ESHORANCE: AN ONLINE METHODOLOGY FOR ESTIMATING THE RESPONSE OF ESTUARINE SHORES FROM SEA LEVEL RISE

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ABSTRACT

Estuarine shorelines are some of the most diverse and dynamic environments along the coast. As sea levels rise, it is expected that permanent inundation will shift these shorelines landward. For some shores, erosion will also exacerbate this movement. This research looks at a methodology called eShorance, that helps understand and quantify change in wave dominated estuaries from sea level rise.

eShorance and is a simple online tool for assessing the potential movement of an estuarine shore as a result of rising sea levels. eShorance is freely available online from www.lakemac.com.au/eshoreance.

eShorance estimates shoreline movement from progressive inundation using a basic slope profile. It also estimates shoreline recession by assessing the relationship between the sediment size and the wave energy, and then the shoreline angle that will reshape towards equilibrium. eShorance allows for key factors such as sediment size and rise in sea levels to be altered and hence simulate different shoreline conditions.

Although the extent of inundation and foreshore recession in estuaries will depend very much on local conditions, the application of eShorance to Lake Macquarie shorelines shows a "typical" foreshore will retreat in the order of 5 - 20 metres for each metre of sea level rise, significantly less than the generally accepted figure for open coasts of 50 - 100 metres.

The eShorance methodology can help understand how an estuarine shore may respond to rising sea levels, and therefore provide a starting point as to how to best manage and prepare for such change.

Keywords: sea-level rise, estuaries, climate change, erosion, inundation, recession.

INTRODUCTION

Australia hosts some of the most beautiful and productive estuaries in the world. As a result of anthropogenic climate change, the global mean sea level is projected to rapidly increase. This will have a range of impacts on estuaries, particularly the landward migration of shorelines.

How estuarine shores will change as a result of rising sea levels has been difficult to quantify – the commonly used ‘Bruun Rule’ (1962) equilibrium equation cannot be easily applied to estuaries as the wave climate and sediment is often vastly different to that of the open coast. Therefore, as an outcome of a study into estuarine change, a simple methodology for estimating shoreline change was developed. The tool is called eShorance and is publically available from www.LakeMac.com.au/eShoreance

eShorance is designed as a starting point to understanding the vulnerability of a specific shoreline. Using simple field tests and basic equilibrium calculations, eShorance gives estimated change to a specific shoreline that incorporates the effects of progressive inundation and recession. It also allows for key factors such as sediment size and rise in sea levels to be altered and to therefore assess different shoreline conditions. The tool is best suited to estuarine shores where the wave energy is generated from wind, rather than tides or currents.

STUDY LOCATION

Primary research was conducted in Lake Macquarie, a large wave dominated estuary located just south of Newcastle, Australia. Lake Macquarie covers an area of approximately 115km^2 with 174km of foreshore made up of a range of shoreline types including rocky headlands, silty deltas, gravely and sandy shores. The lake is comprised of a number of coalescing bedrock valleys with small river catchments (Roy, 1984). Much of the shoreline, particularly on the western side, consists of muddy sands that thinly cover the bedrock valley sides. On the eastern side of the lake the shoreline is a finely sorted marine sand barrier. (AWACS, 1995).

Lake Macquarie, like nearly half of all south-eastern Australian estuaries is wave dominated estuary (OzCoasts 2010). The channel is relatively narrow and the main energy within the basin is wind waves.

METHODS, TECHNIQUES AND MATERIALS

The eShorance methodology was developed from both primary and secondary research.

A literature review into Australian and international estuary and sea level rise research concluded that how an estuary will change greatly depends on the estuarine morphology, which is the relative importance of tidal, wave and fluvial influences. These driving factors were further researched then distilled down into the key drivers for change.

Following this, field work and observation was carried out around Lake Macquarie to establish shoreline types and behaviours, and to trial different methods for predicting change.

Environmental consultants, Cardno Lawson and Treloar, were engaged by Lake Macquarie City Council to conduct field tests and run hydrological computer models on 10 sites around the lake. The modelling included hydraulic, wave, sediment transport, and morphological processes. These studies were used to qualify the parameters used in eShorance and develop the relationship between nearshore depth to nearshore wave height, and then from nearshore wave height to near bed velocity.

Estuary Processes

An estuary is, simply put, a semi-enclosed coastal body of water that is open to the sea (Prichard 1967). However, estuaries are far from simple. They are made up of diverse landforms and geology, and have dynamic processes of rivers, tides, and waves constantly shaping and changing the shores.

The eShorance methodology addresses the effects of sea level rise in wave dominated estuaries. As shown in Figure 1, a wave dominated estuary is a coastal bedrock embayment that has been partially in filled by sediment from both the catchment and marine sources. The estuary has a barrier at the mouth which constricts the exchange of water, reducing the energy from tides (OzCoasts 2008).

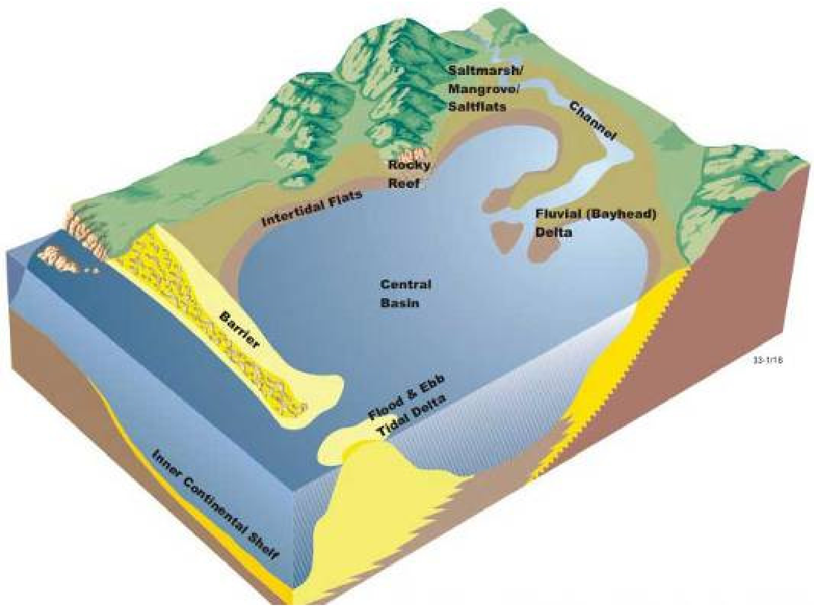

Figure 1: Wave dominated estuary (OzCoasts 2008)

Differences between coasts and estuaries

There has been considerable research into how open oceanic shorelines may respond to rising sea levels. Models such as the Brunn rule (1962) provide a ‘rule of thumb’ as to how an oceanic shoreline may respond. However, there has been less research into the impact of sea level rise onto estuarine environments. Due to the significantly different material properties and physical processes found within an estuary, coastal research and methodologies for assessing shoreline change cannot be easily transferred to estuarine environments.

Some of the key differences between estuaries and oceans, and how they will respond to sea level rise are:

- Estuaries are typically not directly exposed to oceanic swells and storm waves other than around the estuary mouth. Rather, estuaries are exposed to smaller wind waves generated across the available fetch of the estuarine water. (Sharples 2006)

- The materials that make up estuarine shorelines are often significantly different to that of coasts. Estuaries are generally drowned river valleys, and therefore have shorelines dependant on local geology. Sediment has also been received from fluvial sources.

The movement of sediment is different for coasts and estuaries. Small scale littoral (longshore) sand transport may occur on shores within an estuary, however not on the large scale that is common along ocean beaches. (Sharples 2006)

RESULTS

As a result of the literature review, a simplified methodology for assessing estuarine shoreline change from rising sea levels, eShorance was developed. The methodology consists of 5 key steps covering the key elements of estuarine change from sea level rise.

The first step is gathering a slope profile for both the back shore and offshore. This slope profile is used to calculate rates of inundation, and an average water depth is then used in step three to calculate nearshore wave velocity.

In step three, a soil sample is taken to determine average particle size. Although there are many factors that contribute to soil erosion, eShorance is simplified to only test for particle size.

Step three looks at the relationship between average water depth and near shore wave height. Then the relationship between near shore wave height and velocity. Using the ratio between particle size and wave velocity, an adaptation of the Hjulstrom diagram determines the likelihood of erosion.

Step four uses basic triganomic equations to calculate the additional shoreline erosion for an estuarine shore to maintain its shoreline profile.

This methodology has been built into an interactive web tool, available from www.LakeMac.com.au/eShoreance

eShorance has 5 key steps, which are as follows:

Step One: Creating A Shoreline Profile And Setting A Rise In Sea Levels.

The first step in eShorance is to generate a two-dimensional profile of the shoreline, perpendicular to the waterline. It includes both the topographic (backshore) and bathymetric (offshore) slope.

The backshore profile is the land directly behind the mean water mark. The extent of the backshore can be adjusted depending on any significant changes to the slope or obstructions to measurement. Generating the backshore profile is through measuring a fixed vertical height at the mean water line then measuring back to where this intersects with the land. Based on these figures, eShorance uses a slope equation to calculate the slope percentage:

Rise/run * 100 = Slope profile (%)

Where
Rise = vertical height
Run = distance to where this height connects with the land

For example:
Rise = 1.5m
Run = 18.75m
Backshore profile percentage = 8%

The offshore profile is a measurement of the shorelines bathymetry, that is, the shape of the underwater topography. The offshore profile plays a role in how water interacts with the shore, specifically the energy of waves hitting a shoreline. The methodology for generating the offshore profile is to measure the water depth at 10m from the mean water mark.

Ten metres was specified as the approximate extent of the nearshore zone. As waves approach the shoreline and enter shallower water, the waves are affected by bed friction, where the sea bed reduces wave energy and causes shoaling (the concentrating of wave energy). To what extent this occurs depends on the wave period and the change in the water depth. For simplicity, a limit to this zone was set at 10 meters, which was found through the field work to be a sufficient area to measure the nearshore activity. (CLT 2010).

Based on this 10m zone and the depth at this point , eShorance again uses a slope equation to calculate the offshore slope percentage:

Slope profile (%) = Depth/run * 100
Where
Depth = water depth at 10m
Run = 10m

For example:
Depth = 0.5m
Run = 10m
Backshore profile percentage = 5%

eShorance also automatically calculates the average nearshore depth, which is the average depth of the water over the 10m period. This is used at a later stage in the tool to estimate wave height.

Average Nearshore Depth = Depth10 + Depth 0 / 2
Where
Depth 10 = water depth at 10m from mean water mark
Depth 0 = Depth at the mean water mark (0m)

For example:
Depth of water at 10m = 0.5m
Average nearshore depth = 0.5 + 0m / 2 = 0.25m

Setting Rise In Sea Levels:

Sea levels are not static – they are in a constant state of change from tides, waves, response to air pressure and nearshore winds. However, as well as these periodic changes, there is a slower and more permanent rise in global sea levels as a result of anthropocentric climate change. An adopted projection of rise for New South Wales is an increase of 0.9m by 2100 on 1990 levels. (DECCW 2009)

eShorance allows a variable input of a projected rise in sea levels. For example, if the shoreline is to be assessed for a 50 year period, a rise of 0.5m may be selected. This figure can be later changed to assess how different rises in sea levels can alter the shoreline movement.

Step 2: Calculate Shoreline Inundation

Now that a basic shoreline profile has been generated, eShorance uses the backshore slope and selected rise in sea levels to estimate the landward movement of the shoreline from progressive inundation. This is shown in figure 2.

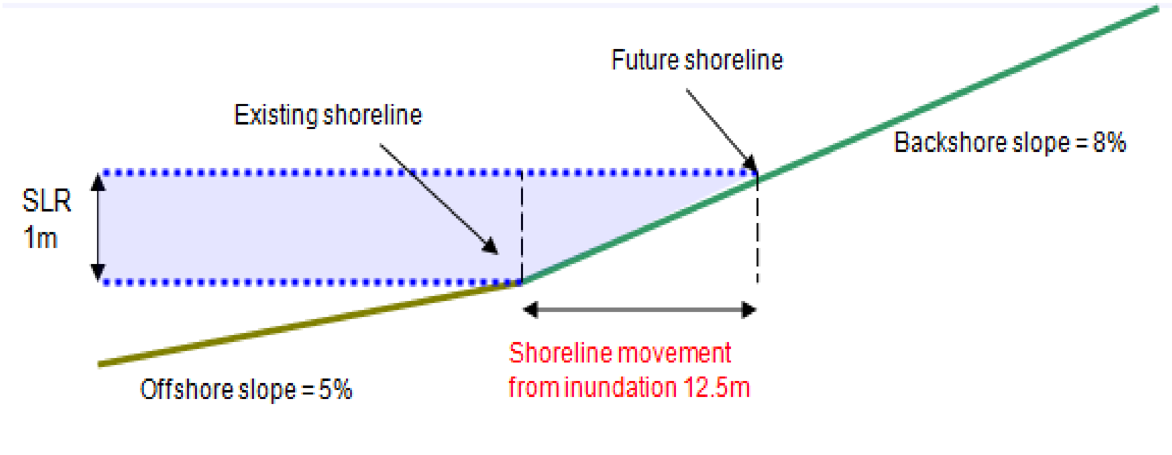

Figure 2: Calculating shoreline movement from inundation using slope profile.

If the backshore has a profile of 8% and the sea level rise is 1m, the distance the shoreline will move from progressive inundation is 12.5m.   The slope equation used to calculate this is as follows:

Slope (%) = Rise / Run multiplied by 100

Where:

Slope = Backshore profile
Rise = sea level rise
Run = Shoreline movement from inundation (x)

For example:

Slope = 0.08
Rise = 1m
8 = 1 / run multiplied by 100
1/8 * 100 = Run

Therefore the total shoreline movement from inundation = 12.5m

It is important to note that the effects of inundation from long term sea level rise will be exacerbated by existing periodic or temporary hydrological processes such as tides, wind waves, floods, and storm surge.

Step 3: Determine Shoreline Erodibility

Step 3 of eShorance determines the shorelines susceptibility to recession through calculating the sediment particle size and the shoreline wave energy.

Shoreline recession is the progressive landward shift of the shoreline from erosion. Recession occurs when wave energy dislodges and removes sediment from a shoreline. When the outgoing sediment from a shoreline is greater than the incoming sediment, a shoreline will shift landward.

Recession depends on the shoreline material as well as the wave energy hitting the shore. For example if the shoreline material is unconsolidated sand and the wave energy is high, recession may occur. Whereas, if the shoreline material is hard rock or the shoreline is protected from waves, the erosion rates will be slow or negligible.

The rate of shoreline recession as a result of rising sea levels is hard to predict as, generally, it does not proceed evenly as sea levels rise, but occurs periodically during major storm events, when energetic waves can reach the backshore to cause erosion. Therefore there is a lag between the sea level rise and the corresponding degree of erosion. The lag will depend on the frequency and intensity of storms affecting the shoreline.

Not all shorelines will erode – it is a complex ratio between the shoreline material and wave energy. eShorance uses the average particle size of the shoreline's sediment and the nearshore wave velocity (wave energy) acting against those particles to calculate the likelihood of erosion.

Shoreline Erodibility:

There are a range of elements that determine how erodible a shoreline is, such as the particle size, the coherence between them, the dispersibility of the fine particles, and the amount of clay present. For simplicity, eShorance only takes into consideration the sediment particle size as an indication of erodibility.

Within a shoreline's two-dimensional profile there may be many different sediment particle sizes. Diversity can be found between the high and low water marks, with larger sediment being moved further into the backshore from strong waves and finer particles along the mean shoreline. Further back the sediment type can change – for example a sandy shore backed by bedrock. Diversity can also be found by digging vertically downwards – as waves wash over a shore, there is a tendency for particles to sort themselves, smaller particles that move with lighter wave energy along the top covering larger particles below. Of course, moving along the shoreline away from the profile may also see significant changes – a rocky outcrop that transitions into a gravelly mud.

This diversity of shoreline material can make it difficult to quantitatively describe and therefore assess. It is not known exactly how each unique combination of sediments will respond to sea level rise. For example, a shoreline with a mix of sand and gravel may erode in a different way to one where there is a mix of sand and cobbles.

eShorance uses the average particle size of a sediment sample taken at the mean water mark down to a depth of approximately 10cm. Greater accuracy would be attained by taking additional samples along the profile.

Calculate Shoreline Wave Velocity:

The next step in identifying if a shoreline is erodible is to calculate the nearshore wave velocity that is reaching the shoreline.

The depth of the water limits the height of a wave. A wave is not just felt on the top of the water, but moves along below the surface as well, causing seabed shear force. As a large wave approaches the shore and enters shallower water, the wave is subject to bed friction, where the shoreline bed reduces the wave energy. Bed shear force induced by waves has the ability to mobilise sediment and remove it.

The wave then meets shallow water and shoals, concentrating the wave energy. In order for the wave to maintain its wave energy, its height increases. The rate at which this occurs depends on the wave period (the time between successive wave crests) and the change in water depth (bed slope). At some critical depth, the waves become too steep and break. (Cardno 2010). The near-bed stress from these waves act on the bed sediments to move sediment and cause erosion.

Based on this hydrological process, computer modelling conducted by Cardno Lawson Treloar (2010) at 10 sites around Lake Macquarie developed a correlation between near-bed velocities and wave height (figure 3). The modelling was developed using the Delft Technical University SWAN wave model and included wind input, offshore wave parameters, refraction, shoaling, non-linear wave interaction, wave propagation, bed friction, white capping, currents, and wave breaking. For the case sites, a historical wave climate was developed by modelling a large range of wind directions and a range of wind speeds from 2.5 to 30m/s. This generated 176 wave modelling cases which were then run at the lake mean water level. This model output provided a long-term time series of wave parameters at each of the foreshore locations in terms of wave height (Hs), wave period (Tz) and direction, together with wind speed and direction.

Site Location	H_s (m)				
	Mean	H_e	ARI (years)		
			5	10	100
1	0.07	0.38	0.80	0.88	1.16
2	0.10	0.46	1.01	1.13	1.53
3	0.05	0.25	0.66	0.73	0.99
4	0.08	0.45	0.86	0.93	1.17
5	0.06	0.09	0.77	0.87	1.19
6	0.07	0.31	0.87	0.97	1.32
7	0.09	0.41	0.55	0.57	0.64
8	0.05	0.55	0.83	0.89	1.06
9	0.11	0.51	1.01	1.10	1.41
10	0.08	0.39	0.94	1.05	1.40

Figure 3: Hydrological modelling on wave conditions for 10 sites around Lake Macquarie (CLT 2010).

The waves that cause erosion are generally those generated during high energy storm events, and are episodic in nature. Therefore from the model, the peak storm wave heights were identified, which were analysed to provide extreme wave conditions for selected average recurrence intervals (ARI). To identify the more ‘typical’ storm condition waves, the effective significant wave height (H_e) was used, which is the wave height that is exceeded 12 hours per year.

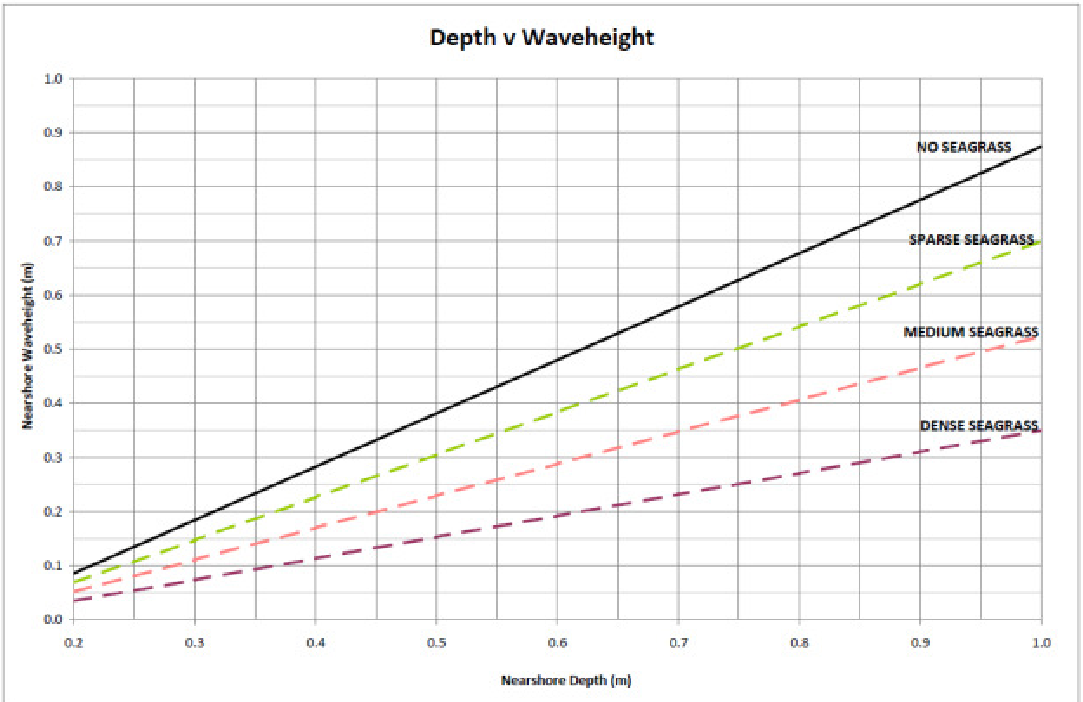

Figure 4: Relationship between average nearshore depth (10m) and nearshore wave height

Figure three shows the plotted case study sites and a line of best fit to create a relationship between the case sites average nearshore depth and their nearshore wave height. It also shows the attenuation from sea grass - it has been found that the effectiveness of sea grass to reduce wave energy depends on the wave length, water depth, the width of the sea grass meadow and the sea grass density. (Wallace and Cox, 2000; Bouter, 1992; Thomson et.al, 2003 from CLT 2010).

eShorance requires the user to chart their nearshore water depth to find the nearshore wave height.

Calculating Nearshore Velocity:

In the same way as calculating nearshore wave height, the 10 case sites around the lake were used to create a relationship between nearshore wave height and nearshore velocity.

The height of a wave is proportional to its near shore velocity, that is, the wave energy entering the nearshore zone. The relationship between bed shear forces and near bed velocities are a standard parameter used in sediment transport studies (CLT 2010). The plotted relationship is as shown in figure five.

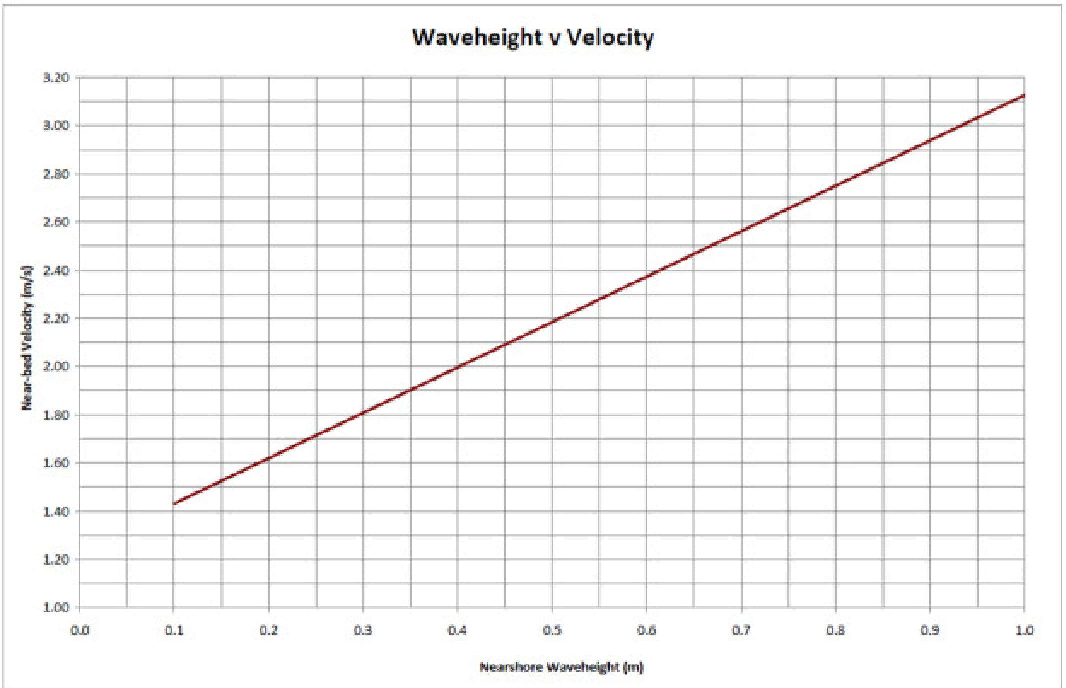

Figure 5: Relationship between nearshore wave height and near-bed velocity

eShorance requires the user to chart their nearshore wave height to find the corresponding near bed velocity along the line of best fit.

Determining Erodibility:

Once the shoreline average sediment size and near bed velocity has been determined, it is possible to assess the ratio between the two factors and determine the likelihood of erosion.

One of the most widely used relationships for sediment movement was published by Hjulström (1939). It provides the relationship between grain size and water velocity for erosion, transportation and deposition of sediment. Figure six is an adapted version of the Hjulström curve for critical velocity up to 1m depth of water. Use of the Hjulström curve allows an assessment to be made as to whether a shoreline is likely to erode given the average sediment size and the near-bed wave velocities at the site.

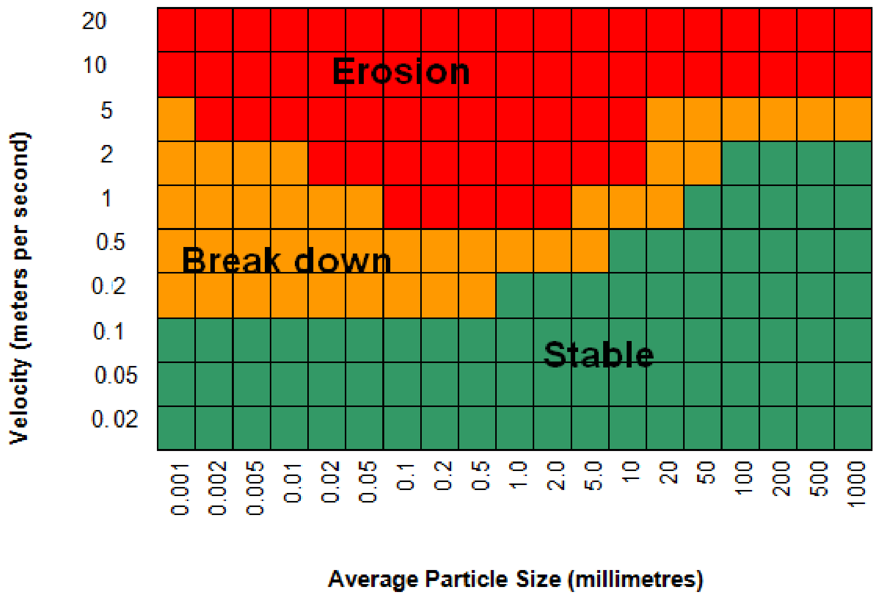

Figure 6: Adaption of the Hjulström Diagram

Shorelines that fall within the red zone are where there is sufficient velocity to move sediment and are likely to erode. Shorelines that fall within the orange zone may have sediment movement however not sufficient to remove from the nearshore zone. Shorelines in the green band remain largely stable. The smaller particle size has a wider band of possible break down as at this size the sediment is often fine silts or clays, which have a higher cohesiveness.

This graph creates a visual relationship between what would be the ideal particle size for the shoreline for it to be stable. For example, if a shoreline has a near bed velocity of 1m/s then the average particle size should be above 5mm for it to be a stable shoreline.

Step 4: Calculate Shoreline Recession

If the shoreline has been deemed as erodible, then Step four of eShorance calculates how far recession would occur in order to move towards its original shoreline profile.

Most estuaries within Australia formed as a result of flooding from the end of the last ice age, stabilising somewhere between 15000 and 6000 years ago (Kench 1999). During this relatively stable period, the localised wave climate has continuously shaped the shorelines underwater profile. It would be expected that as sea levels rise, the same wave climates will continue to act upon the shoreline, maintaining the same offshore profile.

One of the best known models for calculating shoreline recession from sea level rise is the Bruun Rule (1962). However, the Bruun Rule is applied largely to open oceanic sandy shores, and as such it does not necessarily provide a good model of the response of bedrock, coarse sediment or very fine sediment shorelines (as in those found in estuaries) to sea level rise. (Cooper & Pilkey 2004). Other reasons it cannot be applied to estuaries are that within an estuary, eroded material is often not re-deposited offshore but is lost to the basin (Lee and Mehta, 1997; Kirby, 2000, in Rossington 2008). Sediment once removed is often not likely to return, unlike sediment on an open oceanic sand beach. Rather, sediment being returned to an estuarine shore depends on the supply of sediment from wider sources, for example fluvial or marine sediment. Also, once a severe weather event has passed, the wave energy in an estuary is not sufficient to move sediment back to its place in the profile. This is unlike oceanic shores, where the daily tides and daily wave action can redeposit sediment back onto the shore.

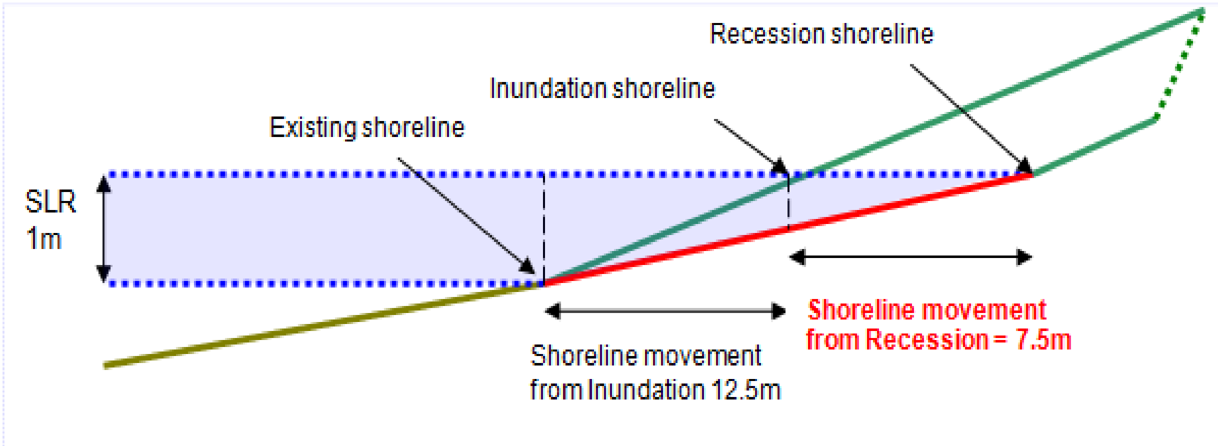

Figure 7: Shoreline recession caused by shifting towards equilibrium.

eShorance uses simple trigonomic equations to calculate the landward movement from recession, as shown in figure seven. For simplicity, the eShorance profile assumption does not take into consideration where the dislodged sediment would settle. For an open ocean coast, the sediment generally remains within the active nearshore zone. However for an estuary, this sediment is often lost into the wider basin and therefore is not considered in obtaining equilibrium.

The calculation used is:

***R* = (*s/mb* – *s/mt*) * 100**

Where

R = Shoreline recession
s = sea level rise
mb = bathymetric slope
mt = topographic slope

For example,

Sea level rise = 1m
Offshore slope = 5%
Backshore slope = 8%
= (0.2 – 0.125) * 100 = 7.5m

When applying this methodology to shorelines around Lake Macquarie it was found that the retreat for a typical shoreline with a 1 meter rise in sea levels was around 5-10m. This is significantly less than the Bruun rule estimates of 50-100 meters.

Step 5: Summary of Results

Step five of eShorance is to combine any potential shoreline movement from progressive inundation and shoreline recession to give a total shoreline movement.

For example, the outcome may look like:

With a predicted rise in sea levels of **1m**, **Boonai Shoreline**, located in **Lake Macquarie** is projected to have shoreline movement of **12.5m** from inundation, **7.5 m** from recession and total shoreline movement of **20m.**

This step also highlights qualifiers as to the many factors that can impact the results. They include, among others, artificial modifications, vegetation, changes to soil types, tidal and fluvial currents and sediment budgets.

DISCUSSION

Developing a quantitative tool for accurately predicting shoreline change is extremely difficult, as there are many factors influencing shoreline change. To be of use to the greatest number of stakeholders, this complexity has been greatly reduced and as such, eShorance has a number of limitations to its application and accuracy.

Application Of Tool:

eShorance is designed only for estuaries and does not apply to open oceanic coasts. The modelling and research has been done within Lake Macquarie, which is a wave dominated estuary. As such, eShorance will provide the most accurate results when applied to wave dominated estuaries.

Application of eShorance is along a two-dimensional profile, running perpendicular to the shoreline. This however cannot take into account the considerable differences in its sediment and wave climate along its span. If there are significant changes along the shore, for example, a sandy beach with rocky outcrops, eShorance should be applied at all points where change is evident. However, running the tool several times will not accommodate for the interaction between the shoreline types - for example, how the rocky outcrops may hinder or help the sandy regions to recess.

Quantified Results:

Whilst it is relatively straightforward to assess the ‘theoretical’ impact of sea level rise on estuaries, it is more difficult to quantify the potential magnitudes of change. (Haines 2008). There can be many variables for any shoreline, and these factors can change over time. When considering changes to the climatic system, it is possible that the impact of one variable may exaggerate or dampen the impact of another, making the result better or worse than initially projected. As such, it is difficult, if not impossible, to predict exactly the likely result on coastal processes once all factors are taken into consideration. (Haines 2008)

eShorance takes into consideration key factors at play – the erodibility of a shoreline, the wave velocity and the shape of the offshore and backshore profile. It quantifies these factors in a way that results can be giving in terms of metres that a shoreline may move in response to sea level rise. It does not however quantify the effects of the many other factors, such as vegetation, artificial modifications, or localised tides and currents.

Simplified Methodology

The data collection and processing for eShorance is very basic. eShorance only requires a simple backshore and offshore slope profile and one sediment sample taken at the mean water mark. This allows the tool to be easily used without technical knowledge or expensive equipment. However, it does decrease the accuracy of the results. The more data collected, the more accurate the results will be.

Entrance Dynamics

All estuaries have an opening either permanently or intermittently to the ocean. Climate change is likely to have significant impacts onto the entrances' processes and behaviour. Given the entrance to an estuary largely control the sensitivity of the estuary, any significant change to these conditions is likely to have major repercussions for other physical, chemical and biological processes (Haines and Thom 2007).

eShorance looks at the potential change to a shoreline from sea level rise without taking into consideration the other major changes that may occur to the estuary from climate change, including the channel.

Other Climatic Changes

eShorance does not take into consideration the other changes to an estuary that may occur as a result of climate change. For example, it is expected that storms will increase in both their intensity and frequency along some parts of the Australian coast line (DCC 2008). eShorance also does not adequately allow for the recession assessment to consider inundation. For example, a shoreline that may experience a 1m rise in sea levels may be several hundred meters back from the shoreline which is being assessed, and therefore may have vastly different sediment and slope profile.

CONCLUSION

Rising sea levels are set to significantly change the face of estuarine shores. Understanding, estimating and quantifying this change is a first step in being able to manage and prepare.

Much research has been done into how open ocean shorelines may respond, but this research cannot be easily transferred over to estuaries. The Bruun 'rule of thumb' indicates a 50-100 meter recession for every 1 meter rise in sea levels however eShorance indicates that this is more likely to be Instead the eShorance methodology was developed as a starting point tool to provide a quantifiable estimate for shoreline change.

Due to the complexity of estuarine morphology, eShorance is greatly simplified and as such cannot give great accuracy. It does however have the ability to show the relationship between progressive inundation and recession and provide a first point assessment as to how a shoreline may move over time. It also easily allows for key factors such as particle size and a rise in sea levels to be altered. It is expected that the eShorance methodology will be developed and improved into the future.

ACKNOWLEDGEMENTS

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