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# A semi-empirical model of a tidal inlet system

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# Contents

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# 1 Introduction

Tidal inlets are among the most distinguishable features on a coast. They are important for humans by providing natural harbors and shipping channels and for marine species by providing breeding grounds and natural habitats.

Only in the last 25 years have coastal engineers begun to come to an understanding of the physical processes in and around tidal inlet systems. This lack of knowledge has caused tremendous surprises and problems due to unanticipated reactions of the system to changes caused by human interference. Examples of such interference are: (partial) closure of the tidal basin, dredging of shoals and channels and fixing the inlet gorge by constructing jetties. The system also reacts to changes in the environmental conditions, such as a change in the mean sea level and in wave conditions.

In this report we explore the reaction of a tidal inlet system to a number of changes in the conditions. To this end a model is formulated which is partly based on physical processes and partly on empirical formulas. This has to be done because the physics are largely unknown. Hence the word "semi-empirical" in the title.

In the next chapter, the elements of a tidal inlet system and the sediment transport mechanisms between the elements are described and schematized. Some of the empirical equilibrium parameters are described in Chapter 3. In Chapter 4 the governing equations are formulated. Finally, the model is run and analyzed for four scenarios (partial closure, dredging of tidal flats, sea level rise, and dredging of the ebb tidal delta).

# 2 Tidal inlets and sediment bypassing

Figure 1 shows a typical planform of a tidal inlet system. The most important elements of a tidal inlet system are the updrift and downdrift barrier inlands, the gorge that separates them, the tidal basin with its tidal flats and tidal channels, and the ebb tidal delta just offshore of the inlet gorge. This delta stores a great volume of sediment in sand bars which are cut through by flood and ebb channels. In many inlets there are two distinguisable main flood channels near the island tips and one main ebb channel in the middle through which water is jetted out from the basin. Additionally, there are many secondary channels which bifurcate from the main channels. This complicates the actual sediment transports immensely.

Sediment is continuously being moved through this system by waves, wave-induced currents and tidal currents, either in calm weather or during short storm periods. These sediment transport mechanisms can augment or oppose each other, again complicating matters.

However, four general types of net sediment flow around an inlet, also called *sediment bypassing*, can be identified:

- bar bypassing around the margin of the ebb tidal delta, mainly by wave action.
- tidal bypassing by tidal currents which transport sediment into and out of the inlet gorge and basin through the tidal channels.
- sediment movement across the delta into the gorge during extreme conditions known as *bulldozering.*
- migration of shoals and channels in the outer delta on a larger time-scale. Migrating channels gradually become more hydraulically inefficient which forces the creation of new channels. In this way, whole shoals become part of either the updrift or downdrift islands.

# 3 Schematization

The complexity of the system compels us to make simplifications to be able to model the principal processes in the inlet. Figure 2 shows the schematized planform of the inlet system. It consists of four major elements in which sediment can be stored: the tidal basin, the ebb tidal delta (sometimes called *outer delta*) and two barrier islands.

## 3.1 Tidal basin

The tidal basin has a triangular shape and is confined by the barrier islands, the main land and the drainage divides. It consists of a single channel and a tidal flat area which increases linearly toward the back of the basin. This is consistent with many tidal basins which have relatively more flats in the back of the basin than in the front. We will assume that the length of the basin is much shorter than a tidal wave length which means that the water level rises and falls uniformly over a tidal period. We also assume that the level of the flat area is at MSL which means that during a tidal cycle the amount of water or *prism* stored is:

$$P = (A_b - A_{fl}) \cdot TR + \frac{1}{2} \cdot TR \cdot A_{fl} \tag{1}$$

where $A_b$ is the basin area, $A_{fl}$ is the flats' area and $TR$ denotes the tidal range. In the model the channel and flats are discretized into sections. Sediment exchange occurs between consecutive channel sections and between channels and flats. There, sediment is eroded from the tidal flats in storm conditions and is deposited on the flats in calmer weather. For details of the rationale behind the assumptions, we refer to Van Dongeren & De Vriend (1994).

## 3.2 Barrier islands

We schematize the barrier islands as initially long and straight coastlines. The islands are discretized as well. Sediment exchange between sections is assumed to occur along the breakerline only (which makes this model a one-line model) and is considered wave-driven. This allows us to use the so-called CERC-formula which energy-based. The equation is given in the next chapter.

## 3.3 Ebb tidal delta

The most profound and therefore most limiting schematizations are made for the ebb tidal delta. We will assume that the delta consists of two flood channels along the islands' heads and one ebb channel, which are not allowed to migrate which prevents sediment by-passing through the fourth mechanism described above.

The ebb tidal shoals are schematized as two triangles between the flood channels and the ebb channel. These triangles are not necessarily of the same area. Their relative sizes are determined by the ratio of the sediment transports in the two flood channels in the equilibrium situation. This is described below.

Sediment is transported through the two flood channels, called $F_u$ and $F_d$ where the subscripts denote *updrift* and *downdrift* channels. Sediment is also transported along the margin of the delta. In nature, this sediment transport is due to waves and currents. It also very dependent on the meteorological conditions. Most sediment transport will occur in stormy weather. Then sand will be pushed along the margins to the coast and even across the ebb tidal delta directly into the gorge. In this model, we will assume that there is only transport along the margin and that it is governed by the CERC-formula, which implies that it is wave-driven.

# 4 Equilibrium parameters

Before we proceed with the formulation of the model, some empirical equilibrium parameters are given which are needed to close the model. Various researchers have found that some of the characteristic variables in a tidal inlet system are functions of the tidal prism. O'Brien (1931, 1969) found that the throat cross-sectional area has a linear relationship with the prism

$$\bar{A}_c = 6.6 \cdot 10^{-5}\, \bar{P} \tag{2}$$

Walton & Adams (1976) found that the equilibrium volume of the ebb tidal delta is

$$\bar{V} = .00656\ \bar{P}^{1.23} \tag{3}$$

Among others, Sha (1990) found that the maximum horizontal protrusion of the delta is governed by

$$\bar{\lambda} = .044\ \bar{P}^{0.6} \tag{4}$$

for inlets in the Dutch Waddensea. Eysink (1990) found for the same area that the equilibrium flats' area has a relationship to the total basin area as:

$$\frac{\bar{A}_{fl}}{A_b} = 1 - 2.5 \cdot 10^{-5} \sqrt{A_b} \tag{5}$$

# 5 Governing Equations

## 5.1 Tidal basin

Every tidal cycle a sediment volume $F_u + F_d$ is imported into the basin through the flood channels. Most of this sediment will be jetted out during the ebb tide, but some, $S_o$, may be retained in the basin. As Van Dongeren & De Vriend (1994) have stipulated, this net sediment import (or export, depending on the sign) is a function of the difference between the instantaneous flat area $A_{fl}$ and the equilibrium flat area $\bar{A}_{fl}$, as given by Eq. (5). Their Eq. (23) is here modified to:

$$S_o = \beta \left(F_u\ +\ F_d\right) \left(\bar{A}_{fl} - A_{fl}(t)\right) \tag{6}$$

where $\beta$ is an input parameter.

As described above, the basin consist of channels and flats, which characteristic variables are $A_c$ (the vertical channel cross-sectional area) and $A_{fl}$ (the horizontal flat area) respectively. The change in the channel cross-sectional area is assumed to show an asymptotic response to changes as

$$\frac{\partial A_c}{\partial t} = \frac{\bar{A}_c - A_c}{\tau_c} \tag{7}$$

where $\tau_c$ is the inherent time scale of the channel response. This response can only be asymptotic if sufficient sediment is supplied to the channel section. In other words, the channel response is supply-limited. As stated above, the channel section interacts with the channel sections on either side through $S_o\,(y)$ and $S_o\,(y+\Delta y)$. In addition, there is an autonomous storm erosion from the flats called $E$

$$E = \mu\, A_{fl}\, h_c \tag{8}$$

where $\mu$ is an input parameter and $h_c$ is the channel bank height. $A_{fl}$ enters this equation because there will be a larger volume of erosion from a larger flats' area. Some of the sediment, $D$, which is imported into a channel section will be deposited on the channel banks to increase the flats' area. This means that the response of the channel cross-sectional area is limited by:

$$\frac{\partial A_c}{\partial t} = \frac{S_o(y+\Delta y) - S_o(y) + D - E}{\Delta y} \tag{9}$$

which replaces the previous asymptotic equation (7) if the sediment supply is too small.

The change in flats' area is determined by the net gain or loss through deposition and erosion:

$$\frac{\partial A_{fl}}{\partial t} = \frac{D - E}{h_c} \tag{10}$$

## 5.2 Barrier islands

The sediment transport along the coast is assumed to be governed by wave action for which the CERC-formula is chosen. It can be written in many ways, and in this model it reads as:

$$S = 0.02\, H_o^2\, c_o\, \cos\phi_o \sin(\phi_b - \phi_s) \tag{11}$$

where $H_o$ is the offshore wave height, the deep water celerity $c_o = \frac{g\,T_w}{2\pi}$, $T_w$ is the wave period. $\phi_o$ is the offshore wave angle, $\phi_b$ is the angle at breaking and $\phi_s$ is the local angle of the beach. The angle at the breaker line can be found using linear shoaling, Snell's law and a breaker criterion. Here the most simple approach of depth-limited breaking is used.
With these sediment transport rates, the change in shoreline position $y$ can be calculated using the sediment continuity equation:

$$h\frac{\partial y}{\partial t} = -\frac{\partial S}{\partial x} \tag{12}$$

where $h$ is a representative height of the active beach face.

### 5.3 Ebb tidal delta

The transport along the delta margins is assumed to also be governed by the CERC-formula despite the limitations that this produces.
In principle the transport capacities in the flood channels and the ebb channel are unknown. However, we can calculate them if we assume that initially the system is in equilibrium before it is perturbed (De Vriend *et al.*, 1994). As is shown in Figure 3, the following sediment continuity conditions have to be met in that case:

$$\bar{F}_u = S_1 - S_2 \tag{13}$$

$$\bar{F}_d = S_3 - S_4 \tag{14}$$

where the littoral transports $S_1$ and $S_4$ are known because $\phi_s$ is known on a straight coast. The other sediment transport rates are not known yet and will be determined below.

If we prescribe the ratio of the transport through the updrift channel to the total flood transport as

$$\alpha = \frac{\bar{F}_u}{\bar{F}_u + \bar{F}_d} \tag{15}$$

and assume that the tidal transport is a function of the flood velocity in the gorge, then

$$\bar{F}_u + \bar{F}_d = \int_0^{\frac{T}{2}} m\, u^3\, dt \tag{16}$$

where $u = \frac{Q}{A_c}$, $Q$ is the flux through the gorge, $T$ is the tidal period and $m$ is some proportionality parameter which will be eliminated in the following. Using the fact that the prism in the equilibrium state (as in any state) is given by

$$\bar{P} = \int_0^{\frac{T}{2}} Q\, dt \tag{17}$$

(which satisfies continuity), we can rewrite Eq. (16) as

$$\bar{F}_u = \alpha\, m' \left(\frac{\bar{P}}{\bar{A}_c}\right)^3 \tag{18}$$

where $m'$ is a lumped constant. Similarly we find

$$\bar{F}_d = (1 - \alpha)\, m' \left(\frac{\bar{P}}{\bar{A}_c}\right)^3 \tag{19}$$

Given $\bar{F}_u$ and $\bar{F}_d$, and with the constraints of having to satisfy Eqs. (3) and (4) for the equilibrium values of the delta volume and protrusion, we can calculate $\phi_s$

along the delta margin and determine $S_3$ and $S_4$.
The amount of sediment flowing out of the ebb channel is consequently

$$\bar{S}_{ebb} \equiv \bar{F}_u + \bar{F}_d \equiv S_3 - S_2 \tag{20}$$

This determines the equilibrium state.

If we perturb the system, the updrift flood channel transport can be written in a similar form

$$F_u = \alpha m' \left(\frac{P}{A_c}\right)^3 \tag{21}$$

where the overbars are dropped. Combined with Eq. (18), this leads to the governing relationship for the updrift flood channel

$$F_u = \bar{F}_u \left(\frac{P}{\bar{P}}\right)^3 \left(\frac{\bar{A}_c}{A_c}\right)^3 \tag{22}$$

where the ratio $\frac{\bar{A}_c}{\bar{P}}$ is determined by equation (2). Similarly we have for the downdrift channel

$$F_d = \bar{F}_d \left(\frac{P}{\bar{P}}\right)^3 \left(\frac{\bar{A}_c}{A_c}\right)^3 \tag{23}$$

In words, these equations mean that if the prism of a system would be increased the velocities would increase as well, intensifying the sediment transports to the third power. If on the other hand the cross-sectional area would increased from equilibrium, the transports would decrease due to smaller velocities in the tidal cycle.

The last governing equation is the sediment transport in the ebb channel in the transitional stage which closes the system:

$$S_{ebb} = F_u + F_d - S_o \tag{24}$$

# 6 Scenarios

The model is run for four scenarios: partial closure, a reduction of tidal flats' area, a sea level rise and ebb tidal delta mining. The parameters used are:

| | |
|---|---|
| Wave height | $H_o = 1\,m.$ |
| Wave period | $T_w = 7\,s.$ |
| Wave angle | $\phi_o = 20°$ |
| Tidal period | $T = 43200\,s.$ |

| | |
|---|---|
| Space step coast | $\Delta x = 100\,m.$ |
| Space step basin | $\Delta y = 100\,m.$ |
| Time step | $\Delta t = 10\,T$ |
| Prism | $P = 100 \cdot 10^6\,m^3.$ |
| Tidal range | $TR = 2\,m.$ |
| Time scale | $\tau_c = 20\,yrs.$ |
| | $\mu = 1 \cdot 10^{-5}\,s^{-1}$ |
| | $\beta = 1$ |

## 6.1 Scenario #1: partial closure

When part of a basin is reclaimed, the gross basin area is reduced. This will lead to an instantaneous reduction in the prism. Since such a reclamation usually occurs in the back of the basin with a relatively large flat area, the total flats' area in the rest of the basin will be below the new equilibrium value as prescribed by Eq. (5). This will lead to an import of sediment according to Eq. (6) which is used to decrease the channel cross-sectional area and increase the flats' area until a new equilibrium is reached, see Van Dongeren & De Vriend (1994). In the following case, the basin area is reduced by 80%. The distribution parameter $\alpha$ is chosen to be .8 in case 1A and .95 in case 1B.

Figure 4a shows the change of the characteristic variables inside the basin for both cases. According to O'Brien's empirical formula, a reduction in the prism will lead to smaller cross-sectional areas. Fig 4a shows the change in the cross-sectional area in the most seaward section. It has sufficient supply of sediment to adjust according to its inherent time scale. Fig. 4b shows the change for a section halfway down the length of the basin. Since sediment imported from the ocean is used up already in the most seaward sections, at first an insufficient amount is available to adjust this section and only locally eroded material from the shoals is used to decrease $A_c$. Only after the "sand wave" reaches this section will it adjust according to its inherent time scale. Fig 4c shows that the total flats' area reacts to the disturbance by decreasing in size in order to "donate" sediment to the demand of the channels and later increasing to its new equilibrium value when sediment becomes available again.

The behavior of the planform of the ebb tidal delta and the shoreline is shown in Figs. 5a and 5b for four time instances. After closure, the prism is reduced instantaneously while the channel cross-section remains unaltered. This leads to a decrease in transport capacity in the flood channels according to Eqs. (22) and (23). However, the littoral transports along the coast and the delta have not changed yet, causing deposition at the entrances of the flood channels which is shown as an accretion of the shoreline and the delta at $t = 10\,yrs.$ As the basin adjusts to a new equilibrium, sediment is retained in the basin which means that the sediment transport through the ebb channel is reduced. This results in a reduction of the protrusion of the ebb tidal delta.

However, later in time the basin cross-sectional areas have been reduced which increases the sediment transport capacity in the channels according to Eqs. (22) and (23). As a result the previously accreted sediment near the flood channel entrances is eroded again. During the transitional stage, the flats' area has increased in area which reduced $S_o$. This means that more sediment is jetted out through the ebb channel, so accretion can take place at the tip of the delta.

Figs. 6a and 6b show the change of the volume of the ebb tidal delta in time. It shows that the volume drops below the new equilibrium before sediment is available to restore it. The model quite accurately predicts the new equilibrium value for the ebb tidal volume, even though Eq. (3) was only used in the initial condition. This behavior indicates that the ebb tidal delta serves as a buffer of sediment to be used by other elements in the system (i.e. the tidal basin) to meet demand.

## 6.2 Scenario #2: tidal flat reduction

This scenario simulates the effect if the tidal flat area inside the basin is reduced, for instance through mining of sand or channel dredging. As a result of this disturbance the system will start to import sediment in order to bring the flats' area back to its previous equilibrium area (the total basin area does not change). Temporarily the prism will be increased since the dredged sand volume is replaced by water.

Figs. 7a and b shows the effect on the channel cross-sectional areas in two places for both values of $\alpha$. After the instantaneous reduction of the flats' area, the prism increases immediately, forcing the channel cross-section (the solid line) to increase in area toward a new equilibrium (the dotted line). However, since the flats' area is growing (see Fig. 7c) the prism decreases which reduces the equilibrium value itself. As a consequence, the cross-sectional area in Fig. 7b overshoots its target and starts decreasing after ten years.

Figs. 8a and 8b show the change in the delta planform for two time instances for both values of $\alpha$. The changes according to this model are less than spectacular. There is a general retreat of the delta and the coastline because of the sediment demand of the basin.

Fig. 9 shows the time-change of the volume. According to theory, an increase in tidal prism should yield an increase in the volume. However, this does not happen. Because of the delta's buffer function, sediment is drawn from its volume to replenish the basin without the basin ever donating this sediment back.

## 6.3 Scenario #3: sea level rise

In this scenario we subject the system to a moderate sea level rise of 40 cm/century. We may assume that the tidal flats and channels in the basin will rise with the sea level in order to avoid drowning, which causes a large sediment demand on the ocean side of the system.

Figs. 10a and b show the planform of the delta for both values of $\alpha$. If we would consider only a sea level rise on a plane beach, the shoreline retreat would be about 12 m/century. With the basin present, the shoreline retreat near the island heads is of the order of 100 m., which in a real situation would have disastrous effects on an island and its dune protection. Most of the sediment demand comes from the ebb tidal delta, which again buffers the impact of the disturbance. The Figures show that the distribution of the sediment transport over the flood tidal channels has a large impact on where the erosion will be most severe.

The assumption that the flats rise with the sea level might not hold. A slowly drowning flats' area would have disastrous effects on marine species that live on the intertidal shoals. This scenario is not explored here.

## 6.4 Scenario #4: ebb tidal mining

Since a large amount of sand is stored in the ebb tidal delta, it could appear tempting to use this easily accessible resource to dredge material to be used in beach replenishments. The effects of this are shown in this scenario, where annually 1% of the total volume is mined. Figs. 11 a and b are essentially the same as in the previous case. An interesting effect is that the sediment transport capacity along the margins of the delta is reduced due to the more acute angle of wave attack. This draws more sediment from the islands into the basin to make up for the deficit. As a result, ebb tidal mining causes not only a retreat of the ebb tidal delta but also of the island shores. This practice would therefore be very dangerous.

# 7 Conclusions

The model presented in this report is derived to simulate the changes in a tidal inlet system upon human-induced disturbances from the equilibrium which can be found from empirical data. The model domain includes the principal elements of a tidal inlet system: the basin, the outer delta, the barrier island beaches and the flood and ebb channels.

The sediment transport processes that connect these elements are based on some very simplifying assumptions about the actual physics of an inlet. We only consider wave-driven transports along the beaches and the tidal delta margin. We assume that the transports in the tidal channels are depended on the tidal flow only and that they can be calculated from some equilibrium situation.

Furthermore, we assume that inside the basin the channels will adjust to a new equilibrium according to an inherent time-scale if enough sediment is provided. Also, we consider the net exchange of sediment from the basin to the rest of the system to be a function of the flats' area and its equilibrium value.

The model is run for four different scenarios. The results are according to how we would expect the system to behave. Focusing on the ebb tidal delta, we can conclude that the equilibrium value is not always attained. Only in the case of a partial closure does the volume tend to its theoretical value. However, all scenarios show that the delta functions as a buffer, which means that is acts as a primary source of sediment should the basin need it to adjust itself to changing conditions. In the mean time, the effect of disturbances on the shoreline position of the island can be relatively severe given the finite width of an island.

One obvious conclusion is that the physics of a tidal inlet system are still poorly understood and hardly modeled. This warrants more theoretical and empirical research.

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## 9 Figures

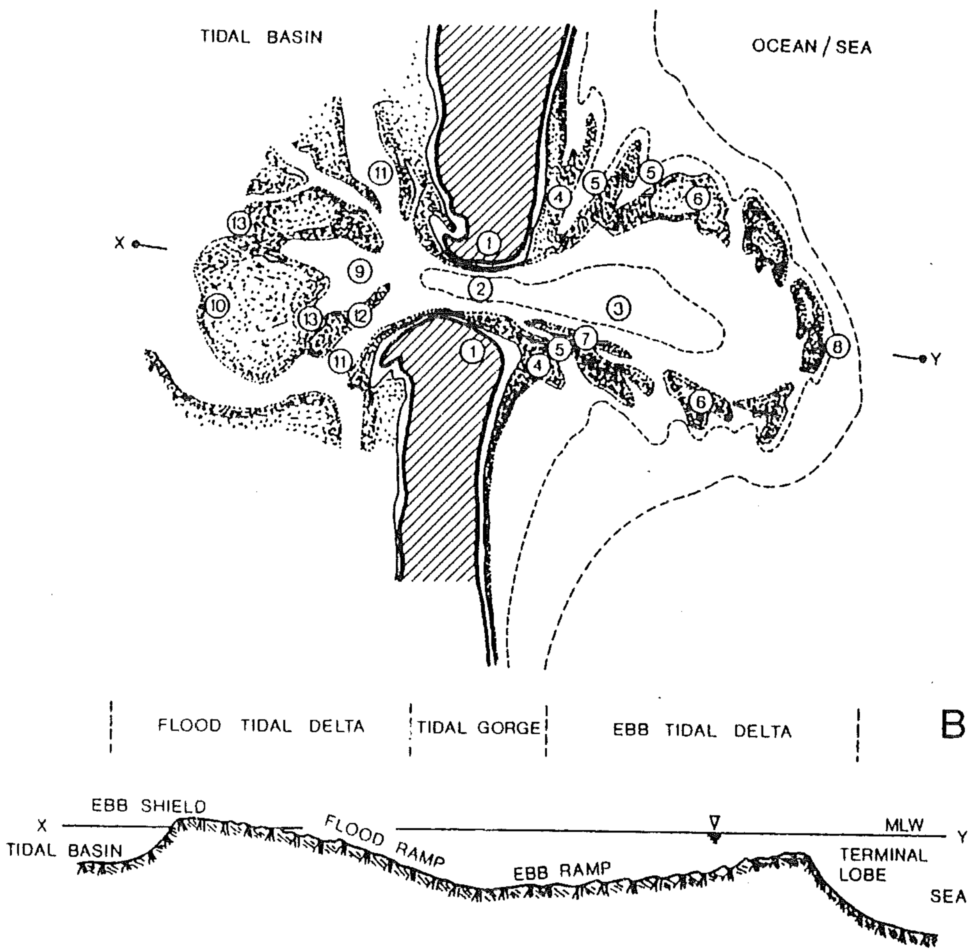



Figure 1: A typical planform of a tidal inlet system (from Smith, 1984)

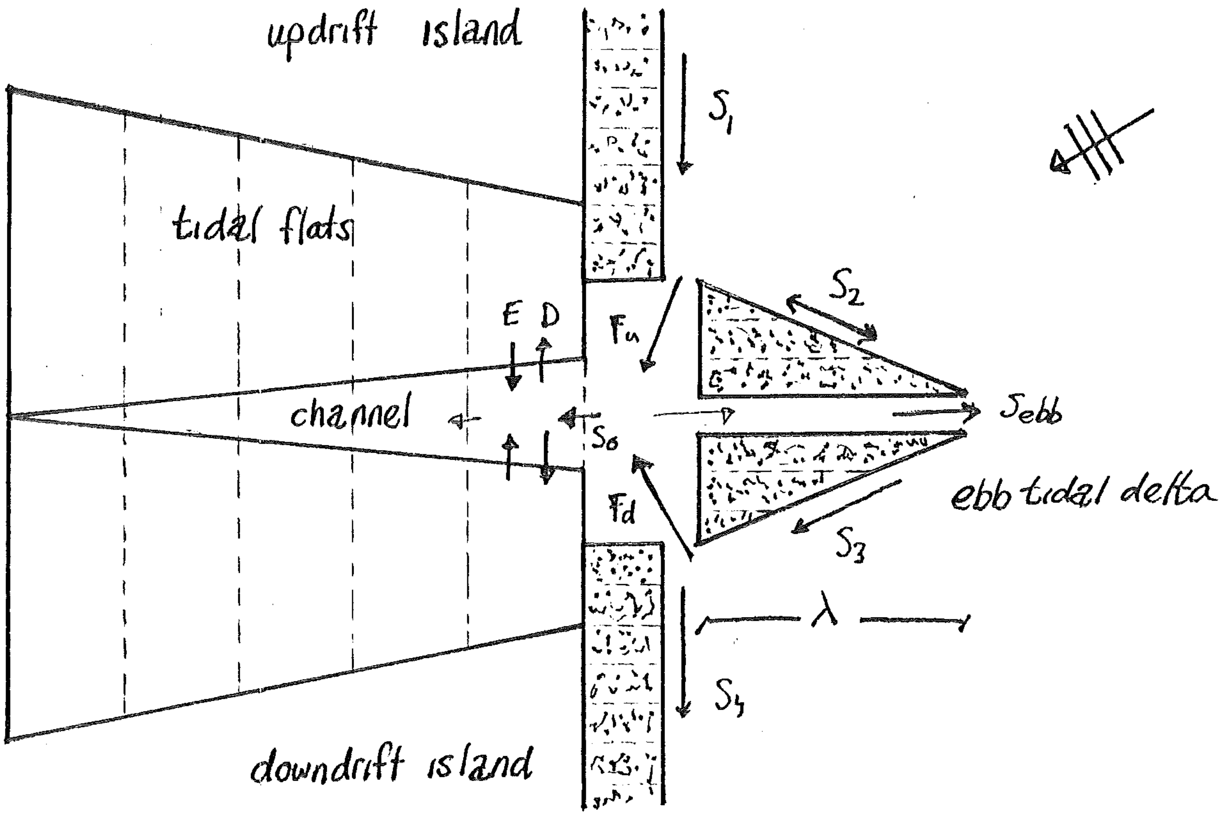



Figure 2: Schematized planform

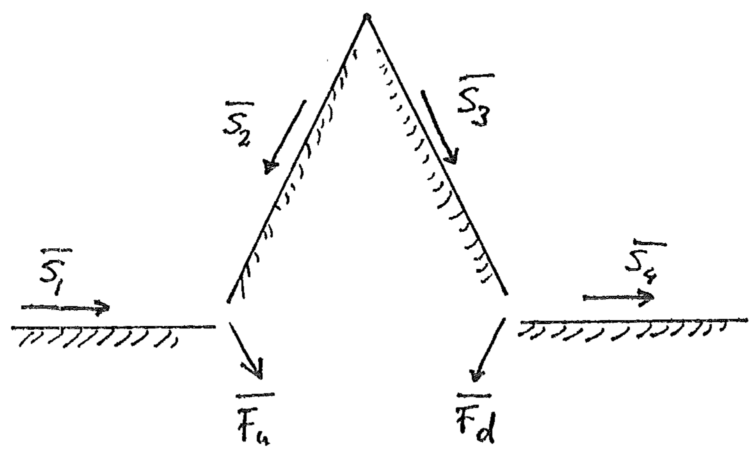



Figure 3: Equilibrium sediment transports along the coast

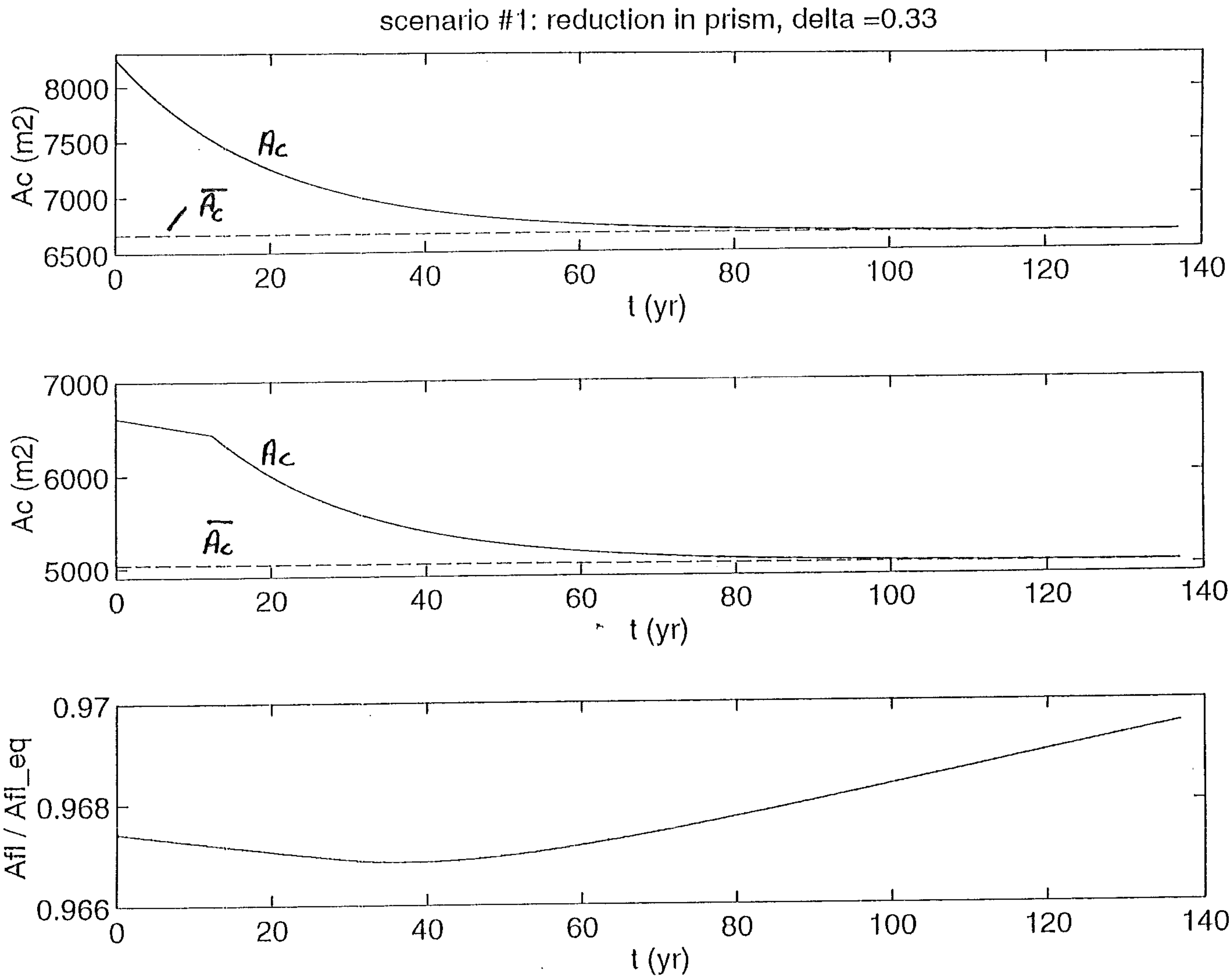
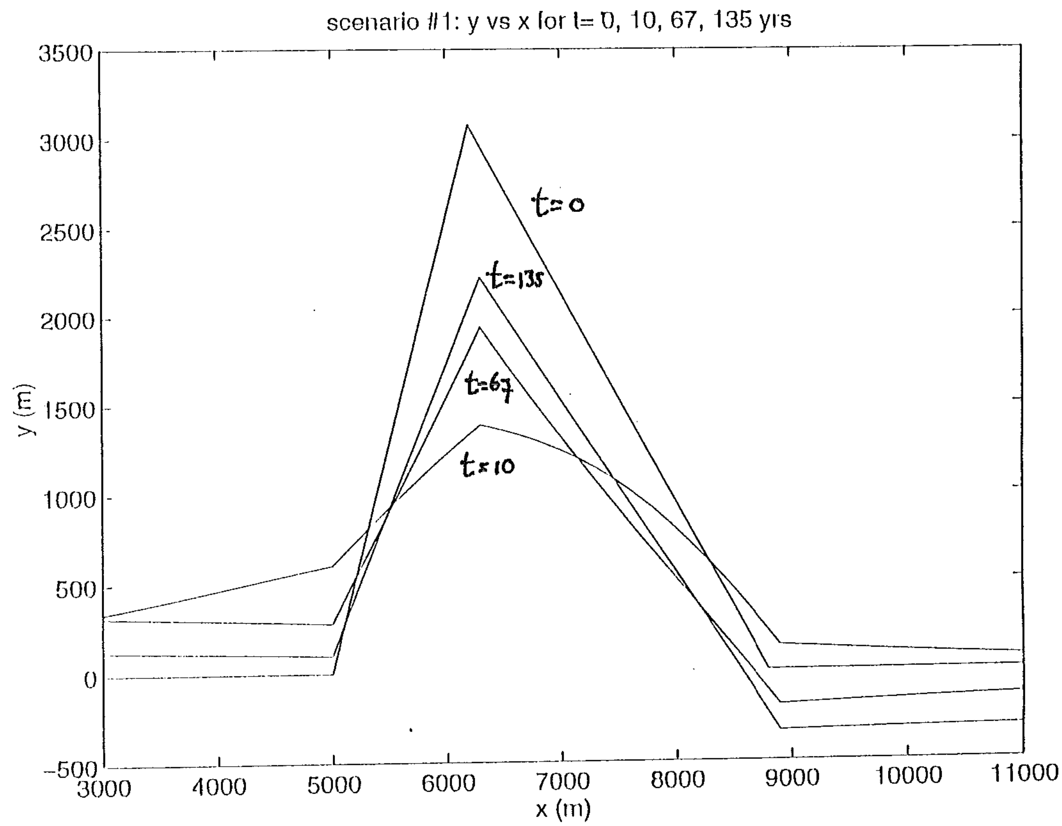



Figure 4: Scenario #1: a) cross-sectional area at throat, b) halfway basin, c) normalized flat area



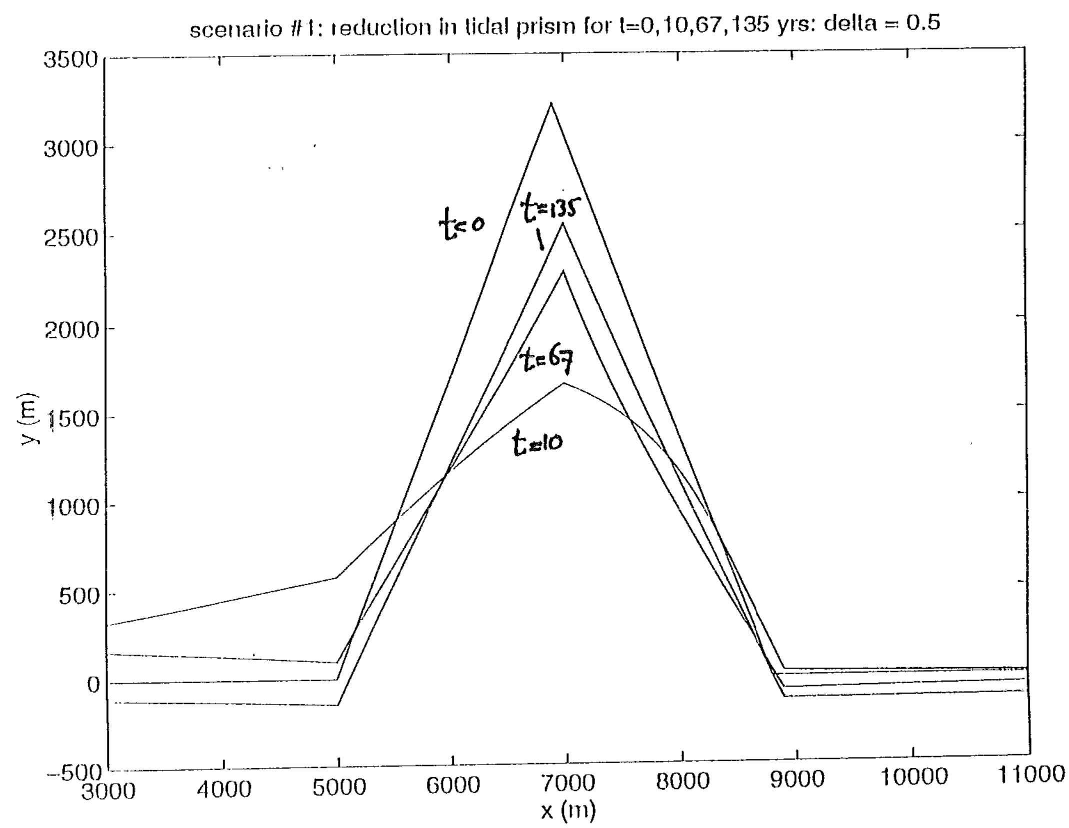
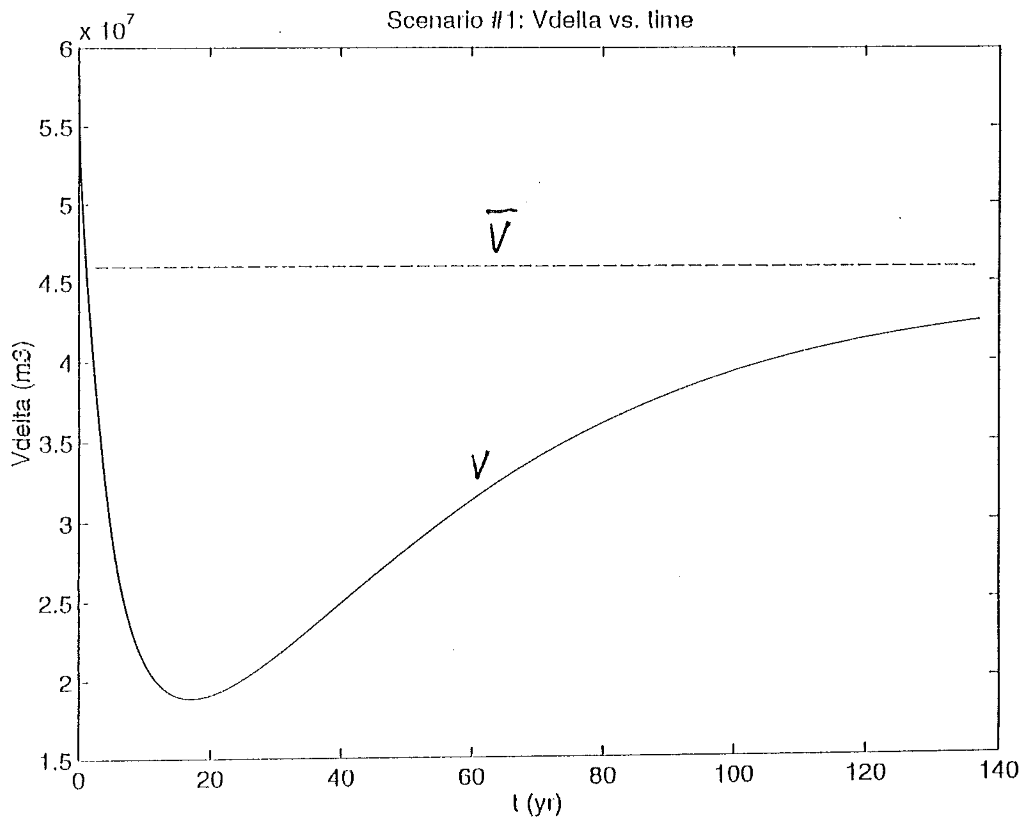




Figure 5: Scenario #1: planform of the outer delta at t=0, 10, 67 and 135 yrs a) $\alpha = 0.8$, b) $\alpha = .95$



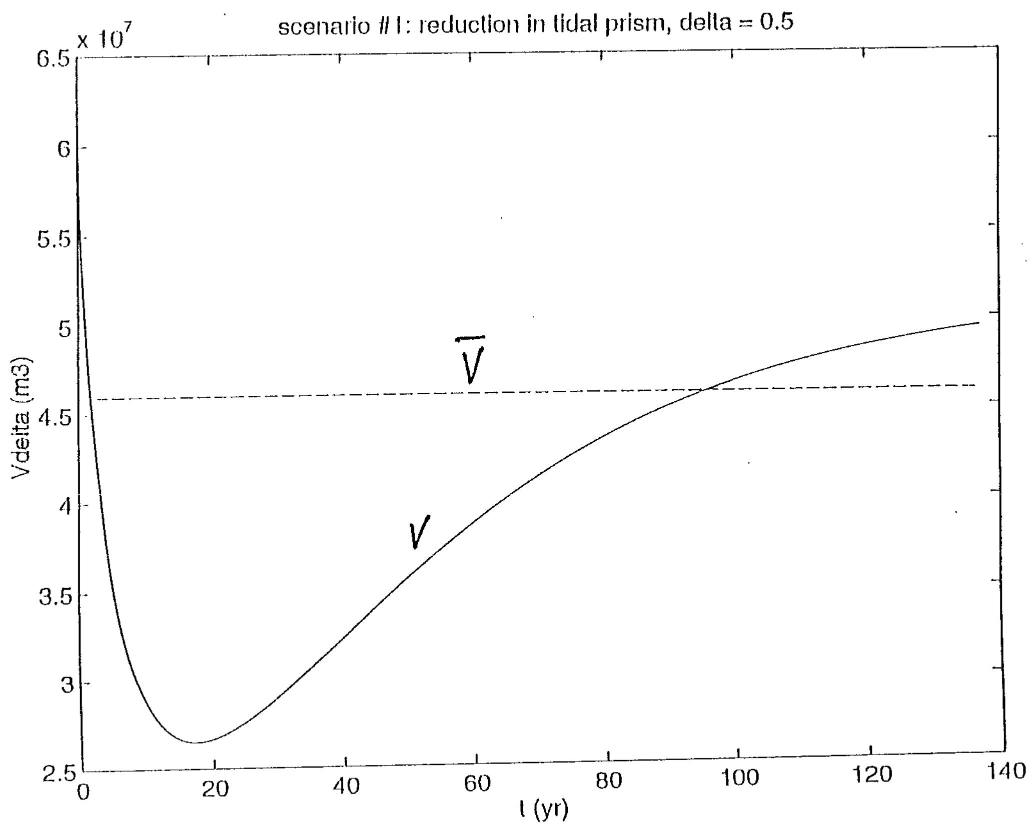




Figure 6: Scenario #1: change in the volume of the outer delta a) $\alpha = 0.8$, b) $\alpha = .95$

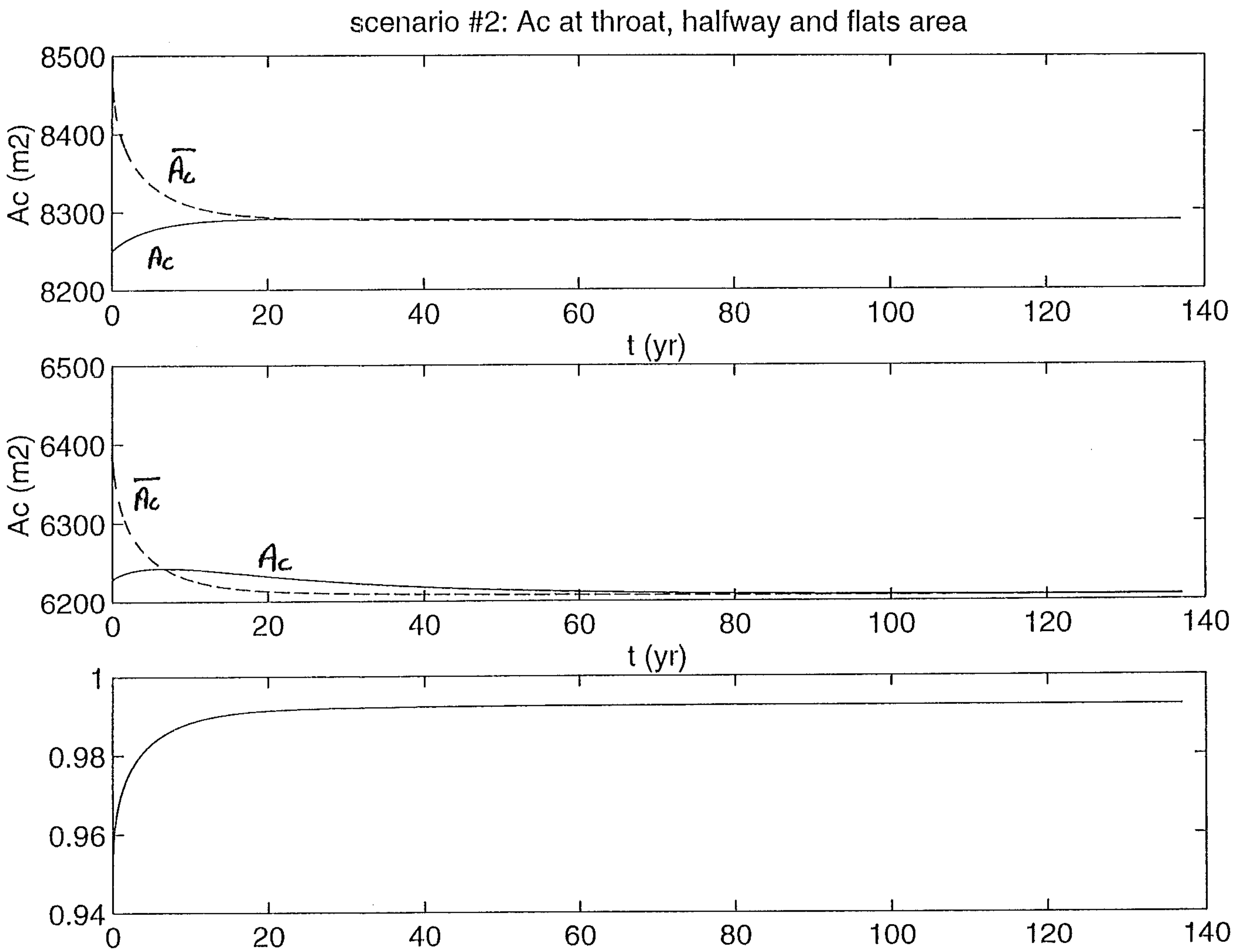
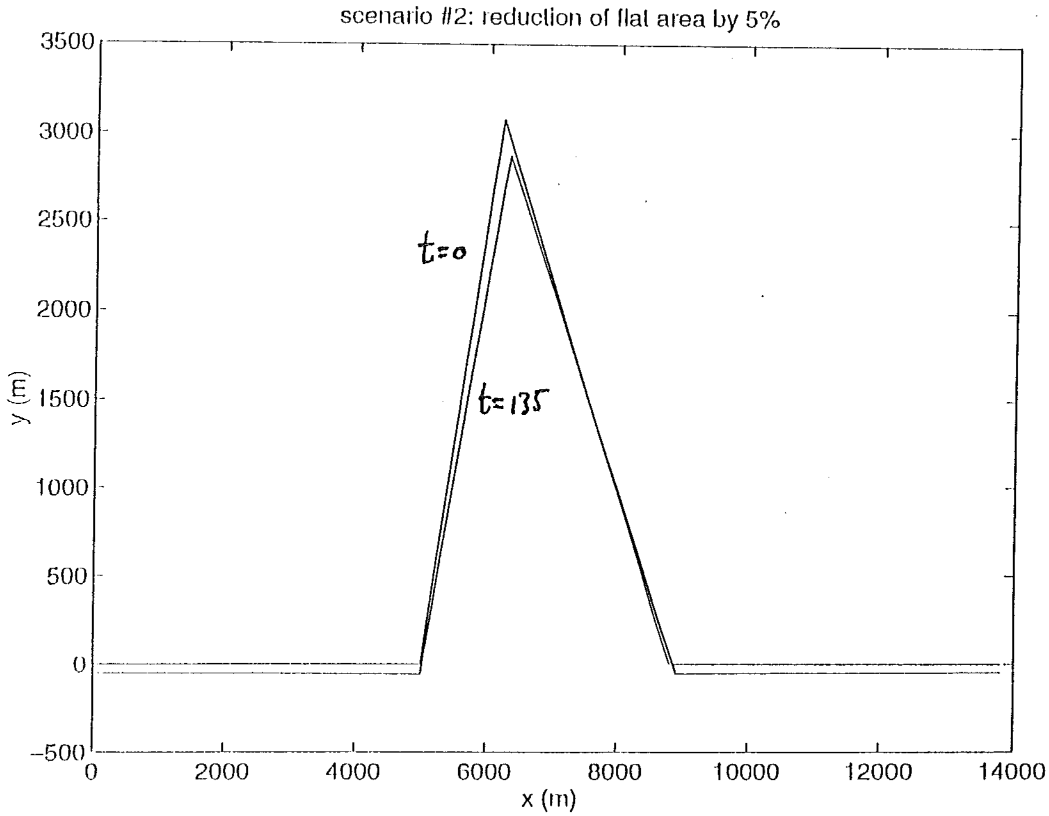



Figure 7: Scenario #2: a) cross-sectional area at throat, b) halfway basin, c) normalized flat area



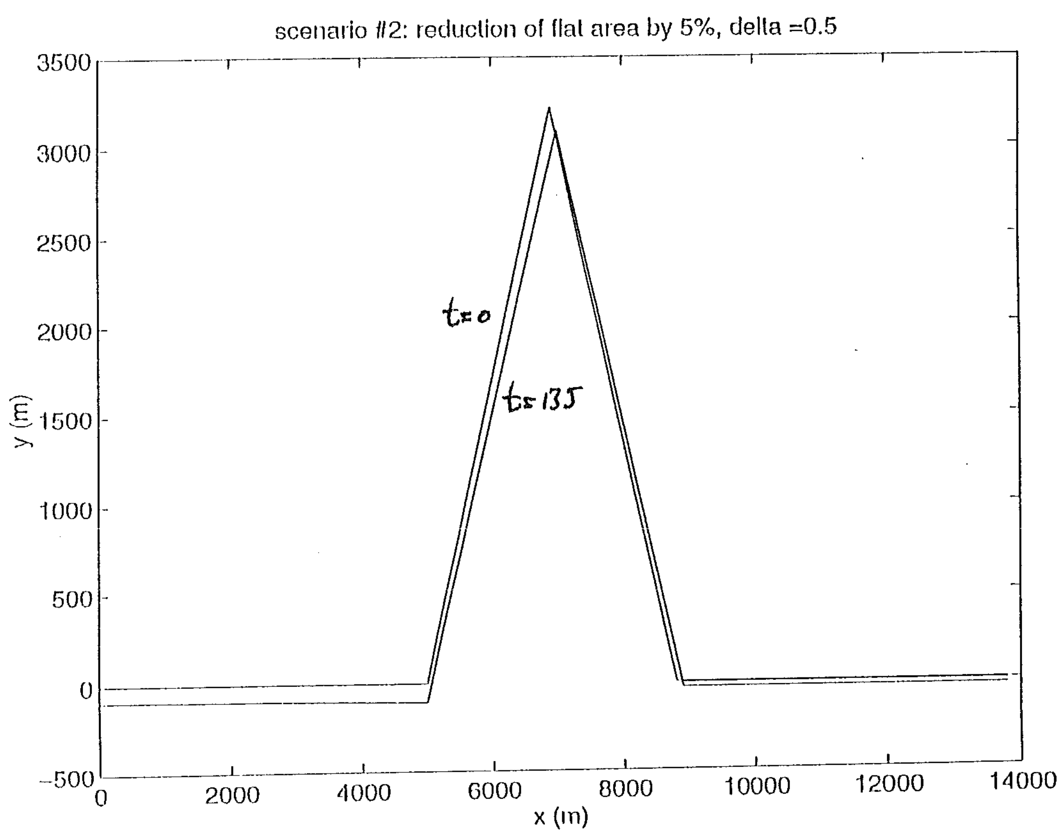




Figure 8: Scenario #2: planform of the outer delta at t=0 and 135 yrs a) $\alpha = 0.8$, b) $\alpha = .95$

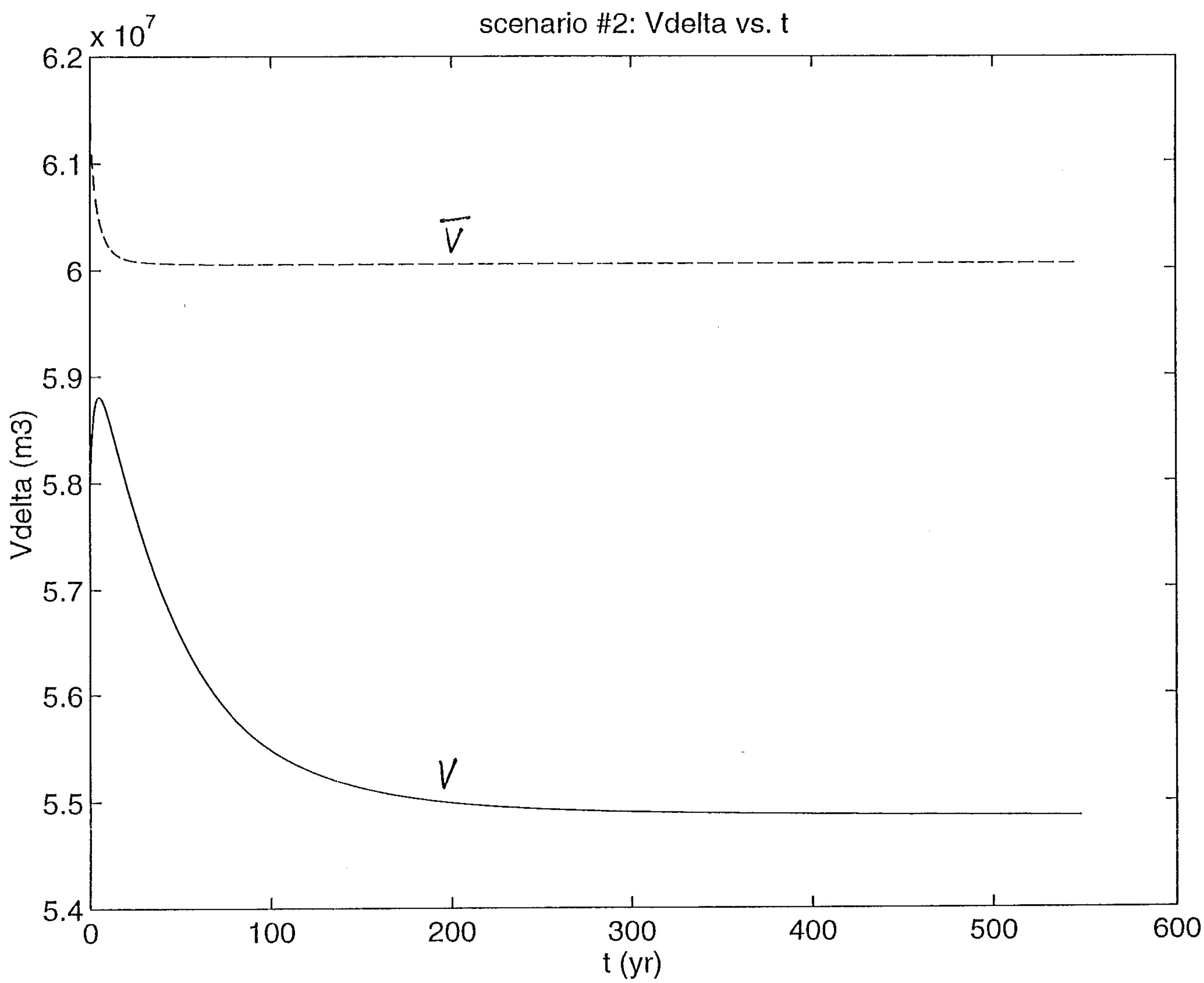



Figure 9: Scenario #2: change in the volume of the outer delta for $\alpha = 0.8$

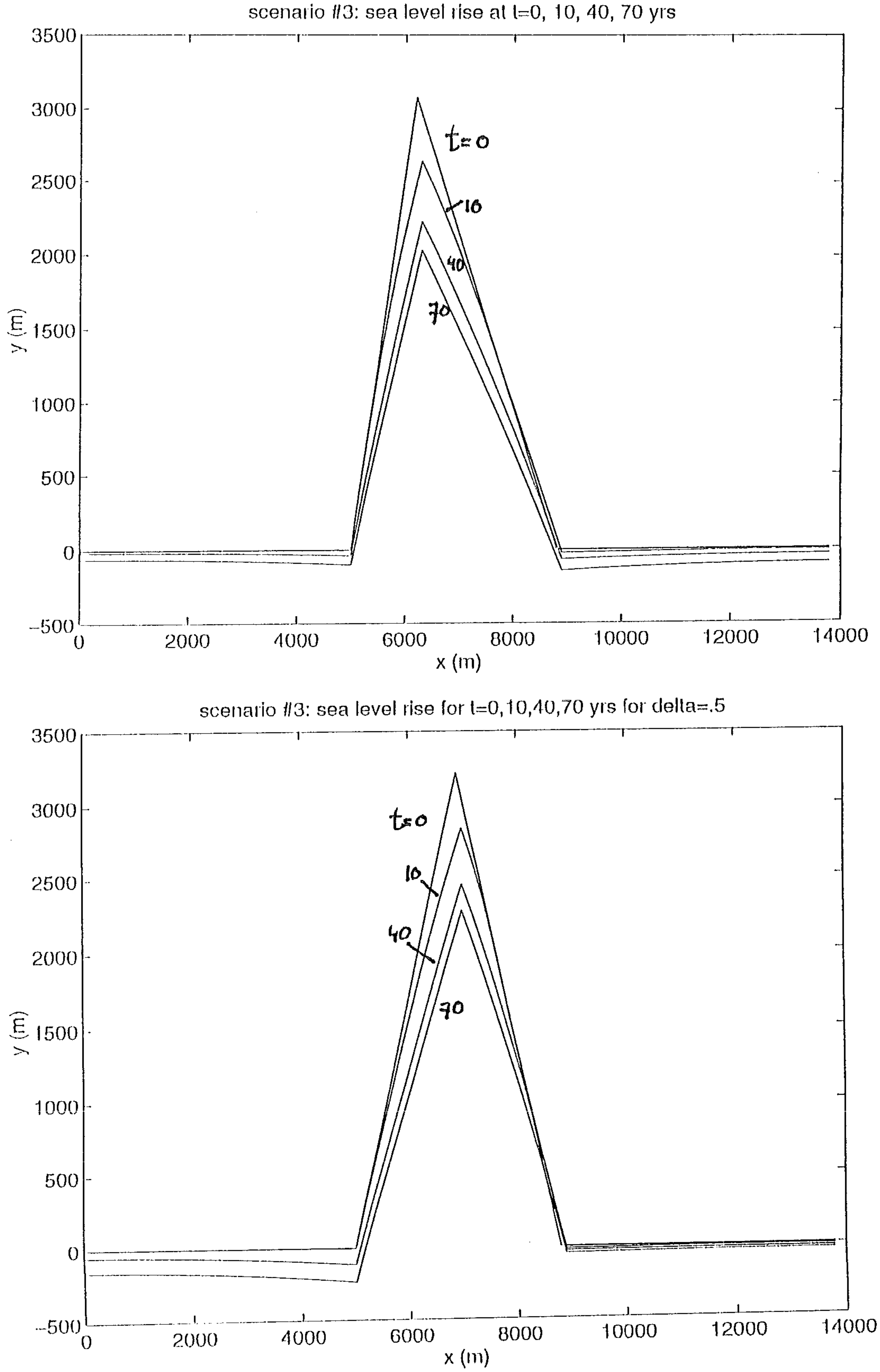



Figure 10: Scenario #3: planform of the outer delta at t=0, 10, 40 and 70 yrs a) $\alpha = 0.8$, b) $\alpha = .95$

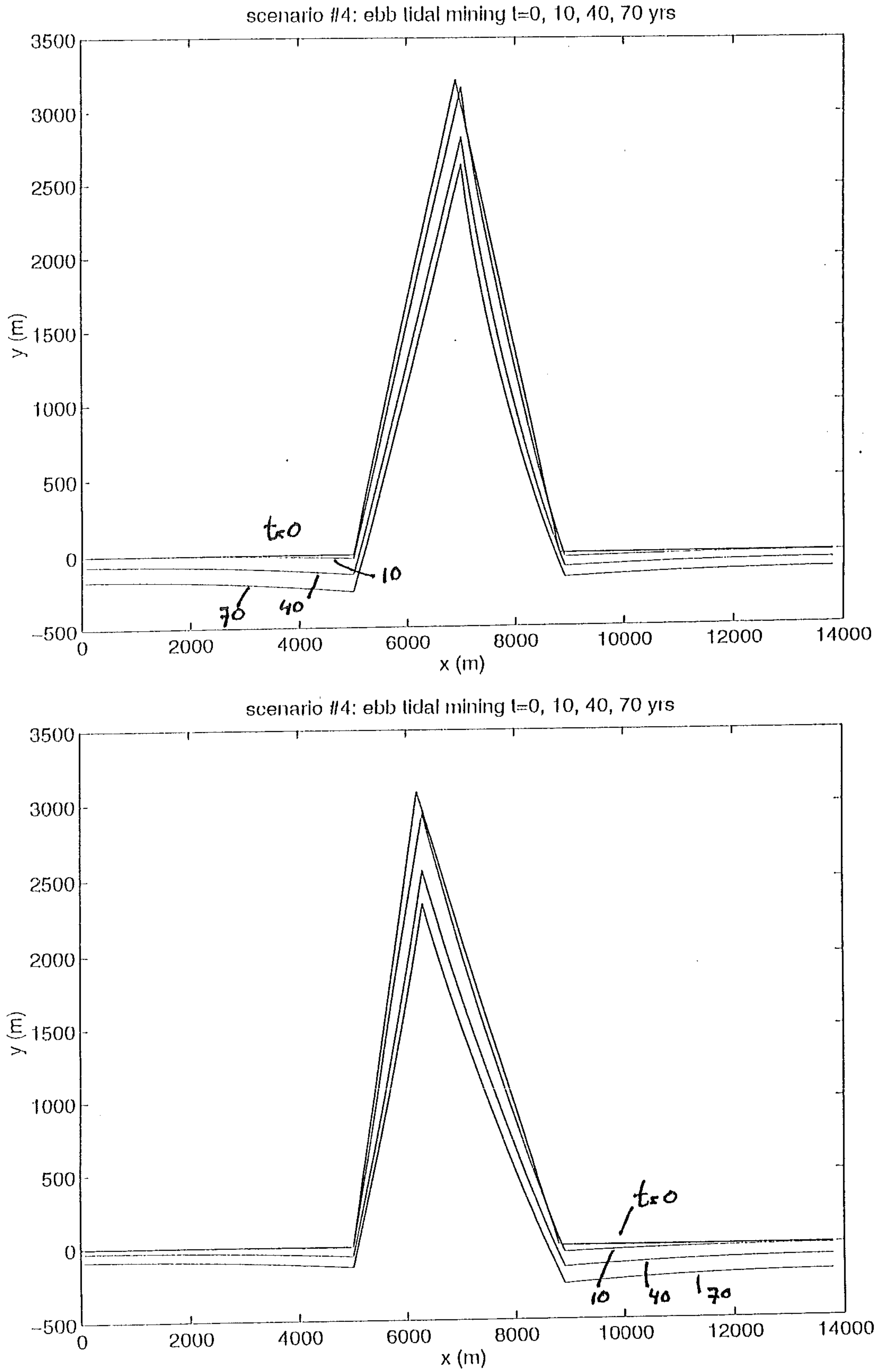



Figure 11: Scenario #4: planform of the outer delta at t=0, 10, 40 and 70 yrs a) $\alpha = 0.8$, b) $\alpha = .95$