditti (2019) in Figure 1.
 73 Bradley and Venditti (2019) stated a “tremendous variability” between bed states at a higher
 74 transport stage, and reasoned that numerous observations of the bed are needed to get an
 75 average bed state that actually scales with transport state. Saunderson and Lockett (1983)
 76 did experiments around the transition from dunes to plane bed. They found four different
 77 bed states (asymmetrical dunes, convex dunes, humpback dunes, and flat bed) that the
 78 bed alternated between. They attributed this behavior to the close position of the system
 79 to a bed-phase boundary (from dunes to USPB). Venditti et al. (2016) more thoroughly
 80 explored the variability at large transport stages, and they grouped the resulting geometries
 81 into three phases: a plane bed with washed-out dunes, a field of large dunes, and a field
 82 of small dunes. They observed that the transition between these phases was continuous,
 83 and that water depth, shear stress and water surface slope co-varied with bed state. During
 84 plane bed conditions, intense erosion on the flat areas lead to localized incision, followed by
 85 the formation of small or large bedforms, which in turn washed out into a flat bed. The
 86 time they observed between the phases varied between minutes to more than half an hour,
 87 with transitions between the phases happening in seconds or minutes.

88 Despite this phenomenon being observed for multiple decades, it has received little
 89 attention, and an explanation for the increase in variability in bedform geometry with
 90 increasing transport stage is lacking. In this study, we suggest a possible explanation for
 91 this behavior, based on the theory of critical transitions (Scheffer et al., 2009; Scheffer et
 92 al., 2012; Lenton, 2013; Strogatz, 2018). This framework describes how sudden shifts to a
 93 qualitatively different (stable) regime can occur, once a system exceeds a critical bifurcation
 94 or tipping point. We hypothesise that in the transition from the dune regime towards
 95 Upper Stage Plane Bed, the bed exhibits flickering behavior (Dakos et al., 2013), resulting
 96 from repeated state shifts between alternative stable states due to stochastic perturbations.
 97 To support this hypothesis, we reanalyze the data from Bradley and Venditti (2019) and
 98 Venditti et al. (2016) and show how the results seamlessly fit in the critical transition
 99 framework.

100 2 Methods

101 2.1 Temporal data of bed morphology

102 To test our hypothesis, we reanalyze the temporal bedform data obtained in Venditti
 103 et al. (2016) and Bradley and Venditti (2019), which are visualized in Figure 1. The exper-
 104 iments from both studies were executed in the River Dynamics Laboratory at Simon Fraser
 105 University, Canada. Their flume has an adjustable flow, recirculates water and sediment,
 106 and is 15 m long (12 m working section), 1 m wide and maximum 0.6 m deep. In both
 107 studies, the experiments were performed with unimodal sediment with a D_{50} of 550 μm .

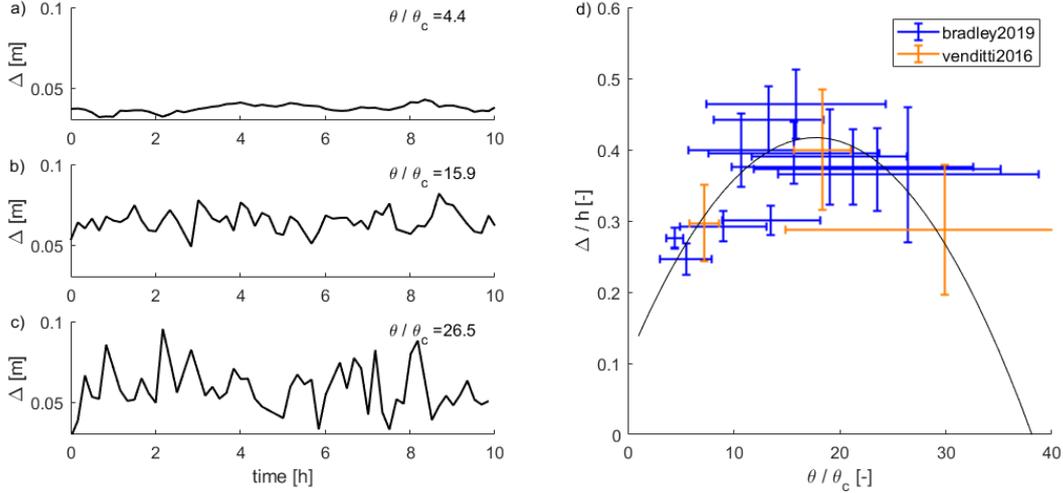


Figure 1. a-c) Dune height Δ over time for three experiments of Bradley and Venditti (2019), for three different transport stages θ/θ_c (i.e., bed shear stress divided by critical shear stress). d) Variability in non-dimensional dune height Δ/h increases with transport stage. Here, h is time-averaged water depth. The predictive equation of Venditti and Bradley (2022) (equation 1) is shown in black. Colored error bars indicate standard deviation for the experiments of Venditti et al. (2016) (red) and Bradley and Venditti (2019) (blue).

108 Venditti et al. (2016) conducted three experimental runs, under bed load, mixed load
 109 and suspended load-dominated conditions, resulting in mean flow velocities of 0.43, 0.59
 110 and 0.87 m s⁻¹ with corresponding observed transport stages of 7.12, 18.3 and 29.7. These
 111 suspended load-dominated conditions were at the threshold of washing out. The bathymetry
 112 was measured every 10 minutes for the bed load and mixed load conditions, and every 5
 113 minutes for the suspended load-dominated experiments. Measurements started after the
 114 bed already had fully adjusted to the flow.

115 Bradley and Venditti (2019) broadened the scope of these experiments by performing 15
 116 experiments under five different transport conditions: threshold of motion, bed load, lower
 117 mixed load, upper mixed load, and suspended load-dominated conditions. Additionally,
 118 they varied the water depth in three steps between 15 and 25 cm, although for the highest
 119 water depth they only performed threshold and bed load-dominated experiments due to the
 120 capacity of the flume. These conditions resulted in a mean velocity of 0.43 and 1.1 m s⁻¹,
 121 and resulting mean transport stages between 4.4 and 26.45. They scanned the bed every 10
 122 minutes, but only after the bed had fully adjusted to flow.

123 **2.2 Theoretical framework: critical transitions**

124 The unstable behavior close to the bed-phase boundary can be interpreted using the
 125 framework of critical transitions (Scheffer et al., 2009). A critical transition is a regime
 126 shift where a system shifts rapidly to a qualitatively different state or dynamical regime,
 127 once a critical threshold (a critical bifurcation or tipping point) is exceeded (Scheffer et al.,
 128 2009; Lenton, 2013). The framework of critical transitions has been successfully employed to
 129 interpret observations of large and rapid shifts, amongst others in ecology, climate dynamics,
 130 medicine and finance Scheffer et al., 2012; Lenton, 2013, whereas it has found relatively little
 131 consideration in geomorphology (Hoitink et al., 2020). Many different types of tipping points
 132 exist, each described by different mathematical equations (Strogatz, 2018). Here, we focus

133 on the so-called supercritical pitchfork bifurcation, as we hypothesize that this model system
 134 could explain the observed increase in bedform variability towards higher transport stages
 135 (Figure 1).

136 The simplest model that generates a supercritical pitchfork bifurcation is given by the
 137 following differential equation:

$$\frac{dy}{dt} = ry - y^3 \quad (2)$$

138 with state variable y , control parameter r and time t . For $r < 0$, this differential equation
 139 has one equilibrium solution (i.e., where $dy/dt = 0$), namely $\bar{y} = 0$. This equilibrium is
 140 stable to small perturbations (Strogatz, 2018), meaning that perturbations dampen out
 141 and the system returns to equilibrium. For $r > 0$, the solution $\bar{y} = 0$ becomes unstable,
 142 meaning that small perturbations amplify and the system moves away from its equilibrium
 143 when perturbed. For $r > 0$, two other stable solutions emerge, $\bar{y} = \pm\sqrt{r}$. When visualized
 144 in a stability diagram, which shows how equilibrium state \bar{y} varies with r , this behavior
 145 resembles a pitchfork; hence the name.

146 The increased variance with increasing transport stage (Figure 1d) can be explained
 147 by the emergence of a second equilibrium state, resembling the behavior in a supercritical
 148 pitchfork bifurcation. However, instead of a “central” equilibrium solution that is indepen-
 149 dent of control parameter r , i.e. $\bar{y} = 0$, we expect this central equilibrium to be a parabola,
 150 similar to the dune height predictor (equation 1). We therefore substitute $y = -a + br^2 + x$
 151 in equation 2, with constants a and b and state variable x . Assuming that changes in r are
 152 much slower than changes in x , we can write $dy/dt = dx/dt$, and equation 2 becomes

$$\frac{dx}{dt} = r(-a + br^2 + x) - (-a + br^2 + x)^3 \quad (3)$$

153 Instead of the constant equilibrium $\bar{y} = 0$, the “central” solution of this modified pitchfork
 154 bifurcation now becomes a parabola, i.e. $\bar{x} = a - br^2$, which again is stable for $r < 0$ and
 155 unstable for $r > 0$. For $r > 0$, the two newly emerging solutions, $\bar{x} = a - br^2 \pm \sqrt{r}$, are
 156 stable. These equilibria are shown in Figure 2, with stable equilibria indicated in solid black
 157 lines, the unstable equilibrium as a dashed black line, and the bifurcation point ($r = 0$) as
 158 a black circle.

159 We hypothesize that the rapid shifts between high and low dune height observed at
 160 high transport stages (Figure 1c) are an expression of flickering. Flickering is a phenomenon
 161 described within the framework of critical transitions as a back-and-forth tipping between
 162 alternative stable states due to stochastic perturbations (Horsthemke and Lefever, 1984;
 163 Scheffer et al., 2012; Dakos et al., 2013). Indicators for flickering are multi-modality and a
 164 high variance (Scheffer et al., 2012; Dakos et al., 2012; Carpenter and Brock, 2006). As long
 165 as a system only has one stable equilibrium ($r < 0$ in Figure 2a), observation time-series
 166 of system state will show a unimodal frequency distribution spread around the theoretical
 167 equilibrium solution (Figure 2b). However, once a second equilibrium solution emerges
 168 ($r > 0$ in Figure 2a), the stochastic perturbations will occasionally cause the system to tip
 169 from one stable state into the other, which is reflected in a bimodally distributed system
 170 state (Figure 2d-f).

171 To illustrate flickering in the case of the modified pitchfork bifurcation, we generated a
 172 synthetic time series by numerically solving equation 3 while imposing continuous stochastic
 173 perturbations in x . We gradually vary control parameter r over time, i.e. $r(t) = r(0) + \frac{dr}{dt}t$,
 174 with $\frac{dr}{dt}$ a fixed rate of change. We numerically discretize equation 3 over time using a
 175 4th-order Runge-Kutta scheme (Strogatz, 2018). Writing

$$\frac{dx}{dt} = f(x, t) \quad (4)$$

176 we then time-integrate the differential equation by calculating subsequent steps

$$dx = f(x, t)dt + dW(0, \sigma_W) \quad (5)$$

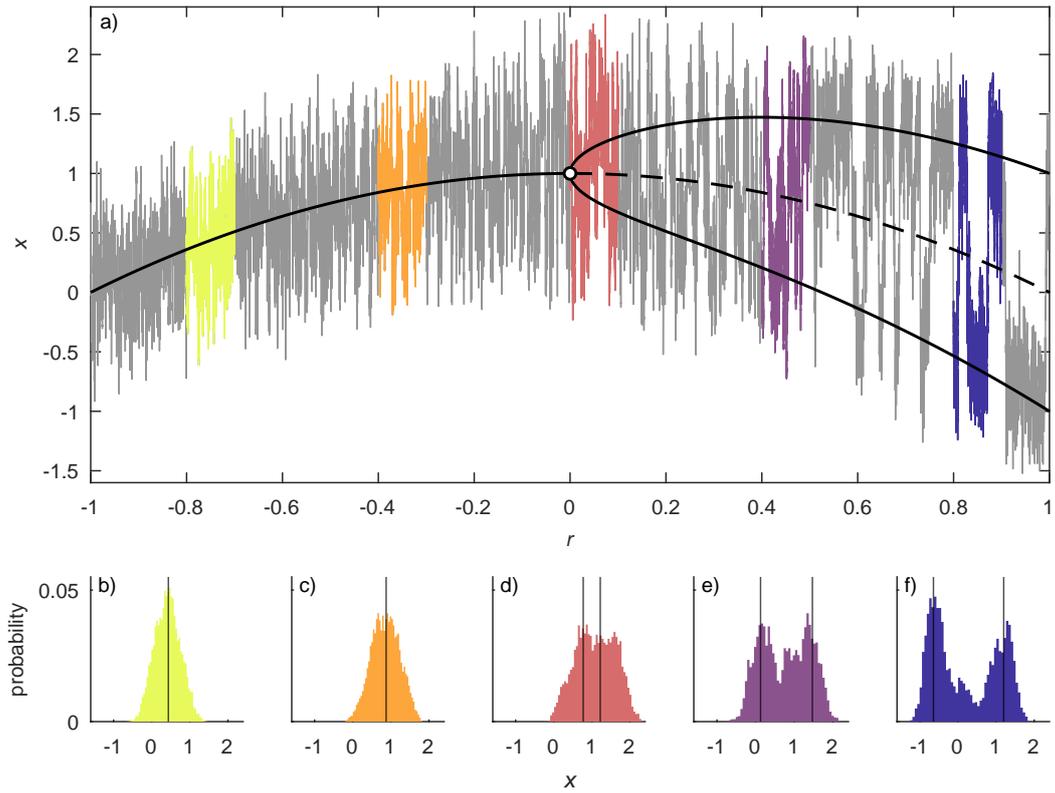


Figure 2. Model-generated flickering around a modified pitchfork bifurcation, i.e. the equilibrium solutions of equation 3. Solid black lines indicate stable equilibria, dashed black line indicates an unstable equilibrium, and the black circle indicates the pitchfork bifurcation point. Grey lines are simulated time series, i.e. the solution of the differential equation, with white noise added. Histograms of five time intervals are shown in corresponding colors below. Vertical black lines indicate the location of the stable equilibrium solution(s).

177 where $dW(0, \sigma_W)$ is a white noise signal, i.e. a random number drawn at each time step
 178 dt from a Gaussian distribution with mean 0 and standard deviation σ_W . In our case,
 179 $r(0) = -1$, $dr/dt = 0.001$, $dt = 0.01$, $a = 1$, $b = 1$ and $\sigma_W = 0.05$. This simple model
 180 demonstrates how flickering around the only existing equilibrium state $\bar{x} = a - br^2$ for $r < 0$
 181 results in a unimodal frequency distribution of x , and a bimodal frequency distribution for
 182 $r > 0$, with the modes corresponding to the two emerging stable solutions $\bar{x} = a - br^2 \pm \sqrt{r}$.

183 2.3 Statistical analysis

184 To quantify variability in dune height, the standard deviation (σ) is determined as:

$$\sigma = \sqrt{\frac{\sum_{i=1}^N |x_i - \mu|^2}{N}} \quad (6)$$

185 in which x_i are the observations, μ is the mean of the data set, and N is the number of data
 186 points in the population.

187 To determine if a dune height distribution is bimodal, and to locate the modi of the
 188 distribution, a method based on Laplace's demon is used (Statisticat, 2021). This is a
 189 deterministic function that uses the kernel density of the dataset and reports a number of
 190 modes equal to half the number of changes in direction (i.e. where it switches from going
 191 up to going down). The function does not report modi that cover less than 10% of the
 192 distributional area.

193 If the distribution is indeed bimodal, the bimodality is considered significant if the
 194 distance between the two modi d_{modi} is larger than the coefficient of variation CV (i.e. the
 195 normalized standard deviation):

$$CV = \frac{\sigma}{\mu} \quad (7)$$

196 3 Results and Discussion

197 3.1 Increasing variability of bedform height with transport stage

198 The raw data as shown in Figure 1 indirectly identify the increase of variability in dune
 199 height with transport stage. When this variability is expressed in the standard deviation σ
 200 (equation 6), a significant linear relation ($R^2 = 0.67$) between transport stage and standard
 201 deviation in non-dimensional dune height (Figure 3a) is revealed. Clearly, dune height
 202 becomes more variable with increasing flow strength.

203 From the 15 experiments analyzed, nine of them were characterized by a bimodal
 204 distribution (Supplementary Materials Figure S1). The distance between the identified
 205 modi, d_{modi} , increases with an increasing transport stage (Figure 3b), featuring a significant
 206 linear relation ($R^2 = 0.74$). The modality of the distributions becomes significant if the
 207 distance between the modi is larger than the coefficient of variation, which is true for all
 208 experiments with a transport stage higher than 18. This behavior is comparable to the
 209 increase in d_{modi} as result of a pitchfork bifurcation (Figure 2).

210 3.2 Emergence of a second bedform state

211 The observed increase in bed height variability with increasing transport stages can
 212 be interpreted as the emergence of a second equilibrium branch. This becomes apparent
 213 when visualizing the raw data from Figure 1 in a two-dimensional histogram or density
 214 plot (Figure 4). For $\theta/\theta_c < 18$, the dune height observations are distributed in a relatively
 215 narrow zone around the theoretical dune height predictor (equation 1). The fitted modal
 216 distributions are either unimodal, or bimodal but with non-significant bimodality. For
 217 $\theta/\theta_c > 18$, the observations fan out towards higher and lower values of Δ/h . For three

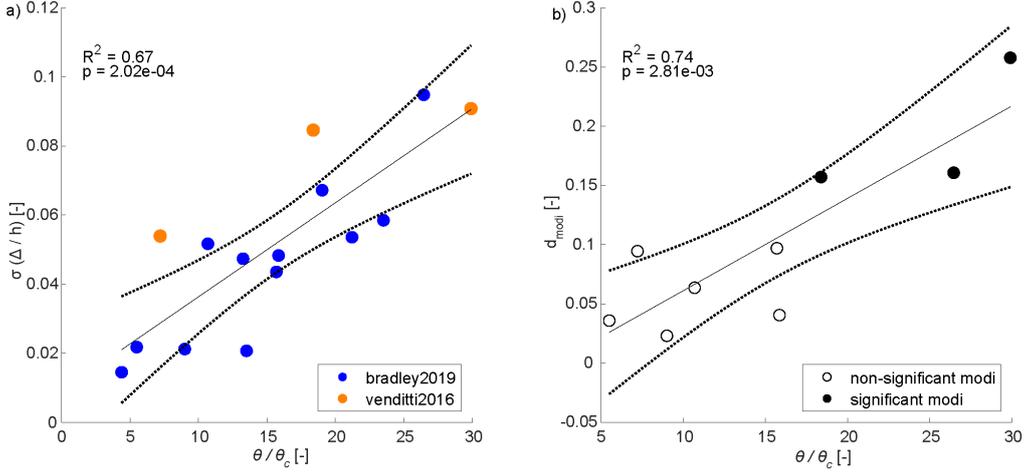


Figure 3. a) Standard deviation σ of the non-dimensional dune height Δ/h against transport stage θ/θ_c . b) The distributions of non-dimensional dune height are often bimodal, and the distance between the modi (d_{modi}) increases with increasing transport stage. Significant bimodal distributions ($d_{modi} > CV$) are indicated with a filled marker; non-significant bimodality with an open marker.

218 different transport stages, the observed dune height distribution is significantly bimodal
 219 (Figure 3b).

220 For transport stages where dune heights are unimodally distributed, the parabolic dune
 221 height predictor (equation 1) is a good fit through these dune height modes. For transport
 222 stages where dune height is bimodally distributed (either with significant or non-significant
 223 bimodality), the dune height predictor is a good fit through the lowest modal value of of these
 224 bimodal distributions. For transport stages exceeding 18, the emergence of a statistically
 225 significant second mode at higher dune heights suggests a second equilibrium solution that
 226 branches off the parabolic dune height predictor, starting roughly at the top of the parabolic
 227 relation.

228 The pitchfork bifurcation (Figure 2) is no perfect model to fit to the observations. This
 229 bifurcation type shows a parabolic “central” solution that becomes unstable beyond the top
 230 of the parabola, and two diverging solutions branching off from there. Our observations,
 231 on the other hand, suggest that the parabolic solution itself remains stable for all transport
 232 stage values, but that a second solution branches off towards higher dune heights. Nonethe-
 233 less, we consider the pitchfork bifurcation here, as it is the simplest mathematical model
 234 to illustrate how a second equilibrium can emerge beyond a tipping point (here: a critical
 235 transport stage), and how this may result in flickering between two states (Figure 1b,c) and
 236 bimodal dune height distributions with increasing spacing between modes (Figures 3, 4).

237 3.3 Physical explanation

238 We hypothesise that the changing states are a result of a temporary shift from suspended-
 239 dominated conditions to mixed- or bed load-dominated conditions. During bed load or mixed
 240 load conditions, there is a neutral or negative spatial lag between dune crest and maximum
 241 sediment transport rate, causing maintenance or growth of the dunes (Naqshband et al.,
 242 2017). During high flow conditions (suspended load dominated), a high concentration of
 243 sediment near the bed (Baas and Koning, 1995; Naqshband et al., 2014) causes the spatial
 244 lag to be positive, resulting in the washing out of dunes. Suspended load does not con-

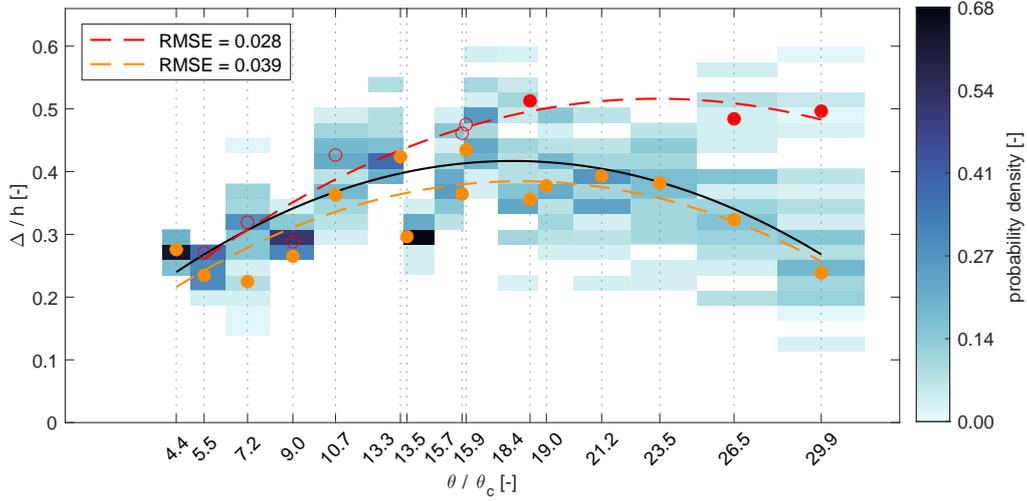


Figure 4. Density plot of the observations from Venditti et al. (2016) and Bradley and Venditti (2019), binned as a function of dune height Δ scaled by mean water depth h , and mean transport stage θ/θ_c . Mean values of transport stage are chosen since they are independent of the bed state. Orange bullets indicate the lower modal value found for that transport stage; red bullets indicate the higher modal value, if found for that transport stage. If the distribution for a specific transport stage is significantly bimodal, the red bullet marking the higher mode is filled; if non-significant, the red bullet is kept open. Quadratic relations were fitted through the orange bullets (orange dashed line) and through the red bullets (both filled and open; red dashed line). The black line indicates the dune height predictor (equation 1). Note that the vertical axis is divided into equidistant bins, while the transport stages along the horizontal axis are non-equidistant. Therefore, it was here assumed that, along the horizontal axis, each bin ranges until halfway between two subsequent transport stage values, which causes the bullets to not always be in the middle of the bins. For the left-most (right-most) transport stage value, the leftward (rightward) bin width is chosen the same as the rightward (leftward) bin width. Some tick labels along the horizontal axis are slightly displaced to avoid overlap, but ticks themselves are in the correct place.

245 tribute to the migration of dunes (neither in subaqueous (Naqshband et al., 2017) or aeolian
 246 conditions (Courrech du Pont, 2015)), but only to the deformation, causing a transition to
 247 plane bed (Naqshband et al., 2017; Naqshband and Hoitink, 2020). Washout conditions
 248 Best and Bridge (1992) found episodic short-lived outbursts of bed load sediment transport,
 249 that are also observed in aeolian transport (Livingstone et al., 2007; Butterfield, 1991; Baas
 250 and Sherman, 2005). A local outburst of sediment (local erosion, or local disruptive pulses)
 251 can result into local bed- or mixed load conditions. This can temporarily result in dune
 252 formation, until suspended load conditions dominate and the bed flattens out.

253 The temporary formation of dunes and flattening out again could be the cause for the
 254 observed flickering. This flickering can be seen as noise-induced tipping. Noise-induced
 255 tipping means that a system is perturbed by a forcing whose time-scale is shorter than
 256 the system's intrinsic time scale (Ashwin et al., 2012; Scheffer et al., 2009). Local bed
 257 load conditions can cause the noise that tips the system. With an increase in transport
 258 stage, the likelihood of those outbursts to actually result into local bed load transport
 259 decreases, and local outbursts are more likely to be transported as suspended load. This
 260 means that the magnitude of the noise (i.e. the intensity of the local bed load conditions)
 261 decreases with increasing transport stage. Since a decrease in the lower modi of dune height
 262 is observed with an increasing transport stage (if the transport stage is larger than 18), it
 263 can be recognized that the magnitude of the noise scales with the state of the system (dune
 264 height), a phenomenon that is more generally observed in flickering processes (Dakos et al.,
 265 2013). Practically, this means that the system might eventually become 'trapped' in the
 266 stable state that is Upper Stage Plane Bed, while the alternative state becomes abandoned.
 267 This theory needs to be tested, as to date it is unclear if a fully stable USPB exists.

268 The observed flickering behavior is not an artifact from the recirculating flume. Parker
 269 (2003) suggests that an artifact of recirculating flumes could be migrating lumps of sediment
 270 that persist for a long period of time until equilibrium is achieved. In the experiments of
 271 Venditti et al. (2016) and Bradley and Venditti (2019), a constant flow was applied until
 272 the bed reached equilibrium. Venditti et al. (2016) defined equilibrium conditions when no
 273 changes in the water depth and bed slope appeared anymore, which was after 72 hours for
 274 low transport stage runs, and after 30 hours for high transport stage runs. Bradley and
 275 Venditti (2019) allowed a constant flow of 10 to 25 hours depending on the transport stage
 276 until bedform height did not change anymore. Finally, Venditti et al. (2016) pointed out
 277 that one configuration is stable for a few minutes to half an hour. This indicates that there
 278 is no obvious regularity in the changes in bed configuration, which would be expected if this
 279 was due to migrating lumps in the recirculation system.

280 3.4 Implications

281 Flickering alternative stable bed morphological states at high transport stages has several
 282 implications. At higher flow stages, the bed may not necessarily get flatter (by an
 283 increase in dune length), but rapidly switch between bed configurations. This means that
 284 one single snapshot is not enough to capture the state of the system. Field monitoring with
 285 multi-beam measurements at high flow stages only provide a snapshot of the bed state, and
 286 accompanying logistical decisions (for e.g. high water protection, fairway depth, stability
 287 of buried pipes and cables) could not solely be based on this snapshot. At high flow condi-
 288 tions, many measurements in time are needed to get a complete appreciation of occurring
 289 bed states, and the large standard deviations here (Figure 1) indicate that mean values
 290 might be meaningless.

291 Laboratory experiments are known to be effective representations of the field, due
 292 to the natural scale independence of physical (geomorphological) processes (Paola et al.,
 293 2009). However, in scientific study designs, the repeatability of experiments should be
 294 considered. The presence of flickering behavior results in serious dependence of the results
 295 to the timing of the measurements. This means that studies should not only focus on

296 reproducibility (confirmation of the findings using different resources in an independent
 297 program), as suggested by Church et al. (2020), but also on repeatability (exact repetition
 298 of experiments to establish precision of results) of the experiments. When the temporal
 299 resolution of the measurements is less than the occurrence of flickering, there is a need for
 300 repetition of the experiments, because alternative bed states might not be detected. Geng et
 301 al. (2023) found that the development of a morphological system depends on the the initial
 302 bed conditions. The existence of multiple equilibria potentially increases the sensitivity to
 303 initial bed conditions, which once more stresses the need for repetition of experiments.

304 The classic equilibrium predictors might need to be revised to include this flickering
 305 behavior. Although Bradley and Venditti (2019) already suggests the need for averaging
 306 many values, and Venditti and Bradley (2022) binned observations to obtain the equation
 307 relating dune height to transport stage, it is questionable if the average dune height is a
 308 relevant parameter when a bimodal distribution is featured with high transport stages. The
 309 equilibrium predictor is based on empirical relations fitted through averaged data, and may
 310 not grasp the right physical processes.

311 Future research about the flickering behavior around the transition from dunes to USPB
 312 is critical, and longer high frequency time series of laboratory and field data should be
 313 acquired. A suggested next step could be detailed experimental observations of the critical
 314 transition over a longer (weeks) time scale. From this, the life time of the different phases
 315 could be determined (Arani et al., 2021), and a physical explanation for this phenomenon
 316 can be sought. This could be followed up by experiments using an increasing discharge
 317 over time, to observe the temporal changes in bed configuration and to confirm the type of
 318 tipping point.

319 4 Conclusion

320 We reanalyzed 15 laboratory experiments of bedform height over time from Venditti
 321 et al. (2016) and Bradley and Venditti (2019). The standard deviation and the bimodality
 322 of the datasets indicate flickering behavior at high transport stages:

- 323 • The standard deviation of bedform height over time increases with an increasing
 324 transport stage. The bed can rapidly switch between bed configurations. The quan-
 325 tified distributions of bedform height show increasingly strong signs of bimodality.
 326 The distance between the two modi increases with increasing transport stage, and
 327 bimodality is significant for transport stages exceeding 18.
- 328 • The modi in the dune height distributions feature two branches. The lowest modi
 329 represents the branch that is also captured by the dune geometry predictor of Venditti
 330 and Bradley (2022). The other branch, that indicates the presence of large dunes at
 331 high transport stages, is not captured by the predictor.
- 332 • This behavior is an indication that a second equilibrium state emerges for transport
 333 stages beyond approximately 18. Above this tipping point, repeated critical transi-
 334 tions triggered by stochastic perturbations (flickering) between the two alternative
 335 states results in the bimodal distribution as observed in the experiments.
- 336 • We hypothesise that this is the result of local outbursts of bedload sediment, result-
 337 ing in a localized bedload transport, enabling dune growth. The likelihood that these
 338 outbursts actually result in local bedload conditions decreases with increasing trans-
 339 port stage, and decreasing averaged dune height. Therefore, the system eventually
 340 gets trapped in the Upper Stage Plane Bed-state, where perturbations are not strong
 341 enough to tip the system to the alternative state.
- 342 • The existence of flickering of a sediment bed has far-reaching consequences for field
 343 measurements, laboratory experimental design, and calls for reinterpretation of the
 344 classical equilibrium relations.

Open Research Section

Data is available through Venditti et al. (2016) and Bradley and Venditti (2019). The code used to generate the results in this study will be made available through the public repository of 4TU upon acceptance.

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References

- Amsler, M.L. and M.H. Garcia (1997). “Sand-dune geometry of large rivers during floods”. In: *Journal of Hydraulic Engineering* 123.6.
- Amsler, M.L. and M.I. Schreider (1999). “Dune height prediction at floods in the Paraná River, Argentina”. In: *River sedimentation: Theory and applications*, pp. 615–620.
- Arani, Babak M.S. et al. (2021). “Exit time as a measure of ecological resilience”. In: *Science* 372.6547. ISSN: 10959203. DOI: 10.1126/science.aay4895.
- ASCE Task Force (2002). “Flow and transport over dunes”. In: *Journal of Hydraulic Engineering* 127, pp. 726–728.
- Ashwin, Peter et al. (2012). “Tipping points in open systems: bifurcation, noise-induced and rate-dependent examples in the climate system”. In: *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences* 370.1962, pp. 1166–1184. ISSN: 1364-503X. DOI: 10.1098/rsta.2011.0306.
- Baas, A. C. W. and D. J. Sherman (2005). “Formation and behavior of aeolian streamers”. In: *Journal of Geophysical Research: Earth Surface* 110.F3. ISSN: 0148-0227. DOI: 10.1029/2004JF000270.
- Baas, J.H. and H. de Koning (1995). “Washed-Out Ripples: Their Equilibrium Dimensions, Migration Rate, and Relation to Suspended-Sediment Concentration in Very Fine Sand”. In: *SEPM Journal of Sedimentary Research* Vol. 65A. ISSN: 1527-1404. DOI: 10.1306/D42680E5-2B26-11D7-8648000102C1865D.
- Berg, J.H. van den and A. van Gelder (1993). “A new bedform stability diagram, with emphasis on the transition of ripples to plane bed in flows over fine sand and silt”. In: *Spec. Publs Int. Ass. Sediment* 17, pp. 11–21.
- Best, Jim (2005). “The fluid dynamics of river dunes: A review and some future research directions”. In: *Journal of Geophysical Research: Earth Surface* 110.4, pp. 1–21. ISSN: 21699011. DOI: 10.1029/2004JF000218.
- Best, Jim and John Bridge (1992). “The morphology and dynamics of low amplitude bed-waves upon upper stage plane beds and the preservation of planar laminae”. In: *Sedimentology* 39.5, pp. 737–752. ISSN: 13653091. DOI: 10.1111/j.1365-3091.1992.tb02150.x.
- Bradley, Ryan W. and Jeremy G. Venditti (2017). *Reevaluating dune scaling relations*. DOI: 10.1016/j.earscirev.2016.11.004.
- (2019). “Transport Scaling of Dune Dimensions in Shallow Flows”. In: *Journal of Geophysical Research: Earth Surface* 124.2, pp. 526–547. ISSN: 21699011. DOI: 10.1029/2018JF004832.
- Butterfield, G. R. (1991). “Grain transport rates in steady and unsteady turbulent airflows”. In: pp. 97–122. DOI: 10.1007/978-3-7091-6706-9_{_}6.
- Carpenter, S. R. and W. A. Brock (2006). “Rising variance: a leading indicator of ecological transition”. In: *Ecology Letters* 9.3, pp. 311–318. ISSN: 1461023X. DOI: 10.1111/j.1461-0248.2005.00877.x.
- Church, M. et al. (2020). “Are Results in Geomorphology Reproducible?” In: *Journal of Geophysical Research: Earth Surface* 125.8. ISSN: 2169-9003. DOI: 10.1029/2020JF005553.

- 395 Courrech du Pont, Sylvain (2015). “Dune morphodynamics”. In: *Comptes Rendus Physique*
396 16.1, pp. 118–138. ISSN: 16310705. DOI: 10.1016/j.crhy.2015.02.002.
- 397 Dakos, Vasilis, Egbert H. van Nes, and Marten Scheffer (2013). “Flickering as an early
398 warning signal”. In: *Theoretical Ecology* 6.3, pp. 309–317. ISSN: 18741738. DOI: 10
399 .1007/s12080-013-0186-4.
- 400 Dakos, Vasilis et al. (2012). “Methods for detecting early warnings of critical transitions
401 in time series illustrated using simulated ecological data”. In: *PLoS ONE* 7.7. ISSN:
402 19326203. DOI: 10.1371/journal.pone.0041010.
- 403 Geng, L. et al. (2023). “The Sensitivity of Tidal Channel Systems to Initial Bed Condi-
404 tions, Vegetation, and Tidal Asymmetry”. In: *Journal of Geophysical Research: Earth*
405 *Surface* 128.3. ISSN: 2169-9003. DOI: 10.1029/2022JF006929.
- 406 Gilbert, G.K. (1914). “The transport of debris by running water”. In: *USGS Professional*
407 *Paper* 86, pp. 1–263.
- 408 Greene, H. Gary, Matthew Baker, and John Aschoff (2020). “A dynamic bedforms habitat
409 for the forage fish Pacific sand lance, San Juan Islands, WA, United States”. In: *Seafloor*
410 *Geomorphology as Benthic Habitat*. Elsevier, pp. 267–279. DOI: 10.1016/B978-0-12
411 -814960-7.00014-2.
- 412 Guy, H.P., D.B. Simons, and E.V. Richardson (1966). “Summary of alluvial channel data
413 from flume experiments, 1956–1961.” In: *USGS Professional Paper 462-I, 1–96.*, pp. 1–
414 96.
- 415 Hoitink, A. J. F. et al. (2020). “Resilience of River Deltas in the Anthropocene”. In: *Jour-*
416 *nal of Geophysical Research: Earth Surface* 125.3. ISSN: 2169-9003. DOI: 10.1029/
417 2019JF005201.
- 418 Horsthemke, W. and R. Lefever (1984). *Noise-induced transitions: Theory and applications*
419 *in physics, chemistry and biology*. 1. Springer. DOI: 10.1007/BF00047115.
- 420 Julien, P.Y. and G.J. Klaassen (1995). “Sand-dune geometry of large rivers during floods”.
421 In: 121.9, pp. 657–663.
- 422 Karim, F. (1995). “Bed configuration and hydraulic resistance in alluvial-channel flows”. In:
423 *Journal of Hydraulic Engineering* 121.1, pp. 15–25.
- 424 Lenton, Timothy M. (2013). “Environmental Tipping Points”. In: *Annual Review of En-*
425 *vironment and Resources* 38.1, pp. 1–29. ISSN: 1543-5938. DOI: 10.1146/annurev
426 -environ-102511-084654.
- 427 Livingstone, Ian, Giles F.S. Wiggs, and Corinne M. Weaver (2007). “Geomorphology of
428 desert sand dunes: A review of recent progress”. In: *Earth-Science Reviews* 80.3-4,
429 pp. 239–257. ISSN: 00128252. DOI: 10.1016/j.earscirev.2006.09.004.
- 430 Naqshband, S. and A. J. F. Hoitink (2020). “Scale-Dependent Evanescence of River Dunes
431 During Discharge Extremes”. In: *Geophysical Research Letters* 47.6. ISSN: 0094-8276.
432 DOI: 10.1029/2019GL085902.
- 433 Naqshband, S., J.S. Ribberink, and S.J.M.H. Hulscher (2014). “Using both free surface effect
434 and sediment transport mode parameters in defining the morphology of river dunes
435 and their evolution to upper stage plane beds”. In: *Journal of Hydraulic Engineering*
436 140.6, pp. 1–6. ISSN: 19437900. DOI: 10.1061/(ASCE)HY.1943-7900.0000873.
- 437 Naqshband, S. et al. (2017). “A Sharp View on River Dune Transition to Upper Stage
438 Plane Bed”. In: *Geophysical Research Letters* 44.22, pp. 437–11. ISSN: 19448007. DOI:
439 10.1002/2017GL075906.
- 440 Paola, Chris et al. (2009). “The “unreasonable effectiveness” of stratigraphic and geomorphic
441 experiments”. In: *Earth-Science Reviews* 97.1-4, pp. 1–43. ISSN: 00128252. DOI: 10
442 .1016/j.earscirev.2009.05.003.
- 443 Parker, Gary (2003). “Persistence of sediment lumps in approach to equilibrium in sediment-
444 recirculating flumes”. In: *Proceedings, International Association of Hydraulic Research*
445 *Congress*.
- 446 Saunderson, Houston C and Francis P J Lockett (1983). “Flume experiments on bedforms
447 and structures at the dune-plane bed transition”. In: *Spec Publ. int. Ass Sediment* 6,
448 pp. 49–58.

- 449 Scheffer, Marten et al. (2009). *Early-warning signals for critical transitions*. DOI: 10.1038/
450 nature08227.
- 451 Scheffer, Marten et al. (2012). “Anticipating Critical Transitions”. In: URL: [https://www](https://www.science.org)
452 .[science.org](https://www.science.org).
- 453 Southard, John B and Lawrence A Boguchwal (1990). “Bed configurations in steady unidi-
454 rectional water flows, part 2. Synthesis of flume data.” In: 60.5, pp. 658–679.
- 455 Statisticat, L.L.C. (2021). *LaplacesDemon: Complete Environment for Bayesian Inference*.
456 URL: [https://web.archive.org/web/20150206004624/http://www.bayesian](https://web.archive.org/web/20150206004624/http://www.bayesian-inference.com/software)
457 [-inference.com/software](https://web.archive.org/web/20150206004624/http://www.bayesian-inference.com/software).
- 458 Strogatz, Steven H. (2018). *Nonlinear Dynamics and Chaos with Student Solutions Manual*.
459 CRC Press. ISBN: 9780429399640. DOI: 10.1201/9780429399640.
- 460 Venditti, Jeremy G. and Ryan W. Bradley (2022). “Bedforms in Sand Bed Rivers”. In: *Trea-*
461 *tise on Geomorphology*. Elsevier, pp. 222–254. ISBN: 9780128182352. DOI: 10.1016/
462 B978-0-12-409548-9.12519-9.
- 463 Venditti, Jeremy G., C. Y.Martin Lin, and Moslem Kazemi (2016). “Variability in bedform
464 morphology and kinematics with transport stage”. In: *Sedimentology* 63.4, pp. 1017–
465 1040. ISSN: 13653091. DOI: 10.1111/sed.12247.
- 466 Warmink, J. J. et al. (2013). “Quantification of uncertainty in design water levels due to
467 uncertain bed form roughness in the Dutch river Waal”. In: *Hydrological Processes*
468 27.11, pp. 1646–1663. ISSN: 08856087. DOI: 10.1002/hyp.9319.