Land-use strategies for coastal erosion zone based on a risk-informed approach

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Abstract: Dunes play a significant role as sea defenses along the coast in protecting inland area from storms. Dune erosion during severe storms may lead to dramatically coastal recession that threatens property located within the eroded strip. The changes in the dune defense role is consequently of interest as the global climate changes. A prudent land-use strategy is required to balance the potentially huge economic profits with the high erosion risks. In this paper, a guideline which is based on a trade-off analysis and the time-dependent probability of coastal recession distance will be developed to maximize the total profit function. Coastal management approaches of setting a buffer zone and beach nourishment will be analyzed and optimized. The probabilistic economic model will provide an optimal land-use planning tool for sandy coastal zones, which can assist decision makers in efficiently exploiting coastal resources.

Keywords: Coastal management, dune erosion, coastal recession, trade-off analysis, land-use

1. Introduction

It is known that the world’s coastal regions are generally more heavily populated than the continental interior (Small C. et al. 2000). Many metropolises are located in coastal regions and attracting more and more people to inhabit and invest in. More over, many coasts with sunny beach and warm water are popular tourist resort, where have lots of hotels, restaurants, shops and houses near the sea. Unfortunately, any investors who intend to gain benefit in the coastal zone will not only face the market risk but also the natural hazards from the changeable sea than other investors. Coast erosion is one of the risk resources. While protecting the coast, dunes along the coast will be eroded due to the severe storms and the sea level rise (SLR). Therefore, in the coastal context a land-use strategy is expected to propose a compromising solution between the huge commercial potential and the high erosion risk.

Based on the model proposed by Callaghan et al. (2008), a probabilistic estimation of dune recession distance can be derived, that is, an erosion contours paralleling to the coastline is available. Building on the previous work by Vrijling et al. (2002) and Jongejan and Ranasinghe (2009), two alternative strategies are studied in this paper, “retreat” and “attack”, i.e. setting a buffer zone to keep far from the high probability of being eroded and extending the coast width to move the iso-risk contours seaward.
The main purpose of this study is to provide a guideline to optimize the property configuration in coastal zone according to the time dependent erosion probability. More specifically, the study aims to achieve the following objectives:

a. To develop a coastal land-use planning framework considering the changing trend of coastline position.
b. To determine the economical optimal “retreat” or “attack” distance from present shoreline for each strategies.

The paper is organized as follows. First, coastal risk and relative elements are introduced and a hypothetical coastal zone is proposed to make some simplification and assumptions for practical situations. Next, a trade-off analysis is executed to find the economic optimization of land-use strategies in coastal zone. The article ends with conclusions and recommendations of the study.

2. Risk in the coastal zone

2.1 Risk

A definition of risk contains three components: outcomes that have an impact on what humans value, the possibility of occurrence (uncertainty) of an event and a formula to combine both elements (Renn, 1998). In the case of coast zone, risk can be defined as the damage (economical, social, ecological and environmental) induced by a storm event times the occurrence probability of the event. If the occurrence probability is expressed by return period, the risk equals to the expected annual cost for storm hazards. In this paper, “risk” refers to the expected annual cost due to the erosion, it is important to note that the probability of erosion itself does not represent risk. It is a component factor of risk.

2.2 Dune erosion

Dune erosion is usually the result of a combination of reasons, both episodic erosion and long term shoreline retreat trend with different time scales. Short term dune erosion is that, once the storm impacts on the sandy beach, sediments from the mainland and upper parts of the beach are eroded and settled at deeper water, while the long term dune erosion is caused by climate change, alongshore sediment transport and anthropogenic impacts et al..

Recently, Callaghan et al. (2008) proposed a model (JPM model) to derive joint probabilities of the main involved variables in extreme wave climate to be used in beach erosion, this model can be used to determine the probabilities for a range of dune erosion volume. Ranasinghe et al. (2011) extended the model by taking into account the SLR. The model (PCR model) can provide probabilistic estimates of coastal recession distance, which is the distance between the initial edge of the dune and the edge of the dune after a period time. Therefore, the probabilistic recession distance can be described as a function of distance from coastline $p(x)$, see Fig. 1.
Vrijling et al. (2002) made a simple approximation to the probability of exceedance of erosion with exponential distribution. In this paper, we assume the probability of eroded at position $x$ is:

$$p(x) = e^{cx}$$  \hspace{1cm} (1)

Where, $c$ is a constant coefficient.

![Figure 1. Erosion probability as a function of distance form shoreline.](image)

The erosion probability contour is a set of lines, on which the erosion probability is the same, as shown in Fig. 2. It is predicted to shift landward gradually because of the relative SLR, in consequence the erosion probability $p(x)$ at certain point in the erosion prone zone will increase over time. Jongejan et al. (2010) simulated the increasing probability trend by the way of establishing an exponential formula, that is, increasing rate is assumed to be exponential:

$$p(x,t) = p(x,0)e^{at} = e^{cx+at}, \quad \text{and} \quad a \cdot t \leq - \ln p(x,0)$$  \hspace{1cm} (2)

Where $t = \text{time (year)}$, $a$ is probability rising rate.

![Figure 2. Example of the coastal zone and erosion probability contours.](image)
2.3 Economic value in the coastal zone

Many coast regions can be characterized as high density land-use area, where has booming economy and population. For instance, in a seaside resort, a large number of buildings are constructed for tourist trade, such as hotel, restaurant and waterfront promenade. The distribution of the economic value in the coast zone is parameterized as a function of the distance from the shoreline by the economic value density function \( v(x) \) (Vrijling et al. 2002), if \( L \) is length of the coastal block, \( x_1 \) and \( x_2 \) are distance from shoreline as indicated in Fig.2, then the total value of the properties \( V \) from \( x_1 \) to \( x_2 \) is:

\[
V = L \cdot \int_{x_1}^{x_2} v(x) \, dx
\]  

With regard to the quantification of property loss, several assumptions and simplifications are made here:

a. Only the property damage due to the erosion is considered. This paper aims to suggest a most reasonable coastal land-use planning in the view of economy, but it does not mean that other damage is less important or can even be neglected. On the contrary, environmental factors usually should come first;

b. The structures will be totally destroyed if being eroded, and will be rebuilt immediately after the erosion;

c. We assume that the properties locate further than \( D \) m from shoreline will have neither additional risk nor additional benefits form the sea. For the purpose of explaining the way of finding optimal position, the return rate on investment is simply assumed as

\[
\begin{cases}
R(x) = A - B \cdot x & \text{for } (0 < x < D) \\
R(x) = R_m & \text{for } (x \geq D)
\end{cases}
\]  

(4)

\( A, B \) and \( D \) are constant coefficients, and \( R_m \) is the mean return rate where properties locate inland.

d. \( v(x) \), as shown in Fig.2, is assumed as a constant, and Eq. (3) becomes

\[
v = \frac{V}{(x_2 - x_1) \cdot L}
\]  

(5)

These approximations are made for easily explaining how this risk informed approach work. The limitations can be relaxed in reality by employing the expressions closer to practical circumstance.

3. Economic optimization of land-use strategy in coastal zone
3.1 Buffer zone

Buffer zone is the transition region between shoreline and the constructions development area. It is a natural land area where has intense interaction with ocean. And establishing a buffer zone is a land-use policy to keep properties away from unexpected storm hazards, as well as mitigate the anthropophagic intervenes to coastal zone. In the view of economy, buffer zone is an area with larger economic loss due to natural hazard than benefit from the investment.

To analyze the trade off between benefit and loss, the Net Present Value (NPV) per length of shoreline (i.e. total NPV divided by shoreline length \( L \), \( \text{euro} / \text{m} \)) is calculated by considering the time value of money. In this context, the optimal width of the buffer zone is where the properties on the coast can gain its maximum NPV. And the NPV can be expressed as the sum of present value of annual return minus investment and the sum of present value of annual payment for erosion.

Jongejan et al. (2010) gave a general equation, which proposes an optimal position \( x \) for a single property during its limitless life time.

\[
\text{NPV} = \int_0^\infty R(x) \cdot v \cdot e^{-\gamma t} \cdot dt - v - \int_0^\infty P(x,t) \cdot v \cdot e^{-\gamma t} \cdot dt
\]  

In the proposed artificial case study, considering the limit economical life of the properties and the changing damage probabilities, the equation becomes:

\[
\text{NPV} = v \int_{x_1}^{x_2} R(x) dx \cdot \beta - v \cdot (x_2 - x_1) - v \sum_{i=1}^\tau p(x,i) \cdot \frac{1}{(1+r)^i}
\]

\[
\beta = \sum_{i=1}^\tau \frac{1}{(1+r)^i} \approx \frac{(1+r)^\tau - 1}{r \cdot (1+r)^\tau}
\]

\( r = \) the interest rate; \( T = \) the economic lifetime of the buildings (year); \( \beta = \) the transfer coefficient of net present value and ordinary annuity.

To find the optimal value of \( x_1 \) which makes NPV maximal, Eq.(7) is differentiated with respect to \( x_1 \):

\[
\frac{d\text{NPV}}{dx_1} = v[R(x_2) - R(x_1) + \sum_{i=1}^\tau \frac{p(x_1,t)}{(1+r)^i}] = 0
\]

Generally, \( x_2 \) will be long enough and make \( R(x_2) = R_m \) and make \( p(x_2,t) = 0 \).

Rearranging Eq. (9):
\[
\beta \cdot [R(x_i) - R_m] = p(x_i, 0) \cdot \sum_{t=1}^{\infty} \frac{e^{\alpha t}}{(1 + r)^t} 
\]

Hence, the solution of Eq. (10) is the optimal width of the buffer zone, \( x_{opt} \). When \( a = 0 \), that is to say, the coast is under a stationary morphological condition, the erosion probability contours do not shift landward over time. Then Eq. (10) becomes:

\[
R(x_i) - R_m = p(x_i, 0) 
\]

This result is the same with the informed research by Jongejan et al. (2009). \( x_{opt} \) should be where the erosion probability equals to the difference between the return rate at \( x_i \) and the inland mean return rate.

We suppose a rectangular coastal block (\( L \times d \) m^2 as shown in Fig.2) and some artificial data so as to manifest the interrelation among some key coefficients. The hypothetic values of coefficients are listed in Table.1. Under this hypothesis, Eq. (7) and Eq. (10) are applied to derive the simulated outcome from this example. These values of coefficients can be adjusted corresponding to specific situation in practical application.

<table>
<thead>
<tr>
<th>Coefficient</th>
<th>Description</th>
<th>Value</th>
<th>Dimension</th>
</tr>
</thead>
<tbody>
<tr>
<td>( v )</td>
<td>Economic value density</td>
<td>1</td>
<td>euro/m^2</td>
</tr>
<tr>
<td>( A )</td>
<td>Return rate coefficient</td>
<td>0.15</td>
<td>-</td>
</tr>
<tr>
<td>( B )</td>
<td>Return rate coefficient</td>
<td>0.00045</td>
<td>-</td>
</tr>
<tr>
<td>( c )</td>
<td>Erosion probability coefficient</td>
<td>-0.1</td>
<td>-</td>
</tr>
<tr>
<td>( d )</td>
<td>Width of the coastal block</td>
<td>1000</td>
<td>m</td>
</tr>
<tr>
<td>( D )</td>
<td>Critical distance for return rate</td>
<td>200</td>
<td>m</td>
</tr>
<tr>
<td>( R_m )</td>
<td>Mean return rate inland</td>
<td>0.06</td>
<td>-</td>
</tr>
<tr>
<td>( r )</td>
<td>Discount rate</td>
<td>0.025</td>
<td>-</td>
</tr>
</tbody>
</table>

When the economic lifetime of the properties is assumed as 50 years, Fig.3 illustrates the effect of probability rising rate \( a \) on the NPV and \( x_{opt} \). As expected, the buffer zone will be wider according to the higher \( a \), meanwhile the NPV decreases. The shape of the curves is related to \( R(x) \). The NPV increases rapidly at first as the erosion probability falls down more dramatically than return rate, and after reaching the peak value, the NPV decrease gradually with the slop according to the return rate coefficient \( B \).
Figure 3. The effect of probability rising rate on optimal $x_1$ and NPV. ($■$) is the maximum NPV according to $x_{opt}$. The Fig. 4 shows the NPV and the optimal $x_1$ as a function of the economical lifetime of the properties with fixed $a$ (0.05 and 0.005). The greater the erosion probability rising rate the larger $x_{opt}$, but the NPV does not decrease dramatically. As illustrated by Fig. 3 and Fig. 4, the rate of the long-term trend does not impact the maximum NPV significantly, but the $x_{opt}$, comparing to NPV. One reason for less impact on the NPV is that, within the large coastal block, only the forward part of the block will be strongly influenced by erosion hazard, for the rest part of the block, NPV does not change a lot.

Figure 4. The effect of the economic lifetime ($T$) and $a$ on optimal $x_1$ and maximum NPV.

3.2 Beach nourishment

An alternative land-use strategy for coastal zone is extending the dune width by beach nourishment. Beach nourishment is the supply of sand to the shore to increase the recreational value and/or to secure the beach against shore erosion by feeding sand on the beach (Mangor, 2004). In order to make the strategy economical, the inequality below has to be satisfied:
\[
\int_{x_1}^{x_2} R(x)dx - \int_{x_1+lr}^{x_2+lr} R(x)dx + \frac{N(l_r)}{\beta v} < \sum_{t=1}^{r} \int_{x_1}^{x_2} p(x,t)dx \frac{1}{(1+r)^{t}} - \sum_{t=1}^{r} \int_{x_1}^{x_2+lr} p(x+l,t)dx \frac{1}{(1+r)^{t}}
\]

(12)

In which, \( l_r \) (m) is the running meter of the beach nourishment and \( N(l_r) \) is the corresponding cost of nourishment of unit coastline length (\( \text{euro} / \text{m} \)). The inequality means that the cost of beach nourishment and the loss of return should be less than reduction of the risk due to the nourishment. A simple approximation of \( N(l_r) \) is given by:

\[
N(l_r) \cdot L = (I_0 + \mu \cdot h \cdot l_r) \cdot L
\]

(13)

\( I_0 \) (\( \text{euro} / \text{m} \)) is the initial cost, \( h \) is the sand nourishment height (m), \( \mu \) is the nourishment cost per \( m^3 \) (\( \text{euro} / \text{m}^3 \)). Let

\[
\Phi(l_r) = \frac{v}{(1+r)^t} \left[ \sum_{t=1}^{r} \int_{x_1}^{x_2} p(x,t)dx - \sum_{t=1}^{r} \int_{x_1}^{x_2+lr} p(x+l,t)dx \right] - [\beta \cdot v \cdot \int_{x_1}^{x_2} R(x)dx - \beta \cdot v \cdot \int_{x_1+lr}^{x_2+lr} R(x)dx - N(l_r)]
\]

(14)

To find the optimal value of \( l_r \), the equation is differentiated with respect to \( l_r \):

\[
\frac{d\Phi(l_r)}{dl_r} = \left[ \sum_{t=1}^{r} \frac{v}{(1+r)^t} p(x_1 + l_r, t) \right] - \mu \cdot h + \beta \cdot v \cdot R_m - \beta \cdot v \cdot R(x_1 + l_r) = 0
\]

(15)

The solution of Eq. (15) is the optimal nourishment width. As the return rate decreasing rate is small, \( R(x_1 + l_r) \approx R(x_1) \) and Eq. (15) becomes approximately:

\[
v \cdot \left[ \sum_{t=1}^{r} \frac{e^{at}}{(1+r)^t} \right] e^{c(x_1+lr)} = \mu \cdot h + \beta \cdot v \cdot R(x_1) - \beta \cdot v \cdot R_m
\]

(16)

Then the optimal \( l_r \) is:

\[
l_{r, \text{opt}} = \ln[\frac{\frac{\mu \cdot h}{v} + \beta \cdot R(x_1) - \beta \cdot R_m}{\sum_{t=1}^{r} \frac{e^{at}}{(1+r)^t}}] - x_1
\]

(17)
Eq. (17) indicates that, the higher the erosion probability increasing rate, or the cheaper the nourishment sand per $m^3$, or the nearer the properties from shoreline, the wider the optimal running meter of beach nourishment. When $a = 0$, Eq. (17) becomes:

$$e^{c(l_{r, opt} + x_1)} = \frac{\mu \cdot h}{\beta \cdot v} + R(x_1) - R_m = p(l_{r, opt} + x_1, 0) \quad (18)$$

If erosion probability does not change over time, the erosion probability at $(l_{r, opt} + x_1)$ will be the difference between $R(x_1)$ and $R_m$ plus the ratio between cost of nourishment per running meter and the property per $m^3$.

Supposing that the coastline moves $l_r$ meters seaward by beach nourishment, the unit length NPV of the coastal rectangular block is:

$$NPV = \beta \cdot v \cdot \int_{x_1 + l_r}^{x_2 + l_r} R(x) dx - V \cdot (x_2 - x_1) - V \cdot \sum_{t=1}^{T} \int_{x_1 + l_r}^{x_2 + l_r} p(x, t) dx - \mu \cdot h \cdot l_r - I_0 \quad (19)$$

As shown in Fig. 5, the NPV performs a convex curve with respect to $l_r$, and reaches its peak at $l_{r, opt}$, about 4 meters in this case. Note that for specific coastal topography, local economic value density and other practical situations, the NPV may reach its maxima at “$l_r = 0$”. That means beach nourishment is not an economical land-use option for that coastal zone. This is different from setting up a buffer zone, which will always have an optimal scheme. When all the relative coefficients are known, the “retreat” and “attack” policies can be compared and selected as the chosen strategy in specific coastal zone by comparing the final NPV.

![Figure 5. NPV as function of beach nourishment width.](image)

### 4. Conclusions and recommendations

Although suffering high erosion risk along the coast, it can be compensated by higher return on investment, and the investment will be cost-efficient under some reasonable
land-use strategies, which is analyzed by constructing the aforementioned probabilistic economic model. For two alternative strategies, the optimal retreat and attack distance are found by solving Eq. (10) and Eq. (17), meanwhile, the choice can be made by comparing respective maximal NPV. This study is conducted by considering the whole coastal economic zone rather than single constructions. Therefore, what the result indicates is a regional optimization.

Coastal flood hazard due to storm surge, always accompanied with coastal erosion is another risk source for coastal management. The properties locate on the dune will partially or even totally destroyed by flood. This should be coupled with erosion risk in the future study. Besides, in this paper, model is established without taking account of the engineering defense along the coast, which compresses the iso-risk contours before the sea defense, and the probability of being destroyed by storm surge is the same as the failure probability of the structural measures. In this case, the optimal land-use strategy is dependent on the safety level of the sea defense.

In reality, the economic value density and return rate may become more complicated than foregoing example. They will vary according to their specific building type and commercial use. Moreover, long-term erosion probability trend should be treated as an uncertain coefficient in practical application for the further study.

Reference