INFLUENCE OF SEASONAL HYDROLOGICAL VARIATION ON SWASH ZONE MORPHOLOGICAL CHANGES

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DEDICATION

To my beloved family

My Parents;

Othman Hj. Maidin

Normah Mohd Jani

My wife;

Shairul Rohaziawati Samat

My children;

Nurul Syauqina Norasman

Naim Syauqi Norasman

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ABSTRACT

Studies on hydrodynamics of sediment transport in recent years stressed on knowledge advancement and practical applications of swash processes. The hydrodynamic processes significantly affect sediment transport mechanisms that control beach face morphology. In Peninsular Malaysia, seasonal variation of dry and wet periods in the months of May to September and November to March respectively, noticeably influenced the evolution of beach profile. This study investigates the influence of seasonal hydrological variation to beach groundwater table and how it affects swash zone morphological changes. Field monitoring was carried out at a section of Desaru beach, Johor for 30-months consisting of data on a beach cross-shore profile, rainfall distribution, groundwater table, tidal variation and swash flow velocity and depth. These were monitored and investigated to check for patterns of interrelationships among the parameters. Results indicated that the seasonal variation of Desaru beach morphology was primarily controlled by the cross-shore exchange of sediment in the swash zone. The beach profiles showed erosive condition due to seaward sediment movement during the wet season, while during the dry season, the beach profile showed accretion condition due to the increase of landward sediment movement. The total sand volume at Desaru beach was found to be highly correlated ($R^2 = 0.86$) with the shoreline position. For detailed beach profile analyses, the Empirical Orthogonal Function (EOF) technique was applied and showed changes in profile configuration as a function of space and time. The analysis confirmed that the swash zone of Desaru beach is the most dynamic region on sandy beach with cyclic processes of erosion and accretion. Most of the variation in the beach profiles can be explained by the first five eigenfunctions (EOF1-EOF5) that has the highest eigenvalues. It was revealed that 99.99% of the data variance was captured by these eigenfunctions. This confirmed that the method provides a means of presenting space and time variability of beach profiles. The study also illustrated that the groundwater table elevation was influenced by rainfall patterns where higher groundwater table during the wet season and lower groundwater table during the dry season was observed. The fluctuating groundwater table is an important mechanism to explain the role of infiltration and exfiltration processes in the morphology of swash zones. The relationship between the average shoreline position with groundwater level monitored at wells BH2 and BH3 indicated moderate correlation with values of R^2 equals to 0.75 and 0.67, respectively. The velocity reduction of uprush to backwash flow during the dry period was higher (73.08%) compared to during wet period (46.00%). Similar pattern was found in the swash flow depth analysis where the reduction percentage showed higher reduction during the dry period (52.17%) compared to during the wet period (24.64%). This study quantified seasonal hydrological variation influence on the swash zone morphological changes and provided a better understanding of beach profile evolution, leading to improved beach management practices in Malaysia.

ABSTRAK

Kebelakangan ini, kajian tentang hidrodinamik pengangkutan enapan menekankan kemajuan pengetahuan dan kegunaan praktikal dalam proses di zon damparan. Proses hidrodinamik sangat memberi kesan terhadap mekanisma pengangkutan enapan yang mengawal morfologi permukaan pantai. Di Semenanjung Malaysia, kesan perbezaan musim kering dan lembap yang masing-masing berlaku di bulan Mei hingga September dan di bulan November hingga Mac mempengaruhi evolusi profil pantai. Kajian ini menyiasat kesan variasi hidrologi terhadap paras air bumi pantai dan bagaimana ia mempengaruhi perubahan morfologi pantai. Kerja-kerja pemantauan lapangan telah dilakukan di satu bahagian pantai Desaru, Johor, selama 30 bulan yang meliputi profil keratan rentas pantai, taburan hujan, paras air bumi, air pasang surut dan ciri-ciri halaju dan ketinggian aliran di zon damparan. Pemantauan ini adalah untuk menyiasat corak perhubungan di antara semua parameter yang terlibat. Keputusan menunjukkan perubahan morfologi di pantai Desaru dikawal sepenuhnya oleh pertukaran rentas pantai di zon damparan. Profil pantai menunjukkan keadaan menghakis disebabkan oleh pergerakan sedimen ke arah laut semasa musim lembap manakala semasa musim kering, keadaan enap timbus telah disebabkan oleh peningkatan pergerakan sedimen ke arah darat. Jumlah isipadu pasir di pantai Desaru didapati mempunyai kolerasi yang tinggi (R^2 = 0.86) dengan posisi garis pantai. Untuk analisis profil pantai yang lebih terperinci, kaedah fungsi ortogon empirik (EOF) telah digunakan dan ia berhasil menunjukkan perubahan profil sebagai fungsi ruang dan masa. Analisis ini juga mengesahkan zon damparan di pantai Desaru sebagai bahagian pantai yang paling dinamik dengan kitaran kejadian hakisan-enap timbus. Kebanyakan variasi pada profil pantai ini boleh dijelaskan oleh lima fungsi eigen yang pertama (EOF1 – EOF5) yang mana mereka mempunyai nilai-nilai eigen tertinggi. Analisis mendapati 99.99% varian data telah diperolehi daripada fungsi-fungsi eigen ini. Ia mengesahkan bahawa kaedah yang digunakan berupaya menggambarkan perubahan profil pantai daripada segi ruang dan masa. Kajian ini juga menunjukkan bahawa paras air bumi dipengaruhi oleh taburan hujan di mana paras air bumi adalah lebih tinggi semasa musim lembap dan lebih rendah semasa musim kering. Paras air bumi merupakan satu petunjuk penting untuk menerangkan peranan proses penyusupan dan penyusupan keluar semasa berlaku perubahan morfologi di zon damparan. Hubungan antara posisi purata garis pantai dengan paras air bumi di perigi pemantauan BH2 dan BH3 menunjukkan korelasi sederhana dengan nilai R^2 masing-masing bersamaan 0.75 dan 0.67. Pengurangan halaju aliran air naik berbanding dengan aliran air turun semasa musim kering adalah lebih tinggi (73.08%) berbanding semasa musim lembap (46.00%). Corak yang sama didapati dalam analisis kedalaman aliran di zon damparan di mana peratusan pengurangan adalah lebih tinggi semasa musim kering (52.17%) berbanding musim lembap (24.64%). Kajian ini telah menilai kesan perbezaan hidrologi bermusim terhadap perubahan morfologi di zon damparan pantai dan memberi pemahaman yang lebih baik tentang evolusi profil pantai, seterusnya membawa kepada penambahbaikan amalan pengurusan pantai di Malaysia.

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LIST OF ABBREVIATIONS

1-D - One Dimensional
BH - Borehole
CCA - Canonical Correlation Analysis
CD - Chart Datum
DID - Department of Irrigation and Drainage
ECM - Electromagnetic Current Meter
EOF - Empirical Orthogonal Function
HAT - Highest Astronomical Tide
JUPEM - Jabatan Ukur Dan Pemetaan Malaysia
KEJORA - South East Johore Development Authority
LAT - Lowest Astronomical Tide
LSD - Land Survey Datum
MHHW - Mean Higher High Water
MHLW - Mean Higher Low Water
MLHW - Mean Lower High Water
MLLW - Mean Lower Low Water
MSL - Mean Sea Level
PCA - Principal Component Analysis
PT - Pressure Transducer
PVC - Polyvinyl Chloride
SEOF - Spatial Empirical Orthogonal Function
SPT - Standard Penetration Test
TEOF - Temporal Empirical Orthogonal Function
UK - United Kingdom
USA - United States of America

LIST OF SYMBOLS

C_n - Temporal orthogonal function

e_n - Spatial orthogonal function

$h_{x\mathrm{t}}$ - Profile depth

K - Hydraulic conductivity

N - Total of measurement

n_t - Number of cross-shore profile survey

n_x - Number of measurement point

x - Distance of measured point

σ - Standard deviation

λ - Eigenvalue

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CHAPTER 1

INTRODUCTION

1.1 Background of the Study

Recently, the scientific community has recognized the importance of swash zone role on a natural beach. Swash zone is a beach area where the sediment transport takes place and acts as a conduit of sediment movement between the surf zone and the upper beach. The swash zone is an important part on beach profile evolution. The hydrodynamic process in the region plays a very important role in a beach profile evolution because it can determine whether the shoreline will be eroded or accreted.

Previous researchers such as Beach et al. (1992) defined the swash zone as the boundary of a beach and the process of sediment transport at this zone is greater than that of the surf zone. The hydrodynamic process in the swash zone also plays a role in determining the sediment movement either the sediment shifts to the inner surf zone (transported offshore) or the sediment deposits on the upper beach area (transported onshore).

Brocchini (2006) reported that the swash zone flows are of fundamental importance not only due to their influence on the entire zone but also their effects on the whole surf zone processes. Butt and Russell (2000) also found that numerous physical processes such as unsteady movements including the development of turbulent structures within the uprush and backwash flows, gravitationally driven fluid motion, and the percolation process of the seawater into the unsaturated, porous beaches are heavily determined by the swash zone hydrodynamic processes.

As the physical process occurrences at the swash zone are very complicated, it is difficult to conduct a field measurement. Although the swash zone has been studied since years back, there is still much gap to be investigated on the swash zone hydrodynamics. Hughes et al. (1997) stated that the time scale of swash motion at the swash zone is highly varied and ranged from seconds to minutes on calm-steep and reflective beaches. Meanwhile, Butt and Russell (1999) reported the time scale of swash motion is varied and ranged from second to minutes on energetic, low-gradient, and dissipative beaches. From their study, Puleo et al. (2000) were able to characterize the swash zone as strong and unsteady flows, high turbulence levels, large sediment transport rates, and rapid morphological changes. Longo et al. (2002) also reported that the swash zone is generally referred to as an extreme and energetic area of inner surf zone, where there is a range of flows at different scales, turbulence, involving short and long waves, vortices, and currents. The complexity of processes occurring at the swash zone is also proven by Elfrink and Baldock (2002) where they reported that the swash zone is the most dynamic part of the nearshore region and was characterized by large flow velocities, high turbulence levels, and large suspended particle concentrations. A study from Baldock et al. (2009) acknowledged that the swash zone’s role involved in the sediment transport process on sandy beaches (bed and suspended load) and shingle/steep beaches (bed-load) is significant.

Basically, a beach groundwater system is classified as highly dynamic in an unconfined aquifer in which the flows are subjected to change in both saturated and unsaturated beaches by waves, tidal, rainfall, and interactions with deeper aquifers (Horn, 2006). The beach groundwater also has a significant impact on shaping the beach profiles during the tidal cycle. Typically, a lower groundwater level will cause accretion while a higher groundwater level will influence the erosion on beach profile. There are two types of interactions involving the groundwater in the swash zone. First, when the beach groundwater is lower than the seawater as shown in Figure 1.1, an uprush flow will naturally infiltrate into the unsaturated beach. The propagation of waves up the beach is referred to as an uprush and the return of the water is denoted as a backwash. Li et al. (2002) and Jamal (2011) stated that this infiltration process can reduce the duration and velocity of the backwash flow, thus will reduce the sediment transport within the beach profile. Second, if the beach groundwater is higher than the seawater level, the backwash flow will mix with an addition of water rising to the surface or the seepage face and therefore will produce a greater backwash flow (Horn, 2002), as shown in Figure 1.2. This situation will enhance the offshore sediment transport as it increases the velocity and depth of the backwash flow.

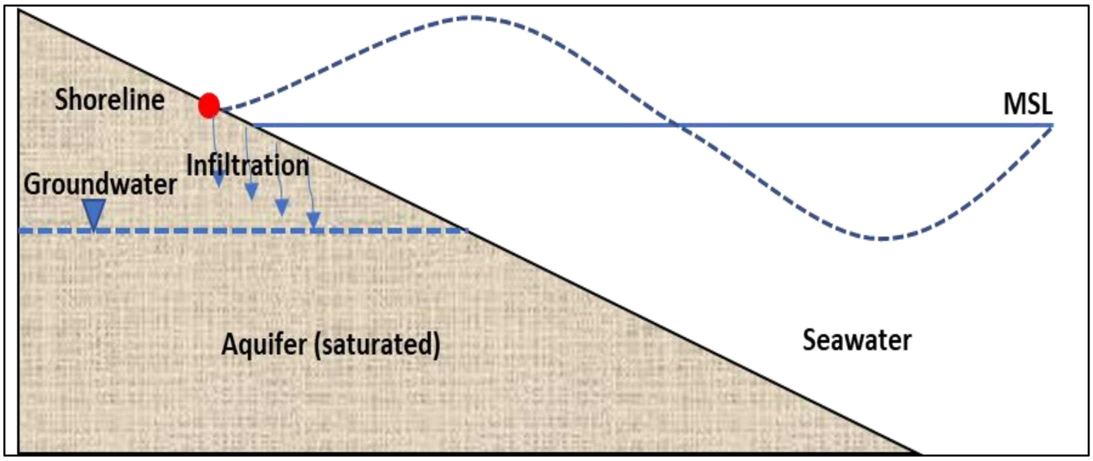


Figure 1.1 Beach groundwater system (infiltration process)

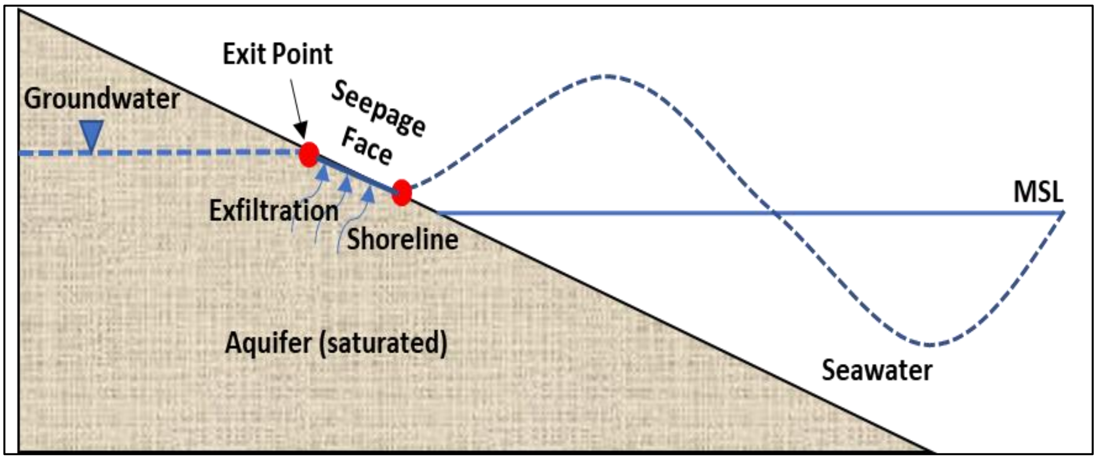


Figure 1.2 Beach groundwater system (exfiltration process)

The interaction between swash dynamics and the beach groundwater plays an important role as a controller for the swash zone sediment transport. This relation can adjust the intertidal beach morphology entirely by controlling the potential movement of onshore or offshore sediment transport as well as the deposition or erosion around mean sea level (MSL). Many previous researchers have studied and reported a cyclic erosion and accretion of the beach profile which is the result of the beach groundwater table and swash hydrodynamics interaction (Turner & Nielsen, 1997; Li & Barry, 2000; Elfrink & Baldock, 2002; Li et al., 2002; Austin & Masselink, 2006; Horn et al., 2007). Most of these studies reveal that a beach with low groundwater table has a potential to accrete while a high groundwater elevation beach tends to erode. Moreover, laboratory experiments conducted by Horn et al. (2007) concluded that the onshore sediment transport and berm development were increased when the beach groundwater table was lowered. The flows at the swash zone area have affected the beach profile seaward of the intertidal profile hence influencing sediment transport in the bar region. Furthermore, to date, there are only a few field measurement works that have been conducted to get a clear view for better understanding about swash hydrodynamic processes and other related parameters in controlling the beach region entirely. Thus, the swash sediment transport at the coastline is not satisfactorily signified and understood especially under local seasonal hydrological variation effect.

1.2 Problem Statement

Generally, erosion and accretion processes of a coastal morphology occur on the surf and swash zones. The morphological evolution of a beach is mostly affected by tide, wave, beach material, and slope. However, the distribution of rainfall events especially in a tropical area may affect the groundwater level, which may directly change the beach profile especially in the swash zone.

The interactions between beach profiles and factors that control the change have been studied extensively before by previous researchers using field measurements, laboratory experiments, statistical and numerical models, covering a different range of study periods from short-term to long-term investigations especially at four season countries such as UK, USA, Japan and Australia. Identification of a beach profile change due to different climate also has been studied extensively by many researchers which focused on the beaches under seasonal variation effect due to winter and summer seasons or storm and post-storm events.

In general, the rainfall distribution pattern across the tropical regions of Southeast Asia is heavily influenced by the different monsoon seasons combined with the local topography characteristics. During the northeast monsoon season (November–March), heavy rainfall and storms as well as energetic wave condition due to strong onshore wind at the east coast region of Peninsular Malaysia contribute to a high possibility of erosion activities at the beach area. This erosive condition is driven by energetic uprush and backwash activities. In contrast, the dry season is observed during the southwest monsoon season (May–September) when weaker waves activities associated lesser rainfall events are recorded. These situations contribute to a significant drop of groundwater level and beach saturation degree. In the meantime, it is believed that the beach accretion process during this period is increased due to a calmer wave condition and a higher infiltration process in the swash zone. Another factor to be considered in the study is the influence of tidal elevation towards the beach groundwater fluctuations in controlling the beach morphological changes under different periods. This process is important to evaluate the beach groundwater table response due to the beach characteristics.

Thus, it is noteworthy to investigate the variability of Desaru beach profiles in the swash zone in accordance with the effects of Malaysian seasonal hydrological variation to further understand its morphodynamic behavior.

1.3 Objectives of the Study

The aim of this study is to quantify the influence of natural forces such as rainfall distribution and tidal elevation on the beach groundwater table variability towards cross-shore morphological changes in the swash zone under different local seasonal hydrological variation (dry and wet periods). The changes of the beach profile in the swash zone were analyzed using appropriate statistical methods to determine the expected trend of the beach profile in the future. To achieve this aim, the objectives of the study are as follows:

1. To quantify the influence of local seasonal variation on the beach profile morphological changes based on field observation and statistical analysis.
2. To investigate the variability of swash zone morphological profile under spatial and temporal variations using empirical orthogonal eigenfunction EOF analysis.

3. To evaluate the cross-shore morphological changes and groundwater table variability under the influences of seasonal rainfall and tidal elevation.

4. To determine the swash velocity and depth for sandy beach under seasonal hydrological variation.

1.4 Scope of the Study

The present study focused on the development of the relationship between cross-shore profile and beach groundwater table in the swash zone under seasonal hydrological variation effect. In terms of seasonal variations, two different periods were selected and considered as a dry period during southwest monsoon from May to September and a wet period during northeast monsoon from November to March for 30 months of field data collection which started from June 2013 until January 2016.

The study area considered for this study was Desaru beach, which is a natural and undisturbed sandy beach located at eastern Johor, Peninsular Malaysia. For this study, one cross-shore transect was selected from this site which had the least impact from longshore sediment transport due to the location of the beach and direction of incoming waves.

For data collection in the field work, the swash hydrodynamic data (swash depth velocities and swash velocity), hydrological data (rainfall depth and groundwater table), and morphological data (profile elevation and shoreline position) were collected and analyzed under different seasonal variations. The related data from offshore such as wave height and wave period were not considered for this study.

A series of investigation work using several statistical models such as bulk statistics (e.g. mean, range, standard deviation and correlation) and empirical orthogonal function (EOF) analysis were applied for this study to analyze the relationship between rainfall, beach groundwater level, and tidal response directly to the swash zone morphological changes.

1.5 Significance of the Study

A better understanding of the interaction between the swash and groundwater flows in swash zone today is essential to understand a beach profile evolution. Coastal scientists have recognized the importance of swash and beach groundwater table and the interaction of accretion and erosion above the MSL but the exact nature of the relationship between swash flows, beach groundwater table flow, and their impact on cross-shore morphology under seasonal hydrological variation effect (dry and wet periods) in Malaysia is still not fully understood.

The hydrodynamics of the uprush and backwash flows are not performed in the same way. During an uprush, the flow is decelerating while during a backwash, the flow is accelerating. In addition, no study has been conducted about the impact of seasonal variations of tropical climate (dry and wet periods) on the beach profile changes especially in the swash zone to date. In Peninsular Malaysia, the rainfall distribution patterns are typically influenced by the seasonal wind flow patterns together with the local topographic features. The influence of heavy rain and storms can contribute to a higher potential of beach groundwater table elevation and erosion rate at the nearshore zone during the wet season starting from November to March. Meanwhile, during the dry season which starts from May to September, lesser rainfall will significantly drop the beach groundwater table. From this unique condition, the seasonal hydrological variation factor in tropical countries like Malaysia is believed to have a great influence on beach sediment transport processes due to groundwater table variability predominantly in the swash zone which beaches are likely to erode during the wet season and accrete during the dry season. The benefits that would be gained from this study may include the following:

i. Provide essential quantification information of the swash zone characteristics under Malaysia’s seasonal hydrological variation effect to beach groundwater hydrodynamic system and cross-shore morphological changes.

ii. Understand the response of the swash zone morphological changes for a sandy beach using a historic measurement of beach profiles, swash characteristic, rainfall distribution, tidal elevation and beach groundwater data.

Last but not least, the biggest factor of motivation to conduct this study is to produce a pioneer research about morphological changes in the swash zone for Malaysian sandy beach. This study also can hopefully assist or guide other researchers from other universities and agencies to study or investigate about the beach profile evolution and sediment transport processes in the swash zone especially under Malaysia's seasonal hydrological variation.

1.6 Structure of the Thesis

This thesis is structured into five chapters: introduction in Chapter 1, literature review in Chapter 2, research methodology in Chapter 3, results and discussion in Chapter 4, and conclusions and recommendations in Chapter 5.

The general principle and background of the study are described in Chapter 1. Apart from the problem statement, Chapter 1 also discusses the objectives, scopes, and significance of the present study.

The related research work and review of the literature are presented in Chapter 2. This chapter mainly provides detailed descriptions about the physical processes in the swash zone, effects of beach groundwater dynamics in terms of infiltration/exfiltration activities to swash zone morphological changes. Chapter 2 also outlines different methodologies of field monitoring works, laboratory experiments, and statistical models that were employed in the previous studies especially on beach profile evolution.

Chapter 3 is organized to describe the methodology of the present study particularly the field monitoring works at Desaru beach and the statistical techniques that were used in this study.

Subsequently, Chapter 4 in this thesis is related to the results and analyses of the collected data. In this chapter, a series of beach profiles from the study area were selected depending on the different types of analysis for this study. Several simple statistical techniques (bulk statistical) were used to analyse and discuss the outputs from the relationship between rainfall, beach groundwater level, and tidal response directly to the swash zone morphological changes at Desaru beach. In order to investigate the profile variability in terms of space and time during the study period, an advanced statistical technique was employed. This chapter also presents and discusses the swash zone characteristics in detail (i.e., swash flow velocity, swash depth) under different seasonal periods of monitoring. These results can provide a better assessment on how the local seasonal hydrological variation factor in tropical countries like Malaysia could affect the swash hydrodynamic processes such as infiltration and exfiltration. It can also provide additional information for the future development of better prediction models or equations related to beach profile evolution in tropical countries.

The final chapter (Chapter 5) presents the conclusions of the research work based on the results obtained in the study. Finally, recommendations for future research especially in this particular area is suggested.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

Many works have been conducted in order to investigate the influence of swash zone processes on beach profile morphological changes by previous researchers (e.g. Horn and Mason, 1994; Butt and Russell, 2000; Elfrink and Baldock, 2002; Foote et al., 2002; Longo, 2002; Brochini, 2006; Masselink and Puleo, 2006; Moreno, 2006; Bakhtyar et al., 2009 and Alsina et al., 2012).

Various definitions of the swash zone may depend on the works or studies that have been taken by various researchers. However, the main definition of the swash zone according previous researchers can be described as the part or section of the beach area that is continuously covered and exposed by uprush (run-up) and backwash (run-down) flows and is located entirely within the inter-tidal zone as shown in Figure 2.1. These continuous processes of uprush and backwash flow activities on this area automatically form a beach shape where majority of incoming offshore waves will be dissipated or reflected their remaining wave energy when traveling towards the beach area. From previous observation, the sediment transport movement on this area are significantly influenced by the swash flow processes which also depend on various factors that contributed to the swash flow hydrodynamics for example beach gradient, sediment properties, wave energy, groundwater dynamics and tidal variation. However, all the mentioned factors are believed to affect the swash zone morphodynamics particularly under local seasonal variation effect such as summer-winter seasons or dry-wet periods depending on the beach location. That is why the swash zone has recently been recognized as one of a major contributor to beach profile changes due to shoreline accretion or erosion and is directly affected by the sediment transport activities in the area.

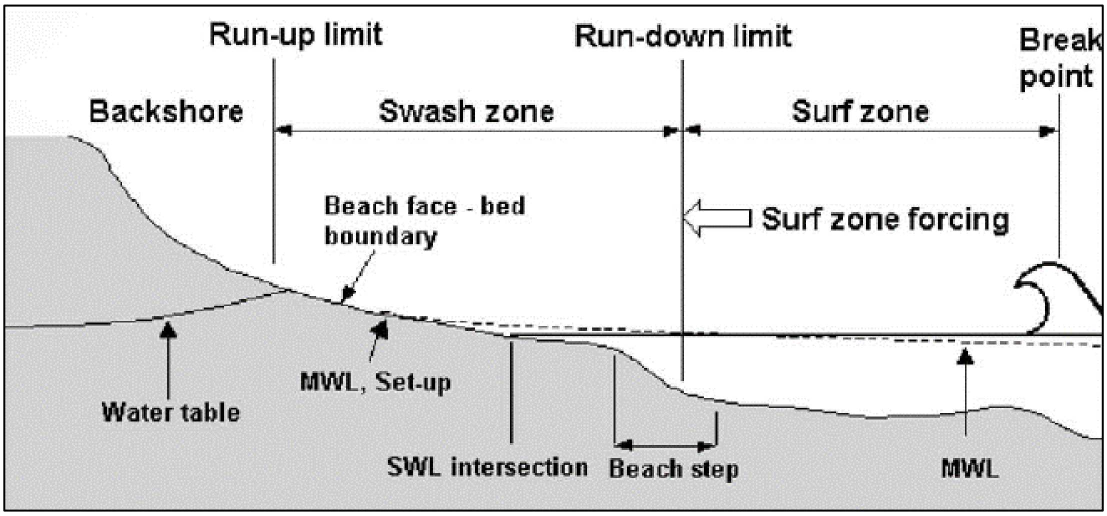


Figure 2.1 Definition of swash zone in the beach area (Elfrink and Baldock, 2002)

Additionally, the swash zone dynamic processes still need a further understanding or advance study due to the complexity of the mechanisms involved in the area especially on the beach sediment transport. The swash zone study on a natural beach area is considered important because significant amount of the sediment transport occur in this region. It is basically recognized that the strong relationship between seawater and sediment in the nearshore zone contribute to movement of sediment suspension and transport that control the beach morphology. Because of that reason, the main factor of beach erosion or accretion processes in the nearshore region is the effect of swash zone hydrodynamics. It is clear that the swash processes also decide whether onshore sediment is transported to the upper beach or is instead returned to the inner surf zone as potential offshore transport. Thus, the swash zone acts as a sediment channel between the upper beach and the surf zone. Also, the swash zone is known as the landward boundary of the beach that plays a key role to determine whether the beach either erodes or accretes (Bakhtyar et al., 2009).

This chapter presents the main processes involved in the swash zone and their effect in controlling the beach morphodynamic changes under seasonal variation. The main element in this study is the investigation of the Desaru beach profile variations. This chapter also highlights the potential of natural forces such as rainfall and tidal effect on the beach groundwater table variation in the swash zone.

2.2 Swash Zone Processes

Most of studies on beach profile variability investigated hydrodynamics and sediment transport processes in the swash zone. According to Bakhtyar et al. (2009) regarding the main physical processes in the swash zone, majority of these studies are mainly concentrated on flow in the swash zone involving different rates induced by waves, turbulence due to wave breaking and uprush–backwash flow interaction, sediments and pore water interaction; infiltration and exfiltration processes, layer flow and shear stress, and longshore current.

Since all the related activities in the swash zone are very complicated, any field measurement or experiment is difficult to conduct in order to explore in-depth or details about swash zone hydrodynamic processes. Today, the importance of the swash zone consideration in coastal engineering study evidently motivate researchers to give more attention on swash zone hydrodynamic processes. Furthermore, the swash zone effect has been recognized to contribute significantly in sediment transport on sandy beaches (bed and suspended load) and most significantly on steep/shingle beaches (bed-load) (Horn and Mason, 1994). This statement also supported by Butt and Russell (2000) with their statement that the swash zone hydrodynamics are influenced by many physical processes including unsteady, turbulence process due to uprush and backwash flow movement, gravitationally driven fluid motion, percolation of the flow into the unsaturated or porous beach and the development of turbulent structures within advancing and retreating flows.

Meanwhile, Brocchini (2006) also found that the swash zone hydrodynamics are not only fundamentally important because of their local effects to longshore sediment transport, structure overtopping and more but also their influence on the entire beach system especially in surf zone dynamics. Previous researches (e.g. Holman, 1981; Herbers et al., 1995) revealed that swash zone flows are often conquered by infra-gravity motions (low frequency), which be likely to have a cross-shore standing wave structure. In terms of sediment volume, the maximum sediment transport load in the swash zone can be larger than those in the surf zone. Because of that condition, it may determine the overall sediment budget for beaches (Beach et al., 1992). The concentration of sediment transport are regularly high in the swash zone which may normally be several orders of higher magnitude in the swash zone than in the inner-surf zone (Osborne and Rooker, 1999; Beach and Sternberg, 1991). The understanding of swash zone processes is also necessary to get a better view about beach morphology and shoreline stability. Eventually, the net sediment transport in the swash zone is considered important because it determines the status of beach physical condition, whether it is eroded, accreted or in an equilibrium condition (Hughes et al., 1997). In the swash zone, the uprush activities move sand towards onshore while the backwash transports it offshore. Additionally, the swash flow activities during uprush and backwash flow in the swash zone offers an interesting process which can be explored to understand their role on the swash sediment transport in controlling the profile shape of the beach. This swash flow processes can give valuable information about beach profile evolution under seasonal variation influence.

Basically, swash cycle consists of two main processes; first the uprush where the swash flow undergoes rapid acceleration in landwards direction and second the backwash where it decelerates down the beach in the seawards direction. Generally, for swash-swash interaction or usually known as uprush-backwash interaction, the flow during uprush becomes slower while during the backwash, the flow is accelerating (Hughes et al., 1997; Butt and Russell, 2000; Elfrink and Baldock, 2002). All this uprush and backwash flow in the swash zone usually follow an oscillatory motion (Hughes and Baldock, 2004; Horn, 2002; Foote et al., 2002). Hydrodynamics processes in the swash zone affect the mechanisms of sediment transport during wave uprush and backwash and extensively controls the beach face morphodynamics (Weir et al., 2006; Butt et al., 2007). Change of shoreline position is also generated by either or both of cross-shore sediment transport and gradients in longshore material flux (Hughes, 1992).

From observation, the uprush process is dominated by bore turbulence, especially on steep beaches whilst the backwash is conquered by turbulent dissipation resulting from boundary layer formation near the bed. As a result, the sediment tends to be mixed into the water column and transported as suspended load during the uprush, whereas sheet flow and bedload transport dominate during backwash

(Masselink and Puleo, 2006) with the backwash duration typically longer than uprush (Hughes et al., 1997, Hughes and Baldock, 2004). However, all these are mostly related to sandy beaches. Swash processes are shaped by inner surf zone mechanisms and the topography of the beach face (Pedrozo-Acuña, 2005). For example, during calm situations, most sediment transport is restricted in the swash zone, meanwhile, during storm conditions, the sediment transport may take place over a larger nearshore region. But the swash backwash flow is not basically just the reversal of swash uprush flow and therefore irregularity still occurs (Hughes et al., 1997, Barnes et al., 2009).

In coastal design, according to Kobayashi (1999), the swash zone processes like breaking waves, uprush and backwash flow are considered important in most coastal projects design and development. Bakhtyar et al. (2009) concluded in his review that the swash zone plays an important part in mostly all coastal natural processes including coastal currents and sediment transport. Obviously, interaction between seawater and sediment in this region could decide whether the beach is in erosion or accretion mode. Another natural process, breaking waves could also adjust the wave forces on coastal structures during interaction between wave and structures. The swash zone also provides the basic mechanism for sediment exchange between the subaerial and subaqueous zones of the beach (Masselink and Hughes, 1998; Puleo et al., 2000) and a detailed understanding of this process is vital importance to the modelling of shoreline evolution (Masselink et al., 2005). Another important finding from the previous study of swash identified by Jackson et al. (2004) who reported that the bore-related turbulence process and their interaction between uprush and backwash flow will increase the turbulence level and resulted in an effect on the swash zone sediment transport. Meanwhile in beach groundwater studies, the variation of groundwater table in the swash zone was found to significantly influence the swash zone hydrodynamics and sediment transport processes (Conley and Griffin, 2004; Horn, 2006). It was observed that the infiltration and exfiltration processes by the groundwater dynamics significantly controlled sediment transport movement in the swash zone.

2.3 Swash Flow Velocity

In the swash zone, field measurements of the hydrodynamic processes for uprush and backwash activities have been conducted using a variety of methods, but individual studies have repeatedly revealed some general features of the swash zone internal flows and confirmed the significant differences between uprush and backwash flow events.

One of the most important hydrodynamic parameters for sediment transport process in the swash zone is flow velocity. There are a lot of previous studies that study about flow velocities obtained in the swash zone. For examples, Kemp (1975) discusses some findings from his laboratory examples, whereas Schiffman (1965), Kirk (1971), Beach and Sternberg (1991), Masselink and Hughes (1998), Katori et al. (2001) present about field measurements from a variety of natural beaches. Jago and Hardisty (1984) and Hardisty et al. (1984) report about the field measurements of time-averaged velocities for the uprush and backwash separately. Several field studies (e.g. Hughes et al., 1997; Masselink and Hughes, 1998; Masselink and Li, 2001; Alsina et al., 2012) have recorded the total sediment load for every single uprush and backwash activities in the field and related this to swash flow velocity. They concluded that the sediment load was significantly correlated to the uprush and backwash velocities but with different coefficients for both processes. The studies also concluded that the sediment transport processes that occur in the swash zone was basically affected directly by swash uprush and backwash processes which results in deposition and removal of sediment on the beach surface, respectively.

One of the biggest challenges when conducting any field measurement in the swash zone especially for velocity profiles is to confirm that equipment like current meter still remain at the same location or at a fixed distance from the bed or beach surface. According to the findings by Austin et al. (2011), even modest changes in the bed level can either cause burial of the current meters (accretion) or cause the current meter to be placed too far from the bed (erosion). In order to make sure that good quality swash velocity data is recorded during the beach surface movement, they suggest that the current meter must be manually maintained or kept at a fixed elevation.

Assessment of swash velocity data need special attention especially when the current meter is submerged, either they are wet or dry. In order to ensure the quality of the velocity measurement in the swash zone, an automated routine based on the water depth recorded at the location of the current meter, as well as manual inspection of the current meter data were used to identify any invalid data. This study also stated that detailed field measurement of swash zone hydrodynamics obtained from a sandy and gravel beach show that the alongshore-directed flow velocities within the swash zone can be of the same order of magnitude as the cross-shore flows.

From previous studies on different type of beach slopes, a maximum velocities approaching 2 m/s for uprush were recorded on gently sloping natural beaches (Beach et al., 1992; Butt and Russell, 1999). On steeper beaches, uprush flows are commonly greater and may reach up to 3.5 m/s (Hughes et al., 1997; Masselink and Hughes, 1998). For swash flow velocities, the readings of maximum values recorded by a current meter varies depending on the location of current meter in the swash zone. From the field observations, if the current meter is dry before being flooded by the next uprush flow, the maximum velocity occurs instantly (e.g. Hughes and Baldock, 2004; Hughes et al., 1997; Masselink and Hughes, 1998; Puleo et al., 2000; Masselink et al., 2005), but if the current meter is already inundated, the maximum uprush velocity could happen just after the leading edge passes (Butt and Russell, 1999; Osborne and Rooker, 1999). Another technique that has been used in the laboratory is remote sensing techniques that captures a rapid, short-timed acceleration of the flow during the initial stages of uprush (Jensen et al., 2003). According to Nielsen (2002), the presence of flow velocity process in the swash zone is very important, because it may potentially move the sediment during the uprush processes. Results from the study by Baldock and Hughes (2006) reported the possibility of the uprush accelerating temporarily at the bottom of the swash zone, following bore collapse. However, the acceleration during the uprush events does not always happen further up the beach. Therefore, additional attention or effort on swash velocity profiles investigation during uprush and backwash is crucial especially under influence of seasonal hydrological variations in Malaysia (dry and wet periods) in order to get better understanding of sediment transport mechanism for beach profile evolution.

2.4 Implications of Sediment Transport in the Swash Zone

In this section, some important physical properties will be explained about the sediment transport process in the swash zone. At first, it is important to understand the main key differences between uprush and backwash hydrodynamic conditions. Basically, the uprush consists of decelerating flow, while during backwash the flow gradually accelerates until it reaches a maximum in the final phase of the backwash process. Conversely, the duration during the backwash is typically longer than the duration during the uprush (e.g. Larson and Sunamura, 1993; Baldock and Holmes, 1997; Masselink and Hughes, 1998). In addition, infiltration of seawater into the beach face happens during uprush, while exfiltration occurs during backwash (Masselink and Hughes, 1998; Conley and Inman, 1994). Meanwhile, Masselink and Hughes (1998) and Osborne and Rooker (1999) documented the importance of differences in suspended sediment concentrations at the beginning of uprush and backwash activities.

The importance of suspended load as compared to bed load have been discussed by several authors in the past. Horn and Mason (1994) have conducted experiments at shingle beaches and they found that the majority of the sediment transport in the swash zone of the beaches occurred as bed load. Butt and Russell (1999) measured suspended sediment concentrations in a high energy swash zone of sandy beach at Perranporth Beach, UK and found that the sudden velocity transition from offshore to onshore and turbulence in the swash zone leads to onshore advection of sediment by uprush activities. Butt and Russell (1999) noted the importance of low frequency movement in the swash zone, and Beach and Sternberg (1991) found that under high energy conditions, the highest concentrations of suspended sediment occurred on infra-gravity time scales. Low rate of movement in the swash zone are associated with negative vertical and horizontal asymmetry of the flow velocity, with the irregular high velocity of backwash leading to offshore sediment transport. High suspended sediment concentrations in the swash zone created high rates of sediment transport and finally can change the beach profile entirely. Comprehensive field measurements can lead to a better understanding of the nature of swash zone physical processes especially on different type of beaches. It is important in order to provide a good foundation effort to model beach profile evolution (Butt and Russell, 2000; Elfrink and Baldock, 2002).

Hughes et al. (1997) recommended another mechanism for net onshore transport in the swash zone. Onshore transport during the uprush is expected to be significantly affected by sediment advection and turbulence from bores arriving at the beach surface. Masselink and Hughes (1998) claimed that processes that affect uprush and backwash are totally different from each other. Flow acceleration/deceleration, infiltration/ exfiltration and bore collapse all seem to support uprush sediment transport greater than backwash sediment transport. Osborne and Rooker (1999) stated that high measurement of concentrations level during uprush are highly expected to be connected with intense turbulence and high stresses linked with the front of onshore propagating bores. However, they also confirmed that measurements with higher spatial and temporal resolution are required in order to determine the relative contribution of advection.

Puleo et al. (2000) also recognized the possible prominence of bore turbulence effect on swash zone sediment transport. They recommended that bore-generated turbulence, which is focussed in the leading edge of a bore and spreads downward towards the bed, differs from bottom shear turbulence, and that the fundamental difference is the capability of the bore turbulence to alter the bed directly and significantly affect the bottom boundary layer. From their data, it was revealed that suspended sediment concentrations during uprush events is two times larger than those in the backwash near the bed, and up to seven times higher than the backwash suspended sediment concentrations at 5 cm above the seabed. Puleo et al. (2000) also attempt to evaluate the importance of bore-generated turbulence to swash zone sediment transport and they found a high correlation between suspended sediment transport and bore-generated turbulence.

Watters and Rao (1971) found that infiltration events can reduce the turbulence level, while exfiltration increased the turbulence effects. Conley and Inman (1994) found that the turbulence maximum was drawn closer to the bed under infiltration. Conversely, although turbulence due to exfiltration was witnessed to be increased, the time required for this to happen led to a higher vertically averaged turbulence in the half-cycle of the oscillation where infiltration was happening. Turbulence generated in the infiltration half-cycle was retained in a compact layer much closer to the bed. Conley and Inman (1994) reflected the implications of these findings for sediment transport and thought that if sediment transport is approximated by the effect of suspended sediment and local velocity and the level of suspension is comparative to the instantaneous turbulence levels, transport would be in the direction of flow during infiltration.

2.5 Swash Zone Morphodynamics

The hydrodynamic processes in the swash zone govern sediment transport mechanism that largely controls beach morphology. The profile of the beach morphology ranges from planar to concave, in which the erosion process dominated due to sand losses. When the beach is in accretion mode, the beach face may have a convex shape (Sonu and James, 1973; Makaske and Augustinus, 1998; Alegria-Arzaburu et al., 2017).

Initially, Bagnold (1940) stated that the most important factor controlling the slope of the beach face is the sediment size and stressed that it is the only significant factor. Later, Komar (1998) concluded that there are two justifications for the dependency of beach face slope or gradient on beach sediment size.

On sandy beaches or finer sediment, suspended sediment transport is likely to control the beach face slope. The slope of beach face will be expected to increase with the ability of the sediments to deposit on the beach face and will increase due to the effect of sediment settling velocity which is a function of the density and size of sediment particles (Dean, 1973). Meanwhile, based on further observation by Masselink and Li (2001), the correlation between beach face slope and sediment characteristics cannot be used to classify the most significant process in controlling the beach face slope. This is because sediment size, fall velocity and permeability are highly interconnected with each other. It is clearly shown that when beach face slope data are plotted versus each of these sediment parameters, similar trends are detected, giving no perception against either the mechanism based on the sediment fall velocity or the sediment permeability.

Meanwhile, on coarser beaches, the equilibrium of beach face gradient was found to be controlled by sediment size factor through their effect on swash flow infiltration process where the uprush flow will infiltrate into the unsaturated beach face due to percolation process that will reduce the energy of backwash flow move to offshore. The following swash flow irregularity enhances the onshore sediment transport, which results in a steepening of the beach surface until a gradient is achieved whereby the onshore force due to swash asymmetry is composed by the offshore gravity component (Grant, 1948; Quick, 1991).

Field observations or monitoring of beach morphological changes during swash events until now have been limited by the technology available. Kulkarni et al. (2004) measured bed level changes using calibrated and manual measurement of morphology rods employed in the swash zone. From the study, they found that the beach was steep and highly dynamic, giving ranges of bed level change in the swash zone rising up to 40 cm. The measurement works revealed complex deviations in bed level when the tide rising and falling. From this monitoring, even though the method is not technologically advanced, it observes the possibly highly energetic dynamic process in the swash zone.

Holland and Puleo (2001) also recorded large bed level changes in the swash zone using a video technique to measure bed level changes until 1 m high during a storm event. The beach face was found to adjust the minimum difference between incident wave period and swash period, suggesting that feedback between morphology incident and wave conditions is important in predicting beach profile evolution.

The beach faces response to varying hydrodynamic conditions is usually observed by changes in equilibrium conditions on the beach face either the beach face is too gentle or too steep and resulting in a net onshore or offshore sediment transport. Another specific impact is the recognition of seasonal and cyclic changes in bar-berm morphology and offshore-onshore sediment transport in reaction to storm induced changes in the wave steepness (Komar, 1998).

For example, in Figure 2.2a, if the beach face is flatter than the equilibrium slope, the uprush flow will transfer more sediment than the backwash flow, enhancing net onshore sediment transport. The lower part of the beach sediment is eroded and deposited on the upper part by swash flow activities, resulting in a steeper beach face and development of beach berm. In Figure 2.2b, if the beach face is too steep compared to the equilibrium gradient, the backwash flow will shift more sediment than the uprush flow, promoting higher rate of net offshore sediment transport. The sediment will be eroded from the upper part of the beach and is settled down on the lower part as sandbars, resulting in a flatter beach face. According to both cases, morphological changes of beach face will continue until a new equilibrium phase is attained. Even though the beach faces morphological changes as shown in Figures 2.2a and 2.2b may be unrealistic in real world application but they need maximum accretion and erosion to happen at the least energetic part of the beach face which is located at the upper swash zone. As shown in Figures 2.2c and 2.2d, the maximum bed level changes are more likely expected to occur from the lower to the middle part of the swash zone and resulting in the development of a convex profile during accretion process, and a concave profile during erosion process are more likely to happen.

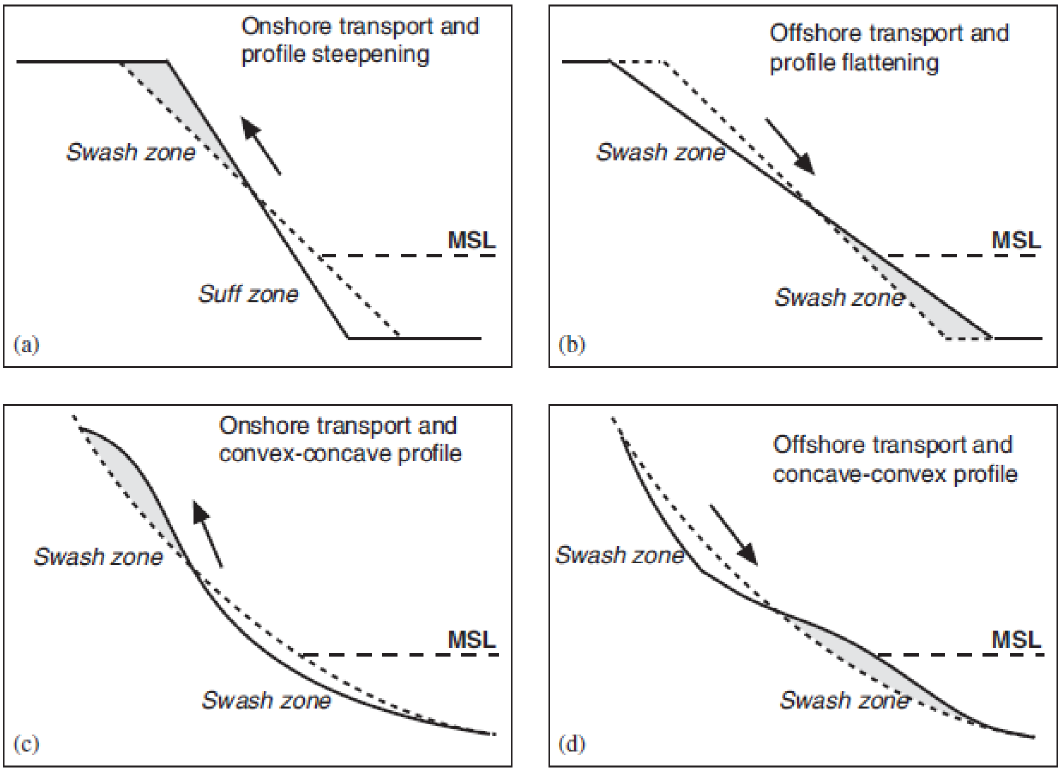


Figure 2.2 Idealised (a, b) and realistic (c, d) beach face response to changing wave conditions (Masselink and Puleo, 2006)

Usually, most of these swash morphodynamic investigations concentrated on recognizing cyclic forms of beach profile accretion and erosion in response to tidal water level variations, specifically accretion on the upper part and erosion of the lower part of the beach profile (Duncan, 1964; Eliot and Clarke, 1988; Nordstrom and Jackson, 1990). Similar technique has also been used to examine beach profile reaction due to changing wave conditions and it has proven to be principally useful for determining beach limit of morphological change (Eliot and Clarke, 1986; Masselink et al., 1997).

However, currently no studies or efforts have been conducted or reported yet about another significant factor such as rainfall distribution effect under different seasonal variations in the swash zone. It is hypothetically important to assess the beach morphological changes under the groundwater table variation due to the local climate. Therefore, the significance of the influence of beach groundwater table variation on the swash zone sediment transport is still not clear especially about their interaction or relation towards beach profile changes especially in the swash zone.

2.6 Beach Volume Changes and Shoreline Position

The variations of total sand volume and shoreline position related to beach morphological changes are another good indicator to explain the cyclic processes of beach erosion and accretion. Theoretically, the net beach volume and the shoreline position (beach width) will be decreased due to significant erosion process and flatter beach profile (concave shaped). Meanwhile the increasing of net beach volume and shoreline position will indicate the accretion process and stepper beach profile (convex shaped).

The field work conducted by Dail et al. (2000) at Waimea Bay, Hawaii reported that the total sand volume and the average shoreline are found to be highly correlated with a correlation value of 0.96. The result provides that the shoreline position is very useful information for sub-aerial sand volume. This result is also supported by Karunarathna et al. (2015) through in their work at Joetsu-Ogata Coast, Japan which indicated that the beach profile shape and shoreline position are two useful indicators of beach change. The study also reported the function of averaged lines of annual beach volume and shoreline position to indicate the long term beach shapes either in decreasing or increasing trends. All these findings also give a good motivation to the current study in order to investigate the relationship between beach volume and shoreline position under tropical seasonal hydrological variation effect during dry and wet seasons. Previous studies were mostly concentrated on beach profile changes during winter and summer seasons. It was found that the accretion process always happens during the summer season, while erosion process mostly occurred during winter season (Masselink and Pattiaratchi, 2001; Karunarathna et al., 2012; Algeria-Arzaburu et al., 2017). This situation could be explained well by the significant effect from higher and lower wave energy attack during winter and summer seasons, respectively. Interestingly, it could be different in tropical countries like Malaysia where the beach groundwater table variation due to seasonal hydrological variation could control the swash zone morphological changes. This is considered to be as important as the effect by wave attacks.

2.7 Review on Statistical Analysis Used in Morphological Changes

Understanding of beach profile changes at multiple timescales is significantly important for better sustainable beach management and coastal design especially for beach users or local authorities. Additionally, the beach mophodynamics response to external environmental drivers totally depends on its location, beach characteristics and type. There were several efforts to understand the variability of cross-shore morphodynamics for beach profile through statistical analysis like bulk statistical and empirical orthogonal eigenfunction (EOF) analyses. This is explained in the next section.

2.7.1 Bulk Statistical Analysis

The key of a successful statistical analysis strongly depends on the total size of the data set characterized by the specific spatial coverage, spatial resolution, temporal resolution and overall length in time (Kroon et al., 2008). Bulk statistical measures such as mean, range, standard deviation and correlation have been applied to provide basic information about beach profile and geometric variability analysis by several authors, including Larson et al. (2003), Kroon et al. (2008) and Karunarathna et al. (2012).

Generally, bulk statistical analysis was used to provide basic important information about the mean beach profile and profile variability around the mean. In bulk statistical analysis, a few simple analyses will be used such as mean, standard deviation, range and correlation. These methods are very popular in beach profile variability analysis among coastal engineers or researchers because they are easy to compute and can give a first impression of the profiles data for any study. For example, bulk statistical analysis could reveal the average position of cross-shore bar or berm positions over time. The standard deviation is a basic statistic parameter that describe how closely all the observations data are clustered around the mean in a set of data. It could be used to obtain the spatial variation of elevation along a shoreline when it is important to check variability of beach profiles at any interest points.

Karunarathna et al. (2015) used standard deviation analysis to determine seasonal variability of beach profile shape at Joetsu-Ogata Coast, Japan and reported that the highest standard deviation is detected at the upper part of the beach. This result may be attributed to rapid erosion during winter season and fast beach recovery during short intervals of calm weather between storms. The study also reveals that the annual average cross-shore profiles vary from erosive profile (concave), then changed to a steep beach face (convex) and finally transformed to composite, dissipative beach face and gentle uniform lower beach.

Karunarathna et al. (2012) also used this technique to analyse the variability of beach profile at Milford-on-Sea Beach, UK and Narrabeen Beach, Australia. They used simple bulk statistical analysis to develop a beach profile envelope based on maximum and minimum elevation profiles for every cross-shore points. At Milford-on-Sea beach, UK (Figure 2.3), the profile envelope (dashed line) shows the development/recession of beach berm at the upper beach due to accretion/erosion processes in the swash zone. The mean profile (solid line) is indicative of a high energy upper part and inter-tidal beach. The standard deviation analysis confirms that the highest variability occurred for this beach profiles indicated the peak located in the supra-tidal zone (2-3 m MSL). This happen due to strong swash movement associated with incident wave groupiness and wave breaking on or at close proximity to the shoreline. Figure 2.4 shows mean cross-shore profile (solid line) with profile envelope (dashed line) revealing that the shoreline varies by 70 m in the on-offshore direction at Narrabeen Beach. The highest variability from the standard deviation analysis of the beach profiles discovered about three peaks with the largest peak occurring at the upper region of the inter-tidal zone. This condition can be related to the importance of swash zone hydrodynamics influencing the beach morphological changes. Therefore, it can be concluded that better understanding of the swash zone hydrodynamics is vital for better shoreline evolution assessment.

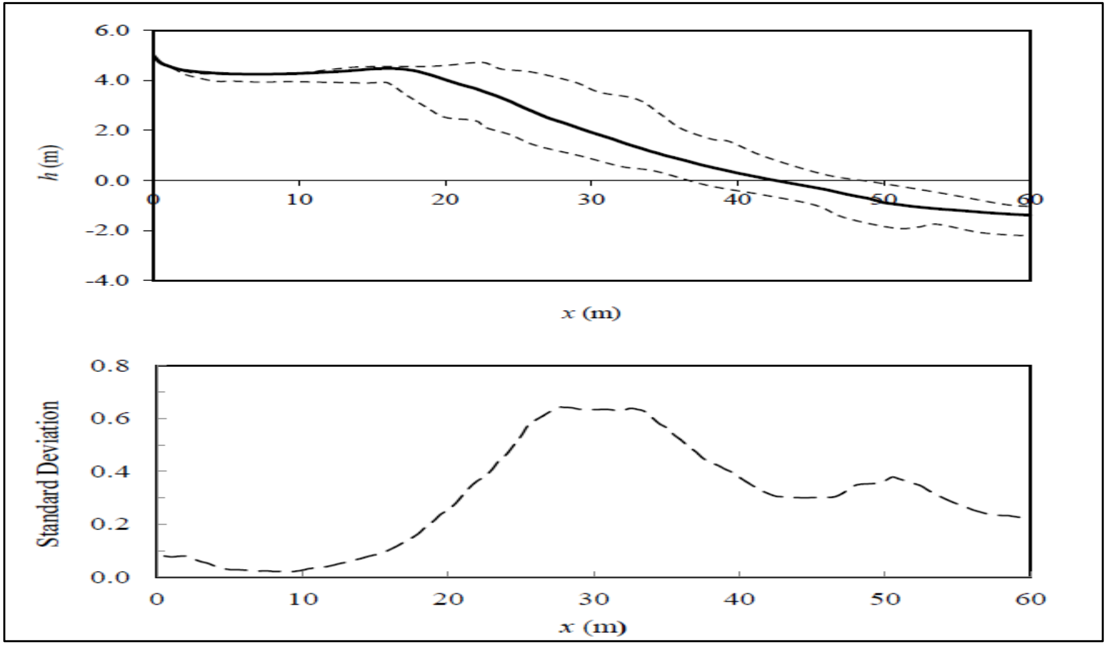


Figure 2.3 Time-averaged beach profile, profile envelope (top) and standard deviation of profile depth (bottom) at Milford-on-Sea Beach (Karunarathna et al., 2012)

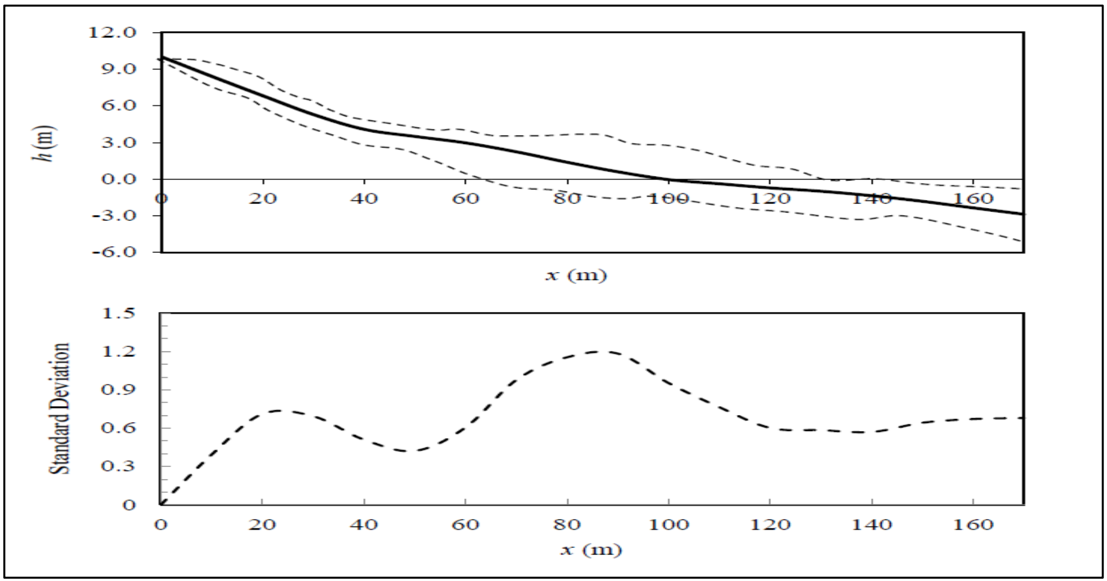


Figure 2.4 Time-averaged beach profile, profile envelope (top) and standard deviation of profile depth (bottom) at Narrabeen Beach (Karunarathna et al., 2012)

2.7.2 Empirical Orthogonal Function (EOF)

The interaction between beach morphological changes and natural environmental forces under different range of space and time scales is a complex process. Therefore, an understanding of beach profile changes at multiple timescales is extremely important for better sustainable beach management and also coast protection (Karunarathna et al., 2015). Relationship between natural environmental forces and beach profile change at different timescales have been extensively studied and established using field and laboratory works at various locations worldwide such as nearshore wave (e.g. Jensen et al., 2010; A. Ruiz de Alegeria-Arzaburu et al, 2017), offshore waves (e.g. Hsu et al., 1994; Larson and Hanson, 2000; Horrillo-Caraballo and Reeve, 2011), tides (e.g. Aubrey and Emery, 1983; Solow, 1987; Ding et al., 2001), sediment characteristics (e.g. Swart, 1974; Dean, 1991; Vellinga, 1984) , groundwater level (e.g. Li et al., 2002; Horn et al., 2007) and El Nino-La Nina atmospheric oscillation (e.g. Haxel and Holman, 2004; Thomas et al., 2010).

The EOF analysis is commonly used to investigate the measured beach profiles using principal component analysis. The EOF was initially developed by Hotelling (1933) to determine the fundamental shapes in seemingly random data. The method maps the observed coastal morphological data into a set of shape functions known as eigenfunctions that are determined from the data itself. When applied to cross-shore beach profiles, it can reveal patterns of variation about the mean profile shape, such as bars and troughs. Winant et al. (1979) was the first to use the EOF to study variations of beach profiles at Torrey Pines Beach, California.

Theoretically, the method examines the modes of variability in a compact technique in which the data determines the importance of the variations. Figure 2.5 shows the spatial and temporal components, where the higher eigenfunction explains the greatest percentage of variation within the data set, while other, lower eigenfunction mode represents the lesser variance. The temporal eigenfunction analysis of beach profile data can identify the seasonal variations such as seasonal transition between the summer and winter profiles during the survey period. Usually, a large proportion of the data variance is contained within a small number of eigenvalues, λ and therefore only a limited number of eigenfunctions is used to describe the most variations in the set of data. Each eigenfunction corresponds to a statistical description of the data with respect to how the data variance is concentrated in that function. The functions are usually ranked according to the magnitude of their corresponding eigenvalues which are proportional to the data variance. Typically, a large proportion of the data variance is contained within a small number of eigenvalues and hence, only a limited number of eigenfunctions are needed to explain most of the variation in the measurements (Pruszak, 1993; Reeve et al., 2001; Larson et al., 2003). The original observed profile can be defined by the summation of each eigenfunction multiplied by its corresponding coefficient. The weight of the coefficient defines the degree of variation from statistical mean (Aubrey, 1979).

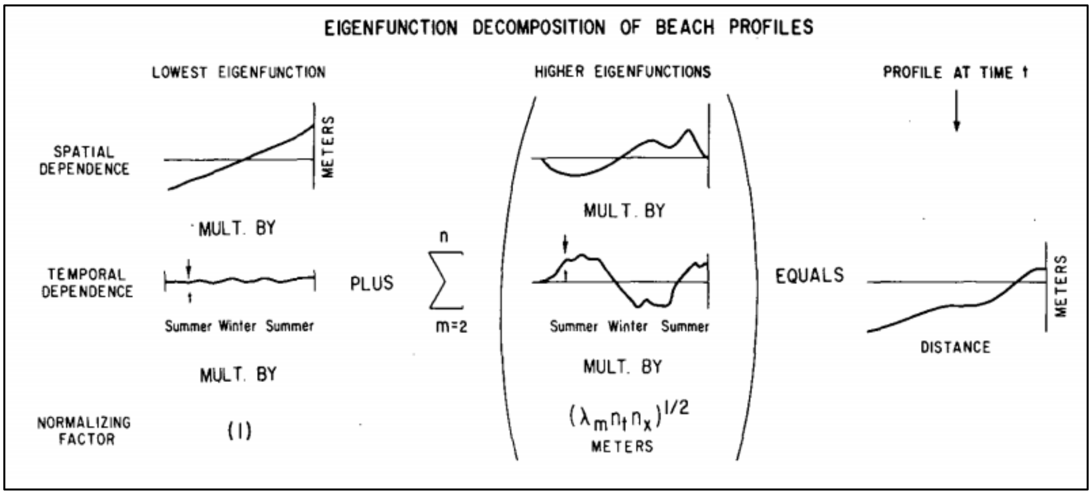


Figure 2.5 Empirical eigenfunction decomposition of beach profile data (Aubrey, 1979)

When applied to cross-shore beach profiles, the functions can reveal the patterns of variation for the mean beach profile shape, such as bars, troughs and also the sediment movement along the profile. However, this method is only a descriptive tool and does not produce any information relating to the processes that govern the beach profile due to the lack of any physical deterministic derivations. In term of temporal variation, the changes of beach profile under influence of seasonal variation such as summer-winter season, pre-post storm event and dry-wet period can be evaluated along a survey profile.

The EOF method also was used as a pre-processing step in another advanced statistical technique for further analysis such as Canonical Correlation Analysis (CCA) in order to reduce the noise in the study data and to become familiar with the general structure of the data. According to Clark (1975), CCA is one of the correlation technique which was often used to investigate the inter-correlation between two sets of variables where the EOF identifies the pattern of relationship within the set of data. All these mentioned methods were initially applied in meteorological and oceanographic studies, and only lately becoming popular applications in coastal engineering especially in morphological studies. One of the particular interest are bed topography studies in complicated coastal zones, such as a nearshore zone with multiple bars, where analyses of EOF are capable of identifying or analyzing complex processes in various limited time scales. According to Winant et al. (1975), theoretically, the main objective of the analysis using EOF is to separate the spatial and temporal dependence of the data which can be represented as a linear combination of corresponding function of time and space. These functions then represent the variation of the beach profile shape in terms of distance from fixed data points and in terms of temporal changes in profile configuration over the period of study.

The EOF analysis was widely used by researchers in coastal engineering community as statistical tool which focused to analyze or investigate patterns in beach profile variations and other coastal features (Winant et al., 1975; Larson and Kraus, 1994; Wijnberg and Terwindt, 1995; Larson et al., 2000; Reeve et al., 2001; Rozynski, 2003; Horillo-Caraballo and Reeve, 2008; Kroon et al., 2008; Reeve et al., 2008; Horillo-Caraballo and Reeve, 2011; Karunarathna et al., 2012; Li, 2016; Joevivek et al., 2018) to determine their variation through time or along a beach.

Table 2.1 summarizes the study area, data collection and statistical outputs from the selected articles about the beach profile variability studies using the EOF analysis around the world. Most of the studies were located at areas experiencing winter-summer seasonal variations such as USA, UK, Australia, Germany, Dutch, Poland, Bulgaria, Japan, China, Taiwan and India. The time span of beach profiles data surveys varies depending on the data available of the project area consisting hourly, daily, biweekly, monthly, quarterly, biannually, annually or irregular time period. Generally, all the studies using the EOF analysis specifically focused to investigate the morphodynamic change of beach profiles in terms of spatial and temporal variation.

Pruszak (1993) also mentioned about the importance of this method as a tool providing vast possibilities of estimating and predicting many characteristic geometric and dynamic features of the cross-shore profile. From the study, it was reported that one-dimensional (1-D) EOF can find distinct correlations between the first three EOFs and various features of which the first function represent the geometry of mean profile bars, troughs etc. The second EOF indicates the location and intensity of occurrence of deformation of various types on the profile and the third EOF is related to onshore and offshore sediment transport and intensity of erosive-accumulative processes along profile.

For the case of a beach with multiple bars, based on review by Rozynski (2003), Canonical Correlation Analysis (CCA) offers a decent understanding into interaction between components of multibar system revealed with the EOF method. Therefore, the capability of EOF gives promising results and are expected to be utilized as one of the novel techniques in coastal engineering study. At Nanwan beach, South China, Dai et al. (2008) used the EOF analysis to quantify seasonal changes of the sandbar for proper management of coastal resources, particularly in light of widespread coastal retreat. From the study, the first spatial eigenfunction (SEOF1) accounts about more than 95% of sand-bar variability during summer and winter seasons, respectively. This result shows that the mean beach profile of the bar crest are almost similar during both seasons.

Karunarathna et al. (2012) investigated two different cross-shore morphodynamic evolution of a sand (Narrabeen Beach, Australia) and sand-gravel composite beach (Milford-on-Sea, UK). In this study, multi-scale morphodynamic trends of space and time are determined using the EOF analysis which reported that the swash zone is the most active region for both sites as shown in Figures 2.6. The dark lines in the figure gives the first eigenfunction which closely corresponds to the mean beach cross-shore profile. The spatial eigenfunction (SEOF) analysis from both sites revealed that more than 93% of the data variation is captured by the first five eigenfunctions. At Narrabeen Beach, the second eigenfunction (SEOF2) reflects an intertidal beach trough and terrace. The third eigenfunction (SEOF3) reflects the presence of sub-tidal bar and a trough. The forth eigenfunction (SEOF4) implies sediment exchange across the profile which detected erosion of the intertidal zone. The fifth eigenfunction (SEOF5) corresponds to small scale accumulative-erosive features of the profile. At Milford-on-Sea beach, SEOF2 shows the presence of an upper beach ridge while SEOF3 reflects the existence of a sub-tidal bar and trough. SEOF4 corresponds to sediment exchange between the upper beach and the intertidal zone while SEOF5 may be related to small scale changes which is similar to that at Narrabeen Beach. The study also indicated that the strongest variability at Milford-on-Sea beach was detected at the sub-aerial area or above MSL and this reflects the importance of swash zone in controlling the beach morphodynamic. At Narrabeen Beach, the most dynamic region was at inter-tidal and sub-tidal zone and it was also found that the swash zone has smaller variability compared to other areas. Both sites indicated that the spatial eigenfunctions do not reach constant values at the end of seaward direction of the profiles due to further sediment transport occurring outside the measuring range. Result from the field studies conducted at Hasaki Coast and Joetsu-Ogata Coast, Japan by Karunarathna et al. (2016) shows that inter-annual scale dominates profile change at Hasaki Coast while annual scale changes dominate morphodynamic variability at Joetsu-Ogata Coast. Both beaches show clear evidence of the swash zone sediment exchange especially the areas between upper shore face, inter-tidal and sub-tidal zones.

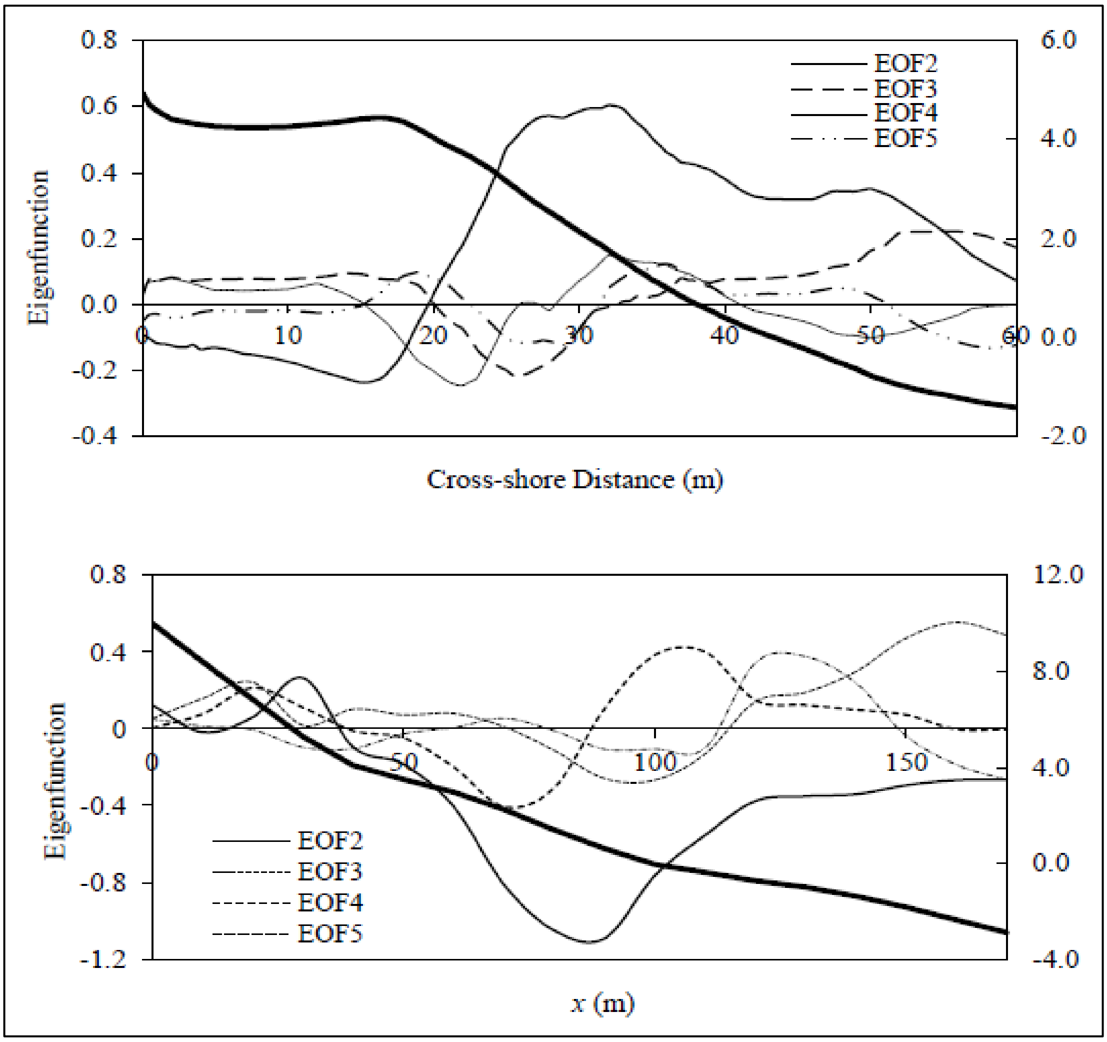


Figure 2.6 Spatial variation of first five EOF at Milford-on-Sea (top) and Narrabeen Beach (bottom) (Karunarathna et al., 2012)

In term of temporal variation for both sites at different range of time scales (Figure 2.7), the temporal eigenfunction (TEOF) was used to investigate the variability patterns of the beach profiles along the study period. The first temporal eigenfunction (TEOF1) for both studies are approximately constant as it corresponds to the time-mean cross-shore beach profiles. For the second temporal eigenfunction (TEOF2), at Milford-on-Sea beach, it reflects a gradual decline over time and showing long term beach erosion while Narrabeen beach shows a high frequency for every 3-5 months duration and 3-8 years cyclic variability for long term periods. This type of observation is important to examine the seasonal variation effect on beach profile changes. The third temporal eigenfunction (TEOF3) shows clear seasonal signal for both sites.

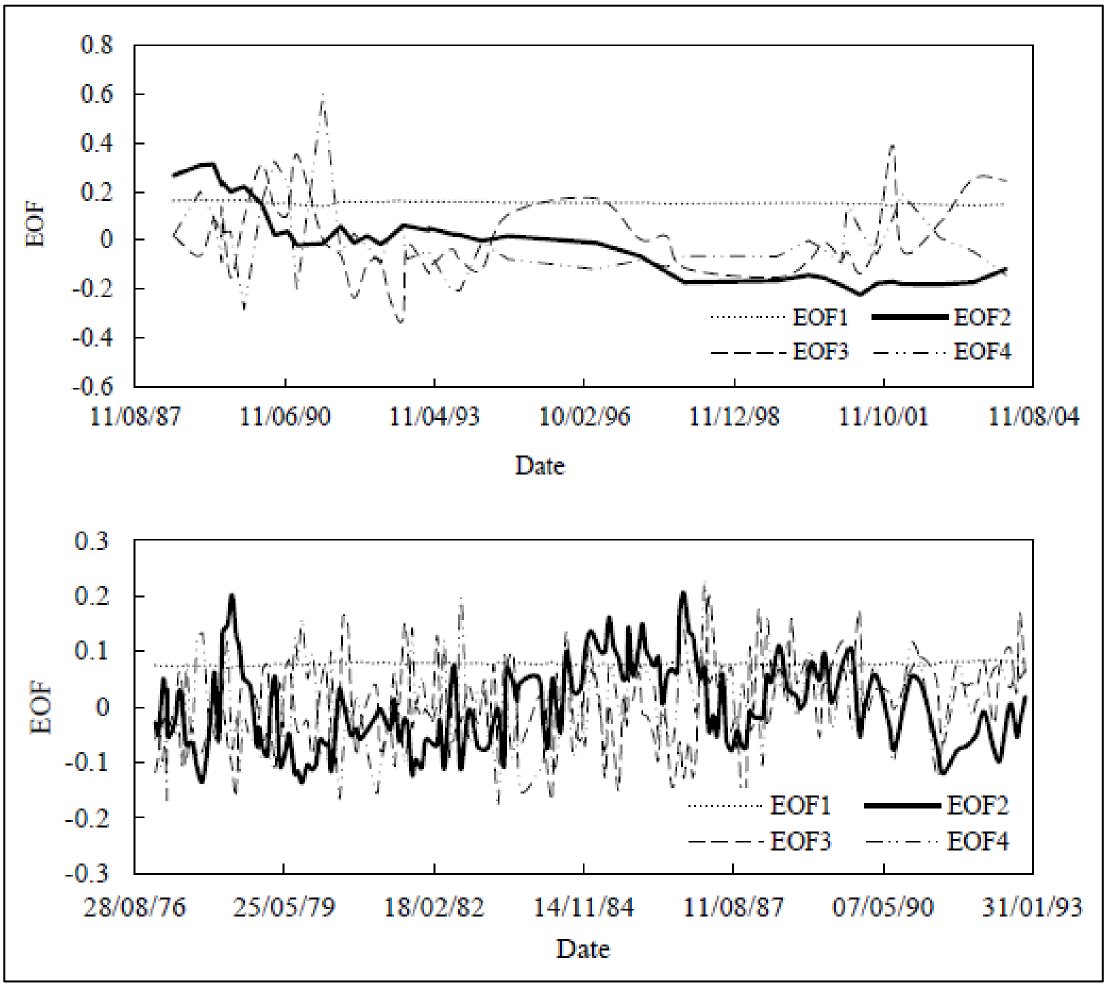


Figure 2.7 Temporal variation of EOF at Milford-on-Sea Beach (top) and Narrabeen Beach (bottom) (Karunarathna et al., 2012)

For beach profile variability analysis, the results of averaging a number of profiles located along the shore did not deliver detailed profile features and this type of analysis are more challenging to interpret. Therefore, the use of the EOF method is more efficient and suitable for this type of analysis. The data required for the EOF analysis consist of multiple beach profiles, either over time at fixed location or over distance at a fixed time. These profiles are given in digital form with a table of distances offshore and the associated depth for each profile.

Table 2.1 Summary of studies using EOF method for beach profiles analysis

Authors	**Location of Study Area**	**Data**	**EOF Reviews**
Winant et al. (1975)	3 beach profiles at Torrey Pines Beach in San Diego County, California, USA - North Range - Indian Canyon Range - South Range	1972-1974 (monthly)	- North Range (EOF1-5 = 99.98%) - Indian Canyon Range (EOF1-5 = 99.98%) - South Range (EOF1-5 = 100%)
Aubrey (1979)	3 beach profiles at Torrey Pines Beach in San Diego County, California, USA - North Range - Indian Canyon Range - South Range	1972-1977 (monthly)	- North Range (EOF1-5 = 99.88%) - Indian Canyon Range (EOF1-5 = 99.91%) - South Range (EOF1-5 = 99.93%)
Aranuvachapun & Johnson (1979)	2 beach profiles at Norfolk, USA - Gorleston - Yarmouth	1928-1976 (irregular) 1966-1976 (irregular)	- Gorleston (EOF1-5 = 100%) - Yarmouth (EOF1-5 = 100%)
Uda & Hashimoto (1982)	Misawa Port, Ogawarako Coast, Japan	1973-1977 (annually)	EOF1-3 (ratio only)
Dick & Dalrymple (1984)	Bethany Beach, Delaware, USA	1938 1954 1968 1973 1977	EOF1-3 = 100%

Table 2.1 Summary of studies using EOF method for beach profiles analysis (cont.)

Authors	Location of Study Area	Data	EOF Reviews
Aubrey & Ross (1985)	3 beach profiles at Torrey Pines Beach in San Diego County, California, USA - North Range - Indian Canyon Range - South Range	1972-1977 (monthly)	- North Range (EOF1-3 = 91.5%) - Indian Canyon Range (EOF1-3 = 95.4%) - South Range (EOF1-3 = 90.5%)
Pruszak (1993)	Lubiatowo, Baltic Sea, Poland Golden Beach, Black Sea, Bulgaria	1964-1991 1972-1978 (monthly)	EOF1-3 (graphs only)
Hsu et al. (1994)	Redhill Coast, Taiwan	1983-1986 (every 2 months)	EOF1-6 = 99.54%
Reeve et al. (2001)	Great Yarmouth, the East Coast UK	1946-1992 (16 profiles)	EOF1-6 = 99.3%
Munoz-Perez et al. (2001)	Victoria Beach, Spain	1991-1994 (Dec/June) Biannually	EOF1-2 = 99.89% (highest)
Larson et al. (2003)	The Terschelling, Dutch Sylt Island, Germany	1965-1995 (annually) 8 times within 4 years	Terschelling (EOF1-3 = graphs only) Sylt (EOF1-3 = 82.8%)
Barletta et al. (2006)	Southern Brazilian Beach, Brazil	1996-1999 & 2002 (daily & seasonal)	EOF1-5 > 99% (for all beaches)
Kroon et al. (2008)	Duck, North Carolina, USA	1981-1991 (every 2 weeks)	EOF1-3 = 77%
Dai et al. (2008)	Nanwan Bay Beach, South China	July-Aug 2001 (summer) & Feb-Mar 2002 (winter)	Summer (EOF1-4 = 98.61%) Winter (EOF1-4 = 99.43%)

Table 2.1 Summary of studies using EOF method for beach profiles analysis (cont.)

Authors	**Location of Study Area**	**Data**	**EOF Reviews**
Reeve et al. (2008)	Great Yarmouth, UK	1848-1974 (33 profiles)	EOF1-8 > 99.1%
Karunarathna et al. (2012)	Narrabeen Beach, NSW, Australia Milford-on Sea, Christchurch Bay, UK	1976-1992 (monthly) 1987-2005 (every 4-months)	EOF1-5 > 93% (both beaches)
Lemke et al. (2014)	Long Branch, New Jersey, USA	2009-2011 (varies from weekly to monthly)	EOF1-4 = 99.98%
Karunarathna et al. (2015)	Joetsu-Ogata Coast, Japan	1997-2005	EOF1-5 > 99.9%
Karunarathna et al. (2016)	Naraabeen Beach, Australia Milford-on Sea, Christchurch Bay, UK Hasaki Coast, Japan Joetsu-Ogata Coast, Japan	1976-1992 (monthly) 1987-2005 (every 4-months) 1986-2010 (weekly) 1986-2006 (monthly)	EOF1-5 > 90% (all beaches)
Joevivek et al. (2018)	Nagapattinam Coast, India	2011-2013 (monthly & seasonal)	EOF1-3 = 99.79%

2.8 Beach Groundwater Dynamics

A deep understanding of the seawater flow and beach groundwater dynamics interaction is needed to provide a better evaluation or estimation of how it affect the beach profile changes particularly in the swash zone. In order to investigate the importance of the beach groundwater table as a main factor in cross-shore sediment transport on a sandy beach, many research works have been conducted. Previous researchers (e.g. Grant, 1948; Duncan, 1964; Li et al., 2002) have investigated the relationship between the elevation of the beach groundwater table to beach erosion and accretion. It has been reported earlier by Grant (1948) that a high groundwater table relative to mean sea level (MSL) tends to promote offshore sediment transport which resulting the beach going into erosion mode, while a relatively low groundwater table enhances onshore sediment transport and thus promotes beach accretion.

A few studies have investigated groundwater movement in coastal regions (e.g. Nielsen and Kang, 1995; Turner et al., 1997; Nielsen and Voisey, 1998; Nielsen, 1999), watertable fluctuations in estuarine environments (Li et al., 1999) and gravel beaches (e.g. Ericksen, 1970; Carter and Orford, 1993) or sand moisture content effects on sediment transport (e.g. Jackson and Nordstrom, 1997; Sherman et al., 1998). The beach groundwater table variation is an important factor in cross-shore sediment transport process on a sandy beach. It was shown in several field studies conducted by Grant (1948) and Duncan (1964) where it was reported that the elevation of the beach groundwater table influenced the beach erosion and accretion processes.

Generally, the groundwater system in the beach is a highly dynamic, shallow, unconfined aquifer in which flows are driven though saturated and unsaturated region of the beach face (Figure 2.8a). The groundwater table on the beach is influenced by the wave action, tidal elevation, rainfall distribution and also sediment properties such as shape, size, permeability, porosity and sorting (Foote et al., 2002). Horn (2006) defined that the beach groundwater system is an unconfined aquifer with flows are driven though saturated and unsaturated sediments by tides, waves and swash, and to a lesser extent by atmospheric exchanges, such as evaporation and rainfall, and exchanges with deeper aquifers.

In Figure 2.8b, the phreatic zone is the permanently saturated zone under the beach groundwater table. In the saturated phreatic zone, pore spaces are filled with water and pore water pressures are equal to or greater than atmospheric pressure. The vadose zone located above the beach groundwater table and also known as the aeration zone or the unsaturated zone, is the unsaturated region of a beach sand body extending from the groundwater table to the beach surface. In the unsaturated zone above the groundwater table, the beach material pores are filled with both water and air and pore water pressure is less than atmospheric pressure.

A capillary fringe can develop instantly above the groundwater table due to the force of mutual attraction between water molecules and the molecular attraction between water and the surrounding sand matrix. The capillary fringe may also be referred to as the tension-saturated zone, where tension refers to a pressure which is negative relative to atmospheric pressure. In the capillary fringe, pore spaces are fully saturated, but the capillary fringe is different from the groundwater table because of the negative value of pore water pressures (Horn, 2006).

Usually, the beach groundwater table is sometimes assumed to be an extension of the mean water surface inside the beach, and expected to have the same elevation with the tide. However, the tidal elevation usually drops more quickly than the beach groundwater table elevation and decoupling will occurs when the groundwater table elevation higher than the tidal elevation during low tide. From this moment, an exit point of groundwater will develop as the position on the beach profile where the decoupled groundwater table intersects the beach face as illustrated in Figure 2.8b.

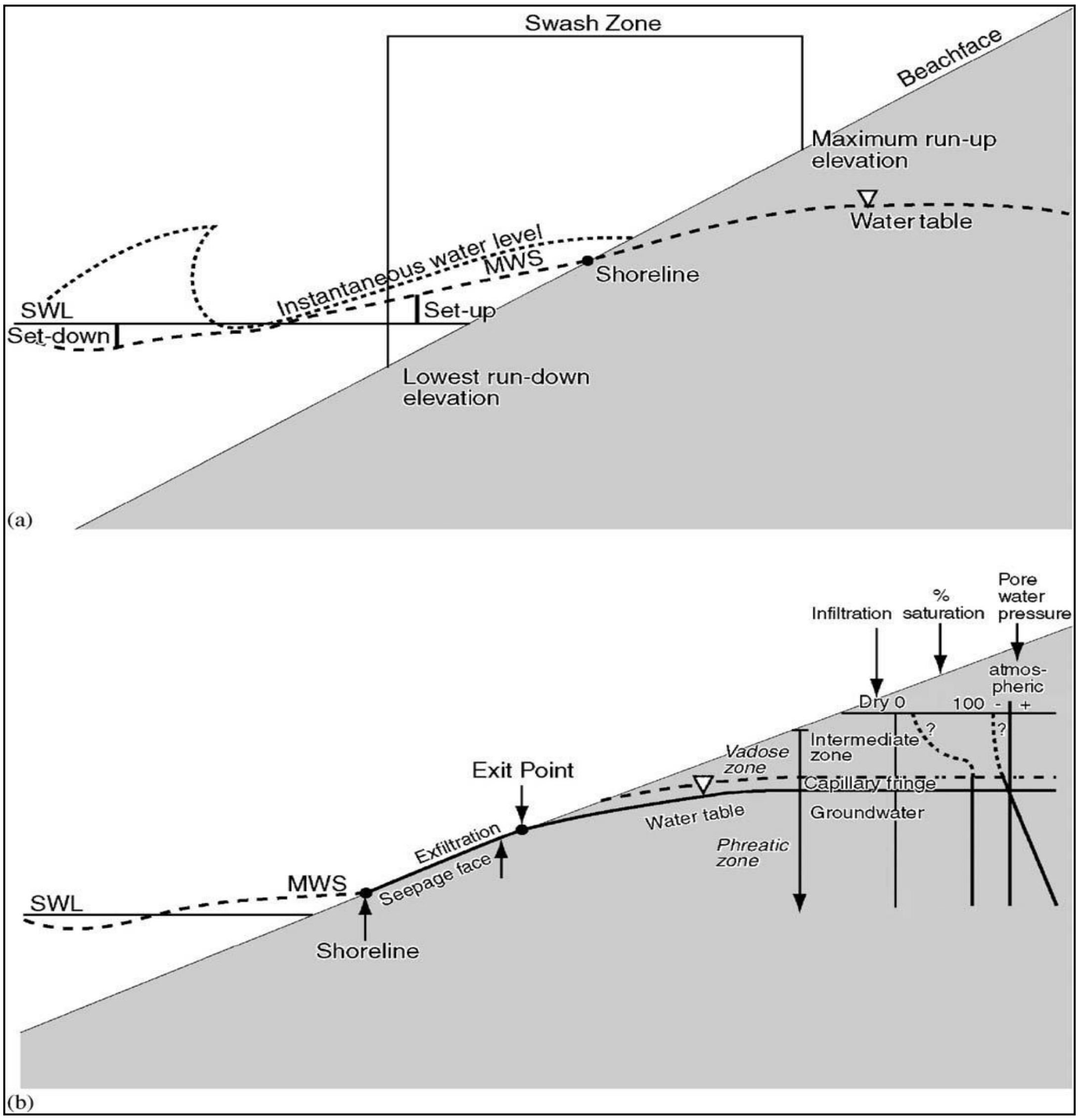


Figure 2.8 (a) Definition sketch of surface and subsurface water levels in the swash zone. (b) Definition sketch of beach ground water zones when the water table is decoupled from the tide (Horn, 2006)

The uprush and the backwash activities in the swash zone will directly affect the shape and position of the groundwater table by changing the saturation level on the beach face (Butt and Russell, 2000). However, according to Hoque and Asano (2007), the beach groundwater table cannot response with the rapid swash uprush and backwash. A sufficiently low groundwater table will enhance infiltration on the dry beach face during uprush event. Conversely, a higher groundwater table will increase seepage especially during the backwash event (Li and Barry, 2000; Hoque and Asano, 2007). The water table elevation inside the beach is generally not flat. Several studies showed that the beach groundwater table is affected by tidal elevation, sloping seaward on a falling tide and landward on a rising tide (Turner 1995; Raubenheimer et al., 1999;

Horn, 2002; Kim et al., 2005; Horn, 2006; Lee et al., 2007). Kim et al. (2005) found that groundwater level fluctuation varies according to the tidal period. From effort by Austin and Masselink (2006) for series measurements at Slapton beach, UK, it was found that the groundwater level was closely related to the tidal elevation during flood and ebb periods. In general, Slapton beach is porous and permeable, therefore it easily allows seawater to infiltrate quickly inside the beach. Higher permeability levels on gravel beach type is expected to provide a quick response between the swash flow and groundwater compared to sandy beaches, so reducing the irregularity detected in sandy beaches (Austin, 2005).

The elevation of the beach groundwater table depends on prevailing hydrodynamic conditions such as tidal elevation, wave run-up and rainfall, and characteristics of the beach sediment that determine hydraulic conductivity, such as sediment size, sediment shape, sediment size sorting, and porosity (Gourlay, 1992). Investigation of beach groundwater table variation showed that the groundwater table is generally not flat. The slope of the water surface has been found to be steeper on a rising tide than a falling tide (Lanyon et al., 1982).

2.8.1 Effects of Infiltration and Exfiltration on Beach Profiles

Several factors have been studied to get a clear view how beaches with a higher groundwater table tend to erode while a lower groundwater table tend to accrete. Previous works and reviews reported that the main factors that influence the swash morphological changes are the infiltration and exfiltration processes (Turner and Masselink, 1998; Baldock et al., 2001; Butt et al., 2001; Li et al., 2002; Horn, 2006; Butt et al., 2007; Horn et al., 2007; Bakhtyar et al., 2009).

Li et al. (2002) developed a process-based numerical model “BeachWin” to simulate the interacting wave motion on the beach, coastal groundwater flow, swash sediment transport and beach profile changes. From the simulation results, it showed that the accretion process occurred when the beach groundwater table is lower while higher groundwater level may promote beach sediment transport process. The results also confirmed that at the maximum uprush during lower groundwater table scenario, significant infiltration happens in the swash zone on the upper part of the beach, accompanied by lesser infiltration rate at the lower part of the beach. Meanwhile, during higher groundwater table scenario, no infiltration activity was detected during uprush flow simulation and exfiltration effect enhances a seeping flow across the beach. This model also studied the effects of the swash infiltration. It reduces the duration and velocity of the backwash flow. This in effect increases the onshore flow symmetry and thereby enhancing the onshore sediment transport and made the gradient of the beach steeper. The study also found that a large berm was developed in the swash zone due to a higher infiltration effect occurring at low groundwater table scenario and also concluded that infiltration effect enhances the onshore sediment transport and beach accretion.

Horn et al. (2007) conducted a laboratory experiments to investigate the influence of infiltration on sediment transport and beach profile changes for sand and coarse sand beaches in the swash zone under swell and storm conditions. From the results, when the groundwater table was lowered, onshore sediment transport was increased, meanwhile offshore sediment transport happens during higher groundwater table condition. This infiltration effect clearly observed on the coarse-grain beach with onshore transport and berm developed in all cases for lower groundwater table. The study also reported that under storm waves condition, the groundwater table of sand beach had less impact on beach profile changes and found that lowering groundwater table technique during this storm condition did not offer the best solution to mitigate erosion problem. The results also proved that infiltration plays a significant role on the fine sand beach when the groundwater table was lowered which earlier suggested that infiltration process is only significant on coarse-grained beach.

Figure 2.9 shows the swash flow losses during backwash due to infiltration process. This caused the flow velocities to be significantly reduced during run-down (Jamal, 2011). Basically, the effects of infiltration and exfiltration on beach morphological changes especially in the swash zone can reduce the backwash volume and duration by infiltration effect. Other effects are increasing/decreasing of bed sheer stress, stabilisation/destabilisation of beach surface layer and thinning/thickening of boundary layer by infiltration/exfiltration, respectively. A numerical study using non-linear shallow water wave equation by Packwood (1983) reported that infiltration will increase the irregularity of the swash flow on beach face by weakening the backwash. Thus, offshore sediment transport will be difficult to occur due to high deposition on the upper part of the beach.

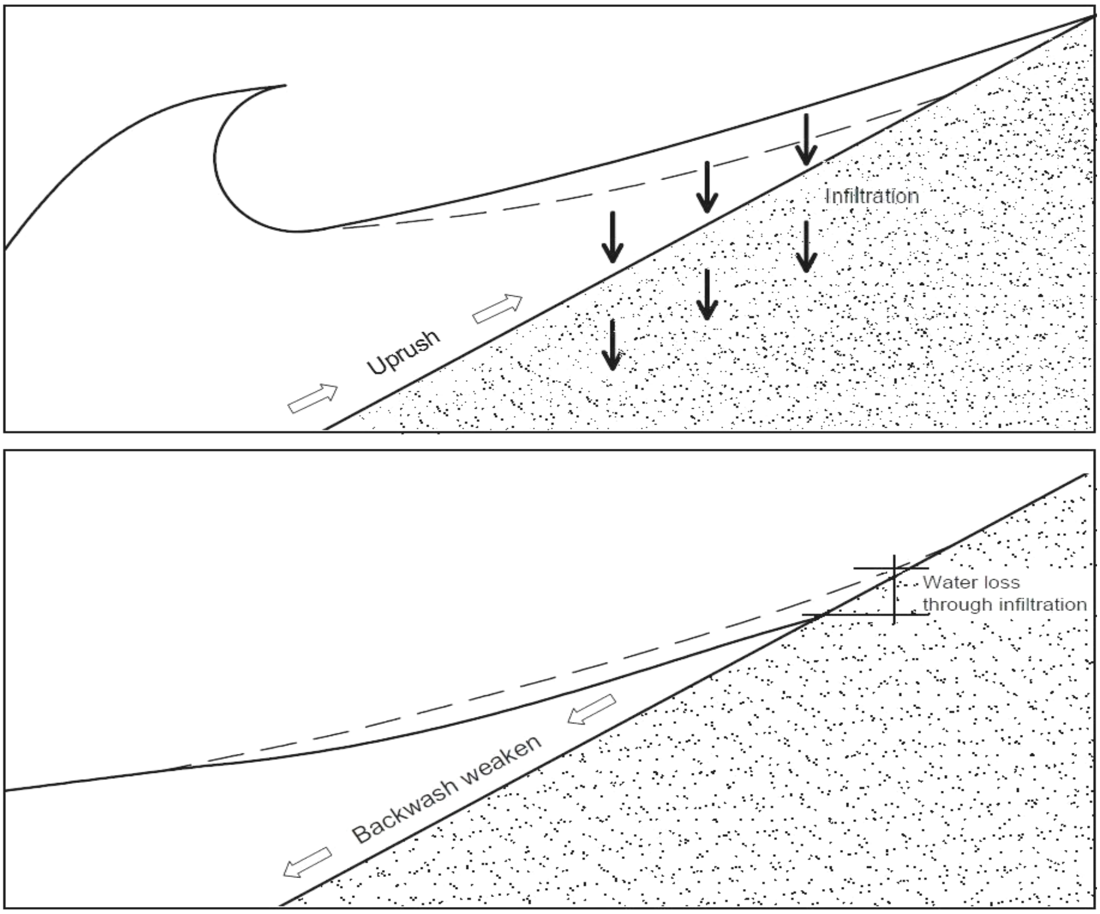


Figure 2.9 Sketch of backwash weakening because of water losses through infiltration (Jamal, 2011)

From the observation that beach groundwater table can influence the erosion and accretion processes on the beach surface, one method has been developed, known as the beach dewatering technique. The technique enhances the accretion process on the beach surface by lowering the beach groundwater table through drainage or pumping out the beach groundwater flow. According to Obhrai et al. (2002), this technique is quite popular for combating beach erosion and beach dewatering has been recommended as a practical technique of shoreline stabilization. Li et al. (1997) developed a numerical model to study the behaviour of a coastal aquifer under beach dewatering process, beach water table lowering and seepage face reduction. Bowman et al. (2007) also investigated the effectiveness of the dewatering processes in Alassio Beach, north Italy and concluded that the technique developed a berm crest and a scarped foreshore with a narrow swash zone. However, this technique needs further research in order to better understand how the beach groundwater hydrodynamics affects the swash zone sediment transport.

Even though extensive improvement has been made in sediment transport modelling, a better prediction of swash flow–groundwater dynamics interaction on a beach is still needed. In order to gain better understanding of this process, a field investigation of the infiltration and exfiltration effect on the swash zone dynamics under seasonal influence is conducted for Malaysia climate. The seasonal dry and wet periods would have bearing on the beach groundwater level. Previous studies on the interaction between seawater and coastal aquifer have been developed based on tidally induced water table fluctuations but no studies have been conducted on the variation effect in tropical countries. This is an important aspect of understanding beach profile evolution.

Moreover, strong correlations exist between the swash hydrodynamics (velocity, depth and duration) and sediment concentration. This will improve the prediction of the swash zone sediment transport characteristics. In addition, the beach morphological changes can also be considerably influenced by the interaction of the swash flow and beach groundwater table. For that reason, better predictions of beach profile changes cannot be accomplished unless the effects of infiltration and exfiltration processes on swash zone sediment transport are better understood. All the related studies about infiltration and exfiltration processes at the beach area are tabulated and summarized in Table 2.2. However, the infiltration and exfiltration studies under seasonal variation effect are still lacking especially in tropical countries that experience seasonal dry and wet periods. It is strongly believed that the fluctuations of beach groundwater table significantly influence the swash zone morphological changes through the infiltration and exfiltration processes. This essential information could provide better understanding about the exfiltration effect on beach erosion process.

Table 2.2 Summary of past infiltration and exfiltration studies

Authors	Description of Study	Infiltration	Exfiltration
Bagnold (1940)	Laboratory Regular waves tan β = 0.34 Gravel (3-9 mm)	Reduced infiltration flow Enhanced offshore transport (backwash)	Not measured
Longuet-Higgins and Pakin (1962)	Field (Chesil Bank, UK) swash zone tan β = 0.114 to 0.157 Gravel (760 mm)	Reduced infiltration flow Enhanced offshore transport (backwash)	Not measured
Watters and Rao (1971)	Laboratory Flat bed Plastic spheres (95.25 mm)	Enhanced sediment movement	Reduced sediment movement
Nelson and Miller (1974)	Laboratory Swash zone tan β = 0.035 to 0.052 Sand (0.55 mm)	Reduced backwash flow Enhanced sand deposition at uprush limit	Not measured
Packwood (1983)	Modelling	Reduced	Not measured
Baldock and Holmes (1998)	Laboratory Flat bed Sand (0.2 mm) Anthracite (3 mm)	Reduced sediment movement	Enhanced sediment movement
Turner and Masselink (1998)	Field & modelling Swash zone tan β = 0.0143 Sand (0.24 mm)	Reduced sediment movement	Enhanced sediment movement
Butt et al. (2001)	Field & modelling Swash zone tan β = 0.0143 Gravel (760 mm)	Reduced sediment movement	Enhanced sediment movement

Table 2.2 Summary of past infiltration and exfiltration studies (cont.)

Authors	**Description of Study**	**Infiltration**	**Exfiltration**
Masselink and Li (2001)	Modelling (process based) Swash zone	Enhanced offshore transport Reduced velocity, depth & duration of backwash	Not reported
Nielsen et al. (2001)	Laboratory Regular waves Flat bed	Reduced sediment movement	Not reported
Li et al. (2002)	Modelling Swash zone Fine & coarse sand	Enhanced onshore transport Reduced velocity and duration of backwash flow	Not reported
Obhrai et al. (2002)	Laboratory Regular waves Flat bed Sand (0.25 mm)	Reduced suspended sediment load	Not measured
Karambas (2003)	Modelling Swash zone	Enhanced onshore transport (lower groundwater table)	Not reported
Austin and Masselink (2006)	Field (Slapton Sands, UK) Swash zone $\tan \beta = 0.15$ Gravel (6 mm)	Enhanced onshore transport (rising & falling tide)	Enhanced offshore transport (rising tide)
Horn et al. (2007)	Laboratory Swash zone Regular waves Sand (0.197 mm) & gravel (0.840 mm)	Enhanced onshore transport (lower groundwater table)	Not measured
Hoque and Asano (2007)	Modelling (process based) Swash zone	Enhanced onshore transport (finer particles)	Enhanced offshore transport (coarser particles)

2.8.2 Influence of Exit Point Position and Seepage Face in the Swash Zone

Generally, the groundwater table elevation with respect to mean sea level will influence the beach saturation level and the rate of infiltration and exfiltration (Bakhtyar et al., 2009). The groundwater table can be assumed as an extension of the mean water surface into the beach, and therefore should have the same elevation as the tide (Horn, 2006). However, decoupling process might happen between the tide and the beach groundwater table when the groundwater exit point becomes separated from the shoreline This occurs due to the rapid drop of tidal elevation compared to the gravity influenced groundwater drop (Horn, 2006). By definition, the exit point is the position on the beach profile where the decoupled groundwater table intersects the beach face.

During decoupling period, the exit point position is separated from the mean sea level until it is inundated by the rising tide. During this time, a seepage face phenomenon develops below the exit point where the groundwater spreads out on the beach face. At the beach, the seepage face can be observed as a glassy surface as shown in Figure 2.10. This particular process can be commonly observed on sandy beaches with a low permeability rate. Water on the seepage face is at atmospheric pressure, as is water on the groundwater table. The extent of the seepage face depends on the tidal regime, the hydraulic properties of the beach sediment, and the geometry of the beach face.

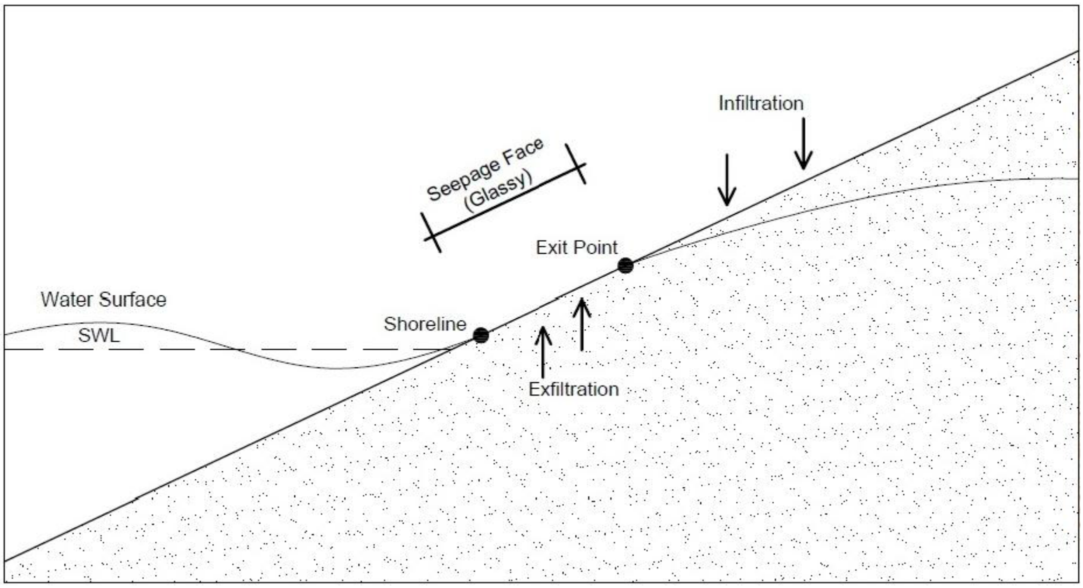


Figure 2.10 Sketch of beach groundwater decoupled from surface water (Jamal, 2011)

During high tide, the beach area is generally exposed seawater to infiltration, compared to during low tide. The area of the beach from which groundwater flows is defined by the length of the beach under water (below the tide) and the extent of the seepage face. The exit point is at the boundary between saturated soil at the lower section of the beach and unsaturated soil at the upper part of the beach. The variation of exit point position due to local seasonal variation effect is hypothetically important in order to provide better explanation about the erosion process in the swash zone during wet season. It is strongly believed that the occurrence of seepage face will enhance the offshore sediment transport due to the higher exfiltration rate in the swash zone during uprush and backwash flows.

2.9 Fluidisation of Beach Area by Tidal and Rainfall Influences

Response of beach groundwater table due to tidal fluctuations effect has been studied and reviewed (e.g. Nielsen et al., 1988; Gourlay, 1992; Baird and Horn, 1996; Turner et al., 1997; Turner, 1998; Horn, 2002; Horn, 2006; Bakhtyar et al., 2009). Most of the studies focused on groundwater in sandy beaches, especially on the effect of tide-induced fluctuations directly on beach groundwater table in the cross-shore direction. These studies also indicated that beach groundwater table is generally not flat due to effect by rising or falling tides. The beach groundwater table will be sloping seaward during falling tide and sloping landward during rising tide.

Although the effects of infiltration and exfiltration flow are the main processes that influence the sediment transport in the swash zone, consideration of the potential beach bed failure due to the beach groundwater fluctuations still remain important in the swash zone study. Basically, fluidisation of beach area occurs when the upward-acting seepage force exceeds the downward-acting immersed particle weight. It has been recommended that groundwater flow out from a beach by tidal elevation effect during the ebb tide will increase the potential of beach fluidisation phenomenon and resulted in the sediment to be transported easily by swash flows (e.g. Duncan, 1964; Heathershaw et al., 1981; Turner and Nielsen, 1997). However, it is not clear whether this process enhances fluidisation of the beach because hydraulic gradients under the sand surface will likely be small.

Baird et al. (1996) discussed that beach fluidisation is only high potential of swash flow on a seepage face during low tide condition. Pore water pressures under the beachface will rise quickly during the saturated beachface experienced the swash flow activities and resulted the beach sediment works like a confined aquifer. Due to that reason, infiltration of swash flow into the saturated beach is particularly limited until the porosity changes at minimum level due to expansion and contraction of the sand. However, water pressures in the beach will be distributed quickly through the sediment. During the low tide condition, the pressure on the beach face will be released and provide large hydraulic gradients acting vertically upwards directly under the beachface. The effect of seepage force and upward-acting hydraulic gradients could be satisfactory to encourage beach fluidisation at the beachface.

Commonly, tidal level variations have an important effect on the beach groundwater fluctuations. The beach groundwater table fluctuations in sandy beach is believed to be vital to beach erosion and accretion (Grant, 1948; Duncan, 1964; Eliot and Clarke, 1988; Li et al., 2002; Horn, 2006), beach dewatering technique (Turner and Leatherman, 1997) and many more. The impact of tidal fluctuations pressure will influence the beach groundwater table variations behaviour (Kim et al., 2005; Guo et al., 2007). Earlier, Duncan (1964) studied the variation of beach profile based on a daily tidal cycle and concluded that groundwater table increases quicker during the flood than the ebb. Due to this situation, the beach groundwater table is sloping shoreward during flood and sloping seaward during ebb as shown in Figure 2.11. For that reason, the infiltration process of swash flow into sandy beaches is more possible to occur during the flood period as the beach is moderately dry (Baird et al., 1998; Masselink and Li, 2001). From field observation by Carter and Orford (1993) also mentioned that the seepage might happen during ebb period and enhance the offshore sediment transport.

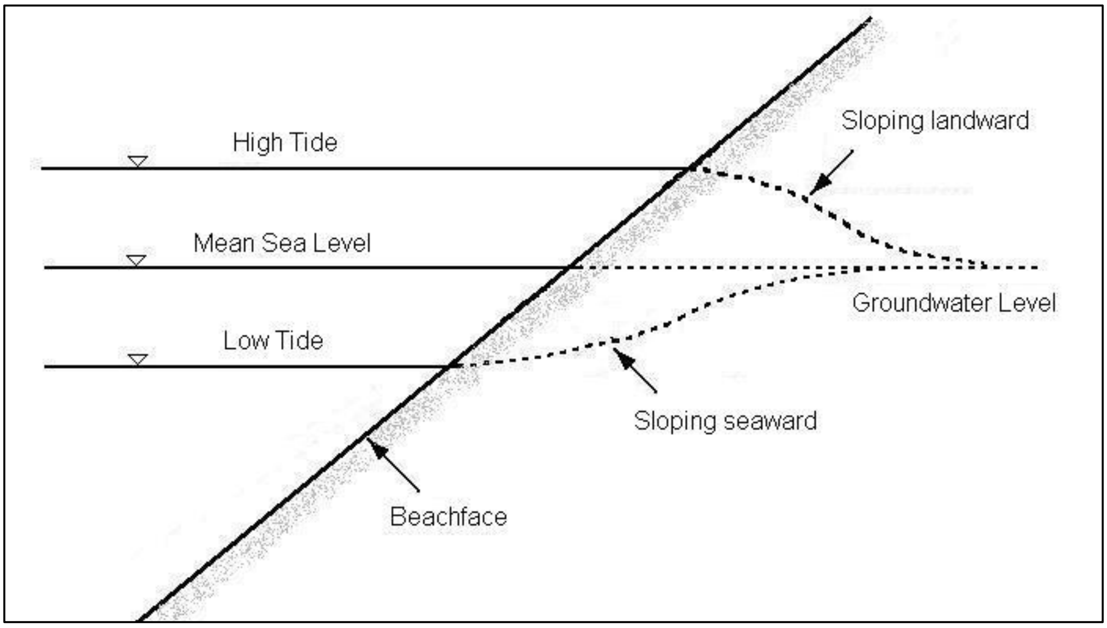


Figure 2.11 Tide and groundwater level (modified from Jamal, 2011)

The beach morphological changes by tidal elevations effect has been studied extensively by previous researchers for many years (Duncan, 1964; Masselink and Hegge, 1995; Kim et al., 2005; Austin and Buscombe, 2008). During flood, higher tidal elevation will enhance the infiltration process and a beach berm will build up on the upper beach but in contrast during ebb, the offshore sediment movement might be occurred due to seepage influence at the beachface (Kulkarni et al., 2004). This observation is also consistent with Horn and Mason (1994) which reported that the sediment transport rate would be different during the tidal cycle where it is higher during flood and lesser during ebb. Therefore, the berm developed earlier during flood might remain on the upper beach until a greater wave attack erode the beach profile.

For gravel beach, tidal elevation will not disturb the character and slope of the gravel beach profile but it may control the location of the profile on the beach face (Powell, 1990). However, under constant water level, the beach profile variation is found to be just around the mean water level while a beach with tidal influence has put the entire beach face affected. Additionally, the tide effect will also increase the berm size. Under swell situation the berm moves landward and the sandbars shift seaward under storm condition (Trim et al., 2002).

Rainfall events would influence the elevation of the beach groundwater table and therefore beach morphological profile would be changed (Foote et al.,2002; Gourlay, 1992). Huisman et al. (2011) showed that a high level of rainfall distribution could elevate the beach groundwater table relative to the mean sea level through a study conducted at Ngaranui Beach, New Zealand. They concluded that the influence of rainfall on beach groundwater dynamics is often not taken into account in existing groundwater modelling and also suggested that heavy rainfall distribution may partly cause the beach groundwater to become higher than usual. This super elevation is not related to incident rainfall but only affected by high cumulative rainfall distribution.

More recently, Vallejos et al. (2015), investigated the effect of seasonal climate beach groundwater dynamic at Andarax Delta, Spain. Their findings concluded that rainfall can cause greater impact on beach groundwater table than other factors such as atmospheric pressure and wave patterns. Their study showed that higher rainfall event during rainy months (65-70% from annual rainfall) produce a clear rise of groundwater level approximately of 25-30 cm. They also found that after the rain, the groundwater level dropped much lower that before the rainfall event.

2.10 Summary

The importance of groundwater level in influencing the beachface profile makes it particularly important to understand the process involved especially in tropical regions such as Malaysia, which is experiencing annual dry and wet seasons. It is evident from previous studies that the uprush and backwash processes in the swash zone provides the control factor for the swash morphological changes with the uprush activities tend to move sand onshore, while the backwash process promotes offshore sand transport.

The beach groundwater elevation with respect to the mean sea level (MSL) also will affect the beach saturation level and the rate of infiltration and exfiltration on the beach face. It has been concluded from laboratory works that a high groundwater table relative to mean sea level (MSL) tends to promote offshore sediment transport in which the beach is in an erosive mode. A relatively low groundwater table enhances onshore sediment transport and beach accretion.

Statistical analysis of beach profile using EOF is widely used and was also successfully proven as a suitable technique to separate the spatial and temporal dependence of the profiles data. It can represent as a linear combinations of corresponding functions of time and space. These functions represent the variation of the beach profile shape in terms of distance from fixed data points and in terms of temporal changes in profile configuration over the period of any study either short or long periods.

Although many researchers have emphasized the importance of swash zone hydrodynamic processes on beach morphological changes, there is still more work to do related to the following issues:

i. In recent years, the importance of swash zone processes in determining net sediment transport rates and hence accretion and erosion of beach profiles has become clearer. However, in Malaysia and other tropical countries, such studies are still limited especially involving seasonal hydrological variation effect such as rainfall.

ii. The influence of the groundwater table fluctuation on a beach was normally neglected in morphological assessment or prediction, as most studies preferred more influencing parameters such as wave height and tidal elevation. Furthermore, studies on the groundwater table effect on beach morphological changes have only been conducted in lab scale. Even so, those studies only looked at tidal elevation effect on beach groundwater table fluctuations. Little consideration has been given to seasonal hydrological variation like rainfall which theoretically could impact the beach groundwater table variation and swash sediment transport especially in tropical countries.

iii. Until now, almost all studies of seasonal variation effect on beach profile changes around the world covered summer and winter seasonal cycles and are mainly focused on incident wave attack. Unfortunately, there are very limited studies related to tropical seasonal variation. This type of study is important in order to further explain beach profiles variability, especially in Malaysia. Higher rainfall distribution during the wet period due to the northeast monsoon season effect could significantly increase the level of beach groundwater table which resulted in a higher rate of beach erosion. The outcomes from this study could provide better understanding about beach profile evolution under local seasonal hydrological variation effect.

iv. The major challenge in conducting a swash zone study in any field works is equipment availability and budget constraint due to the complexity of natural processes in that area.

Hence, a research on swash zone processes under seasonal variation effect is compelling to contribute to the body of knowledge of the field. The outcome can be very useful for future reference in swash zone research, especially in Malaysia and other tropical countries. This can be a good platform to enhance better understanding about seasonal variation effect towards swash zone morphological changes for the future planning or development in coastal areas.

CHAPTER 3

RESEARCH METHODOLOGY

3.1 Introduction

In general, the morphological changes of beach profiles are characterized by the cross-shore and longshore sediment movement. For the current study at Desaru beach, the cross-shore beach profile changes were investigated in terms of space and time. Moreover, measuring beach profile is an ideal and fundamental activity for the knowledge on the beach changes and its effects. Beach profile often changes especially under the local seasonal variation effect and therefore the information should be gathered within the time interval. This chapter present the methodology to investigate the cross-shore morphological changes at Desaru beach under local seasonal hydrological variation influence using various statistical techniques.

During this period of study, field monitoring such as beach profiles, rainfall distributions, groundwater elevations, tidal elevation, swash velocities and depths were conducted and evaluated for Desaru beach from September 2013 to January 2016. The field work covered a few cycles of seasonal wet and dry periods at Desaru beach. By measuring the profile of a beach at set intervals, the amount of erosion and accretion can be determined over the period of the surveys as well as some indications of where the material may be going (Dean and Dalrymple, 2004). Understanding the site conditions is the most important stage or procedure before implementing any study. This chapter will also present the statistical techniques which have been applied to analyze the beach profiles data to understand the behavior of the beach variability under seasonal hydrological variation influence especially in the swash zone.

The overall methodology used to monitor and investigate the beach profiles changes and nature forces is shown in Figure 3.1. For this study, the methodology was separated into two major parts as follows;

i. Field Data Collection

Desaru beach profiles were surveyed at least six months per year from 2013 until 2016 for this study. All the profiles were measured at a fixed cross-shore beach transect along the beach which is referred at a reference baseline at well BH2. Figure 3.2 shows that the monitoring of local hydrological data such as rainfall distribution and groundwater table are important factors to be considered to evaluate their influence to the morphological changes. Furthermore, the tidal elevation data from the study area were also monitored to check any influence on the beach groundwater level variation. In this study, the swash zone characteristics such as flow depth and velocity during uprush and backwash activities were recorded and analyzed to check the effect of both processes.

ii. Statistical Techniques

Basically, simple bulk statistical methods such as the minimum, maximum, mean, range, standard deviation, and correlation were used to characterize the beach profile response. In the study, similar methods were employed for analyses of beach profile variability for predicting the probability that a certain variation in the certain elevation will occur. Moreover, advance statistical methods such EOF was used in this study to separate the spatial from the temporal variability of the profiles. The EOF method also provides means of removing the less predictable part from the profile data itself which is very important in beach morphological changes study. For EOF purpose, all the recorded beach profiles from the study were analyzed as biannually assessment to check the effect of dry and wet periods.

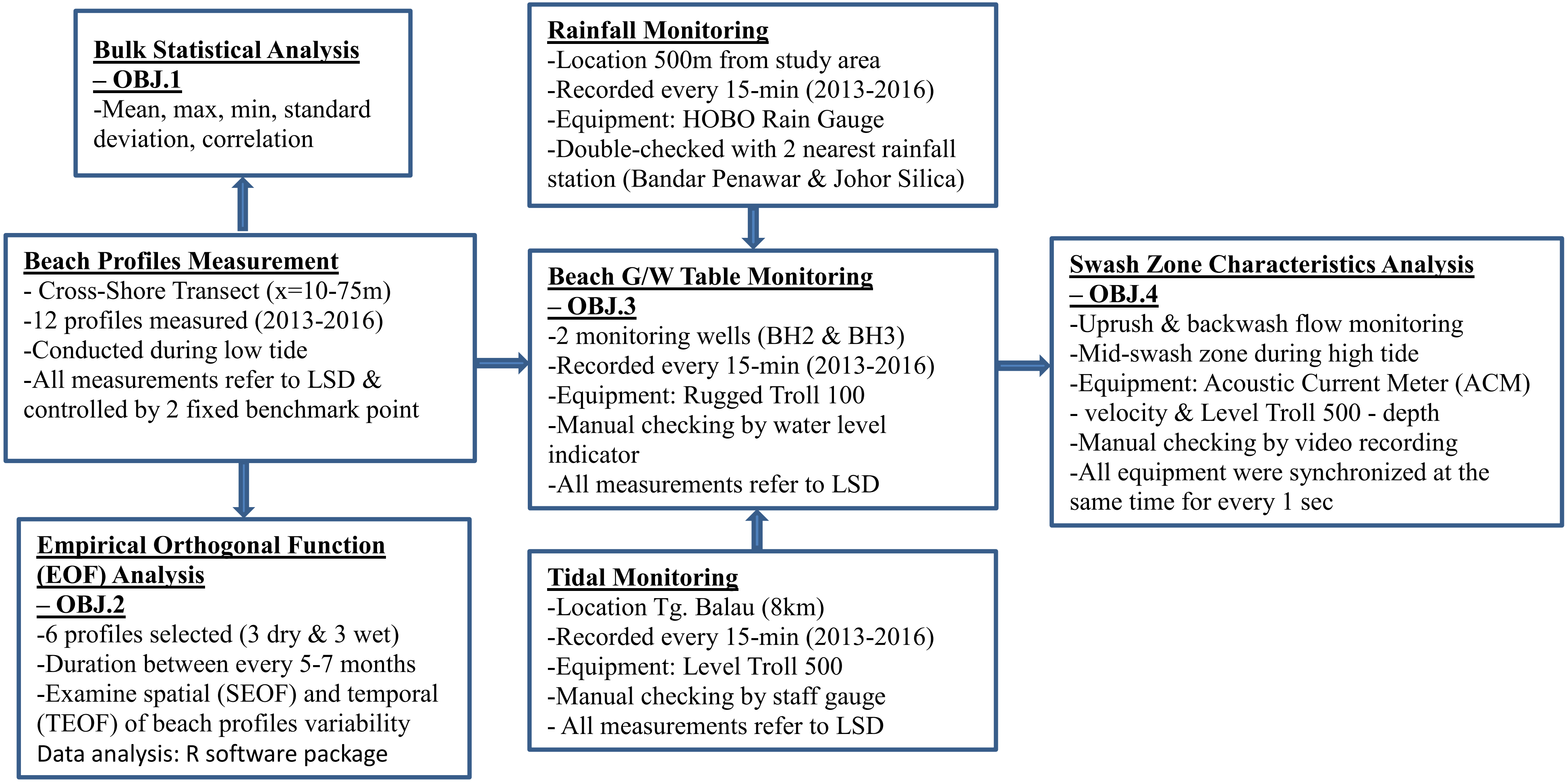


Figure 3.1 Flow chart of the research

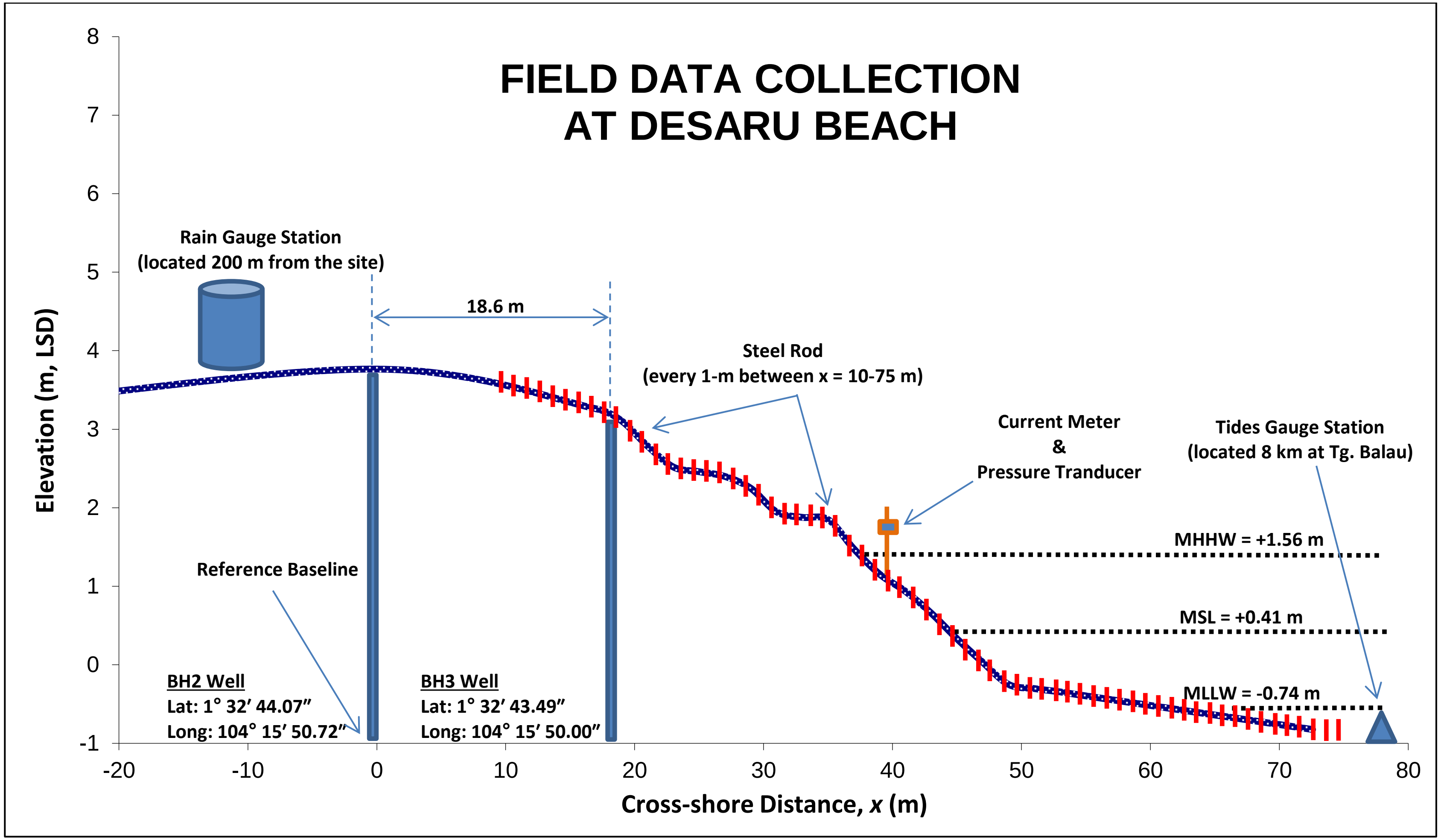


Figure 3.2 Schematic diagram of the experimental setup at Desaru beach

3.2 Description of Study Area

The field site used for the present study was Desaru beach, Johor as shown in Figure 3.3 a. The beach is located on the east coast of the Peninsular Malaysia. It has clean sandy white beaches and located approximately 88 km east of Johor Bahru, facing the South China Sea. It is a very popular tourism place for Malaysian and traveller who come to enjoy the 25 km stretch of undisturbed beaches and golf courses. For this study, one part of the cross-shore of the beach as shown in Figure 3.3 b & c was to choose because it experiences a very distinct seasonal hydrological variation of dry and wet periods. This is the main factor to be considered in this study. In terms of climate as shown in Figure 3.4, Desaru beach is strongly influenced by the northeast monsoon when it received a greater wave height and higher average monthly rainfall between the months of November to March of about 158.4 mm. The most wet period is in December with average monthly rainfall of 224.4 mm. In contrast, during the southwest monsoon between May to September, there is a lower average monthly rainfall of 116.8 mm and smaller incident wave energy. The driest period is in February with average monthly rainfall of 57.5 mm. Figure 3.5 shows the wave rose of the study area for May and June representing the southwest monsoon and December and January representing the northeast monsoon. The wave rose showed that during the northeast monsoon, the dominant wave direction is from north, while during the southwest monsoon, the dominant wave direction is from south-southwest. The wave height may reach 2.5 m during southwest monsoon and higher than 3.0 m during northeast monsoon.

The familiar name of Desaru comes from two Malay words which are “desa” and “baru” that means “new village”. Before Desaru was developed by the South East Johore Development Authority (KEJORA), it was purely a forest. Desaru was officially opened to the public in the year 1977. In the beginning, Desaru lacks any tourism facilities such as chalet, resort, restaurant, and mosque. Nowadays, Desaru has become the main tourist destination in the southern part of Peninsular Malaysia due to its beautiful ocean view, environment, and facilities and services available. Therefore, the need for better understanding of the local beach profile evolution is essential for local authorities or public agencies to predict beach behavior which is an important aspect of effective coastal management and decision making.

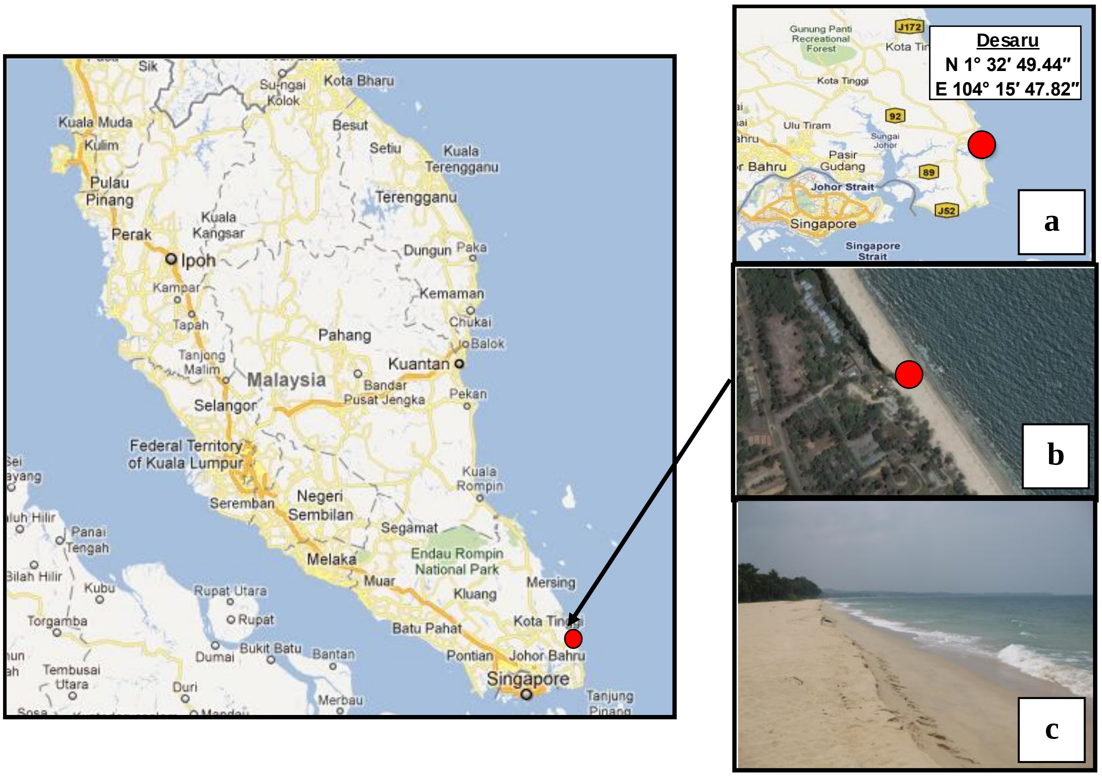


Figure 3.3 (a) Desaru beach and its location in Peninsular Malaysia, (b) Location of cross-section and (c) A view of the beach

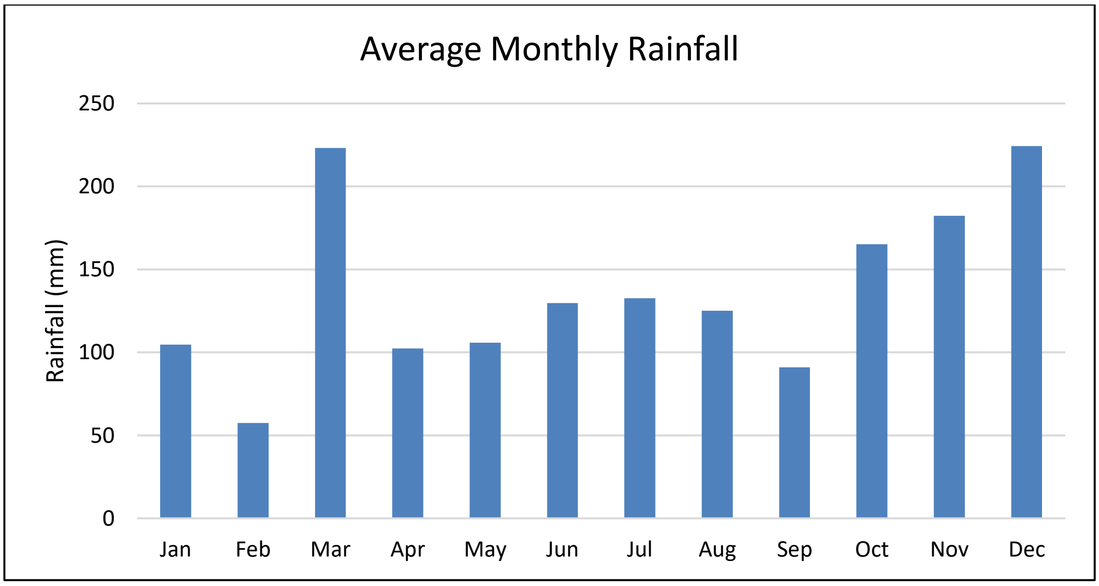


Figure 3.4 Average monthly rainfall of the study area

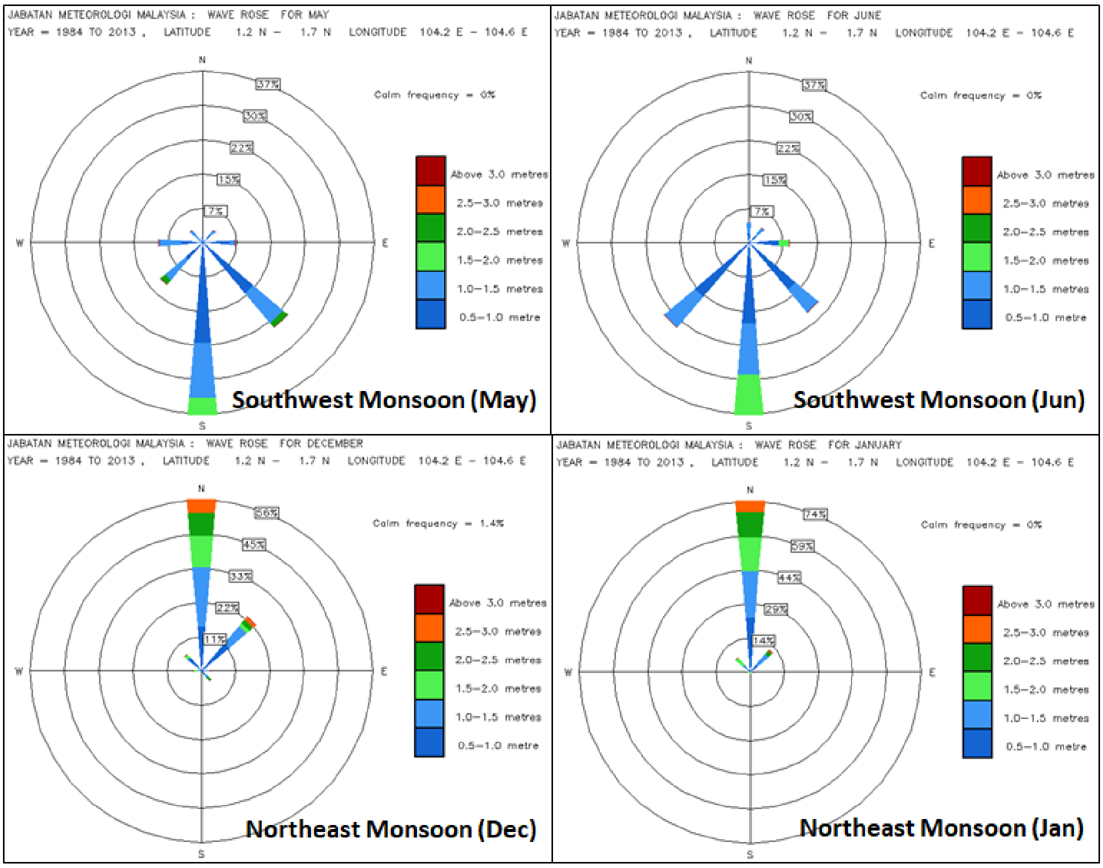


Figure 3.5 Wave rose at Desaru during southwest and northeast seasons

In this study, one cross-shore transect of the beach was set-up as shown in Figure 3.6. It has the least impact from longshore sediment transport due to the orientation of the beach and the direction of incoming waves. Generally, the beach is exposed to various variables; low and calm waves during southwest monsoon season, when it is relatively drier from May to September, followed by moderate to high energy waves attack during the northeast monsoon season, when it is relatively wetter, from November to March annually. The beach is composed of fine sand (D_{50} = 0.2–0.4 mm). Desaru beach has a steep upper beach face with a gradient of between 1:5 and 1:7, and a moderate intertidal beach with a gradient of between 1:10 and 1:20. For this study, the survey measurement for subtidal beach profile was not included due to equipment availability and scope of study.

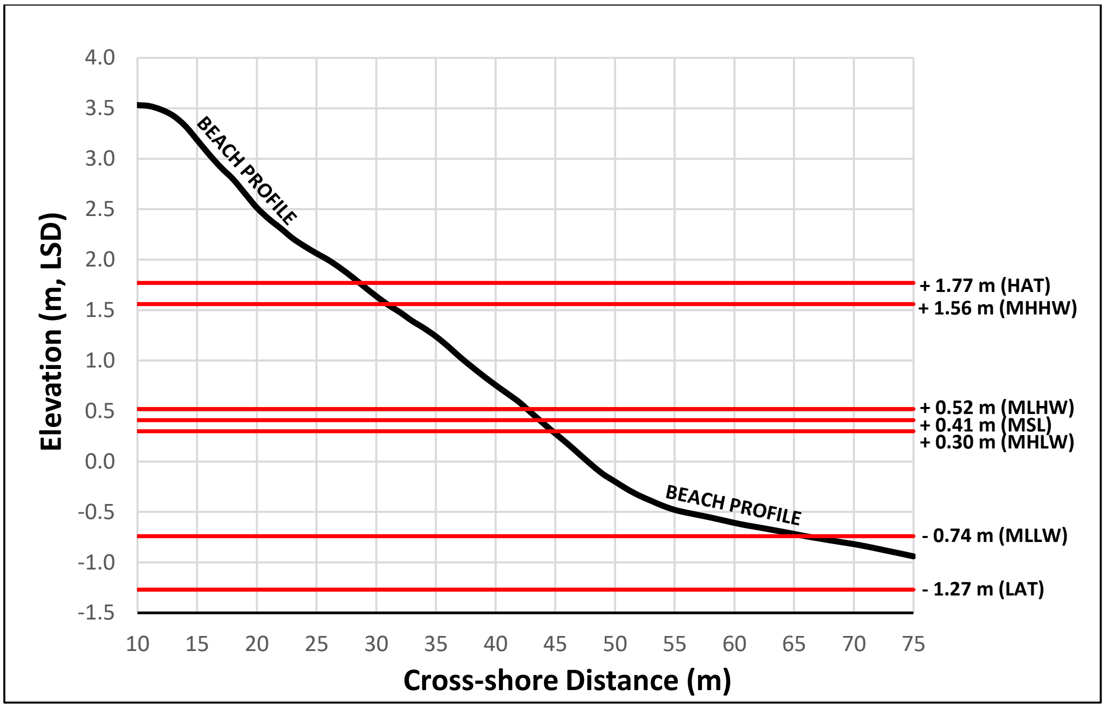


Figure 3.6 Profile of the selected cross-section at the study area

The semi-diurnal tides in the study area are mesotidal with a moderate mean spring tidal range of 2.0 m, reducing to 0.8 m during neap tidal cycle. Tidal elevation data for the study area according to Chart Datum (CD) and Land Survey Datum (LSD) were shown in Table 3.1.

Table 3.1 The tidal elevation data of study area

	CD (m)	**LSD (m)**
Highest Astronomical Tide (HAT)	+3.04	+1.77
Mean Higher High Water (MHHW)	+2.83	+1.56
Mean Lower High Water (MLHW)	+1.79	+0.52
Mean Sea Level (MSL)	+1.68	+0.41
Mean Higher Low Water (MHLW)	+1.57	+0.30
Mean Lower Low Water (MLLW)	+0.53	−0.74
Lowest Astronomical Tide (LAT)	0	−1.27

3.3 Fieldwork Monitoring

During the field monitoring, data were collected in different range of time based the type of parameter as shown in Table 3.2. For the beach profile changes analysis, 12 beach profiles were selected from the surveyed profiles which are purposely selected due to the local seasonal variation effect. For detail analysis of the profile changes in terms of time and space using the EOF method, six profiles were selected and analyzed.

Table 3.2 Data period of monitoring data

Types of Data Monitoring	Data Period
Beach profiles	Every dry and wet periods (irregular)
Rainfall distribution	Every 15 minutes
Beach groundwater elevation	Every 15 minutes
Tidal elevation	Every 15 minutes
Swash flow depths	Every 1 second
Swash flow velocities	Every 1 second

3.3.1 Cross-Shore Beach Profiles

Morphological variation of cross-shore beach profiles especially in the swash zone takes place in a series of time scale that varies from days to several years with respect to the local weather conditions and seasonal variations. From the field and laboratory investigations, it can be concluded that the hydrodynamics in the swash zone is governed by a sediment transport mechanism that largely controlled the beach face morphology.

For beach profile measurements, as suggested by a similar field method by Jensen et al. (2010), several steel rods were placed in a cross-shore transect along the beach with a space between 1 to 2 m. In order to estimate the net accretion or erosion across the beach face for the monitoring, volumetric changes were recorded with the assumption that changes in elevation at each rod represents the average bed level changes within 1 m^2. In Figure 3.7, several rods were installed and measured during low tide and all the surveyed data were referenced to a JUPEM benchmark using the total station (Figure 3.8). During the study period, all the cross-shore beach profiles were measured with respect to a reference point at wells BH2 (1°32′44.07″ and 104°15′50.72″) which is located at the beach crest ($x = 0$ m) and BH3 (1°32′44.46″ and 104°15′51.20″) which was placed about 18.6 m seaward from the benchmark point BH2 (Figures 3.9). The BH3 point also acted as a control point for straight line of cross-shore profile survey for this study. This reference line is perpendicular to the shoreline and was intended to monitor the cross-shore variability of Desaru beach.

Figure 3.7 A view of the steel rods used for the cross-shore profile measurement

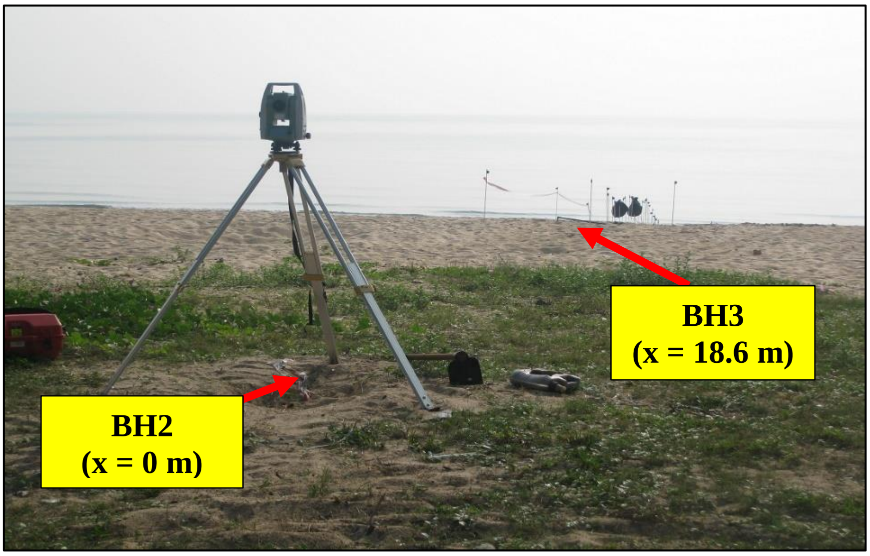


Figure 3.8 Surveying works of cross-shore profiles based on the reference points

Figure 3.9 The location of the monitored beach profile at Desaru

The cross-shore beach transect was selected due to the minimal net long-shore transport at its location. Twelve (12) survey profiles were measured between June 2013 and January 2016 as shown in Table 3.3. This adequately covered the seasonal variation analysis for Desaru beach. Basically, the length of profiles measured varied from survey to survey but was always extended out to at least the MLLW. Thus, all beach profiles were truncated around MLLW to provide a constant foundation for analysis. For this study, the shoreline is defined as the intersection between points of the cross-shore profile and the MSL. Due to the prevalence moderate to high energy waves especially during the northeast monsoon from November until March annually and the exposed nature of the beach, the morphodynamic response of Desaru beach is highly variable and extremely rapid where the accretion and erosion of beach face can take place at any time of the year.

Table 3.3 List of profile survey works

Date of Beach Profiles	**Condition of Beach-Face**	**Types of Period**
27/06/2013	Accretion	Dry
23/10/2013	Erosion	Wet
06/12/2013	Erosion	Wet
25/01/2014	Erosion	Wet
16/03/2014	Accretion	Wet
18/05/2014	Accretion	Dry
07/11/2014	Erosion	Wet
25/12/2014	Erosion	Wet
01/03/2015	Accretion	Wet
06/06/2015	Accretion	Dry
01/10/2015	Erosion	Wet
23/01/2016	Erosion	Wet

3.3.2 Rainfall Data Collection

In Malaysia especially in the east coast region of Peninsular Malaysia, the annual variations of seasonal period during dry and wet periods will significantly control the condition of the beaches. During the dry period, there is limited rainfall and this situation will significantly drop the groundwater table. This situation will automatically enhance the infiltration process and promotes beach accretion due to the unsaturated condition of the beach surface. During wet periods, due to the northeast monsoon season effect, the exposed areas especially in the study area will experience heavy rain events and contribute to increase the level of groundwater table. This condition will induce increased erosion at the nearshore area especially in the swash zone. So, it is posited that the seasonal variation factor in Malaysia have significant influence on the sediment transport processes especially in the swash zone.

For the monitoring of Malaysian seasonal variation especially for dry and wet periods, one rain gauge station (Figure 3.10) was installed close to the study area at Desaru Development Holding One Sdn. Bhd. office about 500 m from the field monitoring site. The rainfall data was recorded by a HOBO data logging rain gauge every 15 minutes. The rain gauge consists of two major components: a tipping-bucket rainfall collector and an event/temperature data logger. The collector consists of a black-anodized aluminium knife-edged ring, screen, and funnel assembly that diverts rainwater to a tipping-bucket mechanism located in an aluminium housing. The housing is coated with a white-baked enamel surface designed to withstand years of exposure to the environment. The tipping-bucket mechanism is designed such that one tip of the bucket occurs for each 0.01" (RG3) or 0.2 mm (RG3-M) of rainfall. Each bucket tip was detected when a magnet attached to the tipping bucket actuates a magnetic switch as the bucket tips, thus affecting a momentary switch closure for each tip. The spent rainwater then drains out of the bottom of the housing. The switch is connected to a HOBO event/temperature data logger, which records the time of each tip. The data logger is a rugged, weatherproof event logger with a 10-bit temperature sensor. It can record 16,000 or more measurements and tips. It uses a coupler and optical base station with USB interface for launching and data readout by a computer.

The rainfall data is very important for this study to relate the contribution of seasonal variations during the dry and wet periods to the swash zone characteristics. The station was checked monthly to make sure that the rain gauge functions well and the data from this station were downloaded at the same time by to a laptop computer. The rainfall data was also double-checked with the data taken from the nearest rainfall station from Malaysia’s local agency, Department of Drainage & Irrigation (DID) at Bandar Penawar and Johor Silica rainfall stations, located about 10 and 30 km from the study area, respectively.

Figure 3.10 Rain gauge installed at the study area

3.3.3 Groundwater Table Monitoring

The groundwater table on the beach is affected by the tidal elevation, waves, and to an extent the rainfall and sediment properties such as size, shape, porosity, permeability, and sorting (Foote et al., 2002). Previous researchers (e.g. Grant, 1948; Duncan, 1964; Park, 1991) investigated the relationship between the elevation of the beach groundwater table to beach erosion and accretion. Groundwater dynamic processes such as infiltration and exfiltration are among the significant factors which are stated by most researchers to explain the likelihood of erosion process in high water table beaches and accretion process in low water table beaches. It is believed that the beach groundwater table position will affect the infiltration and exfiltration processes during the uprush and exfiltration, and finally would affect the beach morphological changes especially in the swash zone. Initially, for the beach groundwater table monitoring data at Desaru, three monitoring wells (BH1, BH2, and BH3) were constructed but only two wells (BH2 and BH3) were used for monitoring purposes as shown in Figure 3.11. All the groundwater tables data were recorded using the water level logger which was installed and set up to record at 15 minutes intervals. All the loggers were installed from October 2013 to October 2015.

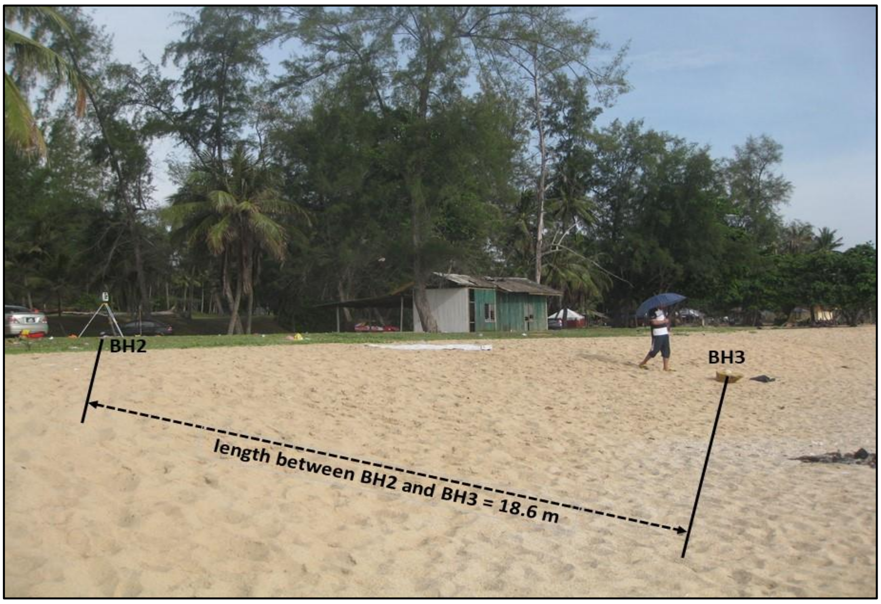


Figure 3.11 Location of the monitoring wells BH2 and BH3

3.3.3.1 Well Construction

In this study, the locations of the monitoring wells are very important for field data monitoring. Along the 22 km of undisturbed beach in Desaru, suitable well points were chosen based on the following criteria:

i. The constructed wells are accessible for testing, monitoring, cleaning, maintenance, and repair works.

ii. The wells are installed away from the public beach or visitor access to prevent any unexpected disturbances or damages to any equipment installed inside the wells.

iii. The wells are constructed at a suitable depth from beach face to gauge the groundwater table during dry seasons.

For that purpose, rotary wash boring was used as a drilling method for all boreholes used in this study. By using this method, drilling activities were accomplished by rotating a drill pipe with a bit attached to the bottom of the pipe.

Then, the bit cut and broken up the materials as it penetrated the formation. The drilling pump was also used to circulate water to wash out the cuttings and cool the drill bit and drill rods.

In the study area, three monitoring wells were installed at different locations in a straight line facing the beach. Figure 3.12-3.14 show the location of boreholes and the installation method at the field site where BH1 was installed at the upper part, further away from beach, BH2 was installed at 29.5 m from BH1, towards the beach; and BH3 was installed at 18.6 m from BH2, nearest the beach. The latitude and longitude for: BH1 are 1°32′43.49″ and 104°15′50.00, BH2 are 1°32′44.07″ and 104°15′50.72″ and BH3 are 1°32′44.46″ and 104°15′51.20.

Figure 3.12 Boring and drilling pump of well BH1

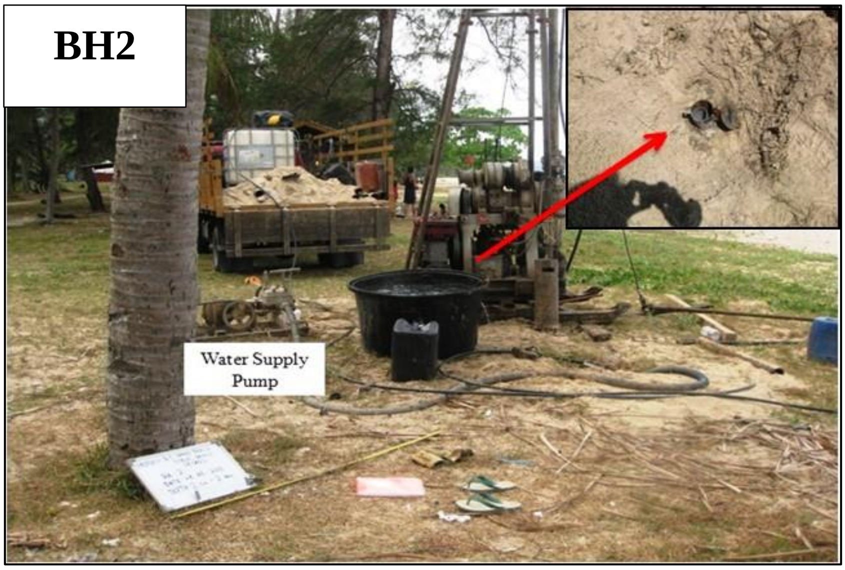


Figure 3.13 Boring and drilling pump of well BH2

Figure 3.14 A view of well BH3

Three standpipes of monitoring wells were used in this study which consists of tubes with a porous filter element on the end of each monitoring wells as shown in Figure 3.15. The standpipe monitoring wells were chosen for this study due to its simplicity and reliability, while the porous filter element can be sealed onto the ground at the appropriate level. A standard size of monitoring well 100 mm diameter at 10 m depth was used. Fine sand was placed between the borehole and the casing to reduce the rate of surface runoff from moving downward along the casing. Additionally, concrete cement was placed at the top of borehole (Figure 3.16), mainly to seal off poor quality aquifers and prevents mixing of water from different aquifers. The well constructions were carried out by an appointed contractor, Geo Strata Sdn Bhd started on 27 March 2013 and successfully completed on 1 April 2013. The detailed schematic of the monitoring well can be found in Figure 3.17.

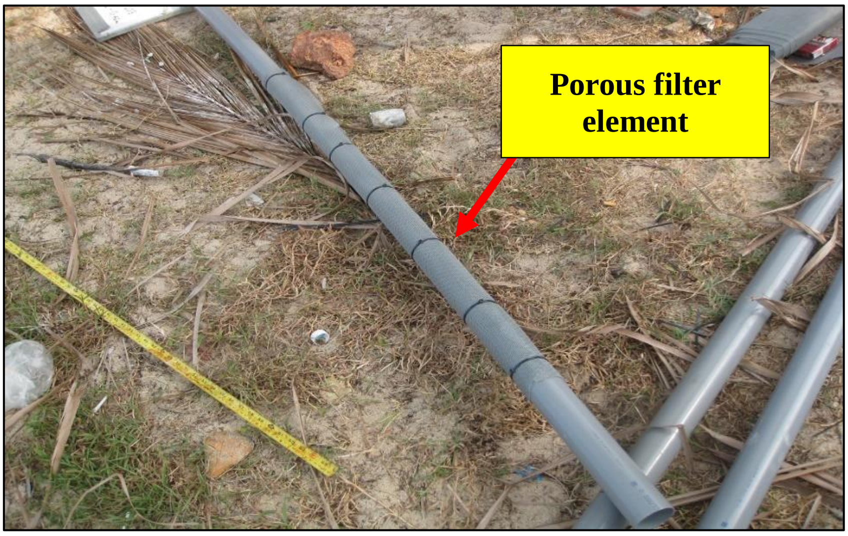


Figure 3.15 A porous filter element on the end of each monitoring wells

Figure 3.16 The concrete cement is placed at the top of borehole

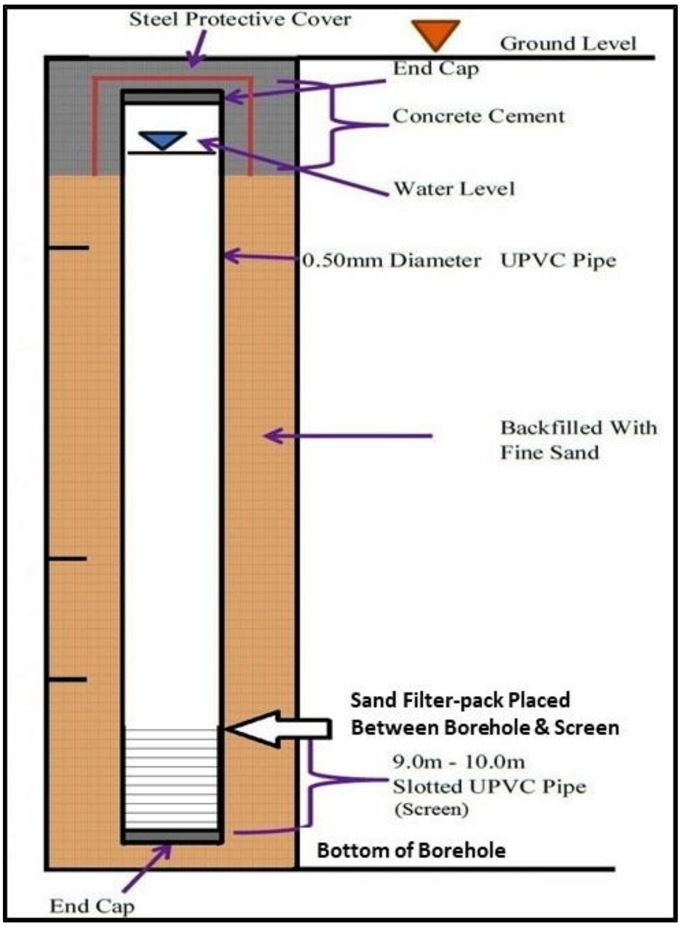


Figure 3.17 Typical monitoring well diagram designed for this study

3.3.3.2 Site Investigation at the Well

According to BS 1377: 1990, Desaru beach is composed of medium sand at average medium grain size, D_{50} of 0.37 mm. Standard penetration test (SPT) was carried out in accordance with Test No. 19 BS 1377: 1975 by means of split spoon sampler for the disturbed samples. The undisturbed sample employs hydraulic thrust on thin wall sampling tubes. The water level in each borehole was recorded using an electric dip-meter at the specific time interval during the day.

Construction of BH1 was completed on 27 March 2013 at groundwater level of 2.24 m but unfortunately, on 1 April 2013; this groundwater level was already full. BH2 was completed at 29 March 2013 at 1.24 m while BH3 was completed at 31

March 2013 at 1.72 m of groundwater level. A hydraulic head is the level which water will rise in the monitoring well to level with the subsurface. This hydraulic head comprises elevation head (potential energy per unit weight of water) and pressure head (elastic energy). In summary, the main reason for the full groundwater level is due to the pressure head in BH1. Hence, the measurements of groundwater level from BH1 will not be used in this study.

Next, the data of groundwater level inside the monitoring wells were analyzed and converted into a soil profile as shown in Figure 3.18. It was found that the thickness of sand layer in BH2 was larger than that of the BH3. This situation may affect the infiltration and exfiltration processes because sand is the top layer of BH2 and BH3 monitoring wells within the swash zone in Desaru beach.

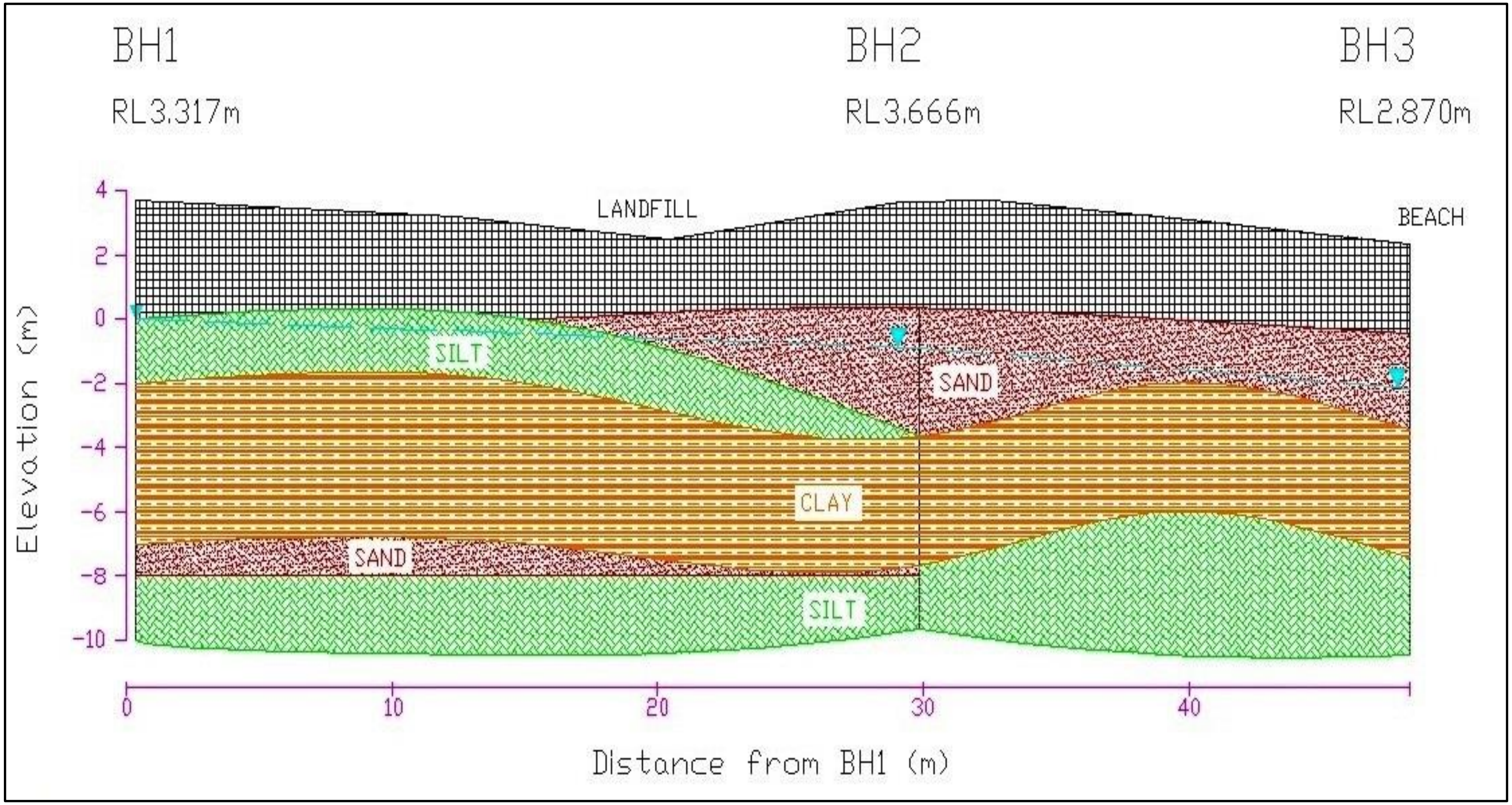


Figure 3.18 Soil profile of cross-section monitoring wells

3.3.3.3 Groundwater Table Measurement

In this study, only groundwater table data from the BH2 and BH3 were recorded using a standard pressure transducer (PT) as a groundwater level logger for every 15 min intervals and monitored monthly by a researcher. A standard PT used in this study was a Rugged Troll 100 model as shown in Figure 3.19. Basically, this instrument is designed for long- or short-term groundwater and surface water monitoring. It is also specifically designed to monitor and record changes in water level, pressure, and temperature. Rugged Troll 100 was used in this study to record the groundwater level data in BH2 and BH3 at 15 min intervals. Using Win-Situ program, all data in the water level logger were extracted by using a special docking station through a laptop. Manual reading was also conducted for every field visit using a water level indicator to ensure the quality of the field data as shown in Figure 3.20.

Figure 3.19 Rugged TROLL 100 for groundwater table monitoring

Figure 3.20 Manual reading used for the quality of the groundwater level data

3.3.4 Tidal Data Monitoring

In general, the cross-shore beach profile evolution is related to the changes to the shape of cross-shore profile in terms of space and time. Changes in cross-shore beach profiles are controlled by many factors in which one of them is tidal flow.

The tidal data for the study was recorded at Tg. Balau jetty which is about 8 km from the field site (Figure 3.21). The location of the tidal monitoring station was selected at Tg. Balau due to the quality of tidal data and to ensure the equipment is free from unexpected disruptions. The tide gauge was installed at 0.39 m above the chart datum to record the tidal levels at 15 mins interval using the water level recorder (Level Troll 500) as shown in Figure 3.22. The Level Troll 500 water level data logger is designed to record water level, pressure, and temperature. The Level Troll 500 will measure the water level with the highest levels of accuracy needed and where the water body (groundwater or surface water) is opened to the atmosphere pressure. Similar with Rugged Troll 100 for beach groundwater table monitoring, the Level Troll 500 also used the same Win-Situ program to retrieve the recorded data. The tide gauge was installed from June 2013 to January 2016.

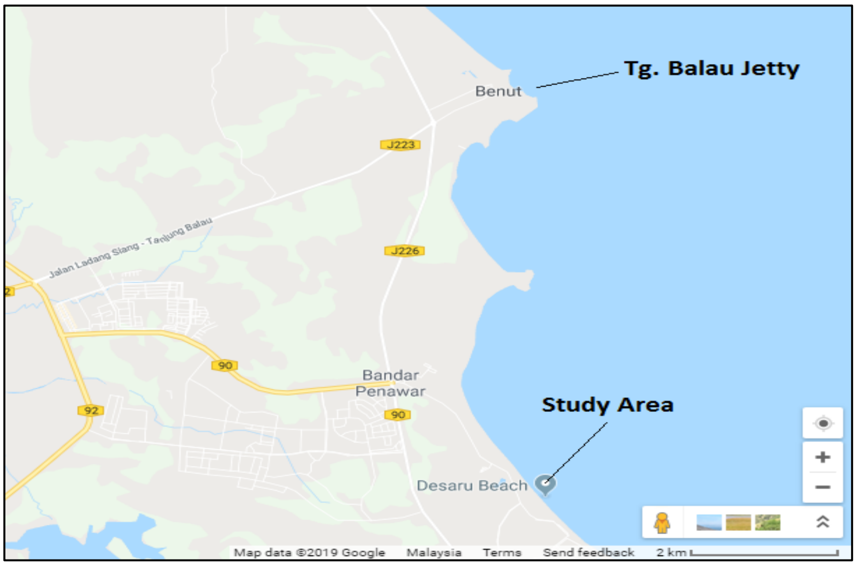


Figure 3.21 Location of Tg. Balau jetty from the study area

Figure 3.22 The tidal station at Tg. Balau jetty

The elevations such as MSL, MHHW, and MLLW can be measured and recorded using the tide gauge. In order to ensure good quality of the recorded tidal data, a manual reading using staff gauge was performed also during the field visit as shown in Figure 3.23. All the recorded data from the Level Troll 500 were checked and finalized for the purpose of the next analysis.

Figure 3.23 Manual checking for tidal elevation at Tg. Balau Jetty

In this study, the value of chart datum (CD) obtained from National Hydrographic Center was converted to LSD with the conversion levels as shown in Figure 3.24.

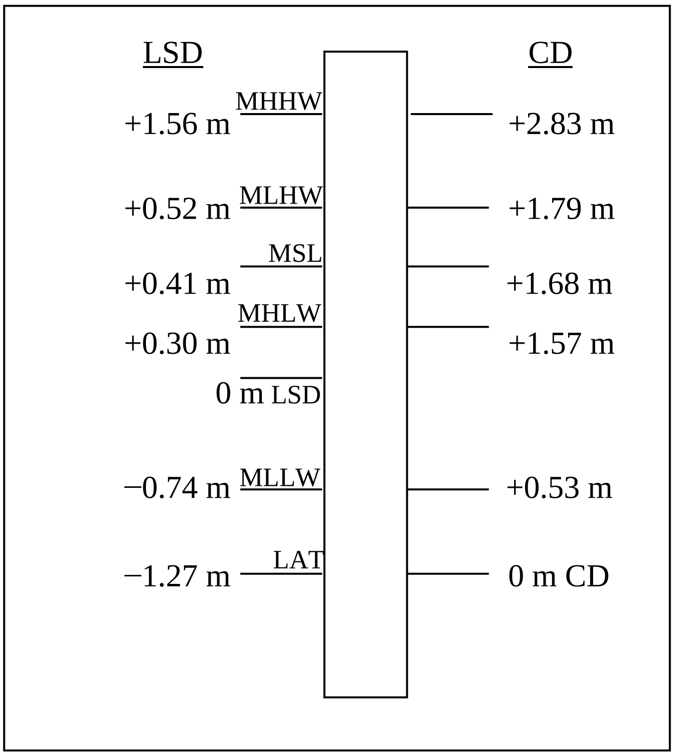


Figure 3.24 Elevation relationship between CD and LSD

3.3.5 Swash Zone Data Collection

Generally, the active part of beach morphology corresponding to the swash zone is often called the beach face or foreshore. It is largely shaped by the hydrodynamic forces in the swash zone. Hydrodynamic and sediment transport conditions in the swash zone are very complex due to the rapidly varying flow (during uprush and backwash activities) and possible occurrence of infiltration and exfiltration.

For swash zone dynamics investigation, the depth of beach face changes and flow depth in the swash zone were recorded using PTs which were buried about 30 cm below the sand surface as shown in Figure 3.25. This method can be used to measure the bed elevation changes over a time frame of several hours or inter-swash changes using the method developed by Baldock et al. (2005) and further discussed by Brocchini and Baldock (2008). As the flow depth falls to zero, the signal recorded by the transducer equals to the elevation of the water table, and hence the elevation of sand above the transducer, provided that the sand is close to fully saturated at that time. Immediately after the backwash on a medium to fine sand beach this is usually the case. An algorithm extracts the bed elevation and swash depths from the measured record. However, it should be noted that the technique relies on the water depth reducing to zero at the measurement location which is not always the case. Extra care is needed to avoid misleading results from slowly draining thin water films of water. Consequently, measurements should be supported by the manual rod measurements around the inner surf-swash zone boundary. Each rod was buried approximately 0.5 m from the bed elevation rods to form a rod-transducer pair at the same cross-shore location as shown in Figure 3.26. The PTs were synchronized and logged at the same frequency for each rod measurement period. The swash bed level and swash water level data were recorded for different periods (dry and wet) using two PTs (Level Troll 500 from InSitu Inc) at two different locations across the swash zone area. All PTs were synchronized at the same time for every 1 s.

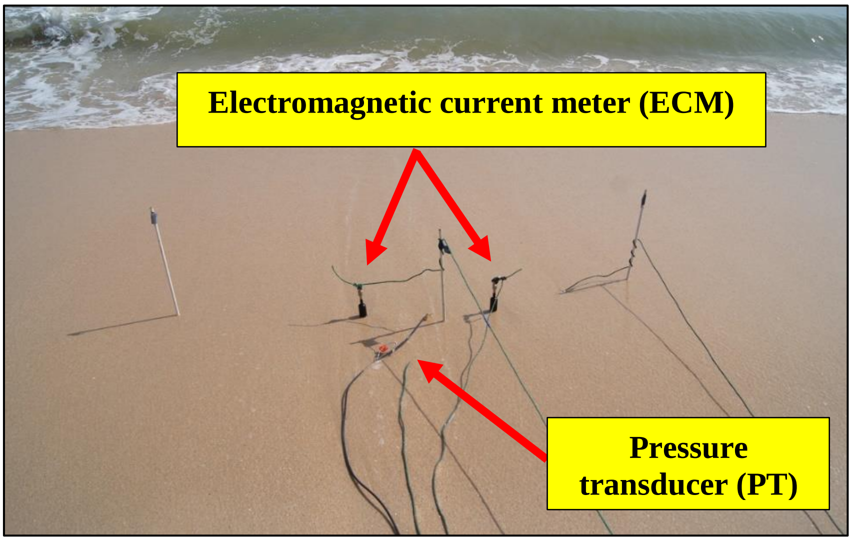


Figure 3.25 Installation of pressure transducer (PT) and electromagnetic current meter (ECM)

Figure 3.26 Installation of 1-m rod steels along the cross-section

Another field measurement conducted for swash zone dynamic in this study was the swash velocity. The patterns of uprush and backwash velocities characteristics in the swash zone were recorded. All velocity data were measured by using an electromagnetic current meter (INFINITY-EM), 2-axis with measurement interval fixed for every 1 s at 1 cm/s accuracy. The device was manufactured by ALEC Electronics Co. Ltd., Japan as shown in Figure 3.27. This instrument is compact and light weight. The velocity sensor utilised is a time-proven electromagnetic velocity sensor, enabling accurate velocity measurement for all currents, from weak to strong with measurement range of 0 to 500 cm/s. This instrument also has other sensors for flow direction and temperature.

Figure 3.27 Electromagnetic current meter (INFINITY-EM)

During monitoring works, the instrument was buried about 30 cm below the bed to make sure the current velocity sensor was located vertically at least 1 cm above the bed as shown in Figures 3.28. The swash velocity data were recorded and monitored at inner surf-swash zone boundary to record uprush and backwash velocities for dry and wet periods. This equipment was also synchronized at the same time with other PTs at every 1 s. In order to differentiate between uprush and backwash flow velocities, a digital camera station was installed within the monitoring area to record swash activities during the monitoring period.

Figure 3.28 The ECM in action for recording the swash flow velocities

3.4 Statistical Analysis

For beach morphological variability analysis and correlation with other factors, several statistical methods or techniques were used in this study to analyze the field data to understand the physical processes related to the Desaru beach profile evolution. The study used bulk statistics (mean, range, standard deviation and correlation) and empirical orthogonal function (EOF) techniques. Basically, bulk statistics were easy to compute and will give a first impression of the data for any related study. In this study, the cross-shore profile surveys were used as input data and the statistics of the profile elevation was computed at the selected cross-shore locations. Such statistics may be used as important tools to predict the probability that a certain variation in the elevation will happen. Furthermore, bulk statistical analysis also has been employed to study the morphological variables from topographic measurement, for example berms, troughs, and sandbars in the beach area.

Advanced technique like the EOF was used to highlight the spatial and temporal behaviours of beach features like berms or sandbars. The EOF method is also popular among coastal communities as an efficient way to describe beach profile changes especially under seasonal variation effect. Conceptually, the main objective of this analysis is to separate the spatial and temporal dependence of the data which can be represented as a linear combination of corresponding functions of space and time.

3.4.1 Bulk Statistics

All the recorded beach profiles from the study area were analyzed using the bulk statistics analysis such as mean, range, standard deviation, and correlation to determine the geometric properties of beach features along the cross-shore. The standard deviation is a commonly used technique for beach profile variability analysis, which was computed at any selected cross-shore location from a series of profile measurements.

The assessment using correlation analysis provides a measure of the linear relationship between the beach profiles and other parameters such as rainfall distribution, groundwater table, and tidal elevation. Establishing the relationships between the different quantities could also be of interest from an analysis perspective, which is on how the beach profiles response to the forcing that might be expected.

3.4.2 Empirical Orthogonal Function (EOF) Analysis

In this study, the survey works started from 27 June 2013, repeated approximately between 5 to 7 months, and finally completed on 23 January 2016 with total about 28 months duration. EOF analysis was then used to examine the seasonal variation effect towards the beach variability during that period. For that reason, only six profiles were selected from the study with the duration of approximately six months intervals as shown in Table 3.4. The EOF method developed the observed beach profiles data into a group shape functions known as eigenfunctions that are determined from the profiles data itself.

Table 3.4 Desaru beach topographical surveys for EOF analysis

Survey	Date	Type of Periods
1	27/06/2013	Dry
2	06/12/2013	Wet
3	18/05/2014	Dry
4	25/12/2014	Wet
5	06/06/2015	Dry
6	23/01/2016	Wet

The objective of the EOF is to describe the changes among the different beach profiles by the least number of eigenfunctions. Each of these functions consist of a contribution to the water depth as a function of the distance along the profile. The primary advantage of this method is that the first eigenfunction is selected so that it accounts for the greatest possible variance of the data (the variance is defined as the mean square of the depths). The successive eigenfunctions are each selected in turn such that they represent the greatest possible amount of the remaining variance. The lower ranked eigenfunctions, which are presently physically uninterpretable, statistically insignificant and have negligible impact on the beach profile was removed as they are considered as "noise" from the data set. In this way, it is usually possible to account for a large percentage of the variance with a small number of terms. A cross-shore profile is considered as a function of $h = f(x,t)$ representing not only a general profile shape but all the irregularities such as bars, troughs, and other accumulative-erosive forms. They are initially regarded as a stable baseline position running across the dry beach and towards offshore to the depth of closure.

EOF analysis is also known as principal component analysis (PCA), which is a method that has been extensively used to identify spatial and temporal patterns in beach morphological study. In EOF analysis of beach profiles, the measured data are analyzed to develop a set of shape functions known as "eigenfunctions" which will be determined from the profile data itself.

The cross-shore profile shape is represented as a linear summation of space and time varying functions as given by Equation (3.1):

$$h_{xt} = \sum_{n=1}^{N} c_n\ (t). e_n\ (x) \tag{3.1}$$

where

h = profile depth,

x = distance measured beach profile,

t = time of profile survey

n = number of measurement

N = total number of measurement

e_n = spatial orthogonal functions

c_n = corresponding time coefficient

Each eigenfunction corresponds to a statistical description of the data with respect to how the data variance is concentrated in that function. The functions are usually ranked according to the magnitude of their corresponding eigenvalues which is proportional to the data variance. Typically, a large proportion of the data variance is contained within a small number of eigenvalues and hence, only a limited number of eigenfunctions are needed to explain most of the variation in the measurements (Pruszak, 1993; Reeve et al., 2001; Larson et al., 2003).

The beach profile data from the study were then used to generate sets of empirical eigenvectors to develop a symmetric correlation matrix below:

$$a_{xt} = \frac{1}{n_x n_t} \sum_{t=1}^{n_t} h_{xt}{}^2 \tag{3.2}$$

in which n_x is the number of measurement points in the cross-shore profile and n_t is number of cross-shore profile surveys.

The generated square matrix from Equation (3.2) possesses a set of eigenvalues $\lambda_n$and set of corresponding eigenvectors e_n, which is defined by the matrix in Equation (3.3):

$$A^{EOF} e_n = \lambda_n e_n \tag{3.3}$$

A direct result of this equation is the sum of all the eigenvalues which is equal to the mean square value of all the profile data. Generally, each eigenvalue, λ_n signifies a portion of the mean square value of the profile data. Basically, the eigenvalues are ordered, so that $\lambda_1 > \lambda_2 > \lambda_3 >... \lambda_n$ or magnitudes of the λ_n decreases. Generally, the first function, known as time-mean function, is approximated by the function $e_1(\lambda n_x)^{1/2}$. Winnat et al. (1975) pointed out that each eigenvalue is a representative of a certain percentage of the mean square value of the data. The principal beach function corresponding to the largest eigenvalue λ_1 represents the largest amount of data based on the eigenfunctions in Equation (3.4):

$$e_n(t)^n = h\ (x, t) e_n = \sum_{t=1}^{n_t} c_{nt} \cdot\ e_{nx} \tag{3.4}$$

Here, $e_n(t)^n$ represent the *n*th spatially varying empirical eigenfunction evaluated at the *t*th location of the profile. This equation also known as the spatial eigenfunctions (SEOF). In this study, for temporal profiles variation analysis, the corresponding time coefficients or known as temporal eigenfunctions (TEOF) is given by Equation (3.5). The equation permits us to determine the TEOF for a given survey once we know the eigenfunctions.

$$c_n(t)^n = \sum_{t=1}^{n_t} h_{xt} \cdot\ e_n\ (x) \tag{3.5}$$

CHAPTER 4

RESULTS AND DISCUSSION

4.1 Introduction

Changes in the cross-shore beach profiles are controlled by many factors, which include waves attacks, tidal flow, and sediment characteristics. In this study, additional factors such as rainfall distribution and groundwater elevation are theoretically believed to have an impact on the beach profile morphological changes of Desaru beach. Several field experiments were conducted in this study during dry and wet seasons to understand the influence of seasonal variations on the sandy beach. All data for swash zone properties such as bed profile, water depth, and velocity were collected during the spring tidal range period. It is commonly assumed that the sediment shifts seasonally across the profile between the berm and the bar, thus the total volume of the transported sand is still theoretically unchanged especially under various cyclic condition such as summer–winter or dry–wet seasons. By measuring the dimensions of the beach repeatedly, the amount of accretion and erosion can be determined over the period of the surveys, as well as some indications of where the material may be transported to.

4.2 Beach Morphological Changes Analysis

In order to understand the seasonal variation effect on the beach morphological change, other researchers (Hayes and Boothroyd, 1969; Davis and Fox, 1972; Masselink and Pattiaratchi, 2001) have successfully conducted field investigations to study a localized seasonal effect (winter versus summer) by using the variability of the incident wave energy level such as wave height. This assumption was used to predict the occurrence of beach erosion (bar formation) under energetic wave condition during winter season and beach accretion (berm formation) under calmer wave condition in summer season. However, according to Short (1978), this assumption is site-specific and is not suitable to be applied outside the region for which it was defined. In this study, it is better to have its own characteristics study to give a better information related to the Desaru beach morphological changes under different types of seasonal variation, which is this case is dry and wet periods.

Figure 4.1 shows the 12 cross-shore beach profiles for Desaru beach measured during the study period that was used for further analysis. Three profiles were considered to occur during dry period (27 June 2013, 18 May 2014 and 6 June 2015). For wet period, nine profiles were selected for analysis (23 October 2013, 16 March 2014, 6 December 2014, 25 January 2014, 7 November 2014, 25 December 2014, 1 March 2015, 1 October 2015 and 23 January 2016). These selections are important in order to get a better understanding of the beach response during dry and wet periods. From the observed profiles, Desaru beach reveals that the strongest variability of beach profiles occurred at the intertidal level boundary (between −0.74 and +2.0 m LSD) which is located entirely at the swash zone boundary. This condition is possibly attributed due to the strong swash movements associated with groups of incoming incident wave and strong activity of wave breaking around the shoreline as mentioned earlier by previous researchers (Karunarathna et al., 2005; Masselink et al., 2010). Meanwhile, the least affected zone of the profile was found to happen at the seaward direction, which starts at point $x = 53$ m onwards or below the MLLW level (−0.74 m LSD).

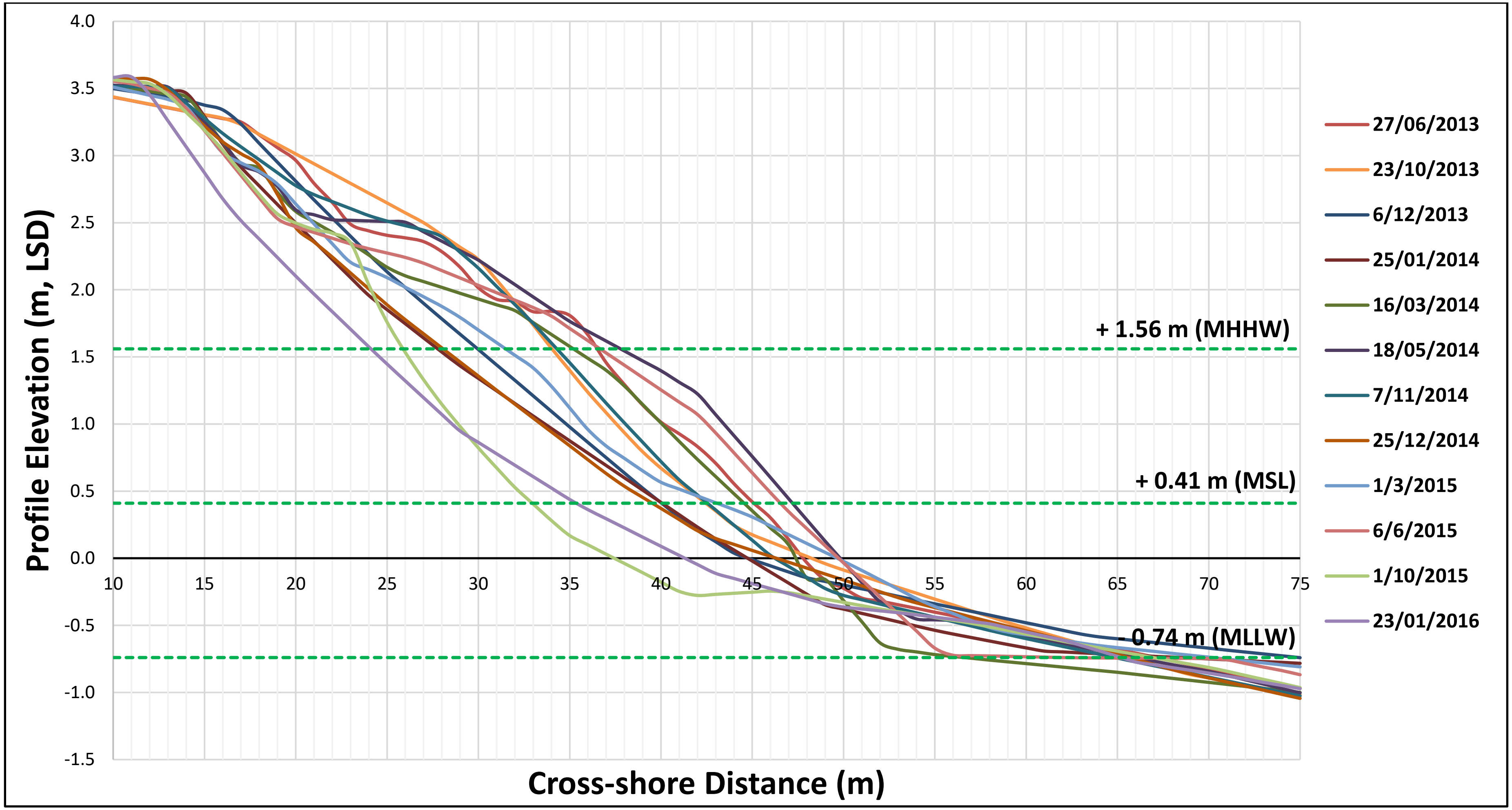


Figure 4.1 Recorded beach profiles at Desaru beach (2013-2016)

4.2.1 Bulk Statistical Analysis

In order to quantify the cross-shore variability of the beach profiles, bulk statistical analysis was used at Desaru beach. All available profiles survey data from the study were used to determine the statistical parameters in this study. The survey profiles at Desaru beach were measured at every 2-4 months intervals to represent the dry and wet periods since June 2013 until January 2016. Surveys were conducted during the low tide and profiles were recorded at irregular spacing depending on the terrain of beach surface. In this study, the bulk statistical analysis provided the information on the mean of Desaru beach profile and profile variability around the mean. A commonly used statistical technique to measure the beach profile variability is the standard deviation in elevation, which may be determined from the selected cross-shore locations from a time series of profile measurements. This technique has been successfully applied in previous studies by Karunarathna et al. (2016) at Narrabeen Beach (Australia), Milford on Sea Beach (UK), Hasaki Coast (Japan), and Joetsu-Ogata Coast (Japan).

In Figure 4.2, the mean cross-shore beach profiles with profile envelope were generated for period of study based on average, minimum, and maximum measured beach profiles at 1-m spacing of cross-shore profile. This simple analysis provides a basis for information on the beach profile variability. The mean profile beach shows two distinct slopes where the gradients of the upper and mid-swash zone ($x < 55$ m) were significantly steeper than that of the lower swash zone and subtidal beach ($x > 55$ m). Generally, the mean profile shape of Desaru beach follows an intermediate beach profile state with the upper beach showing the shape of reflective profile and the lower part showing characteristics of a classic dissipative profile.

Figure 4.3 illustrates the standard deviations at Desaru beach profile based. The standard deviation was used to predict the probability of the variation on any point of the profile as shown in Figure 4.3. This analysis also provides an early information for design or development purposes at the beach area. From the figure, the largest standard deviation around the mean profile ($\sigma = 0.60$ m) was seen dominant in the mid-swash area, which notably indicated that the swash zone processes significantly controlled the beach profile. This situation clearly happened due to the higher erosion and accretion activities during the Northeast monsoon and Southwest monsoon, respectively. In general, the Northeast monsoon was known as wet season in Malaysia which carries more rainfall compared to the Southwest monsoon which is also known as the dry season. The upper part of the swash zone ($x < 20$ m) showed that the secondary lower peak of standard deviation ($\sigma = 0.28$ m), which is due to the cyclic coastal features processes such as berm which happens during the dry period. This is due to the uprush of sediment that subsequently was significantly settled down on that area due to the greater effect of exfiltration process during the dry period compared to the wet period. Based on this figure also, the most dynamic region in the swash zone can be justified where it started at just below the MSL line.

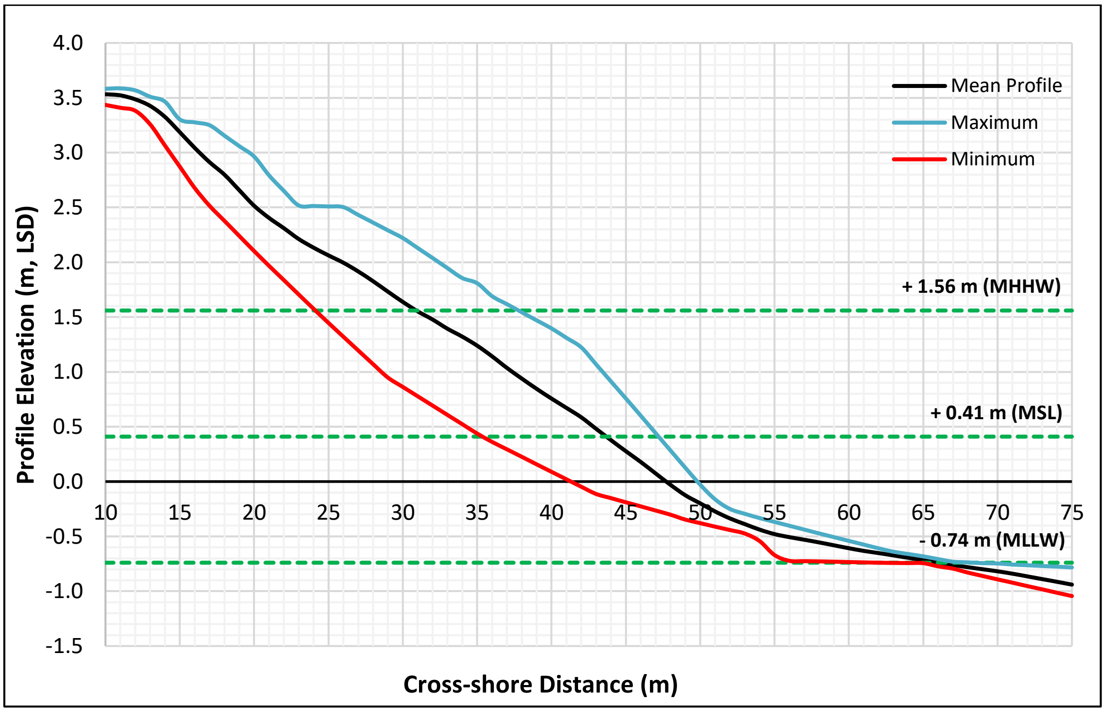


Figure 4.2 Mean beach profile and profile envelope

This key finding is consistent with another study by Elfrink and Baldock (2002), where the effects of infiltration and exfiltration on sediment transport in the swash zone were increased and decreased, respectively. Previous studies found that the reduction of backwash volume and duration is significantly controlled by the influence of infiltration and exfiltration processes. This condition is also supported by Butt and Russell (2000), which concluded that the effect of beach permeability on infiltration process would be enhanced by a lower water table. They also stated that greater degree of infiltration occurred on the dry upper beach compared to the wet lower part. On the upper beach during the dry period, the backwash is weakened due to the reduced flow of water during uprush that has been significantly infiltrated. As a result, the net onshore transport is highly likely to occur in this region.

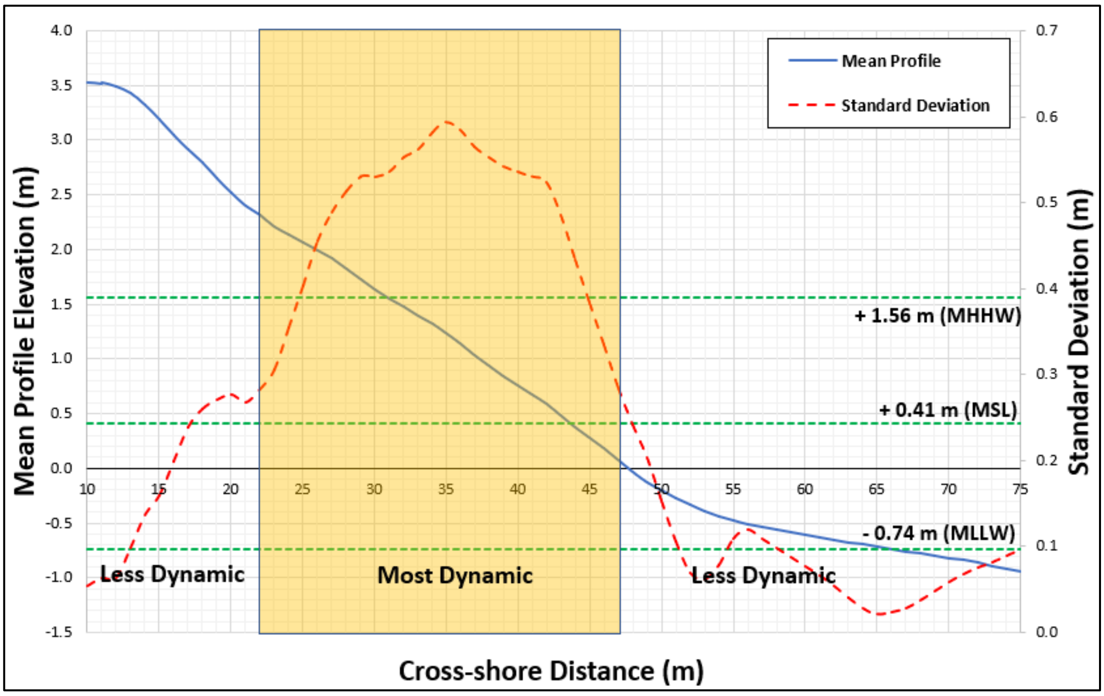


Figure 4.3 Standard deviation along the beach profile

The lowest value of standard deviation ($\sigma = 0.02$ m) from Desaru beach profiles variability was found at the boundary line of intertidal and subtidal area (x = 65 m). This value was confirmed at the MLLW point (−0.74 m LSD), where the variability of profile elevation was very small or almost unchanged. This condition could be happening due to the influence of higher beach saturation degree in this area which significantly reduced the infiltration effect during the swash flow activities. This finding is also consistent with other study by Butt and Russell (2000), which also mentioned that on the lower part of the beach, less water is lost from infiltration in the uprush activities, eventually leading to a less steep equilibrium beach profile.

Figure 4.4 illustrates the detailed variations of sand volume (m^3/m) and shoreline position with respect to MSL at Desaru beach. During the study period, the net volume from the Desaru beach profile was calculated from the benchmark point at x = 10–75 m which covered the whole swash zone. The lowest elevation as a benchmark for the volume calculation was set at –1.044 m LSD. From the figure, the blue boxes represent the total sand beach volume per meter width during the dry period with the average value of 129.06 m^3/m and the highest volume was recorded on 18 May 2014 with value of 136.08 m^3/m. The red boxes denote the total sand beach volume during the wet period with the average volume of 115.84 m^3/m which was lower by 9.71 % compared to that during the dry period. The lowest volume of sand beach was recorded on 23 January 2016 with a value of 100.28 m^3/m. A slight negative slope of the dashed line based on the generated trend line equation ($y = -0.53x + 45.061$) shown in Figure 4.4 indicated that the beach will face further erosion in the future.

In order to quantify the beach profile changes observed between two consecutive surveys, the comparison between the total sand volume and shoreline position for every survey were examined as shown in Figure 4.5. The importance of these parameters as beach profile change indicator was recognized by Karunarathna et al. (2015). From the analysis, the total sand volume variability reveals a local significant seasonal variation. The beach losses approximately 20–30 m^3/m during the wet period compared to the stable condition (average profile). During dry periods, the beach has slightly recovered about 15–25 m^3/m of the sand volume. It is clearly illustrated in the figure that the erosive condition was during the wet season from early October to the end of January and accretion occurs from February to July. The most eroded condition was observed at Desaru beach on 1 October 2015 during the wet period with a mean erosion rate of −0.23 m^3/m/day. On the other hand, the highest recovery rate was observed 18 May 2014 during the dry period, with a value of recovery rate at +0.20 m^3/m/day.

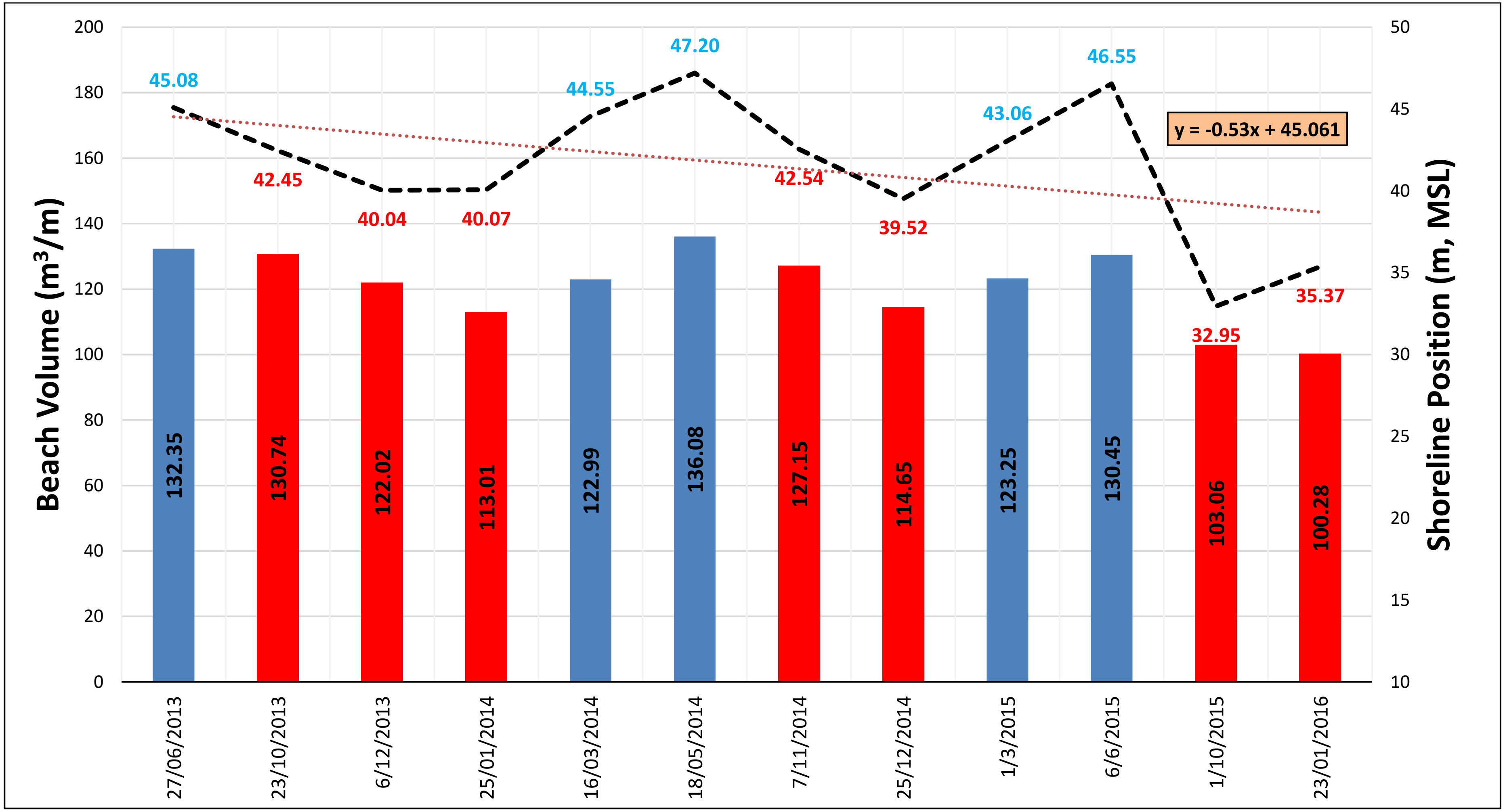


Figure 4.4 Total volume of beach profile at Desaru beach for cross-shore distance (x = 10 m to 75 m)

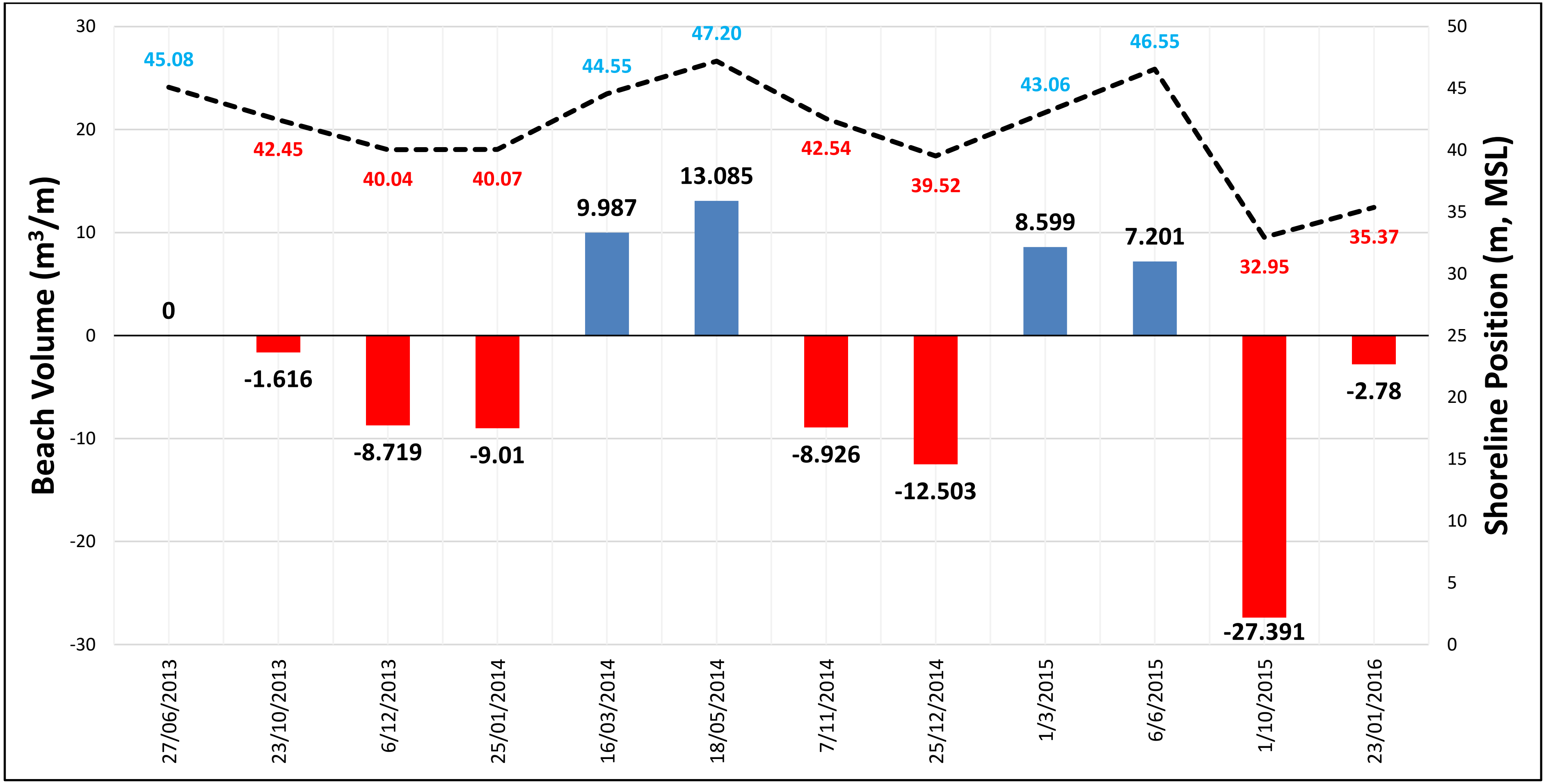


Figure 4.5 Analysis of nett volume changes

Theoretically, the correlation analysis offers a technique to determine a linear relationship between two parameters for which simultaneous measurement time series are available. If a strong correlation is found between the two parameters, models can be developed either empirically or physically based on which it is used to predict one parameter from other parameters. For this study, the total sand volume at Desaru beach was highly correlated ($R^2 = 0.86$) with the shoreline position as shown in Figure 4.6. These results reveal that the shoreline position will become shorter or moving nearer to the upper beach area due to the erosion process during the wet season. In contrast during the dry season, the shoreline position will move further in the seaward direction. This is the result of the significantly deposited onshore sediment transport occurring during the season. Generally, erosion and accretion of the beach profile and the resulting movement of the shoreline position are direct effects from the swash zone sediment transport processes. Therefore, the shoreline position could provide a useful information or option to determine the beach profile volume changes during dry and wet seasons. This information is very useful for the local authority to get better information about the local shoreline anomaly which is significantly important in determination of comfort or low risk zone for future development in coastal areas especially during the annual wet season.

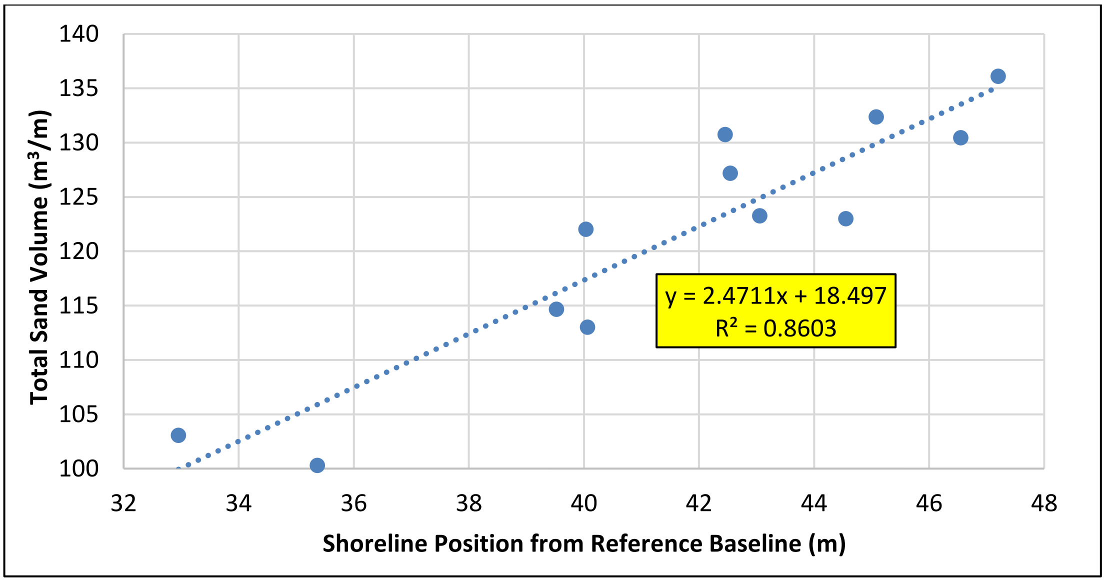


Figure 4.6 Correlation between total sand volume and shoreline position

The beach volume changes between two consecutive survey works were calculated by subtracting the elevation of each survey points of the earlier survey from that of the later survey and multiplying by the 1-m^2 area based on 1-m length for every survey point. Figure 4.7 shows the shape of three consecutive cross-shore profiles (27 June 2013, 3 October 2013, and 6 December 2013) at Desaru beach for the detailed analysis of the beach volume changes. Between 27 June and 23 October 2013, the volume of sand over the survey cross-section slightly decreased by 1.616 m^3/m. The changes clearly indicate that the erosion process over the beach surface within that period due to the early phase of wet period under North-East monsoon event. The beach berm was found to develop at the boundary line between the upper- and mid-swash (x = 30 m) zones. Meanwhile, on 6 December 2013, the effect of energetic wave action due to the monsoon event increased and resulted in the volume of beach profile dropped further to 8.719 m^3/m and the highest eroded point (−0.666 m) was detected at MHHW elevation line.

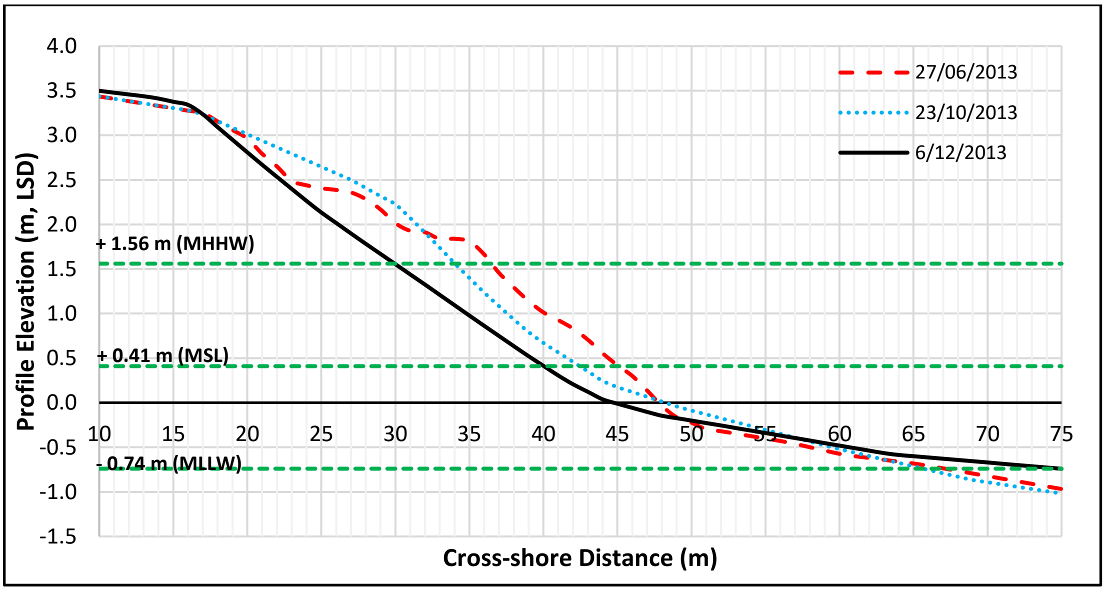


Figure 4.7 Beach profiles measured on 27 June 2013, 23 October 2013 and 6 December 2013

Figure 4.8 illustrates the beach volume changes between the profile measurements on 6 December 2013, 25 January 2014, and 16 March 2014 which is changes from wet to dry periods. These type of profiles were purposely selected to investigate the effect of wet and dry periods. On 25 January 2014, which is considered as the end of the wet period, the total volume still reveals an eroding phase (−9.010

m^3/m) and the highest eroded point was found to occur at the upper part of the swash zone (15 m < *x* < 25 m). This condition is assumed to have higher wave energy attack plus high tide elevation during that period. Conversely on 16 March 2014, which is when the wet period finally ended, the wave becomes calmer and less energetic. This reverse situation leads to the beginning of the accretion phase where the total volume and the highest accretion point recorded increased at +9.987 m^3/m and 0.685 m higher (*x* = 35 m) than the previous profile.

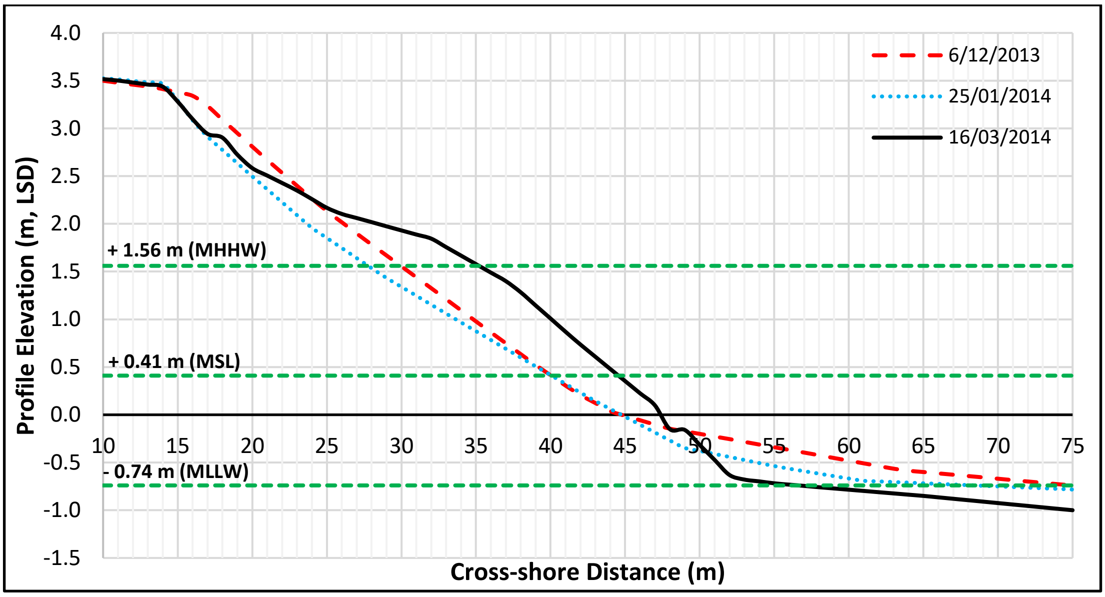


Figure 4.8 Beach profiles measured on 6 December 2013, 25 January 2014 and 16 March 2014

Figure 4.9 shows the effect of accretion phase for the next two months from the previous profile on 18 May 2014. The volume changes were increased (+13.085 m^3/m) and the highest elevation of profile point were detected at MSL elevation line with range of height increasing between 0.2 and 0.4 m. During the early phase of the wet season, the profile become eroded again with the total volume of −8.926 m^3/m. During this time, the beach berm developed around the upper part of the swash zone (25 m < *x* < 30 m). The occurrence of this coastal feature indicates that the swash sediment transport during the uprush flow was significantly controlled by the greater infiltration flow processes at Desaru beach during the dry period.

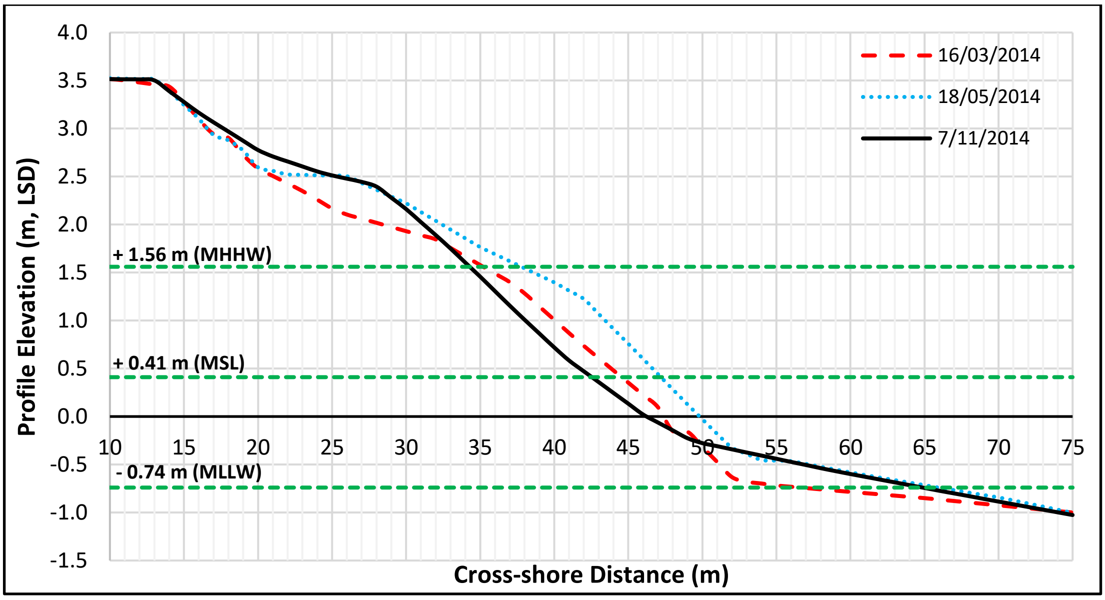


Figure 4.9 Beach profiles measured on 16 March 2014, 18 May 2014 and 7 November 2014

Figure 4.10 illustrates the similar trend during the wet (25 December 2014) and dry periods (1 March 2015) at Desaru beach where the beach profiles volume changes were –12.503 m^3/m and +8.599 m^3/m, respectively. The highest variability of both profiles were detected at the upper and middle part of the swash zone (25 m < x < 35 m). This observation is significant as it will increase the importance of swash zone role in controlling the beach profile shape. This observation is also supported by the similar beach profile changes in Figures 4.11 and 4.12, which showed that in the dry period it tends to accrete (maximum in May or June) and in the wet period it tends to erode especially in January or February.

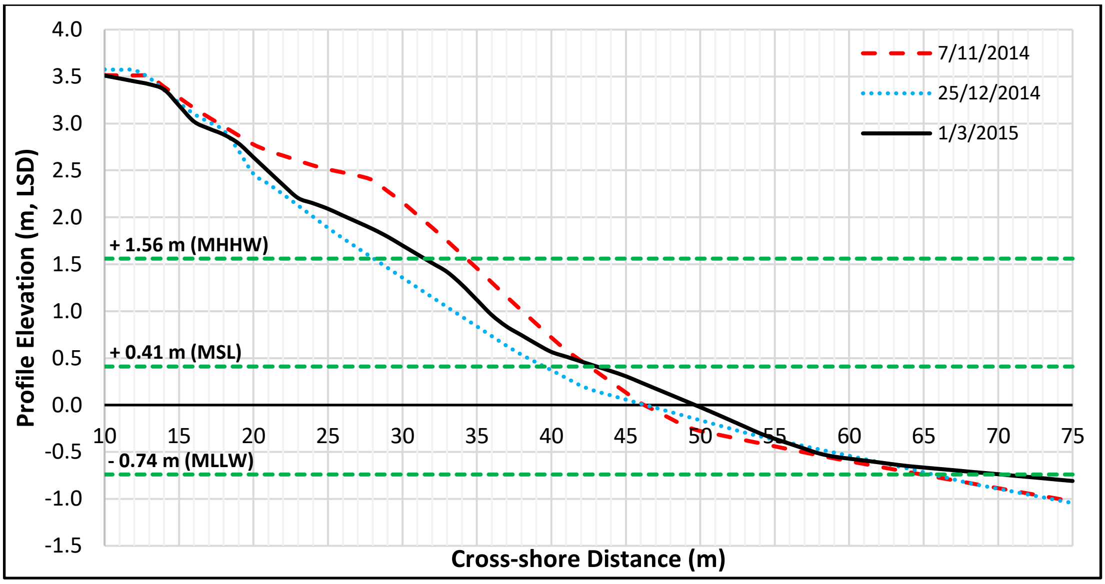


Figure 4.10 Beach profiles measured on 7 November 2014, 25 December 2014 and 1 March 2015

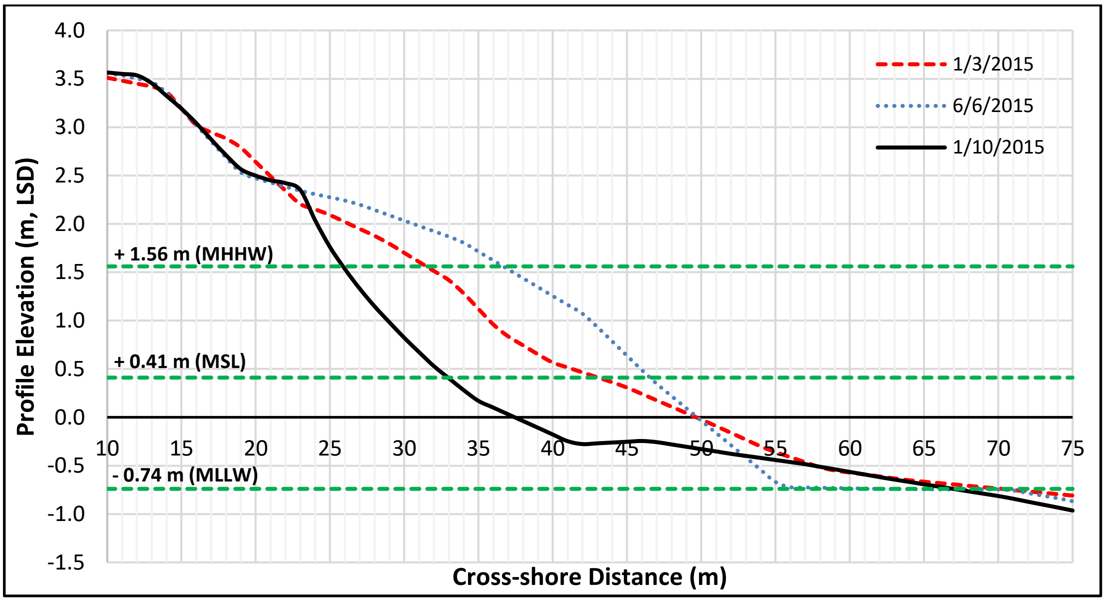


Figure 4.11 Beach profiles measured on 1 March 2015, 6 June 2015 and 1 October 2015

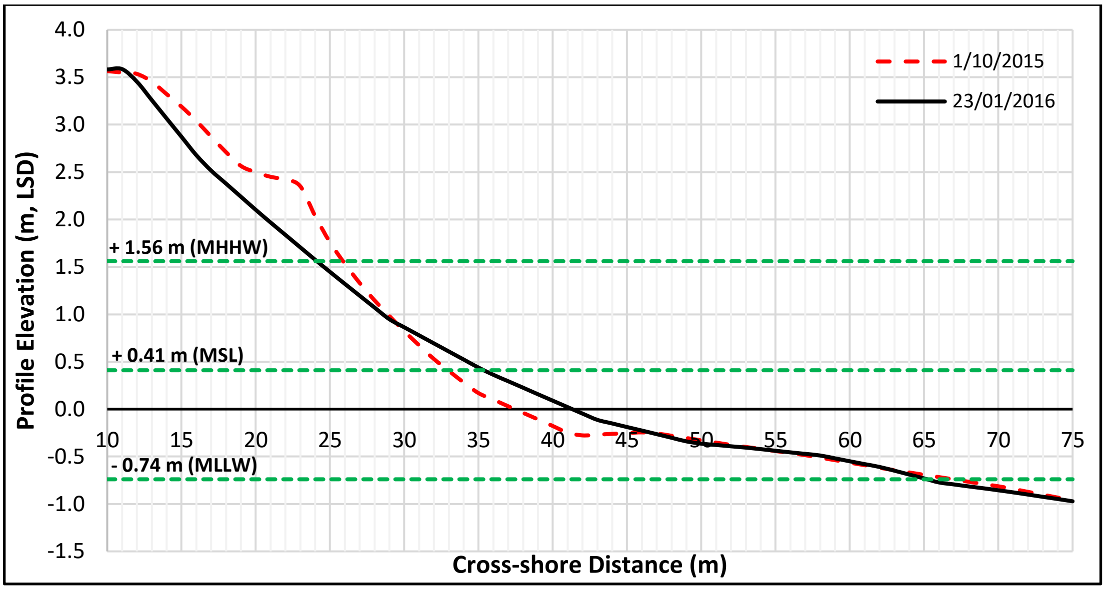


Figure 4.12 Beach profiles measured on 1 October 2015 and 23 January 2016

4.2.2 Empirical Orthogonal Function (EOF) Analysis

Previous studies of beach profile changes were conducted using the EOF method. Generally, the EOF analysis is also known as the principal component analysis (PCA) that is used widely by scientists and researchers to transform beach profile data in terms of a set of inter-correlated variables into a set of statistically independent variables. However, it should be clarified that EOF is a descriptive process and does not reveal any information regarding the governing processes.

Each eigenfunction corresponds to a statistical description of the profile data with detailed analysis about the variability of data concentrated in that function (Karunarathna et al., 2016). The one-dimensional empirical orthogonal functions method (1-D) identifies the occurrence of underwater bars with the most frequent locations along the beach profile. It determines the regions which are dominated by erosion or accretion, and relates the cross-shore profile shape with an on-offshore sediment transport. The new variables are linear combinations of the original variables but are equally orthogonal (uncorrelated). Then, the next analysis can separate the spatial and temporal dependences of the data and reproducing data as a linear combination of products of corresponding functions of space and time. Eigenfunction analysis offers the most efficient method of representing the data, since the first *n* terms in the series explains more of the data variability than the first *n* terms in any other expansions. Usually, there are three types of eigenfunction that were calculated based on the beach profile data. They are the "usual" temporal analysis, spatial analysis of the changes along the beach during each survey profile, and spatial analysis of the changes along the beach from two consecutive survey profiles.

In this section, the data of beach cross-shore topography profiles at Desaru beach were selected and analyzed using EOF to investigate spatial and temporal variations of the cross-shore beach profiles. Each eigenfunction corresponds to a statistical description of the data with respect to the concentration of data variance in that function. The functions are usually ranked according to the magnitude of their corresponding eigenvalues which are proportional to the data variance. When applied to the cross-shore beach profiles, this method can identify the patterns of variation about the mean profile shape, such as bars and troughs (Reeve et al., 2001; Larson et al., 2003). Results from the survey measurements were plotted to give the beach profile. Then, all profiles were digitized at 2–5 m from the benchmark (x = 10 m) to obtain the elevation of the beach surface before it was subjected to the eigenfunction analysis. The data from this method were linearly interpolated to give the elevation of the beach at 1-m intervals. All the measurement at the field work were conducted at low tides with no offshore observation.

Winant et al. (1975) pointed out that each eigenvalue is a representative of a certain percentage of the mean square value of the data. The principal beach function corresponding to the largest eigenvalue λ_1 represents the largest amount of the data. Theoretically, the first spatial eigenfunction (SEOF1) normally reflects the mean beach profile level and was previously called the "mean beach function". If the beach profile is stable or unchanged for a period of time, it has a constant time dependence. The second spatial eigenfunction (SEOF2), known as the seasonal eigenfunction or bar-berm, has a large maximum at the location of summer berm and minimum at the location of winter bar. SEOF2 also explains the rest of the residual variance that are not related to the mean function (Barletta et al., 2006). The third spatial eigenfunction (SEOF3) has a broad maximum near the location of low-tide terrace with a complicated time dependence and is normally called the terrace function. The higher and the rest of the functions, with is normally indicated until SEOF5 explain the rest of the residual variance that are not related to the mean function in SEOF1-SEOF3 earlier. From this stage, these residual functions (SEOF4 and SEOF5) generally accounted for a small percentage of the beach profile variability which may be related to other accumulative-erosive features in the profiles which contribute to deform the profile shape in time and space.

Meanwhile, for the investigation of beach profile in time, the temporal empirical orthogonal function (TEOF) was applied to find the corresponding spatial eigenfunctions variation in time thus indicating temporal trends of beach morphodynamic change. For that purpose, the first five temporal eigenfunctions (TEOF1–TEOF5) were developed and the cross-shore profiles shape variability was examined within the time period of study. Furthermore, the results of the TEOF analysis can reveal the success of the technique in capturing multi-scale temporal changes of highly complex beach system due to the seasonal variation effect.

The first eigenfunction corresponds to the time mean bathymetry and therefore the first function is almost constant and have a smoothed appearance (Reeve et al., 2008). The TEOF2 normally shows a distinct seasonal dependence which can reveal the seasonal offshore or onshore sediment movement. Meanwhile, TEOF3 was more complicated due to the weak seasonal patterns with high-frequency changes. TOF4 and TEOF5 were rarely used in the analysis of profile variability due to the very small mean square value of the data.

Based on the early observation at the study area, the variability of Desaru beach profile shape are likely to be controlled by the local seasonal variation effect. Therefore, this method can provide a better assessment on the cyclic behavior of the beach profile.

4.2.2.1 Spatial Empirical Orthogonal Function (SEOF)

Generally, SEOF identifies the variation along the beach at a time. For this study, the survey profile measurements started from 27 June 2013 and repeated approximately at irregular interval between 2 and 6 months and completed on 23 January 2016 with 30 months duration of the survey period. For the EOF analysis, with consideration of the seasonal variation effect, only six profiles were selected within the study period to represent dry (27 June 2013, 18 May 2014, 6 June 2015) and wet periods (25 January 2014, 25 December 2015, 23 January 2016). The interval duration between the consecutive profiles was approximately every six months as shown in Figure 4.13. Then, the EOF method developed the observed beach profiles data into group shape functions known as eigenfunctions that were determined from the profiles data itself.

At Desaru beach, the highest variability occurred at the intertidal level (between −0.74 and +2.0 m LSD) which was entirely located at the swash zone boundary. This observation is consistent with the works by Karunarathna et al. (2005) and Masselink et al. (2010) which reported that the condition is attributed to the strong swash movements associated with groups of incoming incident wave and strong activity of wave breaking around the shoreline. Meanwhile, the lowest variability of the profiles was concentrated at offshore direction which started at point x = 65 m seaward or below than MLLW level (−0.74 m LSD).

The initial SEOF analysis was performed based on the selected six profiles. The results of eigenfunction analysis from the benchmark point covered about 65-m length from the benchmark point x = 10–75 m. Table 4.1 summarizes the results of analysis for the first five eigenfunctions. It shows that over 97.77% of the mean square data was in the first function and that 99.99% of the mean square data was captured by the first five eigenfunctions. The mean square data is the average of the square of all beach surface levels in the whole data set. The first eigenfunction (SEOF1) corresponds to the mean beach level over the period, with the subsequent eigenfunctions representing the variation about the mean. In this case, the second until the fifth eigenfunctions (SEOF2-SEOF5) accounted for over 99.64%. The expected large value of variance in this analysis describes the variability in the coastal features such as berm, bar, and trough to be extremely efficient. Similar results were obtained by Reeve et al. (2016), which reported that a large proportion of the data variance contained within a small number of eigenvalues. As a result, only limited number of eigenfunctions was used to describe most of the variation in the measurements.

Table 4.1 Results of empirical eigenfunction analysis for Desaru beach

Eigenfunction Number	Normalised Eigenvalue	% Mean square (cumulative)	% Variance	% Variance (cumulative)
EOF1	0.97774	97.774	-	-
EOF2	0.02035	99.809	91.419	91.419
EOF3	0.00116	99.925	5.211	96.630
EOF4	0.00053	99.978	2.381	99.011
EOF5	0.00014	99.992	0.629	99.640

Eigenfunction analysis was performed on the seasonal variation profiles for the first five normalized spatial eigenfunctions (SEOF1–SEOF5) at Desaru beach for 30 months of study period as shown in Figure 4.14. From the analysis, all the eigenfunctions at Desaru beach have shown that the strongest variability occurred between $x = 20$ and 60 m, which covers the entire swash zone except the SEOF4 which was actively occurred beyond $x = 55$ m at the lower swash and the subtidal zone of the profile. The same finding was also revealed in other study by Karunarathna et al. (2016) which reported that the spatial variability of Milford-on-Sea Beach, UK for all eigenfunctions was strongest at the middle of swash zone. This study also noted that the subaqueous of the beach (above MSL) experienced the strongest morphodynamic variability.

The dark blue line in the figure shows the SEOF1 that closely corresponds to the mean cross-shore beach profile (broken black line) and was initially called the “mean beach function” by Winant et al. (1975). The secondary vertical axis corresponds to the SEOF1 and the primary vertical axis corresponds to the subsequent eigenfunctions (SEOF2–SEOF5). From this method, the SEOF1accounted for 97.77%

of the mean square value of profile fluctuations, which is similar to the time-mean cross-shore profile computed directly from the data themselves. This eigenfunction shows the mean position of the beach profile for time period of the study with no clear indication of the bar crest at near-shore area with evidently two different profile slopes were detected along the profile study. The upper profile indicated a steep slope with 40 m long coverage area (14 m < x < 54 m). Another slope at the lower part of the profile was a mild (beyond x = 54 m). This situation clearly shows that the effect of wave breaking activities at nearshore zone have significantly controlled the beach face shape especially at the swash zone. Other than that, only a small berm was traced near the benchmark point at the upper part of the beach (10 m < x < 14 m).

Meanwhile, the SEOF2 (2.04%) indicates the presence of an intertidal beach trough on the upper part of the swash zone and a beach berm was detected actively occurring at the whole middle part of the swash zone (30 m < x < 45 m). These results provide further support for the previous study by Karunarathna et al. (2016) at Narrabeen Beach, Australia which reflected a beach trough at the intertidal zone. This situation clearly explains the swash zone role in significantly controlling the shoreline position due to the dry and wet periods. In this figure also, SEOF2 reflects a separate bar and trough in the swash zone. Meanwhile, the development of sub-tidal sandbars was indicated at the subtidal region (x > 60 m).

The SEOF3 (0.116%) reflects the presence of an intertidal beach trough at the lower swash zone. It was clearly exposed all the time during the low tide event except due to the north east monsoon’s high energetic wave energy. The bar crest on the Desaru beach in the intertidal zone clearly deforms the profile from the mean profile shape. The SEOF4 (0.053%) implies sediment exchange across the profile that indicates shoreward movement and steepening of the shore face. The SEOF5 (0.014%) indicates less significant, localized erosion and accretion of the beach profile especially at the intertidal zone.

Based on Desaru beach profile, all the spatial eigenfunctions did not reach constant values at the seaward end of the profile, indicating that the depth of closure is located further offshore from the benchmark point of the profile as reported in the study by Karunarathna et al. (2012).

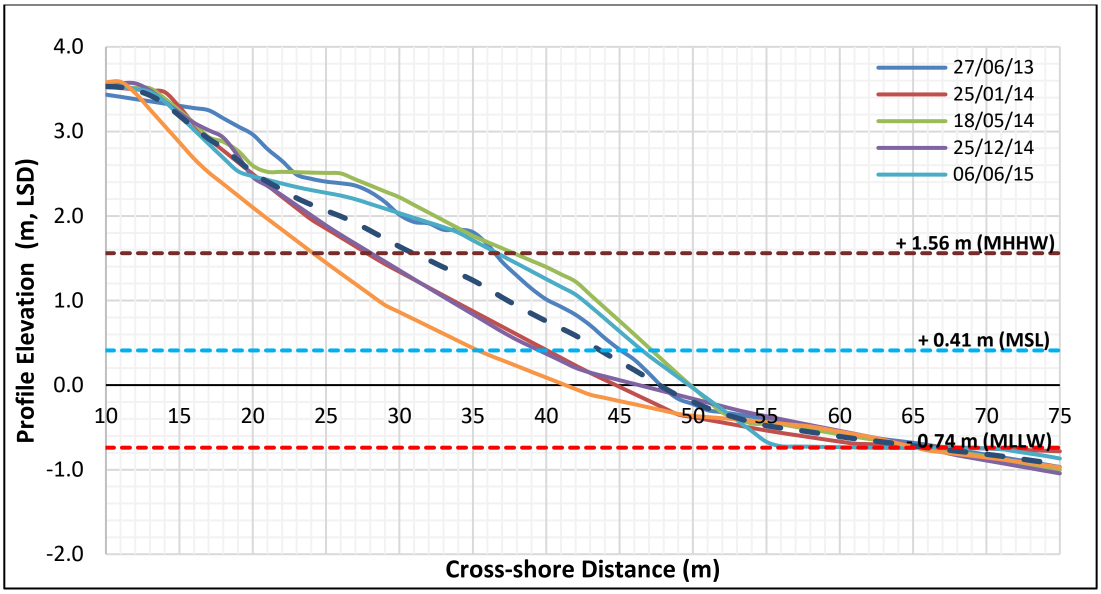


Figure 4.13 Selected survey profiles at Desaru beach for EOF analysis

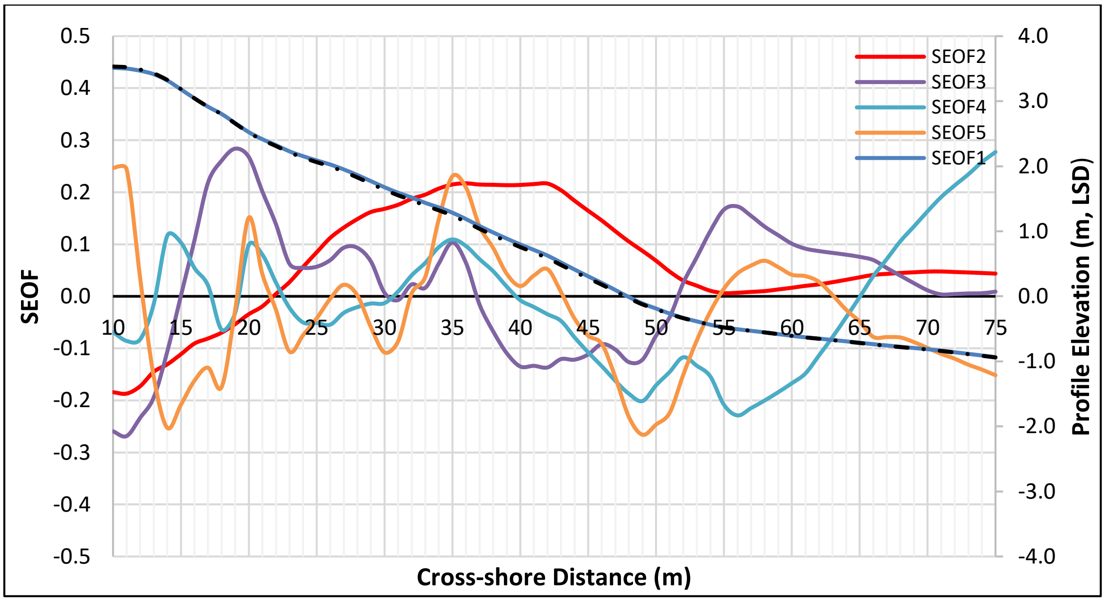


Figure 4.14 Spatial variations of the first five empirical orthogonal eigenfunctions (SEOF1-SEOF5)

4.2.2.2 Temporal Empirical Orthogonal Function (TEOF)

Basically, temporal eigenfunction analysis of beach profile data identifies the seasonal variations effect along a profile during the survey period of any studies conducted. In order to investigate the temporal variability of different cross-shore beach profiles at a range of time scales, the first five temporal eigenfunctions (TEOF1–TEOF5) were examined. The TEOFs are the corresponding spatial eigenfunctions (SEOFs) variation in time, indicating temporal trends for beach profile morphodynamic change.

The first temporal eigenfunction (TEOF1) was approximately constant as it corresponds to the time-mean profile and not shown in this analysis. For the second temporal eigenfunction (TEOF2), the maximum and minimum of the eigenfunctions indicate the locations of the greatest changes during the dry and wet periods at Desaru beach. The time dependence of TEOF2 shows a 1-year periodicity due to the local seasonal variation, indicating that it is related to the annual movement of sand onshore and offshore transports during dry and wet periods, respectively. As mentioned in the previous findings, the TEOF2 identified the berm and bar as locations with the most deviation from the mean profile. As expected in Figure 4.15, the TEOF2 at Desaru beach clearly shows a high frequency signal for every six months due to the seasonal variations effect (dry and wet periods), which positive values for accretion process (during dry period) and negative values for erosion process (during wet period). From the result of TEOF2, it is also confirmed that the local seasonal variation effect is clearly shown and described well by the temporal eigenfunction analysis. Similar results were obtained by Karunarathna et al. (2016) at Hasaki Coast Japan which reported that TEOF2 shows a cyclic signature of around one-year period indicating seasonal sediment movement in the beach. From this analysis also, it reveals that the berm changes extended from the upper swash section or intertidal zone (15 m $< x <$ 30 m) to the starting point of the subtidal region ($x >$ 60 m).

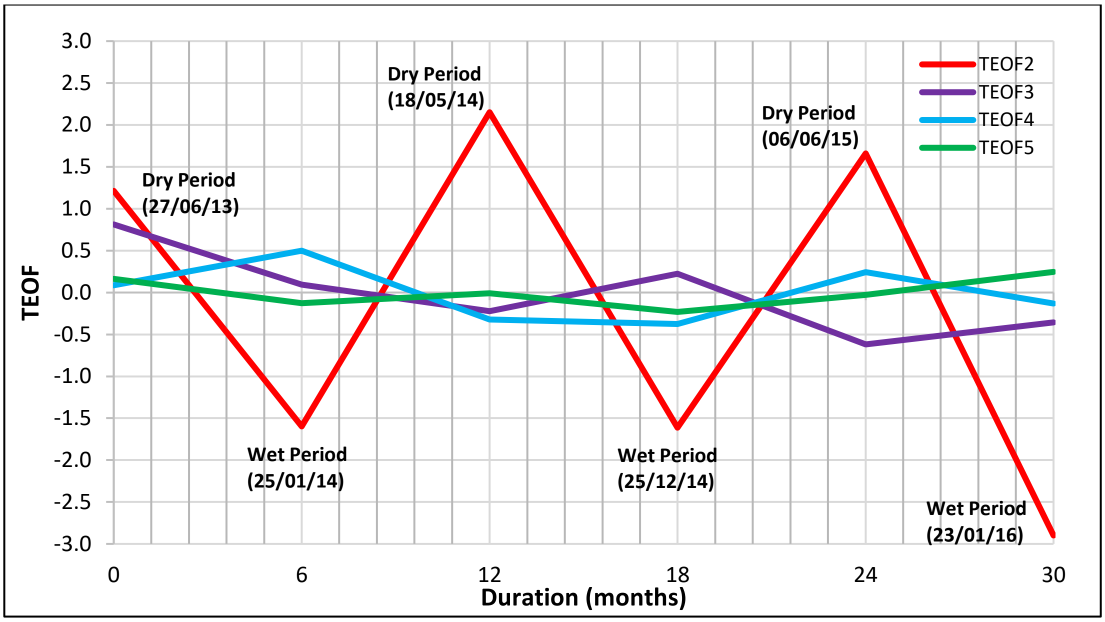


Figure 4.15 Temporal eigenfunction for Desaru beach within 30 months (June 2013-January 2016)

TEOF3 identified the location of the low-tide terrace or subtidal bar and trough and revealed a gradual decline over time, indicating long term beach erosion due to the degradation of upper beach ridge. TEOF3 have a balance of positive and negative eigenfunction values but the overall trend line shows a negative gradient until the end of the study period. This situation indicates a shift in the net sediment transport to seaward direction which resembles the gradual subtidal bar growth (x > 60 m). Additionally, a dominant seasonal variation for every six months of the TEOF3 can be seen clearly with the positive slope during the wet period which indicates an accretion process of the bar at subtidal region. Meanwhile during the dry period, the location of sandbar at the subtidal region have shifted landward due to the calm wave energy and infiltration/exfiltration effect on the swash zone.

There are no significant frequency variabilities of TEOF4 and TEOF5 due to the small percentage of variability of profiles data (less than 0.1 %) but seasonal patterns for both eigenfunctions can be seen with small cyclic variability. The same findings were also revealed in other studies by Barletta et al. (2006) and Karunarathna et al. (2016). Usually, both TEOF results are related to the intertidal–subtidal sediment exchange.

4.3 Effect of Rainfall on Beach Groundwater Table

The relationship between beach groundwater dynamics and swash zone hydrodynamics provides a principal factor for swash zone sediment transport, which significantly affects the morphological of the beach especially by controlling the movement of offshore or onshore transport.

In Malaysia, the seasonal wind flow patterns, combined with the local topographic features, determines the rainfall distribution patterns over the country. During the northeast monsoon, the majority of the east coast region of Peninsular Malaysia experiences heavy rainfall and storms plus energetic waves condition due to the strong onshore wind. This contributes to a higher rate of erosion at the beach area as described by Wong (1981), Husain et al. (1997), and Mustapa et al. (2015). This erosive condition is driven by the energetic uprush and backwash activities on higher saturated beach surface. In contrast, during the dry season, lesser rainfall events are recorded, and this situation contributes to a significant drop of groundwater level and degree of beach saturation. Based on that reason, it is believed that the beach accretion process increases due to the calmer wave condition and higher infiltration process in the porous and unsaturated of beach face. From this unique condition, it is believed that the seasonal variation factor in tropical countries especially Malaysia, have significantly influenced the sediment transport processes in the swash zone where beaches are likely to erode during the wet period and beaches are likely to accrete during the dry season. In order to understand the seasonal variation effect to beach morphological change, other researchers (Hayes & Boothroyd, 1969; Davis & Fox, 1972; Dail et al., 2000; Masselink & Pattiaratchi, 2001) have successfully conducted field investigations to study a localized seasonal effect (winter versus summer). This assumption was used to predict the occurrence of beach erosion (bar formation) under energetic wave condition (winter) and accretion (berm formation) under calmer wave condition (summer). However according to Short (1978), this assumption is site-specific, and not ready to be applied outside the region for which it is defined. Therefore, it is necessary to study the impact of different localized seasonal variation on beach profile changes for tropical countries like Malaysia.

Clearly, hydrodynamic processes such as infiltration and exfiltration are among the significant factors which are suggested by many researchers to explain the likelihood of erosion during high water table and accretion during low water table. The beach groundwater table position will affect the infiltration and exfiltration processes during the uprush and exfiltration. When the uprush reaches the beach face above the water table exit point, the water infiltrates into the bed and consequently reduces the uprush volume, depth, and velocity. It is totally different during the lower exit point (saturated condition), the backwash volume will increase due to the groundwater seepage (Horn, 2006). However, all these factors need to be understood carefully especially for different site conditions and influence of seasonal variation.

The relationship between the monthly rainfall and the beach groundwater table measured at BH2 and BH3 for the 28-months of the study period is shown in Figure 4.16. It can be classified that the wet period occurred annually between November and January, where December was found to be the wettest month with 312.5 and 219.5 mm of precipitation for year 2013 and 2014, respectively. In contrast, the driest period at Desaru beach occurred between February and March annually with February 2014 was recorded as the driest month when no rainfall data (0 mm) was detected. The monitoring work for this study started in June 2013 with the initial groundwater level readings of 1.80 and 1.20 m for BH2 and BH3, respectively. The groundwater tables reading for both wells increased until September 2013 although the rainfall data decreased. This condition was largely attributed by the effect of higher saturation level on the beach face due to the heavy rainfall distribution during that period especially in July and August 2013. In October 2013, the monthly rainfall data were recorded considerably lower at 20.5 mm and this situation caused the beach groundwater level to slightly drop.

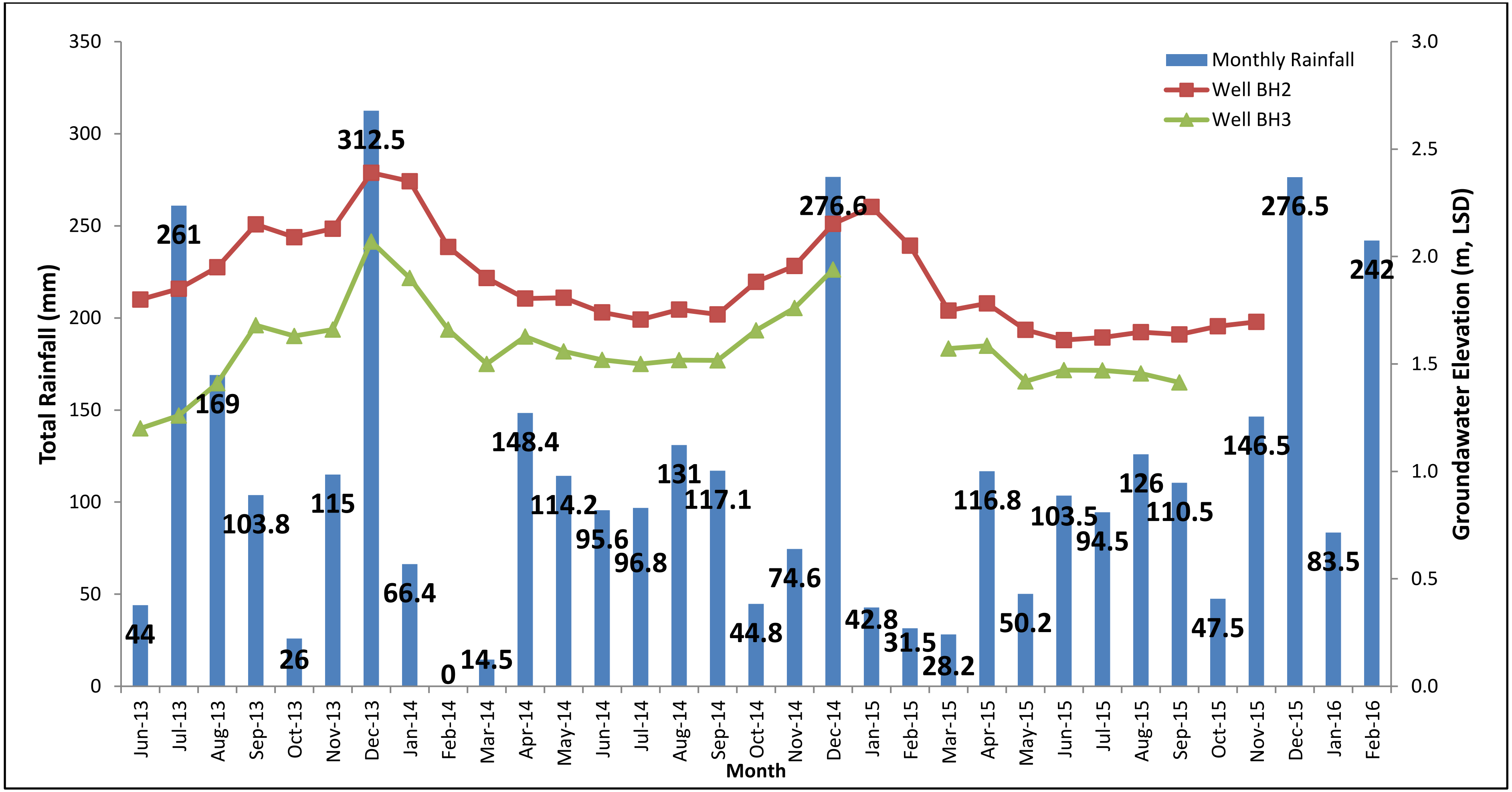


Figure 4.16 Total monthly rainfall and mean groundwater level during the study period

During the wettest month in December 2013, the beach groundwater level significantly rose up to 360 and 300 mm in BH2 and BH3, respectively. This situation can be clearly seen in Figure 4.16 based on the highest positive slope value for the groundwater level line. This was hugely supported by the highest negative slope value occurring in February 2014 and 2015 which were the driest month during the monitoring period.

From the results obtained, the rainfall distribution plays a vital role in controlling the beach groundwater level, but the effect of beach saturation degree is also considered important. It can be clearly seen that in September 2013 and November 2013, there was approximately the same monthly rainfall data, but different positive slope lines were recorded. Both slopes for the raised groundwater table in September 2013 was higher than those in November 2013 due to the level of beach saturation effect by different monthly rainfall. For example, in September 2013, both groundwater tables in BH2 and BH3 were raised quickly due to the heavy rainfall in August 2013, which directly increased the beach saturation level at the study area. It is a different situation compared to the data in November 2013. Both groundwater tables in the wells on that month also responded with approximately the same monthly data in September 2013 but raised slowly due to the lower monthly rainfall in October 2013 which extensively affected the saturation degree of the beach area. The effect of monthly rainfall distribution pattern on the beach saturation degree and the groundwater level can also be clearly seen during the lesser rate of monthly rainfall. For example, in October 2013 and March 2014, both months have approximately the same monthly rainfall rate (26 and 12.5 mm, respectively) but have significant difference in the decrease of groundwater level. In October 2013, groundwater levels were slightly dropped due to the higher monthly rainfall in September 2013. In contrast, the groundwater levels in March 2014 had significantly dropped and this condition was largely contributed by the lower saturation degree in the beach due to no rainfall data during the previous month. These type of results implied that the variations of monthly rainfall distribution in tropical countries like Malaysia could play an essential role on the response of beach groundwater table elevations. This finding also supports the conclusion from previous work by Nielsen et al. (1988), in which the beach groundwater table variation depends partly on rainfall distribution, wave height, and tidal range.

For seasonal variation effect on the beach morphological changes, three days of profiles were selected from the Desaru beach monitoring. They are on 27 June 2013, 25 January 2014, and 16 March 2014 as shown in Figure 4.17. The profile on 27 June 2013 was selected as the initial profile for this study to compare and analyze the effect of beach groundwater level on beach profiles changes during the wet period on 25 January 2014 and the dry period on 16 March 2014. The mean level for beach groundwater table at BH2 and BH3 for those days were compared to investigate the relationship between the rainfall distribution and beach profile changes. The data for both beach profile and groundwater level on 25 January 2014 were considered as the wet period at the study area. The highest erosion rate that occurred in January was due to the heavy rainfall depth between November 2013 and December 2013 with recorded rainfall of 515 mm. This condition significantly increased the beach groundwater level and enhanced the offshore transport due to the higher saturated beach face. The beach groundwater level also increased higher by about 0.6 and 0.8 m in BH2 and BH3, respectively.

A similar conclusion was reported by Grant (1946), who found that higher infiltration rate occurs during the uprush flow activities if the beach is dry or water table is low. During this moment, the uprush flow will infiltrate into the sand and hence slows down which result in a greater settlement of the suspended sediment during uprush flow. These findings are also supported by Horn et al. (2007) which reported that the accretion above the MSL on the fine sandy beach only occur when the beach groundwater level is lowered. This supports the recommendation that that modifying the beach groundwater level will enhance accretion process on a fine sandy beach.

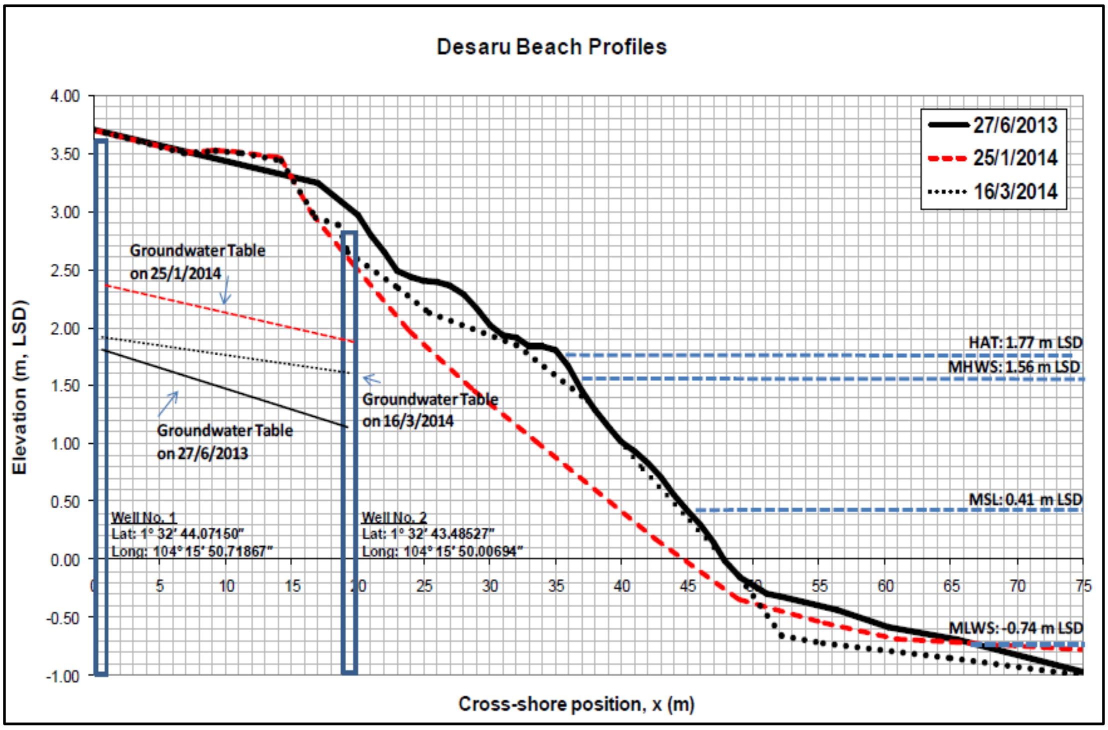


Figure 4.17 Beach profiles and groundwater table analysis during wet and dry periods

Figure 4.17 also shows that the beach was mainly eroded on the upper part and slightly accreted on the lower part especially below the MLLW. The highest erosion depth occurred at point *x* = 35 m with nearly 1.0 m depth of eroded beach surface. At this point, the highest tidal level happened with HAT at 1.77 m LSD and MHHW at 1.56 m LSD. During this wet period, almost all the beach surfaces were eroded except at the upper part of the beach where a small berm had developed on the upper part of beach face which was strongly believed to be established by the effect of greater uprush flow during this period. The entire amount of eroded sand beach was removed by the greater backwash flow activities to offshore direction because of the lower infiltration level. This situation was due to the raised groundwater level that affected the sediment movement on the beach. The effect of the raised groundwater level on beach profile from Desaru beach was consistent with the reported observation of laboratory experiments (Ang et al., 2004; Horn et al., 2007) which show that infiltration was reduced due to the raised groundwater level resulting in offshore transport on the fine beach. As for the beach groundwater table, during the dry period on 16 March 2014, the reading was significantly decreased compared to the level during the wet period on 25 January 2014. The depth was decreased to 0.5 and 0.3 m in BH2 and BH3, respectively. In contrast to the situation during the wet period before this, the beach during the dry period with lower groundwater table show the onshore transport and majority of the accretion was established above the MSL or between point x = 20 and 60 m. The small berm that developed during the wet period still remained at the point between x = 7 and 17 m. This condition was largely attributed by the lower energy of swash velocity throughout the dry season. During the dry period, wave energy from the offshore became slower and calmer due to the end of the northeast monsoon. This condition is largely attributed to the swash zone properties like swash velocity and uprush length maximum limit where the velocity tends to be slower and the length becomes shorter. Thus, the uprush length during this period was limited at point x =17 m and higher than the upper section of the beach during the wet season with x = 7 m. Profiles during the dry period on 27 June 2013 and 16 March 2014 indicated well-developed berms around x = 14–35 m with slope decreased in intensity towards the land. The formation of berm occurred during the dry period, mostly in the unsaturated beach condition where the infiltration rate is high hence reducing the strength of backwash flow. More or less, low strength of the backwash will decrease the transportation of sediment offshore (Jamal et al., 2014). In contrast, the beach face during the wet period is tended to build a relatively steeper gradient. From the observation, strong waves during this period had cut back the beach face, flattened the pervious berms, and smoothed out the beach surface. Generally, the eroded berms that were formed during the dry period are stored in offshore bars during the wet period (Hyndman & Hyndman, 2006). However, it is not covered in this study due to limited profile measurements. In this study, beach saturation level was not measured. Therefore, the influence of rainfall distribution from this study should be considered as another important factor in controlling the beach groundwater level with higher elevations during the wet season and lower elevations during the dry season. This finding is also consistent with the conclusion by Nielsen (1988) in which the beach groundwater table variation can be influenced partly by rainfall events.

The relationship of average shoreline position for both monitoring wells were examined to check whether the beach groundwater table position could affect the movement of the shoreline position during the study period. Figure 4.18 shows that BH2 and BH3 have moderate correlated values with correlation of 0.75 and 0.67, respectively. This situation could be explained by the effect of the sediment movement during the dry and wet periods. During the dry period, the beach area with respect to MSL become wider due to the onshore sediment movement. On the other hand, the offshore sediment movement enhanced the beach and become narrower during the wet period. This relationship can offer additional valuable information regarding the beach management system due to the local seasonal variation effect in Malaysia. From the result obtained, it reveals that the mean groundwater level variation could directly affect the beach profile changes by clear indication of the shoreline position (with respect to MSL). Higher groundwater level results in an eroded profile, and lower groundwater level results in an accreted profile. During the wet season, the beach groundwater level will increase higher and move the shoreline position to the upper part of beach due to the erosion process. Meanwhile, during the dry season, the beach groundwater level reduces and the shoreline position tends to move further from the upper beach due to the accretion process.

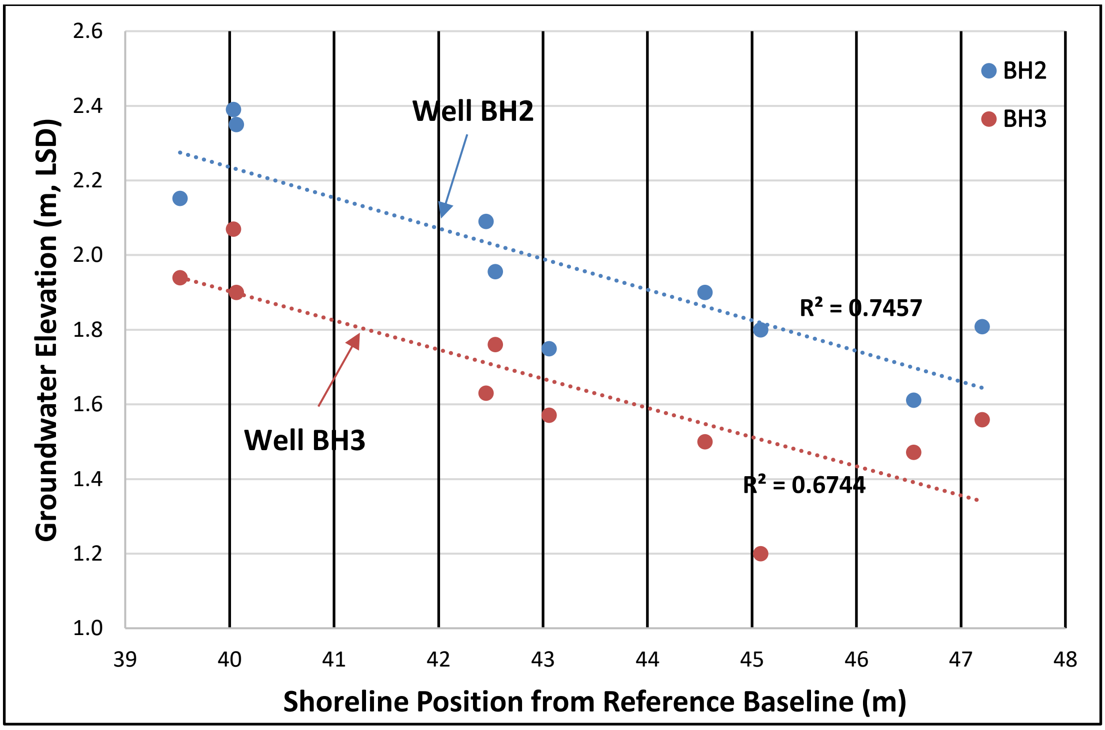


Figure 4.18 Correlation between groundwater level and shoreline position

Another analysis considered in the study was the position of the exit point on the beach face during the study period. The exit point is the position on the beach profile where the decoupled groundwater table intersects the beach face as observed at study area (Figure 4.19). The position of exit point is independent of the mean water surface until it is submerged by the rising tide. During low tides, if the exit point position is higher than MSL due to the higher groundwater level influence, a seepage or exfiltration process will develop as was detected at the study area (Figure 4.20). Figure 4.21 shows the potential of beach erosion during the wet season that is very high due to the higher groundwater table position as shown on 25 January 2014, 25 December 2014, and 23 January 2016. The same finding was also revealed in the computer model simulation result by Li et al. (2002) which reported that no infiltration occurred in the simulation with a high beach groundwater table during the wave uprush.

Meanwhile, for the low beach groundwater table simulation, significant infiltration rate occurred in the upper part of the beach during the uprush flow activities. Figure 4.21 and Table 4.2 shows the position of the exit point during dry and wet periods. It clearly indicates that the exit point position moved further to the upper beach and the elevation of the point also increased due to the higher groundwater level influence during the wet period. This observation is consistent with the previous study by Elfrink and Baldock (2002) which reported that the beach groundwater table position with respect to MSL affects the beach saturation degree and infiltration/exfiltration rate to the beach face. When the swash flow occurred on the beach face above the groundwater table exit point, the flow will infiltrate into the sand and reduce the uprush volume. This situation significantly enhanced the deposition process of suspended sediment especially during the dry period at the upper part of beach as illustrated on 27 June 2013, 18 May 2014, and 6 June 2015. Conversely, when the exit point is higher than the MSL, the backwash flow will increase due to the groundwater seepage influence from the saturated beach. The higher position of exit point compared to the MSL will erode the beach due to the higher exfiltration rate during backwash flow activities. It is different during the dry period when the exit point is located below the MSL and could enhance the infiltration rate during the swash flow activities. During this period also, deposition of sediment movement is very high, and the net beach profile volume will increase. This observation is similar to the study by Turner (1995), who found that water table exists on the beach face at the intertidal zone.

The sediment transport will be affected by the variability of the water table exit point during the uprush and backwash flows with the tidal activities at the beach face. This finding is also supported by Yuan and Lin (2009) which stated that a formation of seepage face and exit point occurred during the falling tide period and as a result the beach groundwater level may be decoupled from the driving head.

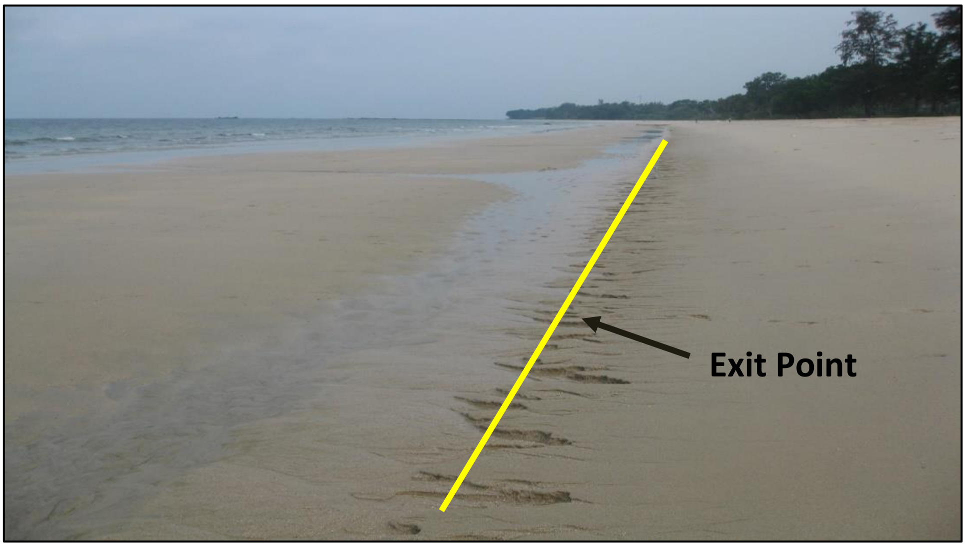


Figure 4.19 A view of exit point at Desaru Beach

Figure 4.20 An example of seepage face on beach area

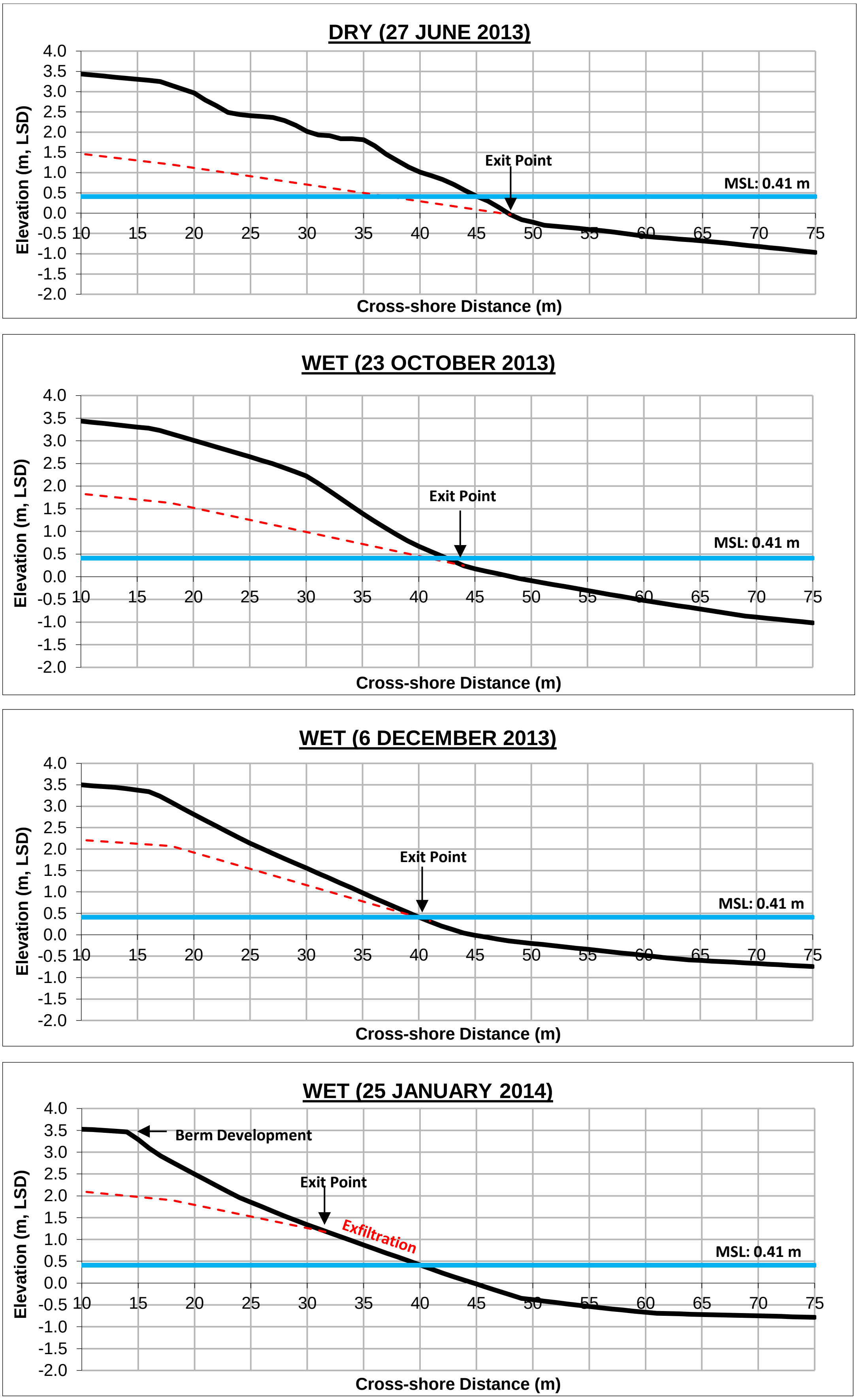
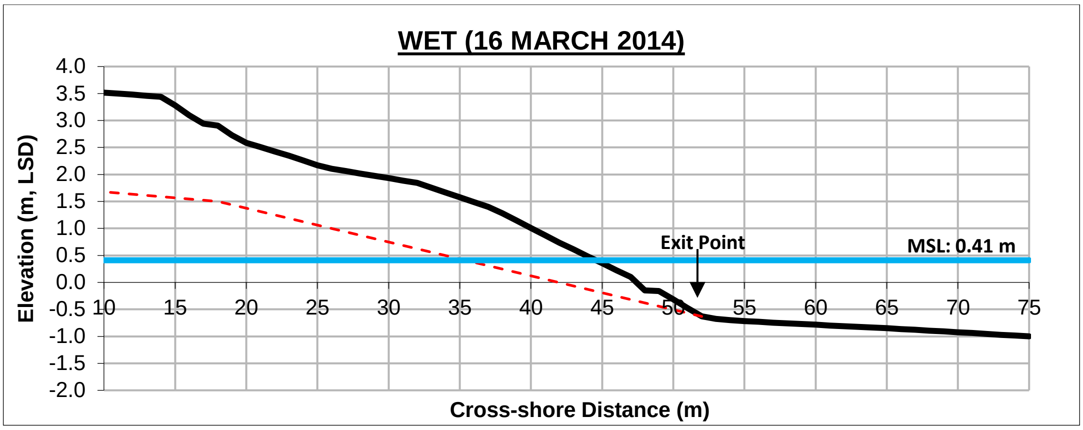
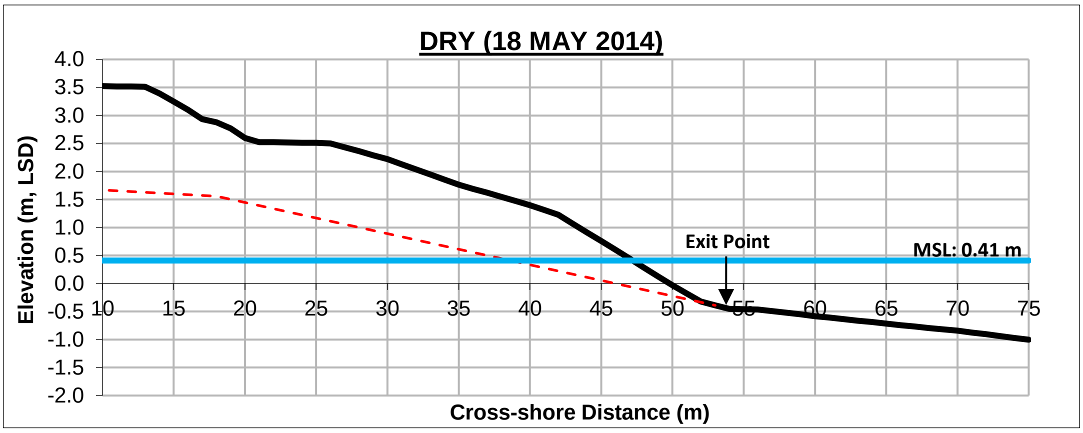
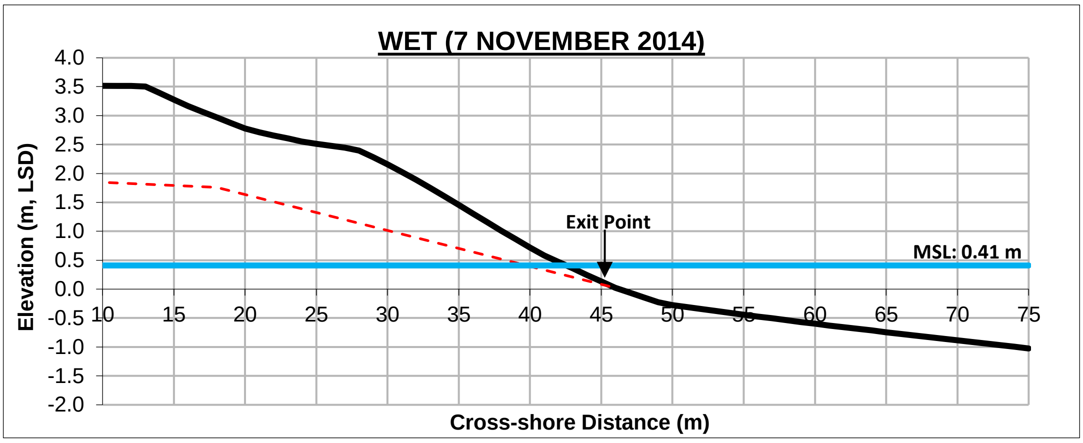


Figure 4.21 The position of exit point during dry and wet periods







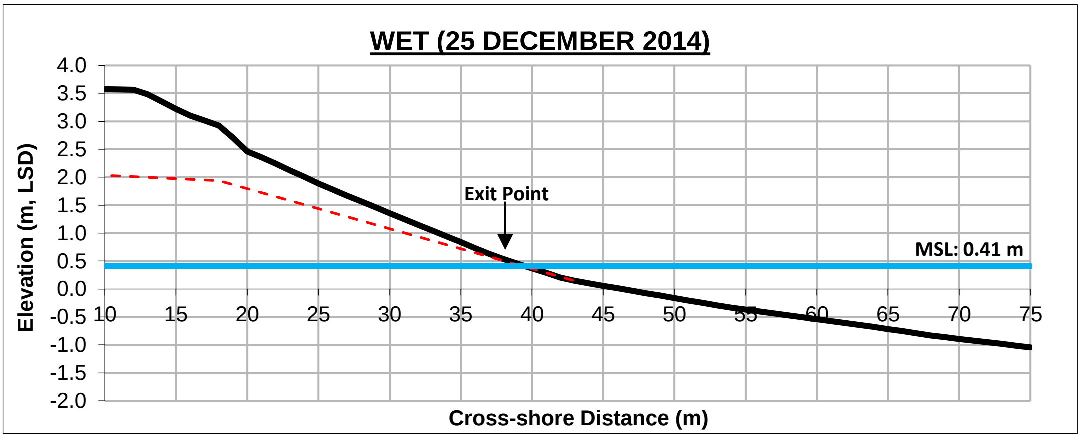


Figure 4.21 The position of exit point during dry and wet periods (cont.)

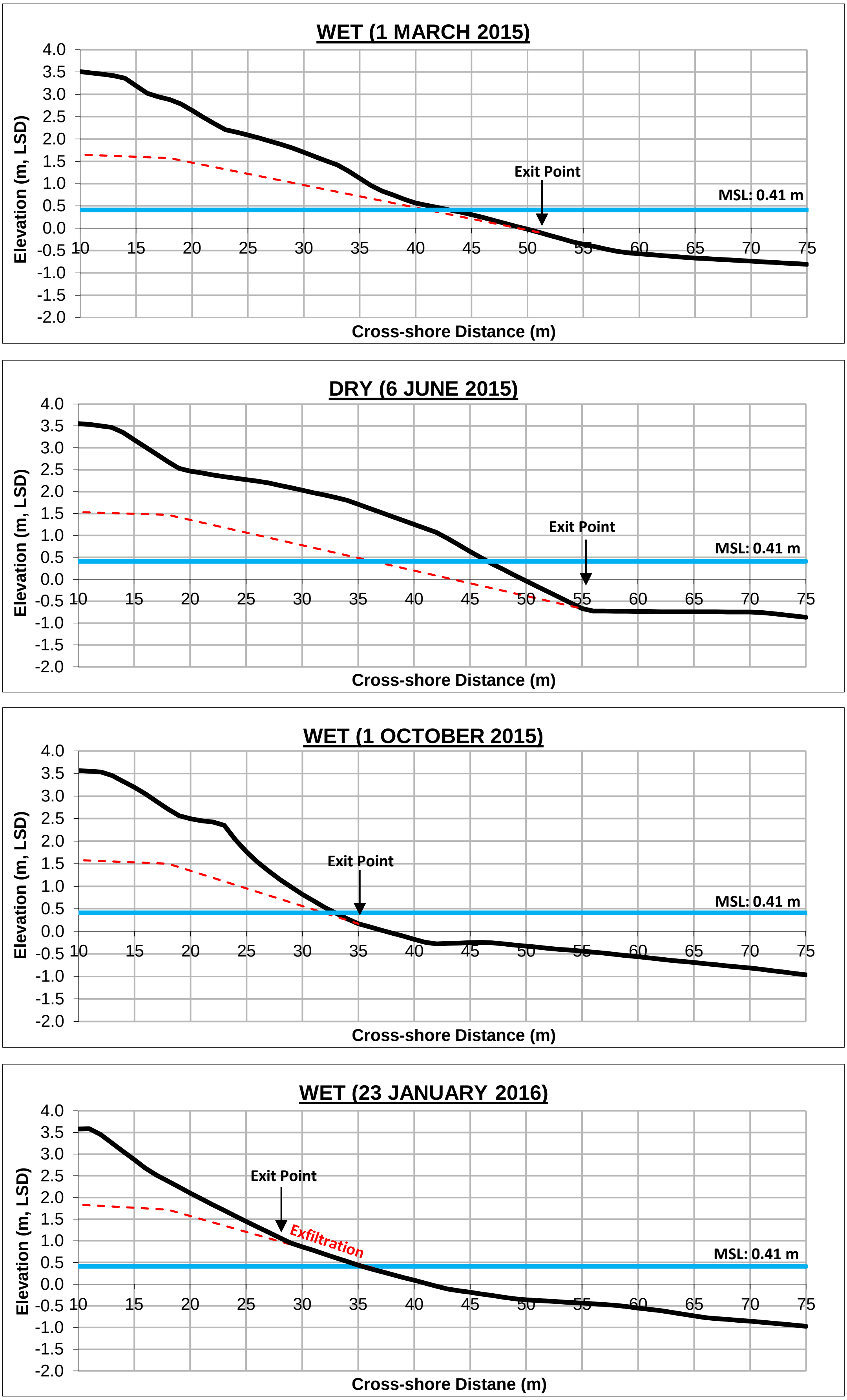


Figure 4.21 The position of exit point during dry and wet periods (cont.)

Table 4.2 The position of exit point

Date	Exit Point Position (m)
27 June 2013	48.0
23 October 2013	44.0
6 December 2013	40.0
25 January 2014	32.0
16 March 2014	52.0
18 May 2014	54.0
7 November 2014	46.0
25 December 2014	38.0
1 March 2015	51.0
6 June 2015	55.0
1 October 2015	35.0
23 January 2016	28.0

4.4 Effect of Tidal Elevation on Beach Groundwater Table

Figure 4.22 & 4.23 show the relationship between tides and groundwater level in BH2 (the furthest well from the shoreline) and BH3 (the nearest well from the shoreline) during wet and dry periods, respectively. Figure 4.22 covers for the selected seven days of monitoring duration during the wet period (15-21 December 2013) and Figure 4.23 is for the dry period (10-16 July 2014).

From both figures, the groundwater level in BH3 showed a more prominent effect of the tides than BH2. It was clearly influenced by the location of BH3 which the nearest well to the shoreline compared with BH2. From the observation, it shows that the highest groundwater table occurred nearly to low tide (ebb) with range of tidal elevation of 2.6 m and 1.5 m during the wet and dry periods, respectively. This phenomenon was also observed by Lanyon et al. (1982) that the beach groundwater table varies due to the tidal variation. From the observation, it seems like the effect of tides on the beach groundwater level at BH3 was delayed by between 2 and 4 hours behind the tides. This situation is partly due to the distance of the well location from the shoreline (approximately 20 m) and the type of beach material that has a lower hydraulic conductivity value.

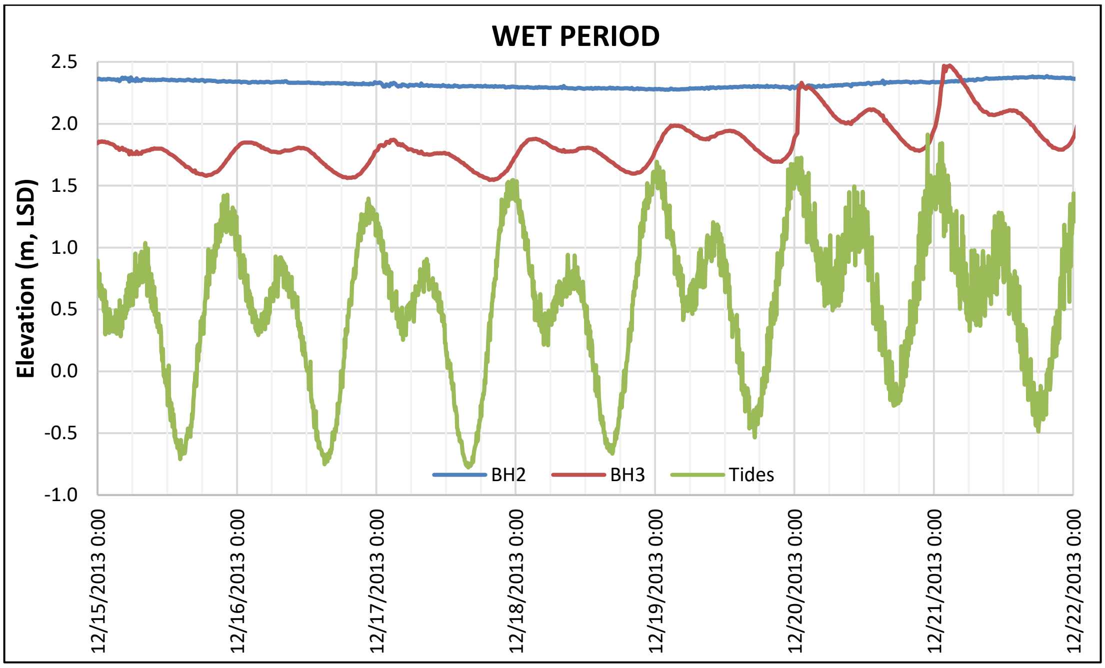


Figure 4.22 Daily groundwater levels and tides during wet period

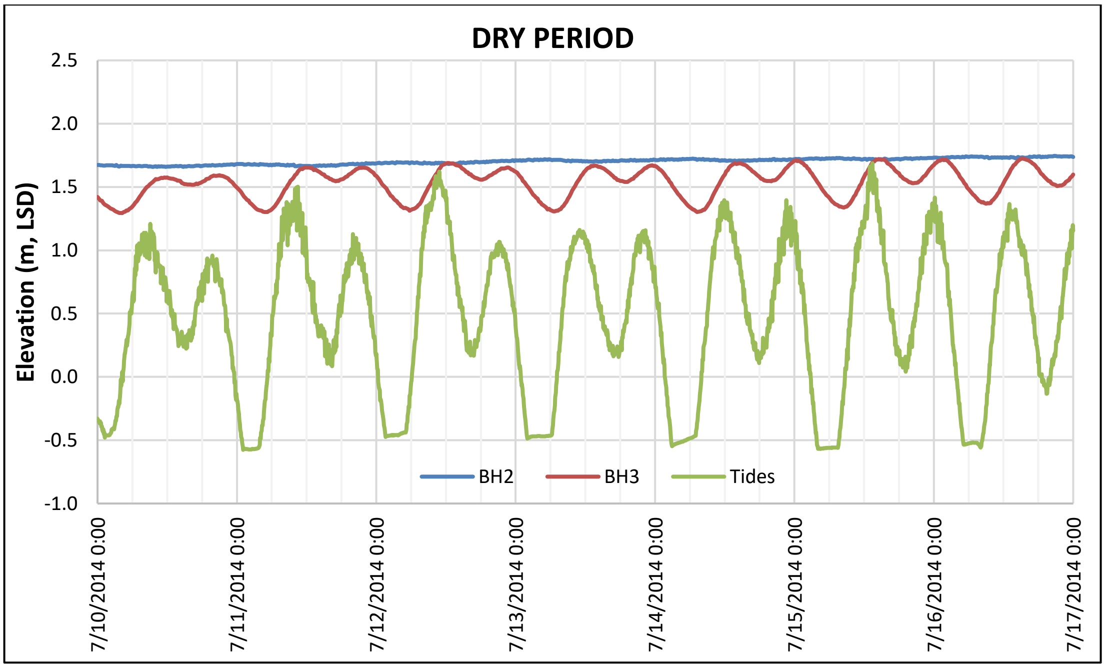


Figure 4.23 Daily groundwater levels and tides during dry period

Therefore, the rising or falling tidal elevation may not directly influence the groundwater table especially in BH3 as the infiltrated seawater needed time to fill and leave the soil. This finding is consistent with the conclusions by Nielsen (1990) and Brakenhoff (2015), that a lag time is mainly due to the response of the hydraulics conductivity of the beach sediment and sandy beach groundwater table takes a longer time to respond due to a lower value of hydraulics conductivity.

4.5 Swash Flow Depth and Velocity Analysis

Generally, the sediment transport processes that happen in the swash zone are directly affected by the continuous cycle of swash uprush and backwash processes, resulting in a deposition and removal of sediment on the beach surface. Field investigations of the hydrodynamic processes in the swash zone for uprush and backwash activities have been conducted using a variety of methods, but every study has repeatedly revealed some general features of the swash zone internal flows and found the significant differences between uprush and backwash flows.

In the swash zone, hydrodynamic properties like flow depth and velocity are among the most significant parameters for sediment transport process in this boundary. Swash flow during the uprush events are typically created by the collapsing bore which is especially found on steep beaches and sometimes may have a turbulent flow through crash with the previous backwash. The collision flow between an energetic accelerating backwash and a continuing energetic uprush can produce a nearly stationary bore or hydraulic jump in the swash region. Therefore, additional attention or effort for swash flow depth and velocity profiles investigation during the uprush and backwash events is fundamental especially under the influence of local seasonal variation in Malaysia. This effort is considered important to get better understanding of sediment transport mechanism for sandy beach profile evolution.

In this chapter, the aim is to compare and analyze the selected swash hydrodynamic data for swash water depth and velocity during wet and dry periods. In order to investigate the effect of seasonal variation, the swash water depth and velocity profiles were selected for the same highest tidal elevation during the wet and dry seasons. In Figures 4.24 and 4.25, the profile data for swash depth and velocity taken at the same tidal elevation on 16 March 2014 have shown the effect of seasonal variations on swash properties. During this month, the study area experienced a dry period and the end of the Northeast monsoon which has a lower wave energy attack. This condition totally affected the swash water depth and velocity levels to become lower than those during the wet season. For the swash water depth comparison, it clearly shows that decreased swash energy happened during this period with an average depth of 2.05 cm with a maximum value of 12.3 cm. This important observation explains the berm development during the dry season when the uprush distance is 10 m shorter that that during the wet season.

For the velocity data during this period, the highest values of uprush and backwash velocities were 2.85 and 1.58 m/s, respectively. It was found that the swash velocity was considerably decreased for the uprush and backwash flows, but the average backwash velocity was significantly reduced by 73.08% caused by greater infiltration due to the high value of unsaturated beach surface. This condition played a major role in the accretion process in the swash zone due to the high infiltration effect and weakened backwash flow. In this condition, the sediment or sand carried by swash water during the uprush and backwash flows settled down easily on the beach face due to the high infiltration process and leads to the accretion process in the beach.

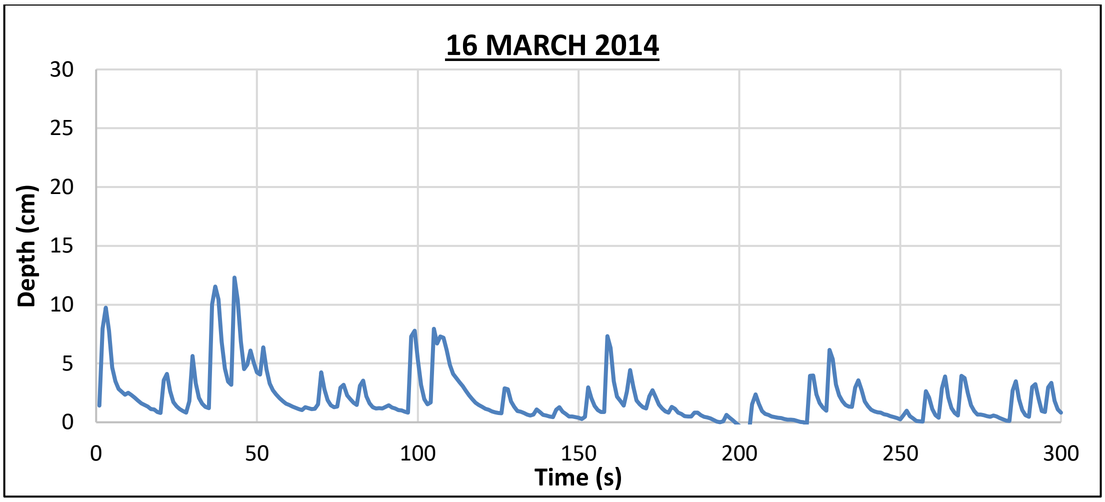


Figure 4.24 Profile of dry season swash flow depth on 16 March 2014

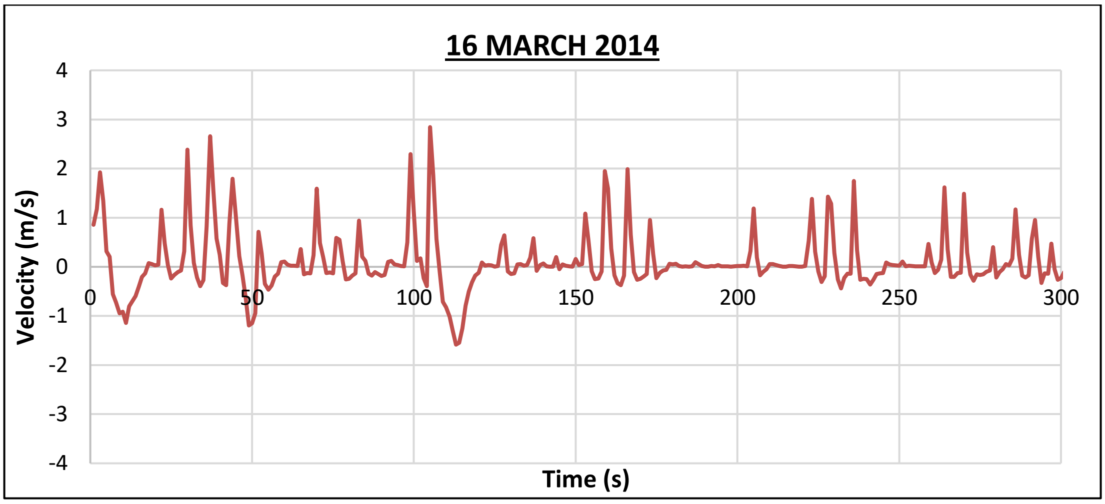


Figure 4.25 Profile of dry season swash flow velocity on 16 March 2014

During the wet period on 29 October 2013 as shown in Figure 4.26, the average depth was 7.1 cm with a maximum value on 27.0 cm. For the velocity data in Figure 4.27, the highest values of uprush and backwash were recorded at 3.76 and 2.13 m/s, respectively.

Similar results were obtained by Masselink and Hughes (1998) which reported that the uprush flows on steeper beach were higher than that of the sloping beach and may be up to 3.5 m/s. However, the timing of maximum velocities measured by a current meter can differ depending on the equipment's location at the swash zone. A maximum instantaneous acceleration in uprush velocity and followed by steadier decrease to zero velocity at the end of the uprush flow was observed at the sampling point data during the wet period. During this moment, the maximum water depth always occurred at zero velocity reading at the end of uprush flow. In contrast, when the backwash flow took action in the swash zone, the velocity increased gradually until it reached its maximum value. Later, the backwash flow depths and velocities decreased to zero until the next uprush flow comes. This observation was consistent with the field work done by Hughes et al. (1997).

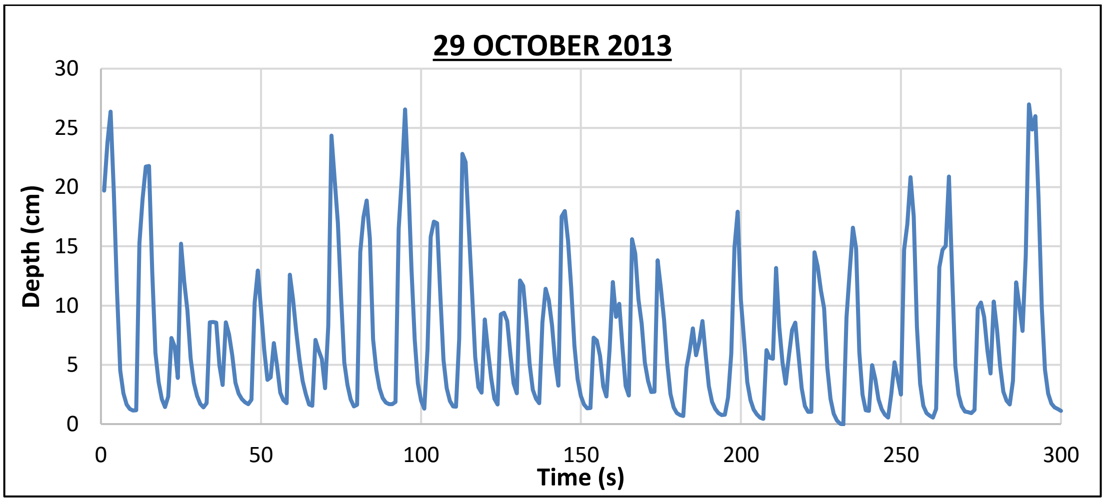


Figure 4.26 Profile of wet season swash flow depth on 29 October 2013

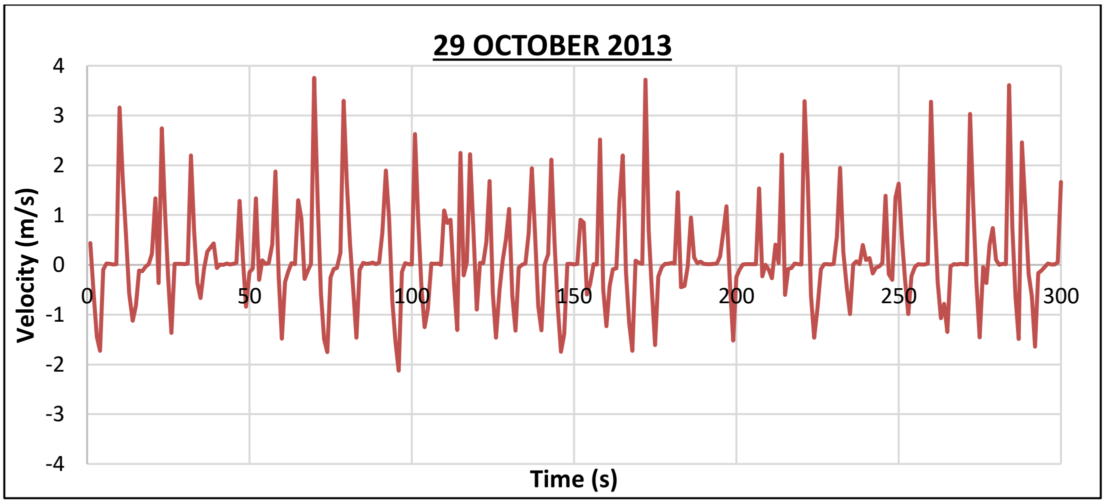


Figure 4.27 Profile of wet season swash flow velocity on 29 October 2013

Table 4.3 Result analysis of dry and wet periods swash water depth and velocity

Swash Zone Characteristics	**Parameters**	**Dry Period**	**Wet Period**
Swash Flow Depth	Average Uprush (cm)	4.6	13.8
	Average Backwash (cm)	2.2	10.4
	Reduction from Uprush to Backwash (%)	52.17	24.64
	Maximum Uprush (cm)	12.3	27.0
	Maximum Backwash (cm)	7.2	21.8
Swash Flow Velocity	Average Uprush (m/s)	1.30	2.00
	Average Backwash (m/s)	0.35	1.08
	Reduction from Uprush to Backwash (%)	73.08	46.00
	Maximum Uprush (m/s)	2.85	3.76
	Maximum Backwash (m/s)	1.58	2.13

Table 4.3 shows that dry and wet periods at Desaru beach have significantly affected the swash zone water depth and velocity. For every single swash event of water depth analysis, the reduction percentage of average uprush flow depth to backwash during dry and wet periods was 52.17% and 24.64%, respectively. These values are clearly important to explain the seasonal hydrological variations effect on beach morphological changes. For example, the reduction percentage during the dry period was higher than the wet period due to the influences of lower value of groundwater table and moisture content of the beach. This phenomenon has promoted the higher infiltration rate of swash flow into the sand beach and it also explains the reduction in water depth of backwash during the dry period compared to that during the wet period. This unique phenomenon also explains a higher reduction percentage of swash velocity for uprush to backwash flows during the dry period (73.08%) than the wet period (46.00%). By using similar mechanism such as swash water depth analysis, the backwash flow velocity during the dry period was significantly reduced by greater infiltration effect and this phenomenon also promoted the accretion processes in the swash zone area due to the deposition of sediment transport especially

during backwash activities. In contrast during the wet period, the backwash flow velocity was reduced only by 46.0% and which was due to the higher degree of moisture content and slight decrease in the flow volume and velocity in the swash zone area especially at the upper part.

The patterns of swash water depths and velocities for every single uprush and backwash during the dry period have shown that the accretion processes significantly occurred in the swash zone due to the high infiltration effect during the dry period. In this condition, the sediment or sand carried by swash water during the uprush and backwash flows has settled down easily on the beach face due to the high infiltration process and this situation put the beach in accretion mode. However, in order to understand swash zone processes clearly and how these affect beach profile response, Horn (2006) stresses the importance of direct measurements of key parameters such as hydraulic conductivity, moisture content and infiltration rates which must be carried out in the field. For the swash water depth and velocity profiles, the data during wet period were higher than those of the dry period due to the higher wave energy and saturation level effect on the infiltration processes on the beach surface. Due to the saturated beach condition, the swash velocities for backwash was slightly lower than those of the uprush in the wet period but significantly lower or none during the dry period.

4.6 Summary of Results

In conclusion, Desaru beach has been eroded during every wet period but the final trend shows that the beach is in eroding mode despite being under the recovery process every dry period. Even though, the beach is showing stable seasonal onshore and offshore sediment movements during the dry and wet periods, but the beach shows likelihood to erode further in the future.

For beach groundwater table at Desaru beach, it was highly affected by the patterns of rainfall distribution which significantly increases and decreases in the wet and dry periods, respectively. The increasing beach groundwater level has led to the beach becoming more saturated and enhanced offshore sediment transport during the wet season and the profile was eroded. However, during the dry season, the beach was accreted. This is because the groundwater level was lower in comparison to the groundwater level during the wet season. Near to the shoreline, groundwater level was highly affected by the tidal fluctuations but other parameters such as the hydraulic conductivity was suggested to be measured to explain clearly the response of groundwater table due to the tidal effect. The analysis of exit point position also reveals that higher groundwater level during the wet season will elevate the exit point position. If the exit point is found higher than MSL, the possibility of seepage or exfiltration process is very high on the beach face and the erosion process during that time will occur easily.

It is normally assumed that the beach sediment moves seasonally between the berm and the bar, so the total volume of sediment transport remains relatively constant as reported by Dick & Dalrymple (1984) but Desaru beach profile measurement reveals that the volume of sand did not remain constant with the beach tending to erode further. It shows clearly in TEOF2 analysis result where the trend was at higher negative slope at the end of study period. The EOF method applied at Desaru beach was a good platform to improve beach data treatment practices for sandy beach in Malaysia. The method was valuable in showing the characteristics of beach profile changes that may have significance in the profile response due to the local parameters variation. A better understanding and interpretation of the processes at the beach can be further improved by using this method. The results from this statistical technique provide a platform for the application of the EOF method in the detailed analysis of beach profile changes, especially for local seasonal variation effect. By using these preliminary results as a foundation, it is now intended to extend the study for a longer period of time, to improve the reliability of these function.

CHAPTER 5

CONCLUSION AND RECOMMENDATIONS

5.1 Conclusions

Seasonal variation effect on sandy beach profile changes were investigated at Desaru beach to gain further understanding of swash zone sediment transport. Field monitoring were carried out at Desaru beach for a 30-months period where the beach cross-shore profiles, groundwater table, rainfall distribution, tides, and swash flow characteristics were measured and recorded. All these data were analyzed to check any patterns of relationship that exists among the parameters. For details of the beach profiles analysis, EOF was applied to examine spatial and temporal variabilities of the cross-shore profiles. The findings of this study in relation to the research objectives are summarized as follows:

Objective one on the analysis of beach profile morphological changes under seasonal variation effect using bulk statistical analysis approach was summarized in the following findings:

i. From the analysis results, it was discovered that the strongest variability of the beach profiles occurred at the intertidal level boundary which is located entirely within the swash zone. This result is also supported by the analysis of standard deviation for all profiles which reveals the highest standard deviation around the mean profile (σ = 0.60 m) which possibly attributed by the strong swash movements. The lowest variability (σ = 0.02 m) of the profiles was found starting from at point x = 65 m seaward or below the MLLW level. The findings also confirmed that the swash zone hydrodynamics is the major factor controlling the Desaru sandy beach profile.

ii. The beach volume changes indicated significant relationship with the influence of seasonal hydrological variation at Desaru beach. During wet period, there was losses of about 20-30 m^3/m, while in the dry period, about 15-25 m^3/m of sand volume were accreted. This situation has been contributed by the higher and lower wave energy occurred during wet and dry periods, respectively. The erosive condition was during the wet season from November until January, while the accretion situation occurs from April until June which confirmed the influence of seasonal hydrological variation on the profile of Desaru beach.

iii. Another interesting finding revealed from this study is the shoreline position movement with respect to MSL under local seasonal variation effect which found that higher correlation ($R^2 = 0.8603$) with the total sand volume of Desaru beach which could provide the essential information about the beach profile changes during dry and wet seasons.

Objectives two on the investigation of Desaru seasonal beach profile variability under spatial and temporal variations using the Empirical Orthogonal Eigenfunction (EOF) technique which mainly focused in the swash zone boundary was accomplished by the following results:

i. For the spatial EOF analysis, all the eigenfunctions (SEOF1-SEOF5) at Desaru beach have shown that the strongest variability occurred between $x = 20$ m and 60 m, which covers the entire swash zone except the EOF4 which was actively occurred beyond $x = 55$ m at the lower swash and the subtidal zone of the profile. This situation clearly indicates the important role of swash zone in controlling the shoreline position.

ii. From temporal EOF analysis, the second temporal eigenfunction (TEOF2) at Desaru beach clearly shows a high frequency signal for every 6 months due to the seasonal variations effect of dry and wet periods. Positive values for accretion process was observed during dry period and negative values for erosion mode was observed during wet period. The result also confirmed that the local seasonal hydrological variation effect is clearly shown and described well by the temporal eigenfunction analysis. It reveals the berm changes extended from the upper swash section or intertidal zone (15 m $< x <$ 30 m) to the starting point of the subtidal region ($x >$ 60 m). Meanwhile, during the dry period, the location of sandbar at the subtidal region have shifted landward due to calm wave energy and greater infiltration effect on the swash zone.

Objective three was on assessment of the rainfall distribution and tidal elevation influences on the beach groundwater table variability. The findings from the beach morphological changes under groundwater table effect are summarized as follows:

i. From the rainfall data, it was found that the wet period occurred annually between November and January, where December was found to be the wettest month with 312.5 mm and 219.5 mm of precipitation for years 2013 and 2014 respectively. During this period, the highest groundwater table for both monitoring wells (BH2 & BH3) was found to occur between December and January.

ii. In contrast, the dry period at Desaru beach is between February and March with February 2014, recording as the driest month where no rainfall data was detected. However, the lowest groundwater table for both wells were between May and July. The delayed reduction could be attributed to the lower value of hydraulic conductivity in the aquifer.

iii. From tidal elevation data, rising or falling tides may not directly influence the variation of groundwater table in well BH3 on the upper part of the beach as the infiltrated seawater needed time to fill and leave the soil. It was found that there is a lag of water table response of two to four hours after the tides event. This situation could be due to the distance of the well point from the shoreline (approximately 20 m) and also the type of beach material (fine sand) that affected the hydraulic conductivity value.

iv. Another finding from this study is the moderate correlation that exists (R^2 = 0.67-0.75) between the variation of groundwater table (BH2 & BH3) with shoreline position movement which reveals the significant effect of the beach groundwater table variation on the beach morphological changes. It concluded that the higher groundwater table during the wet period put the beach in an erosive mode which moved the shoreline to the upper part of the beach and resulted in the beach width becoming narrower. It contrasts during the dry period which the beach groundwater table will lowered and the accretion process will take over which resulted the beach width become wider during this time.

The following results were obtained to support objective four on the analysis of swash velocity and depth characteristics during dry and wet periods:

i. The patterns of swash flow characteristics for every single uprush and backwash during the dry period have shown that a high infiltration effect occurred during this time with more than 50% reduction of depth and velocity. This caused an increase of sediment deposited by the swash flow during the uprush and weakened backwash due to the higher infiltration process. This situation clearly placed the beach profile in an accretion mode and explained well why the beach tend to accrete during dry periods.

ii. During the wet period, the middle and lower part of the swash zone are in saturated condition due to higher level of groundwater table. During this period, the swash flow depth and velocity was significantly higher than dry period due lower infiltration. The percentage of reduction for backwash velocity and depth compared with uprush were found to be in the range of 10-20%. The offshore sediment transport during this time is higher due to significant exfiltration during backwash flow on the beach face.

5.2 Recommendations for Future Research

This study has successfully opened up several potential research on swash zone sediment transport in tropical countries. It provided a significant reason to study the local seasonal variation effect on beach profile changes especially on sediment movement in the swash zone during dry and wet periods. More research could be initiated to get better understanding of the local beach evolution. The following suggestions may be considered for future research:

i. A better quality and more systematic beach profile monitoring system is needed to explore possible use of other advanced mathematical methods or techniques for better prediction or forecasting of beach profile evolution. It also can improve the current coastal vulnerability analysis for Malaysia coastline, which is an important element of shoreline management plan in the future.

ii. Similar field study on other beaches in Malaysia should be conducted. The study should be more intensive, with daily, biweekly or monthly surveys. This would ensure better quality profile changes analysis and in the swash zone with other significant hydrodynamic factors such as offshore waves and nearshore waves.

iii. Sediment concentration monitoring in the swash zone is still difficult to conduct due to the high turbulence level in the sheet flow layer. Nevertheless, the deep understanding about this process is still needed for better prediction of the beach evolution. The requirement to obtain advanced instrumentation to monitor this process is essential in the swash zone sediment transport study.

iv. In order to understand the influence of beach groundwater dynamics on swash zone morphological changes especially under tidal variations effect, it is suggested to also install the groundwater table monitoring wells along the cross-shore profile for a clearer view of groundwater table variation profiles.

v. The application of EOF analysis is widely used to investigate the patterns of spatial and temporal behaviors in the profile elevations but other techniques such as CCA, which can use the EOF results as the main input to determine the dominant patterns of co-variability or changeability between profile data and natural forces could improve the accuracy level of beach evolution prediction model.

REFERENCES

Alegria-Arzaburu, R., Amaia, Jesús, V., Héctor, G.N. and Angélica, R. (2017). Seasonal morphodynamics of the subaerial and subtidal sections of an intermediate and mesotidal beach. *Geomorphology,* 295.

Alsina, J.M., Cáceres, I., Brocchini, M. and Baldock, T.E. (2012). An experimental study on sediment transport and bed evolution under different swash zone morphological conditions. *Coastal Engineering,* 68, pp. 31-43.

Ang, L.S., Sum, C., H.-Y., Baldock, T.E., Li, L. and Nielsen, P. (2004). Measurement and modelling of controlled beach groundwater levels under wave action. *Proceedings of the 15th Australasian Fluid Mechanics Conference, CDROM.*

Aranuvachapun, S. and Johnson, J.A. (1979). Beach profile at Gorleston and Great Yarmouth. *Coastal Engineering,* 2, pp. 201–213.

Aubrey, D.G. (1979). Seasonal patterns of onshore-offshore sediment transport. *Journal of Geophysical Research,* 84 C10, pp. 6347–6354.

Aubrey, D.G. and Emery, K.O. (1983). Eigenanalysis of recent United States sea levels. *Continental Shelf Research,* v. 2, p.

Aubrey, D.G. and Ross, R.M. (1985). The quantitative description of beach cycles. *Marine Geology,* 69, pp. 155–170.

Austin, M.J. (2005). Swash, groundwater and sediment transport processes on a gravel Beach. PhD thesis, Loughborough University, U.K.

Austin, M.J. and Buscombe, D. (2008). Morphological change and sediment dynamics of the beach step on a macrotidal gravel beach. *Marine Geology,* 249 (3-4), pp. 167–183

Austin, M.J. and Masselink, G. (2006). Observations of morphological change and sediment transport on a steep gravel beach. *Marine Geology,* 229 (1-2), pp. 59–77.

Austin, M. J., Masselink, G., Russell, P. E., Turner, I. L. and Blenkinsopp, C. E. (2011). Alongshore fluid motions in the swash zone of a sandy and gravel beach. *Coastal Eng.*, 58(8), pp. 690–705.

Bagnold, R.A. (1940). Beach formation by waves: some model experiments in a wave tank. *Journal of the Institution of Civil Engineers,* Paper No. 5237, pp. 27–53.

Baird, A.J. and Horn, D.P. (1996). Monitoring and modelling ground water behaviour in sandy beaches. *Journal of Coastal Research,* 12 (3), pp. 630–640.

Baird, A.J., Mason, T. and Horn, D.P. (1996). Mechanisms of beach groundwater and swash interaction. *Proceedings of the 25th ICCE Conference*, ASCE, Florida.

Baird, A.J., Mason, T. and Horn, D.P. (1998). Validation of a boussinesq model of beach groundwater behaviour. *Marine Geology,* 148 (1-2), pp. 55-69.

Bakhtyar, R., Barry, D.A., Li, L., Jeng, D.S. and Yeganeh-Bakhtiary, A. (2009). Modelling sediment transport in the swash zone: A review. *Ocean Engineering,* 36 (9-10), pp. 767–783.

Baldock, T.E., Baird, A.J., Horn, D.P. and Mason, T. (2001). Measurements and modelling of swash-induced pressure gradients in the surface layers of a sand beach. *Journal of Geophysical Research,* 106 (C2), pp. 2653–2666.

Baldock, T.E., Cox, D, Maddux, T, Killian, J and Fayler, L. (2009). Kinematics of breaking tsunami wavefronts: A data set from large scale laboratory experiments. *Coastal Engineering, 56* 5-6: pp. 506-516.

Baldock, T.E. and Holmes, P. (1997). Swash hydrodynamics on a steep beach. Thornton, E.B. (Ed.), *Coastal Dynamics'97,* American Society of Civil Engineers, New York, pp. 784– 793.

Baldock, T.E. and Holmes, P. (1998). Seepage effects on sediment transport by waves and currents. *Proceedings of the 26th ICCE Conference,* ASCE, pp 3601-3614.

Baldock, T.E., Hughes, M.G., Day, K. and Louys, J. (2005). Swash overtopping and sediment overwash on a truncated beach. *Coastal Engineering,* 52 (7), 633–645

Baldock, T.E. and Hughes, M.G. (2006). Field observations of instantaneous water slopes and horizontal pressure gradients in the swash zone. *Continental Shelf Research,* 26, pp. 574–588.

Barletta, R. C., Franco, D., Melo, E., PereirA, P., Tozzi, H. and Calliari, L. J. (2006). Application of the empirical orthogonal functions for the analysis of southern Brazilian beach profiles. *Journal of Coastal Research,* SI 39 (Proceedings of the 8th International Coastal Symposium), 351- 354. Itajaí, SC, Brazil, ISSN 0749- 0208.

Barnes, M.P., O'Donoghue, T., Alsina, J.M. and Baldock, T.E. (2009). Direct bed shear stress measurements in bore-driven swash. *Coastal Engineering,* 56 (8), pp. 853–867.

Beach, R.A. and Sternberg, R.W. (1991). Infragravity driven suspended sediment transport in the swash, inner and outer-surf zone. Kraus, N.C., Gingerich, K.J., Kriebel, D.L. (Eds.), *Coastal Sediments '91,* Seattle, pp. 114–128.

Beach, R.A., Sternberg, R.W. and Johnson, R. (1992). A fiber optic sensor for monitoring suspended sediment. *Marine Geology,* 103 (1–3), pp. 513–520.

Bowman D., Ferri S., and Pranzini E. (2007). Efficacy of beach dewatering – Alassio. *Italy Coastal Engineering,* 54, pp. 791-800.

Brakenhoff, L.B. (2015). Interaction of tides, groundwater levels and surface moisture on a sandy beach. Faculty of Geosciences Theses. (Master thesis). Utrecht University.

Brocchini, M. (2006). Integral swash-zone models. *Continental Shelf Research*, 26, pp. 653–660.

Brocchini, M. and Baldock, T.E. (2008). Recent advances in modeling swash zone dynamics: influence of surf–swash interaction on nearshore hydrodynamics and morphodynamics. *Reviews on Geophysics*, 46, RG3003.

Butt, T. and Russell, P. (1999). Suspended sediment transport mechanisms in high-energy swash. *Marine Geology,* 161 (2–4), pp. 361–375.

Butt, T. and Russell, P. (2000). Hydrodynamics and cross-shore sediment transport in the swash-zone of natural beaches: a review. *Journal of Coastal Research,* 16 (2), pp. 255–268.

Butt, T., Russell, P. and Turner, I.L. (2001). The influence of swash infiltration-exfiltration on beach face sediment transport: Onshore or offshore? *Coastal Engineering,* 42 (1), pp. 35-52

Butt, T., Russell, P.E., Miles, J. and Turner, I.L. (2007). Sediment transport processes in the swash zone of sandy beaches. International Coastal Symposium. *Journal of Coastal Research,* 50, pp. 636–640 (Special Issue).

Carter, R.W.G. and Orford, J.D. (1993). The morphodynamics of coarse clastic beaches and barriers: A short and long-term perspective. *Journal of Coastal Research,* SI 15, pp. 158-179.

Clark, D. (1975). Understanding canonical correlation analysis. In: Concepts and techniques in modern geography- No.3. *Geo Abstracts Ltd*, p 36.

Conley, D.C. and Inman, D. (1994). Ventilated oscillatory boundary layers. *Journal of Fluid Mechanics,* 273, pp. 261–284.

Conley, D.C. and Griffin, J.G. (2004). Direct measurements of bed stress under swash in the field. *Journal of Geophysical Research,* 109, C03050.

Dai, Z.J., Chen, J.Y., Du, J.Z. and Li, C.C. (2008). Seasonal changes of sandbar behavior in Nanwan Beach, South China. *Journal of Coastal Research,* 24(5), 1209–1216. West Palm Beach (Florida), ISSN 0749-0208.

Davis, R.A. and Fox, W.T. (1972). Coastal processes and nearshore sand bars. J. Sediment. *Petrol.,* 42, pp. 402– 412.

Dean, R.G. (1973). Heuristic models of sand transport in the surf zone. *Proceedings of the Conference on Engineering Dynamics in the Surf Zone,* Sydney, Australia, pp. 208–214.

Dean, R.G. and Dalrymple, R.A. (2004). Coastal processes with engineering applications. *Cambridge University Press*. ISBN-13: 978-0521602754.

Dail, H.J., Merrifield, M.A. and Bevis, M. (2000). Steep beach morphology changes due to energetic wave forcing. *Mar Geol.,* 162 (2–4): 443–458.

Dean, R.G. (1991). Equilibrium beach profiles: characteristics and applications. *J. Coast. Res.,* 7 (1), 53–84.

Dick, J.E. and Dalrymple, R.A. (1984). Coastal changes at Bethany Beach, Delaware, *Proc. 19th Int. Conf. Coastal Eng*., Houston, pp. 1650-1667. American Society of Civil Engineers, New York.

Ding, X., Zheng, D., Chen, Y., Chao, J. and Li., Z. (2001). Sea Level Change in Hong Kong from Tide Gauge Measurements of 1954-1999. *Journal of Geodesy*, 74, 683-689.

Duncan, J.R. (1964). The effects of water table and tidal cycle on swash–backwash sediment distribution and beach profile development. *Marine Geology,* 2, pp. 186–197.

Elfrink, B. and Baldock, T.E. (2002). Hydrodynamics and sediment transport in the swash zone: a review and perspectives. *Coastal Engineering,* 45, pp. 149–167.

Eliot, I. and Clarke, D.J. (1986). Seasonal and biennial fluctuations in subaerial beach sediment volume on Warilla Beach, New South Wales. *Marine Geology*, 48, pp. 89–103.

Eliot, I. G. and D. J. Clarke. (1988). Semi-diurnal variation in beachface aggradation and degradation. *Marine Geology*, 79, pp. 1-22.

Ericksen, N.J. (1970). Measurement of tide induced change to water table profiles in coarse and fine sand beaches along Pegasus Bay, Canterbury. *Earth Sciences Journal,* 4 (1), pp. 24–31.

Foote, M., Horn, D. and Li, L. (2002). Measuring swash zone hydrodynamics and morphodynamic change – a high-resolution laboratory system using digital video. *Journal of Coastal Research,* SI 36, pp. 300-316.

Gourlay, M.R. (1992). Wave set-up, wave run-up and beach water table: interaction between surf zone hydraulics and groundwater hydraulics. *Coastal Engineering,* 17, pp. 93–144.

Grant, U.S. (1946). Effects of groundwater table on beach erosion. *Geological Society of American Bulletin,* 57, pp. 1952.

Grant, U.S. (1948). Influence of the water table on beach aggradation and Degradation. *Journal of Marine Research,* 7, pp. 655–660.

Guo, Q., Li, H., Boufadel, M.C., Xia, Y. and Li, G. (2007). Tide-induced groundwater head fluctuation in coastal multi-layered aquifer systems with a submarine outlet-capping. *Advances in Water Resources,* 30 (8), pp. 1746–1755.

Hardisty, J., Collier, J. and Hamilton, D. (1984). A calibration of the Bagnold beach Equation. *Marine Geology,* 61, pp. 95–101.

Haxel, J.H. and Holman, R.A. (2004). The sediment response of a dissipative beach to variations in wave climate. *Mar. Geol.,* 206, 73–99.

Hayes, M.O. and Boothroyd, J.C. (1969). Storms as modifying agents in the coastal Environment. Hayes M.O. (Ed.), Coastal Environments. NE Massachusetts, Department of Geology, University of Massachusetts, Amherst, pp. 290–315.

Heathershaw, A.D., Carr, A.P., Blackley, M.W.L. and Wooldridge, C.F. (1981). Tidal variations in the compaction of beach sediments. *Marine Geology,* 41, pp. 223–238.

Herbers, T.H.C., Elgar, S. and Guza, R.T. (1995). Generation and propagation of infragravity waves. *Journal of Geophysical Research,* 100, pp. 24863–24872.

Holland, K.T. and Puleo, J.A. (2001). Variable swash motions associated with foreshore profile change. *Journal of Geophysical Research,* 106 (C3), 1613-1623.

Holman, R.A. (1981). Infragravity energy in the surf zone. *Journal of Geophysical Research,* 86 (C7), pp. 6442–6450.

Hoque, M.A. and Asano, T. (2007). Numerical study on wave-induced filtration flow across the beach face and its effects on swash zone sediment transport. *Ocean Engineering*, 34 (14-15), pp. 2033–2044.

Horrillo-Caraballo, J.M. and Reeve, D.E. (2011). Application of a statistical method to investigate patterns of beach evolution in the vicinity of a seawall. *J Coast Res*, SI64: 95–99.

Horn, D.P. (2002). Beach groundwater dynamics. *Geomorphology*, 48, pp. 121–146.

Horn, D.P. (2006). Measurements and modelling of beach groundwater flow in the swash-zone: a review. *Continental Shelf Research*, 26, pp. 622–652.

Horn, D.P., Baldock, T.E., and Li, L. (2007). The Influence of Groundwater on Profile Changes of Fine and Coarse Sand Beaches. *Coastal Sediments 07*, ASCE, 506-519.

Horn, D.P. and Li, L. (2006). Measurement and modelling of gravel beach groundwater response to wave run-up: effects on beach profile changes. *Journal of Coastal Research* 22(5).

Horn, D.P. and Mason, T. (1994). Swash zone sediment transport modes. *Marine Geology*, 120 (3–4), pp. 309–325.

Hotelling. H. (1933). Relations between two sets of variates. *Biometrika*, 28, 312–377.

Hsu, T.W., Ou, S.H. and Wang, S.K. (1994). On the prediction of beach changes by a new 2-D empirical eigenfunction model. *Coast. Eng.*, 23, pp. 255–270.

Huisman, C.E., Bryan, K.R., Coco, G., Ruessink, B.G. (2011). The use of video imagery to analyse groundwater and shoreline dynamics on a dissipative beach. *Continental Shelf Research*, 31 (16), pp. 1728-1738.

Hughes, M.G. (1992). Application of a non-linear shallow water theory to swash following bore collapse on a sandy beach. *Journal of Coastal Research*, 8 (3), pp. 562–578.

Hughes, M.G. and Baldock, T.E. (2004). Eulerian flow velocities in the swash zone: field data and model predictions. *Journal of Geophysical Research*, 109, C08009.

Hughes, M.G., Masselink, G. and Brander, R.W. (1997). Flow velocity and sediment transport in the swash zone of a steep beach. *Marine Geology*, 138, pp. 91–103.

Husain, M.L., Yaakob, R. and Saad, S. (1995). Beach erosion variability during a Northeast Monsoon: The Kuala Setiu coastline, Terengganu, Malaysia. *Pertanika J. Sci. & Technol*., 3(2), pp. 337-348.

Hyndman, D. and Hyndman, D. (2006). Waves, Beaches and Coastal Erosion: *Rivers of Sand*., Brooks Cole Publishing Company, 32 pp.

Jamal, M. H. (2011). Modelling Coarse-Grained Beach Profile Evolution. PhD thesis, University of Plymouth, UK, pp. 221.

Jamal, M.H., Simmonds, D.J. and Magar, V. (2014). Modelling gravel beach dynamics with XBeach. *Coast. Eng.,* 89, 20–29.

Jackson, N.L., Masselink, G. and Nordstrom, K.F. (2004). The role of bore collapse and local shear stresses on the spatial distribution of sediment load in the up-rush of an intermediate-state beach. *Marine Geology,* 203, pp. 109–118.

Jackson, N.L. and Nordstrom, K.L. (1997). Effects of time-dependent moisture content of surface sediments on aeolian transport rates across a beach, Wildwood, New Jersey, U.S.A. *Earth Surface Processes and Landforms,* 22: 611–621.

Jago, C.F. and Hardisty, J. (1984). Sedimentology and morphodynamics of a macrotidal beach, Pendine Sands, SW Wales. B. Greenwood and R.A. Davis Jr. (Editors), Hydrodynamics and Sedimentation in Wave-Dominated Coastal Environments. *Marine Geology,* 60, 1233154.

Jensen, A., Pedersen, G.K. and Wood, D.J. (2003). An experimental study of wave run-up at a steep beach. *Journal of Fluid Mechanics,* 486, pp. 161–188.

Joevivek, V., Chandrasekar, N., S. Saravanan, S., Anandakumar, H., Thanushkodi, K., Suguna, N. and Jaya, J. (2018). Spatial and temporal analysis of beach and wave dynamics. *Front. Earth Sci.,* 12(2), pp. 349–360.

Karambas, T.V. (2003). Modelling of infiltration-exfiltration effects of cross-shore sediment transport in the swash zone. *Coastal Engineering Journal (JSCE)*, 45 (1), pp. 63-82.

Karunarathna, H., Chadwick, A.J. and Lawrence, J. (2005). Numerical experiments of swash oscillations on steep and gentle beaches. *Coastal Engineering,* 52 (6), pp. 497-511.

Karunarathna, H., Horrillo-Caraballo, J.M., Ranasinghe, R.,Short, A.D. and Reeve,D.E. (2012). An analysis of the cross-shore beach morphodynamics of a sandy and a composite gravel beach. *Mar.Geol.,* 299–302, pp. 33–42.

Karunarathna, H., Ranasinghe, R. and Reeve, D.E. (2015). A Hybrid Beach morphology model applied to a high energy Sandy Beach. *Ocean Dyn*. 65, 1411–1422.

Karunarathna, H., Horrillo-Caraballo, J., Kuriyama, Y., Mase, H., Ranasinghe, R. and Reeve, D. (2016). Linkages between sediment composition, wave climate and beach profile variability at multiple timescales. *Marine Geology*, 381.

Katori, S., Tanaka, K., Kubota, S. and Takezawa, M. (2001). Field Measurements of On- Offshore Sediment Transport Rate in the Swash Zone. *Coastal Dynamics 2001*, pp. 898-907.

Kemp, P.H. (1975). Wave asymmetry in the nearshore zone and breaker area. Hails, J., Carr, A. (Eds.), *Nearshore Sediment Dynamics and Sedimentation*, Wiley-Interscience, London, pp. 47–67.

Kim, J.H., Lee, J., Cheong, T.J., Kim, R.H, Koh, D.C., Ryu, J.S. and Chang, H.W. (2005). Use of time series analysis for identification of tidal effect on groundwater in the coastal area of Kimje, Korea. *Journal of Hydrology*, 300 (1-4), pp. 188-198.

Kirk, R.M. (1971). Instruments for investigating shore and nearshore processes. N. Z. *J. Mar. Freshwater Res*., 5: pp. 358-375.

Kobayashi, N. (1999). Numerical modeling of wave run-up on coastal structures and Beaches. *Marine Technology Society Journa,l* 33 (3), pp. 33–37.

Kroon, A., Larson, M., Moller, I., Yokoki, H., Rozynski, G., Cox, J. and Larroude, P. (2008). Statistical analysis of coastal morphological datasets over seasonal to decadal timescales. *Coast. Eng.*, 55, pp. 581–600.

Kulkarni, C.D., Levoy, F., Monfort, O. and Miles, J. (2004). Morphological variations of a mixed sediment beachface (Teignmouth, UK). *Continental Shelf Research*, 24 (11), pp. 1203–1218

Lanyon, J.A., Eliot, I.G. and Clarke, D.J. (1982). Observations of shelf waves and bay sieches from tidal and beach groundwater records. *Marine Geology*, 49, pp. 23–42.

Larson, M., Capobianco, M. and Hanson, H. (2000). Relationship between beach profiles and waves at Duck, North Carolina, determined by Canonical Correlation Analysis. *Marine Geology*, 163, pp. 275–288.

Larson, M., Capobianco, M., Jensen, H., Rozynski, G., Southgate, H.N., Stive, M., Wijnberg, K.M. and Hulscher, S. (2003). Analysis and modelling of field data on coastal morphological evolution over yearly and decadal time scales, part 1: background and linear techniques. *J. Coast. Res.*, 19 (4), 760–775.

Larson, M. and Kraus, N.C. (1994). Temporal and spatial scales of beach profile change, Duck, North Carolina. *Marine Geology,* 117, 7pp. 5–94.

Larson, M. and Sunamura, T. (1993). Laboratory experiment on flow characteristics at a beach step. *J. Sedimentary Petrology,* 63 (3), pp. 495–500.

Lee, G.H., Nicholls, R.J., and Birkemeier, W.A. (1998). Storm driven variability of the beach-nearshore profile at Duck, North Carolina, USA,1981–1991. *Mar. Geol.,* 148, pp. 163–177.

Lee, K.H., Mizutani, N., Hur, D.S. and Kamiya, A. (2007). The effect of groundwater on topographic changes in a gravel beach. *Ocean Engineering,* 34 (3-4), pp. 605–615.

Lemke, L., Miller, J., Gorton, A. and Livermont, E. (2014). EOF analysis of shoreline changes following an alternative beachfill within a groin field. *Proceedings of the 34th International Conference on Coastal Engineering, ICCE 2014.* American Society of Civil Engineers (ASCE), Vol. 2014-January.

Li, L., Barry, D.A. and Pattiaratchi, C.B. (1997). Numerical modelling of tide-induced beach water table fluctuations. *Coastal Engineering,* 30 (1/2), pp. 105–123.

Li, L., Stagnitti, F., Barry, D.A. and Parlange, J.Y. (1999). Submarine groundwater discharge and associated chemical input to a coastal sea. *Water Resources Research,* 35, pp. 3253–3259.

Li, L. and Barry, D.A. (2000). Wave-induced beach groundwater flow. *Advances in Water Resources*, 23, pp. 325–337.

Li, L., Barry, D.A., Pattiaratchi, C.B. and Masselink, G. (2002). BeachWin: modelling groundwater effects on swash sediment transport and beach profile changes. *Environmental Modelling and Software,* 17, pp. 313–320.

Longo, S., Petti, M. and Losada, I.J. (2002). Turbulence in the surf and swash zones: a Review. *Coastal Engineering,* 45, pp. 129–147.

Longuet-Higgins, M.S. and Parkin, D.W. (1962). Sea waves and beach cusps. *Geographical Journal,* 128, pp. 194–201.

Makaske, B. and Augustinus, P.G.E.F. (1998). Morphologic changes of a micro-tidal, low wave energy beach face during a springneap tide cycle, Rhone-Delta, France. *Journal of Coastal Research,* 14, pp. 632–645.

Masselink, G., Evans, D., Hughes, M.G. and Russell, P., (2005). Suspended sediment transport in the swash zone of a dissipative beach. *Marine Geology,* 216, pp. 169–189.

Masselink, G. and Hegge, B. (1995). Morphodynamics of meso- and macrotidal beaches: examples from central Queensland, Australia. *Marine Geology,* 129 (1-2), pp. l-23.

Masselink, G. and Hughes, M. (1998). Field investigation of sediment transport in the swash zone. *Continental Shelf Research,* 18 (10), pp. 1179–1199.

Masselink, G. and Li, L. (2001). The role of swash infiltration in determining the beachface gradient: a numerical study. *Marine Geology,* 176 (1–4), pp. 139–156.

Masselink, G. and Pattiaratchi, C.B. (2001). Seasonal changes in beach morphology along the sheltered coastline of Perth, Western Australia. *Marine Geology*, 172, pp. 243-263.

Masselink, G. and Puleo, J.A. (2006). Swash-zone morphodynamics. *Continental Shelf Research,* 26, pp. 661–680.

Masselink, G., Russell, P., Blenkinsopp, C. and Turner, I. (2010). Swash zone sediment transport, step dynamics and morphological response on a gravel beach. *Marine Geology*.

Moreno, M., Ferrero, T.J., Granelli, V., Marin, V., Albertelli, G. and Fabiano, M. (2006). Across shore variability and trophodynamic features of meiofauna in a microtidal beach of the NW Mediterranean. *Estuar Coast Shelf Sci.,* 66: pp. 357-367.

Mustapa, M.Z., Saad, S., Hadi, M.S.A., Yunus, K. and Sapon, N. (2015). Beach-face morphodynamics of different morphological setting along Teluk Chempedak to Kuala Pahang, Malaysia. *Jurnal Teknologi (Sciences & Engineering),* 77:25, pp. 51-56.

Nelson, C.L. and Miller, R.L. (1974). The interaction of fluid and sediment on the Foreshore. *Fluid Dynamics and Sediment Transport Laboratory Technical Report No. 15*, Department of Geophysical Sciences, University of Chicago, pp. 175.

Nielsen, P., Davis, G.A., Winterbourne, J.M. and Elias, G. (1988). Wave setup and the watertable in sandy beaches. *Technical Memorandum T.M. 88/1*, New South Wales Public Works Department, Coastal Branch, pp. 132.

Nielsen, P. (1990). Tidal dynamics of the water table in beaches. *Water Resources Research,* 26, pp. 2127–2134.

Nielsen, P. (1999). Groundwater dynamics and salinity in coastal barriers. *Journal of Coastal Research,* 15 (3), pp. 732–740.

Nielsen, P. (2002). Shear stress and sediment transport calculations for swash zone Modelling. *Coastal Engineering,* 45 (1), pp. 53– 60.

Nielsen, P. and Kang, H.Y. (1995). Ground water dynamics in beaches and coastal Barriers. Dally, W.R., Zeidler, R.B. (Eds.), *Coastal Dynamics '95,* American Society of Civil Engineers, New York, pp. 521–532.

Nielsen, P. and Voisey, C.J. (1998). Watertable overheights and salinity in coastal barriers: field measurements. Report CH49/98, Department of Civil Engineering, University of Queensland, pp. 92.

Nielsen, P., Robert, S., Møller-Christiansen, B. and Oliva, P. (2001). Infiltration effects on sediment mobility under waves. *Coastal Engineering,* 42 (2), pp. 105–114.

Nordstrom, K.F. and Jackson, N.L. (1990). Migration of swash zone, step and microtopographic features during tidal cycles on an estuarine beach, Delaware Bay, New Jersey, USA. *Marine Geology*, 92, pp. 147-154.

Obhrai, C., Nielsen, P. and Vincent, C.E. (2002). Influence of infiltration on suspended sediment under waves. *Coastal Engineering,* 45, pp. 111–123.

Osborne, P.D. and Rooker, G.A. (1999). Sand re-suspension events in a high energy infragravity swash zone. *Journal of Coastal Research*, 15(1), pp. 74-86.

Packwood, A.R. (1983). The influence of beach porosity on wave uprush and Backwash. *Coastal Engineering,* 7, pp. 29–40.

Pedrozo-Acuña, A. (2005). Concerning swash on steep beaches. PhD thesis, University of Plymouth, U.K.

Pedrozo-Acuña, A., Simmonds, D.J., Otta, A.K. and Chadwick, A.J. (2006). On the cross-shore profile change of gravel beaches. *Coastal Engineering,* 53 (4), pp. 335–347.

Powell, K.A. (1990). Predicting Short Term Profile response for shingle beaches. Report SR 219, HR Wallingford, Oxfordshire, UK.

Pruszak, Z. (1993). The analysis of beach profile changes using Dean's method and empirical orthogonal functions. *Coastal Engineering*, 19, pp. 245-261.

Puleo, J.A., Beach, R.A., Holman, R.A. and Allen, J.S. (2000). Swash zone sediment suspension and transport and the importance of bore-generated turbulence. *Journal of Geophysical Research*, 105 (C7), pp. 17021-17044.

Quick, M.C. (1991). Onshore-offshore sediment transport on beaches', *Coastal Engineering*, 15, pp. 313–332.

Raubenheimer, B., Guza, R.T. and Elgar, S. (1999). Tidal watertable fluctuations in a sandy ocean beach. *Water Resources Research*, 35, pp. 2313–2320.

Reeve, D.E., Li, B. and Thurston, N. (2001). Eigenfunction analysis of decadal fluctuations in sandbank morphology. *J. Coast. Res.*, 17, 371–382.

Reeve, D.E., Horrillo-Caraballo, J.M. and Magar, V. (2008). Statistical analysis and forecasts of long-term sandbank evolution at Great Yarmouth, UK. *Estuarine, Coastal and Shelf Science*, 79, 387–399.

Różyński, G. (2003). Data-driven modeling of multiple longshore bars and their interactions. *Coast. Eng.*, 48, pp. 151–170.

Schiffman, A. (1965). Energy measurements in the swash-surf zone. *Limnol. Oceanogr*, 10, pp. 255-260.

Short, A.D. (1978). Wave power and beach-stages: a global model. *Proceedings of the 21st International Conference on Coastal Engineering*, ASCE, pp. 1145–1162.

Solow, A. (1987). The application of eigenanalysis to tide-gauge records of relative sea level. *Cont. Shelf Sci.*, 7, 641–692692.

Sonu, C.J. and James, W.R. (1973). A Markov model for beach change. *J. Geophys. Res.*, 78(9), pp. 1462-1471.

Swart, D.H. (1974). A schematisation of onshore–offshore transport. *Proceedings 14th Int. Conference in Coastal Engineering*, pp. 884–900.

Thomas, T., Phillips, M.R. and Williams, A.T. (2010). Mesoscale evolution of a headland bay: Beach rotation Process. *Geomorphology*, 123, pp. 129–141.

Trim, L.K., She, K. and Pope, D.J. (2002). Tidal effects on cross-shore sediment transport on a shingle beach. *Journal of Coastal Research*, SI 36, pp. 708-715.

Turner, I.L. (1998). Monitoring groundwater dynamics in the littoral zone at seasonal, storm, tide and swash frequencies. *Coastal Engineering*, 35, 1–16.

Turner, I.L. (1995). Simulating the influence of groundwater seepage on sediment transported by the sweep of the swash zone across the intertidal profile of macrotidal beaches. *Marine Geology,* 125, pp. 153–174.

Turner, I.L., Coates, B.P. and Acworth, R.I. (1997). Tides, waves and the super-elevation of groundwater at the coast. *Journal of Coastal Research,* 13 (1), pp. 46–60.

Turner, I.L. and Leatherman, S.P. (1997). Beach dewatering as a “soft” engineering solution to coastal erosion-a history and critical review. *J. Coast. Res.,* 13, pp. 1050–1063.

Turner, I.L. and Masselink, G. (1998). Swash infiltration-exfiltration and sediment Transport. *Journal of Geophysical Research,* 103 (C13), pp. 30813–30824.

Turner, I.L. and Nielsen, P. (1997). Rapid watertable fluctuations within the beachface: implications for swash zone sediment mobility. *Coastal Engineering,* 32, pp. 45–59.

Vallejos, A., Sola, F. and Pulido-Bosch, A. (2015). Processes influencing groundwater level and the freshwater-saltwater interface in a coastal aquifer. *Water Resour Manage,* 29, pp. 679-697.

Vellinga, P. (1984). A tentative description of a universal erosion profile for sandy beaches and rock beaches. *Coastal Engineering,* 8 (Issue 2), pp. 177–188.

Watters, G.Z. and Rao, M.V.P. (1971). Hydrodynamic effects of seepage on bed Particles. *Journal of the Hydraulics Division,* ASCE 97 (HY3), pp. 421–439.

Weir, F.M., Hughes, M.G. and Baldock, T.E. (2006). Beachface and berm morphodynamics fronting a coastal lagoon. *Geomorphology,* 82, pp. 331–346.

Winant, C.D. (1979). Coastal current observations. *Reviews of Geophysics*., 17.

Winant, C.D., Inman, D.L. and Nordstrom, C.E. (1975). Description of seasonal beach changes using empirical eigenfunctions. *J. Geophys. Res*., 8(15), pp. 1979-1986.

Wijnberg, K.M. and Terwindt, J.H.J. (1995). Extracting decadal morphological behaviour from high-resolution, long-term bathymetric surveys along the Holland coast using eigenfunction analysis. *Mar. Geol.,* 126, pp. 301–330.

Wong, P.P. (1981). Beach Changes on a Monsoon Coast, Peninsular Malaysia. *Geol. Soc. Malaysia Bulletin,* 14 December 1981, pp. 59-74.

Yuan, D. and Lin, B. (2009). Modelling coastal ground- and surface-water interactions using an integrated approach. *Hydrological Processes,* 23, pp. 2804–2817.

Appendix A Elevations along the study beach profile at Desaru

Distance (x) Date	10	11	12	13	14	15	16	17	18	19	20	21	22
27/6/2013	3.435	3.409	3.382	3.356	3.329	3.303	3.276	3.25	3.155	3.059	2.964	2.793	2.651
25/1/2014	3.524	3.513	3.497	3.481	3.465	3.291	3.086	2.914	2.774	2.635	2.497	2.362	2.226
18/5/2014	3.524	3.519	3.515	3.51	3.39	3.246	3.102	2.933	2.877	2.77	2.596	2.522	2.522
25/12/2014	3.576	3.572	3.568	3.486	3.354	3.221	3.102	3.014	2.926	2.709	2.463	2.356	2.244
6/6/2015	3.554	3.535	3.501	3.467	3.353	3.186	3.019	2.852	2.686	2.53	2.47	2.427	2.384
23/1/2016	3.582	3.586	3.453	3.259	3.065	2.872	2.678	2.515	2.378	2.24	2.102	1.968	1.837
AVERAGE	3.533	3.522	3.486	3.427	3.326	3.187	3.044	2.913	2.799	2.657	2.515	2.405	2.311
STDEV	0.054	0.063	0.063	0.098	0.136	0.160	0.198	0.239	0.261	0.271	0.277	0.268	0.283

Distance (x) Date	23	24	25	26	27	28	29	30	31	32	33	34	35
27/6/2013	2.489	2.439	2.406	2.387	2.359	2.284	2.168	2.015	1.929	1.912	1.837	1.839	1.809
25/1/2014	2.091	1.958	1.852	1.747	1.641	1.536	1.433	1.34	1.247	1.153	1.06	0.967	0.875
18/5/2014	2.518	2.513	2.509	2.503	2.432	2.362	2.291	2.221	2.13	2.039	1.947	1.856	1.765
25/12/2014	2.125	2.007	1.888	1.777	1.672	1.567	1.462	1.357	1.252	1.148	1.044	0.941	0.838
6/6/2015	2.342	2.306	2.274	2.241	2.198	2.143	2.088	2.033	1.978	1.923	1.868	1.804	1.712
23/1/2016	1.706	1.575	1.447	1.321	1.196	1.071	0.948	0.863	0.778	0.693	0.608	0.523	0.438
AVERAGE	2.212	2.133	2.063	1.996	1.916	1.827	1.732	1.638	1.552	1.478	1.394	1.322	1.240
STDEV	0.305	0.354	0.404	0.455	0.489	0.514	0.530	0.530	0.537	0.554	0.562	0.582	0.593

Distance (x) **Date**	**36**	**37**	**38**	**39**	**40**	**41**	**42**	**43**	**44**	**45**	**46**	**47**	**48**
27/6/2013	1.664	1.457	1.294	1.141	1.014	0.927	0.832	0.707	0.555	0.42	0.301	0.138	-0.035
25/1/2014	0.783	0.691	0.599	0.507	0.416	0.324	0.232	0.144	0.061	-0.021	-0.104	-0.186	-0.269
18/5/2014	1.691	1.618	1.544	1.47	1.397	1.311	1.224	1.069	0.913	0.758	0.601	0.442	0.284
25/12/2014	0.734	0.631	0.536	0.453	0.371	0.288	0.205	0.147	0.103	0.058	0.014	-0.03	-0.074
6/6/2015	1.621	1.529	1.438	1.346	1.254	1.163	1.071	0.933	0.785	0.636	0.488	0.346	0.219
23/1/2016	0.362	0.294	0.226	0.157	0.089	0.021	-0.047	-0.113	-0.151	-0.189	-0.226	-0.264	-0.302
AVERAGE	1.143	1.037	0.940	0.846	0.757	0.672	0.586	0.481	0.378	0.277	0.179	0.074	-0.030
STDEV	0.584	0.564	0.553	0.542	0.536	0.530	0.524	0.486	0.433	0.383	0.335	0.285	0.242

Distance (x) **Date**	**49**	**50**	**51**	**52**	**53**	**54**	**55**	**56**	**57**	**58**	**59**	**60**	**61**
27/6/2013	-0.163	-0.224	-0.297	-0.32	-0.347	-0.374	-0.402	-0.429	-0.462	-0.499	-0.536	-0.573	-0.599
25/1/2014	-0.347	-0.379	-0.411	-0.442	-0.474	-0.506	-0.537	-0.565	-0.591	-0.617	-0.643	-0.668	-0.692
18/5/2014	0.126	-0.028	-0.181	-0.324	-0.39	-0.453	-0.459	-0.465	-0.494	-0.524	-0.553	-0.582	-0.61
25/12/2014	-0.118	-0.162	-0.206	-0.25	-0.294	-0.333	-0.368	-0.403	-0.438	-0.473	-0.507	-0.541	-0.575
6/6/2015	0.092	-0.035	-0.162	-0.289	-0.416	-0.543	-0.67	-0.723	-0.726	-0.728	-0.731	-0.734	-0.737
23/1/2016	-0.34	-0.364	-0.378	-0.392	-0.406	-0.422	-0.439	-0.456	-0.472	-0.489	-0.519	-0.55	-0.58
AVERAGE	-0.125	-0.199	-0.273	-0.336	-0.388	-0.439	-0.479	-0.507	-0.531	-0.555	-0.582	-0.608	-0.632
STDEV	0.204	0.153	0.106	0.070	0.062	0.079	0.110	0.119	0.109	0.099	0.088	0.076	0.067

Distance (x) **Date**	**62**	**63**	**64**	**65**	**66**	**67**	**68**	**69**	**70**	**71**	**72**	**73**	**74**	**75**
27/6/2013	-0.619	-0.64	-0.661	-0.682	-0.707	-0.736	-0.765	-0.794	-0.823	-0.852	-0.881	-0.91	-0.939	-0.968
25/1/2014	-0.698	-0.705	-0.711	-0.718	-0.724	-0.731	-0.737	-0.744	-0.75	-0.757	-0.763	-0.77	-0.776	-0.783
18/5/2014	-0.637	-0.663	-0.689	-0.715	-0.742	-0.767	-0.793	-0.818	-0.843	-0.874	-0.906	-0.938	-0.971	-1.003
25/12/2014	-0.609	-0.643	-0.678	-0.716	-0.754	-0.792	-0.83	-0.861	-0.892	-0.922	-0.953	-0.983	-1.014	-1.044
6/6/2015	-0.74	-0.742	-0.743	-0.744	-0.745	-0.745	-0.746	-0.746	-0.747	-0.757	-0.784	-0.811	-0.837	-0.868
23/1/2016	-0.61	-0.649	-0.69	-0.731	-0.773	-0.794	-0.815	-0.835	-0.856	-0.878	-0.901	-0.925	-0.948	-0.972
AVERAGE	-0.652	-0.674	-0.695	-0.718	-0.741	-0.761	-0.781	-0.800	-0.819	-0.840	-0.865	-0.890	-0.914	-0.940
STDEV	0.054	0.041	0.029	0.021	0.023	0.028	0.038	0.048	0.059	0.068	0.075	0.082	0.089	0.096

* All distance values in unit meter and were referred to the baseline point at well BH2 (x = 0 m)

Appendix B Spatial empirical orthogonal function along the study beach profile at Desaru

Distance (x) Eigenfunction	10	11	12	13	14	15	16	17	18	19	20	21	22
SEOF1	-0.25988	-0.25895	-0.25647	-0.25247	-0.24520	-0.23683	-0.22860	-0.21985	-0.21152	-0.20113	-0.19075	-0.18262	-0.17588
SEOF2	-0.17896	-0.18127	-0.16599	-0.13622	-0.11970	-0.10907	-0.09951	-0.09485	-0.08389	-0.06707	-0.04709	-0.03162	-0.00752
SEOF3	-0.24889	-0.25989	-0.22353	-0.16616	-0.07385	0.03203	0.13812	0.20783	0.22031	0.24010	0.24261	0.20437	0.16486
SEOF4	-0.06980	-0.05867	-0.06659	-0.11564	-0.14371	-0.12212	-0.09752	-0.00066	0.11304	0.15108	0.06979	-0.00999	-0.04388
SEOF5	0.05435	0.03278	-0.06989	-0.14012	-0.09831	-0.05773	-0.02994	0.03096	-0.06964	-0.01231	0.19235	0.12116	0.00754
Mean Function	3.50908	3.49661	3.46311	3.40900	3.31095	3.19780	3.08671	2.96865	2.85610	2.71582	2.57571	2.46587	2.37483

Distance (x) Eigenfunction	23	24	25	26	27	28	29	30	31	32	33	34	35
SEOF1	-0.1688	-0.1632	-0.1580	-0.1533	-0.1475	-0.1409	-0.1338	-0.1267	-0.1201	-0.1145	-0.1080	-0.1025	-0.0962
SEOF2	0.0157	0.0451	0.0752	0.1041	0.1248	0.1420	0.1566	0.1641	0.1732	0.1857	0.1952	0.2081	0.2172
SEOF3	0.1208	0.1052	0.0941	0.0919	0.0976	0.0946	0.0810	0.0453	0.0299	0.0334	0.0206	0.0309	0.0403
SEOF4	-0.1005	-0.0667	-0.0257	0.0195	0.0475	0.0449	0.0056	-0.0563	-0.0670	-0.0193	-0.0197	0.0545	0.1270
SEOF5	-0.1157	-0.1253	-0.1156	-0.0988	-0.0339	-0.0236	-0.0519	-0.0981	-0.0567	0.0514	0.1040	0.2254	0.2993
Mean Function	2.2787	2.2038	2.1339	2.0697	1.9912	1.9026	1.8071	1.7102	1.6215	1.5455	1.4585	1.3842	1.2993

Distance (x) Eigenfunction	**36**	**37**	**38**	**39**	**40**	**41**	**42**	**43**	**44**	**45**	**46**	**47**	**48**
SEOF1	-0.0887	-0.0805	-0.0730	-0.0657	-0.0589	-0.0524	-0.0459	-0.0380	-0.0300	-0.0227	-0.0156	-0.0080	-0.0005
SEOF2	0.2207	0.2197	0.2204	0.2207	0.2220	0.2242	0.2253	0.2114	0.1903	0.1680	0.1461	0.1223	0.0990
SEOF3	0.0140	-0.0310	-0.0644	-0.0943	-0.1157	-0.1249	-0.1321	-0.1207	-0.1232	-0.1061	-0.0837	-0.0742	-0.0705
SEOF4	0.1066	0.0358	0.0043	-0.0147	-0.0148	0.0137	0.0281	0.0322	0.0343	0.0206	0.0169	-0.0307	-0.1029
SEOF5	0.2486	0.1384	0.0668	-0.0059	-0.0553	-0.0508	-0.0556	-0.0684	-0.1090	-0.1413	-0.1563	-0.2095	-0.2656
Mean Function	1.1980	1.0870	0.9852	0.8870	0.7948	0.7074	0.6197	0.5129	0.4052	0.3063	0.2109	0.1081	0.0068

Distance (x) Eigenfunction	**49**	**50**	**51**	**52**	**53**	**54**	**55**	**56**	**57**	**58**	**59**	**60**	**61**
SEOF1	0.0062	0.0118	0.0175	0.0224	0.0263	0.0301	0.0331	0.0351	0.0369	0.0388	0.0407	0.0427	0.0445
SEOF2	0.0772	0.0573	0.0356	0.0175	0.0069	-0.0036	-0.0087	-0.0081	-0.0063	-0.0046	-0.0011	0.0025	0.0066
SEOF3	-0.0480	-0.0124	0.0162	0.0574	0.0869	0.1169	0.1397	0.1422	0.1319	0.1207	0.1133	0.1066	0.1024
SEOF4	-0.1504	-0.1361	-0.1286	-0.0759	0.0010	0.0793	0.1771	0.2082	0.1813	0.1494	0.1170	0.0836	0.0601
SEOF5	-0.2809	-0.2273	-0.1812	-0.0964	-0.0939	-0.0997	-0.1686	-0.1942	-0.1732	-0.1550	-0.1457	-0.1371	-0.1181
Mean Function	-0.0838	-0.1596	-0.2362	-0.3018	-0.3545	-0.4059	-0.4467	-0.4744	-0.4985	-0.5234	-0.5501	-0.5768	-0.6011

Distance (x) Eigenfunction	62	63	64	65	66	67	68	69	70	71	72	73	74	75
SEOF1	0.0462	0.0480	0.0497	0.0514	0.0532	0.0547	0.0563	0.0577	0.0592	0.0609	0.0629	0.0648	0.0667	0.0687
SEOF2	0.0111	0.0170	0.0229	0.0286	0.0341	0.0369	0.0394	0.0415	0.0435	0.0445	0.0441	0.0439	0.0435	0.0429
SEOF3	0.0998	0.0992	0.1020	0.1077	0.1128	0.1097	0.1070	0.1034	0.1004	0.1006	0.1063	0.1124	0.1180	0.1251
SEOF4	0.0421	0.0205	-0.0088	-0.0452	-0.0857	-0.1250	-0.1637	-0.2003	-0.2362	-0.2650	-0.2800	-0.2949	-0.3112	-0.3224
SEOF5	-0.0944	-0.0766	-0.0601	-0.0426	-0.0286	-0.0092	0.0107	0.0250	0.0383	0.0515	0.0561	0.0594	0.0656	0.0666
Mean Function	-0.6242	-0.6484	-0.6716	-0.6942	-0.7178	-0.7388	-0.7600	-0.7797	-0.7998	-0.8226	-0.8487	-0.8747	-0.9008	-0.9276

* All distance values in unit meter and were referred to the baseline point at well BH2 (x = 0 m)

Appendix C Temporal empirical orthogonal function along the study beach profile at Desaru

Distance (x) / Date	10	11	12	13	14	15	16	17	18	19	20	21	22
27/6/2013	-14.6189	1.120187	0.613739	0.328196	0.299982	-0.02146	-5.37E-14	-6.12E-14	1.98E-14	-2.19E-15	1.63E-14	1.98E-14	4.73E-15
25/1/2014	-13.3681	-1.26514	0.949715	-0.33325	-0.06519	0.075356	5.62E-14	4.55E-14	-1.05E-15	-3.30E-15	1.23E-14	-1.84E-14	1.27E-14
18/5/2014	-14.7212	2.095308	-0.29145	0.128465	-0.31259	0.132439	1.85E-13	2.85E-13	-1.19E-14	3.13E-14	-1.93E-14	-4.68E-14	-3.73E-15
25/12/2014	-12.8106	-1.68262	-0.04023	0.136212	-0.24167	-0.20705	-1.25E-13	-6.09E-14	-4.59E-14	-2.72E-14	1.98E-14	9.02E-14	-2.07E-14
6/6/2015	-14.1424	1.641805	-0.63282	-0.34953	0.174098	-0.09356	-1.39E-13	-2.87E-13	9.92E-15	-3.75E-14	5.26E-15	2.89E-14	-2.11E-15
23/1/2016	-10.9865	-2.91019	-0.72022	0.087751	0.156694	0.121263	9.63E-14	6.82E-14	2.26E-14	2.56E-14	-2.29E-14	-5.11E-14	6.31E-15

Distance (x) / Date	23	24	25	26	27	28	29	30	31	32	33	34	35
27/6/2013	2.57E-15	1.94E-14	-6.31E-15	4.98E-15	2.03E-14	-1.08E-14	2.54E-14	1.16E-14	-2.32E-14	-3.55E-14	1.11E-15	-1.05E-15	-4.98E-15
25/1/2014	7.86E-15	-1.38E-14	4.08E-15	-2.48E-15	-5.91E-15	2.69E-15	-1.06E-14	-7.44E-15	2.21E-14	6.08E-15	-7.56E-16	1.12E-15	1.78E-15
18/5/2014	4.64E-15	1.26E-14	-4.18E-15	-3.33E-14	7.69E-15	1.65E-14	-1.72E-15	-1.22E-15	9.71E-15	2.52E-14	4.02E-15	6.16E-15	-3.28E-15
25/12/2014	-3.42E-14	-3.71E-16	3.68E-14	1.31E-14	-8.99E-15	1.08E-14	-1.09E-14	-1.16E-14	-9.62E-15	-1.39E-15	-2.16E-15	-1.20E-14	1.30E-14
6/6/2015	-2.09E-14	-6.49E-15	-1.01E-14	2.70E-14	-2.53E-14	-8.24E-15	-1.32E-14	-7.49E-16	9.08E-15	-8.35E-15	-5.33E-15	-1.83E-15	5.43E-15
23/1/2016	6.19E-15	1.38E-14	-2.14E-14	-1.47E-14	6.38E-15	-2.14E-15	1.23E-14	8.72E-15	-1.40E-14	-1.19E-15	2.55E-15	9.88E-15	-6.59E-15

Distance (x) / Date	36	37	38	39	40	41	42	43	44	45	46	47	48
27/6/2013	-8.27E-15	1.51E-14	1.26E-15	-1.44E-15	3.89E-16	1.15E-14	1.46E-16	5.70E-15	1.10E-14	6.49E-16	1.40E-15	8.60E-16	-2.00E-14
25/1/2014	-2.41E-15	-8.34E-15	-4.12E-15	1.22E-15	3.48E-15	1.02E-14	2.15E-15	-4.26E-15	-8.59E-15	-3.40E-15	-2.32E-15	-1.78E-15	8.66E-15
18/5/2014	-1.13E-14	-1.57E-14	-6.40E-15	-1.11E-15	4.79E-15	-4.44E-16	3.25E-15	-4.58E-15	-4.47E-15	-3.08E-15	-2.80E-15	-2.91E-15	1.68E-14
25/12/2014	2.19E-14	2.50E-15	-2.15E-16	-6.08E-15	-6.77E-15	-4.49E-14	-3.56E-15	4.48E-15	-3.44E-15	9.85E-16	3.10E-15	4.16E-15	8.72E-15
6/6/2015	1.31E-14	7.02E-15	4.25E-15	2.66E-15	-5.11E-15	-5.08E-15	-2.50E-15	7.36E-16	-1.44E-15	3.16E-15	2.21E-15	1.28E-15	2.58E-15
23/1/2016	-1.74E-14	-2.80E-15	7.56E-16	2.21E-15	3.86E-15	1.96E-14	2.13E-15	-2.05E-15	6.88E-15	9.19E-16	-1.19E-15	-3.22E-15	-2.55E-15

Distance (x) Date	49	50	51	52	53	54	55	56	57	58	59	60	61
27/6/2013	2.17E-15	-1.06E-15	-1.26E-15	1.79E-15	-7.45E-15	1.92E-15	-1.92E-15	4.75E-15	-1.89E-15	-3.00E-15	1.02E-15	-1.21E-15	6.42E-15
25/1/2014	-2.18E-16	-1.40E-15	2.07E-15	-3.24E-16	-1.28E-15	-2.57E-16	6.11E-16	-9.84E-15	1.08E-15	1.93E-15	-2.60E-15	2.69E-15	-8.68E-15
18/5/2014	-8.38E-15	-3.81E-15	2.73E-15	1.56E-15	3.05E-16	-2.18E-15	-3.36E-15	-9.71E-15	-7.77E-16	8.92E-15	-7.40E-15	3.89E-16	3.03E-15
25/12/2014	8.35E-15	-1.71E-15	-2.62E-15	1.09E-15	1.01E-14	-1.36E-15	1.17E-15	6.22E-15	-3.50E-15	-1.04E-14	1.93E-15	-1.01E-14	4.72E-16
6/6/2015	7.00E-15	5.60E-15	-1.90E-15	-1.80E-15	-4.49E-15	-5.83E-16	5.32E-15	6.74E-15	4.72E-16	-5.06E-15	6.85E-15	-3.41E-15	-2.48E-15
23/1/2016	-8.15E-15	1.49E-15	2.11E-15	-8.55E-16	-4.66E-15	1.53E-16	-1.25E-15	-2.72E-15	1.55E-15	8.41E-15	8.27E-16	4.36E-15	5.47E-15

Distance (x) Date	62	63	64	65	66	67	68	69	70	71	72	73	74
27/6/2013	4.47E-15	-4.86E-15	8.13E-15	3.12E-15	-4.58E-15	-4.62E-15	-3.89E-15	2.90E-14	-1.39E-16	-6.42E-15	2.17E-14	4.47E-15	1.35E-14
25/1/2014	-1.37E-14	6.05E-15	-7.98E-16	-1.64E-15	7.15E-15	3.14E-15	-5.70E-15	-2.80E-14	6.34E-15	-4.02E-15	-9.66E-15	1.41E-14	-4.41E-15
18/5/2014	-1.10E-14	-7.48E-15	3.76E-15	-2.87E-15	-1.19E-14	-1.64E-15	-5.66E-15	-3.24E-14	-1.56E-14	7.08E-15	-8.90E-15	-8.19E-15	-3.45E-14
25/12/2014	1.17E-14	7.70E-16	-1.05E-14	1.76E-15	1.54E-14	9.95E-15	4.04E-15	2.12E-14	4.46E-14	9.70E-15	-2.66E-14	-2.77E-14	-4.41E-14
6/6/2015	1.25E-14	9.24E-15	-6.10E-15	-2.91E-16	1.86E-14	1.01E-14	5.01E-15	1.22E-14	1.21E-14	-9.66E-15	1.63E-14	2.14E-15	4.08E-14
23/1/2016	-6.22E-15	-5.40E-15	8.65E-15	-6.94E-16	-1.38E-14	-5.56E-15	-4.09E-15	9.63E-15	-3.77E-14	-7.18E-15	2.95E-14	1.83E-15	3.38E-14

Distance (x) Date	75
27/6/2013	7.04E-14
25/1/2014	-4.28E-14
18/5/2014	-1.48E-13
25/12/2014	2.60E-14
6/6/2015	1.13E-13
23/1/2016	-5.54E-14

* All distance values in unit meter and were referred to the baseline point at well BH2 (x = 0 m)

LIST OF PUBLICATIONS

Indexed Conference Proceeding

1. Ahmad Khairi Abd Wahab, **Norasman Othman**, Mohamad Hidayat Jamal and Shairul Rohaziawati Samat (2014). Effect of Rainfall and Groundwater Level on Sandy Beach Profile. *Applied Mechanics and Materials,* Vol. 567 (2014), pp 32 – 37. **(Indexed by SCOPUS)**

2. **Othman, N.**, Ahmad Khairi, A. W. and Jamal, M. H. (2014). Effects of seasonal Variation on Sandy Beach Groundwater Table and swash Zone Sediment Transport. *Coastal Engineering Proceedings*, 1(3), pp. 1–12. **(Indexed by SCOPUS)**

Non-Indexed Conference Proceeding

1. Abd. Wahab. Ahmad Khairi, **Othman. Norasman** and Jamal. Mohamad Hidayat. (2012). The Effect of Groundwater Table on a Swash Zone Sediment Transport: A Review. 2nd International Conference on Water Resources (ICWR 2012).

2. **Norasman Othman**, Ahmad Khairi Abd Wahab, Mohamad Hidayat Jamal and Shairul Rohaziawati Samat (2015). Field Investigation of Seasonal Variations Impact on Flow Depths and Velocities in the Swash Zone. 3rd International Conference on Water Resources (ICWR 2015).