

1 **Sand suspension and fluxes by wave groups and equivalent monochromatic waves**

2 Joep van der Zanden¹, Dominic A. van der A², Peter D. Thorne³,
3 Tom O'Donoghue², Jan S. Ribberink¹

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- 6 1. Water Engineering and Management, University of Twente, P.O. Box 217, 7500 AE, Enschede,
7 the Netherlands
- 8 2. School of Engineering, University of Aberdeen, King's College, AB24 3UE, Aberdeen, United
9 Kingdom
- 10 3. National Oceanographic Centre, 6 Brownlow Street, L3 5DA, Liverpool, United Kingdom

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14 acoustic backscatter sensor.

15

16 **Abstract**

17 Sand transport dynamics under non-breaking regular waves and wave groups are studied in a
18 large-scale wave flume. The water surface elevation, flow velocity, suspended sand
19 concentration (SSC) distributions, and bedforms were measured over a horizontal test section
20 of medium sand. The experiment involved five wave groups that had equal root-mean-square
21 water surface elevation and mean period, but which differed in terms of modulation, wave group
22 length, and short wave sequencing. In addition, three monochromatic wave conditions were
23 generated which were equivalent to the wave groups in terms of root-mean-square water surface
24 elevation or maximum wave height. Temporal and vertical distributions of SSC suggest a more
25 effective sediment pumping for symmetric and backward leaning 'waxing' wave groups.
26 Vertical distributions of the SSC phase lag indicate a more rapid vertical pumping for the short-
27 duration wave group. Overall, the differences between wave group conditions are small and the
28 time-averaged SSC and sediment diffusivity profiles are very similar. The total net suspended
29 sand flux consists of current-related, long-wave-related and short-wave-related contributions
30 that are all of similar magnitude. The net total suspended sand flux was always offshore-
31 directed, but its magnitude depends on the vertical and temporal variation of SSC at short- and
32 long-wave time scales. The results are used to discuss the applicability of the 'equivalent wave
33 concept' for time-averaged SSC distributions and net suspended sand transport.

35 **1 Introduction**

36 Coastal regions are of vital importance as they are commonly densely populated and offer various
37 ecosystem services. Coastal systems are dynamic: their morphology changes in time as sediment is
38 displaced by currents, waves, and turbulent velocities. A profound understanding of the morphodynamic
39 processes at various time scales is relevant in view of protecting and reinforcing coastal systems. Despite
40 ongoing efforts, the mechanisms explaining the wave-driven cross-shore transport of sediment are not
41 fully understood, leading to uncertainties in numerical morphodynamic models that are applied for
42 research and engineering purposes.

43 As indicated by van Rijn *et al.* (2013), a specific topic that requires further research is the cross-shore
44 transport of sand under irregular and grouped waves. Waves propagating toward a sandy beach exert a
45 shear stress on the bed which entrains sand grains. Due to the dynamic flow fields under individual
46 waves and under wave groups, the suspended sand concentration (SSC) varies at both short-wave and
47 long-wave (infragravity-wave) frequencies (Hanes & Huntley, 1986; Beach & Sternberg, 1988; Osborne
48 & Greenwood, 1992). Depending on the temporal variation in SSC compared to the wave-induced
49 orbital velocities, the short and long waves may transport suspended sand in the onshore or offshore
50 direction (Jaffe *et al.*, 1984; Osborne & Greenwood, 1992; Ruessink *et al.*, 1998).

51 Shoaled waves, which have propagated to intermediate and shallow waters, are generally positively
52 skewed: the wave crests are high and of short duration relative to the shallow, long-duration wave
53 troughs. Skewed waves induce different sand pick-up and vertical mixing rates between the crest and
54 trough phase, which leads to a phase-dependent variation in SSC and to a net wave-related cross-shore
55 sand flux. The magnitude and direction of this net flux depends on wave conditions, sand characteristics,
56 and the presence of bedforms. For medium sand over flat beds, i.e. for high orbital velocities and bedload
57 transport in a sheet flow regime, sand grains are picked up primarily during maximum bed shear stress
58 by the orbital flow and, consequently, the SSC close to the bed is approximately in phase with free-
59 stream velocity (Ribberink & Al-Salem, 1995). On the other hand, over steep sand ripples, the pick-up
60 occurs predominantly during flow reversals when sediment-laden vortices are ejected into the flow
61 (Sleath, 1982; van der Werf *et al.*, 2007; O'Hara Murray *et al.*, 2011; Finn *et al.*, 2016).

62 For positively skewed waves, the pick-up over a rippled bed is highest during the onshore-to-offshore
63 flow reversal, commonly leading to maximum suspended load during the trough phase and a net
64 offshore-directed wave-related suspended transport (Sato, 1987; Ribberink & Al-Salem, 1994; van der
65 Werf *et al.*, 2006). The strongest time-dependency in SSC occurs in a near-bed layer of about two ripple
66 heights that is characterised by convective mixing due to ripple-induced coherent vortices; at higher
67 elevations these vortex structures are weakened and lead to more random diffusive mixing and a reduced
68 time variation in SSC (Davies & Villaret, 1997; Thorne *et al.*, 2002; Davies & Thorne, 2016). With
69 distance from the bed, SSC exhibits a progressively increasing phase lag with respect to velocity and
70 consequently, net wave-related sand fluxes may show strong vertical variation in terms of magnitude
71 and direction (van der Werf *et al.*, 2007; Hurther & Thorne, 2011).

72 Sand suspension also responds to hydrodynamic forcing at the wave group time scale. Field
73 measurements have shown that the SSC under short waves may be enhanced by the wave group (Hanes,
74 1991; Williams *et al.*, 2002), which relates to a progressively increasing suspended sand load under the
75 sequentially larger waves within a wave group (Osborne & Greenwood, 1993; Hay & Bowen, 1994),
76 also referred to as ‘sediment pumping’ (Villard *et al.*, 2000). Sediment pumping has been studied in
77 more detail through wave flume experiments involving random waves (Villard *et al.*, 2000; Vincent &
78 Hanes, 2002; Dohmen-Janssen & Hanes, 2005; Williams & Bell, 2006; O'Hara Murray *et al.*, 2012) and
79 bichromatic waves (Sato, 1992). With increasing distance from the bed, the SSC variations at the wave
80 group time scale become progressively more significant compared to variations at short wave time scales
81 (Dohmen-Janssen & Hanes, 2005; O'Hara Murray *et al.*, 2012). The SSC variations at wave group time
82 scale lag the wave group envelope by about one short-wave half-cycle near the bed, but this phase lag
83 increases progressively with distance from the bed, reaching values up to about 2-3 short-wave periods
84 at elevations outside the wave bottom boundary layer (Villard *et al.*, 2000; O'Hara Murray *et al.*, 2012).
85 The pumping process has been explained by a build-up of turbulent kinetic energy by ripple vortex
86 shedding during a wave group which reduces the settling and promotes vertical mixing of suspended
87 sediment (Villard *et al.*, 2000; Vincent & Hanes, 2002); numerical simulations of sand suspension over
88 a flat bed reaffirm the important role of turbulence in sediment pumping (Holmedal *et al.*, 2004).

89 Suspended sand transport at long-wave (infra-gravity) frequencies generally tends to be offshore-
90 directed under non-breaking wave groups (e.g. Ruessink *et al.*, 1998; Vincent *et al.*, 1999; Conley &
91 Beach, 2003; de Bakker *et al.*, 2016). This can be explained by the fact that the larger waves in a group
92 entrain the most sand, i.e., the suspended load is in phase with the wave group envelope, while the cross-
93 shore velocity associated with the bound long wave is in anti-phase with the envelope, thereby leading
94 to a net offshore-directed long-wave transport (Shi & Larsen, 1984; Sato, 1992; Deigaard *et al.*, 1999).
95 Since the magnitude of the long-wave transport depends on the phase coupling between SSC and the
96 wave group envelope, insights into sediment pumping mechanisms contribute to an improved
97 understanding of wave group effects on beach morphology.

98 Measurements by O'Hara Murray *et al.* (2012) suggest that wave group characteristics such as shape
99 and duration could significantly affect the SSC dynamics. Except for the small-scale study by Sato
100 (1992), the aforementioned studies on suspension under wave groups involved (repeating sequences of)
101 random waves. Consequently, these studies did not allow a systematic and quantitative investigation of
102 how the key characteristics of wave groups affect SSC dynamics and net suspended transport rates.
103 Therefore, the present study aims to extend insights into the effects of wave group shape and duration
104 on suspended sand transport dynamics and transport. The research objective is firstly to inter-compare
105 suspended sand transport processes and net fluxes for non-breaking wave groups with similar offshore
106 wave statistics. A second research objective is to study the equivalence in suspended sand transport
107 dynamics between the wave groups and monochromatic waves.

108 The research approach consists of large-scale wave flume experiments involving non-breaking waves
109 that propagate over a horizontal, medium-sand test section. The measurements and analyses focus on
110 bedform dimensions, spatial and temporal SSC distributions, and net suspended sand fluxes. These
111 features are studied for five bichromatic wave group conditions, with similar wave group energy and
112 short-wave period, and three 'equivalent' monochromatic wave conditions.

113 The text is organised as follows. Section 2 describes the experiment and the data treatment. Section 3
114 presents the measured hydrodynamics, followed by an analysis of the measured bedforms in Section 4.

115 Section 5 presents the suspended sand concentration and sand flux measurements. The results are
116 discussed in Section 6 and Section 7 presents the main conclusions of this study.

117

118 **2 Methodology**

119 **2.1 Experimental description**

120 The experiments were conducted in the 100 m long, 3 m wide and 5 m deep CIEM wave flume at the
121 Universitat Politècnica de Catalunya in Barcelona. Figure 1 illustrates the experimental set-up. The
122 water depth h_0 near the wedge-type wave paddle was 2.65 m. The experiment involved a mobile bed
123 section consisting of medium sand (median diameter $D_{50} = 0.24$ mm; $D_{10} = 0.15$ mm, $D_{90} = 0.37$ mm;
124 $D_{90}/D_{10} = 2.5$) with a measured mean settling velocity $w_s = 0.034$ m/s. Based on the measured geometric
125 mean of moments ($\sigma_g = 1.36$), the sand is classified as ‘well sorted’ (Blott and Pye, 2001). The initial
126 bed profile consisted of a 1:10 offshore slope, followed by a 20 m long and 1.35 m high horizontal test
127 section. The shoreward side of the test section was enclosed by a fixed beach, consisting of sand covered
128 with geotextile and perforated concrete slabs that promoted wave energy dissipation. Throughout the
129 paper, the horizontal coordinate x is defined positively shoreward from the wave paddle in its lowest
130 position, the vertical coordinate z is defined positively upward from the still water level, and the vertical
131 coordinate $\zeta = z - z_{\text{bed}}$ is defined positively upward from the instantaneous local bed level.

132

133 **2.2 Measurements**

134 The water surface elevation η was measured at 13 cross-shore locations using resistive wave gauges
135 (RWGs) deployed from the flume side-walls (Figure 1). At eight additional locations, pressure
136 transducers (PTs) were deployed from the flume side-walls, and another PT was deployed from the
137 mobile frame. The water surface elevation was retrieved from these pressure measurements after
138 correcting for pressure attenuation using linear wave theory (following Guza & Thornton, 1980). All
139 RWG and PT measurements were sampled at a data rate $f_s = 40$ Hz.

140 Flow velocities, suspended sand concentration, and bedform geometry were measured with instruments
141 deployed from a measurement frame that was attached to a carriage at the top of the flume. The frame
142 could be vertically repositioned with sub-mm accuracy using a spindle, and was ‘alongshore’-centred
143 between the flume side-walls. More details on this ‘mobile frame’ can be found in Ribberink *et al.*
144 (2014). The frame was positioned near the middle of the horizontal test section (at $x = 58.5$ m). Figure
145 2 shows a photograph of the instrument arrangement on the frame.

146 Cross-shore and vertical velocities u , w were recorded at $f_s = 100$ Hz using a Nortek ADV-Vectrino,
147 deployed from the mobile frame at free-stream elevation $\zeta = 0.16$ m and $x = 58.4$ m. Vertical profiles of
148 the time-dependent SSC were obtained with a multi-frequency AquaScat acoustic backscatter sensor
149 (ABS). The ABS measured at acoustic frequencies of 2.0, 3.0 and 4.0 MHz, was deployed from the
150 mobile frame at elevation $\zeta = 0.82$ m and cross-shore location $x = 58.5$ m, and sampled with 5 mm
151 vertical bin size resolution. The ABS measured the instantaneous backscattered signal at $f_s = 64$ Hz. The
152 inversion from acoustic backscatter intensity profiles to SSC is explained in Section 2.5.

153 Additional measurements of the time-averaged SSC were obtained with a Transverse Suction System
154 (TSS), consisting of seven stainless-steel nozzles, each connected through plastic tubing to a peristaltic
155 pump on top of the flume. The nozzles had an intake diameter of 3 mm and an intake velocity of 2.3
156 m/s, which is approximately twice the maximum orbital velocity and therefore ensures a constant
157 sediment trapping efficiency (c.f. Bosman *et al.*, 1987). TSS sampling was started after one minute of
158 wave action, when SSC reached a semi-equilibrium state (as confirmed by the ABS measurements).
159 Suction samples were collected in 15 litre buckets, weighed and carefully drained to remove excess
160 water, and then dry-weighed to determine the sand concentration. The obtained concentrations were
161 corrected for the nozzles’ trapping efficiency following Bosman *et al.* (1987). The uncertainty in TSS
162 concentration measurements due to the processing procedures was estimated to be about 10%.
163 Variability in the vertical elevation of nozzles above the evolving bed introduces a further measurement
164 uncertainty. The TSS design and procedures are explained in more detail in van der Zanden *et al.* (2017).
165 The grain size distribution of each dry-weighed sample was measured with a laser-diffraction particle
166 sizer (Beckman Coulter LS 13 320).

167 Bedform geometry was measured with an acoustic sand ripple profiler (SRP), consisting of a 2 MHz
168 disc transducer mounted on a stepper motor, assembled in a waterproof aluminium and PVC housing
169 (Bell & Thorne, 1997b, 1997a; Bell *et al.*, 1998). The transducer has a conical beam pattern of 1.1° and
170 the motor has a 0.9° step size. The SRP was deployed from the mobile frame at $x = 59.1$ m and $\zeta = 0.81$
171 m. For the chosen settings, the SRP measured with a 0.6 mm along-beam bin resolution and over a 120°
172 swathe, corresponding to a bed level transect covering 1.8 m with horizontal resolution $\Delta x \approx 0.01$ m in
173 cross-shore direction and 0.6 to 1.2 mm in vertical direction. In continuous measuring mode,
174 approximately three scans per minute were collected.

175

176 **2.3 Wave conditions**

177 Five wave group and three monochromatic wave conditions were generated. The wave group conditions
178 comprised three bichromatic cases ('groups bichromatic', GB1, GB2 and GB3) and two sawtooth-
179 modulated wave groups ('groups modulated', GM1 and GM2) as summarised in Table 1 and shown in
180 Figure 3. Each wave group had the same root-mean-square (rms) water surface elevation η_{rms} and mean
181 short wave period T_m .

182 The three bichromatic conditions (GB1, GB2 and GB3) were generated from two short wave
183 components with frequencies f_1, f_2 and wave heights H_1, H_2 with a difference in frequency such that the
184 group contained an integer number of half cycles. Table 1 presents the frequencies and wave heights of
185 the bichromatic wave components. Conditions GB1 and GB2 are both fully modulated with $H_1 = H_2 =$
186 0.30 m, but condition GB2 is of shorter duration ($T_{\text{gr}} = 6.5T_m$) than GB1 ($T_{\text{gr}} = 9.5T_m$). Condition GB3
187 was generated from the same frequency components f_1, f_2 as condition GB1, but with different wave
188 heights for each component ($H_1 \neq H_2$) resulting in a partially modulated group.

189 In addition, two 'asymmetric groups' (GM1 and GM2) were generated by modulating a regular sine
190 wave time-series (short wave period $T_m = 4.4$ s, wave height $H = 0.30$ m) with a longer sawtooth-shaped
191 wave signal that was based on Malarkey and Davies (2012), i.e.:

$$\eta(t) = A(t) \frac{H}{2} \sin\left(\frac{2\pi t}{T_m}\right) \quad (1),$$

192 with

$$A(t) = 1 + \frac{\arctan\left(\frac{b \sin\left(\frac{2\pi t}{T_{gr}}\right)}{1 - b \cos\left(\frac{2\pi t}{T_{gr}}\right)}\right)}{\arctan\left(\frac{b}{\sqrt{1 - b^2}}\right)} \quad (2),$$

193

194 in which $T_{gr} = 44.0$ s is the group period and $b = 2\beta - 1$, where the factor β describes the degree of
 195 forward or backward leaning ('sawtoothiness'). A backward leaning 'waxing' group corresponds to $\beta <$
 196 0.5 , while $\beta > 0.5$ produces a forward leaning 'waning' group. For conditions GB1 and GB2, waxing
 197 and waning wave groups were produced by selecting $\beta = 0.2$ and 0.8 , respectively (Figure 3d,e).

198 Experiments were also conducted for three monochromatic wave conditions (M1, M2, M3). These
 199 experiments were designed to be 'equivalent' to the corresponding grouped wave conditions at the
 200 horizontal test section (Table 1). All wave conditions were generated by the wedge-type wave paddle
 201 using steering signals based on first-order wave theory.

202

203 **2.4 Experimental procedure**

204 Each wave group experiment consisted of five consecutive 35-minute runs. Prior to each experiment,
 205 the flume was drained, bedforms were flattened out, and the bed profile shown in Figure 1 was restored.
 206 Table 1 indicates what was measured (SRP, ABS, TSS) during each run. Because the SRP interfered
 207 with the 2 MHz ABS transducer, no simultaneous SRP and ABS measurements were collected. Single
 208 bedform scans with SRP were collected after each run; continuous scans were obtained during the 1st
 209 and 3rd run only for each condition. The continuous SRP data indicated that bedforms reached a quasi-
 210 equilibrium state after about 15 minutes, which is well within the duration of the 35-min run. ABS

211 measurements were therefore collected during every 2nd, 4th and 5th run. TSS samples were collected
212 during every 2nd and 4th run.

213 The monochromatic wave experiments also started from a restored bed profile. The duration of each
214 monochromatic run was 22 min. Three runs were conducted for condition M1 and M2 and two runs for
215 condition M3. Because of time constraints and because bed changes during these short runs were minor,
216 the bed profile was not restored after each condition and the eight runs were instead conducted
217 successively. SRP scans were collected after each run, and additional continuous scans were collected
218 during the first run of conditions M1 and M2. The ABS measured during all other runs, but only the
219 final run for each condition is used in the analysis to ensure that bedforms were adjusted to the wave
220 condition. TSS samples were collected during the last run of each monochromatic condition.

221

222 **2.5 Data processing**

223 For the wave group conditions, the wave group envelope $\eta_{\text{env}}(t)$ was calculated based on the measured
224 water surface elevations. The upper and lower envelopes ($\eta_{\text{env, upper}}(t)$, $\eta_{\text{env, lower}}(t)$) were calculated by
225 cubic interpolation of the maximum and minimum water surface displacements for each short wave in
226 the $\eta(t)$ time series. The envelope $\eta_{\text{env}}(t)$ was then calculated as $\eta_{\text{env}}(t) = \eta_{\text{env, upper}}(t) - \eta_{\text{env, lower}}(t)$.

227 Spurious ADV measurements were identified using minimum criteria for the signal-to-noise ratio
228 criterion (15 dB) and correlation (50%). Spurious velocity measurements were removed from the time
229 series and were not replaced.

230 The radial-coordinate SRP backscatter was transformed to a regular grid using a triangular-based linear
231 interpolation algorithm. Following O'Hara Murray *et al.* (2011), the bed level was defined as the level
232 where the product of the backscatter and the gradient of the backscatter was maximum. The vertical
233 accuracy of the SRP bed level measurements is approximately 5 mm (Thorne *et al.*, 2002). Bedform
234 dimensions were quantified by identifying the crests and troughs of each bedform. The bedform length
235 λ_r is defined as the cross-shore distance between two troughs. The bedform height Δ_r is defined as the
236 maximum crest height relative to the mean of the two adjacent troughs.

237 The acoustic backscatter was converted to concentration C using the implicit iterative routine described
 238 by Thorne and Hurther (2014). The inversion routine was improved by accounting for vertical variations
 239 in median grain diameter based on the TSS measurements (Appendix A). The system constant \mathfrak{R} of each
 240 ABS frequency transducer was calibrated using the TSS measurements of the time-averaged SSC. This
 241 calibration was done, per transducer, using all collected ABS and TSS data. For each transducer, a single
 242 value of \mathfrak{R} was established and applied for the inversion of all runs. Similar to the SRP data, the bed
 243 level under each ABS transducer was obtained as the elevation where the product between backscatter
 244 and vertical gradient of the backscatter was maximum.

245 For the wave group conditions, the time series of water surface elevation, velocity, and SSC were
 246 decomposed into a low-frequency (long wave, annotated with subscript ‘lf’) and a high-frequency (short
 247 wave, annotated ‘hf’) component by applying an 8th-order Butterworth filter with 1/16 Hz cut-off
 248 frequency. This cut-off frequency was selected as it is approximately equal to $2/(T_m + T_{gr})$ for the shortest
 249 wave group (GB2), hence it correctly separates the short- and long-wave frequencies.

250 Time series of SSC profiles measured by ABS indicated that, for all conditions, it took about one minute
 251 before the suspended sand was vertically mixed over the 0.82 m depth. For this reason, data
 252 corresponding to the first minute were discarded. Phase-averaged quantities were then computed over
 253 the remainder of each run, corresponding to about 50 to 70 wave group repeats for the wave group
 254 conditions and about 250 repeats for the monochromatic wave conditions. Phase-averaged quantities are
 255 denoted with angular brackets and were computed, here for SSC, through:

$$\langle C(\zeta, t) \rangle = \frac{1}{N} \sum_{n=0}^{N-1} C(\zeta, t + nT) \quad 0 \leq t < T \quad (3),$$

256
 257 where T is equal to the wave period for the monochromatic waves and equal to the group period for the
 258 wave groups. All phase-averaged quantities are phase-referenced such that $t/T = 0$ corresponds to the
 259 local beginning of the wave (group) cycle. Time-averaged quantities are denoted with an overbar.
 260 Periodic quantities are denoted with a tilde, e.g., the periodic or orbital velocity $\tilde{u} = \langle u \rangle - \bar{u}$.

261 During each run, typically two to three sand ripples migrated below the measurement instrumentation.
 262 Observations of the bed when the flume was drained revealed an irregular three-dimensional bed
 263 morphology. For this reason, the data were bed-averaged by transforming the vertical profiles of ABS
 264 concentration to local bed level coordinates (i.e., from $C(z)$ to $C(\zeta)$, with $\zeta = 0$ corresponding to the
 265 instantaneous bed level) prior to phase-averaging. This means that the spatial variability of SSC over
 266 bedforms, as demonstrated by previous studies (Nakato *et al.*, 1977; Fredsøe *et al.*, 1999; Thorne *et al.*,
 267 2003; van der Werf *et al.*, 2007; Hurther & Thorne, 2011), is not considered in the present study. The
 268 irregularity of bedforms affects especially the time-dependent concentrations and net sand flux
 269 measurements at $\zeta/\Delta_r < 3$, which depend strongly on the phase of a migrating bedform (van der Werf *et al.*,
 270 *et al.*, 2007; Hurther & Thorne, 2011). The time-averaged suspended sand concentration, on the other
 271 hand, can be assumed to be well converged as its variation with bedform phase is minor (Hurther &
 272 Thorne, 2011).

273

274 **3 Hydrodynamics**

275 The phase-averaged water surface elevation η and free-stream horizontal velocity u at cross-shore
 276 location $x = 58.5$ m are shown in Figure 4 (bichromatic groups GB1-3), Figure 5 (sawtooth-modulated
 277 groups GM1-2) and Figure 6 (monochromatic waves M1-3). Table 2 presents an overview of the main
 278 water surface and velocity parameters for all conditions. The velocity skewness $Sk(\tilde{u})$ was calculated
 279 from the orbital velocity as follows

$$Sk(\tilde{u}) = \frac{\overline{\tilde{u}(t)^3}}{\overline{\tilde{u}(t)^2}}^{3/2} \quad (4).$$

280

281 The orbital excursion diameter d_0 is commonly defined as the trajectory covered by a water parcel during
 282 one wave half cycle, i.e., d_0 equals the time-integral of the orbital velocity \tilde{u} over a half cycle. From the
 283 latter, it follows that the mean excursion diameter for irregular waves can be calculated through:

$$d_0 = \frac{1}{2N_w} \int_0^{T_{(gr)}} |\langle \tilde{u}(t) \rangle| dt \quad (5),$$

284 with N_w is the number of short waves in the wave group ($N_w = 1$ for monochromatic waves). In addition,
 285 the maximum orbital excursion diameter $d_{0,max}$ was derived by time-integrating $\langle \tilde{u} \rangle$ over each wave half-
 286 cycle and taking the maximum.

287 All wave group conditions GB and GM were similar in terms of η_{rms} , \tilde{u}_{rms} , and d_0 (Table 2). The relatively
 288 small variability between conditions can be attributed to the differences in total wave energy dissipation
 289 between the wave paddle and the test section. For all wave group conditions, the time-averaged free-
 290 stream velocity \bar{u} is offshore-directed and is of small magnitude compared to the maximum onshore and
 291 offshore orbital velocity. At intra-group time scale the wave groups differ significantly, which can for
 292 instance be seen in the maximum and minimum water elevation, $\langle \eta \rangle_{max}$, $\langle \eta \rangle_{min}$, and the maximum cross-
 293 shore velocity in onshore and offshore direction, $\langle u \rangle_{max}$, $\langle u \rangle_{min}$. From the GB conditions, the shortest-
 294 duration bichromatic group GB2 contains the highest short wave and produces the flow with highest
 295 onshore velocity and highest velocity skewness (Figure 4, Table 2). The two GM conditions are similar
 296 in terms of H_{max} , $\langle u \rangle_{max}$ and $\langle u \rangle_{min}$ (Table 2), but the timing of the highest wave within the group is
 297 different (Figure 5). The sawtooth modulation further leads to higher $d_{0,max}$ for the GM conditions
 298 relative to GB.

299 Note that the beach was too steep for complete dissipation of the incident short and long waves and that
 300 the wave paddle did not feature active wave absorption. In order to assess any effects of spurious incident
 301 and reflected long waves, the phase behaviour of the low-pass filtered water surface $\langle \eta_{lf} \rangle$ and velocity
 302 $\langle u_{lf} \rangle$ are examined (Figure 4 and Figure 5, dashed black lines). Figures 4a and 5a reveal that the trough
 303 of the long wave $\langle \eta_{lf} \rangle$ occurs around $t/T_{gr} = 0.60$ to 0.75 , corresponding to a phase lag of 0.2π to 0.5π
 304 with respect to the short-wave envelope. This phase lag of the bound long wave is typical for shoaling
 305 wave groups and the magnitude of the observed phase lag is similar to previous observations (Janssen
 306 *et al.*, 2003; Battjes *et al.*, 2004; Padilla & Alsina, 2017). The low-frequency velocity $\langle u_{lf} \rangle$, on the other
 307 hand, is maximum in offshore direction under the highest short waves (Figures 4b and 5b), consistent
 308 with equilibrium theory of Longuet-Higgins and Stewart (1962). Based on the agreement with previous

309 studies, the effects of spurious incident and reflected free long waves on the hydrodynamics are expected
310 to be minor and sand transport is considered to be largely controlled by the velocity forcing associated
311 with the incident short and the bound long waves.

312 The measured water surface elevation and velocity for the monochromatic cases are shown in Figure 6
313 and the corresponding hydrodynamic parameters are summarised in Table 2. Conditions M1 to M3 are
314 characterised by a progressively increasing wave height, which leads not only to an increase in d_0 and
315 magnitudes of $\langle u \rangle_{\max}$ and $\langle u \rangle_{\min}$ but also to increasing return current magnitude and velocity skewness.
316 The approximate equivalence with the corresponding grouped wave conditions follows from Table 2:
317 condition M1 is equivalent to all GB and GM conditions in terms of η_{rms} ; M2 is equivalent to GB1 in
318 terms of H_{\max} ; M3 is equivalent to GB2, GM1, and GM2 in terms of H_{\max} . Note, however, that the
319 equivalence in terms of velocity is limited. Most importantly, the monochromatic cases M2 and M3
320 have higher \tilde{u}_{rms} and $Sk(\tilde{u})$, and consequently, higher d_0 and $\langle u \rangle_{\max}$ than their GB and GM equivalents.

321 **4 Bedforms**

322 Sand suspension processes are strongly controlled by bedforms. Visual inspection of the bed after
323 draining the flume revealed the formation of three-dimensional irregular sand ripples for all wave
324 conditions. Table 3 presents the sand ripple dimensions which were extracted from the SRP
325 measurements after each experimental run. Ripple migration speeds c_r were established from continuous
326 SRP measurements for all conditions except M3. The relatively high standard deviations reflect the
327 irregularity of the bedforms. For reference, Table 3 lists the non-dimensional velocity forcing parameters
328 d_0/D_{50} and $\psi_{\max} = \langle u \rangle_{\max}^2 / ((s - 1)gD_{50})$, where $s = 2.65$ is the specific gravity of sand and g is the
329 gravitational acceleration.

330 The GB and GM conditions produce ripples with a height $\Delta_r \approx 0.015$ m, length $\lambda_r \approx 0.20$ m, and steepness
331 $\Delta_r/\lambda_r \approx 0.07$. The differences in ripple dimensions between the various wave group conditions are small
332 and within the measurement uncertainty. The monochromatic waves (M1-3) produce ripples that have
333 a similar steepness but that are slightly higher and longer ($\Delta_r \approx 0.02$ to 0.03 m; $\lambda_r \approx 0.25$ to 0.57 m)

334 compared to the wave group conditions. This likely relates to the higher flow excursion diameter d_0 for
335 the monochromatic waves relative to the wave groups.

336 The non-dimensional bedform heights and lengths can be used to classify the ripples. Ripples can be
337 classified as ‘orbital’ (when λ_r is proportional to d_0), ‘suborbital’ (when λ_r is inversely proportional to
338 d_0), and ‘anorbital’ (when λ_r is independent of d_0) (Clifton & Dingler, 1984). The increasing ripple size
339 for condition M1 to M3 suggests that bedforms scale with d_0 and are therefore in an orbital ripple regime.
340 Note that the widely applied classification by Wiberg and Harris (1994) would predict ripples in a
341 suborbital range for the present flow and sediment conditions ($1800 < d_0/D_{50} < 5500$). However,
342 O'Donoghue *et al.* (2006) showed that the orbital regime may extend to $d_0/D_{50} > 1800$ for full-scale
343 laboratory experiments.

344 The ripple steepness has a large effect on suspended sand transport. For sufficiently steep ripples, flow
345 separation will occur during each half-cycle, leading to the formation of sediment-laden vortices that
346 contribute significantly to sand pick-up (Bagnold, 1946). This vortex ripple regime occurs for ripples
347 with Δ_r/λ_r higher than 0.10 to 0.15 (Clifton & Dingler, 1984; Malarkey & Davies, 2002). The ripples in
348 the present experiment (Table 3) do not exceed this threshold, on average. Such more gentle ripples
349 have been termed ‘post-vortex ripples’ (Clifton & Dingler, 1984), and ‘dynamically plane’ beds (Davies
350 & Villaret, 2002); the term ‘post-vortex ripples’ is adopted in the present study. The vertical transfer of
351 momentum and suspended sand grains over post-vortex ripples is due to turbulent diffusive processes
352 rather than organised vortices (Davies & Villaret, 2002; Amoudry *et al.*, 2016) and the sand pickup rate
353 is lower than over a vortex rippled bed (O'Hara Murray *et al.*, 2011; Davies & Thorne, 2016). Note that
354 12% of the measured irregular ripples have a steepness higher than 0.10 and could thus be classified as
355 vortex ripples.

356 On the basis of measurements in oscillatory flow tunnels and wave flumes, O'Donoghue *et al.* (2006)
357 presented the following empirical relations for ripple dimensions as function of mobility number ψ :

$$\frac{\Delta_r}{d_0} = \frac{\alpha_{3D}}{2} (0.275 - 0.022\psi^{0.42}) \quad (6)$$

$$\frac{\lambda_r}{d_0} = \frac{\beta_{3D}}{2} (1.97 - 0.44\psi^{0.21}) \quad (7).$$

358 Here, the empirical constants $\alpha_{3D} = 0.55$ and $\beta_{3D} = 0.73$ account for the smaller dimensions of 3D ripples
 359 compared to 2D ripples (see, e.g., Sato *et al.*, 1988; O'Donoghue *et al.*, 2006). Following O'Donoghue
 360 *et al.* (2006), the mobility number ψ is for regular waves based on the maximum velocity and for
 361 irregular waves on the mean of the highest one tenth peak velocity.

362 Figure 7 shows a quantitative comparison between the measured and predicted 3D ripple heights and
 363 lengths. The measured ripple heights and lengths correlate positively with ψ , which confirms that the
 364 ripples are in an orbital regime. The model and data agree reasonably well in terms of ripple height and
 365 length: the data corresponding to the wave groups and to condition M1 are within the $\pm 50\%$ bands,
 366 which is the typical accuracy of the formula (see O'Donoghue *et al.*, 2006). The monochromatic
 367 conditions M2 and M3 produce ripples that are higher and longer than predicted. O'Donoghue *et al.*
 368 (2006) indicated that their formula is applicable for $\psi \leq 190$ and that the model uncertainty is largest for
 369 3D ripples at high mobility, which likely explains the discrepancy between measurements and
 370 predictions for conditions M2 and M3.

371 Bedform migration speeds c_r were quantified from the continuous bed level scans by comparing the start
 372 and end position of individual ripple crests for each run. Values of c_r are defined positively shoreward
 373 and are included in Table 3. Note that only few ripples could be tracked during an entire run, which
 374 explains the relatively high measurement uncertainty. It follows that ripples migrated onshore for all
 375 conditions, with slightly higher migration speeds for the regular waves than for the grouped waves.

376 **5 Suspended sand**

377 This section investigates the vertical and temporal distributions of suspended sand concentration
 378 (Sections 5.1 to 5.3), the net suspended flux distributions (Section 5.4) and net suspended sand transport
 379 rates.

380

381 5.1 Suspended sand concentration time series

382 This section presents time series of the phase-averaged suspended sand concentration (SSC). The
383 vertical mixing of suspended sand typically scales with the ripple height (Nielsen, 1984; van Rijn, 1993).
384 In order to facilitate comparisons between the different conditions and with other studies, the vertical
385 coordinate ζ is normalised by the mean ripple height Δ_r for each condition.

386 Figure 8 shows the phase-averaged SSC for the monochromatic conditions. Figure 8a-c shows the
387 concentration field as a colour contour; Figure 8d-f shows the concentration time series at $\zeta = \Delta_r$, which
388 can be expected to relate closely to the pick-up of sediment from the bed. For each condition, SSC
389 decreases strongly with distance from the bed: from $C = 10 \text{ kg/m}^3$ close to the bed ($\zeta/\Delta_r < 1$) to 0.1 kg/m^3
390 at $\zeta/\Delta_r \approx 5$. These magnitudes match closely to observations by Hurther and Thorne (2011) in the same
391 experimental facility and for the same sediment. The concentrations at $\zeta = \Delta_r$ differ notably between the
392 conditions, with two pickup events for M1, three pickup events for M2 and one main pickup event for
393 M3 (events indicated by arrows in Figure 8d-f). These differences are partly attributed to differences in
394 bedform dimensions, as explained in what follows.

395 For condition M1 (Figure 8a), SSC between $\zeta/\Delta_r \approx 1$ and 5 reveals two intra-wave peaks, corresponding
396 to two main pickup events that are indicated by the arrows in Figure 8d. The highest pickup event occurs
397 during crest-to-trough flow reversal at $t/T = 0.35$. The entrained sediment spreads gradually upward to
398 yield the main SSC peak at $\zeta/\Delta_r \geq 3$ during the trough half-cycle ($t/T = 0.80$) (Figure 8a). A second,
399 smaller, pickup event occurs during maximum negative velocity at $t/T = 0.85$ (Figure 8d). The entrained
400 sand associated with the trough-phase pickup, in combination with sand that has remained into
401 suspension, is spread upward during the trough-to-crest flow reversal and produces the main suspension
402 peak during the crest phase at $\zeta/\Delta_r \geq 3$ (Figure 8a). The ‘lifting’ of the concentration field between $t/T =$
403 0.9 and 0.2 in the next wave cycle is partly attributed to suspended sand advection by the upward-
404 directed orbital flow under the wave front.

405 Condition M2 induces three intra-wave suspension events (Figure 8e; $t/T = 0.18, 0.58, \text{ and } 0.85$). Similar
406 observations of three or more intra-wave suspension peaks were reported by van der Werf *et al.* (2007)

407 over vortex ripples with similar d_0/λ_r . Following the explanation by van der Werf *et al.* (2007), the
408 suspension events at $t/T = 0.18$ and 0.58 are associated with vortex formation around the negative-to-
409 positive and the positive-to-negative flow reversal, respectively, while the third suspension peak at t/T
410 $= 0.85$ might relate to the horizontal advection of a sediment-laden vortex that was generated at the
411 neighbouring ripple. Note that bedforms for conditions M1 and M2 were both qualified as post-vortex
412 ripples, but ripple heights are considerably higher for M2 (Table 3). The latter may explain the
413 qualitative agreement of the suspension events for condition M2 with observations over vortex ripples.

414 Condition M3 produces one main intra-wave pickup event that occurs shortly after the crest-to-trough
415 flow reversal ($t/T = 0.38$), leading to maximum concentrations during the early stage of the trough half
416 cycle (Figure 8c,f). The pickup during the trough half cycle is minor, although a small increase in C can
417 also be observed around the trough-to-crest half cycle ($t/T \approx 1.0$). Note that for this condition, bedforms
418 are longer and less steep than for conditions M1 and M2 (Table 3), hence reducing the tendency of flow
419 separation and vortex-induced suspension to occur (e.g., Osborne and Vincent, 1996). The transport is
420 likely confined to a very thin near-bed layer during most of the wave cycle and the threshold for
421 suspension is only exceeded during the crest phase, when the velocity is maximum.

422 Comparison of SSC distributions for conditions M1 to M3 (Figure 8a-c) shows that the $C = 0.1 \text{ kg/m}^3$
423 isoline progressively reaches higher intra-wave elevations with increasing wave height. This indicates
424 that the vertical mixing rate at $\zeta/\Delta_r > 5$ increases with wave height. In contrast, the $C = 1$ and 10 kg/m^3
425 isolines ($\zeta/\Delta_r < 5$) are lower for M2 and M3 than for M1, which suggests a lower pickup rate. The latter
426 could be attributed to the increasing bedform length, and the consequent reduction in d_0/λ_r , from
427 condition M1 to M3 (Table 3): studies over vortex ripples have suggested a general reduction in vortex
428 strength with decreasing d_0/λ_r , with a lower limit of $d_0/\lambda_r = 1$ for flow separation and vortex suspension
429 (Malarkey & Davies, 2002; O'Hara Murray *et al.*, 2011). Although most of the present ripples are in a
430 post-vortex regime, the measurements indicate a similar trend of decreasing sand pick-up rates for
431 decreasing d_0/λ . This may partly relate to the fraction (12%, measured value) of ripples that have a
432 steepness corresponding to a vortex ripple regime.

433 Figure 9 shows the phase-averaged SSC for the grouped bichromatic (GB) waves. It is evident that SSC
434 varies both at short-wave and wave-group time scales. As the suspended load gradually builds up during
435 the wave group, the suspended load is much higher under short waves at the end of the group (e.g. t/T_{gr}
436 ≈ 0.8) than under waves with similar wave height at the start of the group ($t/T_{gr} \approx 0.2$). This illustrates
437 that SSC is not only controlled by the instantaneous wave forcing at short-wave time scale but is also
438 strongly affected by the preceding waves. This ‘sediment pumping’ is consistent with other laboratory
439 studies (Sato, 1992; Villard *et al.*, 2000; Vincent & Hanes, 2002; O’Hara Murray *et al.*, 2012).

440 The three GB conditions in Figure 9 induce a similar response in SSC at short-wave time scales: the
441 peaks in SSC due to short-duration ‘clouds’ of suspended sand near the bed ($\zeta/\Delta_r < 5$) are approximately
442 the same. However, at wave group time scale, condition GB1 shows a stronger build-up of the suspended
443 sand load toward the end of the group ($t/T_{gr} \approx 0.8$) than conditions GB2 (shorter duration) and GB3 (only
444 partially modulated). This higher build-up of the suspended load for GB2 relative to GB1 agrees with
445 field observations by Williams *et al.* (2002), who also observed the suspended sand concentration to
446 increase with the number of short waves in a group. On the other hand, at the start of the wave group
447 ($t/T_{gr} \approx 0 - 0.2$) there is more sediment settling out of suspension for condition GB1 than for GB2 and
448 GB3.

449 Figure 10 shows the phase-averaged SSC for the sawtooth-modulated GM conditions. Sediment
450 pumping is especially evident for the ‘waxing’ condition GM1, which produces a gradual build-up of
451 SSC during the wave group (Figure 10a, $t/T_{gr} = 0.2$ to 0.85). Subsequently, a relatively long period with
452 little wave action follows between $t/T_{gr} = 0.8$ and 0.1 into the next wave group ($|u| < 0.2$ m/s for
453 approximately 13 s). During this interval, most suspended sand settles out of suspension and the SSC
454 decreases to nearly 0 upon the start of the next group (Figure 10a). Compared to the symmetric group
455 GB1 (Figure 9a), the suspended load at the end of the wave group is higher for the waxing group GM1
456 (Figure 10a), hence suggesting that the latter is more effective in terms of sediment pumping. However,
457 during two subsequent wave groups the suspended sediment settles out almost completely for GM1
458 whereas it remains partly in suspension for condition GB1. Consequently, as explored in more detail in
459 Section 5.3, conditions GB1 and GM1 produce a similar time-averaged suspended sediment load.

460 The ‘waning’ condition GM2 shows fluctuations at short-wave and wave group time scales, similar to
 461 the other wave group conditions (Figure 10b). The suspended load at the end of the group ($t/T_{gr} = 0.8$)
 462 is lower for GM2 than for GM1. This suggests more effective sediment pumping for a ‘waxing’ group,
 463 where short-wave heights increase gradually and fall back rapidly, than for a ‘waning’ group. The same
 464 was concluded by O’Hara Murray *et al.* (2011) by studying SSC under random waves.

465

466 5.2 SSC phase lags

467 The phase behaviour of suspended sand is explored in more detail through the cross-correlation R
 468 between water surface level $\eta(t)$ and suspended sand concentration $C(\zeta, t)$, calculated for each condition
 469 through:

$$R(\zeta, \tau) = \frac{1}{N} \sum_{n=0}^{N-m-1} [\eta(t_n + \tau) - \bar{\eta}][C(\zeta, t_n) - \bar{C}(\zeta)] \quad (8).$$

470

471 Herein, $\Delta t = 1/64$ s is the temporal resolution of ABS measurements; $\tau = m\Delta t$ is a time displacement; t_n
 472 is the time index corresponding to the integer n ; N is the number of measurements in the time series.
 473 Cross-correlations are calculated for both the short waves and the wave groups. For the latter, the short-
 474 wave envelope of the water surface elevation, η_{env} , was considered to be the most suitable parameter for
 475 analysing the phase behaviour of SSC. For consistency, the water surface elevation (rather than the
 476 velocity) was also used for the calculations of R for the monochromatic waves. Equation (8) was
 477 evaluated using $\eta(t)$ measurements by the pressure transducer on the measurement frame, which were
 478 linearly interpolated to the same temporal resolution as the ABS data ($f_s = 64$ Hz).

479 The cross-correlation results provide insights into the phase lag of SSC with respect to the water surface
 480 elevation. Positive $R(\zeta, \tau)$ indicates that SSC at height ζ and time lag τ is in phase with η ; negative $R(\zeta,$
 481 $\tau)$ indicates that $C(\zeta)$ at time lag τ is in anti-phase with η . Of particular interest is the time displacement
 482 $\tau_{max}(\zeta)$ that corresponds to maximum $R(\zeta)$: this time displacement, normalised by the wave period (i.e.,
 483 $\tau_{max}(\zeta)/T$), represents the phase lag of $C(\zeta)$ relative to the water surface elevation. An additional

484 parameter of interest is the cross-correlation at zero phase lag, $R_0(\zeta) = R(\zeta, \tau = 0)$. Note that $R_0(\zeta) > 0$
485 indicates that $C(\zeta)$ is in phase with the water surface elevation, i.e., highest SSC under the wave crest,
486 while $R_0(\zeta) < 0$ indicates that SSC is maximum under the wave trough.

487 Figure 11 shows the cross-correlations for the monochromatic conditions M1 to M3 (top to bottom).
488 The left-hand panels show $R(\zeta, \tau)$ as colour contours, with the white circles in each panel indicating the
489 phase lag $\tau_{\max}(\zeta)/T$. To avoid false identification of phase lags, τ_{\max} values were truncated for $R < 0.01$
490 kg/m^2 . The right-hand panels show the R_0 profiles. Note that the phase behaviour of sand suspension
491 close to the bed ($\zeta/\Delta_r < 3$) is strongly affected by the phase of local bedforms (van der Werf *et al.*, 2007;
492 Hurther & Thorne, 2011), hence leading to an increased uncertainty in the cross-correlation results at
493 these elevations.

494 Figure 11a shows the vertical distribution of the phase lag for condition M1 (solid white circles). At the
495 bed, $\tau_{\max}/T \approx 0.1$ indicates that sediment pickup lags the water surface elevation by about $0.1T$. τ_{\max}
496 increases gradually with distance from the bed as the entrained sediment spreads vertically. At $\zeta/\Delta_r \approx 2$,
497 the phase lag experiences a sudden, rapid increase from $\tau_{\max}/T \approx 0.2$ to 0.6 . This phase behaviour suggests
498 that SSC is almost in phase with η at $\zeta/\Delta_r < 2$ but SSC lags η by more than half a wave cycle at $\zeta/\Delta_r > 2$.
499 This may be explained by two vertically separated mixing regimes: a near-bed ‘convective’ mixing
500 regime where coherent turbulent structures induce rapid vertical mixing (here found at $\zeta/\Delta_r < 2$) and a
501 more gradual ‘diffusive’ mixing regime at higher elevations (which dominates in the present experiment
502 at $2 < \zeta/\Delta_r < 5$) (see also Nielsen, 1992; Thorne *et al.*, 2002).

503 The strong variation of SSC phase lags with height leads to a complex R_0 profile (Figure 11b), composed
504 of a three-layer structure with alternating positive and negative constituents that respectively correspond
505 to SSC that is on average in phase and in anti-phase with the water surface elevation. Very close to the
506 bed ($\zeta/\Delta_r < 1$), positive R_0 suggests that SSC is approximately in phase with the water surface elevation.
507 Further from the bed, at $1 < \zeta/\Delta_r < 4$, negative R_0 corresponds to the highest SSC occurring during the
508 troughs of the waves due to a phase lag of about half a wave cycle. At even higher elevations ($\zeta/\Delta_r > 4$),
509 R_0 is positive again (although of small magnitude), corresponding to slightly higher SSC during the

510 wave crest relative to the trough phase. The strong vertical variation of the phase behaviour of SSC with
511 elevation, as reflected in $R_0(\zeta)$, shows that the local flux measured at a free-stream elevation of a few
512 ripple heights above the bed can be a poor predictor for the magnitude and direction of the net depth-
513 integrated flux. This reaffirms previous conclusions by e.g. Conley and Beach (2003) and emphasises
514 the necessity of high-resolution measurements of SSC near the bed.

515 The cross-correlation and phase lag behaviour for conditions M2 and M3 are qualitatively similar to
516 M1, yet quantitatively different (Figure 11c-f). Condition M2 yields phase lags of $\tau_{\max}/T \approx 0.35$ at $\zeta =$
517 $3\Delta_r$ (Figure 11c), which is consistent with the timing of the three intra-wave suspension events for this
518 condition. The cross-correlation for condition M3 (Figure 11e) is dominated by the single main intra-
519 wave suspension event, which lags the water surface elevation by about 0.2 to 0.25 T . Inter-comparison
520 of τ_{\max} for M1 to M3 shows that the phase lag of SSC reduces with increasing wave height H . This
521 indicates more rapid vertical mixing, which can be explained by stronger vertical advection by the orbital
522 velocity and possibly by higher turbulence levels. The sudden vertical jump in $\tau_{\max}(\zeta)/T$ appears only for
523 M1, possibly because of a lower vortex strength for conditions M2 and M3 due to the lower d_0/λ_r (as
524 discussed in Section 5.1). Figure 11b,d,f shows that the differences in SSC phase lag are also reflected
525 in the R_0 profiles. For M2, SSC is on average in anti-phase with η (negative R_0) over a major fraction of
526 the near-bed region. For M3, $R_0 \approx 0$ at most elevations, because SSC is maximum during the crest-to-
527 trough zero crossing of the water surface elevation, i.e., when $\eta \approx 0$.

528 Next, the SSC phase lag is explored for the wave group conditions. This is done by examining the cross-
529 correlation R between water level η and SSC as before, and also by the cross-correlation R_{hf} between the
530 high-pass filtered water level (η_{hf}) and concentration (C_{hf}), and the cross-correlation R_{env} between the
531 wave group envelope (η_{env}) and low-pass filtered concentration C_{lf} .

532 Figure 12 shows the cross-correlations R , R_{hf} and R_{env} for condition GB1. The cross-correlation $R(\zeta, \tau)$
533 (Figure 12a) reveals a complex pattern with positive and negative values at short- and long-wave time
534 scales. Around $\tau = 0$, negative R generally prevails due to SSC variations at the wave group time scale:

535 the highest concentrations occur under the highest short waves, i.e., during the trough phase of the bound
536 long wave. This also explains the negative R_0 near the bed at $\zeta/\Delta_r < 2$ (Figure 12b).

537 In order to better understand the distributions in Figure 12a-b, the cross-correlations at short- and long-
538 wave frequencies R_{hf} and R_{env} were explored. R_{hf} (Figure 12c) shows patterns that are similar to the
539 monochromatic cases. Positive R_{hf} occurs near the bed around $\tau = 0$ and spreads upward with increasing
540 time displacement to $\tau/T_m \approx 0.5$ at $1 < \zeta/\Delta_r < 3$. A region of positive R_{hf} between $\zeta/\Delta_r = 1.5 - 10$ around
541 $\tau/T_m = 0$ stands out. This region is not clearly connected to the red region at $\zeta/\Delta_r < 1$, which suggests that
542 it is not induced by local sand pick-up but that it may instead be explained by suspended sand that is
543 horizontally advected. Previous studies have indicated that cross-shore advection of suspended sand
544 leads to an increase in SSC under the wave crest (Kranenburg *et al.*, 2013), which would indeed be
545 consistent with the positive $R_{\text{hf},0}$ at these elevations (Figure 12d). This advection effect is more evident
546 for condition GB1 than for the monochromatic conditions because of its relatively low wave skewness.
547 The monochromatic waves, on the other hand, are characterised by a relatively high skewness, which
548 induces a stronger intra-wave variation in SSC that dominates the calculated cross-correlation.

549 The cross-correlation at wave group frequency (Figure 12e-f) reveals positive R_{env} at $\tau/T_{\text{gr}} \approx 0$, indicating
550 highest SSC under the crest of the wave group envelope. Figure 12e (white markers) shows the phase
551 lag at the wave group frequency. The phase lag at the bed is $\tau_{\text{max}} \approx 0.1T_{\text{gr}} \approx T_m$ and it increases with
552 distance from the bed due to sediment pumping by the successive waves, yielding a value of $\tau \approx 0.2T_{\text{gr}}$
553 $\approx 2T_m$ at $\zeta \approx 8\Delta_r$. A similar magnitude and vertical distribution of the phase lag at wave group time scale
554 was measured by O'Hara Murray *et al.* (2012) for random waves.

555 Figure 13 shows the cross-correlation for the other wave group conditions. For brevity, only the cross-
556 correlation at wave group frequency R_{env} is shown. All conditions yield $R_{\text{env}}(\tau)$ and $\tau_{\text{max}}(\zeta)$ distributions
557 that are qualitatively similar to GB1. Condition GB2 results in a lower τ_{max} at the bed than the other
558 conditions, which indicates that suspended sediment pumping commences a bit earlier within the wave
559 group. Moreover, this condition produces the highest steepness $d\zeta/d\tau_{\text{max}}$ of all grouped waves, hence
560 indicating the most rapid vertical spreading of suspended sediment. This may relate to the highly skewed

561 and high short waves for GB2, which induce rapid vertical advective mixing of suspended sand. The
 562 phase lags for conditions GB1, GB3, GM1 and GM2 are similar for $\zeta/\Delta_r < 4$. At $\zeta/\Delta_r > 4$, conditions
 563 GB3 and GM2 yield higher phase lags than GB1 and GM1, hence indicating a more gradual vertical
 564 mixing of suspended sand.

565

566 **5.3 Time-averaged SSC and sediment diffusivity**

567 In equilibrium conditions, the time-averaged SSC profile $\bar{C}(\zeta)$ can be described as a balance between
 568 sand settling and upward vertical mixing. The latter can be described as a diffusive process, yielding
 569 (e.g. Nielsen, 1992):

$$w_s \bar{C} + \epsilon \frac{d\bar{C}}{d\zeta} = 0 \quad (9).$$

570 Here, ϵ is the local sediment diffusivity, which is linked to the turbulent viscosity but also includes the
 571 effects of vertical wave-related mixing (Nielsen, 1992). Another factor that controls $\bar{C}(\zeta)$ is the reference
 572 concentration C_{ref} that defines the time-averaged sediment pickup from the bed.

573 In this section, the $\bar{C}(\zeta)$ distributions are analysed and related to C_{ref} and $\epsilon(\zeta)$. Following van Rijn (2007),
 574 C_{ref} is defined:

$$C_{\text{ref}} = \bar{C}(\zeta_a) \quad (10),$$

575 where the reference level ζ_a is defined (van Rijn, 2007) as:

$$\zeta_a = \max\left(\frac{\Delta_r}{2}, 0.01 \text{ m}\right) \quad (11).$$

576 The reference concentration is directly calculated from the measurements using Equations (10) and (11).
 577 The sediment diffusivity distribution $\epsilon(\zeta)$ was obtained following the same approach as Thorne *et al.*
 578 (2009), that is, by solving Equation (9) numerically. The settling velocity $w_s(\zeta)$ was estimated with the
 579 empirical formula of Soulsby (1997), using the power-law-distributed $D_{50}(\zeta)$ (Appendix A) as input.
 580 The vertical concentration gradient in Equation (9) was calculated over two vertical concentration
 581 measurement bins for $\zeta < 0.20$ m and over four vertical bins for $\zeta > 0.20$ m.

582 For reference, predictions of $\epsilon(\zeta)$ were calculated using the empirical model of van Rijn (1993):

$$\begin{aligned}
 \epsilon &= \epsilon_{\text{bed}} = 0.012U_0\Delta_r D_{50}[(s-1)g/\nu]^{1/3} && \text{for } \zeta \leq \zeta_s \\
 \epsilon &= \epsilon_{\text{bed}} + (\epsilon_{\text{max}} - \epsilon_{\text{bed}}) \left(\frac{\zeta - \zeta_s}{0.5h - \zeta_s} \right) && \text{for } \zeta_s < \zeta \leq 0.5h \\
 \epsilon &= \epsilon_{\text{max}} = 0.035H_s h/T_m && \text{for } \zeta > 0.5h
 \end{aligned} \tag{12}.$$

583 Here, $U_0 = \sqrt{2}\tilde{u}_{\text{rms}}$ is the representative orbital velocity amplitude; $s = 2.65$ is the specific gravity of sand
 584 in water; g is the gravitational acceleration; $\nu = 10^{-6} \text{ m}^2/\text{s}$ is the kinematic viscosity; $H_s = 4\eta_{\text{rms}}$ is the
 585 significant wave height; h is the local water depth. Equation (12) predicts vertically uniform $\epsilon(\zeta)$ over a
 586 near-bed mixing layer with thickness $\zeta_s = 3\Delta_r$ that is characterised by strong vertical mixing by bed-
 587 shear-generated vortices. At higher elevations, $\epsilon(\zeta)$ increases linearly up to a maximum value ϵ_{max} at $\zeta =$
 588 $0.5h$. The diffusivity in the upper half of the water column, ϵ_{max} , represents the vertical mixing by waves.
 589 Note that the bed-averaging method (Section 2.5) differs from the treatment by Van Rijn (1993, 2007),
 590 who uses a fixed, mean bed level. Therefore, the calculations were repeated using Van Rijn's bed level
 591 definition. This alternative approach does not lead to substantially different results, except near the bed
 592 (at $\zeta < 2\Delta_r$) since Van Rijn's definition requires truncation of the SSC profiles at a higher elevation.

593 Figure 14a,c,e shows the vertical distributions of $\bar{C}(\zeta)$ measured by ABS and TSS. Both instruments
 594 yield similar concentration profiles. The variability in ζ for the TSS measurements is considered to be
 595 the largest source of measurement uncertainty. Figure 14b,d,f shows the ABS measured (symbols) and
 596 predicted (dashed lines) $\epsilon(\zeta)$ distributions, normalised by $U_0\Delta_r$ (following Thorne *et al.*, 2009). Table 4
 597 presents the measured reference concentrations and the depth-averaged diffusivities over the near-bed
 598 mixing layer. The measurement uncertainty of C_{ref} was established by shifting the reference height ζ_a by
 599 5 mm (one vertical bin of the ABS) upward and downward. The uncertainty of ϵ in Table 4 was
 600 calculated as the standard deviation over the near-bed mixing layer.

601 The three monochromatic conditions produce $\bar{C}(\zeta)$ with similar shapes but different magnitudes (Figure
 602 14a). Each profile increases exponentially (i.e. straight line on semi-log scale) near the bed (up to ζ/Δ_r
 603 ≈ 5 for M1 and $\zeta/\Delta_r \approx 3$ for M2 and M3) and is upward concave at higher elevations. Such concentration
 604 distributions are consistent with previous observations over rippled beds (Thorne *et al.*, 2002; Vincent

605 & Hanes, 2002). As explained by e.g. Thorne *et al.* (2009), the near-bed exponentially increasing $\bar{C}(\zeta)$
606 corresponds to vertically constant $\epsilon(\zeta)$, while the upward concave $\bar{C}(\zeta)$ segment indicates a linearly
607 increasing $\epsilon(\zeta)$. The measured $\epsilon(\zeta)$ distributions in Figure 14b confirm this two-layer structure, which is
608 also conceptually consistent with van Rijn's (1993) empirical model (Equation (12)).

609 Quantitatively, the three monochromatic conditions show clear differences. Firstly, the near-bed mixing
610 layer thickness ζ_s , characterised by depth-uniform diffusivity, decreases with increasing wave height: ζ_s
611 $\approx 5\Delta_r$ for M1, $\zeta_s \approx 3.5\Delta_r$ for M2, and $\zeta_s \approx 2.5\Delta_r$ for M3 (Figure 14b). Secondly, the SSC in the near-bed
612 layer decreases with increasing wave height (Figure 14a), which relates primarily to a decreasing
613 reference concentration (Table 4). The decrease in suspended load and near-bed mixing layer thickness
614 may physically relate to the reduction in d_0/λ (Table 3), as discussed in Section 5.1 and in other studies
615 (Malarkey & Davies, 2002; O'Hara Murray *et al.*, 2011).

616 Figure 14c-d shows $\bar{C}(\zeta)$ and $\epsilon(\zeta)$ for the bichromatic GB conditions. Both concentration and diffusivity
617 profiles follow similar distributions as for the monochromatic waves. The corresponding $\epsilon(\zeta)$ profiles
618 show a less abrupt transition from the near-bed mixing layer with depth-uniform ϵ to the section with
619 vertically increasing ϵ than in Figure 14b, possibly due to contribution from the varying short waves
620 within the group which smoothens the transition. In addition, the mixing layer thickness ζ_s is somewhat
621 thicker than for the monochromatic waves, which possibly relates to a gradual build-up of bed-shear-
622 generated turbulence kinetic energy under the wave groups (Villard *et al.*, 2000).

623 The three GB conditions produce $\bar{C}(\zeta)$ profiles that are nearly identical (Figure 14c). GB1 produces a
624 higher suspended sand concentration far from the bed ($\zeta/\Delta_r > 8$) but lower concentration close to the bed
625 than GB2 and GB3. This may indicate more vertical mixing, i.e., more effective suspended sediment
626 pumping, for condition GB1. However, the differences are small. The latter is also reflected in the
627 reference concentrations and near-bed diffusivity for the GB conditions, which are very similar with
628 differences within the measurement uncertainty (Table 4).

629 The SSC and diffusivity profiles for the sawtooth-modulated GM conditions (Figure 14e-f) are similar
630 to those measured during the GB conditions. Consistent with descriptions in Section 5.1, \bar{C} is higher for

631 GM1 than for GM2, hence reflecting the stronger ‘sediment pumping’ effect for GM1. The latter is also
632 revealed by the 20% higher $\epsilon/(U_0\Delta_r)$ for GM1 than for GM2 (Figure 14f, Table 4). Conditions GM1
633 (waning) and GB1 (no saw-tooth modulation) produce almost identical $\bar{C}(\zeta)$ at $\zeta/\Delta_r < 10$, but GM1
634 produces higher concentrations further from the bed (Figure 14e). This difference is especially explained
635 by the higher diffusivity at $\zeta/\Delta_r > 10$; the near-bed diffusivity is similar for GB1 and GM1 (Figure 14d,f,
636 Table 4).

637 Comparing the wave group conditions with the monochromatic conditions shows that $\bar{C}(\zeta)$ is on average
638 higher for the wave groups (Figure 14a,c,e). The wave group conditions also yield higher $\epsilon/(U_0\Delta_r)$ than
639 the monochromatic waves (Table 4). This could be attributed to sediment pumping by the groups.
640 However, this result depends strongly on the vertical scaling of elevation with ripple height and the
641 differences disappear when no scaling is applied.

642 Finally, the measured $\epsilon(\zeta)$ distributions are compared with the empirical predictions from Equation (12)
643 (Figure 14b,d,f). For all conditions, the measurements and empirical predictions both follow a three-
644 layer structure, which implies that Van Rijn’s (1993) model is likely preferable over models that assume
645 linearly increasing $\epsilon(\zeta)$ from the bed (e.g. Grant & Madsen, 1979). Two main differences between the
646 experimental observations and Van Rijn’s model are observed. Firstly, the near-bed diffusivity over $\zeta =$
647 0 to $3\Delta_r$ is overestimated for the monochromatic waves. For the present D_{50} , Equation (12) predicts
648 $\epsilon_{\text{bed}}/(U_0\Delta_r) = 0.076$ for all conditions. A comparison with the measured data in Table 4 shows that
649 $\epsilon_{\text{bed}}/(U_0\Delta_r)$ is overestimated by 20 to 70% for the monochromatic waves. Note that van Rijn’s model was
650 based on measurements for ripples with higher steepness than those in the present experiment, which
651 may explain some of the observed deviation between model and measurements. For the grouped wave
652 conditions, which produce a higher near-bed diffusivity, $\epsilon_{\text{bed}}/(U_0\Delta_r) = 0.076$ is in good agreement with
653 the measurements (Table 4).

654 A second difference between modelled and measured diffusivity is the height of the near-bed mixing
655 layer, ζ_s , which appears to exceed $3\Delta_r$, especially for the grouped wave conditions. This may not relate
656 entirely to wave group effects but also to a general uncertainty in ζ_s , since past measurements under
657 regular waves also indicated $\zeta_s > 3\Delta_r$ (Thorne *et al.*, 2009). Moreover, in a more recent version of his

658 diffusivity model, Van Rijn (2007) proposed a modification of the near-bed mixing layer thickness to ζ_s
 659 $= 2\delta_w$, where δ_w is an estimate of the wave bottom boundary layer thickness and is calculated as:

$$\delta_w = 0.214d_0^{0.75}\Delta_r^{0.25} \quad (13).$$

660 Figure 15 shows diffusivity profiles for all conditions, using different normalizations for the vertical
 661 axes. In Figure 15a the elevation is normalized by $\zeta_s = 3\Delta_r$. Significant variability in diffusivity
 662 distributions between conditions and a large discrepancy between measured and predicted diffusivity
 663 (solid line, for condition GB1) can be observed. If, instead, the elevation is normalized by $\zeta_s = 2\delta_w$, the
 664 variability between the conditions reduces significantly (Figure 15b). Moreover, the measurements show
 665 significantly better agreement with the empirical prediction when $\zeta_s = 2\delta_w$ is assumed.

666

667 **5.4 Sand flux**

668 In this section the net (i.e. time-averaged) sand flux distributions $\overline{u(\zeta, t)C(\zeta, t)}$ are explored. Because no
 669 measurements of the velocity distribution $u(\zeta, t)$ were obtained, the flux distribution is estimated here as
 670 $\overline{u(t)C(\zeta, t)}$, where $u(t)$ is the free-stream velocity at $\zeta = 0.16$ m. This means that the flux profiles do not
 671 consider the vertical variations in cross-shore velocity. This especially reduces the accuracy within the
 672 wave bottom boundary layer, where the phase and magnitude of the velocity are affected by the presence
 673 of the bed. Experiments in regular oscillatory flow showed that the phase and magnitude variations of
 674 velocity occur mainly within a thin layer of 1 ripple height above the bed (van der Werf *et al.*, 2007).
 675 For that reason, the estimated flux is truncated for $\zeta < \Delta_r$. Although the accordingly derived flux profiles
 676 may not be fully accurate, they are accepted for the primary objective in this section, which is to compare
 677 the various wave conditions in terms of net sand transport. The net flux $\overline{u_0 C}$ was decomposed as

$$\overline{u(t)C(\zeta, t)} \approx \overline{u(t)C(\zeta, t)} + \overline{\langle \tilde{u}_{hf}(t) \rangle \langle \tilde{C}_{hf}(\zeta, t) \rangle} + \overline{\langle \tilde{u}_{lf}(t) \rangle \langle \tilde{C}_{lf}(\zeta, t) \rangle} \quad (14),$$

678 where the three terms on the right-hand side define the net flux contributions by the current, the short
 679 waves, and the long (infra-gravity) wave. The turbulent diffusive flux $\overline{u' C'}$ could not be quantified on
 680 the basis of the present measurements and is not considered further.

681 Figure 16a shows the vertical distributions of the net total flux for the monochromatic conditions. Flux
682 magnitudes decrease rapidly with distance from the bed, with the strongest offshore-directed flux over
683 $\zeta/\Delta_r = 1$ to 3 for all conditions. All conditions generate small net onshore fluxes over a short segment
684 ($\zeta/\Delta_r \approx 4$ to 10 for M1; $\zeta/\Delta_r \approx 4$ to 6 for M2 and M3); at higher elevations the net total flux returns to
685 negative values. The different flux distributions for the three monochromatic conditions can be better
686 understood by analysing the contributions of the current-related flux (Figure 16b) and wave-related flux
687 (Figure 16c). The current-related flux is offshore for all conditions due to negative \bar{u} (see Table 2). The
688 magnitude and direction of the wave-related flux depend on the vertical and intra-wave temporal
689 variation of SSC. Figure 16c shows alternating offshore- and onshore-directed constituents, which relate
690 directly to the R_0 profile (Figure 11b-d-f). The wave-related fluxes at $\zeta/\Delta_r < 4$ are offshore because the
691 SSC lags the velocity by approximately half a wave cycle at these elevations. Higher up, the wave-
692 related flux is onshore because SSC is on average in phase with the water surface elevation. However,
693 these onshore flux magnitudes are much smaller because the concentration decreases rapidly with
694 distance from the bed.

695 The net fluxes for the wave group conditions are shown in Figure 17. Here, the total flux (Figure 17a)
696 was decomposed into a current-related (Figure 17b), short-wave-related (Figure 17c) and long-wave-
697 related (Figure 17d) contribution. Similar to the monochromatic conditions, the current-related
698 component is offshore-directed due to $\bar{u} < 0$. Strongest offshore current-related fluxes are produced by
699 conditions GB2 and GB3, which relate to relatively high $|\bar{u}|$ for these conditions (Table 2). The short-
700 wave-related component (Figure 17c) varies greatly between the various wave conditions. Condition
701 GB1 produces an onshore short-wave flux over $\zeta/\Delta_r = 1 - 7$, which is attributed to the low velocity
702 skewness of this condition (as explained in Section 5.2). The other conditions produce generally
703 offshore-directed short-wave-related fluxes, with greatest magnitudes for the partially-modulated
704 condition GB3.

705 Figure 17d shows the net flux by the long wave, driven by the phase coupling of SSC at the wave group
706 time scale. The long-wave flux is offshore-directed for all conditions, which agrees with previous sand
707 flux observations under non-breaking wave groups in field (e.g. Shi and Larsen, 1984) and laboratory

708 (e.g. Sato, 1992) conditions. The differences in flux magnitudes between the conditions are explained
709 by the timing of the ‘pumped’ suspended load relative to the phase behaviour of the long-wave velocity
710 $\langle \tilde{u}_{0,lf} \rangle$. For conditions GB1 and GM1, this timing leads to the greatest magnitudes of the net long-wave
711 flux.

712

713 **5.5 Net suspended sand transport rates**

714 The conditions are further compared in terms of net sand transport rates. The net depth-integrated
715 suspended transport rate q_s is calculated here as

$$q_s = \int_{\Delta_r}^{0.50} \overline{\langle u_0(t) \rangle \langle C(\zeta, t) \rangle} d\zeta \quad (15).$$

716 The upper bound of $\zeta = 0.50$ m is chosen here for pragmatic reasons as the highest elevation at which
717 the SSC measurements are considered unaffected by the mounting arrangement for the ABS transducers
718 at $\zeta = 0.82$ m. Note that the present experimental set-up does not allow quantification of sand transport
719 over the whole water column, and the accordingly obtained q_s neglects the transport contributions at $\zeta <$
720 Δ_r and $\zeta > 0.50$ m. For the objective of analysing the differences in net suspended transport rates between
721 the various wave conditions, this is considered a reasonable approach.

722

723 Figure 18 shows the net suspended sand transport rates, decomposed into current-, short-wave-, and
724 long-wave-related contributions. It directly follows that all transport components are of similar order of
725 magnitude and are therefore significant to the total suspended transport. All wave group conditions (GB
726 and GM) generate offshore-directed total q_s , yet the magnitudes differ substantially. The offshore
727 transport is relatively low for GB1 and relatively high for GB3, while the other conditions (GB2, GM1,
728 and GM2) yield approximately similar total q_s . These differences are primarily caused by variations in
729 the short-wave-related transport, which is onshore-directed for GB1 and is offshore-directed for GB3.
730 The GB and GM conditions also differ in terms of current-related and long-wave-related transport rates,
731 but these differences are small compared to those observed for the short-wave-related transport. The

732 three monochromatic conditions produce total q_s that is of similar magnitude to the wave group
733 conditions. Magnitudes of q_s increase from M1 to M2 due to an increase in suspended load with
734 increasing wave height, but decrease from M2 to M3 due to the reduced slopes of bedforms for the latter
735 condition.

736 The equivalence between the monochromatic and wave group conditions in terms of transport rates is
737 discussed in the next section.

738

739 **6 Discussion**

740 The experimental program was designed to study the differences in suspended sand concentration and
741 transport rates for various ‘equivalent’ wave groups and monochromatic conditions. The five wave
742 groups produced similar η_{rms} , \tilde{u}_{rms} , and d_0 over the test section, yet differed in terms of velocity skewness
743 $Sk(\tilde{u})$ due to variations in wave shape transformation during the shoaling process. These differences
744 complicate the interpretation of the measurements in the present experiment, especially the phase
745 behaviour of SSC at intra-wave time scale and the net short-wave-related flux, which are both strongly
746 affected by the degree of velocity skewness (see e.g. van der Werf *et al.*, 2007; Amoudry *et al.*, 2016).
747 As a result, the differences in net short-wave-related and net total transport rates between the various
748 GB conditions (Section 5.5) cannot be attributed solely to wave group shape (i.e. wave group duration
749 and degree of modulation), but also to differences in $Sk(\tilde{u})$. Consequently, the effects of wave group
750 duration and degree of modulation on intra-wave SSC and on net short-wave-related suspended sand
751 transport cannot be fully analysed on the basis of the present data, leaving this topic partly open for
752 future experimental and/or numerical research.

753 The ‘equivalent’ monochromatic conditions also deviate from the wave group conditions in some
754 respects, producing flows with higher \tilde{u}_{rms} , d_0 and $Sk(\tilde{u})$ than their wave group equivalents. An additional
755 complicating factor is that the monochromatic condition M2 and M3 produced significantly higher and
756 longer bedforms than the wave groups.

757 While taking these differences into consideration, the bichromatic wave conditions are compared to their
758 monochromatic equivalents in terms of time-averaged SSC. The wave group conditions lead to generally
759 higher time-averaged SSC than the monochromatic waves. This is explained by a similar reference
760 concentration C_{ref} for all wave conditions, but a higher non-dimensional near-bed sediment diffusivity
761 $\epsilon_{\text{bed}}/(U_0\Delta_r)$ for the grouped wave conditions. The latter may reflect a sediment pumping effect over the
762 wave groups that is absent for the monochromatic waves. Such pumping effects could be accounted for
763 in numerical models by means of an empirical factor β_{gr} in the formulation for the near-bed diffusivity,
764 e.g.:

$$\epsilon_{\text{bed, gr}} = \beta_{\text{gr}}\epsilon_{\text{bed}} \quad (16).$$

765 Here, $\epsilon_{\text{bed,gr}}$ is the near-bed diffusivity for wave groups. A value for the wave group correction β_{gr} in the
766 range of 1.3 to 1.9 is proposed based on the present observations.

767 The wave group and monochromatic conditions can be further compared in terms of net suspended sand
768 flux and transport rates. The various wave groups (GB and GM) result in notably different net suspended
769 sand transport rates, with q_s varying by up to a factor 3 (see Section 6). This is especially attributed to
770 variations in the short-wave suspended transport component, which varies significantly for the different
771 wave group conditions due to variability in the short-wave skewness. All three equivalent
772 monochromatic conditions produce q_s that is within the q_s variability of the wave group conditions. This
773 happens even though the processes driving net suspended sand transport are fundamentally different for
774 the wave groups versus the monochromatic waves; for instance, there is no transport by the long wave
775 for the monochromatic conditions.

776 In summary, the present data suggest that an equivalent wave concept is applicable for suspended sand
777 distributions and suspended sand transport rates, although a modification to near-bed diffusivity
778 formulations is proposed to account for sediment pumping effects. The time-averaged suspended sand
779 concentrations are best represented by a monochromatic wave with η_{rms} equal to the wave groups
780 (condition M1).

781 Based on these results, further development of numerical modelling concepts for irregular waves would
782 particularly benefit from the development of parameterizations for wave group shape, duration, and
783 short-wave skewness effects on the time-averaged diffusivity. The results further stress the importance
784 of accurate model formulations for the short-wave-driven suspended sand transport rate, which shows,
785 from all suspended transport components, the strongest variability between wave conditions. The
786 presented data are made publicly available to facilitate model validation and development. In addition,
787 field measurements may verify the relationships between sand transport and wave group characteristics
788 (duration, degree of modulation, and short wave sequencing) observed in the present experiments.

789

790 **7 Conclusions**

791 The present study focused on sand transport dynamics by five wave groups, and three monochromatic
792 wave conditions that had the same mean period and ‘equivalent’ root-mean-square water surface
793 elevation or maximum wave height as the wave groups. Experiments were conducted in a large-scale
794 wave flume, involving non-breaking waves propagating over a horizontal medium-sand bed. All wave
795 conditions produced sand ripples in a post-vortex regime. Measurements were obtained of the water
796 surface elevation, free-stream velocity, suspended sand concentration (SSC) profiles, and bedform
797 dimensions and migration rates.

798 The five grouped wave conditions produce similar time-averaged SSC profiles, near-bed time-averaged
799 sediment diffusivity, and reference concentration. On the other hand, the groups differ in terms of time
800 variation of SSC. The symmetric group and the backward leaning ‘waxing’ group are the most effective
801 in terms of sediment pumping as they produce the highest SSC at the end of the group. However, for
802 these conditions, the suspended sand settles out almost completely between two consecutive groups,
803 which explains why the differences in time-averaged SSC profiles between all groups are small.

804 The SSC phase lag at short-wave time scale, for both the grouped and monochromatic wave conditions,
805 depends strongly on velocity skewness and bedform dimensions. The lag varies importantly with
806 distance from the bed, reflecting the vertical spreading of suspended sand. At wave group time scale,

807 SSC lags the wave envelope by one wave cycle at the bed and the phase lag increases approximately
808 linearly upward. The vertical mixing of suspended sand is the most rapid for the shortest wave group,
809 while the other groups generate similar SSC phase lags.

810 All wave group conditions produce net offshore-directed suspended sand transport, but magnitudes vary
811 by a factor three. All transport components (current, short wave, long wave) contribute significantly to
812 the total net suspended sand transport. Differences in the total net suspended sand transport between the
813 five grouped wave conditions are primarily caused by variations in the short-wave-related sand transport
814 rate.

815 The wave group conditions lead to consistently higher non-dimensional near-bed sediment diffusivity
816 than the ‘equivalent’ monochromatic waves. The monochromatic wave with root-mean-square water
817 surface elevation similar to that of the wave group conditions produces time-averaged SSC and
818 diffusivity distributions that match closest to the observations for the grouped waves. The net suspended
819 sand transport rate for this monochromatic wave is within the variability of the transport rates for the
820 wave groups. This suggests that, for the present conditions, the equivalent wave concept seems
821 applicable for time-averaged SSC distributions and net suspended transport. An empirical correction
822 factor to the near-bed diffusivity is suggested to account for sediment pumping effects and to further
823 improve numerical predictions of SSC and suspended sand transport under wave groups.

824

825 **Appendix A: grain sorting**

826 The vertical distributions of the median grain diameter D_{50} of the suspended sand samples is shown in
827 Figure A1. The samples do not show a clear differentiation between the various wave conditions. The
828 D_{50} data suggest a power-law distribution, i.e.:

$$D_{50}(\zeta) = D_{50,\text{bed}} \left(\frac{\zeta}{\zeta_T} \right)^{-n} \quad (\text{A1}),$$

829

830 where $\zeta_r = 0.01$ m is a reference elevation and the exponent n is a vertical decay parameter. The latter
831 was calibrated using the D_{50} measurements for all conditions, yielding $n = 0.23$ as best fit. The fitted
832 power-law distribution is included in Figure A1.

833

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844 85513bb29c3d](https://doi.org/10.4121/uuid:30496cc3-9803-4c18-8a6f-85513bb29c3d)).

845

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1035 **Tables and Figures**

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1037 Table 1. Overview of wave conditions. f_1 and f_2 are the frequencies of the bichromatic wave components;
 1038 T_m is the mean short-wave period; T_{gr} is the wave group period; N is the number of short waves in the
 1039 group; H_1 and H_2 are the measured wave heights of the two bichromatic wave components; η_{rms} and
 1040 H_{max} are the measured root-mean-square water surface elevation and maximum wave height. All water
 1041 surface level parameters are measured near the wave paddle ($x = 6.3$ m). Also indicated is during which
 1042 runs continuous SRP, ABS and TSS measurements were made.

Condition	f_1 (Hz)	f_2 (Hz)	T_m (s)	T_{gr} (s)	N	H_1 (m)	H_2 (m)	η_{rms} (m)	H_{max} (m)	Number of runs	SRP runs	ABS runs	TSS runs	Description
GB1	0.239	0.215	4.4	41.8	9.5	0.30	0.30	0.15	0.58	5	1, 3	2, 4, 5	2, 4	Bichromatic, fully modulated
GB2	0.245	0.210	4.4	28.6	6.5	0.32	0.31	0.16	0.60	5	1, 3	2, 4, 5	2, 4	Bichromatic, fully modulated
GB3	0.239	0.215	4.4	41.8	9.5	0.41	0.14	0.15	0.54	5	1, 3	2, 4, 5	2, 4	Bichromatic, partially modulated
GM1	-	-	4.4	44.0	10	-	-	0.15	0.66	5	1, 3	2, 4, 5	2, 4	Waxing, $\beta = 0.2$, fully modulated
GM2	-	-	4.4	44.0	10	-	-	0.15	0.64	5	1, 3	2, 4, 5	2, 4	Waning, $\beta = 0.8$, fully modulated
M1	-	-	4.4	-	-	-	-	0.17	0.48	3	1	2, 3	3	$\eta_{rms} \approx \eta_{rms}$ of wave groups
M2	-	-	4.4	-	-	-	-	0.23	0.65	3	1	2, 3	3	$H \approx H_{max}$ of GB1 at test section
M3	-	-	4.4	-	-	-	-	0.26	0.72	2	-	1, 2	2	$H \approx H_{max}$ of GM at test section

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1047 Table 2. Measured hydrodynamic parameters at the test section. The water surface level measurements
 1048 were obtained by an RWG, the velocity measurements were recorded by an ADV at $\zeta \approx 0.16$ m.

Condition	$\langle \eta \rangle_{\text{rms}}$ (m)	$\langle \eta \rangle_{\text{max}}$ (m)	$\langle \eta \rangle_{\text{min}}$ (m)	H_{max} (m)	\bar{u} (m/s)	$\langle u \rangle_{\text{max}}$ (m/s)	$\langle u \rangle_{\text{min}}$ (m/s)	\tilde{u}_{rms} (m/s)	$Sk(\langle \tilde{u} \rangle)$	d_0 (m)	$d_{0,\text{max}}$ (m)
GB1	0.17	0.61	-0.22	0.83	-0.016	0.67	-0.59	0.31	0.27	0.56	1.08
GB2	0.18	0.66	-0.22	0.88	-0.021	0.84	-0.49	0.32	0.79	0.57	0.91
GB3	0.18	0.52	-0.18	0.70	-0.023	0.69	-0.52	0.33	0.54	0.61	0.93
GM1	0.16	0.68	-0.25	0.93	-0.012	0.82	-0.56	0.30	0.44	0.53	1.14
GM2	0.16	0.68	-0.24	0.92	-0.018	0.75	-0.58	0.31	0.38	0.53	1.22
M1	0.18	0.41	-0.16	0.58	-0.012	0.69	-0.37	0.35	0.77	0.67	0.67
M2	0.23	0.58	-0.21	0.79	-0.060	0.83	-0.47	0.42	0.94	0.78	0.78
M3	0.27	0.73	-0.24	0.97	-0.071	0.93	-0.54	0.45	0.99	0.83	0.83

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1051 Table 3. Measured mean ripple height Δ_r , ripple length λ_r , steepness Δ_r/λ_r , and migration speed c_r .
 1052 Brackets denote standard deviation.

Condition	Δ_r (m)	λ_r (m)	Δ_r/λ_r	c_r (mm/s)	d_0/Δ_r	d_0/λ_r	d_0/D_{50}	ψ_{\max}
GB1	0.017 (0.010)	0.22 (0.12)	0.077 (0.021)	0.46 (0.14)	33	2.5	$2.2 \cdot 10^3$	110
GB2	0.014 (0.010)	0.20 (0.11)	0.070 (0.024)	0.48 (0.10)	41	2.9	$2.3 \cdot 10^3$	175
GB3	0.013 (0.009)	0.19 (0.08)	0.067 (0.023)	0.70 (0.03)	47	3.2	$2.5 \cdot 10^3$	117
GM1	0.013 (0.005)	0.20 (0.09)	0.066 (0.017)	0.50 (0.16)	41	2.6	$2.1 \cdot 10^3$	167
GM2	0.016 (0.013)	0.23 (0.14)	0.068 (0.023)	0.33 (0.04)	34	2.3	$2.1 \cdot 10^3$	138
M1	0.020 (0.013)	0.25 (0.16)	0.078 (0.022)	0.81 (-)	34	2.7	$2.7 \cdot 10^3$	116
M2	0.033 (0.027)	0.38 (0.24)	0.081 (0.027)	0.62 (-)	24	2.0	$3.1 \cdot 10^3$	170
M3	0.032 (0.023)	0.57 (0.17)	0.053 (0.020)	(-)	26	1.4	$3.3 \cdot 10^3$	212

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1055 Table 4. Measured reference concentrations and depth-averaged sediment diffusivities over the near-
 1056 bed mixing layer.

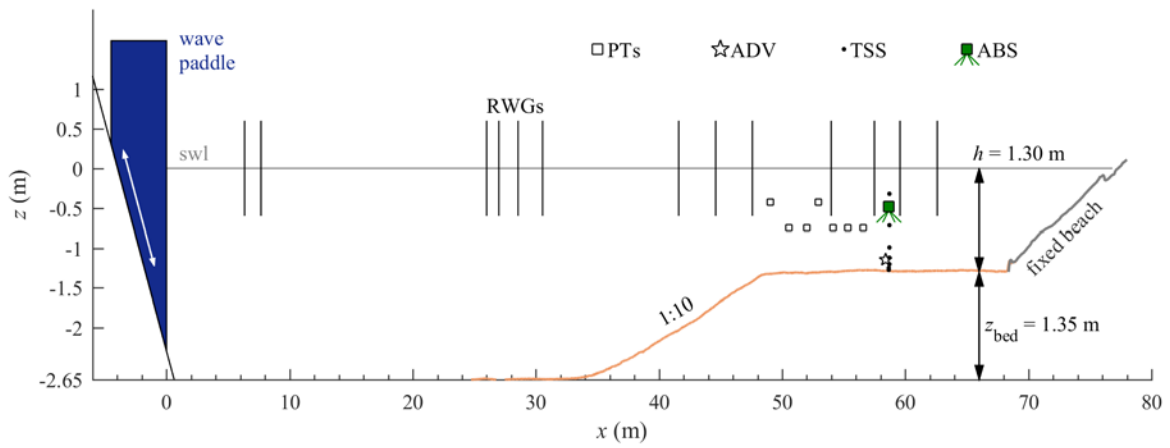
Condition	C_{ref} (kg/m ³)	Measured ϵ over $\zeta/\Delta_r = 0$ to 3 ($\cdot 10^{-3}$ m ² /s)	Measured $\epsilon/(U_0\Delta_r)$ over $\zeta/\Delta_r = 0$ to 3
M1	9.6 ± 2.9	0.62 ± 0.05	0.064 ± 0.005
M2	5.9 ± 1.2	0.88 ± 0.15	0.045 ± 0.008
M3	4.1 ± 0.8	0.88 ± 0.23	0.043 ± 0.011
GB1	9.1 ± 5.0	0.61 ± 0.08	0.082 ± 0.011
GB2	11.8 ± 6.1	0.49 ± 0.05	0.077 ± 0.007
GB3	8.7 ± 2.8	0.51 ± 0.06	0.084 ± 0.011
GM1	6.0 ± 2.0	0.52 ± 0.09	0.095 ± 0.017
GM2	5.5 ± 1.8	0.54 ± 0.08	0.078 ± 0.011

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1060 **Figures:**



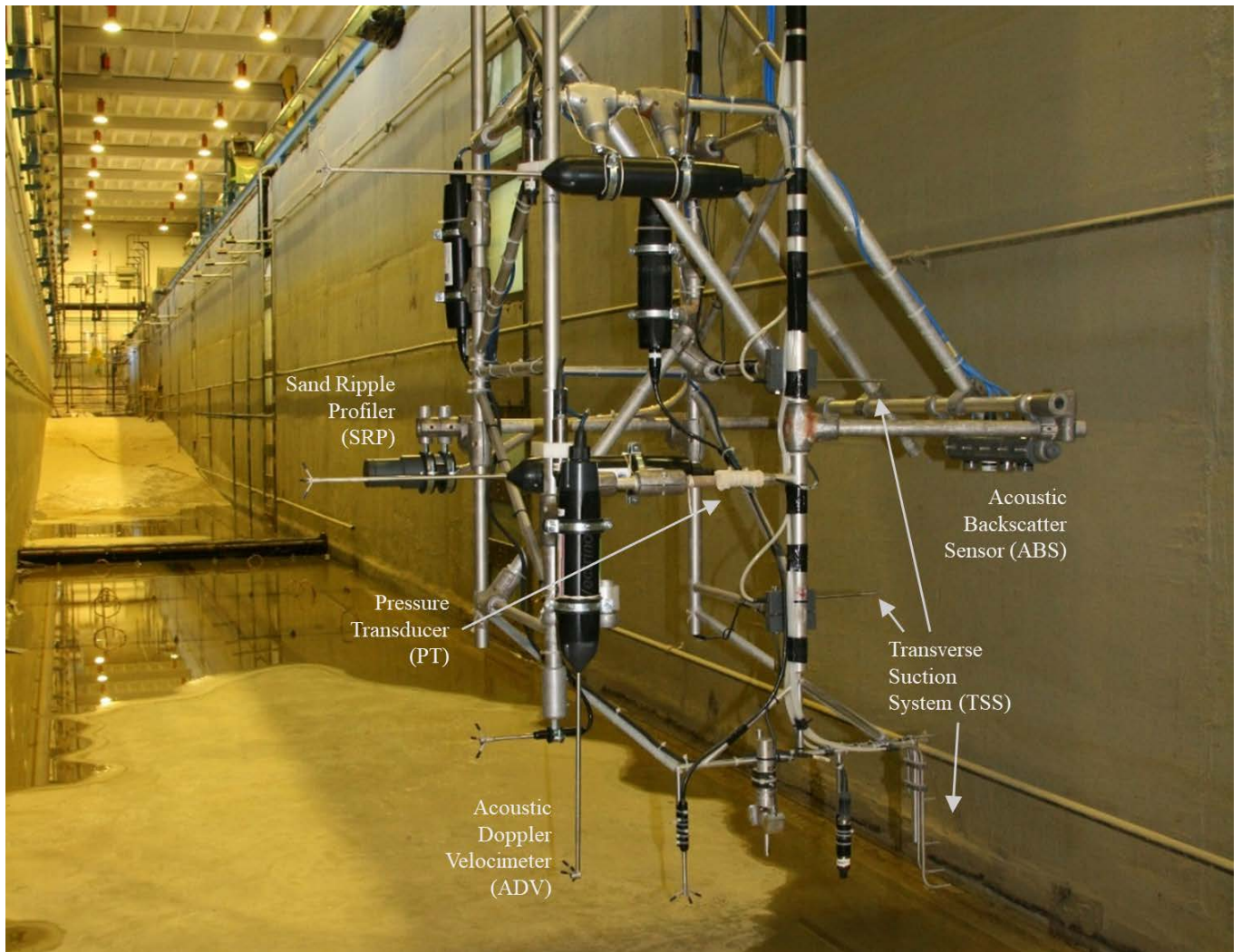
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1062 Figure 1. Experimental set-up, including positions of the resistive wave gauges (RWGs), pressure
1063 transducers (PTs), acoustic Doppler velocimeter (ADV), transverse suction system (TSS) nozzles, and
1064 acoustic backscatter sensor (ABS).

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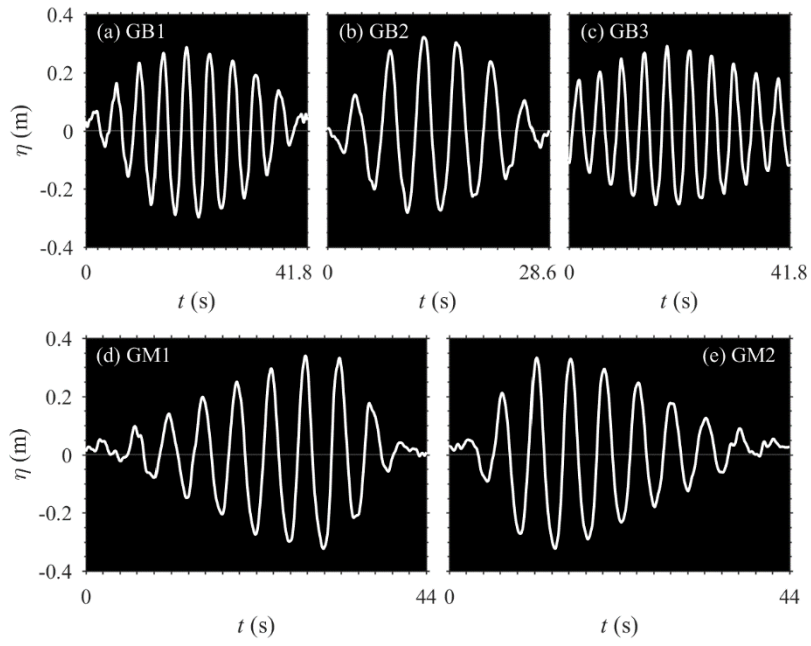
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Figure 2. Photograph of instrumentation on the measurement frame. The frame is positioned here in the deep part of the flume (around $x = 15$ m), the photograph is taken looking towards the test section and beach.



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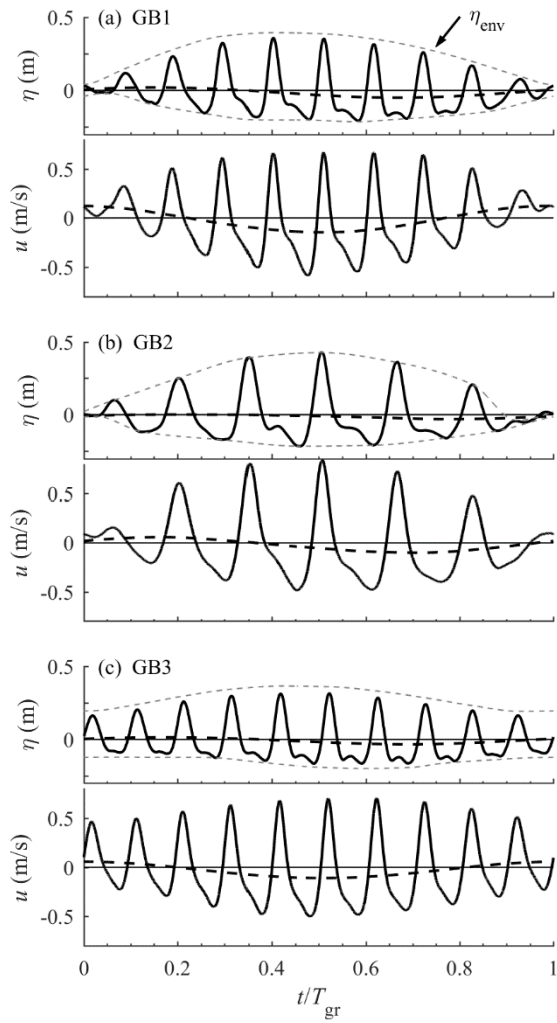
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Figure 3. Phase-averaged water surface elevation near the wave paddle for the wave group conditions GB and GM, measured by the RWG at $x = 6.3$ m.



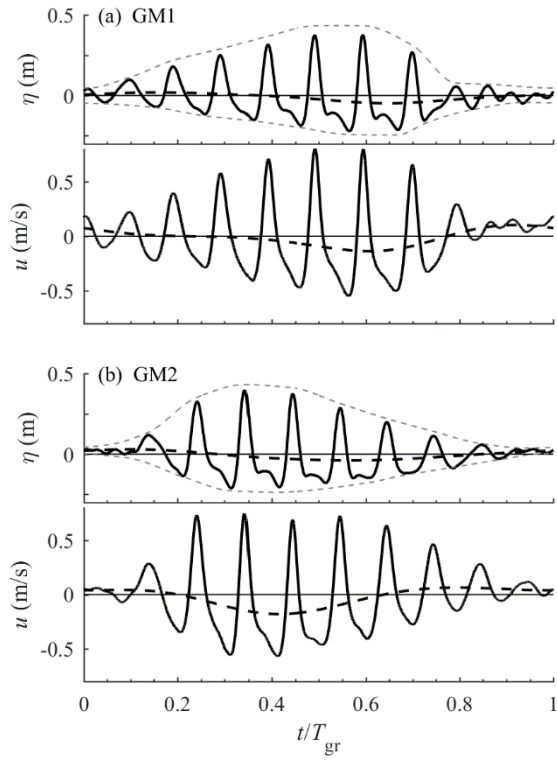
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1080 Figure 4. Time series of phase-averaged water elevation η and horizontal free-stream velocity u at $\zeta =$
 1081 0.16 m for the bichromatic groups GB1 (a), GB2 (b) and GB3 (c) (solid lines). Black dashed lines
 1082 mark low-pass filtered water elevation η_{lf} and velocity u_{lf} . Grey dashed lines indicate wave group
 1083 envelope η_{env} .

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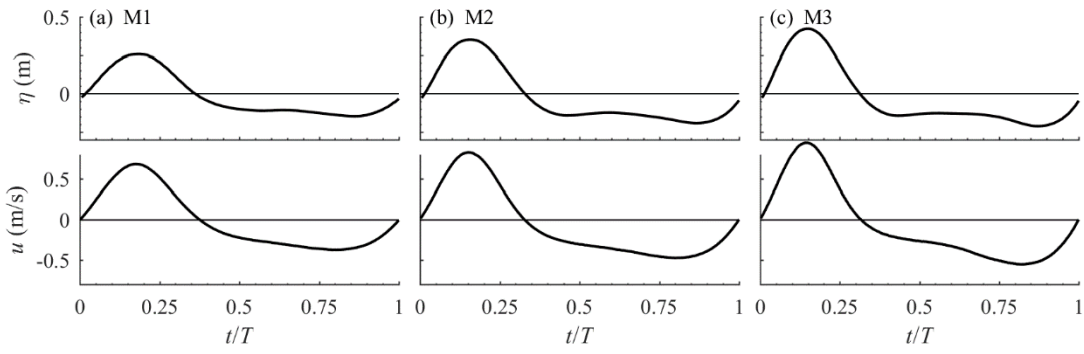
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1088 Figure 5. Time series of phase-averaged water elevation η and horizontal free-stream velocity u for the
 1089 sawtooth-modulated groups GM1 (a) and GM2 (b). Black dashed lines mark low-pass filtered water
 1090 elevation η_{lf} and velocity u_{lf} . Grey dashed lines indicate wave group envelope η_{env} .

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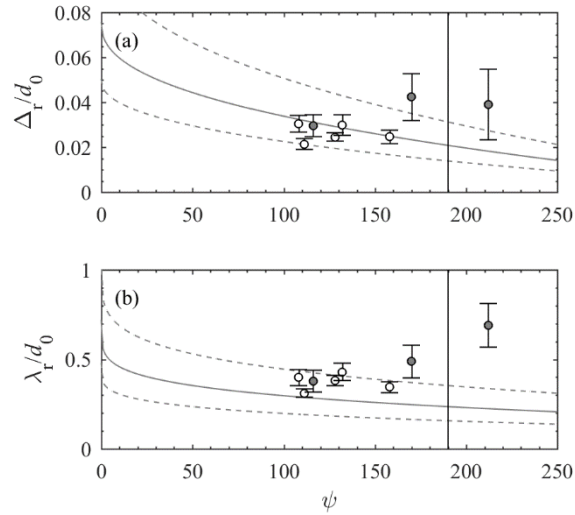
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Figure 6. Time series of phase-averaged water elevation η (top) and horizontal free-stream velocity u (bottom) for the monochromatic conditions M1 (a), M2 (b) and M3 (c).

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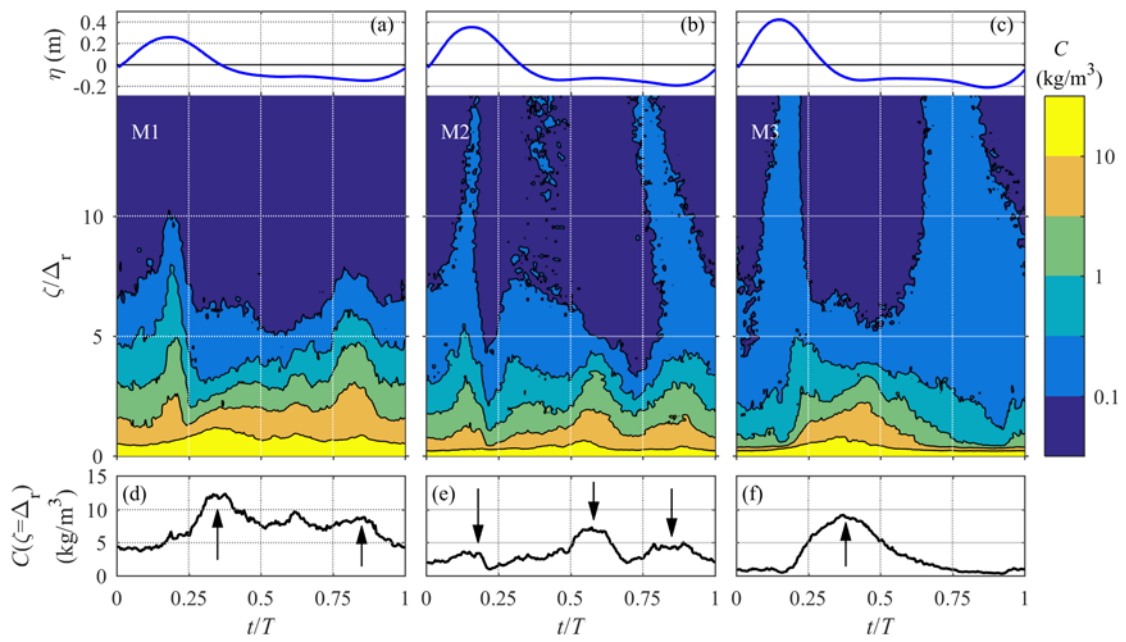


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1100 Figure 7. Non-dimensional ripple height (a) and length (b) as function of mobility number.

1101 Measurements are denoted by white (wave groups) and grey (monochromatic waves) markers, the
 1102 error bars indicate \pm one standard deviation. Solid line indicates empirical prediction by O'Donoghue
 1103 *et al.* (2006), dashed lines indicate $\pm 50\%$. The vertical line marks the range of applicability ($\psi < 190$)
 1104 of the empirical formula.

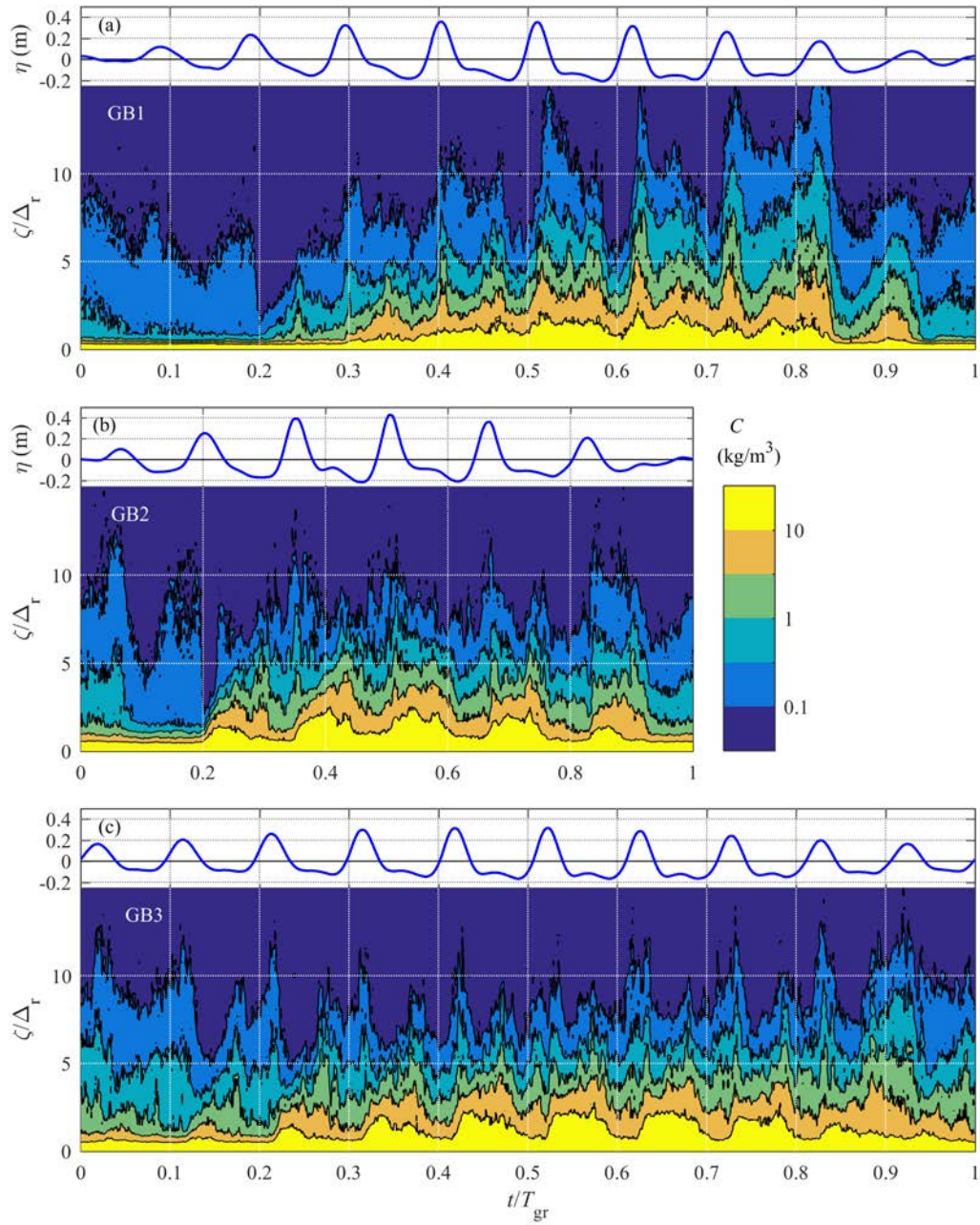
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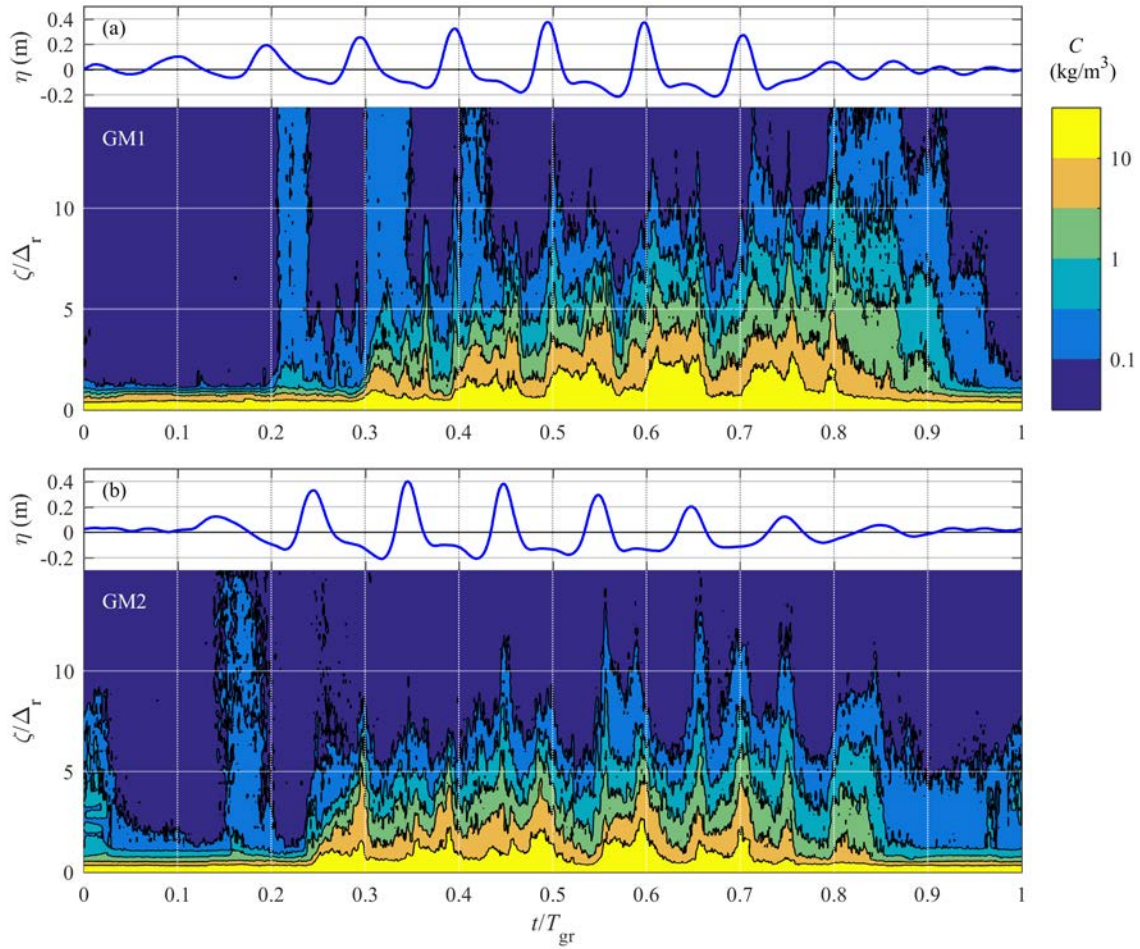
1107 Figure 8. (a-c) Water surface elevation and colour contour plots of the phase-averaged suspended sand
 1108 concentration field $C(\zeta, t)$ for the monochromatic wave conditions M1 (left), M2 (middle) and M3
 1109 (right). Note the logarithmic scale of the colour axis. (b-f) Phase-averaged concentration at $\zeta = \Delta_r$, with
 1110 arrows indicating the primary pickup events.

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1113 Figure 9. Colour contour plots of the phase-averaged suspended sand concentration field $C(\zeta, t)$ for the
 1114 bichromatic wave groups GB1 (a), GB2 (b) and GB3 (c). Each panel includes the phase-averaged
 1115 water surface level η (blue solid line) for reference. Note the logarithmic scale of the colour axis.

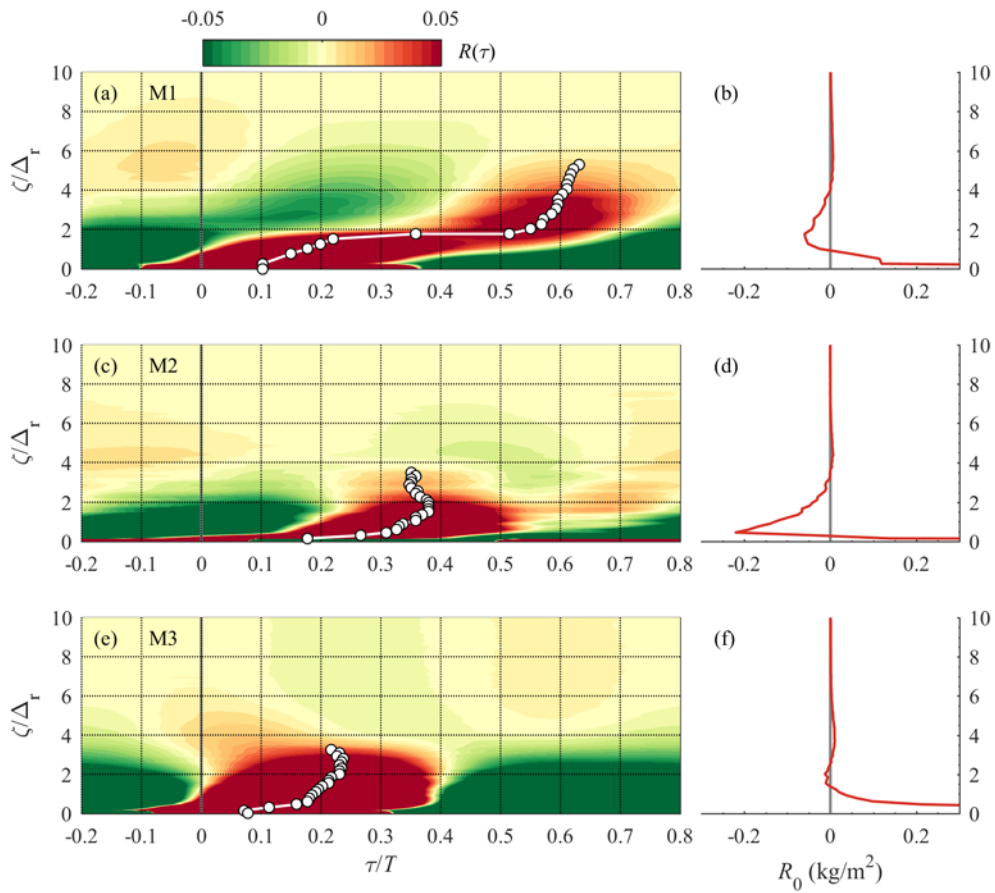


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1117 Figure 10. Colour contour plots of the phase-averaged suspended sand concentration field $C(\zeta, t)$ for the sawtooth-modulated wave groups GM1 (a) and GM2 (b). Note the logarithmic scale of the colour
 1118 axis.
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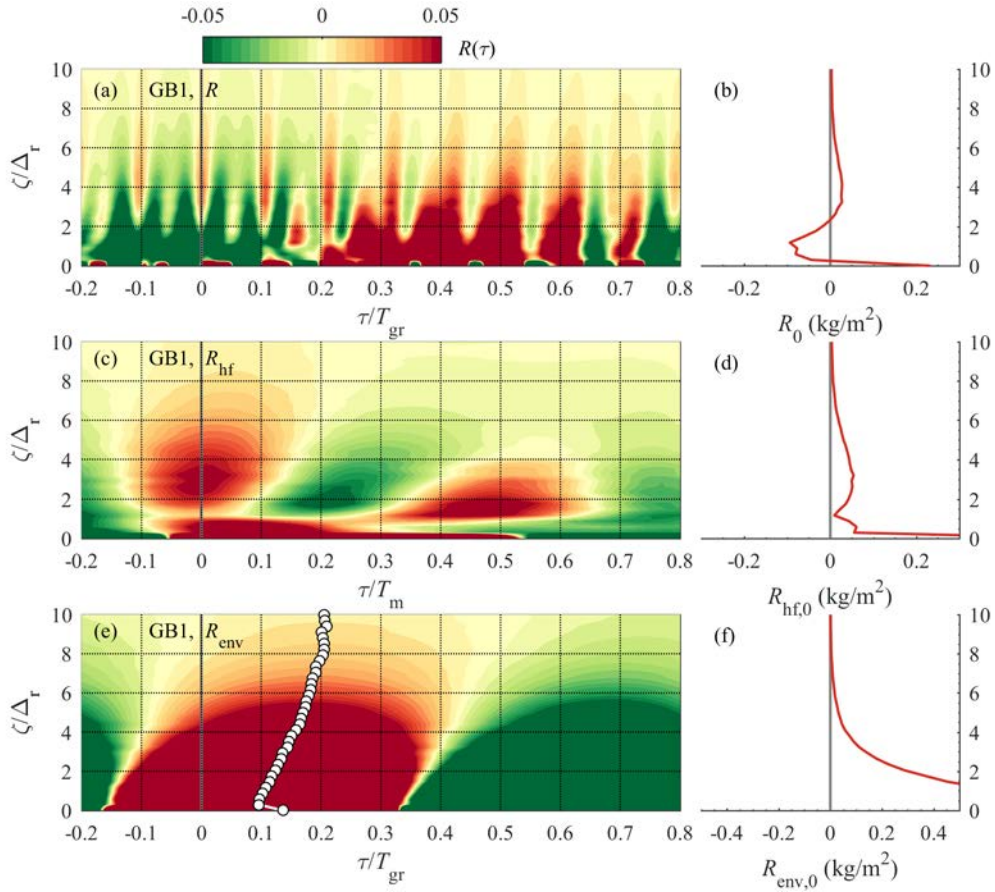


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1123 Figure 11. Cross-correlation $R(\zeta, \tau)$ between the water surface level and $C(\zeta, t)$, monochromatic
 1124 conditions M1 (a,b), M2 (c,d) and M3 (e,f). Left panels: colour contours of $R(\zeta, \tau)$, with the solid white
 1125 circles indicating the phase lag τ_{\max}/T between SSC and η ; Right panels: cross-correlation at $\tau = 0$.

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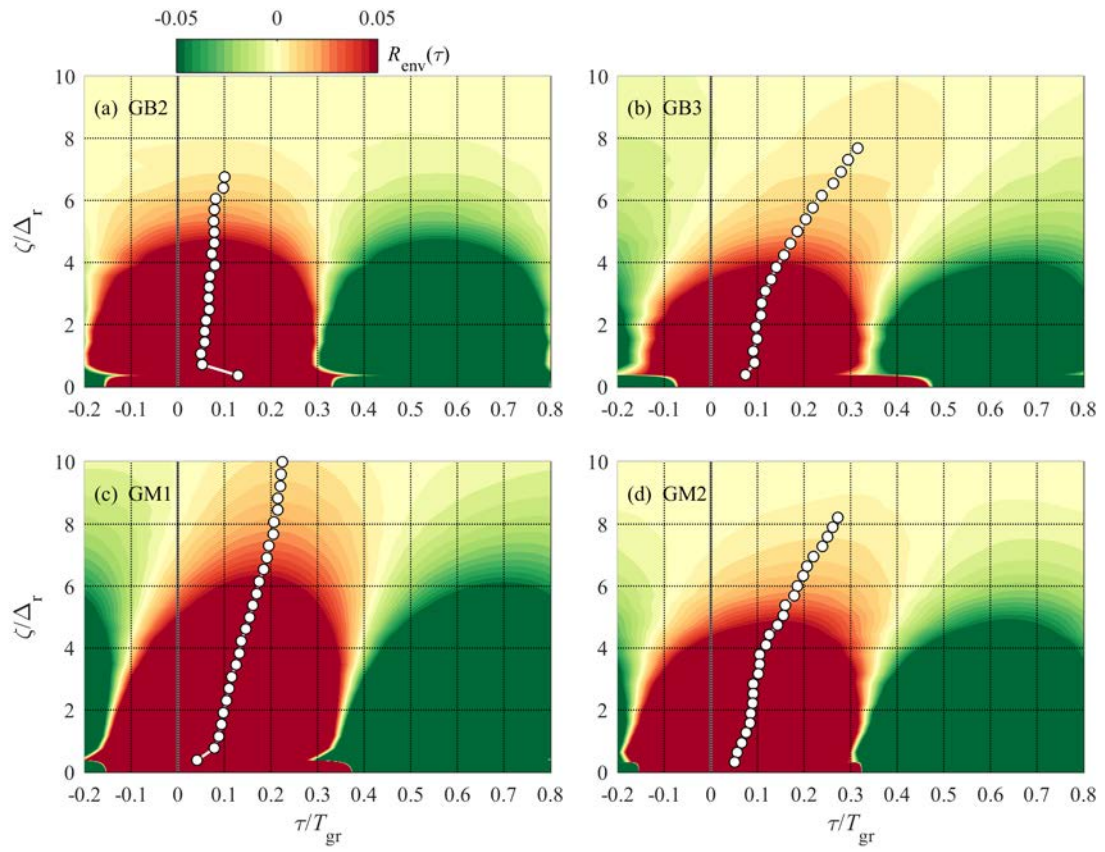
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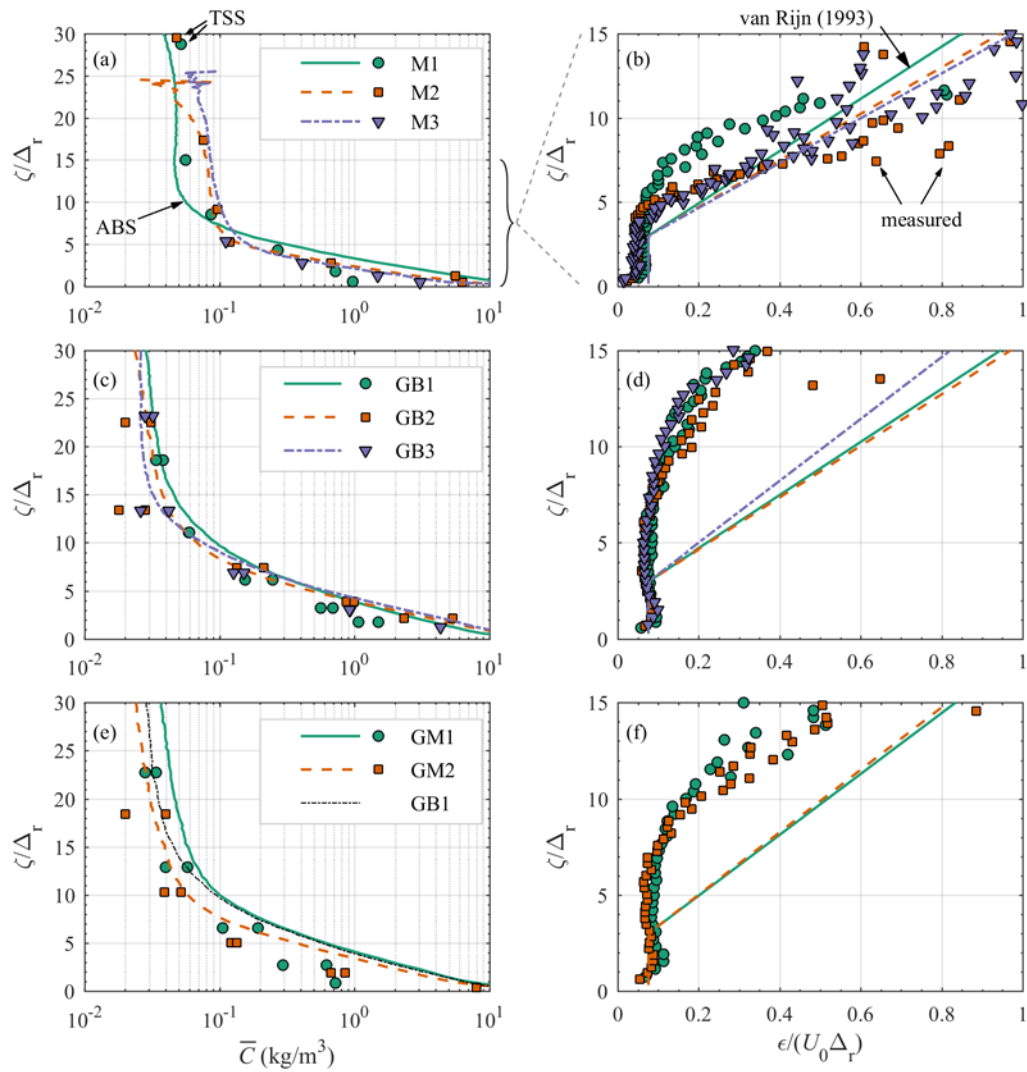
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Figure 12. Cross-correlation $R(\zeta, \tau)$ (left) and $R_0(\zeta)$ (right) between the water surface elevation and $C(\zeta, t)$ for condition GB1. (a,b) cross-correlation R between $\eta(t)$ and $C(\zeta, t)$; (c,d) cross-correlation R_{hf} between the high-pass filtered time series $\eta_{hf}(t)$ and $C_{hf}(\zeta, t)$; (e,f) cross-correlation R_{env} between the water surface envelope $\eta_{env}(t)$ and low-pass filtered $C_{lf}(\zeta, t)$, with solid white circles marking the phase lag distribution.



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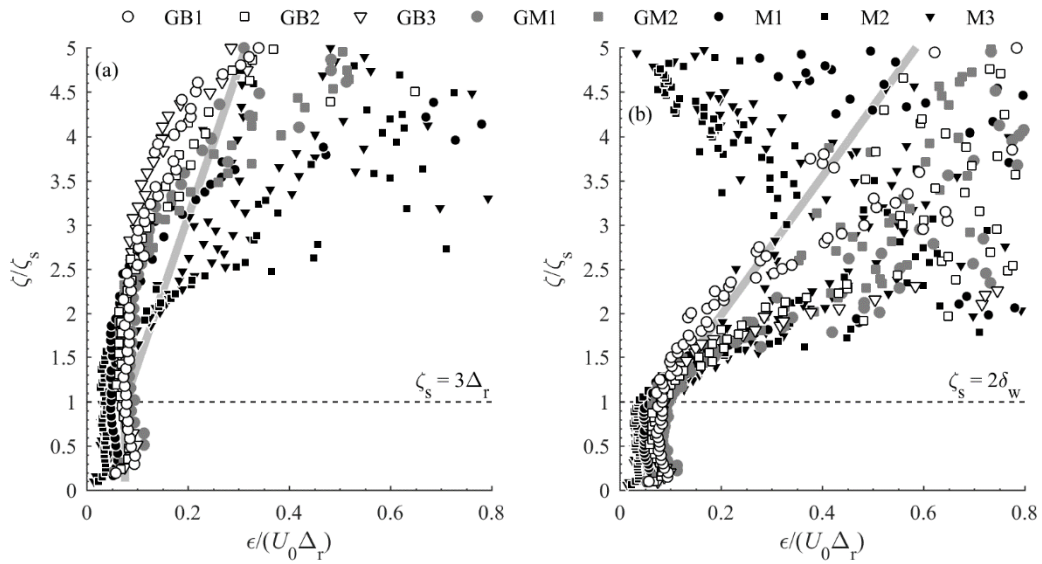
1136 Figure 13. Cross-correlation R_{env} between the water surface envelope $\eta_{\text{env}}(t)$ and low-pass filtered $C_{\text{lf}}(\zeta,$
 1137 $t)$ for conditions (a) GB2; (b) GB3; (c) GM1; (d) GM2. White solid circles indicate the phase lag τ_{max}
 1138 between C_{lf} and η_{env} .



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1140 Figure 14. Vertical profiles of the time-averaged concentration $\bar{C}(\zeta)$ (left) and sediment diffusivity $\epsilon(\zeta)$
 1141 (right), for wave conditions M1-3 (top), GB1-3 (middle) and GM1-2 (bottom). (a, c, e) $\bar{C}(\zeta)$ measured
 1142 with ABS (lines) and TSS (markers) (to facilitate comparisons, panel (e) also includes $\bar{C}(\zeta)$ for GB1);
 1143 (b, d, f) $\epsilon(\zeta)$ from ABS measurements (markers) and predictions following Equation (12) (lines).

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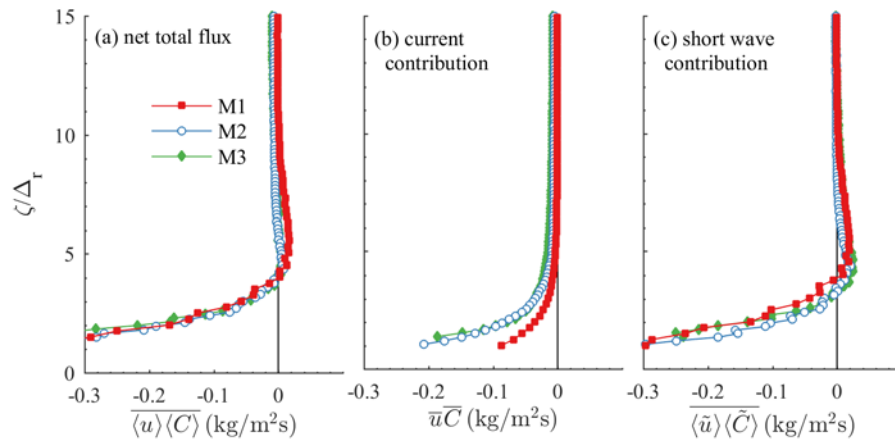
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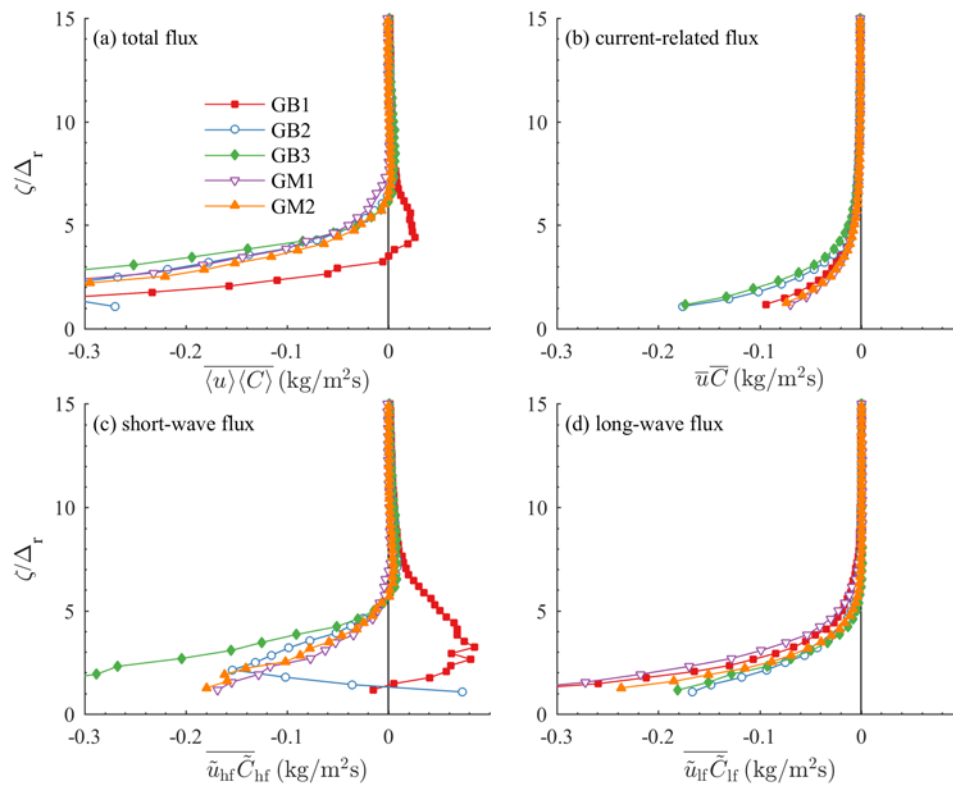
Figure 15. Vertical profiles of the sediment diffusivity using different vertical scaling for the vertical axis: (a) elevations normalized by $\zeta_s = 3\Delta_r$; (b) elevations normalized by $\zeta_s = 2\delta_w$. The symbols represent the measured $\epsilon(\zeta)$ for all wave conditions, the solid line represents the predicted $\epsilon(\zeta)$ following Equation (12) for condition IGB1.



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1152 Figure 16. Net horizontal suspended sand flux distributions for the monochromatic conditions. (a) Net
 1153 total flux; (b) Current-related flux contribution; (c) Short-wave flux contribution.

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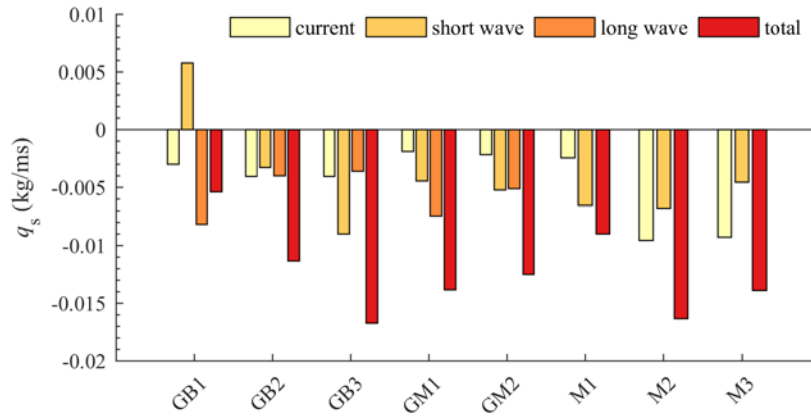
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Figure 17. Net horizontal suspended sand flux distributions for the wave group conditions. (a) Net total flux; (b) Current-related flux; (c) Short-wave flux; (d) Long-wave flux.

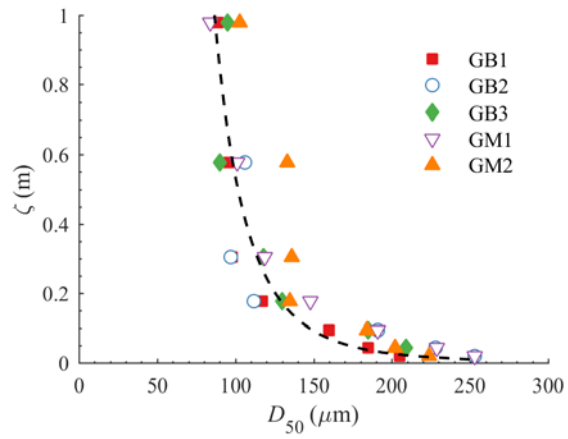


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1160 Figure 18. Net depth-integrated suspended transport between $\zeta = \Delta_r$ and 0.50 m, decomposed into
 1161 contributions by the current, short waves, and the long wave. Note that there is no long-wave transport
 1162 for M1-3.

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1166 Figure A1. Vertical profiles of the median grain diameter D_{50} . Symbols indicate the measured D_{50} of
 1167 the suction samples, dashed line indicates power-law fit (Equation (A1)).

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