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Surfzone-Beach-Dune interactions: Flow and Sediment Transport across the Intertidal Beach and Backshore

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Patrick A. Hesp[†] and Thomas A.G. Smyth[†]

[†]Beach and Dune Systems (BEADS) Laboratory,
School of the Environment, Flinders University,
Faculty of Science and Engineering,
Bedford Park, Adelaide, South Australia

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ABSTRACT

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The original wave-beach-dune model (Hesp, 1982) stated that in the medium to long term, modal dissipative beaches display maximum onshore wave driven sediment transport, maximum aeolian transport off beaches, the largest foredune heights and volumes, and the largest Holocene dunefields. Modal reflective beaches display the opposite, while modal intermediate beaches display a trend in these from relatively high to relatively low sediment transport, foredune volumes, and Holocene barrier volumes with a trend from dissipative to reflective. New Computational Fluid Dynamic (CFD) modelling of flow and calculation of sediment transport over three modal beach types presented here shows that the original conceptual ideas and field data regarding aeolian sediment transport are correct. Dissipative beaches show the greatest long term potential for sediment delivery to the backshore whilst reflective beaches display the least, with a trend from relatively high to low in the intermediate beach state range.

ADDITIONAL INDEX WORDS: *Surfzone-beach-dune model and interactions, modal beach types, flow and aeolian transport.*

INTRODUCTION

The original generation of the wave-beach-dune model of beach and dune interactions was formulated by Hesp (1982) for micro-tidal beaches in eastern and southern Australia, although it might be argued that it would work in many cases for meso-tidal beaches (< ~4m range). Most of these micro-tidal beaches were apparently not limited in sediment supply during the latter part of the Holocene transgression and particularly in the last 7000 years (cf. Thom and Roy, 1985). Sea level crossed the present around 6,500 to 7000 years ago, rose +1m and eventually fell to the present following a typical southern hemisphere pattern (Dillenburg and Hesp, 1999).

The model development followed the publication of a robust micro-tidal beach model with reasonably high predictability (Short, 1979; Wright and Short, 1984). The beach model enabled one to classify micro-tidal beaches into six states ranging from dissipative through intermediate to reflective states with characteristic morphologies and mobilities. Subsequent research has extended the original model to meso- and macro-tidal beaches and as Aagaard et al. (2013) note, later research has largely confirmed the basic model. An analysis of beach and backshore morphologies and flow characteristics for different surfzone-beach types allowed Hesp (1982) to develop actual and theoretical links between beach backshore morphology, potential aeolian transport, foredune state and morphology, and dunefield type and development (Short and Hesp, 1982; Hesp, 1988). In brief, the model claims that in the medium to long term, modal dissipative beaches display maximum onshore wave driven sediment transport, maximum aeolian transport off beaches, the largest foredune heights and volumes, and the largest Holocene dunefields. Modal reflective beaches display the opposite, while modal intermediate beaches display a trend in these from relatively high to relatively low sediment transport, foredune volumes, and Holocene barrier volumes with a trend from dissipative to reflective.

In the following, the six surfzone-beach types and their morphologies are taken as read (see Sherman and Bauer, 1993). Recent research on wave driven sediment transport to the different beach types is reviewed. Post-1982-1988 research on medium to long term aeolian transport off beaches is largely lacking, and in addition, Houser and Ellis (2013) state that discrepancies between the beach-dune models “largely reflects a poor understanding of the relative importance of sediment supply and aeolian transport potential” (p.281). Thus, in the following, the importance of beach morphology and mobility for long term landwards aeolian sediment transport is re-stated. In concert with this, new research on wind flow and sediment transport over three modal or typical beach types is presented.

METHODS

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*Corresponding author: Patrick.Hesp@flinders.edu.au

Three modal beach types were selected for modelling in this study. The dissipative profile is a mean or modal profile from Goolwa Beach, SA, and is taken from 30 years of survey data. The intermediate and reflective modal profiles are from several years of beach surveys in Fens embayment near Hawks Nest and Jimmy's Beach, Port Stephens, NSW respectively (Hesp, 1982).

All computational fluid dynamics (CFD) modelling was performed using OpenFOAM. The SIMPLE (Semi-Implicit Method for Pressure Linked Equations) algorithm was used to solve the Navier-Stokes equations (cf. Smyth and Hesp, 2015). This method produces a steady-state, averaged solution of flow. Turbulence was modelled using the RNG k-epsilon method which accounts for the smaller scales of motion and offers improved predictions for separated flows than the original k-epsilon model. A second-order, linear spatial discretisation scheme was employed and simulations were deemed complete once the initial residuals for Ux and Uz were 4 orders of magnitude smaller than the maximum residual calculated.

The mesh for each beach had a horizontal resolution of 0.1 m and a vertical resolution of 0.02 m at the surface, increasing to 1.05 m at the top of the computational domain, 24 m above the surface of the beach.

In each simulation, wind at the inlet was defined as a logarithmic boundary layer with a wind speed of 10 m s^{-1} at 1 m above the surface. Surface roughness for each simulation was defined as the grain diameter divided by 30 (Bagnold, 1954). Aeolian sediment transport was calculated using White's (1979) corrected derivation of Kawamura's (1951) equation.

SURFZONE TO BEACH SEDIMENT TRANSPORT

Hesp (1982; 1999) and Short and Hesp (1982) argued that dissipative surfzones would have the highest potential wave driven onshore transport while reflective beaches would have the lowest, based on observations of Holocene sediment volumes contained in some Australian barrier systems developed landwards of those beaches. In more recent times, while models such as SBEACH and CROSMOR generally predict offshore rather than onshore transport (e.g. Aagaard et al., 2004; Aagaard and Sorensen, 2012), large-scale modelling (e.g. Cowell et al., 1995) and field observations (e.g. Aagaard et al., 2004, 2013; Miot da Silva, 2011) indicate the opposite. It is also a fact that very many of the largest barrier and coastal dunefields in the world are found on high energy surfzone-beach types, particularly dissipative beaches (Short, 1988, 2010; Aagaard et al., 2004; Hesp, 2013; Hesp and Walker, 2013; Houser and Ellis, 2013). For example, transgressive dunefields are most commonly found on high energy dissipative and high energy intermediate surfzone-beach systems (e.g. Australian east, southern and west coasts, South Africa, Brazil; west coast USA; east and west coast Mexico; NZ North Island west coast; Peru and Chile coasts; France, Spain, Holland and Portugal coasts). Research by Dillenburg and Hesp (2009), Miot da Silva and Hesp (2010), and Miot da Silva et al., 2012) support this contention for southern Brazilian transgressive dunefield barrier systems.

BEACH MOBILITY

Beach mobility refers to the coefficient of variation of mean shoreline position (see Short and Hesp, 1982; Short (1999, his table 7.1), and in reality indicates the amount of volumetric and profile change the beach and backshore experiences over time, and through erosion to accretion phases. Dissipative and reflective beaches have minimal backshore mobility, while intermediate beaches range from relatively low, through moderate–high to relatively low as one progresses from the dissipative to reflective ends of the intermediate range. In a review of surfzone-beach interactions Houser and Mathew (2011) ignored beach mobility as a factor in such interactions, but mobility is important because the greater the beach mobility, the greater the beach morphological variability, and therefore the greater the potential for variations in net aeolian sediment transport. If a beach's mobility is moderate to high, the fetch distance across which the wind can blow towards the backshore can vary significantly both temporally and spatially, and as Bauer and Davidson-Arnott (2003) note, less beach width equals less transport potential. For example, Houser and Mathew (2011, p.66, para 3) show that the largest dunes on South Padre Island are associated with the largest supratidal volumes and widths (although confusingly, they later contradict this (see their p. 70, section 6). In addition, the presence of scarps, and/or curvaceous to stepped topography result in reductions in the near-surface wind flow and aeolian sediment transport (Hesp, 1988; see below).

FLOW AND AEOLIAN SEDIMENT TRANSPORT ACROSS MODAL BEACH TYPES

In 1994 Sherman and Lyons conducted a model test to examine if aeolian sediment transport did actually differ across the three modal beach types, dissipative, intermediate and reflective. Their model utilised three different typical beach slopes but all beaches had the same width and shear stress was constant at 0.5 ms^{-1} across the profiles. They found that sand transport off the dissipative beach was 20% higher than off the reflective beach if just slope and grain size were taken into account. When moisture content was added, transport rates were nearly two orders of magnitude higher off the dissipative beach compared to the reflective beach. We have repeated *exactly* Sherman & Lyons (1994) non-moisture model which utilised White's (1979) *incorrect* transport equation (see corrections in Namikas and Sherman, 1997). The results are similar; there is significantly greater transport across the dissipative profile compared to the reflective profile.

Since it is unlikely that shear stress would remain constant over a beach surface with variable slope and topography, a CFD model was then run over three modal beaches, (a typical dissipative, intermediate and reflective beach) but in this case with the shear stress computed continuously across the three beach topographies. Sediment transport in this case was calculated using White's (1979) derivation of Kawamura's (1951) equation as corrected by Namikas and Sherman (1997). Figure 1 illustrates the velocity bands, Figure 2 the sediment transport across the three topographies, and Figure 3 the velocity profiles sensed at various positions across the beach topographies. The velocity bands depicted in Figure 1 show there is minimal disturbance of the flow across the dissipative beach, and only when the wind approaches the topographic break where the beach meets the seaward toe of the backshore is there a slight reduction in flow velocity.

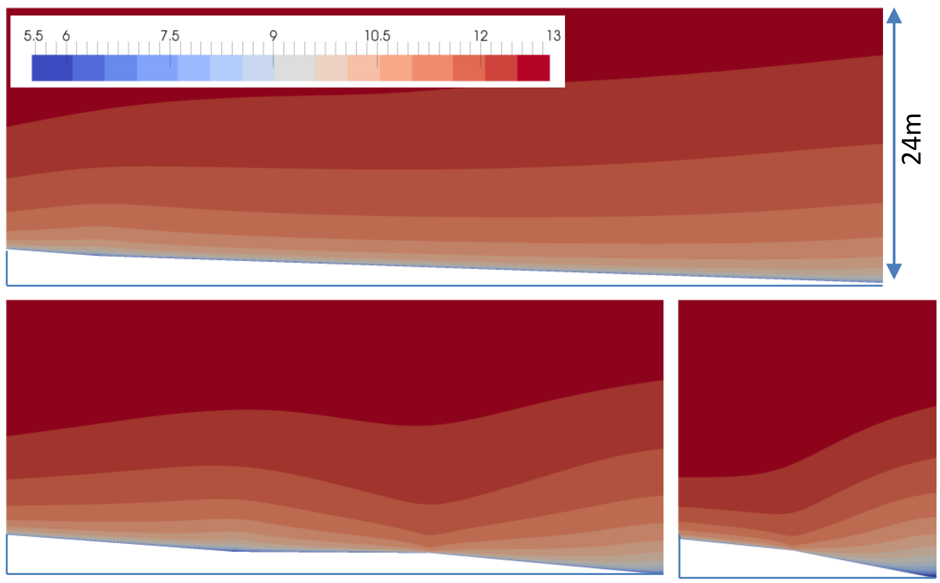

Figure 1. CFD generated velocity bands (scale bar in msec^{-1}) across dissipative (Goolwa, uppermost), intermediate (Hawks Nest, lower left) and reflective beach (Jimmys) profiles illustrating minimal flow disturbance across the majority of the dissipative profile compared to the intermediate and reflective beaches. Horizontal distances are 80m, 60, 23m respectively (see fig 2). Wind flow is from right to left (and in the following diagrams).

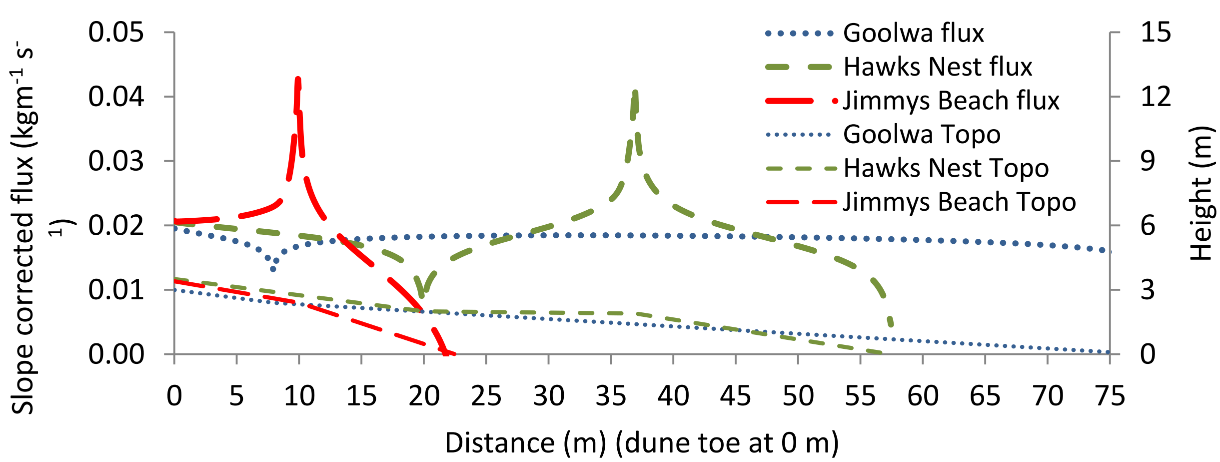

Figure 2. CFD modelling of sediment transport (upper lines) across modal dissipative (Goolwa), intermediate (H. Nest) and reflective (Jimmys) beach profiles (lower less weighted lines) calculated using White's (1979) corrected sediment transport equation derived from Kawamura (1951) and constantly adjusting the shear velocity across the profiles. Transport is initially increasing then constant across the majority of the dissipative beach slope until the topographic break is reached at the lower backshore position (~ 8m distance). Transport peaks at the berm crests of the intermediate and reflective beaches but drops significantly landwards of the berm crests.

Sediment transport slightly increases and then is largely constant across much of the dissipative profile. The sediment transport peaks locally at the berm crests, and is lower landwards of these crests on the intermediate and reflective topographies (Figure 2). The velocity profiles increase up- and across-slope in the case of the dissipative beach. On the intermediate and reflective beaches, the velocity accelerates up the beach face (highest speedup for the reflective beach as shown by Hesp's 1982 velocity profiles), reaching a maximum at the berm crests. It then decelerates in the back berm crest swale (berm tread region) on the intermediate beach, and is somewhat lower on the steeper reflective upper beach (Figure 3).

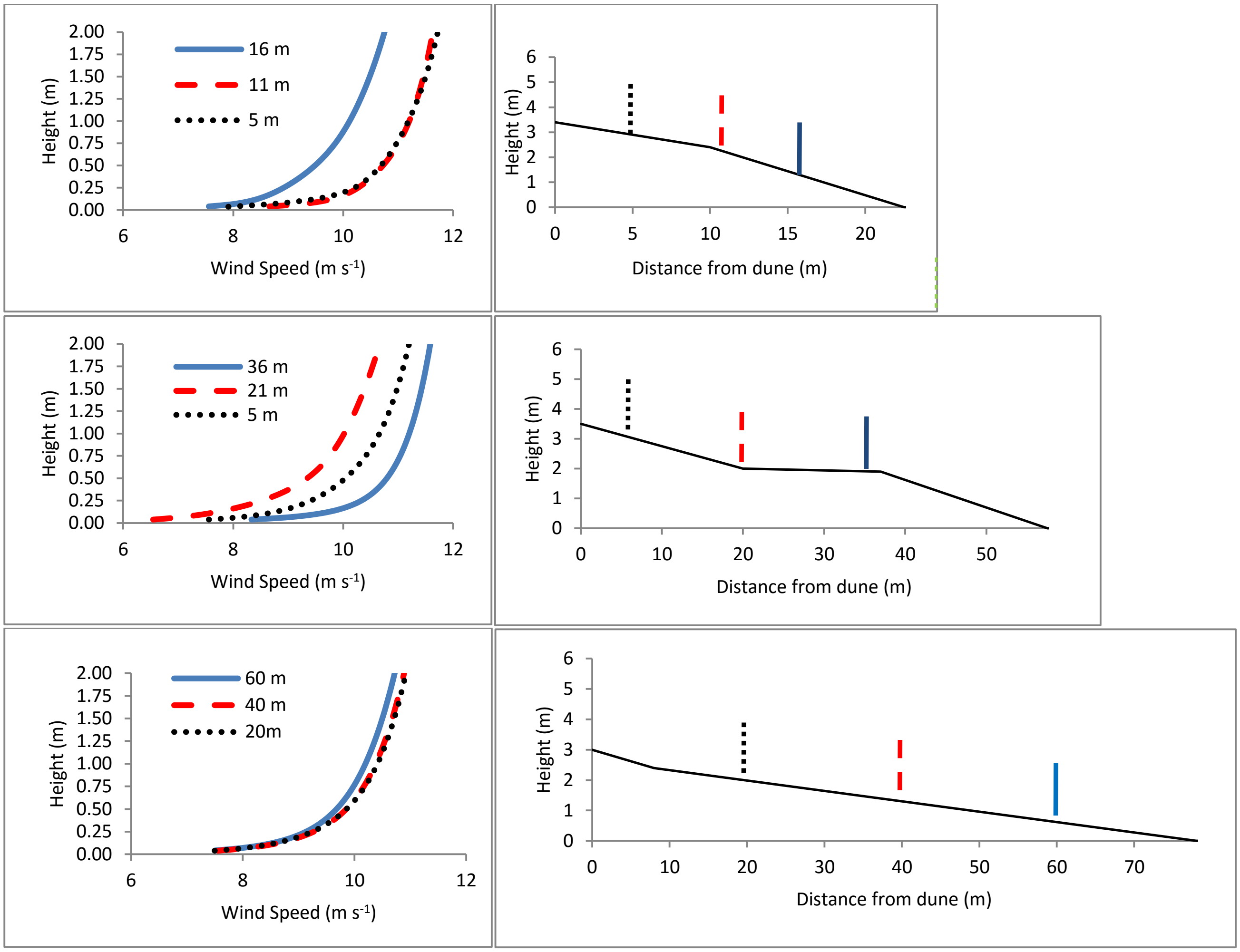

Figure 3. Wind velocity profiles derived from CFD simulations and sensed at every 1cm height (starting at 2cm) above the bed across the three modal beach topographies. Note the consistently high velocity profiles across the dissipative beach, and minimal flow disturbance compared to the other two.

CONCLUSIONS

The sediment transport portions of the wave-beach-dune model published in 1982 (Hesp, 1982; Short and Hesp, 1982) were part conceptual, part field validated (the beach mobility, beach flow fields and foredune volume data in particular) (Hesp, 1988). In this work utilising a CFD model shows that the original conclusions regarding sediment transport off the modal intertidal beach to backshore types were largely accurate. Dissipative beaches (without berms) display minimal topographic variability, maintain máximum fetch widths, and experience mínimum flow disturbance and decelerations across the profiles, thus mazimising aeolian sediment transport across those beaches. While at times, higher wide berm portions (the berm tread) can have high aeolian sediment transport, particularly because they can remain dry for reasonable periods compared to curvilinear to straight dissipative beaches, their greater mobility means that on average, net medium to long term aeolian transport is greater off dissipative beaches. The surfzone-beach-dune model clearly does include and characterise the relative importance of sediment supply and aeolian transport potential for the range of modal beach types.

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