1 The second international workshop on swash-zone processes

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14 Abstract: A workshop on swash-zone processes was convened in July of 2014 aimed to present
15 the most recent research advances and to identify topics of future research. This paper presents
16 the most critical topics discussed at the workshop with future perspectives. Recurring themes
17 throughout the workshop (and this paper) are the ability to: tie the research to problems of
18 societal interest, focus efforts on understanding extreme conditions, and improve sediment
19 transport and morphodynamic prediction from numerical models. Subsequent papers in the
20 special issue highlight recent advances in swash-zone processes research.

23 Keywords: beach face; foreshore; extreme events; numerical modeling;runup

1. Introduction

This paper follows the 2nd International Workshop on Swash-Zone Processes (hereafter 2nd workshop) attended by 25 researchers (Table 1) and held at the University of Delaware Newark, DE, USA (July 14-15, 2014). This work describes the ideas, concepts, and future directions that were identified/discussed during the workshop and in the process revisits some of the key issues addressed at the 1st International Workshop on Swash-Zone Processes (Puleo and Butt, 2006; hereafter 1st workshop). An effort was made to be more inclusive of graduate research assistants studying swash-zone or related processes due to their important role in the future of swash-zone research.

The main topics discussed at the second workshop were:

a. Defining the swash zone in terms of hydrodynamics (e.g. as a larger region extending from the inner surf to back beach dunes during extreme conditions) or other natural geomorphological features.

b. The need to obtain new measurements and perform model simulations of storm and extreme events to identify the role that swash-zone processes have on the beach morphodynamics under such conditions.

c. Processes happening at the edge of the swash zone and in the initial stages of uprush and final stages of backwash may be the most important with regard to sediment transport but are the most difficult to measure/model.

d. Some strides have been made in understanding/measuring sediment transport, but these processes remain the most difficult to quantify fully and parameterize.

e. A variety of new models exist but there is a wide range in model capability and assumptions involved. Model suitability depends on the physical processes of interest.

f. Continued interaction between experimentalists and modelers of small-scale and large-scale processes is required to further advance knowledge. On one hand, the modelers should be aware of field and laboratory efforts in order to give feedback to experimentalists on the required information for model testing and calibration leading to model improvement. On the other hand, high-resolution modeling should be employed in order to improve current parameterizations.

Aspects of these topics are described more fully below with sections related to hydrodynamics, sediment transport and morphology, and numerical modeling. Many topics overlap but for this paper are placed into a particular category at the authors' discretion. Subsequent papers in the special issue highlight recent advances in swash-zone processes research (Chardon-Maldonado *et al.*, This Issue), modeling subsurface processes (Pokrajac and Sparrow, This Issue) and foreshore morphodynamics (Incelli *et al.*, This Issue), provide an overview of recent advances in swash-zone numerical modeling via "benchmark" testing of several hydrodynamic models of swash-zone processes (Briganti *et al.*, This Issue), and investigate runup on storm, seasonal and interannual time scales and under dune erosion scenarios (Palmsten and Splinter, This Issue; Park and Cox, This Issue; Ruggiero and Cohn, This Issue).

2. Hydrodynamics

The 1st workshop identified several key areas for future research related to hydrodynamics including a robust definition of the swash zone, investigating horizontal pressure gradients and turbulence, alongshore flows and velocity profiles over the swash depth. Several of these areas (e.g. turbulence and velocity profiles over depth) have been addressed in recent research and discussed further at the 2nd workshop. However, workshop attendees also discussed new areas for future hydrodynamics research (e.g. void fraction and boundary layer evolution) in addition to revisiting areas that have yet to receive adequate attention (e.g. alongshore flows and swash-swash interaction). This section focuses on the topics related to hydrodynamics that were identified within breakout groups during the 2nd workshop.

2.1. Turbulence

Swash zone hydrodynamics and sediment transport are affected by high turbulence levels; specifically during uprush initiation. Bed-generated turbulence is also prevalent during uprush and in the latter stages of backwash. Much of our knowledge of turbulence in the swash zone arises from laboratory studies over fixed beds or from numerical modeling. Repeatability under laboratory studies is a major factor contributing to successful estimations (e.g. via ensemble averaging). Quantifying turbulence in the field or for mobile bed conditions under irregular waves continues to elude researchers. Sensors that can sample rapidly the velocity field are more readily available than in the past. Extracting turbulence information from the data is still problematic owing to separation of wave, mean and turbulence quantities in a consistent way. Some strides have been made using multiple sensors with a short separation distance or velocity profile data for quantifying turbulent kinetic energy dissipation. However, these approaches may

need to invoke some assumptions that could make inter-comparison with data/approaches from other sites difficult. In addition, turbulence length scales are not well known and will likely differ under different conditions. Swash zone turbulence is a major unsolved problem from both a theoretical and measurement standpoint. Future work should be devoted to determine the most practical approaches to quantify turbulence under natural field conditions.

2.2 Void Fraction

To our knowledge, void fraction measurements in the swash zone do not exist. It is clear the incoming bore is laden with bubbles and foam. The importance of the multi-phase nature of the flow on the flow field itself, pressure gradients, turbulence, momentum flux, and stress variability remain unknown. In addition, the void fraction adversely affects optical and acoustic sensors that are used to measure suspended sediment concentration and velocity.

2.3 Velocity Profiles

New instrumentation such as the Nortek Vectrino II now permit the collection of velocity profiles in the field over a small range (0.02 to 0.03 m) at 1 mm vertical bin spacing. Data over more of the water column are needed to investigate the full velocity profile. Some approaches using multiple overlapping sensors in the vertical have been attempted with moderate success. But required alongshore separation of sensors complicates concatenation of individually-measured segments of the velocity profile. A single sensor spanning a larger range of the water column would provide a more robust measurement. Difficulties may arise from the required distance above the bed the sensor must be to increase the sensing range. Laboratory experiments allow for an extension of the measurement range through the use of imaging techniques such as

the Particle Image Velocimetry (PIV). However, PIV may still fail during bore arrival due to highly aerated flow. Measurement of the velocity profile into the highly-concentrated near bed region (sheet flow) in field and laboratory settings are still in their infancy.

2.4 Wave Boundary Layer Evolution

Laboratory observations and numerical models suggest that the boundary layer thickness in the swash zone increases quickly during the uprush, vanishes during flow reversal, and becomes depth-limited during the backwash. The logarithmic model has been applied with moderate success in the swash zone of several laboratory studies over fixed beds and in the field under mobile bed conditions. The model can describe the general shape of the velocity profile and the bed shear stress during uprush. The model has more discrepancy predicting the velocity profile and bed shear stress in the backwash when compared to ground truth data over fixed beds. The model still requires more validation/testing over mobile beds. Other approaches to investigate the boundary layer velocity profile shape and evolution are necessary including in the presence of infragravity waves or during swash-swash interaction.

2.5 Pressure Gradients

Past work has mainly focused on horizontal pressure gradients, showing that the sea surface slopes offshore for the majority of the swash cycle except near the runup tip and at the surf/swash transition. Non-hydrostatic conditions, swash-swash interaction, and bed exfiltration/infiltration may require improved measurements of the dynamic pressure that could enhance sediment transport during these instances when measurement of the surface slope alone may be insufficient. Vertical pressure gradients also deserve further investigation.

2.6 Alongshore Flows

The importance of alongshore flows in the swash zone has been raised at both swash zone workshops. Yet, little research either by modelers or experimentalists has been published regarding the importance of these flows. Flows are generally assumed to be cross-shore directed but any alongshore component enhances the flow magnitude and can increase the bed shear stress. In addition, alongshore flow variability and associated sediment transport gradients will lead to morphological change that cannot be modeled or predicted solely with a cross-shore flow/sediment transport model. The effect of alongshore flows on turbulence, bed shear stress, sediment mobilization, and morphological variability requires further study. For instance, it is well known that alongshore sediment transport is important on sea-breeze dominated beaches where swash-zone dynamics may play an important role in the total nearshore sediment transport budget.

2.7 Complete Swash Cycle Measurements

Swash events are initialized in some form of bore collapse or swash-swash interaction. The process is turbulent and can be quite violent. Backwash flows can thin quickly leaving only a thin film of fluid rushing down the beach face for an extended duration. This thin film, though, generally has the capacity to transport sediment via sheet flow or bed load. Measuring hydrodynamics (or sediment transport) during these stages has proved difficult. Sensors relying on acoustics or optics struggle when inundated by the bubbly and sediment-laden uprush. Other sensors, relying on for instance, electromagnetics, have difficulty when transitioning from a dry to wet environment leaving a short time (perhaps $\frac{1}{4}$ s or more) before sensor stabilization.

Measuring flows in the backwash is also problematic because the water level eventually falls below an elevated sensor. Our knowledge of swash-zone hydrodynamics is largely confined to the times when measurements are or can be made rather than throughout the swash cycle. The artificial truncation of the true swash cycle based on in situ measurements may lead to inaccurate physical description of the truly important processes or times when particular processes are most relevant. Non-intrusive (remote sensing) techniques are showing some promise for resolving time- and space-dependent hydrodynamics for a larger portion of the swash cycle. For instance, ultrasonic distance meters and LIDAR-based methodologies have improved understanding of the depth-average flows. Improved methodologies/approaches are still needed to more fully understand the processes occurring at a given cross-shore location from swash initiation until cessation. These approaches may include newer remote sensing techniques or imaging approaches (perhaps borrowing from the medical field). Additional information may be quantified from imaging observations of the processes of interest through the glass walls of laboratory flumes.

2.8 Cross-shore Advection

The swash zone is linked to the inner surf zone through the propagating bore that carries momentum, turbulence and sediment loads. Only a few studies have investigated explicitly the importance of advection from the inner surf zone. Is this bore advection the most important aspect of swash zone (uprush) signals observed in the field? Understanding the importance of advection requires knowledge of the turbulence details in the shallow inner surf zone. But quantifying turbulence in the inner surf zone has also proved challenging. The seaward limit for

swash zone sediment transport is not limited by the extent of backwash motion owing to the sediment advection potential.

2.9 Swash-Swash Interaction

Swash motion is essentially free following bore collapse. However, backwash motion rarely completes a full cycle. In fact, the concept of a full swash cycle is unclear since at some point in the rundown cycle a subsequent uprush begins. Interacting swashes should lead to flow separation, near bed turbulent eddies, enhance shear stresses and sediment transport, and maybe alter the vertical pressure gradient. Yet, only a few studies have investigated the details of the importance of this swash-swash interaction. In contrast, many recent studies (laboratory and numerical) have focused on the dam break swash that is more analogous to a single free swash event. It remains to be seen how results obtained from these studies relates to natural swash where interaction occurs. More recently experimentalists and numerical modelers are investigating a double dam break problem wherein a second mass of water is released with a delay relative to the first mass of water to mimic this interaction. These approaches show promise in quantifying the importance of swash-swash interaction.

2.10 Infiltration and Exfiltration

The interface between seawater and the coastal aquifer is generally located within the swash zone. The water table elevation helps control the level of beach saturation on longer time scales. Bed porosity and permeability allow fluid to flow into or out of the foreshore depending on hydraulic gradients. Variability in permeability (usually associated with grain size) can also lead to changes in the boundary layer structure affecting bed shear stress, turbulence and

sediment mobility. Laboratory and numerical studies over fixed permeable and impermeable beds detail these processes. Much less effort has addressed the importance of through bed flow on mobile/natural beaches. More effort should be focused on measuring actual flow rates while simultaneously measuring boundary layer structure. The use of pressure gradients to infer vertical flow, although informative, should be supplemented with a direct measure of through bed flow.

2.11 Extreme Events

It is acknowledged that extreme events are responsible for the largest changes to the foreshore. However, to our knowledge, no field measurements of swash-zone flows have been collected under an extreme storm. The severity of the flows and forces that supporting structures would need to withstand may imply that measurements under these conditions are not possible. In addition, the swash zone translates landward during extreme events through wave and wind set up. Sensor deployment in anticipation of an extreme event would have to take this into consideration. Still, swash zone researchers should contemplate scenarios where measurements under extreme events may be possible so that our knowledge of the processes leading to severe erosion can be extended and provide potentially critical information for upscaling normal conditions to extreme conditions.

2.12 Inter-swash Variability

A main thrust from the first workshop was investigating processes occurring on a swash-by-swash basis. Detailed measurements provide an insight into the small-scale dynamics. However, the practical impact of the research must be borne through investigating inter-swash variability

that drives the longer term processes on the foreshore. For example, are the details of an individual swash cycle during an extreme event important? What is the performance of sediment transport and shear stress parameterizations for individual events during extreme wave conditions? Is the inter-swash variability important in order to predict the bulk changes at the foreshore? Or is knowledge of the forcing associated with a “mean” or “typical” event (as is often done through ensemble-averaging) sufficient?

2.13 Infragravity Motions

Many recent efforts have focused on individual swash events and trying to understand the processes occurring for incident-band time scales. However, it is known that infragravity energy may be the dominant (dissipative beaches) or a significant (intermediate beaches) component of the total energy in the swash zone. There have been advances incorporating the effect of infragravity motions in runup models. Less emphasis has been placed on the infragravity induced bed shear stresses, hydrodynamics and associated sediment transport.

3. Sediment Transport and Morphology

This section highlights the continued difficulty faced by swash-zone researchers in quantifying sediment transport and morphological change. Recent advances have been made in quantifying morphology using acoustic and LIDAR sensors and in situ measurements of sheet flow concentrations are now available. However, greater advances have been made in understanding and predicting hydrodynamics than for sediment transport processes. The subsections contained here identify key areas for future research that are needed to enhance predictive capability for sediment transport and morphology.

3.1 Swash Zone Definition

The swash zone has numerous definitions that may depend on the research being undertaken. However, most researchers would suggest the swash zone extends from the instantaneous runup tip to some distance offshore. The definition of the swash zone is thus instantaneous and local rather than a more global view point. Perhaps the landward extent of the swash zone should be defined more in this global context as extending all the way to the dunes even if they are rarely inundated. An argument for augmenting the definition of the landward extent of the swash zone is that it will encompass a larger area that can/will lead to newer/linked physical processes occurring within the foreshore/backbeach. Continuing to define the swash zone via local processes only may be limited with regard to describing longer term change.

3.2 Bed Shear Stress

Shear stresses in the swash zone are generally obtained via a quadratic drag law or the assumption of a logarithmic velocity profile. The former requires an estimate of the friction coefficient that may be time-dependent and/or difficult to justify/quantify over a highly mobile bed. The latter methodology was developed for steady, hydraulically rough flows. Swash zone flows are unsteady but some success has occurred using the logarithmic velocity approach. Discrepancies have been found from laboratory and shear stress plates over fixed beds. Results obtained over mobile beds are more difficult to validate. Most sediment transport formulations include shear stress so methodology to determine the time-dependent shear stress throughout a swash cycle is needed. Future modifications of shear plates or other sensors that can function during intense sediment transport are needed to obtain this critical information.

3.3 Sediment Transport

Sediment transport sensors for the swash zone do not exist. Instantaneous transport estimates arise from concentration-velocity products. Total load transport is obtained via vertical integration of that product. Dense vertical profiles of either constituent of the product are rarely available causing error in the estimate. Suspended sediment concentrations are obtained via optical backscatter sensors but laboratory calibrations are difficult to perform. Sediment concentration in the sheet flow layer can now be obtained but synchronous velocity measurements are difficult to obtain. Total load transport can be inferred from dense cross-shore morphology measurements under the assumption of negligible alongshore sediment transport gradients. These values can be used to refine sediment transport estimates based on instantaneous *in situ* measurements. However, if large, rather than incremental steps in understanding swash-zone sediment transport processes are to occur, new sensors are needed that more accurately quantify the instantaneous sediment transport signal. Additionally, laboratory wave flume studies that focus on detailed measurements of the cross-shore swash-zone morphology with simultaneous dense measurements of velocity and sediment concentration signals may help unify the estimates obtained via morphology and those from *in situ* gauges. Furthermore, the development of new techniques that allow for direct measurement of swash-zone sediment transport would lead to significant breakthroughs in understanding sediment transport processes.

3.4 Beach Accretion

Studies of sediment transport and morphology are often designed around trying to understand beach erosion. The importance of beach erosion is clear, but beaches also have some capacity to

repair themselves following large erosion events. There are also the smaller scale oscillations between erosion and accretion but these receive less attention. Future studies should also aim towards understanding the accretion/repair process of beaches as governed by swash-zone processes. Accretion is often thought of as a slow process relative to erosion. However, foreshores can begin to accrete even before a large storm has fully subsided and the accretion (foreshore and berm growth) can be rapid. There is a need to study the cumulative effects of multiple swashes to determine this process of beach recovery. Therefore, the relative role that processes across different temporal scales and under different forcing/beach conditions needs to be investigated.

3.5 Extreme Events

Recent work using ultrasonic distance meters and conductivity concentration profilers has shown that swash zone morphology changes on a swash-by-swash basis. The cumulative effect of these small changes could lead to larger change or individual events can remove or deposit a sediment layer on the order of centimeters. Are the details of these individual swash cycles important during an extreme event or do they just represent noise during the wholesale offshore transport during the extreme event? The question can only be answered if swash zone elevations can be measured *during* active storm conditions with simultaneous hydrodynamic measurements to quantify the forcing. As mentioned previously, obtaining measurements during extreme forcing will be a daunting task. It is not clear which sensor is appropriate to acquire time series of elevation measurements across the foreshore even if the sensors can be maintained in place.

3.6 Turbulence on Sediment Motion

Recent efforts (dam break, numerical modeling, high-resolution velocity profiles) have led to improved quantification of turbulent kinetic energy and energy dissipation in the swash zone. There is still a dearth of data relating any quantification of turbulence or associated quantities to the sediment response. High levels of turbulence in the bore front should enhance sediment transport but it remains unclear exactly how this process can be included in standard sediment transport formulations. There is still no straightforward means to quantify turbulent kinetic energy in the swash zone of a natural beach and its effect on sediment transport.

3.7 Upscaling Individual Events

Researchers are now focusing on the smallest scale processes occurring in the swash zone and may be approaching the point of diminishing returns. Researchers must be able to connect the small-scale processes to the larger spatial and temporal domains (e.g. entire beaches rather than single location or cross-shore profile; storm, seasonal or annual rather than event- or tide-based) otherwise the research has less impact on environmental issues facing society as a whole. The concept of determining net sediment flux by integrating across numerous swash events may be impractical given that all sensors have some associated error, empirical “constants” may not be constant and rarely if ever are measurements made throughout the entire water column and/or across the swash zone. Any errors in instantaneous sediment flux estimates will propagate through integration and are likely to be additive in the net sediment flux calculation.

3.8 Air content

Air content, specifically in coarse-grained beaches, may be significant. The effect of air content in beaches is now being investigated in laboratory settings. Interstitial voids filled with air can alter fluid pathways, change hydraulic conductivity and negate the assumption of hydrostatic pressure into the bed. Air escaping vertically via downward water intrusion may facilitate sediment suspension by vertical pressure gradients. These processes are difficult to quantify under mobile beds, even in laboratory settings, but efforts should be made to understand these processes on natural beaches.

3.9 Cross-shore Sediment Advection

The concept of advection (turbulence and sediment) from the surf zone has been addressed in several prior studies. The sediment transport aspect was addressed via sediment trapping and numerical modeling but little effort has focused on instantaneous quantities. Is instantaneous inner surf-to-swash-zone advection a concern relative to longer-term processes reshaping the beach? It is assumed that strong advection of sediment from the surf zone can occur under calmer, accretive conditions but that advection is from the swash zone to the surf zone under erosive conditions.

3.10 Profile Concavity

The foreshore can be planar or near planar. Yet, the foreshore of many beaches displays concavity. Almost all modeling and laboratory studies (mobile or fixed beds) of swash zone processes start or maintain a planar slope. Does the requirement of a planar slope that is not in equilibrium with the forcing conditions create unnatural swash interaction/conditions that lead to

an incorrect understanding of the net driving forces over a swash cycle? The effect of concavity (or even in the rare case some slight convexity) has generally been ignored.

3.11 Definition of the Seabed Location

The instantaneous location of the sea bed must occur at the highest elevation where sediment grains are immobile. This concept is straightforward to describe but difficult to quantify under active forcing. Knowledge of the instantaneous bed location is important because it determines the varying elevation relative to the bed of a deployed instrument. That elevation may have important consequences when, for instance, a value related to boundary layer thickness or bed shear stress is to be calculated. Most past research operated under the principle that the swash zone bed level changed relatively slowly in whatever net direction of change (accretion or erosion) was occurring. Thus, the bed level was assumed to vary linearly between elevation measurements taken before and after a tidal cycle. It is now known that this is incorrect. Data collected using ultrasonic distance sensors following individual swash cycles show the bed can vary up or down by several centimeters regardless of the net direction. In fact, other work using buried conductivity sensors or partially buried cameras has shown that the bed level can fluctuate up *and* down *during* a swash cycle. Improved measurements of the instantaneous bed level throughout swash events, across the foreshore and when the bed is inundated are needed to quantify the potential for these small-scale changes on net sediment transport.

3.12 Other Topics

To the authors' knowledge, little research has focused on the effect of rain, wind, or vegetation on swash-zone sediment transport. Some efforts have investigated vegetation effects on earthen

dikes but without a detailed study of sediment transport. There is increased interest in using natural roughness elements (vegetation) to dissipate tsunami energy further indicating the importance of understanding vegetation effects on hydrodynamic processes.

4. Numerical Modeling

Significant improvement on the numerical modeling of swash-zone dynamics has occurred since the 1st workshop. The development of advanced computer technology over the past decade has enabled the use of more sophisticated numerical models. Much effort has been devoted to improve the detailed modeling of swash-zone hydrodynamics (Briganti *et al.*, This Issue), whereas less effort has been devoted to sediment transport and beach morphology (Incelli *et al.*, This Issue). This section identifies some of the key processes where future research efforts related to numerical modeling could be devoted.

4.1 Swash Zone Velocities

Numerical modeling of velocity profiles in the swash zone has improved due to implementation of more sophisticated models. The coupling of boundary layer models with Nonlinear Shallow Water Equations has allowed a better description of the flow in this region. On the other hand, Reynolds-Averaged Navier-Stokes (RANS) models resolve the flow variability with fewer assumptions about the boundary layer evolution. Therefore, the prediction of velocity time series at various locations within the water column and across the swash zone is now possible. Numerical models for simulating water depth and velocities for normally incident waves are mature and robust. However, few efforts have been devoted to the understanding of alongshore

flows in the swash zone despite the availability of three-dimensional models. One issue may be related to the lack of suitable lateral boundary conditions in sophisticated numerical models.

4.2 Turbulence

Turbulence modeling in the swash zone has been mostly limited to the use of volume of fluid (VOF) RANS type models with, for example, $k-\varepsilon$ turbulence closure. The VOF models have indicated temporal variability of turbulent kinetic energy and energy dissipation across the swash zone. VOF models generally have a fixed bed so the turbulence effect on sediment motion and sediment mobility effect on altering turbulence in the swash zone are not well studied. The use of more sophisticated Large Eddy Simulation (LES) and Direct Numerical Simulations (DNS) models that can model turbulence structure and coherent eddies will further enhance understanding of these processes and provide guidance on the limitations of more simplified turbulence closure schemes. A specific emphasis is the interaction between consecutive swash events and the effect on local and advected turbulence.

4.3 Wave Runup

Predicting wave runup is important for coastal inundation and dune and coastal structure overtopping. Phase-resolving models can be employed for the simulation of different wave conditions and beach characteristics that will allow for development/improvement of runup parameterizations. Site-specific runup parameterizations may need to be developed for engineering applications. For instance, directional spread and frequency spread have been shown to affect runup and have been incorporated in recent parameterizations. Other processes such as

the role of the water table, wind, and bed roughness on the runup statistics deserves further investigation using numerical models.

4.4 Pressure Gradients

Numerical results suggest that the incorporation of the horizontal pressure gradients improve coarse sediment transport predictions. However, the horizontal pressure gradient is poorly correlated with local fluid acceleration in the swash zone where fluid stress and advection can play an important role. Improved parameterizations of the pressure gradient and/or additional studies are needed if the pressure gradient is to be routinely incorporated in sediment transport formulations. On the other hand, vertical pressure gradients are thought to be important for fluidization and plug flow conditions. High resolution numerical models have not been employed to address the importance of vertical pressure gradients on sediment transport in the swash zone.

4.5 Sediment Advection

The role of advection has been studied using different numerical models. More specifically, the studies have focused on understanding the contribution of sediment advected from the point of bore collapse into the swash zone. Numerical results suggest that the turbulence advection from the surf zone into the seaward swash zone is important for the net sediment transport during a singular swash event. However, numerical studies considering multiple swash events are necessary to determine the importance of advection over a longer time scale.

4.6 Small-scale Sediment Dynamics

Recent advances in computational power allow for the implementation of more sophisticated numerical models incorporating sediment. Approaches such as the two-phase and discrete particle models allow the understanding of small-scale sediment dynamics occurring at the grain scale. However, most of the work has been limited to U-tube simulations without considering the effect of a free surface. Some past work investigated particle motion but the coupling was one way in that the sediment did not alter the flow hydrodynamics. Fully coupled swash-zone simulations over a range of conditions will allow a better understanding on the physics of the sediment transport mechanisms and to simulate sheet-flow sediment transport.

4.7 Boundary Layer

The boundary layer evolution inside the swash zone is difficult to measure, especially over mobile beds. Numerical models are more adept at quantifying this evolution and suggest that the boundary layer vanishes during flow reversal and becomes depth limited during the backwash. Knowledge of boundary layer structure and evolution is necessary for predicting the time history of bed shear stress. The validity of the log-law at only certain stages of the swash cycle suggests that numerical models are needed to investigate the boundary layer evolution. It is not possible to evaluate/validate numerical model performance during the peak shear stress occurring at bore arrival. The applicability of standard boundary layer models in the swash zone over permeable or mobile beds have not been investigated.

4.8 Sediment Transport Modeling and Beach Morphology

Different models have been employed for the simulation of sediment transport and beach morphodynamics at different scales (see(Briganti *et al.*, This Issue). Phase-resolving models are often coupled with sediment transport models based on a simple velocity-cubed law even though measurements have shown the velocity-cubed law might be inadequate. The incorporation of infiltration/exfiltration and water table effects in numerical models has been shown to be important for prediction of beach profile evolution. It is shown that the degree of coupling between hydrodynamics and morphodynamics plays an important role in the net sediment transport. However, the major drawback on the beach morphology modeling is that sheet-flow sediment transport is not simulated. Thus, future modeling efforts should address total load transport including sheet flow processes.

4.9 Swash Zone Data for Model Validation

We stress the need for continued communication between modelers and experimentalist for the design of field and laboratory experiments and model enhancement. Dense inner surf boundary conditions (hydrodynamics and sediment concentration/transport) are needed to refine advection, sediment pickup, and sediment transport modules leading to improved predictive capability. Numerical models tend to be validated with cross-shore data only or for final morphological state. Thus, it is difficult to identify important processes that are poorly represented in the numerical models. Measuring intra-wave bed evolution at multiple locations across the foreshore in addition to detailed measurements with alongshore separation will provide enhanced (and more difficult) opportunities for model validation.

503

504 4.10 Model Selection

505 The choice of which numerical model to use depends on the processes of interest. (Briganti *et*
506 *al.*, This Issue) discuss the variety of models used for the modeling of a single dam-break driven
507 swash event. Both depth-averaged models and depth-resolving models are able to predict the
508 water depth, shoreline trajectories, and the cross-shore velocity within the swash zone. Depth-
509 resolving models are in better agreement with respect to the velocity data during the backwash
510 but at a higher computational cost. Current sensor limitations prevent a more detailed verification
511 of the model performance for bed shear stresses. RANS models simulate the turbulence intensity
512 near the bed, whereas LES yields a better performance near the free surface. Swash-zone
513 morphodynamics can only (presently) be addressed with depth-averaged models coupled with
514 simplified sediment transport formulations due to the computational constraints in depth-
515 resolving models.

516

517 4.11 Uncertainty

518 The uncertainty in predicting physical processes has been considered in other fields such as
519 fluvial hydraulics. However, uncertainty in predicting swash-zone processes has not been fully
520 investigated. Numerical models are an excellent tool to investigate uncertainty by using different
521 model parameters and employing multiple realizations (Monte Carlo simulations) to assess the
522 natural (expected) variability of swash-zone processes such as runup and erosion. Utilizing
523 multiple realizations enables a reliable assessment of large-scale models considering natural
524 variability. Operational modeling/forecasting and parameterizations should include uncertainty
525 in the output predictions.

5. Summary

Extensive progress over the last 10 years has been made with regard to swash-zone processes (Chardon-Maldonado *et al.*, This Issue). Yet, numerous, difficult issues still face swash zone researchers. The major difficulties are focused around quantifying and modeling sediment transport (new sensors, more robust and dense measurements, higher resolution models) and net morphological change (Incelli *et al.*, This Issue) and subsurface processes (Pokrajac and Sparrow, This Issue) that may alter sediment transport processes. Future efforts should focus on swash-zone research with clear societal impacts. An obvious example is understanding swash-zone processes on seasonal and interannual timescales, under extreme conditions where severe coastal damage can occur (Palmsten and Splinter, This Issue; Park and Cox, This Issue; Ruggiero and Cohn, This Issue). However, beach recovery is an overlooked topic that also warrants future consideration.

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Table 1. Attendees at the second international workshop on swash-zone processes.

Researcher	Institution
Dylan Anderson*	Oregon State University
Roham Bakhtyar	University of North Carolina
Joe Calantoni	Naval Research Laboratory
Patricia Chardon-Maldonado*	University of Delaware
Nick Cohn*	Oregon State University
Daniel Conley	Plymouth University
James Heiss*	University of Delaware
Diane Horn	Birbeck College
Tom Hsu	University of Delaware
Brad Johnson	United States Army Corps of Engineers
Nobu Kobayashi	University of Delaware
Holly Michael	University of Delaware
Ryan Mieras*	University of Delaware
Mary Munro*	Woods Hole Oceanographic Institution
Aline Pieterse*	University of Delaware
Jose Carlos Pintado Patino*	Universidad Nacional Autonoma de Mexico
Dubravka Pokrajac	University of Aberdeen
Matteo Postacchini	Universita Politecnica delle Marche
Jack Puleo	University of Delaware
Britt Raubenheimer	Woods Hole Oceanographic Institution
Peter Ruggiero	Oregon State University
Chris Russoniello*	University of Delaware
Stefan Schimmels	Forschungszentrum Küste
Hilary Stockdon	United States Geological Survey
Babak Tehranirad*	University of Delaware
Alec Torres-Freyermuth	Universidad Nacional Autonoma de Mexico

*Indicates student research assistant