Application of Parabolic Bay Shaped Beach Model Concept to Natural Beaches in Northern Cyprus

Ramin Layeghi

Submitted to the
Institute of Graduate Studies and Research
in partial fulfillment of the requirements for the Degree of

Master of Science
in
Civil Engineering

Eastern Mediterranean University
September 2014
Gazimağusa, North Cyprus

Approval of the Institute of Graduate Studies and Research

Prof. Dr. Elvan Yılmaz
Director

I certify that this thesis satisfies the requirements as a thesis for the degree of Master of Science in Civil Engineering.

Prof. Dr. Özgür Eren
Chair, Department of Civil Engineering

We certify that we have read this thesis and that in our opinion it is fully adequate in scope and quality as a thesis for the degree of Master of Science in Civil Engineering.

Assoc. Prof. Dr. Umut Türker
Supervisor

Examining Committee

1. Assoc. Prof. Dr. Umut Türker
2. Asst. Prof. Dr. Ibrahim Bay
3. Asst. Prof. Dr. Mustafa Ergil

ABSTRACT

The inevitable necessity of shoreline protection in coastal regions have driven many researchers towards finding several various analytic approaches, concerning shoreline planform preservation. The equilibrium planform concept is being widely used and modified over more than two decades after the introduction of the Parabolic bay shaped beach model by Hsu and Evans in 1989. Cyprus Island has relatively high economical dependency on its sandy shorelines, which are mostly natural headland bays. The fact that most of the rivers located in the island are dried out, duo to careless dam construction over the years; seems to have compromised the main sediment inflow resource for the coastal regions. Hence the existing compulsion for more forecasting and planning, concerning shoreline protection is very clear.

Application of the aforementioned approach to 7 different coastal locations in the northern part of Cyprus island have been carried out, using MEPBAY and also 2 different modifications of the model had plotted alongside the main MEPBAY result to contrast the effect they have on the results. Concerning the shoreline equilibrium the remaining coastlines are more or less stable but because of the unreliable diffraction points associated with these headland bays, in some cases the coastline is not in a desirable stable situation. Accordingly various suggestions for headland extension are presented in the different regions. Also the mathematical algorithm developed in the process of the study, showed several limitations and miss-presentations concerning the available equations, which in one case led to finding a new mathematical expression for one of the constants of the parabolic equation.

Keywords: Parabolic bay shaped beach model, headland bay beaches, shoreline landform stability analysis

ÖZ

Kıyı bölgelerinde kıyı koruma çalışmalarının kaçınılmaz bir zorunluluk haline gelmiş olması ve kıyı kuşbakışı formunun korunmasına yönelik, çeşitli analitik yaklaşımların denenmesi ve uygulanması gerekmektedir. Parabol körfez şeklindeki sahil modellemeleri Hsu ve Evans tarafindan 1989 yılında gündeme getirilip çalışılmaya başlandıktan sonra sahillerdeki denge koşulunun tanımlanabilmesi için sürekli bir şekilde kullanılmaya başlanmış ve son yirmi yılda birçok araştırmacı tarafından modifiye edilmeye başlanmıştır.

Kıbrıs Adası turizme yönelik yoğun yatırmlardan ve ekonominin bu alnlarda yoğunlaşmasından dolayı özellikle kumsal içerikli sahil şeritlerine ihtiyacı olan bir ada konumundadır. Özellikle iklim değişiklikleri ve dikkatsizve inşa edilen baraj inşaatlarından dolayı bölgede bulunan birçok akarsu kurumakta ve son nokta olan deniz kenarlarına (delta) ulaşamamaktadırlar. Bu koşullar altında her yıl denize ulaşması beklenen sediment partikülleri denize ulaşamamakta ve kıyı erozyonunun kaçınılmaz olmasını sağlamaktadırlar. Yukarıda belirtilen nedenlerden dolayı Kıbrıs adasında mutlaka kıyı koruma konusunda planlama yapma ve ileriye yönelik tahminlerde bulunabilmek için bazı çalışmaların gündeme gelmesi zaruri olmuştur.

Kıbrıs adasından 7 farklı kıyı sahil şeridinde “Parabol körfez şeklindeki sahil modellemeleri” yaklaşımı MEPBAY yazılımı kullanılarak uygulanmıştır. Ayni zamanda “parabol körfez şeklindeki sahil modellerine” yapılan 2 farklı modifikasyon modeli de kullanılarak, model yaklaşımları arasındaki etkileşme ve sahil şeridinin modellemesine yaptıkları katkı incelenmiştir.

Kıyıların denge koşullarına uyumluluğu ile ilgili elde edilen sonuçlar, mevcut halleri ile birçok kıyı ortamının dengede olduğunu göstermektedir. Ancak, yaklaşan dalgaların özellikle sahil burun bölgelerindeki doğal kırınım noktalarının kesin olarak belirlenememesinden dolayı bazı sahillerin arzulanan denge durumuna ulaşmadıkları görülmektedir. Bu durumda sahillerdeki kırınım noktasının tam olarak tanımlanmasını sağlayacak ve bu noktaya göre oluşacak kıyı şekillerinin öngörülmesi için çeşitli öneriler yapılmıştır.

Ayrıca çalışma sürecinde oluşturulan matematiksel algoritma, parabolik denkleminin sabitlerinden birinin sağlıklı çalışmadığını göstermiş ve bu çalışmada yeni bir matematiksel ifade bulmak için mevcut denklem ile ilgili çeşitli sınırlamalar geliştirilerek sabit katsayılardan birisi ile ilgili yeni bir denklem üretilmiştir.

Anahtar Kelimeler: Parabol kumsal koy şekl modeli, burun koy kumsallari, kıyı çizgisi stabilize analizi

ACKNOWLEDGMENT

I would like to express my gratitude to my supervisor Assoc. Prof. Dr. Umut Türker for the useful comments, remarks and engagement through the learning process of this master thesis.

I would like to thank my loved ones especially my family, who have supported me throughout entire process, both by keeping me harmonious and helping me putting pieces together. I will be grateful forever for their love.

Last but not least, I am so grateful to my father, who his memory is the motivation behind every step I have taken in my life.

To the memory of my father

The motivation behind every step I take

To my mother for her endless love

And to my dear brother

Who stood tall behind me, throughout the toughest times

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

Chapter 1

INTRODUCTION

1.1 Introduction

Cyprus is an island in eastern Mediterranean Sea and is the third most populated and the third largest island in the Mediterranean. It is located south of Turkey, west of Syria and Lebanon, northwest of Israel, north of Egypt and east of Greece. Because of its critical and strategic location in Mediterranean Sea. Beside its political importance this island has a great touristic attraction because of its beautiful landscapes and sandy beaches. Most of these sandy beaches are being managed and protected by private tourism companies.

Maintaining these sandy beaches are critical to Cyprus`s economy which is one of the income sectors of its overall income. To study the present situation of these beaches and find any patterns governing the sediment supply status of these coastal regions there are different methods. Among these methods, the most popular one is to trace the input and output of sediment sources in quantitative manner to decide on the movement patterns of sand and gravel particles to then theoretically predict the future condition of these beaches. An alternative method is to determine the headland bay`s status by studying its shape using aerial pictures. The first option can be done by very long-term, expensive and difficult field observation to elucidate the sediment movement and beach state by contrasting the historical aerial photographs of usually two or three decades.

Second option, which is going to be used in this study, is based on parabolic bay shaped model suggested by JRC Hsu and Evans (1989) which is the mostly accepted and adopted in academic studies according to Jackson and Cooper (2010). This method have become applicable and beneficial when JR Hsu, Klein, and Benedet (2004) linked it with stability determination and the method was presented as a tool to assess stability of the headland bays. This method provides the ability to measure the full erosion or accretion potential of headland bays and it is highly recommended to be used in order to predict the land deformation outcomes, prior to any artificial disruption of the natural processes. Cyprus is an ideal location for testing the method performed by Hsu and Evans (1989) due to its strongly embayed natural beaches. Hence the method could be used to show that the sediment volume around the island is finite and if its beaches are not protected, they would be eroded.

There are several rivers in Cyprus which are dried out due to irresponsible dam constructions at their upstream tributaries. Due to the short fetch length of coasts of Northern Cyprus, the waves that are approaching to the coastal areas are not strong enough to continuously erode coastal cliffs to supply sediment source to the coastal zones. Therefore, it is merely rivers that have the ability to carry sediment particles through their watershed area and act as the main source of sand and sediment for sandy headland bays. However, due to the construction of man-made water structures on rivers and change in the rainfall pattern of the Cyprus, recently. Therefore at the coastal zone areas appears to be a lot of sandy headland bays with no stream based sediment resources to supply replacement for sediment losses. In this state if an embayment is in a dynamic equilibrium it loses its sediment inflow and would be eroded to a static state.

Considering the aforementioned concepts and methods this study will evaluate the equilibrium status of seven different beaches around the coasts of the northern part of Cyprus. Accordingly the sediment balance system of the different coastal locations will be evaluated to emphasize the importance of the coastline protection issues in present time and for the future. As a result, parabolic models will be used to suggest artificial coastal structures like jetties and breakwaters while proposing correct location and size of these structures for minimizing environmental concerns of natural habitat at coastal areas.

Finally, the overall purpose of this research is to bring to light the critical situation of the Cyprus's beaches and illustrate a starting point towards beach protection planning and maintaining these precious landmarks for future generations with the help of science.

1.2 Thesis Overview

In chapter 2 we will initially introduce the natural coastal wave processes, which form and deform shorelines and create headlands, seacliffs, sandy beaches and other coastal landforms.

Chapter 3 will narrow down the scope by introducing the headland bay beaches, their development, stability and planform, followed by the description of shoreline stability evaluation based on literature.

Chapter 4 will introduce the most recognized methods proposed for headland bay morphological assessment. The parabolic bay shaped method (JRC Hsu & Evans, 1989) will be introduced in detail alongside with its alternative proposed configurations in this chapter as well. Computer programs capable of applying this method would also be introduced and be contrasted at the end of the chapter.

Chapter 5 introduces the shorelines chosen for the application of the method and describes how the assessment is going to be undertaken.

Results and their subsequent discussions are available in Chapter 6 together with the limitations restraining the assessment and the solutions proposed for overcoming them if available.

An overall conclusion is extracted in Conclusion gathers up the results and findings of the research.

Chapter 2

NATURAL PROCESSES ASSOCIATED WITH SHORELINES

2.1 Introduction to Shorelines

Defining shoreline could be as simple as, the shoreline is the border line between land and water. This is a very general description of a very familiar natural phenomena; however this definition lacks detailed scientific explanation which has limits and since in science we need ranges and limits to be able to measure our observed data and get beneficial measurements to predict and plan, we have to have a slightly more detailed definition for shoreline (Monroe, Wicander, & Hazlett, 2006). Shoreline is the area of land which is in contact with the sea or a lake and also expand the definition by adding the range of lowest tide level and the highest level affected by the storm waves. This will give a scientifically useful landscape to be used in this study as well but since the main aim of the study is to work on and study sandy beaches, different definitions about these types of environments should be cleared and defined to avoid in misinterpretations in the following discussions.

Monroe et al. (2006) also distinguished coasts from shorelines by noting that even though they are usually interchangeable terms, coasts are more of an broad term which include shorelines and also an unspecified area seaward and landward of the shoreline. This area includes seaward areas like near shore sand bars and small islands and also landward areas like marshes and sand dunes. This definition is important in this study because in sandy bays the seaward and near shore land shapes like islands effect the waves and change the diffraction and breaking points of the waves; so we should consider the whole coast area to observe and study shoreline and its sediment equilibrium.

According to Monroe et al. (2006) most of the earth`s population are gathered around the narrow belt exactly at or close the shorelines and coastal regions. They usually have a great amount of reliance on their coasts, Shorelines and sandy beaches because of their potential in tourist attraction and beach related businesses. Since one side of these commercial lands is a water border like sea, ocean or a lake their shorelines are continuously strike by massive waves. These constant strikes make coastlines very fragile which emphasizes on the importance of protecting and maintaining them; hence coastal engineers, oceanographers, geologists and many others are trying to come up with new and more sufficient ways to plan and decide about the future of these landscapes to protect them.

In order to plan correctly for maintaining these areas one has to be familiar with various types of processes taking place in shorelines. Following is a brief introduction and basic description to some of the shoreline processes.

2.2 Tide

The tide is due to the fluctuation in the surface of the oceans because of the gravitational pull of the moon and sun. Tide happens twice every day resulting in shorelines to have two daily low tide and two high tide. Tides can be as low as 2 centimeters up to more than 15 meters (Monroe et al., 2006). The progression process of this phenomenon, when the water proceeds towards more and more area of the shoreline, is called flood tide. When flood tide stretches as far as high tide it is followed by the water level retrieving back and exposing the covered near shore land area again and it is called ebb tide process. Figure 1 is two examples of considerable tides proving that their occurrences can affect a vast area of land.

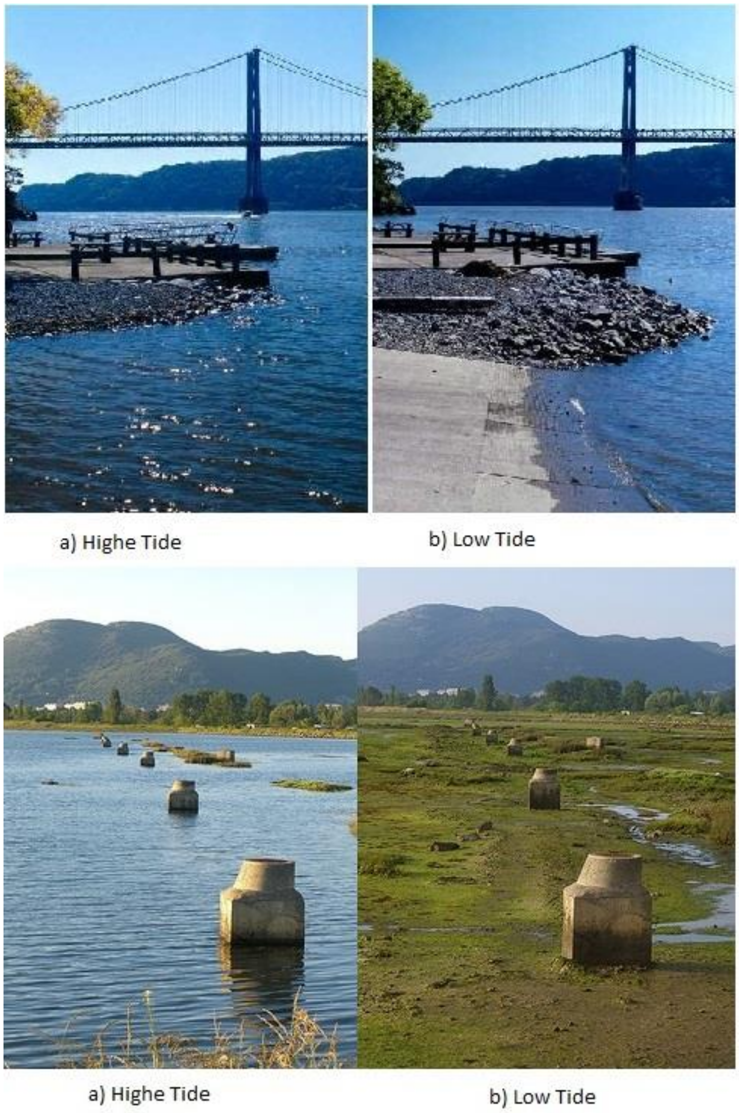

Figure 1. Examples of extreme Tides (Google Images)

2.3 Wave Generation

The main active organ of shoreline processes is wind-generated waves especially during storms. Waves are basically generated as a result of the friction between air and water surface which transfers wind`s energy to the water and creates oscillations on the surface of the water. When the waves travel from the generation area and move towards shorelines they happen to lose a little amount of energy and even though the surface oscillates and deep-water waves move in circular patterns, there is a net displacement occurring in shoreward direction. In this displacement, wind blows the water wave crest and creates the white foamy crest. Also the main water displacement is done by the crest of the waves comparing to deep water waves.

When the waves reach nearshore areas, the wave shape has to change as these deep-water swelling waves are transforming into sharp-crested plunging breakers. This happens as the depth decreases and it begins around the area which the water depth is approximately equal to half the wave length. What happens than is that wave speed increases, wave length decreases while wave height amplifies until the wave crest becomes over infused and ultimately wave crest progresses much faster than other parts of the current, and generates breakers (Figure 2).

Figure 2. Examples of wave Breakers with different wave heights (Google Images)

This is the last step of the process of transferring the kinetic wave energy which is created by wind. When these waves impact the coasts they are changing power in headland bay and sandy beach causing destruction.

2.4 Near-Shore Currents

The definition and limitations that geologist and coastal engineers proposes for nearshore area is the zone which is from the outer borders of the shoreline to the outer limit of the breaking point, which also contains several other zones such as surf zone and breaker zone (Mangor, 2004). These zonings are illustrated in **Error! Reference source not found.**.

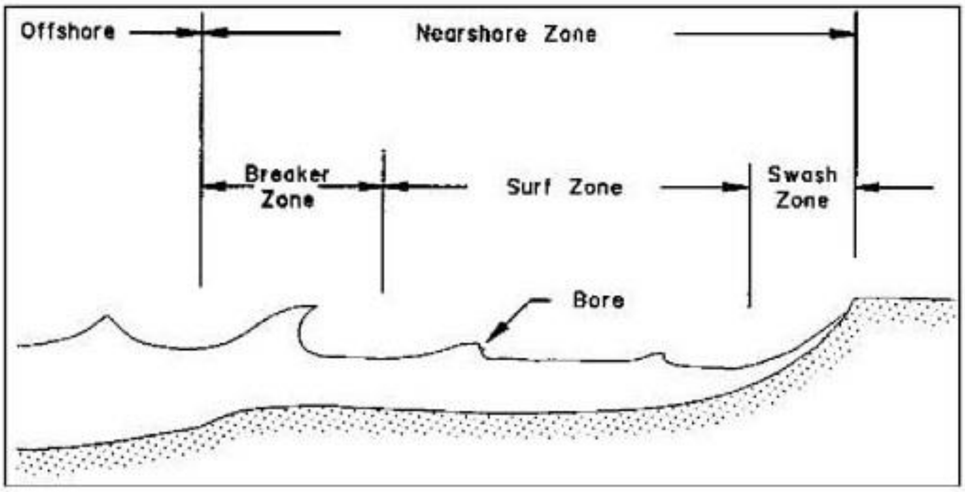

Figure 3. Nearshore wave processes terminology, (Leenknecht, 1992)

One of the most important phenomenon which happens nearshore is *wave refraction* which is the process where the wave orthogonal adjust themselves to become perpendicular to the shoreline. In other words, wave refraction is the bending that happens to the wave crest and makes it more nearly parallel to shoreline. The refracted waves approach the shore at a small angel which generates *longshore currents*. Longshore currents play a particularly important role in sediment transportation along the shore within the nearshore zone. Hence these type of currents are important in studies when their undeniable effect in beach bay shaping and shoreline erosion (Plummer, McGeary, & Carlson, 2001).

Figure 4 is a very simple illustration of the refraction process and creation of the longshore currents.

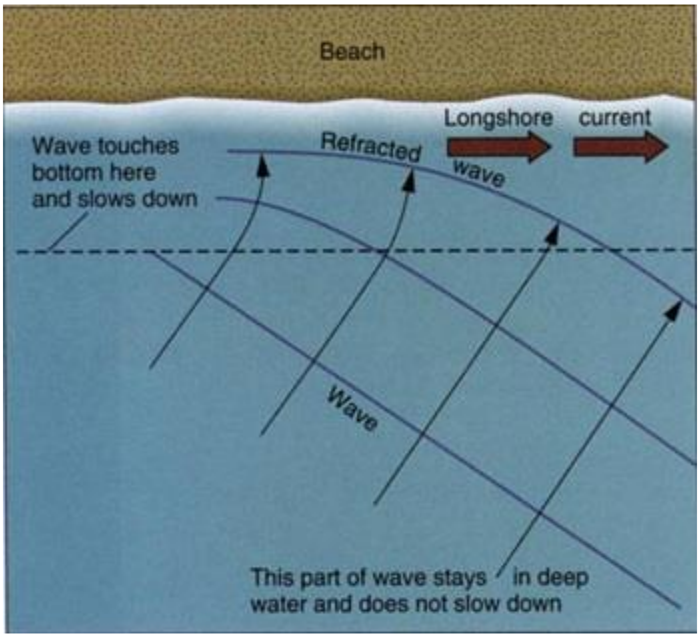

Figure 4. Wave Refraction and Longshore Currents (Plummer et al., 2001)

The direction of longshore currents as it can be seen in Figure 4 is the direction which the beach will be under the risk of erosion. Hence the sediment transport direction is also going to be in the same direction. This process will create bay shaped headlands whenever currents reach an obstacle along their way which would force stop sediment transportation. Hence sediment would accumulate in front of the obstacle and create bay shaped beaches. This obstacle could be natural like land shapes or rocks, or it can be artificial constructions like groins (Figure 5).

Finally the reverse mechanism that delivers the water mass back to the sea is called Rip currents which rush back to the sea through the breaker zone. MacMahan, Thornton, and Reniers (2006) describe rip currents as “approximately shore-normal, seaward directed jets that originate within the surf zone and broaden outside the breaking region”. These currents can erode beaches but they are not usually powerful enough to displace sediments so far that it could deform the beach shape.

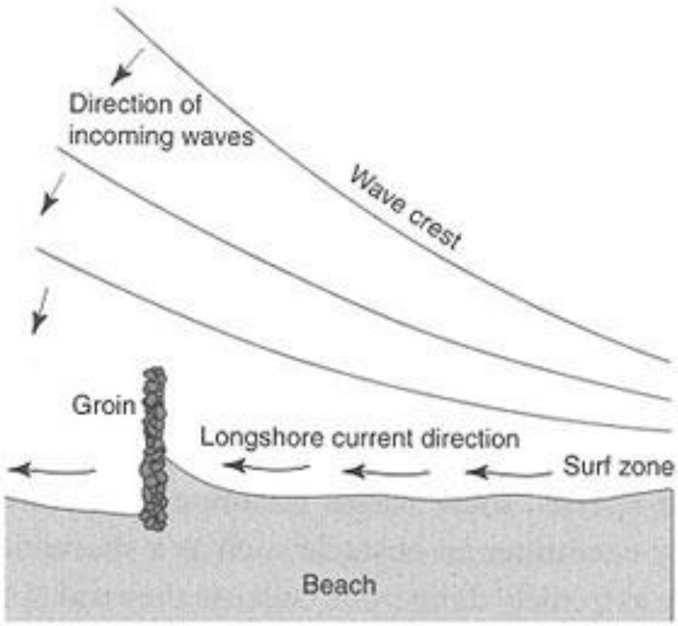

Figure 5. Sediment transportation as a result of longshore currents

Another important process which happens frequently in shorelines and is very closely related to the shoreline shaping is the effect that headland and groin type structures have on wave direction and height which is called wave diffraction. Unlike refraction, diffraction of waves involves energy transfer laterally along the crest line and creates a region downdrift of the structure or the headland called shadow region. The diffracted waves are generally approach to the shoreline with a different pattern and height (Figure 6).

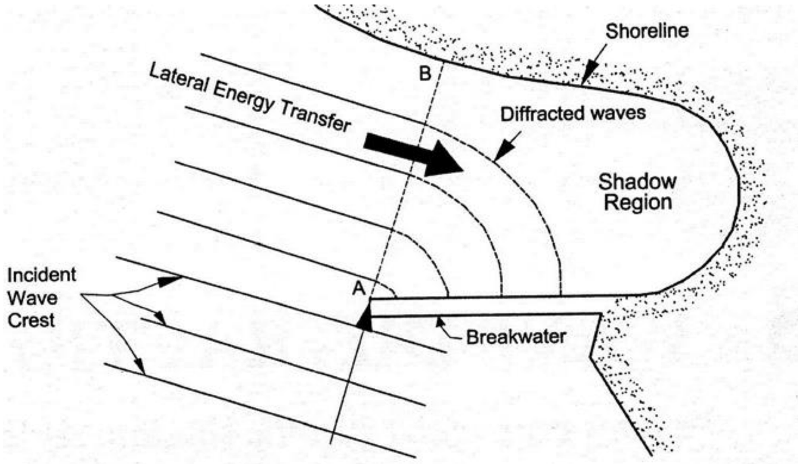

Figure 6. Schematic illustration of wave diffraction process

A simple demonstration of the wave diffraction process could be observed in illustration in Figure 6 where point A is called the diffraction point and it is the incident point where wave deformation happens. It should be noted that the breakwater in this illustration could be a headland or any type of land indentation seaward. The diffraction point is the most inner point (where the line perpendicular to the wave crest passing this point does not go through any other point on the head land, the AB line in Figure 6) of the headland sheltering the shadow region and most cases could easily be found on a clear aerial map of the shoreline (Klein, Vargas, Raabe, & Hsu, 2003).

2.5 Headlands, Beach Deposition and Beach Erosion

Wave will erode seaside lands by pounding on them with waves worn by sand and gravel, abrasion, continuously and decomposing the rocks by breaking them down chemically which is done by the dissolvent reaction of sea water. This process would leave the land in an angled or vertical shape which is called *seacliffs.* This process will slowly make the land retreat and seacliffs would eventually be eroded landward, but this would not happen uniformly because some parts are much more harder, so they would be eroded much slower; this will leave seaward parts of land where they are eroded on both sides by wave refraction (Monroe et al., 2006).

Deposition of eroded sediments from seacliffs would add to sediment budget of *Beaches*. Beaches are the most recognized coastal landforms and they are stretched from low tide to a different type of landscape, like a sea cliff or land vegetation. Beaches are one of the most famous and desirable landforms and millions of people travel from various parts of the world to coastal regions to get to these beautiful land attractions, hence their economic value to their communities is undeniably extreme. They can be discontinuous or concentrated in protected areas like embayments which are usually between to headlands seaward enough to develop a groin like shapes suitable for deposition of sediments.

As mentioned before, some of the sediment available in beaches are stemmed from waves, eroding seacliffs and shorelines and weathering, but the main resource of beach sediment is streams transporting the eroded sediment along their length and distributing them at their delta point, where they are attached to seas, and longshore currents carry the sediment along the shore and leave it where they lose the carrying energy. The longshore currents, deposit their sediment load when their flow is interrupted by an obstacle like a groin and widen the beach in its up current side, side which faces the incoming current, and erosion also washes away the other side of the groin, down current side. Hence longshore currents carrying the sediment supply from stream`s delta, leave them in various regions and create sandy beaches.

2.6 Nearshore Sediment Budget

Apart from longshore currents other coastal processes like rip currents and wind are also effective in shoreline sediment behavior analysis. Wind can blow sand from the beach to landward and create sand dunes behind backshore area. Rip currents cannot do any sediment deposition but they can affect the sand budget considering the tide range (MacMahan et al., 2006) and derive fine-grained sediment off of beach trough the breaker zone. By looking at a sandy coastal region as a closed system, which is called the *nearshore sediment budget*, the sediment budget situation can be assessed by calculating all of the inputs and outputs of this system. Figure 7 is an illustration of this sediment budget system; it shows how each input and output move inside coastline system.

If the inputs of this system exceed the outputs, accretion happens and excess sediment supply would eventually widen the beach area. On the other hand if the sediment output of the system is dominant and is more than its injected sediment supply the beach is in erosion situation and it would eventually retreat. Finally if the output and input of the sediment budget are equal as shown in Figure 7, the beach is going to be at steady state or, static equilibrium and the shoreline position will be remained, unless there is an unusual change in natural ongoing process such as storms.

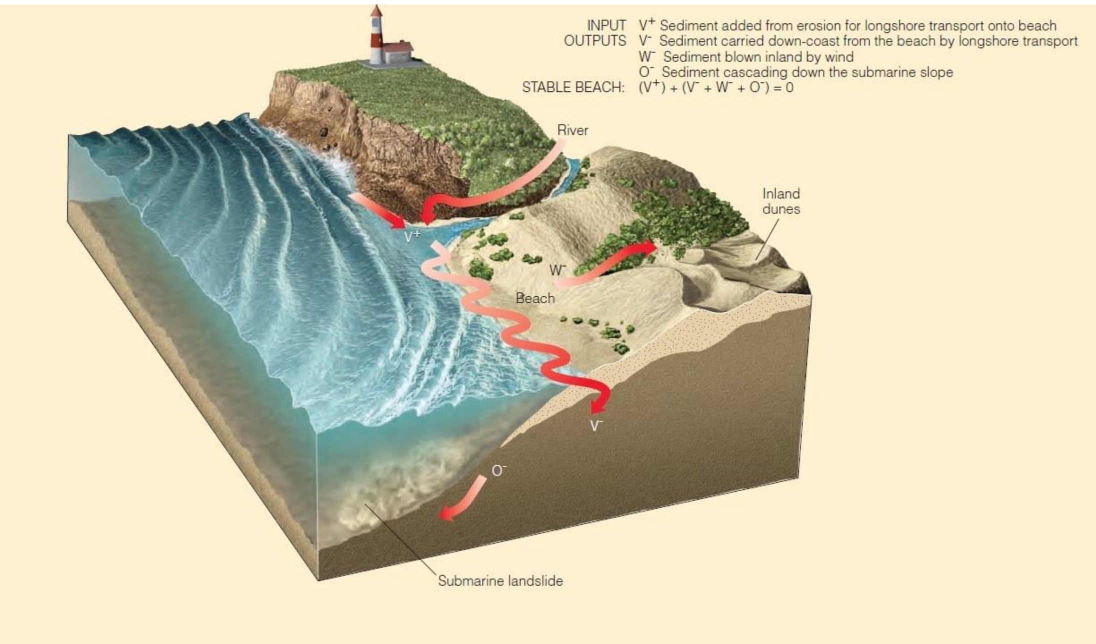

Figure 7. Nearshore sediment budget diagram (Monroe et al., 2006)

This assessment is very challenging since measuring the time dependent changes of regional sediment volumes and their inflows and outflows cannot be predicted accurately due to dynamic behavior. This study will try to approach this assessment by a visual method presented by (JRC Hsu & Evans, 1989) named parabolic bay shape method which is the latest visual assessment method for beach equilibrium.

Chapter 3

HEADLAND BAY SHAPED BEACHES

3.1 Introduction to Headland Bay Beaches

All afore mentioned nearshore processes continuously form and deform coastlines and create different shapes of shorelines like, seacliffs and sandy beaches. According to (Inman & Nordstrom, 1971); Short (1999) about 50% of the world's coastlines are dominated by headland bay beaches, which are not usually straight, some of them have very mild curved periphery while other ones have a more indented edge. Sandy beaches which are created as the result of sand accumulation because in the lee side of the headland are called *Headland Bay Beaches* (J. R.-C. Hsu, Yu, Lee, & Benedet, 2010). Headland bay beaches vary in length from few meters to several kilometers, they also vary in curvature and indentation shape, but there is a pattern in these physiographical landscapes. This pattern is observable in their general plan; the asymmetric curved part which starts from the side of the headland and then a transition begins from the curve to a relatively straight line at the other end (J. R.-C. Hsu et al., 2010).

Generally a headland can be a both natural and man-made. Rocky projection of the land, cape promontory or an off-shore island are examples of natural headlands and any type of harbor breakwater, compound (L-or T-or Y-shaped, fish-tailed, ship anchor .etc) or curved groin and any detached breakwaters are examples of man-made headlands (Hanson & Kraus, 2001). Benedet, Klein, and Hsu (2004) have divided headland bay beaches into five different types considering the embayment`s geographical properties as follows:

1. Embayment with a single curvature downdrift of a headland which either contains a stream emerging into the sea within it or not.
2. Embayment with a single curvature in the shelter of a harbor breakwater.
3. Salient or tombolo which are developed due to the existence of an offshore island or as a result of detached breakwater construction.
4. Double-curved beaches sheltered among continuous headlands.
5. Bays near irregular updrift land or within inner man made structures which have multiple wave diffraction points.

Like other scientific processes, finding a mathematical model to fit the headland bays' asymmetric curvature was and is very essential to do further assessments on other properties of these geographical units.Halligan (1906) initially noticed the pattern existing in headland bays by studying the consistency in their geometry at Australian coasts. The first approach, as it is in many scientific observations, was to categorize the natural landform considering their geometric shape and periphery.

Halligan (1906), originally called them zeta bay, some of the other names and categories that have been assigned to these types of beaches are the half heart bays which was categorized nearly 50 years after Halligan`s study by Silvester (1960); spiral shape beaches studied by Krumbein (1947) and later on by LeBlond (1972); also Rea and Komar (1975) mentioned the hooked beaches in 1975 and Silvester, Tsuchiya, and Shibano (1980) described pocket beaches along side with zeta beaches with a general description of headland controlling. Headland bay beach term presented by Yasso (1965) and later on Leblond (1979) worked on headland bays with logarithmic spiral method approach and Wong (1981) also studied breakwaters in headland bays.

3.2 Stability of Headland Bay Beaches

Initially all of these scientists were concerned about the coastal landforms and shoreline indentations in relation with the properties of the most effective incoming waves. For example (Halligan, 1906) notified this consistency in shoreline patterns by observing the coastlines Fraser island to Sydney in 1906 and studied the almost uninterrupted asymmetrically curved beaches. All of these beaches were like pieces of chain connecting each and every headland to the next one. In 1938 (Lewis, 1938) claimed that there is a tendency for sandy beaches to form crosswise to the loom direction of the most effective wave which is mostly constructive in shoreline forming processes.

Even though scientists like Carter (1988); J. L. Davies and Clayton (1980); Davis Jr (1985); Yasso (1965); and Zenkovich and Zenkovich (1967) were gathering a great amount of knowledge of wave kinematics and dynamic processes in coastlines, they have not appreciated the macroscopic view of the coast as imposed by nature. Recognizing shoreline shapes as a stability feature of the landform was originally done by Jennings (1955). The problem with it was that Jennings (1955) did not consider anything caused by waves and this was because of the lack of knowledge about them then (J. R. Hsu & Silvester, 1996). Three years later J. Davies (1958) presented the relation between persistent wave`s refraction and shoreline orientation but he missed the wave diffraction effects.

On the other hand coastal engineers were looking for a way to evaluate the stability of the shoreline. The concept of a stable curve for bay shaped beaches stabilization was backed up by Silvester (1960) and this led to plentiful amount of research undertakings to reveal the stability principles of shorelines in relation with its curvature properties. According to J. R. Hsu and Silvester (1996) in geomorphological terms sandy shorelines can be in one the following states.

i. *Static equilibrium:* where littoral drift is very small that could be negligible and the shoreline is not going to be eroded. At this situation there is no demand for external sediment resource to maintain the sediment budget of the beach.

ii. *Dynamic equilibrium:* when drift is supplying the coastline with sediment, hence while the shoreline is being fed by this supply it can maintain its periphery and indentation. If the sediment supply decreases the shoreline will retreat until it reaches the static equilibrium.

This concept can be further explained by assuming the beach static equilibrium as the state and shape that the shoreline does not tend to change its form in it, just like a spring when there is no force applied to it. The sediment supply can be assumed as the force applied to the spring in this analogy, where just like pulling or pushing forces deform the spring and the spring is struggling to get back to its static position; shorelines in dynamic equilibrium will reshape instantly as the incoming sediment supply diminishes. Hence the shoreline can remain its curvature for decades if the sediment supply is not interrupted, but as soon as the supply stops entering its system it would be drawn back to a maximum level which is its static equilibrium.

Interruption and interception of sediment flow is what we usually do as humans in our coastal constructions. If on a straight sandy coast a structure is grown out to the sea, instantly the littoral drift would be intercepted and as a result the downdrift of the structure will become more and more concave until either it reaches the static equilibrium or sediment accumulation bypasses the groin and restores the dynamic material flow (J. R. Hsu & Silvester, 1996). This phenomenon is called *natural reshaping state* or *unstable state* which is the state that the shorelines enter when the sediment supply conditions have been changed due to coastal constructions or extension of the existing ones. This process is also called "*groyne effect*" because of the erosion that it causes to the beach at the downdrift (J. R.-C. Hsu et al., 2010).

Afore mentioned argument can be summed up with several key points about sediment budget equilibrium: stable shorelines are either in static equilibrium state or dynamic equilibrium state considering their lateral sediment drift situation. Beaches in dynamic state would become unstable if their sediment supply is being intercepted by any natural or artificial (which is mostly the case) modification to the coastline lateral drift. The unstable state or natural reshaping state would continue until the shoreline system finds stability either in dynamic or static state.

3.3 Evaluating Beach Stability

Sediment movement within embayment system depends on so many things, not only the wave properties like its direction, height and etc. but it is also related to spatial and temporal issues. This makes recognizing the beach equilibrium state convoluted and that is why even today the only way to find the static equilibrium could be conducted by JRC Hsu and Evans (1989)`s parabolic bay shape method. This method is the most applicable and widely accepted way to assess static state shoreline periphery. It uses only the wave direction to predict the static equilibrium plan form of the shoreline. This plan then can be compared with the existing shoreline to estimate the erosion limitations of the shorelines.

Initial laboratory experiments were carried out by Silvester (1960) within the facilities of the University of Western Australia as well as 1960`s experiments of Vichetpan (1969) and later on by Ho (1971) at AIT (Asian Institute of Technology). Nearly twenty five years later, Khoa (1995) used the same facilities in AIT to experiment bay beach formation under small slanted wave conditions. These experiments were all done by applying monochromatic waves with leaning approach direction towards an obstacle working as a headland and sometimes they can get as long as 50 hours long experiments. These experiments not only helped scientists to understand the process of static headland bay beach shaping and its development, they have also developed the required knowledge foundation for them to understand the wave crest spatial distribution within headland bay beach embayment, which Silvester and Ho (1972) and Silvester (1974) conducted very influential studies about the matter.

Same as always science usually has to progress and become more numerical and subsequently more applicable, the concept had to become numerical and formulated to become beneficial for design purposes and also to become an empirical method to help the coastal engineers to predict headland bays behavior. For examplePrice, Tomlinson, and Willis (1972); Rea and Komar (1975); Yamashita and Tsuchiya (1992) attempted to produce a numerical simulation of the development of a crenulated bay shaped beach from a completely straight shoreline. Due to the excess amount of different dents concomitant with headland bay beaches scientist, especially geologists, geographers and coastal engineers among them, have tried to generate an empirical model to fit sections of them or ideally fit their whole periphery.

Between these models, the most recognized ones are three models which are: logarithmic spiral model by Krumbein (1947); and Yasso (1965), hyperbolic tangent model by Moreno and Kraus (1999) and finally the parabolic model by JRC Hsu and Evans (1989). These three models are going to be explained and compared in the following section.

Chapter 4

HEADLAND BAY MORPHOLOGY IN COASTAL ENGINEERING

4.1 Introduction

The three shape models (logarithmic spiral, hyperbolic tangent and parabolic models) are different in several aspects like coordination systems and their orientation and origins, mathematical expressions and also their governing factors. This chapter will be a review of the three main headland bay expressions that are developed to assess the headland bay beaches, a comparison between their application method and their strength and weaknesses.

4.2 Logarithmic Spiral Model

Human beings have gained control of their life on this planet tens of thousands years ago; by finding natural patterns and planning ahead to avoid disasters. Science is the best tool while evaluating assumptions about these patterns, to get as accurate as possible, in order to achieve accurate predictions. Related to headlands and shoreline indentations also geographers, geologists and coastal engineers were always curious to find the pattern lied behind shoreline curvature.

(Krumbein, 1947) was one of the first people who actually found a pattern and proposed the logarithmic spiral model by assessing 1940`s images of the half moon bay which is located in California, United States. (Krumbein, 1947) fitted this bay with following equation:

$$R_2 = R_1 \exp(\theta\ cot\alpha) \tag{1}$$

Equation 1 is the relation between R_1 and R_2. R_1 and R_2 are two different radii from the center of the logarithmic spiral expression and are apart from each other with an angle θ, as illustrated in Figure 8. The logarithmic spiral drawn in Figure 8 as spiral angle of 1. This equation originated from the main general logarithmic spiral, *equiangular spiral* or *growth spiral* equation (Equation 2) which can also be illustrated as Equation 3 (Hemenway, 2005). In these equations b is the spiral angle of the logarithmic expression and (r/a) ratio has exponential relation with changes of the (θ) angle.

$$r = ae^{b\theta} \tag{2}$$

$$\theta = \frac{1}{b}\ln(r/a) \tag{3}$$

Spiral angle (α) in Equation 2 is the angle which each radii crosses spiral`s periphery and it is constant throughout the length of the spiral. This method was merely a fitting attempt, without any feedback about the stability of the shoreline, also it did not have any consideration concerning the wave direction or wave diffraction point and finally the most arguable weakness was the unspecified position of the center of the spiral. About 18 years later (Yasso, 1965) inspected four different bays in east and west side of United States by applying the logarithmic spiral model where he failed to relate the center of the spiral to the wave diffraction point and had offset up to 2000 meters in some cases.

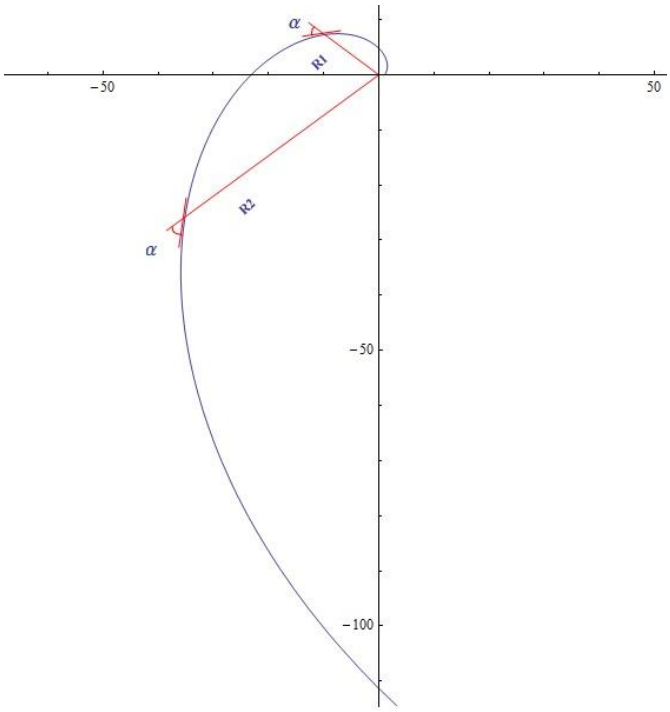

Figure 8. Logarithmic Spiral polar expression with spiral angle of 1

This is not the only attempt in science where scientists tried to find logarithmic spirals in nature. For example Livio (2008) gathered and evaluated many of the claims about the *Golden Ratio* and demonstrated that it requires relatively great amount of assessment for a natural phenomenon, which has a spiral shape to it, to be considered as a golden spiral (which is the spiral expression of the Fibonacci number series) Figure 9. Interestingly enough this study was initiated at the beginning to look for any correlation between Krumbein (1947)`s logarithmic spiral model and the golden spiral of Fibonacci. A brief assessment of this curiosity would be in upcoming sections of this chapter.

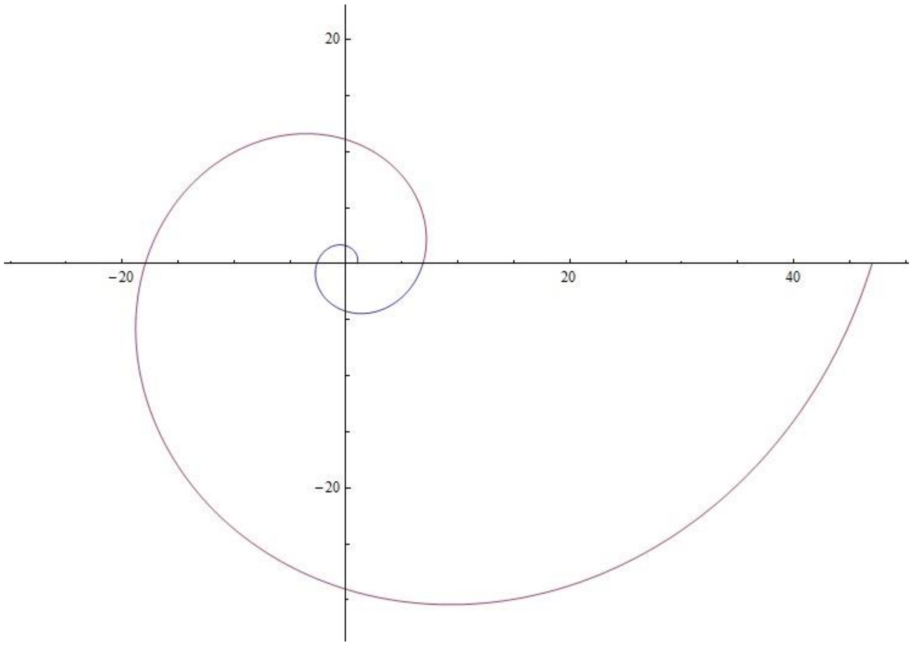

Figure 9. Mathematical Polar Expression of Fibonacci Series (Golden Spiral)

Nevertheless the model was widely accepted among scientist for decades and several scientist tried to modify it in order to make it more applicable and beneficial in coastal engineering. For example (Silvester, 1970) demonstrated that the ratio of the radius ratio, R_2/R_1, and spiral angle , (α) would change as the beach becomes more eroded and changes its orientation from being straight to an indented landform which was later on called bay`s static equilibrium formation. This was the first indirect effort which suggested a correlation between $(\alpha)$ and incoming wave`s slant. In 1970`s (Ho, 1971; Silvester & Ho, 1972) improved the logarithmic spiral model by proposing a relationship between the curvature shape of the beach and wave approach angle concerning (α). Eventually 2 years later (Silvester, 1974) developed a template of different R_2/R_1 ratio and (α) in order to apply on a prototype bay.

Since 1974 many scientists used the modified logarithmic spiral model proposed by (Silvester, 1974) to validate and even design headland bay beaches,(Bishop, 1983; Finkelstein, 1982; LeBlond, 1972; Parker & Quigley, 1980; Phillips, 1985; Walton, 1977). Even though the logarithmic spiral model might be an interesting mathematical expression for this natural plan form, this model was not helpful in coastal engineering processes due to its unspecified relation with wave diffraction point and its inconsistency in different situation. The logarithmic spiral method also fails to fit any part of the straight downdrift section of the headland bays.

4.3 Hyperbolic-Tangent Method

This model was introduced after approximately 60 years by (Moreno & Kraus, 1999). The equation proposed has the following mathematical expression:

$$y = \pm a(\tanh bx)^m \tag{4}$$

This equation was developed after (Moreno & Kraus, 1999) who fitted 46 curved beaches with the resulted curvature Equation 4. These beaches were either from Spain or in North America. In the fitting processes the model is involved with choosing the origin of the coordinate system near the area where the general trend tangent of the shoreline is perpendicular to the local tangent of the beach, which is usually near the headland part of the bay. Then the two axis of the coordinate are drawn out from there on parallel to the tangent of the general trend of the shore (x-axis) and the other one perpendicular to it (y-axis) (Figure 10).

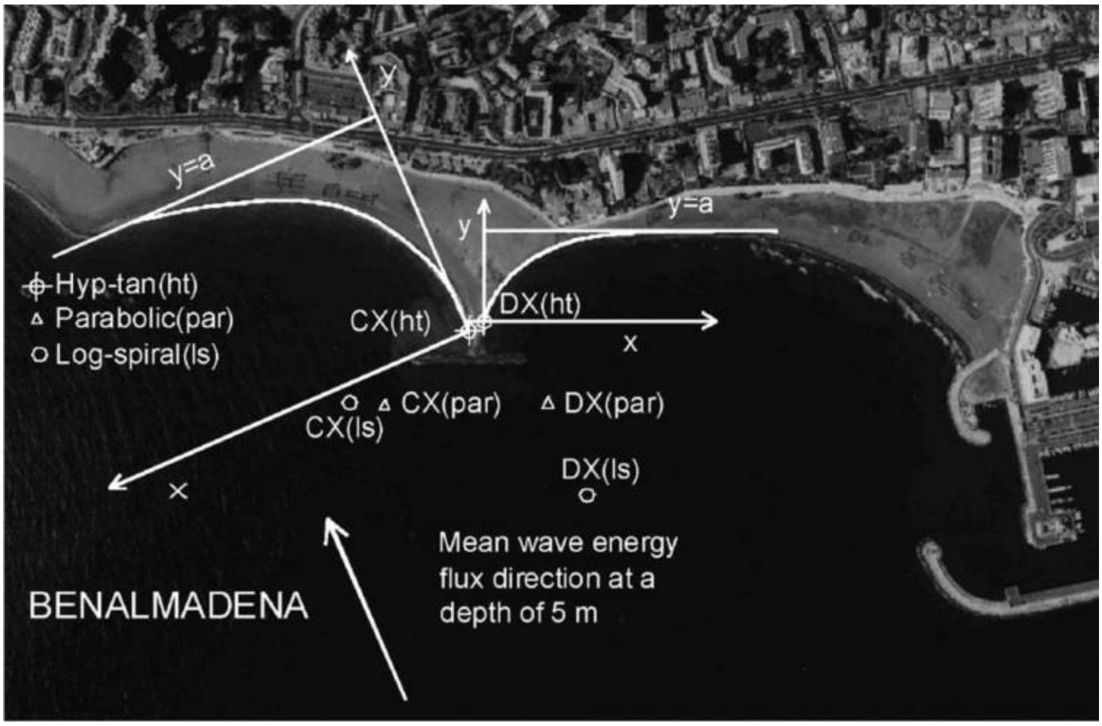

Figure 10. Example sketch of hyperbolic-tangent method application (Moreno & Kraus, 1999) as cited in (J. R.-C. Hsu et al., 2010)

Even though this model also ignored the importance of the wave diffraction it has been said that it is the most appreciated method for coastal engineering design (Moreno and Kraus (1999) as cited in J. R.-C. Hsu et al. (2010)). Later on Martino, Moreno, and Kraus (2003) also suggested this method to be applied in coastal engineering, despite of the tiring trial and error process, which was necessary to find the diffraction point. Eventually Martino et al. (2003) had to use a computer program to do this trial and error, where they found that the diffraction point is actually in the middle of the sea.

This inconvenience is observable in Figure 10; which shows the center of each coordinate system for each model. Since the diffraction point is a physical point which is completely influential on the generation of the final incoming wave crest impacting the shoreline, lack of consideration of these mentioned methods about this point make them slightly unreliable. On the other hand these two methods do not provide any information about the headland bay stability situation, so they are not going to be beneficial in evaluation of the sediment budget of shorelines, therefore, they would not be the proper choice of bay morphology assessment in this study.

Finally because aforementioned models are useless in predicting any environmental changes to the beach periphery due to change in headland position or any addition to the existing one. This could be a deal breaker issue in engineering processes, because engineering processes demand a mean which enable the scientist to compare the alternative outcomes of different system set ups.

4.4 Parabolic Model and its Application

JRC Hsu and Evans (1989) developed the *Parabolic Bay Shape Equation* (PBSE), Equation 5, as a distinct revolutionary method, right after the studies conducted by different researchers (J. Hsu, R. Silvester, & Y. Xia, 1989; J. R. Hsu, R. Silvester, & Y.-M. Xia, 1989) on the static equilibrium bays. JRC Hsu and Evans (1989) introduced the PBSE after fitting 27 different bay shaped beaches, accepted to be in static equilibrium. 14 of these 27 beaches were prototypes and 13 of them were model bays in static equilibrium. The result was a second-order polynomial empirical equation (Takaaki Uda, Serizawa, Kumada, & Sakai, 2010).

$$\frac{R_n}{R_\beta} = C_0 + C_1 \left({}^{\beta}/_{\theta} \right) + C_2 ({}^{\beta}/_{\theta})^2 \tag{5}$$

The equation expresses the dimensionless ratio of $\frac{R_n}{R_\beta}$ where R_β is the length of the control line which is the distance between the upcoast diffraction point and a point approximately in the end of the downdrift straight section of the beach, and R_n is a radius from updrift control point, stretched to a point on the static equilibrium, corresponding to the angle θ. Angle θ is the angle between the main wave crest tangent and R_n radii. Finally β is the angle between the assumed wave crest line and the control line R_β. Each parameter is best observable in Figure 11. The downdrift tangent is parallel to the wave crest line, so it has the same angle with R_β control line which is β.

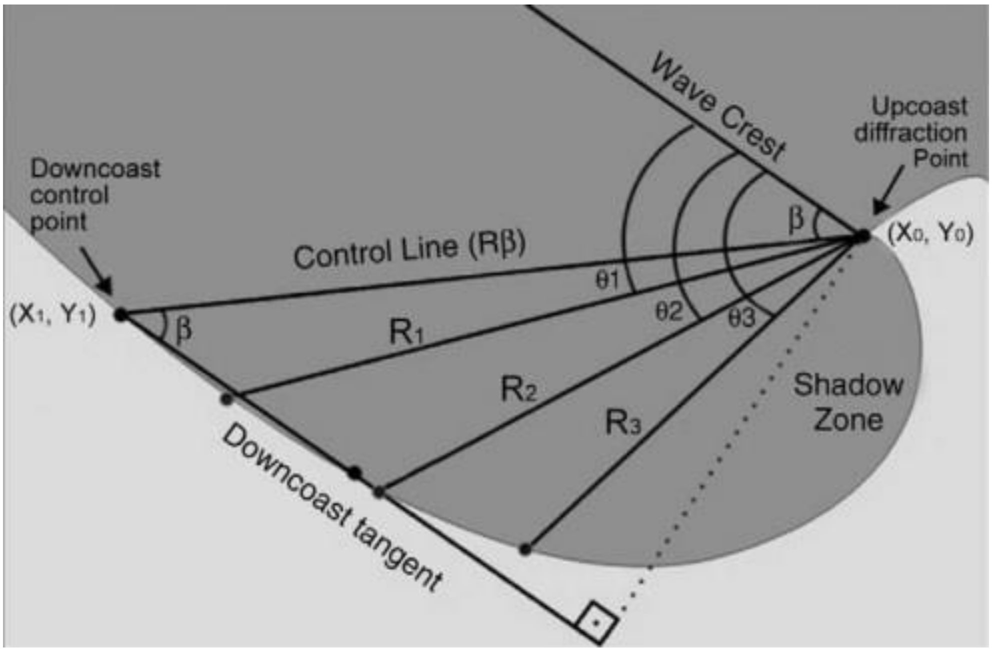

Figure 11. Definition sketch for parabolic bay shape model (Raabe, Klein, González, & Medina, 2010)

The three C constant have been gained originally by JRC Hsu and Evans (1989) with regression analysis for 27 beaches in the study. The original numerical expression of these three C values are fourth-order polynomial functions of the angle β and they are as follows as cited in Klein et al. (2003):

$$C_0 = 0.0707 - 0.0047\beta + 0.000349\beta^2 - 0.00000875\beta^3 + 0.00000004765\beta^4 \quad (6)$$

$$C_1 = 0.9536 + 0.0078\beta - 0.00004879\beta^2 + 0.0000182\beta^3 - 0.000001281\beta^4 \quad (7)$$

$$C_2 = 0.0214 - 0.0078\beta + 0.0003004\beta^2 - 0.00001183\beta^3 + 0.00000009343\beta^4 \quad (8)$$

The range that these constants can obtain value within is from -1 to 2.5 when β is in the usual range of 10 to 80 degrees which is common in normal wave conditions (Silvester & Hsu, 1997; Silvester, Hsu, & Dean, 1994). On the other hand, they have tabulated the $\frac{R_n}{R_\beta}$ values corresponding to different values of β ranging from 20 to 80 degrees with 2 degree interval. Within the two studies they have also illustrated adequate proof of the parabolic equation in several different bay shaped beaches. They have also noted that the flexibility which exist the application of the method concerning the positioning of the downdrift control point is the merit of this method, Nevertheless, Mauricio González and Medina (2001) tried to locate and fix the downdrift control point numerically by applying wave energy flux and relating the downdrift control point to the wave length. Several other studies were also conducted (Schiaffino, Brignone, & Ferrari, 2012; Tan & Chiew, 1994; Takaaki Uda et al., 2010; T Uda, Serizawa, San-Nami, & Furuike, 2002; Yu & Hsu, 2006) with the aim of simplifying the three constants (C coefficients), by applying the tangential boundary conditions of the straight section of the embayment and other modifications.

Most of these expand and modifications to PSBE were generated by using the simple boundary condition which can be easily found through geometrical analysis (Tan & Chiew, 1994) and they are:

$$C_0 + C_1 + C_2 = 1 \tag{9}$$

And

$$C_1 + 2C_2 = \beta \cot \beta \tag{10}$$

Hence, most of the modifications are done using the simplified PBSE by transforming three constants into one and relating it to a new coefficient found by the conducted study.

First modification applied to PBSE subsequently was the work of Tan and Chiew (1994), in which the equation was transformed into the form illustrated in Equation 11. This equation has one coefficient which is α and it differs for static equilibrium and dynamic equilibrium conditions, as shown in Equation 12 and Equation 13 respectively as follows:

$$\frac{R_n}{R_\beta} = \{1 + \alpha - \beta \cot \beta\} + \{\beta \cot \beta - 2\alpha\} \left[\frac{\beta}{\theta}\right] + \alpha \left[\frac{\beta}{\theta}\right]^2 \tag{11}$$

where for Static Equilibrium:

$$\alpha = 0.277 - 0.0785 * 10^{\beta} \tag{12}$$

and for Dynamic Equilibrium:

$$\alpha = -0.004 - 0.0113 * 10^{\beta} \tag{13}$$

Tan and Chiew (1994) listed α values for selected β angels as shown in Table 1.

Table 1. Selected Values of β and Subsequent Values of α extracted from Tan and Chiew (1994)

β	α
5	0.182
10	0.16
15	0.134
20	0.102
25	0.063
30	0.016
35	-0.043
40	-0.114
45	-0.201
50	-0.308
55	-0.438
60	-0.597
65	-0.792
70	-1.029
75	1.321
80	-1.676

The main parabolic equation was revisited by Yu and Hsu (2006) within which the same equation, Equation 5 was used with different structuring of the constant, C. This was achieved by collecting a great set of data from static bay beaches in Brazil and providing more accuracy for application purposes (Tasaduak & Weesakul, 2013). The developed equation for α and constant C's are:

$$\alpha = -0.23833 + 0.2374\beta - 0.0087043\beta^2 + 0.0001236\beta^3 - 6.8815 \times 10^{-7}\beta^4 \quad (14)$$

$$C_0 = 1 - \beta \cot \beta + \alpha \quad (15)$$

$$C_1 = \beta \cot \beta - 2\alpha \quad (16)$$

$$C_2 = \alpha \quad (17)$$

Weesakul and Tasaduak (2012) also developed another set of coefficients which were imitated and understood to be a function of wave obliquity and the ratio of sediment supplied into bay to longshore sediment transport, hence introduced sediment supply ratio (SSR). SSR can be illustrated as Q_R / Q_{lt} where Q_R is the rate of incoming sediment and Q_{lt} is the potential longshore sediment transport at wave obliquity (β).

Another study which was conducted in 2012 concerning PBSE was done by Schiaffino et al. (2012). In this study the same PBSE was used and the constants were modified to reduce error and become applicable in two different manners; one for sandy beaches and the other one for gravel beaches. Their study examined 52 Mediterranean embayed beaches located along Italian, French, Spanish, Tunisian and Turkish coasts. These where all static equilibrium beaches both natural and man-made. The results achieved in this study for two different beach types are:

• Sand beaches: m=−0.8460 and q=0.2281

• Gravel beaches: m=−1.0235 and q=0.2476

Where m and q are two added dimensionless coefficients. Subsequently C coefficients are:

$$C_0 = 1 - \beta \cot \beta + m\beta + q \tag{18}$$

$$C_1 = \beta cot\, \beta - 2\,(m\beta + q) \tag{19}$$

$$C_2 = m\beta + q \tag{20}$$

All of the aforementioned modifications including the original one (JRC Hsu & Evans, 1989) generate a polar curvature of which, the part between angles β and 150 to 180 degrees is going to be fitted over the aerial photo of the coastline in hand for assessment. The generated plot would merely show the layout of the static equilibrium of the beach according to the wave diffraction point and wave direction.

In next section the methodology of determining the stability of the headland bay using this layout of the PBSE would be described.

4.5 Headland Bay Stability Assessment using PBSE

After the application of the PBSE using either one of the methods explained in previous section, stability of the beach could be examined as follows. If the generated static equilibrium prediction is landward comparing to the currently existing shoreline periphery the beach is considered to be in dynamic equilibrium and it would degraded, in case of sediment supply interruption. On the other hand, if the predicted static equilibrium is seaward from the existing shore line the embayment is in unstable to natural reshaping mode and it would gain sediment seaward in time until the distance is filled up, and obviously if the predicted curve of static equilibrium matches the existing beach it would be in static state where change in sediment supply would not affect its periphery and layout. da FKlein (2003) in Santa Catarina, Brazil and J. R.-C. Hsu et al. (2010) in beaches of Northern Ireland, have demonstrated these three possible outcomes of the PBSE stability assessment.

Since the updrift control point can be chosen arbitrarily the effect of any change in diffraction point could be measured and evaluated by merely using the aerial map or photograph. This would provide a wide range of shoreline design and maintenance capabilities to coastal engineers. Finding the minimum extension of the jetties and positioning their tips is a very simple process, using this method. This is very critical since usually when a shoreline begins to erode for any reason the officials do not have any guide line to prevent and maintain it by just constructing or extending an existing harbor or jetty. Hence they usually use artificial beach nourishment which is a very expensive procedure and since the embayment is not protected from erosion properly it would become eroded very soon after the procedure again. Other conventional coastal processes which are often used to protect beaches from erosion, are usually associated with construction of a hard and heavy nearshore or off shore structures like, seawalls, revetments, groins and detached shore parallel breakwaters. Building these relatively heavy structures are usually done by quarry stones or heavy precast concrete blocks in different shapes.

Instead of applying these difficult and expensive artificial beach protection methods, shorelines could be assessed using the PBSE`s predicted static equilibrium and accordingly a one-time solution could be suggested. For example downdrift erosion could be mitigated through simple extension of an existing jetty for a several meters like the examples demonstrated by J. R.-C. Hsu et al. (2010). Illustrations of the usefulness of this widely used method could be found in the research studies of other scientists (da FKlein, 2003; Mauricio González & Medina, 2001; Klein et al., 2003).

Nonetheless, there have been studies conducted concerning the limitations and uncertainties of this method (Mauricio González & Medina, 2001; Jackson & Cooper, 2010; Lausman, Klein, & Stive, 2010a, 2010b). These limitations are basically related to the ones suggested by M González (1995) and they could be briefly described as bellow:

- The assumption that the diffraction points are the only controlling aspect of the wave height gradients, which may lead to missing the effect of other diffraction from local islands and bathymetric anomalies.
- Tidal current effects cannot be measured, hence they are assumed to be negligible.

- In this method the effect of singular diffraction point is considered and other diffraction points are assumed non-existent.
- Local geological properties and sediment availability are important in shoreline morphology but they are not considered in this method.

Cyprus has a very small and actually negligible tidal range so the tidal situation would not be a problem as far as the limitation of the method is concerned. Also offshore islands and complex or multiple diffraction point positioning is not common at the northern coasts of island, at least for the headland bays that will be under analysis in this study. Nevertheless, in this study, analytical procedures are performed by the PBSE method in order to identify the stability of 6 different coastal regions around the Northern part of the Cyprus.

4.6 Assessment Application Tools

All of the methods mentioned before could be used by fitting the result curves to the aerial map or satellite photograph of the subjected shoreline. Especially in the parabolic method this processes is very important because after applying the parabolic curve to the map, the assessment about stability could only be done by comparison between the predicted curve and the existing shoreline. This process is very repetitive and time consuming. Hence in 2003, a software called MEPBAY was developed with the capability of applying the original parabolic bay method to an aerial map of the shoreline (Klein et al., 2003). Also, a more sophisticated software was also developed and verified by Gonzalez and Medina (2002); Mauricio González and Medina (2001); and M González et al. (2007), which was called SMC.

While MEPBAY uses only the aerial photograph of the embayment, SMC needs more preprocess information like bathymetry, wave direction information and it would provide more information which is useful for design phases. Raabe et al. (2010) compared these two computer programs in several aspects and noted that MEPBAY delivers rapid application and predesign assessment to find the trends and best structure positioning choice, while SMC is capable of more detailed and deeper analysis and more precise and more accurate forecast due to the numerical input it uses.

Since there is not any prior and fundamental morphological analysis of this kind available for the Cyprus coastlines, the best software choice for this study would be the MEPBAY software considering the aforesaid arguments and purposes of this study and its methodology.

Chapter 5

CASE STUDY, COASTAL STABILITY ASSESSMENT

5.1 Introduction

This chapter is consist of two sections; the first section is the preparation of a functional script in Wolfram Mathematica 8.0, where different approaches of the PBSE methods are going to be codded in its coding environment to create functions which get β and R_β as its input, and would generate the static equilibrium. The second section is done by applying the original 1989 equation (JRC Hsu & Evans, 1989) to the existing beach using the aerial photographs extracted from Google Earth.

A comparison with different outputs for three of the different PBSE expressions explained in previous section would be carried out. The three different expressions are; the original JRC Hsu and Evans (1989) equation and C coefficients, the 1994 modifications by Tan and Chiew (1994) for the static equilibrium, and the result of the study on the sandy and gravel beaches to improve the accuracy of the PBSE by Schiaffino et al. (2012). Accordingly the stability of the different subjected beaches will be assessed by comparing the predicted static equilibrium to the existing shoreline periphery. Finally, an overall assessment of Cyprus`s headland bays` morphological situation according to the results derived from beaches equilibriums and stability statuses and suggestions of alternative groyne structures necessary for the headlands, would be carried out at the end of the study.

5.2 Introduction to the Environmental Characteristics of the Chosen Coastlines

Coastlines of Cyprus consist of different types of coastal formations (sandy beaches, rocky, gravel beaches, seacliffs and etc.), and among them there are several different important sandy headland bays. Headland bays chosen for this study are either commercial beaches for the use of public in summer for seaside activities or they are protected areas as part of the turtle habitat for egg laying purposes. On the other hand, few of these headland bays are formed at the delta of streams, which are dried due to the inconvenient dam construction, hence the dynamics of their equilibrium had been compromised. Figure 12 is a map of all the rivers which are located in Northern Cyprus

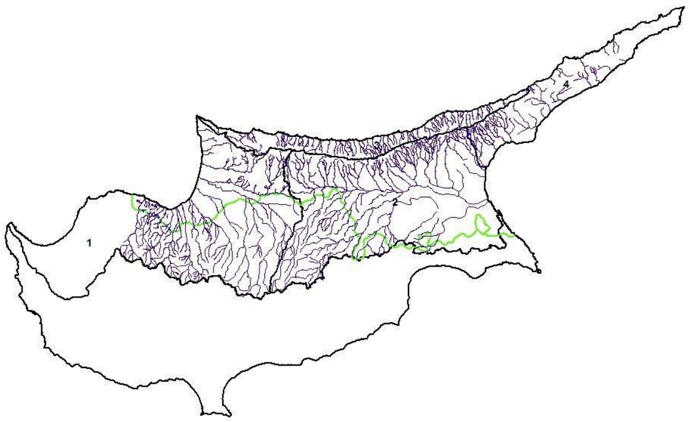

Figure 12. River map of Northern part of Cyprus

Locations of chosen shorelines for the purpose of this study is pinpointed in Figure 13.

.

Figure 13. Shoreline locations on the satellite photograph of the Cyprus Island by Google Erath

5.2.1 The delta of Kanlidere stream

With 1830 meters distance between its two headlands this embayment is one the largest commercial beaches, containing three different seaside beach complexes between its two rocky headlands on its north and south parts shown in Figure 15. The shoreline is mainly made of sand and the main approaching wave`s crest is parallel to the central tangent of the embayment. The embayment also contains the emerging point of a dried out stream, which brings up many questions about the effects of the incoming sediment supply prevention, which as described in the first chapter is the main input source of sediment of coastal regions.

Figure 14. Arieal photo of Kanlidere`s delta (Google Earth)

This coastline which is located on the northern end of the Famagusta city and is one of the most popular beaches at the east coast of the island.


Figure 15. Images from the delta of Kanlidere stream embayment, the northern headland on the left and the southern headland on right

Since this embayment contains three of the main touristic beaches of the Famagusta city, it is one of the most important headland bay beaches in the area. Hence assessing its equilibrium situation could be useful or even necessary for its long-term maintenance management. It is well known that within the last 25 years many dams are constructed on different tributaries of Kanlidere River. As a result sediment supply property of the river is almost vanished. Within the last 10 years the river is diverted from its original path and forced to discharge into Köprü Dam. Since then, Kanlıdere delta is not replenished by sediments transported from the watersheds of the river.

5.2.2 Kaya Artemis Hotel Beach Area

This sandy beach which is located near the Vokolida (Bafra), in front of the Kaya Artemis Hotel and resort is approximately 1.2 km long and is also located at the delta of another dried out stream. The amount of sand sediment stored in this area on land and offshore, could even be seen from the aerial photographs Figure 17. The importance of this shoreline area is exactly due to its accumulated sand budget, which was derived from the dried out river. The existing littoral drift around the whole island would eventually erode this very beautiful and commercial region and since the input sediment had been eliminated, its protection is very critical considering its commercial and touristic potential and importance.

Figure 16. Artemis hotel bay and the tombolo like headland (Google Earth)

This sandy bay is located in the downdrift of a tombolo like headland which is observable in Figure 16. The northern part of this embayment is not being sheltered by any headland or any coastal structure. Hence the longshore currents are continuously transporting sediment off of the region and despite the apparently massive amount of sediment budget of the area which make the observation of the erosion difficult, the area has to be protected in order to maintain its periphery. The trivial distance between this embayment and the Noah`s Ark Hotel`s sandy embayment make the closely related because of the sediment exchange that would happen between them continuously.

Figure 17. Arial photograph of the Kaya Artemis Hotel embayment (Google Earth)

5.2.3 Noah`s Ark Hotel Beach

Few kilometers to the north of the Artemis hotel another resort type hotel is located, and it is called Noah`s Ark which is again one of the largest touristic attractions of North Cyprus. As well as Kaya Artemis Hotel, Noah`s Ark also benefits from the sandy coast located in front of its seaside area. The significant and relatively unique thing about this area is that after the construction of the hotel they have built three breakwaters in the coastline (Figure 18), which are effecting the coastline`s morphology and their effect is completely obvious from comparing the aerial photographs from 2008 and 2010 (Figure 19).

The result of the construction of these structures proves the existence of ongoing and efficient longshore drift that can be either beneficial or disastrous for sandy beach conservation around the island.

Middle Jetty

Northern jetty

Southern jetty

Figure 18. Images for Noah`s Ark Hotel, three constructed jetties

This area can also provide an appropriate basis to examine the different modifications of the PBSE method`s applicability for the Cyprus`s shorelines. Also the construction of these artificial structures will result in downdrift sediment accumulation resulting in dynamic changes of shorelines located at further north, most probably causing a retreat since the incoming sediment supply is interrupted.

Figure 19. Aerial photos of the Noah`s Ark Hotel area from 2008 and 2010 (Google Earth)

5.2.4 Golden Beach

The famous and beautiful sandy shoreline located at the North-Eastern tip of the Cyprus Island, is one of the most important shorelines, providing the egg laying environment for sea turtles (Figure 20). Therefore, this area is protected and any type of commercial construction in the area is forbidden. As part of the reproducing environment and living habitat its protection would become even more important and critical. The ecological importance of this area have been emphasized by many researchers (Snape et al., 2013; Wright, Fuller, et al., 2012; Wright, Stokes, et al., 2012) in order to get more attention and deliver more awareness for the public.

The main part of the Golden beach consists of headland two bays, shaped in both sides of the tombolo created because of the detached island located in the area (Figure 20). The area near the tombolo are more indented and the parts further from tombolo are straighter. Outer parts of the environment (its east and west sides) are thinner because there are no headlands available on its sides to provide the requirements for bay development (Figure 21). Also, the satellite map of this area signs traced of erosion in the downdrift of the bay at the left side of the tombolo. This condition rises concerns about the future situation of the coastal area.

Figure 20. Golden beach

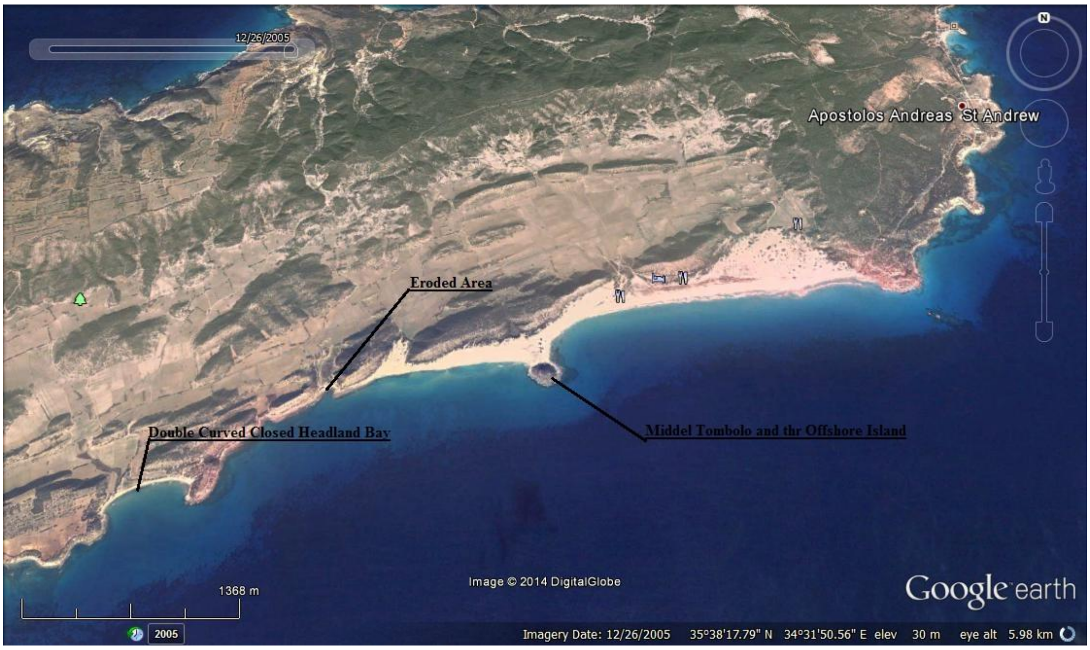

Figure 21. Satellite photograph of Golden Beach region

5.2.5 Alagadi Turtle Beach

As it can be understood from its name this beach is also completely dedicated to turtles egg laying course. This region is an almost 1.7 kilometers long embayment, which contains several headlands and several bays connecting these headlands (Figure 22). Alagadi region also contains another dried stream delta, which could be seen in the satellite picture, and it is probably the original sediment provider of these regions (Figure 23). Hence these shorelines also have to be assessed and analyzed due to their changed dynamics, to be protected from erosion and retreatment.

Alagadi turtle beach is the most important and the most famous ecological shoreline of the northern Cyprus because it provides the most egg laying environment for turtles and a lot scientific, ecological and touristic activities are occurring at its coastlines. Some of the studies that was conducted about the turtle conservation and protection are Broderick, Glen, Godley, and Hays (2002); Snape et al. (2013);

Wright, Fuller, et al. (2012); Wright, Stokes, et al. (2012). Hence examining the stability of this coastal region is important for the survival environment.

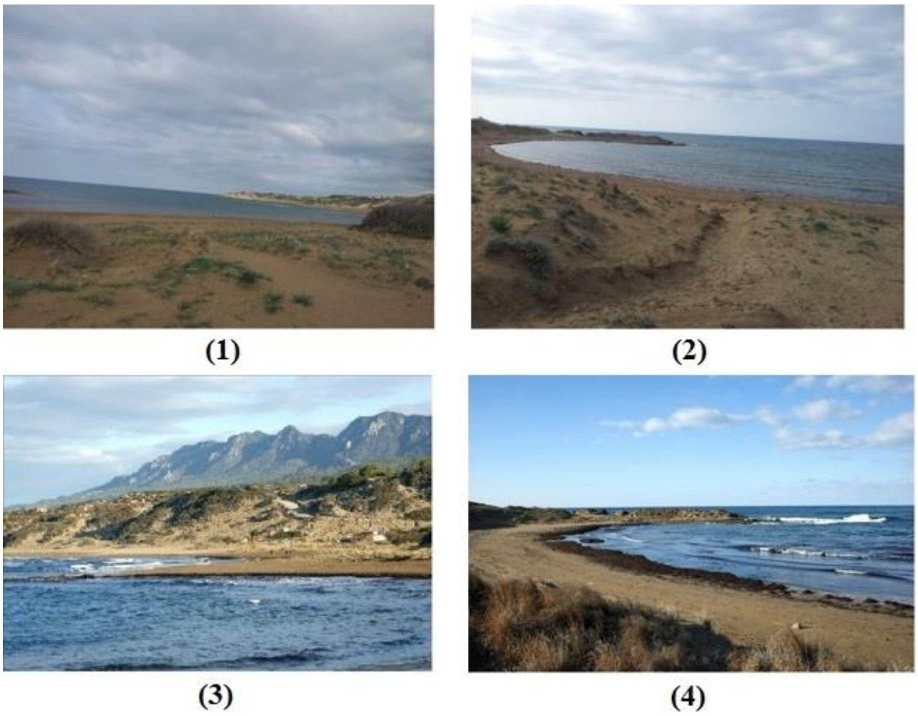

Figure 22. Four main headlands in the Alagadi area. Each headland number is shown in satellite map Figure 23.

Figure 23. Satellite photograph of the Alagadi Area (Google Earth)

5.2.6 Acapulco Beach Embayment

Lara Beach consists of two embayment one known as Acapulco beach and the other as Barış beach. Acapulco is the name of a hotel located at the east side of the Kyrenia city. Acapulco hotel`s beach has a double curved type of headland bay within its approximately 300 meters long shoreline (Figure 24). Its western headland is a share headland with its neighbor shoreline, which is a private beach allocated only for military services as a recreational area for their families. (Figure 24). Barış beach is also double curved shoreline and contains a relatively large amount of sand sediment appearing to be in the static equilibrium.

Figure 24. Acapulco beach and Barış beach headlands

Figure 25. Acapulco and Barış beaches satellite photographs (Google Earth)

5.2.7 Morphou Bay, Gaziveren beach

This beach is not naturally a headland bay, but it is a recreational embayment, created subsequent to the construction of the two jetties, built to develop a sandy beach. As it can be seen on the satellite map of the area at 2008, prior to the construction of the aforementioned jetties, the shoreline of this area did not have any indentation (Figure 26). The satellite map of the 2013 shows the significant effect of the structures on the landform at the area (Figure 26). The obvious land erosion on one side and accumulation of the sediment on the other end of the bay, forming the similar shape of the headland bay landforms can be easily observed from the images.

2008

2013

Figure 26. Satellite maps of the Morphou recreational bay from 2008 and 2013 (Google Earth)

This area which is located on the western part of the northern part of Cyprus, is part of the very long shoreline facing to the Güzelyurt (Morphou) Bay. This coastal zone has the longest fetch distance available for the northern part of the Island. Such a fetch distance helps the sea waves to grow from small ripple shapes to a mature wave with high energy capacity. Without the help of artificial structures, this coastal zone area can never worked out for a beach nourishment project applications. The landform change which happened due to the construction of the jetties shows the potential that this area has beach nourishment possibilities, which can be used by construction of simple and relatively cheap coastal structures. Then, such artificial structures can help to create a possible sandy coastal beach in this area, aiming to perform better ecological environments for the residents of the region.

5.3 Employed Computer Software

Satellite photographs and first measurements of each coastal zone area are extracted from Google Earth software and the initiating stage of each assessment begin with using MEPBAY to plot the JRC Hsu and Evans (1989) model and collect the information about R_β and β. The information then are inputted into the Mathematica algorithm created to plot other expressions of PBSE. Photoshop graphical software was used afterwards to match the aerial map. This algorithm is viewable in Appendix 1.

Chapter 6

RESULT AND DISCUSSION

6.1 Introduction

This section contains the results of the analysis applied to each beach. Initially, the method developed by Hsu and Evans (1989) is applied by using their well-known software MEPBAY. The first step of the modelling is to plot the parabolic bay shape equation curve by using the most obvious and unsubmerged diffraction point and downdrift control point. Afterwards, if necessary, a revised application of the method for alternative diffraction points that can also be a submerged point would be carried out. Also, the results of different modifications of the model constants (*i.e.* C_0, C_1, C_2) described previously by , Tan and Chiew (1994) and Schiaffino et al. (2012) (for sandy beaches) would be plotted to illustrate the differences on the curves fitted for the chosen headland bays. Accordingly, an overall understanding about the applicability of these alternative modifications of the PBSE model to northern Cyprus`s beaches will be attained, while the main analytic data and discussions are based on the original JRC Hsu and Evans (1989) model.

If it is necessary according to the gathered information about the stability of the headland bay, to relocate the diffraction point of the headland bay beach, artificial coastal structures like jetties and breakwater will be suggested according to the original model of JRC Hsu and Evans (1989).

6.2 Kanlidere stream`s delta analysis

Considering the long period evolution of embayment had maintained its planform in a stable state. First we would choose the most viewable unsubmerged points, observable on the satellite map as tips of the two headlands (diffraction point). The result is demonstrated in Figure 27 where the discrepancy of the plotted parabolic curves and the actual shoreline periphery is observable.

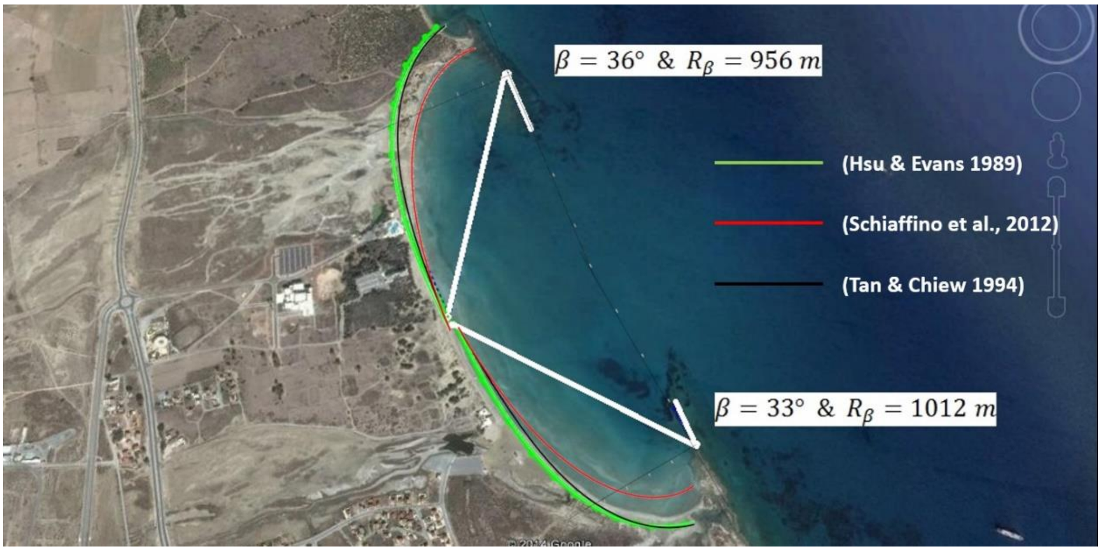

Figure 27. First application of the PBSE and its alternative modifications for unsubmerged headland tips to Kanlidere stream`s delta

As far as the comparison of the different modifications is concerned the (Tan & Chiew, 1994)`s modification is very close to the original model drawn in green color in Figure 27. On the other hand, (Schiaffino et al., 2012)`s model suggests that the northern bay beach is already in static equilibrium while the southern bay beach is in unstable situation and should be in natural nourishment state, which is not compatible with the historical data of the embayment.

This difference would be either because of the miss placing the refraction point or because of the shoreline equilibrium being dynamic considering the predicted curvature is landward of the shoreline mostly. After assessing the shoreline landform more closely and considering the possibility of other diffraction points at the submerged rocky parts located further seaward of the chosen diffraction points, the shoreline could be divided into four different diffraction points.

Figure 28. Multiple diffraction point used to fit the shoreline periphery of the beach by MEPBAY

Figure 28 demonstrates the result of considering more than one diffraction point on each headland side. This was considered because by investigating the beach periphery more closely four different curves were distinguishable, two for each headland, and after several try and error processes the platforms illustrated in Figure 28. The great agreement between the actual shoreline and the predicted planform, indicates that if the headland is in the static equilibrium, the wave diffraction point for headland is not singular but it is more likely that the submerged rocks are effecting the head land formation alongside with the tip of the headlands.

6.2.1 Structure Suggestions for Beach Protection

Hence both of the efforts illustrated above can in some way show that the shoreline is not in a desirable situation. For the first case both sides are suggested to be in dynamic situation, hence they are to be eroded if the sediment supply diminishes. Similarly in the second approach the unavailability of a certain physical diffraction point can be relied on long term beach protection. Hence construction of jetties to stretch both headlands to a position where the predicted static landform, at least matches the existing shoreline, is very reasonable for the protection of this shoreline. The result of minimum distance that the diffraction point has to be moved to satisfy the matching position of the static equilibrium is shown in Figure 29.

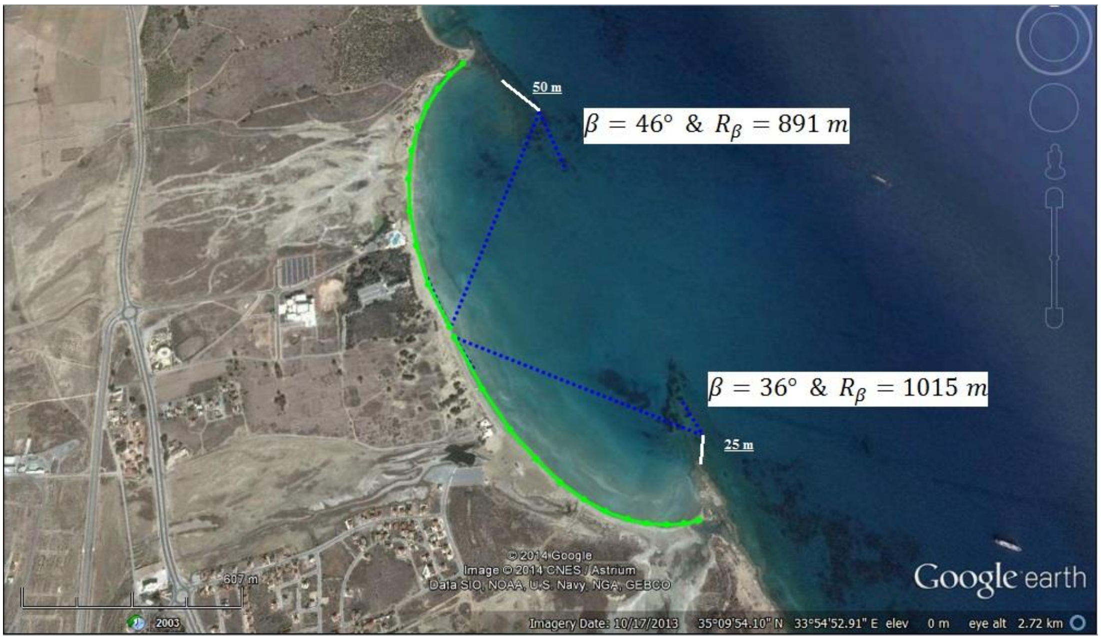

Figure 29. Length and direction of the headlands to reach the satisfactory diffraction point to reach the double curved headland bay static equilibrium

Figure 29 shows the simplest modification can be done to the headlands sheltering this area to protect it from erosion, where the white line show the location, direction and the minimum required length for the jetties needed at the tip of the headlands.

6.3 Kaya Artemis Beach analysis

As before, in first attempt the unsubmerged headland tips are chosen as diffraction points and the results are demonstrated in Figure 30. The results shows that the northern bay is approximately in static equilibrium according to the original equation (the green curve), while in case of southern landform, the predicted static equilibrium curve is significantly landward comparing to the actual landform.

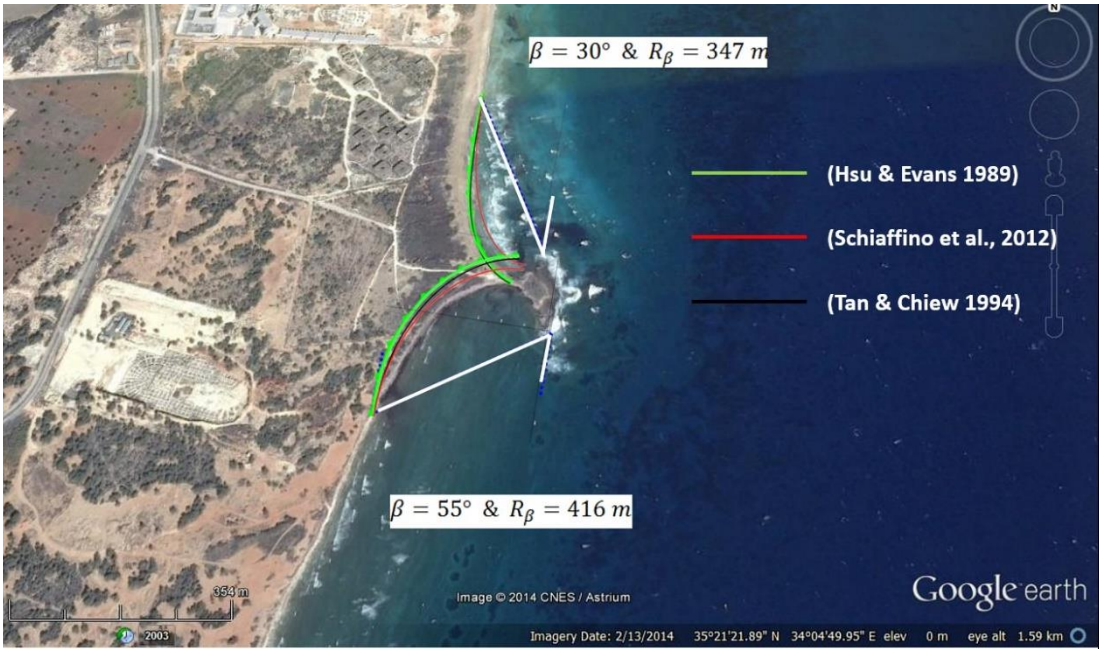

Figure 30. First application of the PBSE and its alternative modifications for unsubmerged headland tips at Artemis Hotel region.

Figure 30 suggests that the southern bay is still in dynamic equilibrium, despite the fact that it is already eroded completely. There is almost no more sediment to be eroded and the coastal region is behaving like a hard rock. Since the shorelines historical and geographical are also aligned with the result of the parabolic equation analysis, there is no need for further assessment to evaluate other possibilities for the position of diffraction points.

6.3.1 Structure Suggestions for Beach Protection

The result of the modified equation illustrated in Figure 30 are mostly in great agreement with the original form, except the result of the Schiaffino et al. (2012)`s modification for the northern bay beach. Again this modification fails to match the situation rationally for the south to north curved beach while it can be considered applicable for the south to north curved bay. Following is the protective construction suggestions that could be derived from the conducted analysis (Figure 31).

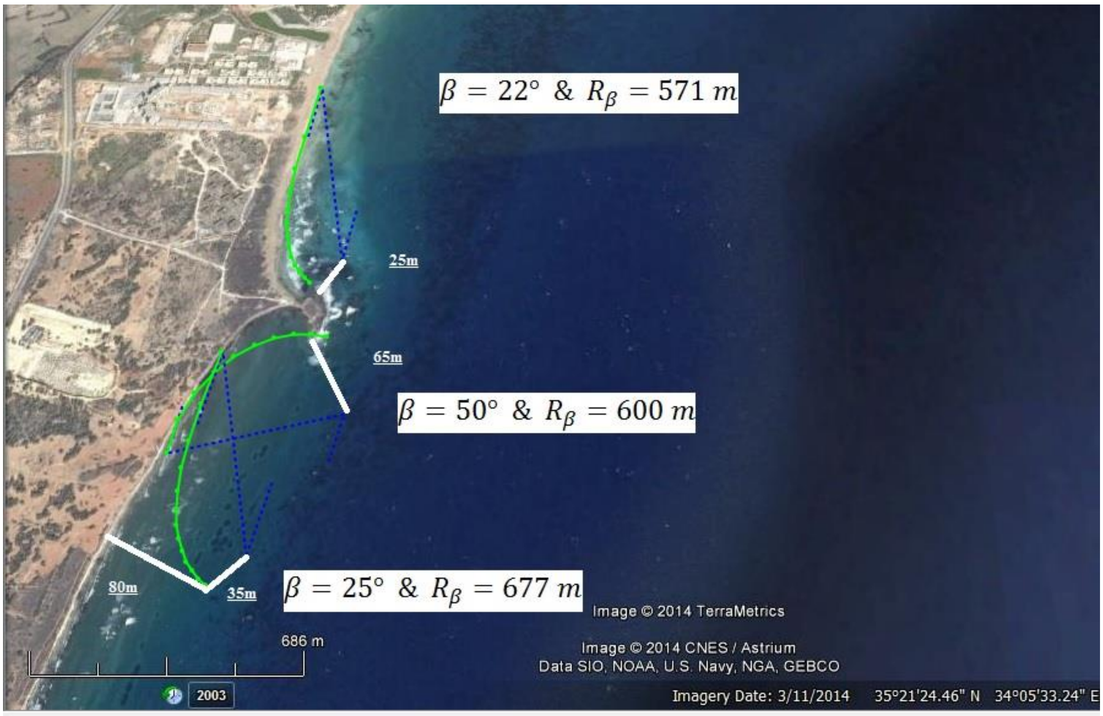

Figure 31. Length and direction of the headlands to reach the satisfactory diffraction point to reach an acceptable headland bay static equilibrium for Artemis Hotel area

The three structures suggested in Figure 31 are simple jetty suggestions which could transform the shoreline equilibrium into the unstable state and natural nourishment would take place in time until the actual shoreline reaches the green lines shown in the figure. Obviously, these are just simple examples of many other designs that could be done using this method. The main purpose is to protect the coastal area from erosion without going through an expensive process of artificial nourishments and other beach development methods.

6.4 Noah`s Ark hotel beach analysis

As mentioned previously, this area is being protected by the constructed jetties and breakwaters. Hence, the assessment for this area is done by focusing on the effects of these artificial structures on the morphology of the shore.

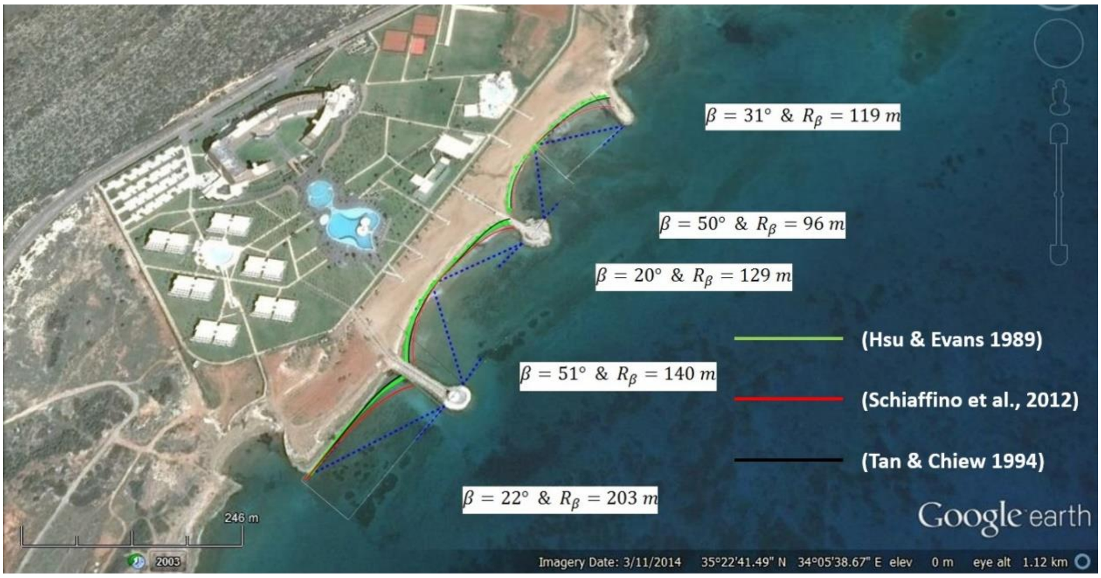

Figure 32. Application of the PBSE and its alternative modifications for unsubmerged headland tips at Noah`s Ark Hotel embayment.

The results show a relatively acceptable coincidence between the shoreline and the predicted results, however while the original equation (the green curve) is more or less matched with the shoreline periphery in general there is still a little gap observable in some part, which suggests that the shoreline is going to extend seaward to reach those points. In the case of Schiaffino et al. (2012)`s modification for sandy beaches, the dissimilarity is slightly more. Also the situation for the most southern beach is different according to these result, because all three modifications suggest that the beach is not stable and should gain wider sand accumulated area in time.

This may be because of the unprotected coast in its downdrift which allows the sediment to be eroded and washed away from the area. More collective data must be gathered for a longer period of time to learn about what is happening in this area since there is also some uncertainty about how the sediment accumulation happened in this region.

Glancing closely at the historical aerial maps of the area (Figure 19) it seems that the sudden sediment accumulation in the area might be due to some sort of artificial nourishment process. However according to the result of this study the important knowledge that is available for us is the fact that according to PBSE the erosion is not a matter of concern for the usual coastal situation and these beaches are safe from retreatment because of the three constructions.

6.5 Golden Beach Analysis and Result

As the illustration in Figure 33 demonstrates the headland bay at the left is in static equilibrium according to the original JRC Hsu and Evans (1989)`s equation and also the static equilibrium prediction, modified version by Schiaffino et al. (2012), have a close agreement with the shoreline. This is while the other PBSE expression by Tan and Chiew (1994) shows that this headland bay is in dynamic equilibrium and it is going to need constant sediment supply to maintain this landform. For the right headland bay beach, all three plotted graphs are landward from the shoreline, suggesting that the shoreline is in dynamic equilibrium, which means it is being supplied with sediment supply continuously to sustain the present periphery. However, the satellite pictures from previous years show that the beach is stable. This can be interpreted in two ways; (1) there is another diffraction point submerged in an unknown location; (2) There is an excess longshore and cross-shore sediment transport at the region supplying sediments to the region.

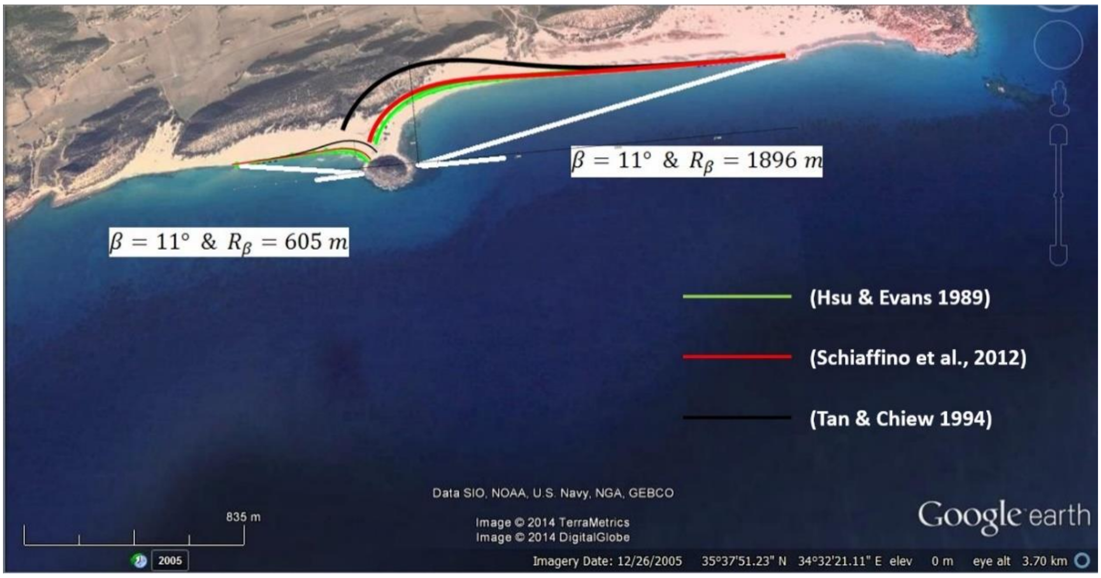

Figure 33. Application of three alternative PBSE modifications to the Golden beach embayment, picking the unsubmerged points on the headland as diffraction point

6.5.1 Structure Suggestions for Beach Protection

To evaluate the first interpretation, a new analysis was carried out on the right side headland bay to try to find an alternative submerged diffraction point and the results are shown in Figure 34. Figure 34 shows how the new chosen diffraction point, which is chosen by considering the shadow of the slightly underwater land near the right side tip of the headland, shows both JRC Hsu and Evans (1989) and Schiaffino et al. (2012), models are approximately covering the shoreline landform. Then the assumption that this is the real diffraction point would be very reasonable. However creating a physical tangible diffraction point for headland bays is more reliable than a natural diffraction point which is always associated with a lot of uncertainty; hence modifying the diffraction position by a simple coastal structure would be a very wise thing to do. Figure 35 is the suggestible structure according to JRC Hsu and Evans (1989) equation applied by MEPBAY software.

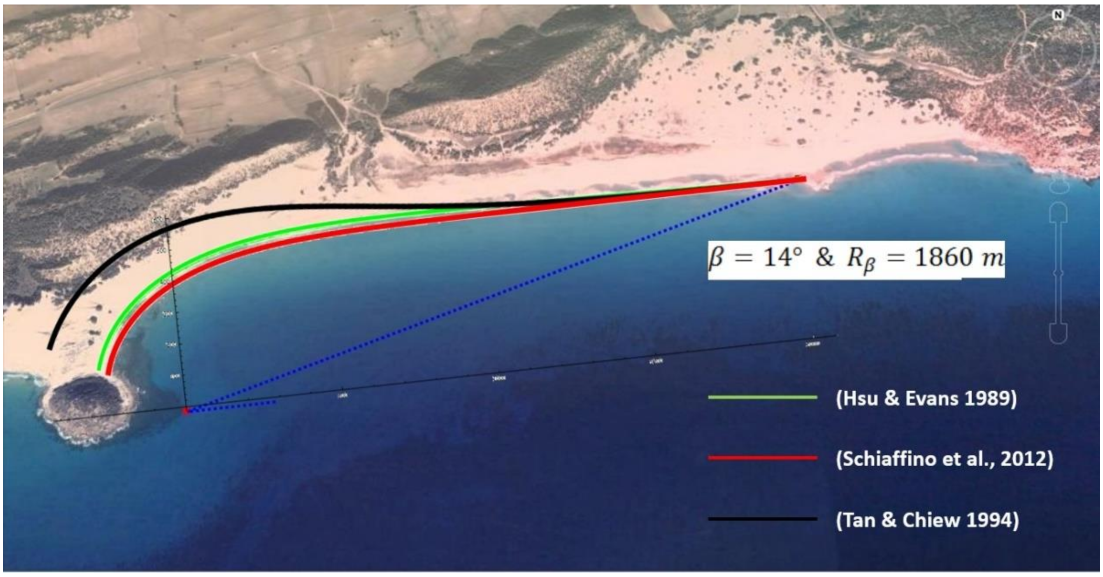

Figure 34. Result of choosing an alternative submerged diffraction point for the right headland of the Golden beach

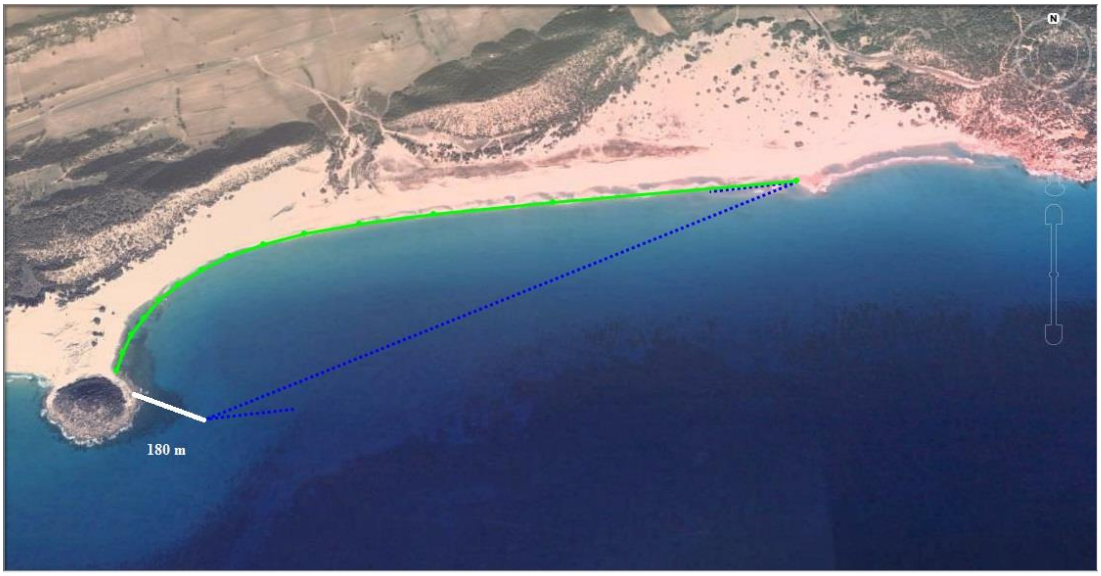

Figure 35. Required structure according to PBSE to protect the Golden beach shoreline

6.6 Alagadi Turtle beach analysis

The first step of the analysis for this embayment, with unsubmerged observable diffraction points, plotted with MEPBAY is illustrated in Figure 36. Due to the relatively large width of this area further detailed results has been divided into two segments. First the double curved headland bay of the eastern part of the Alagadi embayment is demonstrated in Figure 37. It should be noted that the main wave direction in this side of the Cyprus is oblique and it is mainly from north-west.

Figure 36. General implementation of the PBSE to different headland bays of the Alagadi Beach, using unsubmerged headland tips as diffraction points

Figure 37 shows a closer and more detailed assessment of the east side bays of this embayments, where the right bay is in static equilibrium according to JRC Hsu and Evans (1989) and Tan and Chiew (1994) expressions, while the left bay is in dynamic equilibrium, due to the landward position of the static equilibrium predictions. However, the red curve which shows the result of the modified equation by Schiaffino et al. (2012), suggests that both bays are in disequilibrium and in natural nourishment state. Nevertheless, the differences in this assessment are very small such that it could be said that this part of the embayment is more or less in static equilibrium. Even in the case of any change, that will match any of the predicted equilibrium conditions, the width of the beach would not be lessened much and the erosion would not be critical.

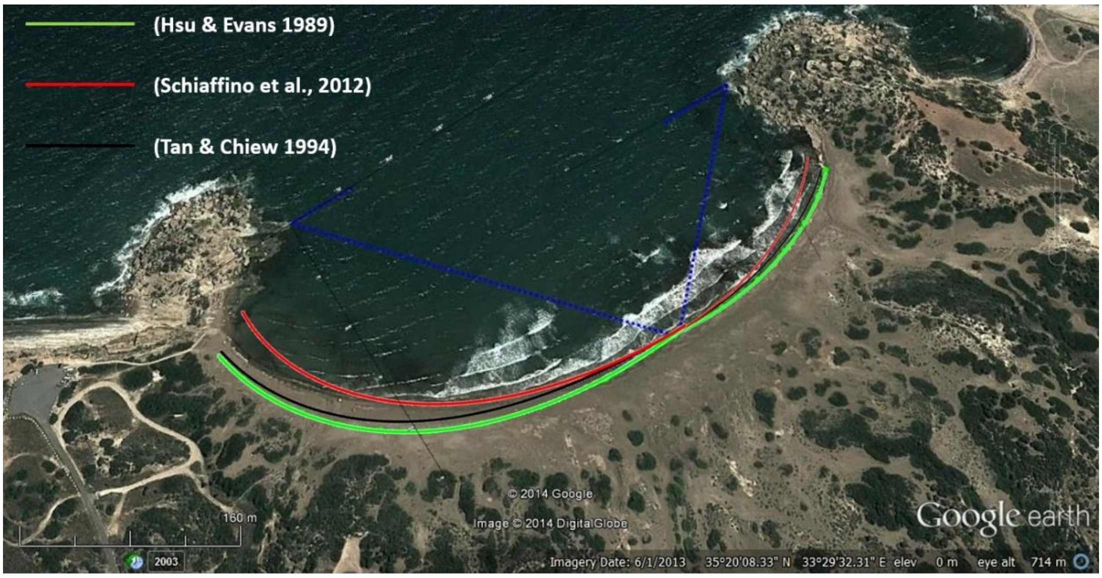

Figure 37. Implementation of different expressions of the PBSE on the east side bays of the Alagadi beach

The west side of this embayment contains four headland bays and by not considering the submerged diffraction point as shown in Figure 36, a good agreement could be seen in between the predicted static equilibriums and the shorelines. The detailed assessment with considering the submerged diffraction points and alternative expressions of the equation is also viewable in Figure 38.

The west side of this embayment (Figure 38) is assumed to be stable and more probably in static equilibrium according to its historical data. The result of the parabolic method is shown in Figure 38. Three of the recognized headland bays on the left show relatively good agreement with this assumption in case of two older methods (JRC Hsu & Evans, 1989; Tan & Chiew, 1994), while the other headland bay appears to be in dynamic state. Results found by Schiaffino et al. (2012) equation, are considerably different, since they show completely different results for each headland bay and they do not match the historical stability of the shoreline periphery. Only the periphery of eastern headland bay has a closer agreement with the static equilibrium equation expression.

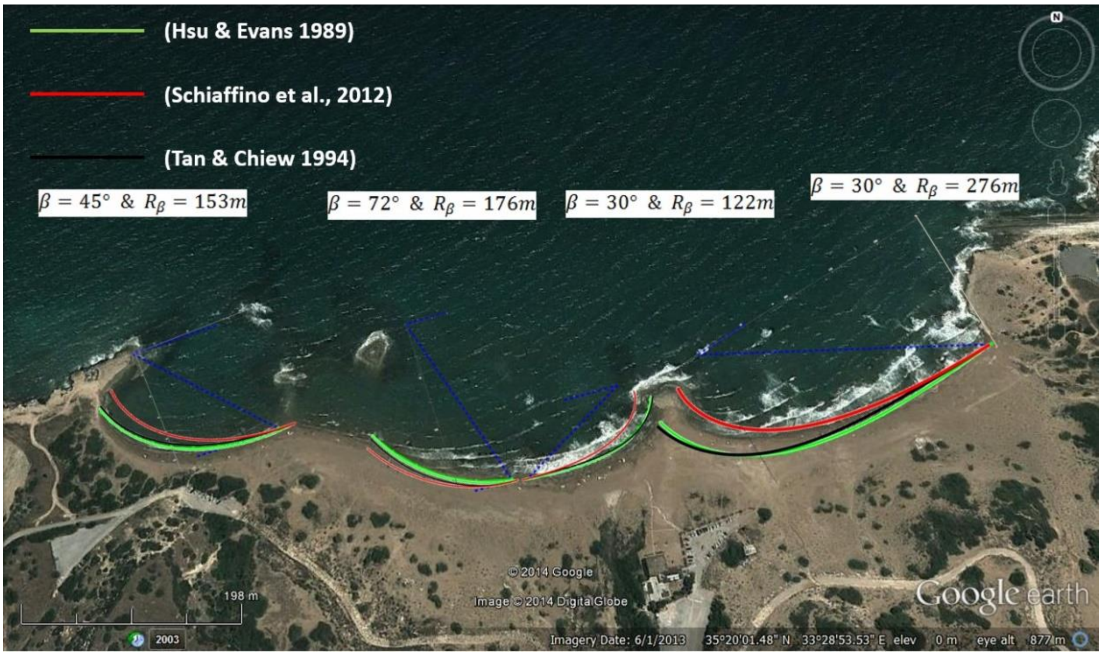

Figure 38. Implementation of different expressions of the PBSE on the west side bays of the Alagadi beach for more detail observation considering submerged diffraction points

6.6.1 Structure Suggestions for Beach Protection

All the results suggest that this famous turtle habitat is naturally stable. Apparently, the stream which its delta is located in the eastern part of this area provided enough sediment for the region when it was flowing and due to the natural headlands the shorelines formed as they are at the present time. The current natural headlands may protect the present planformes from retreatment by erosion, and there may not be any significant necessary constructions required to change the position of the diffraction points; but protecting the existing diffraction points could be very beneficial.

An example of simple protection plan for this area is illustrated in Figure 39. The structures demonstrated in Figure 39 are one 110 meter long breakwater in front of the middle headland and a 30 meter long extension attached to the offshore rocky segment. This way the current situation of the shoreline would be protected as long as the wave situation is normal,

Figure 39. Suggestions for protection plan for the Alagadi beach

6.7 Acapulco Beach Embayment Analysis

The main direction of the wave in this area is mainly from north-west. Finding the right diffraction points in this area fits the static equilibrium planform to the existing shoreline. However, this was very difficult since the direction of the main waves were not dominating the shaping of the coastline. As the results in Figure 40 shows, the unacceptable proportion of the beach that was not matching the models used in this study is open to the waves approaching from north-east waves. It is well known that north-east waves are not capable to erode or haul up the sediment particles but capable to carry the sediments in suspension. The frequent occurrences of these waves are bringing about another control point for the coastline changes in the area. Therefore, main wave direction assumptions are not accurate especially for the coastlines at the center of the coastline.

Figure 40. The closest results of PBSE, while trying to find the static equilibriums in Acapulco embayment

6.7.1 Structure Suggestions for Beach Protection

Taking into consideration the correct wave directions and submerged diffraction points the results are the way that is demonstrated in Figure 41. The static equilibrium of the Acapulco beach shows dynamic state except for the Schiaffino et al. (2012)`s model which suggests that this beach is in static equilibrium. However, the Barış beach on the west side of the region is in safe situation according to all three methods. The results led to a protective structure design which would protect the sandy beach as shown in Figure 42.

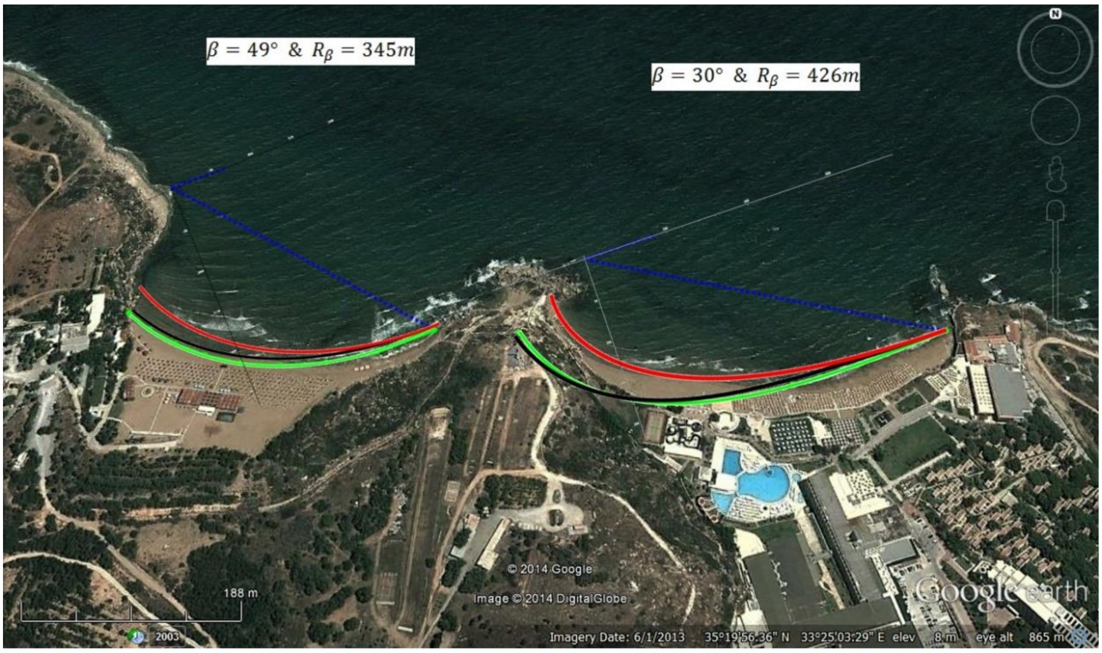

Figure 41. Unsubmerged diffraction points with right wave directions

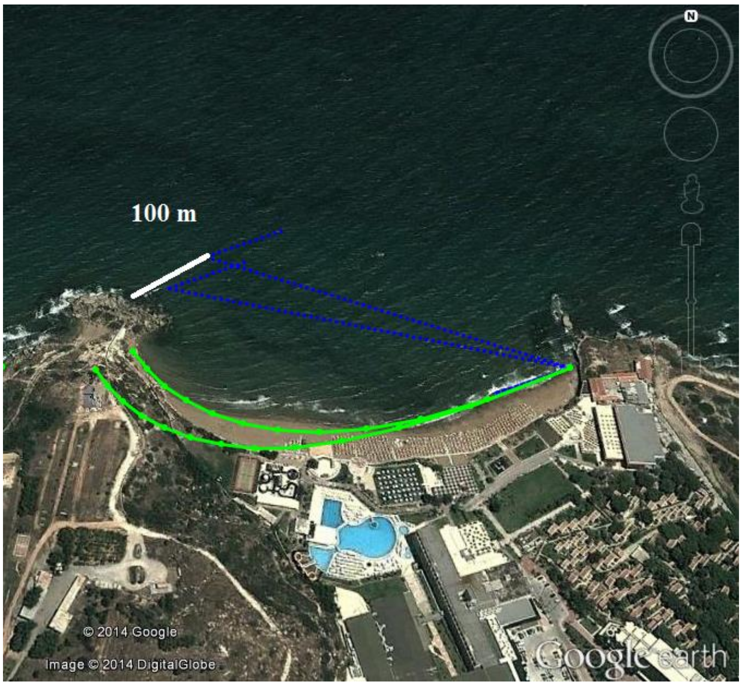

Figure 42. Jetty suggestion to force static equilibrium to the Acapulco sandy beach

6.8 Morphou Bay Analysis

As mentioned before this area had a straight and mostly rocky periphery prior to the construction of the jetties. The result of the structures was sand accumulation on the southern side of each jetty and erosion on their other side (Figure 43). This is a significant sign of the existence of longshore currents at the region. The longshore currents, carrying sediment, shows the incredible potential available in the region to be taken advantage of. The main beach in the middle is in its commencing stage of forming its landform, but the signs of natural nourishment are already noticeable. Also according to the PBSE analysis the beach will gain more sediment and move more seaward till it reaches the static equilibrium, since it is in natural nourishment state (Figure 43).

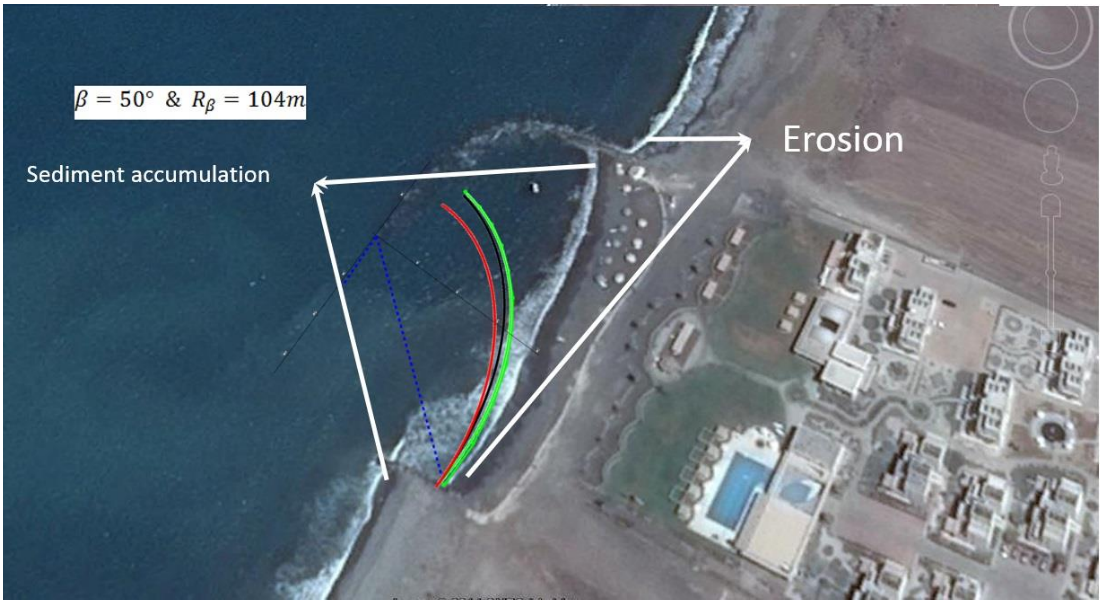

Figure 43. Morphou bay area assessment and application of the PBSE methods

The result of the aforementioned observation required a sand accumulation further updrift in the sheltered area of a headland. Tracing the coastline of the Morphou Bay towards north results in sand accumulations 10 kilometers away, extending along 6 kilometers length (Figure 44). As it is observable in the satellite photograph in Figure 44 the sand accumulation begins from the area which is the pick of the landform curve, where the tangent is turning and facing south west. Hence a slight angle change in shoreline tangent is forcing the longshore currents to release the massive amount of sand that they are carrying. Considering both observations, building appropriate jetty within the eroded area would lead to development of sandy headland bays that could be used for various commercial and ecological purposes.

Figure 44. Sand accumulation location updrift of the Morphou bay

6.9 Limitations of Implication

6.9.1 C_1 Equation in PBSE by JRC Hsu and Evans (1989)

Apparently C_1 equation (Equation 7) is not written down correctly in Klein et al. (2003)`s study , which is the actual “help document” of the MEPBAY application. Also in Raabe et al. (2010) this equation is illustrated in a different manner. After comparing the C values obtained from MEPBAY with the result of these different expressions for C_1, the results turn out to be un-identical. Since the other two coefficients (C_0 and C_2) have identical equation expression in different studies which also matches with the outcomes of the MEPBAY outputs, during the Mathematica programming, C_1 was calculated by the boundary condition mentioned previously as Equation 9, (C_0 +C_1 + C_2 = 1). The resultant equation for C_1 which is used in the Mathematica algorithm is:

$$C_1 = 0.9079 + 0.0125\beta - 0.0006494\beta^2 + 0.00002058\beta^3 - 1.4108 \times 10^{-7}\beta^4 \qquad (21)$$

Results for C_1 attained from Equation 21 are identical to the C_1 values exported from MEPBAY and satisfy Equation 9 as boundary condition. The original (JRC Hsu & Evans, 1989) did not contain any equation for C constant, it merely presented the plotted curves of the three obtained C values, for a range of β illustrated in Figure 45. These results were obtained again using the new equation and are shown in Figure 46.

As it could be seen in Figure 45 and Figure 46 the results are almost identical. The fact that the plotted output of the presented equation for is extremely close to the suggested plots of the original study, and they also are identical with MEPBAY outputs, shows the satisfying reliability of the presented equation.

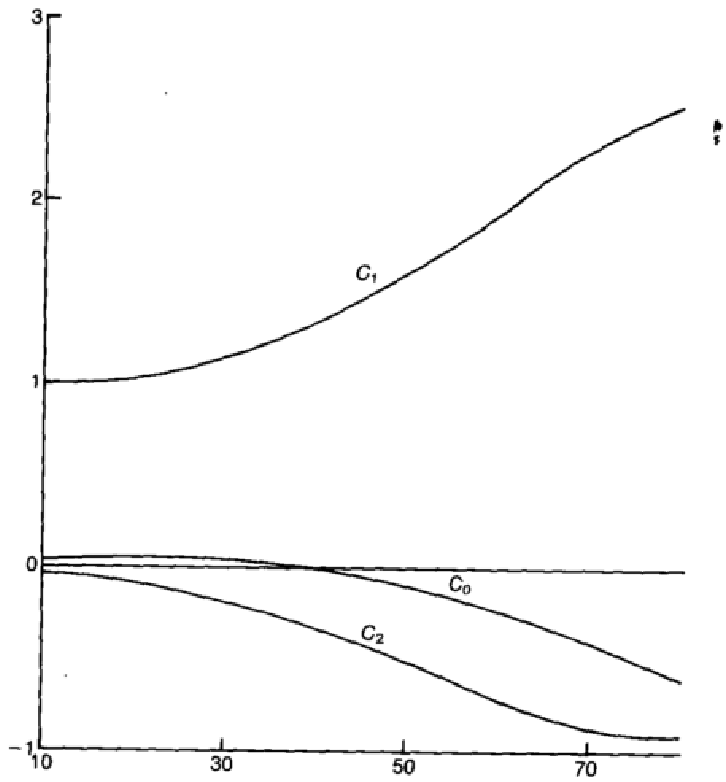

Figure 45. The original C constants for different β valuse (x Axis) plots from JRC Hsu and Evans (1989)

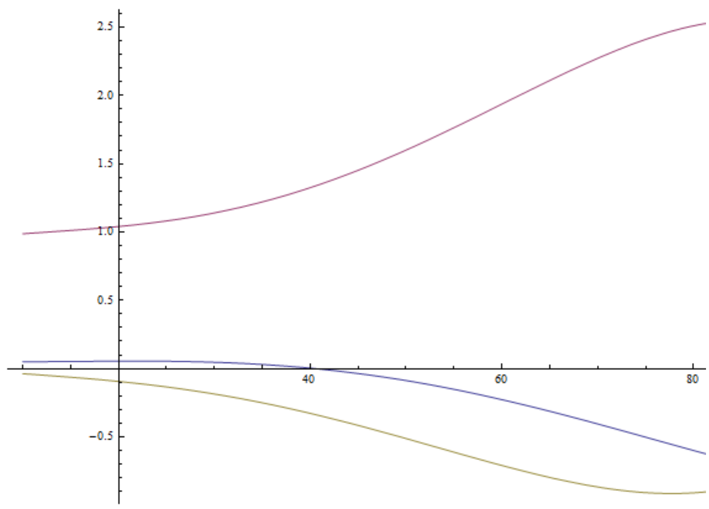

Figure 46. Plotted results C constants for different β valuse (x Axis) using the new equation expresion for C_1

6.9.2 Equation for (α) in Yu and Hsu (2006) modification for PBSE

Initially the revisited model of the PBSE by Yu and Hsu (2006), was supposed to be one of the modifications considered in this case study, beside the other two models proposed by (Schiaffino et al. (2012) and Tan and Chiew (1994)). The original publication of Yu and Hsu (2006) could not be attained during the study, hence its result equation was obtained from another study (Tasaduak & Weesakul, 2013). Equation of the α coefficient used in this modification has the expression shown in Equation 14 as cited in Tasaduak and Weesakul (2013) study, which does not satisfy the boundary conditions of the model. Since α in this approach is used as C_2 in the main PBSE (Equation 5) as well, would appear to be more than 2.5. C_0 and C_1 which are also driven from α in this approach would become out of boundary as well ($-1< C_i <2.5$). Hence this modification was not considered among the chosen modifications. These results could be viewed in Table 2.

Table 2. Values of α and C coefficients derived from Yu and Hsu (2006) modification of PBSE

β	α,(C1)	C0	C1
10	-4.0084	-3.9982	9.0065
15	-4.3842	-4.3613	9.7455
20	-4.5664	-4.5254	10.0918
25	-4.6149	-4.5507	10.1656
30	-4.5798	-4.4867	10.0664
35	-4.5003	-4.3727	9.8730
40	-4.4058	-4.2378	9.6436
45	-4.3151	-4.1005	9.4155
50	-4.2366	-3.9689	9.2055
55	-4.1687	-3.8408	9.0095
60	-4.0992	-3.7038	8.8029
65	-4.0056	-3.5346	8.5402
70	-3.8552	-3.2999	8.1551
75	-3.6050	-2.9557	7.5607
80	-3.2015	-2.4477	6.6492
85	-2.5810	-1.7108	5.2917
90	-1.6694	-0.6694	3.3388

The Mathematica algorithms generated to assess these limitations is available in appendix 2.

Chapter 7

CONCLUSION

Since in the present situation of the island, stream supply not being available anymore, the obligation of investigating the shoreline equilibriums is much higher and more critical. Aforementioned results are the simple examples of how a very simple structure can transform a beach equilibrium from dynamic state to static state, hence protecting it from being vulnerable to sediment supply diminishment. By using PBSE application, the optimized position and direction of the required coastal structures, are attainable. The data then could be used for the infrastructure of the design processes.

According to the results of this study, different modifications of the PBSE can perform different conclusions about headland bays` stability and equilibrium conditions. Evaluating the result of different modifications of the PBSE requires a more focused and dedicated study to gather and analyze more data, which would be incredibly beneficial for Cyprus`s coastal management and shoreline protection plans.

Also, according to the assessments of this study the effects of careless dam constructions on the shoreline sand budgets are irreversible on coastal dynamic equilibrium. These constructions have jeopardized the longshore sediment transport, which was supplying the dynamic equilibrium of the sandy beaches to maintain their landform. By looking at the results of this study, one could realize that most of the sandy shorelines maintained around the island are due to the natural headlands. These natural headlands have just provided an appropriate diffraction position which protected the remaining coast from erosion. This seems dangerously based on chance and unreliable for Cyprus`s economy and ecology.

This study hopefully would provide an alternative approach for future researches, to understand the critical situation of these unprotected headland bays. Simplicity of this approach in reorganization and assessment of the headland bay beaches` equilibrium is the reason why it should be used more frequently in shoreline protection plans in Cyprus.

REFERENCES

Benedet, L., Klein, A. H., & Hsu, J. (2004). *Practical insights and applicability of empirical bay shape equations.* Paper presented at the Coastal Engineering Conference.

Bishop, C. T. (1983). *A shore protection alternative: artificial headlands.* Paper presented at the Proceedings, Canadian Coastal Conference.

Broderick, A. C., Glen, F., Godley, B. J., & Hays, G. C. (2002). Estimating the number of green and loggerhead turtles nesting annually in the Mediterranean. *Oryx, 36*(03), 227-235.

Carter, R. W. G. (1988). *Coastal environments: an introduction to the physical, ecological and cultural systems of coastlines*: Academic press.

da FKlein, A. H. (2003). *Stability of headland bay beaches in Santa Catarina: a case study*. Paper presented at the Journal of coastal research: An international forum for the litoral sciences.

Davies, J. (1958). *Wave refraction and the evolution of shoreline curves*: Birbeck College.

Davies, J. L., & Clayton, K. M. (1980). *Geographical variation in coastal development* (Vol. 1522168): Longman London.

Davis Jr, R. A. (1985). Beach and nearshore zone *Coastal sedimentary environments* (pp. 379-444): Springer.

Finkelstein, K. (1982). Morphological variations and sediment transport in crenulate-bay beaches, Kodiak Island, Alaska. *Marine Geology, 47*(3), 261-281.

González, M. (1995). Morfología de playas en equilibrio. Planta y perfil. *Universidad de Cantabria*, 183-198.

Gonzalez, M., & Medina, R. (2002). *A new methodology for the design of static equilibrium beaches and its application in nourishment projected.* Paper presented at the Proceedings, 29th International Conference on Coastal Engineering.

González, M., & Medina, R. (2001). On the application of static equilibrium bay formulations to natural and man-made beaches. *Coastal Engineering, 43*(3–4), 209-225. doi: http://dx.doi.org/10.1016/S0378-3839(01)00014-X

González, M., Medina, R., González-Ondina, J., Osorio, A., Méndez, F., & García, E. (2007). An integrated coastal modeling system for analyzing beach processes and beach restoration projects, SMC. *Computers & geosciences, 33*(7), 916-931.

Halligan, G. (1906). Sand movement on the New South Wales coast. *Proceedings, Limnology Society, New South Wales, Australia, 31*, 619-640.

Hanson, H., & Kraus, N. C. (2001). *Chronic beach erosion adjacent to inlets and remediation by composite (T-head) groins*: US Army Engineer Research and Development Center.

Hemenway, P. (2005). *Divine Proportion: Phi in Art, Nature, and Science*: Sterling Publishing Company.

Ho, S. K. (1971). *Crenulate shaped bays.* Asian Institute of Technology.

Hsu, J., & Evans, C. (1989). *Parabolic bay shapes and applications.* Paper presented at the ICE Proceedings.

Hsu, J., Klein, A., & Benedet, L. (2004). *Geomorphic Approach for Mitigating Beach Erosion Downdrift of Littoral Barrier.* Paper presented at the Coastal Engineering Conference.

Hsu, J., Silvester, R., & Xia, Y. (1989). Generalities on static equilibrium bays. *Coastal Engineering, 12*(4), 353-369.

Hsu, J. R.-C., Yu, M.-J., Lee, F.-C., & Benedet, L. (2010). Static bay beach concept for scientists and engineers: A review. *Coastal Engineering, 57*(2), 76-91.

Hsu, J. R., & Silvester, R. (1996). Stabalizing Beaches Downcoast of Harbor Extensions. *Coastal Engineering Proceedings, 1*(25).

Hsu, J. R., Silvester, R., & Xia, Y.-M. (1989). Static equilibrium bays: new relationships. *Journal of Waterway, Port, Coastal, and Ocean Engineering, 115*(3), 285-298.

Inman, D. L., & Nordstrom, C. (1971). On the tectonic and morphologic classification of coasts. *Journal of Geology, 79*, 1-21.

Jackson, D. W., & Cooper, J. A. G. (2010). Application of the equilibrium planform concept to natural beaches in Northern Ireland. *Coastal Engineering, 57*(2), 112-123.

Jennings, J. (1955). The influence of wave action on coastal outline in plan. *The Australian Geographer, 6*(4), 36-44.

Khoa, V. (1995). Experimentation on bayed beaches between headlands for small wave angle. *Master's thesis, Asian Institute of Technology, Bangkok Thailand*.

Klein, A. H., Vargas, A., Raabe, A. L. s. A., & Hsu, J. R. (2003). Visual assessment of bayed beach stability with computer software. *Computers & geosciences, 29*(10), 1249-1257.

Krumbein, W. C. (1947). Shore Processes and Beach Characteristics: DTIC Document.

Lausman, R., Klein, A. H., & Stive, M. J. (2010a). Uncertainty in the application of the parabolic bay shape equation: Part 1. *Coastal Engineering, 57*(2), 132-141.

Lausman, R., Klein, A. H., & Stive, M. J. (2010b). Uncertainty in the application of the parabolic bay shape equation: Part 2. *Coastal Engineering, 57*(2), 142-151.

LeBlond, P. H. (1972). On the formation of spiral beaches. *Coastal Engineering Proceedings, 1*(13).

Leblond, P. H. (1979). An explanation of the logarithmic spiral plan shape of headland-bay beaches. *Journal of Sedimentary Research, 49*(4).

Leenknecht, D. A. (1992). *Automated coastal engineering system.* Paper presented at the Coastal Zone'89.

Lewis, W. (1938). The evolution of shoreline curves. *Proceedings of the Geologists' Association, 49*(2), 107-127.

Livio, M. (2008). *The Golden Ratio: The Story of PHI, the World's Most Astonishing Number*: Crown Publishing Group.

MacMahan, J. H., Thornton, E. B., & Reniers, A. J. H. M. (2006). Rip current review. *Coastal Engineering, 53*(2–3), 191-208. doi: http://dx.doi.org/10.1016/j.coastaleng.2005.10.009

Mangor, K. (2004). *Shoreline Management Guidelines*: DHI Water & Environment.

Martino, E., Moreno, L., & Kraus, N. (2003). Engineering guidance for the use of bayed-beach formulations. *Proc. Coast. Sed.. ASCE*.

Monroe, J., Wicander, R., & Hazlett, R. (2006). *Physical geology: exploring the Earth*: Cengage Learning.

Moreno, L. J., & Kraus, N. C. (1999). Equilibrium shape of headland-bay beaches for engineering design: DTIC Document.

Parker, G., & Quigley, R. (1980). *Shoreline embayment growth between two headlands at Port Stanley, Ontario.* Paper presented at the Proceedings of 1980 Canadian Coastal Conference.

Phillips, J. D. (1985). Headland-bay beaches revisited: an example from Sandy Hook, New Jersey. *Marine Geology, 65*(1), 21-31.

Plummer, C. C., McGeary, D., & Carlson, D. H. (2001). *Physical geology*: McGraw-Hill.

Price, W., Tomlinson, K., & Willis, D. (1972). Predicting changes in the plan shape of beaches. *Coastal Engineering Proceedings, 1*(13).

Raabe, A. L. A., Klein, A. H. d. F., González, M., & Medina, R. (2010). MEPBAY and SMC: Software tools to support different operational levels of headland-bay beach in coastal engineering projects. *Coastal Engineering, 57*(2), 213-226. doi: http://dx.doi.org/10.1016/j.coastaleng.2009.10.008

Rea, C. C., & Komar, P. D. (1975). Computer simulation models of a hooked beach shoreline configuration. *Journal of Sedimentary Research, 45*(4).

Schiaffino, C. F., Brignone, M., & Ferrari, M. (2012). Application of the parabolic bay shape equation to sand and gravel beaches on Mediterranean coasts. *Coastal Engineering, 59*(1), 57-63. doi: http://dx.doi.org/10.1016/j.coastaleng.2011.07.007

Short, A. D. (1999). *Handbook of beach and shoreface morphodynamics*: John Wiley & Sons.

Silvester, R. (1960). Stabilization of sedimentary coastlines.

Silvester, R. (1970). Growth of crenulate shaped bays to equilibrium. *Journal of the Waterways, Harbors and Coastal Engineering Division, 96*(2), 275-287.

Silvester, R. (1974). *Coastal engineering* (Vol. 1): Elsevier Amsterdam.

Silvester, R., & Ho, S.-K. (1972). *Use of crenulate-shaped bays to stabilize coasts.* Paper presented at the Coastal Engineering (1972).

Silvester, R., & Hsu, J. R. (1997). Coastal Stabilization. Advanced Series on Ocean Engineering-Vol. 14. *World Science*.

Silvester, R., Hsu, J. R., & Dean, R. (1994). Coastal Stabilization: Innovative Concepts. *Sedimentary Geology, 88*(3), 153-153.

Silvester, R., Tsuchiya, Y., & Shibano, Y. (1980). Zeta bays, pocket beaches and headland control. *Coastal Engineering Proceedings, 1*(17).

Snape, R. T., Beton, D., Broderick, A. C., Çiçek, B. A., Fuller, W. J., Özden, Ö., & Godley, B. J. (2013). Strand Monitoring and Anthropological Surveys Provide Insight into Marine Turtle Bycatch in Small-Scale Fisheries of the Eastern Mediterranean. *Chelonian Conservation and Biology, 12*(1), 44-55.

Tan, S.-K., & Chiew, Y.-M. (1994). Analysis of bayed beaches in static equilibrium. *Journal of Waterway, Port, Coastal, and Ocean Engineering, 120*(2), 145-153.

Tasaduak, S., & Weesakul, S. (2013). Development of Transient to Equilibrium Bay Shape.

Uda, T., Serizawa, M., Kumada, T., & Sakai, K. (2010). A new model for predicting three-dimensional beach changes by expanding Hsu and Evans' equation. *Coastal Engineering, 57*(2), 194-202.

Uda, T., Serizawa, M., San-Nami, T., & Furuike, K. (2002). Shoreline changes of a pocket beach caused by elongation of harbor breakwater and their prediction. *Transactions, Japanese Geomorphological Union, 23*(3), 395-413.

Vichetpan, N. (1969). Equilibrium shapes of coastline in plan.

Walton, T. (1977). *Equilibrium shores and coastal design.* Paper presented at the Coastal Sediments.

Weesakul, S., & Tasaduak, S. (2012). Experimental Investigation on Dynamic Equilibrium Bay Shape. *Coastal Engineering Proceedings, 1*(33), sediment. 37.

Wong, P. (1981). Beach evolution between headland breakwaters. *Shore and Beach, 49*(3), 3-12.

Wright, L. I., Fuller, W. J., Godley, B. J., McGOWAN, A., Tregenza, T., & Broderick, A. C. (2012). Reconstruction of paternal genotypes over multiple breeding seasons reveals male green turtles do not breed annually. *Molecular ecology, 21*(14), 3625-3635.

Wright, L. I., Stokes, K. L., Fuller, W. J., Godley, B. J., McGowan, A., Snape, R., . . . Broderick, A. C. (2012). Turtle mating patterns buffer against disruptive effects of climate change. *Proceedings of the Royal Society B: Biological Sciences, 279*(1736), 2122-2127.

Yamashita, T., & Tsuchiya, Y. (1992). Numerical simulation of pocket beach formation. *Coastal Engineering Proceedings, 1*(23).

Yasso, W. E. (1965). Plan geometry of headland-bay beaches. *The Journal of Geology*, 702-714.

Yu, M., & Hsu, J. (2006). *Parabolic bay shape equation revisited for practical applications.* Paper presented at the Coastal Engineering Conference.

Zenkovich, V. P., & Zenkovich, V. (1967). Processes of coastal development.

APPENDICES

Appendix 1: Mathematica Algorithm for Main Plotting of the Case Study

```
β = 33
r = 1012
maxt = 150 * π / 180
"Classic 1989"
c0 = 0.0707 - 0.0047 β + 0.000349 β^2 - 0.00000875 β^3 + 0.00000004765 β^4
c1 = 0.9537 + 0.0078 β - 0.00004879 β^2 + 0.0000182 β^3 + 0.000001281 β^4
c2 = 0.0214 - 0.0078 β + 0.0003004 β^2 - 0.00001183 β^3 + 0.00000009343 β^4
c0 + c1 + c2
c1 = 1 - c0 - c2
c1 + 2 c2
N[β / Tan[β]]
"Tan & Chiew 1994 "

αstatic = 0.277 - 0.0785 * 10^(β*π/180)
αdynamic = -0.004 - 0.0113 * 10^(β*π/180)
c3 = (1 + αstatic - β * π / 180 (Cot[β * π / 180]))
c4 = (β * π / 180 (Cot[β * π / 180]) - 2 αstatic)
PolarPlot[{r (c3 + c4 (β * π / 180 / t) + αstatic (β * π / 180 / t) ^2), r (c0 + c1 (β * π / 180 / t) + c2 (β * π / 180 / t) ^2)},
 {t, β * π / 180, Pi}]

αres = -2.3833 + 0.2374 β - 0.0087043 β^2 + 0.00012836 β^3 - 6.8815 × 10^(-7) β^4
c5 = (1 + αres - β * π / 180 (Cot[β * π / 180]))
c6 = (β * π / 180 (Cot[β * π / 180]) - 2 αres)
αres + c5 + c6
"r(c5+c6(β*π/180/t)+αres(β*π/180/t)^2),"
c7 = (1 - 0.8460 β * π / 180 + 0.2281 - β * π / 180 (Cot[β * π / 180]))
c8 = (β * π / 180 (Cot[β * π / 180]) - 2 (-0.8460 β * π / 180 + 0.2281))
c9 = (-0.8460 β * π / 180 + 0.2281)
c7 + c8 + c9
PolarPlot[{r (c0 + c1 (β * π / 180 / t) + c2 (β * π / 180 / t) ^2), r (c3 + c4 (β * π / 180 / t) + αstatic (β * π / 180 / t) ^2),
  r (c7 + c8 (β * π / 180 / t) + c9 (β * π / 180 / t) ^2)}, {t, β * π / 180, maxt}, PlotStyle → {{Green}, Black, Red},
 PlotStyle → Thick]
```

Appendix 2: Mathematica Algorithm for Limitation Assessments

```
In[34]:= alpha[x_] := -2.3833 + 0.2374 x - 0.0087043 (x)^2 + 0.00012836 (x)^3 - 6.8815×10^(-7) (x)^4
firstc[x_] := (1 + alpha[x] - x*π/180 (Cot[x*π/180]))
secondc[x_] := (x*π/180 (Cot[x*π/180]) - 2 alpha[x])
Grid[Table[{x, alpha[x], firstc[x], secondc[x]}, {x, 10, 90, 5}]]

c00[y_] := 0.0707 - 0.0047 y + 0.000349 y^2 - 0.00000875 y^3 + 0.00000004765 y^4

c22[y_] := 0.0214 - 0.0078 y + 0.0003004 y^2 - 0.00001183 y^3 + 0.00000009343 y^4

Expand [1 - c00[x] - c22[x]]
c11[y_] := 1 - c00[y] - c22[y]

Grid[Table[{y, c00[y], c11[y], c22[y]}, {y, 10, 90, 5}]]
```