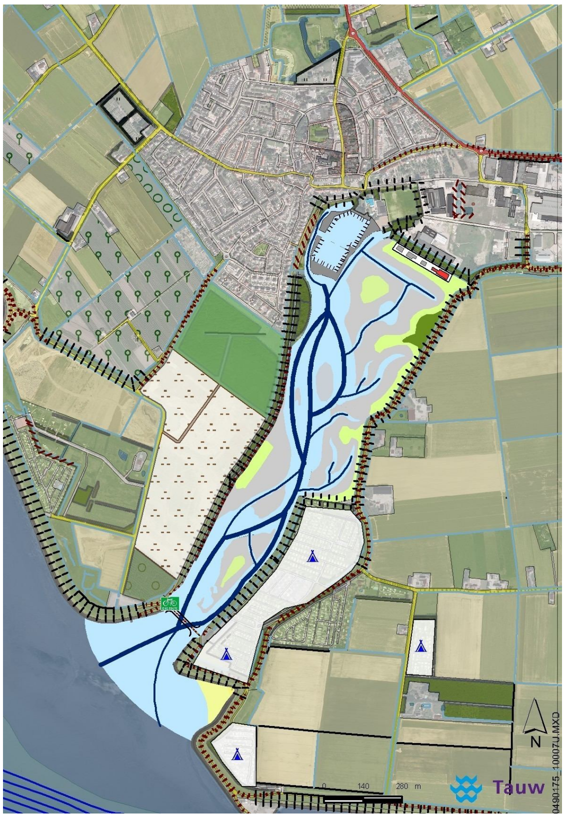
Development of a framework to evaluate locations for tidal creek restoration, based on the effects on surrounding land use



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Abstract

Tauw bv proposes tidal creek restoration to bring back the tide into the upland area of Zeeland in a safe and controllable manner. This will positively contribute to the Water Framework Directive, ecological values and attractiveness of the region. However tidal creek restoration may also lead to negative effects on the surrounding land use, current knowledge is merely focused on the success rate of the ecological restoration. Within this research a framework has been developed to evaluate locations for tidal creek restoration, based on the effects on the surrounding land use. This framework will be used to evaluate three locations, Zierikzee, Colijnsplaat and Sint Maartensdijk, which are selected by Tauw bv.

The framework is mainly formed by a literature study and expert meetings, and handles the relevant factors concerning evaluating locations for tidal creek restoration: safety preconditions and wishes of stakeholders, show the possibilities and restrictions for tidal creek restoration. The lateral extent of groundwater fluctuations and salinity intrusion combined with their valued effects and the surface area of the affected types of land use are the criteria which show the impact of tidal creek restoration on the surrounding land use.

The preconditions in the Netherlands are set by “Wet op de Waterkering” of 1996 and “Waterwet” of 2009 (www.wetten.overheid.nl). In order to ensure these safety standards, the incoming tide via the tidal creek needs to be controlled and damped by water constructions. Tidal creek restoration with the help of a water construction diminishes the wave energy, so the tidal energy is the most important factor from the tidal regime. The wishes of the stakeholders are set by expert meetings

To predict the lateral extent of groundwater fluctuations and salinity intrusion, landscape analysis is needed to find the relevant parameters. The lateral extent of groundwater fluctuations depends on whether the adjacent aquifer is a confined or unconfined aquifer. Unconfined aquifers (Colijnsplaat; ± 200 m) showed a far less extent of groundwater fluctuations compared to the confined aquifers (Zierikzee, Sint Maartensdijk; ± 1,000 m). All the locations showed that the amplitude of the groundwater fluctuations decreases exponentially with the distance. The lateral extent of the intrusion of salinity is not depended on locations characteristic, only on the tidal period (which is the same for all the three locations), and has a fixed distance of 60 meters.

The value of the effect is depending on the land use type, which for Zeeland ca be divided in the following groups: urban areas, agriculture and nature areas. Groundwater fluctuations have especially a negative influence to wooden foundations of constructions in urban areas, due to bacterial decay. The most prominent negative effects of an increase in salinity are on agriculture and most terrestrial nature areas as forests. Finally a quantification of the surface area of a certain land use type with the given valued effect is needed as it makes it able to compare different locations to each other.

Applying the framework to the three locations shows that the framework makes it easily visible to see which, how and how much of a land use type is affected, which can help policymakers to make their decision on which location is the “best option” for tidal creek restoration. However this framework is not meant to point out the best location, it is a tool in the evaluating process for policymakers.

1. Introduction

1.1 Restoring the tidal dynamics in Zeeland

After the flood disaster in 1953 in the southwest of the Netherlands the Delta project, formalized in 1957 by an act of the Dutch parliament, was conceived as an answer to continuous risk of flooding. The core of the Delta project is to maintain a safe, and thus an as short as possible, coastline in the southwest Netherlands (figure 1.1). Hence the main tidal estuaries and inlets, except for the Westerschelde and the Nieuwe Waterweg, were closed with dams and storm surge-barriers from the North Sea. Furthermore, all the existing dikes are raised (*Smits et al., 2006*).

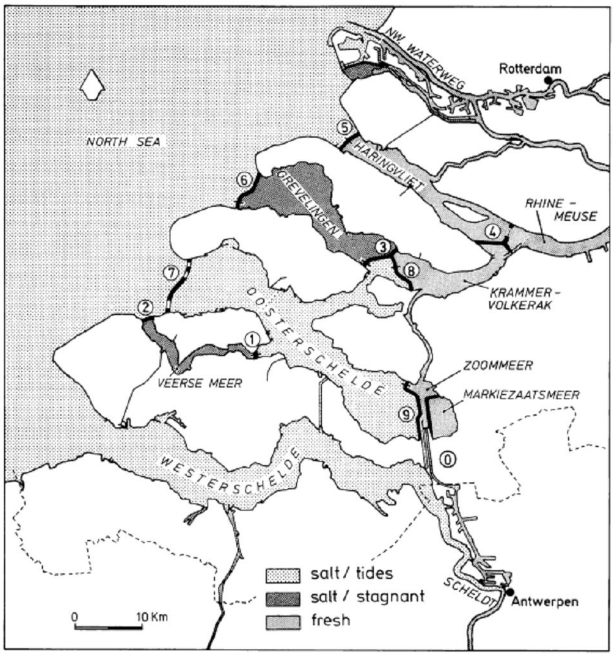


Figure 1.1. Map of the Delta area of the rivers Rhine, Meuse and Scheldt in the southwest Netherlands as resulting from the Delta project engineering scheme. 0 = Kreekrakdam, 1 = Zandkreekdam, 2 = Veersegatdam, 3 = Grevelingedamn, 4 = Volkerakdam, 5 = Haringvlietdam, 6 =Brouwersdam, 7 = Oosterschelde storm surge barrier, 8 = Philipsdam, 9 = Oesterdam (*Smits et al., 2006*).

The installation of the Delta project caused negative side effects as the complicated interplay between the deposition and erosion of marine and river sediments in the delta ceased, leading to uncontrolled alterations in the long-term geomorphologic and hydrodynamic processes (*Smits et al., 2006*). This causes a continuous erosion of tidal flats, strong reduction in the brackish zone, and reduction of the tidal current. These alterations reflected in changes in the local biodiversity, as the estuarine and migratory specie disappeared, and were replaced by an increasing number of exotics in the estuary (e.g. the Japweed and the Japanese oyster; *De Jonge et al., 2002*).

The urge to improve the quality of the ecology and water has been amplified by the implementation of European Union Water Framework Directive (*European Community, 2000*). This directive requires that all river and estuarine surface waters are managed to ensure that they achieve good chemical and ecological status by 2015. The restoration of the tidal dynamics is a method to improve the quality of the ecology and water (Nationaal waterplan 2008).

One way to restore the tidal dynamic in the region is by restoring tidal creeks, which connect the upland coastal area with the sea. Restoration can in this case be defined as connecting the upland area with the tidal regime, so the current state of the mainly agriculturally intensified sites changes into a state with a higher ecological quality. When restoring tidal creeks it is important to understand the influence of the tidal regime to the environment to mitigate any possible negative effects. This will lead to different preconditions because the negative effects to the current types of land use need to be minimized. Hence in order to minimize the negative effects the choice of location is important.

1.2 Tidal creeks

Tidal creeks are water bodies connected to the sea and are characterized by a low relief, shallow depth and expansive intertidal habitats (*Wiegert et al., 1990*). These creeks provide nursery habitats for many species of juvenile fish, shellfish and crustaceans as well as feeding grounds for wading birds and adult fish (*Kneib, 1997*).

Research to tidal creeks and channels was originally stimulated by their resemblance to river channels. Studies were performed to understand the topology (*Knighton et al., 1992*) and creek geometry (*Myrick et al., 1963*) based on the underlying hydrological framework of *Horton (1945).* The conclusion formed after these researches was that the geomorphological characteristics of tidal creeks and channels were similar to those of terrestrial channels and thus that the tidal creeks were formed in response to draining of the tide from surrounding marsh (*French et al., 1992*).

Nevertheless there are essential differences between tidal creeks and terrestrial channels. The most important difference is the bidirectional flow in a tidal creek (*Lawrence et al., 2004*). Besides that, the topography of a tidal basin differs from a fluvial basin. These two differences indicate that creeks are not primarily formed as drainage networks, but form in response to the tide to dissipate tidal and wave energy (tidal regime) entering the upland (*Pethick, 1992*).

This means when the tidal regime is brought back into the tidal creek, the function of the creek changes from only a creek that drains the upland, to a creek which drains and dissipates the tidal and wave energy. This change will influence two important factors: the safety conditions and land use.

1.3 Problem definition

Research to tidal creek or salt marsh restoration has been performed before (*Weinstein et al, 2001; Bakker et al., 2002; Eertman et al., 2002*), however the focus of these researches are merely set to assess the rate of success of the ecological restoration of tidal marshes. When planning the tidal restoration of a creek in a densely populated area with vulnerable land use patterns close to the shore such as in Zeeland, the negative influence of the tidal regime to the upland area needs to be investigated. Current knowledge is lacking in this area so new research is needed, which is performed in this study.

1.4 Aim

The main aim of this study is to develop a framework to evaluate locations for tidal creek restoration, based on the effects on surrounding land use. Furthermore this research aims to apply this framework to evaluate three locations, which are selected by Tauw bv.

1.5 Research questions

In this research the following questions will be addressed:

1) What preconditions exist when restoring a tidal creek?
2) How can a framework be developed to evaluate the effect of tidal creek restoration on the surrounding land use?
3) How are the three locations evaluated, when applying the developed framework?

In order to answer these questions the following sub-questions were made, which can be divided in three parts:

1) What preconditions exist when restoring the tidal creek?

- How can “safe and controllable” be defined when restoring a tidal creek?
- What is the concept of self regulating tide gates, and in what way might it contribute in bringing back the tidal regime to the upland in a safe and controllable manner?
- What is the effect of a tide box and self regulating tide gate on the tidal creek?
- What are the wishes of the stakeholders?

2) How can a framework be developed to evaluate locations for tidal creek restoration, based on the effects on the surrounding land use?

- Which parameters have the potential to affect the surrounding land use, when restoring a tidal creek and how can the lateral extent (area of influence) of these parameters be predicted?
- How are the different land use types, which can be found in the region, affected by these parameters? And how can these effects be valued?
- How can the answers to the former questions be incorporated into an evaluating framework?

3) How are the three locations evaluated, when applying the developed framework?

- What are the relevant geohydrological characteristics of the region necessary to predict the area of influence?
- What is the area of influence from the tidal creek on the three locations?
- What is the surface area of the different affected land use types?

2. Methods

In general this study consists of three parts. In part one the preconditions and the potential effects for tidal creek restoration are evaluated. The second part consists of the development of an evaluating framework, followed by the third part that applies the framework to the three locations. The three locations are selected by Tauw bv, based on expert judgment and knowledge of local experts and are: Zierikzee, Colijnsplaat and Sint Maartensdijk.

2.1 Preconditions of tidal creek restoration

The main goal of this part is to determine the preconditions that are bound to the restoration of a tidal creek. According to Waterschap Zeeuwse Eilanden the most important precondition, when restoring a tidal creek, is the safety factor. In order to find the effect of tidal creek restoration to safety, a definition of “safe and controllable” is needed. This will be followed by a literature review to see which methods are available to restore the tidal regime in the upland area while ensuring these safety standards.

Furthermore a general description of the wishes and demands of stakeholders at the three locations is given, to show the possibilities of the tidal creek restoration at a certain location. This is done by arranging expert meetings with the community board, Waterschap Zeeuwse Eilanden, and with local interested parties, of all the three locations

2.2 Development of the framework

The goal of this part is to develop a framework which is able to evaluate locations for tidal creek restoration, based on the effects on the surrounding land use. To reach this goal, first a literature study and experts meetings will be performed to find which parameters have the potential to affect the surrounding land use, when restoring a tidal creek. Furthermore, a method will be developed to predict the lateral extent (area of influence) of these parameters.

Secondly a literature study will be performed to determine how the different land use types, which can be found in the region, are affected by these parameters. The different land use types are determined by field visits, GIS and aerial photographs. In addition, a value to the influence of the effect will be added. For simplicity reasons it is chosen to work with three values: +, o and -, which respectively represent a positive, neutral and negative effect to the current land use type.

Based on the collected information in this part and in part 1 (chapter 2.1) an evaluation framework can be developed. This framework will handle the relevant factors concerning: safety preconditions, wishes of stakeholders, the extent of groundwater fluctuations and salinity intrusion with their valued effects and the surface area of the affected types of land use.

2.3 Application of the framework to the three locations

The goal of the last part is to apply the framework and to evaluate the three locations. This means that the area of influence needs to be predicted, so knowledge of the geohydrological characteristics of the locations is needed. This is obtained by:

- GIS (Geographical Information System): topographical map, aerial photographs, soil map, and the AHN (relief),
- Dino loket and REGIS (*TNO*, data of drillings in the soil): local hydrology,
- Groundwater map 36 for Zierikzee (*Cornellisen, 1984*) and Groundwater map 39 for Colijnsplaat and Sint Maartensdijk (*Hoogendoorn, 1985*): local hydrology,
- Waterschap Zeeuwse Eilanden: expert knowledge, salinity and tidal creek volume

After the prediction of the area of influence an analysis (with the help of GIS) is made about the surface area of each land use type which is affected. Combining this quantification with the given value (part 2, chapter 2.2), the location of a tidal creek is evaluated. After this a matrix is made which show the surface areas of the affected land use types in a region. This gives the opportunity to compare the total positive, negative or neutral influenced surface area of a certain type of land use in a region.

3. Preconditions and effects of tidal creek restoration.

When restoring tidal creeks in Zeeland, there are safety standards set by “Wet op de Waterkering” of 1996 and “Waterwet” of 2009 (www.wetten.overheid.nl) which must be considered. In order to ensure these preconditions set by the safety standards, the incoming tidal period via the tidal creek needs to be controlled and damped by water constructions. Although the installation of such a construction will lead to creek restoration, there are some ecological and geomorphological limitations of a controlled tidal creek restoration compared to a natural tidal creek. Furthermore the wishes and demands of the stakeholders show the possibilities of the tidal creek restoration.

3.1 Safe and controllable tidal creek restoration

In the Netherlands the safety standard with regards to the risk of being flooded are set by “Wet op de Waterkering” of 1996 and “Waterwet” of 2009 (www.wetten.overheid.nl). These constitutions contain standards which still are the same as during the execution of the Delta project, namely a chance of flooding of 1/4,000 to 1/10,000 per year.

To ensure these safety standards, and to minimize the negative effects to the surrounding land use, it is important that tidal creek restoration happens in a safe and controllable manner. This means that the tidal regime is allowed in the upland area, however the incoming tide is not allowed to flood any other area, besides the ones that are designated for this purpose. Furthermore, in case of extreme weather events there must be enough protection to ensure the safety standards for the upland area. In order to ensure these preconditions, the incoming tide via the tidal creek needs to be controlled and damped by water constructions.

To control the flow of upland water into the diked estuarine areas or river reaches, and to prevent estuarine intrusion behind those dikes, water constructions like tide- or flood boxes are used. The simplest tide boxes exist of a single culvert and a tide gate. The culvert (in Dutch: duiker) is running through a dike connecting the channel to the sea water. To control the water flow in a culvert, doors are attached to the discharge ends of the culvert. These doors are known as flap gates or tide gates (figure 3.1).

These gates close during incoming (flood) tides, when the water level outside the dike is higher than the inside, preventing flooding of the low-lying upland. During the outgoing (ebb) tides the water level inside the dike is higher, hence the tide gate opens, allowing water to flow from the upland area.

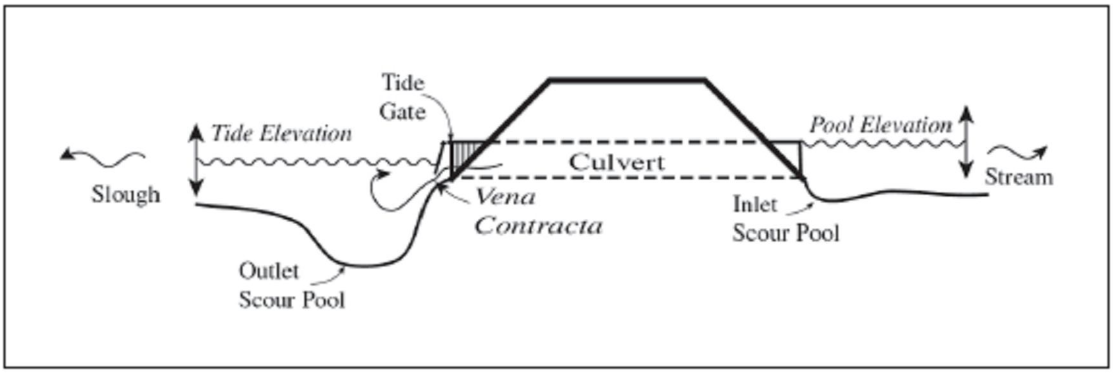


Figure 3.1. Lateral schematic view of a tide box with a tide gate at the discharge ends of the culvert (*Giannico et al., 2005*).

The use of certain tide gates allows tidal creek restoration in a safe and controllable manner. The tide gate that is most suitable for restoring the tidal regime in a tidal creek is the self regulating tidal gate (SRT), also known as the buoyant lid. The main distinguishing features of the SRT are the elevated buoyancy of its lid and a set of counteracting arms with floats on top of the tidal gate (figure 3.2; *Giannico et al., 2005*).

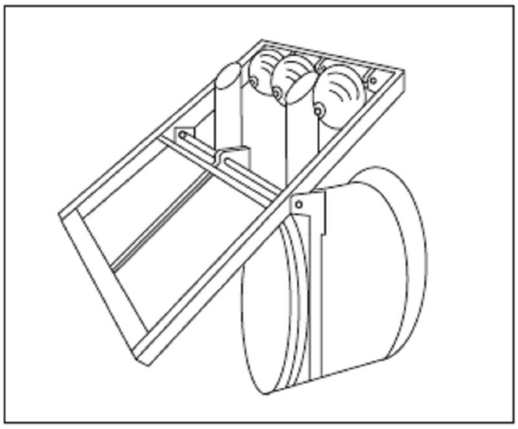


Figure 3.2. Self regulating, or buoyant, tide gate (*Giannico et al., 2005*).

Because the lid is buoyant, the lid floats most of the time on the water surface, which makes the SRT unique when comparing it to other tide gates. This means that the gate remains open most of the time. The open gate allows besides the upland discharge during the outgoing ebb tide, also tidal flushing during the most of the flood tide cycle. The SRT only closes when water outside the tide gate rises above a tolerable level. At that point the counteracting, vertical arms with floats on top of the tidal gate is pushed upwards, thereby acting as a lever that forces the buoyant lid under water to close the gate.

The height of the floats can be adjusted to suit with the site-specific conditions or changing needs. This means that the SRT is able to determine the tidal amplitude that enters the creek and that it can close at each desirable moment, e.g. so throughout the daily tide or only during extreme high tides which occur with storm events. Whenever the tide begins to drop, the upward pressure on the floats ceases and the hydraulic head differential in the culvert is able to lift the buoyant lid and forces to open the tide gate. Hence the use of SRT allows a tidal creek restoration in a safe and controllable manner.

3.2 The effect of tide box and self regulating tide gates on the tidal creek

Research from *Roman et al. (1984)* showed that self regulating tide gates are successful in restoring the estuarine connectivity. Only after one growing season, when the incoming tide was allowed into the upland area during most of the flood cycle, significant changes in vegetation type were found; the freshwater plants died, and salt-water tolerant plants replaced the freshwater invaders. Furthermore it is stated by Waterman Industries Inc, the manufacturer of the SRT, that the SRT is able to restore estuarine plants, fish, shellfish, waterfowl, and wildlife habitat; reestablish tidal flushing of the upland without flooding the upland property, and deepens both upstream as downstream channels which improves the drainage.

Although the SRT is appealing, the ecological and geomorphological limitations of a controlled tidal creek restoration compared to a natural tidal creek are poorly understood. For example, the velocity of the incoming flood tide of a natural tidal channel reaches a peak just when the tide rises above the adjacent surface, while the velocity of the ebb tide peaks as the tide drops below the adjacent surface (*Friedrichs et al., 2001*). As the SRT prevents the tide from overtopping the tidal channel banks, the hydrodynamics of the channel will be altered and characterized by significantly lower tidal velocities than the natural tidal channel.

Besides that, the wave energy is of minor importance, as the tidal regime will be brought back into the tidal creek with a SRT. This means that the tidal energy is the most important factor from the tidal regime when restoring a tidal creek with a SRT. This research will therefore focus only on the effects of the tidal energy.

It is likely that the changing hydrodynamics will have a significant effect on sediment and detrital transport, with effects on e.g.; the channel geometry, fish use and water quality. Hence tidal creek restoration with a SRT is not fully comparable to a completely restored natural creek. Nevertheless the SRT is the most promising option for tidal restoration in an area with competing types of land use.

3.3 Wishes and demands of stakeholders

In this paragraph a general description of the wishes and demands of stakeholders at the three locations is given, to show the possibilities of the tidal creek restoration at a certain location.

In Zierikzee tidal creek restoration is only possible from the pumping station (close to the yellow road) till the national road that lays at the north boundary of Zierikzee (the red road, fig A.1a). Tidal influence is not allowed after this national road because a large fresh water system lies behind this road. The desired tidal amplitude in this creek is 1.0 m.

At Colijnsplaat the most western and eastern branches from the tidal creek will not be part of the restoration of tide, and only the “Valkreek” itself is available (fig A.2a). The branches from the Valkreek could easily be sealed of with e.g. a sluice. The desired tidal amplitude in this creek is 1.0 m.

The community of Sint Maartensdijk only agreed with a restoration of the creek when no tidal damping is applied. This means that tidal creek is going to be exposed to a tidal amplitude of 3.5 m.

4. Developing a framework for tidal creek restoration

4.1 Potential effects of the tidal energy on the surrounding upland

The parameters that have the potential to affect the surrounding land use when restoring a tidal creek are groundwater fluctuations and salinity (*Zedler and Callaway, 2000; Weinstein et al, 2001; Bakker et al., 2002; Blanton et al., 2002; Eertman et al., 2002*). These parameters are based on a set of articles that are merely set to assess the rate of success of the ecological restoration of tidal marshes, and are as follows. The lateral extent of groundwater fluctuations is mostly influenced by whether the adjacent aquifer is a confined or unconfined aquifer. The lateral extent of the intrusion of salinity is mainly influenced by the tidal period, amplitude and the inland hydraulic head. Changes in the tidal amplitude and inland hydraulic head however do not change the lateral extent of the salt plume, which remains more or less fixed at 60 meters from water surface body. The lateral extent of the salt plume does however increase with an increasing tidal period.

4.1.1 Groundwater fluctuations

When restoring a tidal creek, the connection between the tidal driven surface water body and the ground water subsurface flow processes will be restored. This will result in a periodic fluctuation of the groundwater table, as the propagating pressure waves, caused by tidal energy, travel into the upland area from the surface water body (figure 4.1; *Ursino et al., 2004*). As these periodic fluctuations propagate into the upland area, their amplitude decreases and phase-shifts occur until the influence of the tide is damped out. These tidal driven groundwater fluctuations could alter the groundwater table in such a way that current forms of land use such as agriculture or urban areas are troubled (*Schulz et al., 2002*).

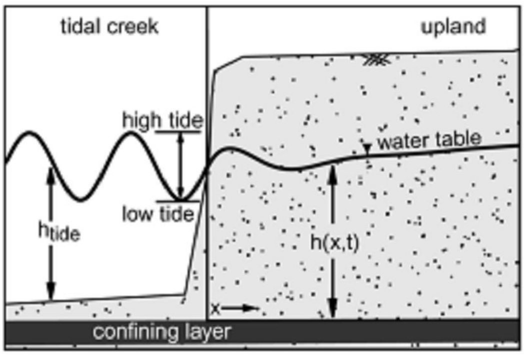


Figure 4.1. Schematic diagram showing the influence of the fluctuating tidal stage (h_{tide}) in the tidal creek to the water table in the adjacent upland (h(x,t)). As can be seen the influence of the tide dampens with increasing distance from the tidal creek (*Schulz et al., 2002*).

Effects of the tidal energy on groundwater fluctuations

The elevation and extent of the groundwater fluctuations are a function of several factors, mainly aquifer characteristics and tide range, which is best described by the following set of equations. Starting with the Boussinesq equation that describes the transient one-dimensional horizontal flow in confined and unconfined aquifers and is based on Darcy's Law and the continuity equation:

$$\frac{\partial h}{\partial t} = -\frac{K}{S_x}\frac{\partial}{\partial x}\left(h\frac{\partial h}{\partial x}\right) \quad (1)$$

where h is the elevation of the free water surface in the aquifer, K is the hydraulic conductivity and S_x is the aquifer storage coefficient.

Assuming that the horizontal flow dominates over the vertical flow, this equation is sufficient to describe the groundwater flow at the upland-estuary interface (*Nielsen, 1990*). When the magnitude of groundwater table fluctuations is small compared to the depth d of the aquifer, formula (1) can be linearised to:

$$\frac{\partial h}{\partial t} = -\frac{Kd}{S_x}\frac{\partial^2 h}{\partial x^2} \quad (2)$$

When substituting the aquifer transmissivity (T), which is the hydraulic conductivity * saturated thickness and equating the specific yield to the unconfined storability to storativity, formula (2) can be reduced to:

$$\frac{\partial^2 h}{\partial x^2} = -\frac{S_x}{T}\frac{\partial h}{\partial t} \quad (3)$$

The input of the groundwater table fluctuations is subject to the periodic rise and fall of the tidal creek. The head at the tidal creek is defined by a simple sinusoidal oscillation (*Gregg, 1966*):

$$h = h_0 \sin \omega t \quad (4)$$

where h_0 is the tidal amplitude and ω is the angular velocity of the tide. When assuming that due to tidal damping the groundwater fluctuations will attenuate to zero, it can be said that at $x = \infty$, $h = 0$. Integrating formula (4) with formula (3) with this assumption will give:

$$h(x,t) = h_0 e^{-x\sqrt{\pi S_x / t_0 T}} \sin\left(\frac{2\pi}{t_0} - x\sqrt{\frac{\pi S_x}{t_0 T}}\right) \quad (5)$$

where t_0 is the tidal period. Formula (5) is the standard solution to tide induced groundwater table fluctuations that is used by many authors (e.g. *Schultz et al.,2002; Fakir et al., 2003; Jha et al., 2008*). In this formula the amplitude of the groundwater fluctuations at a distance x from the water surface body is given by:

$$h(x,t) = h_0 \exp\left(-x\sqrt{\frac{\pi S_x}{t_0 T}}\right) \quad (6)$$

Another way of calculating the influence of the tidal amplitude on the groundwater fluctuations is by calculating the tidal efficiency. The tidal efficiency (TE) is defined as the ratio of the amplitude of groundwater fluctuations in the aquifer to the amplitude of tidal fluctuations at the upland-estuary boundary, which gives a more general oversight than formula as it presents the ratios of the tidal amplitude at a certain distance(6) (*Jha et al., 2008*):

$$TE = \exp\left(-x\sqrt{\frac{\pi S_x}{t_0 T}}\right) \quad (7)$$

Factors influencing the tidal energy on groundwater fluctuations

Formula (6) and (7) show that the lateral extent of groundwater fluctuations is mainly influenced by the tidal period (t_0), the aquifer transmissivity (T) and the aquifer storage coefficient (S_x). The tidal period (t_0) determines the duration of the flood and ebb period which causes the propagating pressures waves that travel into the surrounding upland area.

The aquifer transmissivity (T) is a measure of how much water can be transmitted horizontally and is directly proportional to the average horizontal permeability (hydraulic conductivity, K) and the aquifer thickness (d).

The aquifer storage coefficient (S_x) is important as it determines the tidal propagation by influencing the damping of the tidal response. The coefficient differs noticeably for confined and unconfined aquifers. Confined aquifers (sealed off with an impermeable layer on the bottom and top of the aquifer; figure 4.2) may exhibit low attenuation with water level fluctuations, as the pressure wave is generated due to changes in fluid pressure, extending the fluctuations to a several hundreds of meters from the surface water body (*Lanyon et al., 1982; Fakir et al., 2003*). The aquifer storage coefficient in confined aquifers is predicted by:

$$S = 1.8.10^{-6}(d_2 - d_1) + 8.6.10^{-4}\left(d_2^{\ 0.3} - d_1^{\ 0.3}\right) \quad (8) \quad (\textit{Gun, 1979})$$

In which d_1 and d_2 is respectively the top of and bottom of the aquifer.

Unconfined aquifers (open aquifer; figure 4.2;) are heavily damped as the pressure wave is generated due to changes in storage caused by dewatering and filling of the pores (*Jha et al., 2008*). Therefore fluctuations are unlikely to extend further than a few hundreds of meters from the surface water body (*Schulz et al., 2002; Cheng et al., 2004*). The aquifer storage coefficient in unconfined aquifers corresponds with the effective porosity and varies between the 0.01 and 0.4.

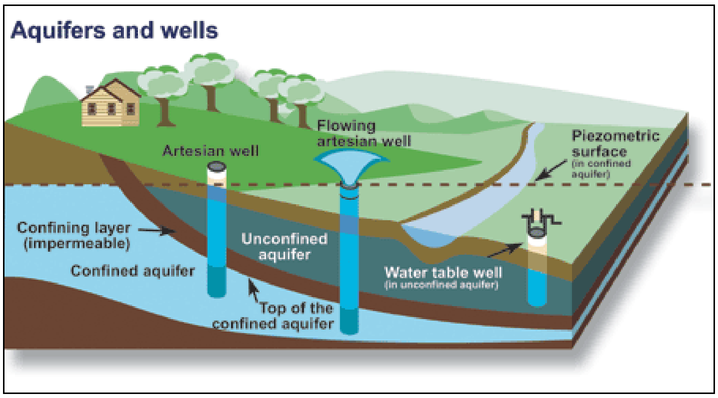


Figure 4.2. Schematic diagram of a confined and an unconfined aquifer (*Environment Canada*). The unconfined aquifer is open aquifer in which water easily can be discharged. The confined aquifer is sealed off with an impermeable layer on the bottom and top of the aquifer. It must be noted that the confined aquifer also can be adjacent at the surface.

4.1.2 Salinity

The biodiversity and health of the upland have been shown to be sensitive to salinity and available groundwater in the soil (*Ridd et al., 1996; Ball, 1998*). The tidal regime is able to change the salinity in the soil due to alterations in the hydrology and hydro-salinity in the surrounding region due to tidal pumping. Such a change will cause stress to the water quality in the environment and is able to seriously affect the biodiversity and health of the upland.

Effects of the tidal energy on salinity

The intrusion of salinity and the behavior of the groundwater flow in a phreatic aquifer, adjoining a partially penetrating tidal estuary is analyzed with the help of an two-dimensional model from *Werner et al., (2006)*, called SUTRA. The outcome of the SUTRA model will be used as an example to determine the effects of tidal energy on salinity intrusion in Zeeland. This can be justified as the parameters used in this model (e.g. tidal period) have a high similarity to the parameters that can be found at the three locations. Furthermore the adoption of specified boundary pressures, like the groundwater flow and the hydraulic conductivity, is the same for different aquifer materials (*Werner, 2004*).

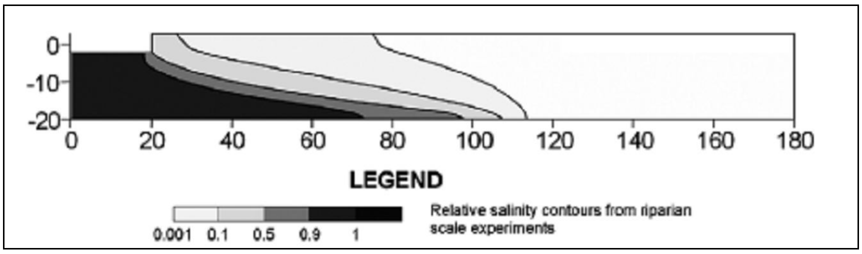


Figure 4.3. The saline plume predicted after 100 years, when only passive intrusion occurs determined by the SUTRA model by *Werner et al., 2006*. The outcome of this model shall be used as reference material to examine the influence of tidal energy on the salinity intrusion. The salinities in the soil are represented as relatives (%) to the salinity in the surface water body. The elevation level of zero represents the mean water level in the surface water body (MWL). The aquifer basement can be seen as a impermeable layer. The spatial units are in meters.

The enrichment of salinity due to the tidal energy is influenced by the inland hydraulic head and tidal amplitude (*Mao et al., 2006; Werner et al., 2006; Robinson et al., 2007b*). Changes in the tidal amplitude and inland hydraulic head however do not change the lateral extent of the salt plume, which remains more or less fixed at 60 meters from water surface body. Similar results for both the influence of the hydraulic head and the tidal amplitude are also reported by *Robinson et al. (2007b)*. The tidal period is also designated as a factor which influences the salt plume intrusion, and it is expected that the lateral extent of the salt water plume will increase with the tidal period (*Waterschap Zeeuwse Eilanden*).

The steady state conditions of passive saltwater intrusions (figure 4.3), which is density driven, will be used as reference material to examine the influence of tidal energy on the salinity intrusion. This figure show a lateral cross section of a creek and the salt plume intrusion. The salinities in the soil are represented as relatives (%) to the salinity in the surface area. This means that the 0.9 relative isochlor represents a border at which the salinity in the soil is 90 % of the salinity in the creek. The steady state conditions as in figure 4.3 (*Werner et al.,* 2006) will be compared to simulations of 1 m amplitude, which varies between +0.5 and -0.5 m of the mean water level of the creek (MWL; figure 4.4).

When comparing the steady state conditions (figure 4.3) to the situation with tidal influence (figure 4.4) it can be concluded that the major differences between the effects of non-tidal and tidal influenced salinity intrusion are located at basement of the aquifer and are within 100 (=80 meters from the creek bank) meters of the creek. Even more when looking at the groundwater level the lateral extent of salinity intrusion remains at a distance of 80 (=60 meters from the creek bank) meters of the creek (figure 4.4; *Werner et al., 2006*).

Besides that three distinct observations can be made regarding influence of tidal energy on the salinity intrusion. Firstly, looking at the 5-year simulation, the total lateral extent of the salinity does not increase, as the 0.001 and 0.1-relative isochlors both remain virtually at the same position at the groundwater table as well as at the aquifer basement. The width of the transition zone between the saline and freshwater zone, however, increases considerably caused by the movement in the 0.9-relative isochlor towards the creek.

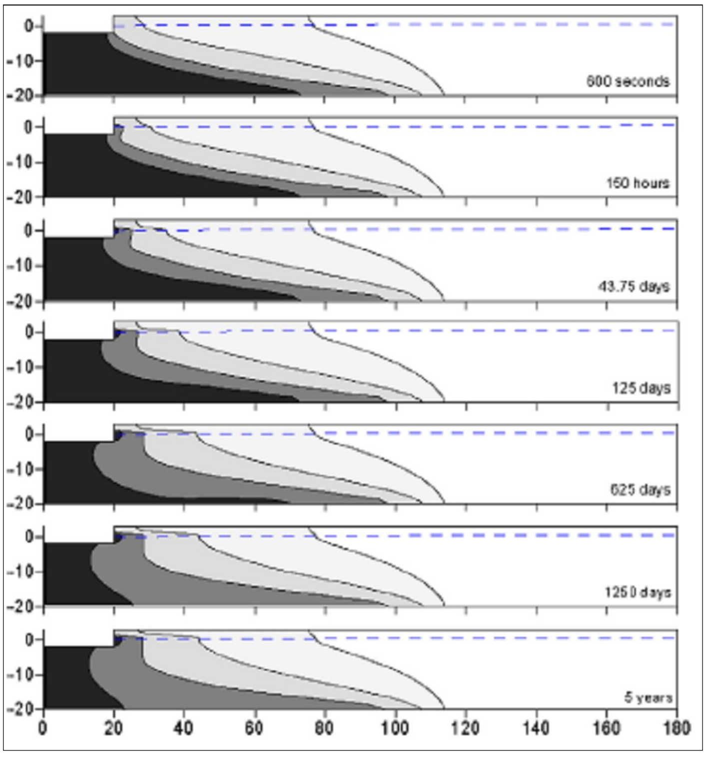


Figure 4.4. Spatial and temporal changes in the distribution of salinity in aquifer caused by the tidal energy from an estuary, determined by the SUTRA model by *Werner et al., 2006*. The outcome of this model shall be used as example to determine the effects of tidal energy to the salinity intrusion in Zeeland. The salinities in the soil are represented as relatives to the salinity in the estuary. The groundwater table height is presented by the dashed line. The legend is the same as in figure 4.3.

Secondly, the movement of this 0.9- relative isochlor, causes a significant reduction in the volume of highly saline groundwater, which is due to a change into the direction of groundwater flux (*Werner et al., 2006*). Compared to the steady state conditions, the influence of tidal energy causes a sharp increase of the groundwater flux through the lower creek bank and the base of the creek occur. This is caused by the intrusion of the dense salt water plume in the upper aquifer.

Thirdly the part, close to the groundwater table and to the creek, is severely enriched in the content of salinity. This is mainly due to the forcing of salts into the aquifer during the flood tide, which is not completely returned during the ebb tide.

4.2 Effects of the tidal regime on the main types of land use in Zeeland.

The main types of land use at the three locations in Zeeland, which are sensitive to changes in salinity or groundwater fluctuations, can be divided in the following groups: urban areas, agriculture and nature areas. Groundwater fluctuations have especially a negative influence to wooden foundations of constructions in urban areas, due to bacterial decay. An increase in salinity will mainly affect agriculture and most terrestrial nature areas like forests.

4.2.1 Effects on urban areas

As the tidal driven influences are subsurface, the tidal energy only has an influence on the foundations, and especially on the wooden foundation piles, of constructions found in urban areas. Wooden foundations are widely used in the Netherlands along coastal areas and at river sites to stabilize constructions. The majority of buildings that were constructed on the wooden pile foundations, date to the beginning of the 20th century when much Dutch cities expanded (*Klaassen, 2007*). Therefore there is a great chance that the three locations contain constructions that have wooden foundations.

The wooden foundations are affected by bacterial decay when oxygen is available, for instance when the groundwater level is lowered (*Kretschmar et al, 2007*). Recent research proved that bacterial wood decay can cause a considerably decrease in the strength of wooden foundations within a time span of only a few decades (*Klaassen, 2007*). Although the conditions that favor bacterial wood decay remain uncertain, research from *Fugro (2003)* and *Klaassen, (2007)* indicated that an increase in the bacterial wood decay is caused by an increase in groundwater flow around wooden foundations.

These findings indicate that tidal driven groundwater fluctuations could form a threat for the stability of the constructions, which have a wooden foundation. Therefore the effect of groundwater fluctuations to the urban areas is valued negatively. It seems logical that the decay of wood also happens to wooden coffins at burial sites which therefore is also valued negatively.

With respect to the effect of salinity to the wooden foundations, little research is done, meaning that no justified positive or negative value towards this effect can be given, therefore it is decided to value the effect neutral.

4.2.2 Effects on agriculture

For agricultural crop fields the availability and quality of groundwater are of major importance and have a high influence on specific yield and biomass of a certain crop. The quality and availability of groundwater in the upland will be affected when a tidal creek is restored.

Effects of groundwater fluctuations

The development of vegetation in tidal influence area can be linked to the rising and falling of the groundwater level which determines the moisture content (originating by rainfall) of the soil (*Naumberg et al. 2005)*. However as Zeeland lies in a semi humid environment, meaning that the soil moisture will be sufficient for the plants during the periodic groundwater falling, it is mainly the rising of the water table that is able to cause a negative effect. This is due to the creation of anoxic conditions, which limit the plants productivity (*Roy et al., 2000*). Hence the productivity and development of a plant depends on the existence, persistence of an unsaturated (aerated) layer under the soils surface.

Research showed that even during high groundwater levels, an unsaturated layer persists because of a balance between the infiltration from soil surface and the plant water uptake. Generally the unsaturated, aerated layer expands and contracts under the tidal energy and is located at 50 cm below the ground surface (figure 4.5; *Marani et al., 2006*). As can be seen in figure 4.5 the aerated zone in the soil during all the different stages in a tidal period is present. When comparing the situation with vegetation (right side) to the situation without vegetation (left side) it is clear that the aerated zone is larger with vegetation than without vegetation, meaning that the presence of vegetation is a determining factor for the occurrence of the aerated layer (*Ursino et al, 2004*).

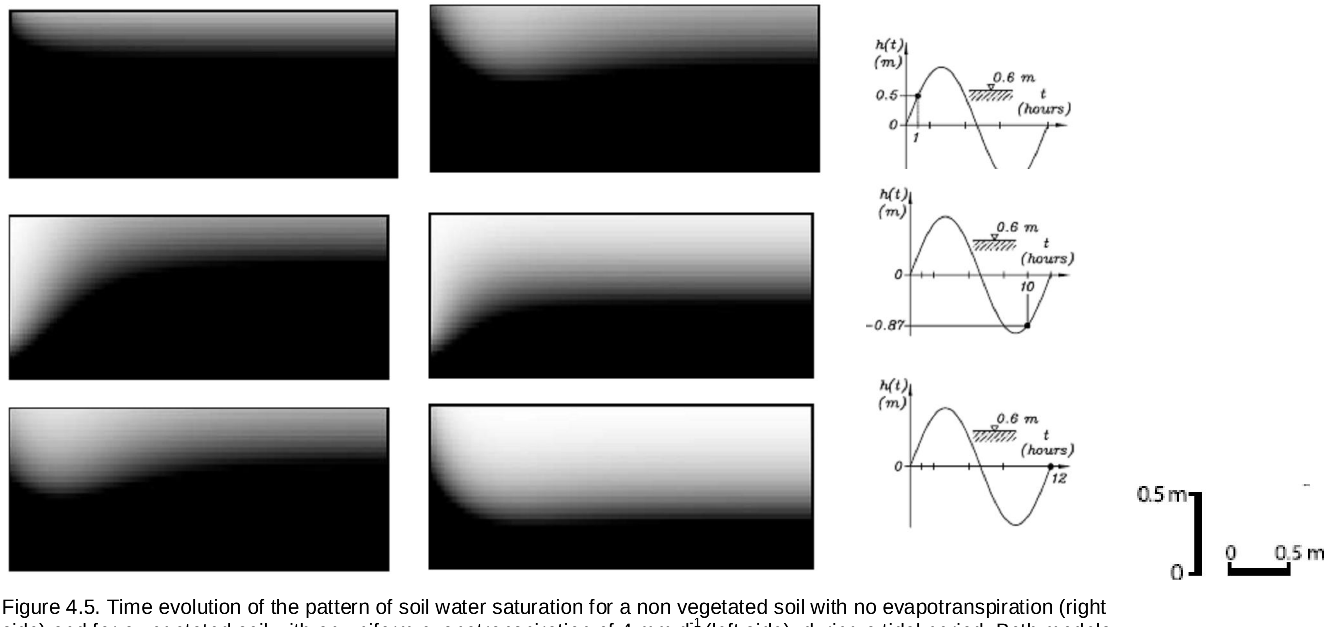


Figure 4.5. Time evolution of the pattern of soil water saturation for a non vegetated soil with no evapotranspiration (right side) and for a vegetated soil with an uniform evapotranspiration of 4 mm d^{-1} (left side), during a tidal period. Both models have a hydraulic conductivity of 10^{-4} $m.s^{-1}$ (*Ursino et al., 2004*). The lighter shades of gray indicate increasingly aerated zones, whereas the black zones indicate the saturated zones. The aerated zone is much smaller when no vegetation exist (right side) compared to the case in which evapotranspiration due to vegetation occurs (left side). Even during flood times a small unsaturated layer exists, which expands rapidly during ebb. The creek is situated at the left side of the figure.

Another result from *Ursino et al. (2004)*, which is consistent with the research of *Marani et al. (2006)*, is that groundwater table fluctuations decreases rapidly in relation with the distance to the creek and that significant fluctuations in the groundwater hardly reaches a noteworthy lateral extent. This means that the distribution of the unsaturated layer is virtually unaffected by the tide and is mainly governed by vertical fluxes (infiltration and transpiration). Hence the tidally driven groundwater fluctuations will barely influence the specific yield of agriculture, as water logging at the rooting zone will hardly occur. Therefore the value given to the effect of groundwater fluctuations to agricultural crops is neutral.

Effects of salinity

Every soil contains a mixture of soluble salts which are sometimes necessary for plant growth. When the total concentration of salts becomes excessive the plant growth is suppressed. The suppression increases with salt concentration until the plant dies. The tidal driven salinity intrusion will increase the salinity content in the soil as the water evaporates or is taken up by crops.

The suppression of plants is caused by osmotic effects and specific ion toxicities (Cl- and Na+), causing reduction in growth, leaf burn, necrosis and defoliation (Francois et al., 1993). Although every crop in salt areas is subjected to these effects, its growth reduction rate and tolerance threshold compared to the salinity varies among different crop species (figure 4.6).

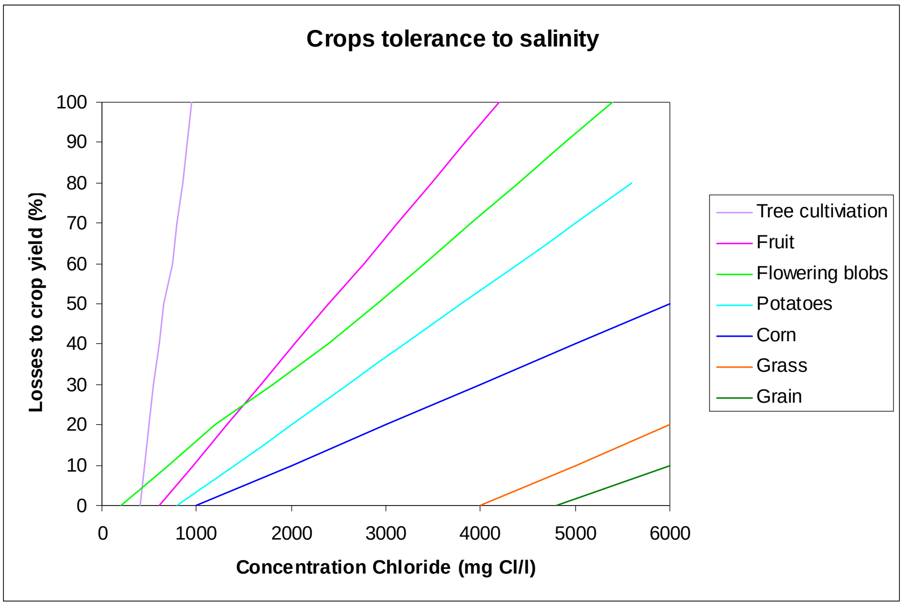


Figure 4.6. Losses of the crop yields for the most common crop species in Zeeland (based on *Francois et al., 1993*), which is based on the maximum allowable salt concentration without loss of yield (threshold) and the percentage yield loss per unit (slope) when the salt concentration is higher than the threshold. The losses to the crop yields are starting from a chloride concentration of 200 mg/l and are significant when the concentration is larger than 1000 mg/l.

Figure 4.6 show that losses to the crop yields for most common crop species in Zeeland are starting when the chloride concentration in the soil reaches 200 mg/l, and that the losses are significant when the concentration is larger than 1000 mg/l. Based on this graph the crops can be categorized into three groups according to their sensitivity to the chloride concentration, namely: pastures (grass) and grain that are tolerant to the salinity content, vegetable crops which belong to the moderately sensitive group (fruit, potatoes, corn, flowering blobs, except for grain who does not fit into this categorization), and the trees cultivation which exhibit a high sensitivity to the salinity content.

Based on this categorization a value can be added to the effect of the salinity intrusion caused by tidal creek restoration. The tolerant group (pastures) is valued neutral, and the moderately sensitive group (vegetable crops) and the high sensitive group (fruit and tree cultivation) are valued to be negatively affected by the salinity intrusion.

4.2.3 Effects on nature areas

Nature areas in Zeeland are protected with several regimes, namely; the Water Framework Directive areas, the Natura 2000 areas and the areas of the “Ecologische Hoofdstructuur”. The Water Framework Directive (WFD) is a directive for the European Union to achieve good qualitative and quantitative status of all surface water bodies (including marine waters) by 2015. The Natura 2000 is an ecological network of protected areas in the territory of the European Union, designed to protect the most threatened habitats and (bird)species across Europe. The Natura 2000 is based on two directives namely the Birds Directive from 1979 and the Habitats Directive from 1992. The “Ecologische Hoofdstructuur” is a national network of areas in which nature development has the priority in The Netherlands.

These nature areas contain a wide range of ecosystems like fluvial areas, intertidal zones but also terrestrial zones as forests, heath land and grass lands. Therefore it is decided that nature areas should be divided according to their characteristics and vegetation type as these will be influenced by the tidal regime. The following separation of the nature types that occur in Zeeland has been made: brackish fluvial areas, intertidal and marine areas, forest, grasslands and grasslands with flowers.

The restoration of the tidal regime in a tidal creek has a positive influence on the brackish fluvial areas and intertidal and marine areas. The terrestrial areas can be valued according the effect of the tidal regime on agriculture (chapter 4.2.2).

4.3 The evaluating framework

In the preceding chapter different factors concerning tidal creek restoration has been investigated. The framework is mainly formed by a literature study and expert meetings and handles the relevant factors concerning; safety preconditions, wishes of stakeholders, the extent of groundwater fluctuations and salinity intrusion with their valued effects and the surface area of the affected types of land use.

4.3.1 Assembling the framework

As can be seen in the framework (figure 4.9), the first step, at the top of the framework is to choose a location for tidal creek restoration. The next step is to determine the wishes and demands of stakeholders at a location and to combine this with the safety preconditions, as this will show the possibilities of a tidal creek restoration at a location. The following step is to determine the location characteristics and especially the tidal regime and aquifer characteristics of a location as they are most influential to the area of influence of a tidal creek.

After the location characteristics are obtained, the area of influence can be determined. This can be divided in the lateral extent of groundwater fluctuations and the lateral extent of salt plume intrusion. After this the land use types that lay within the area of influence are determined. This is necessary to calculate the surface areas per land use types, which are affected by the tidal driven groundwater fluctuations and salt plume intrusion. When calculating the surface areas it is possible to quantify the effects of tidal creek restoration, which makes it possible to compare several situations and locations.

The last step is to combine the quantification of the surface areas with the given value per land use area. The value of a given impact on a land use type is given by: + = positive, o = no effect, - = negative effect. This gives opportunity to compare the total positive, negative or neutral influenced surface area of a certain type of land use in a region.

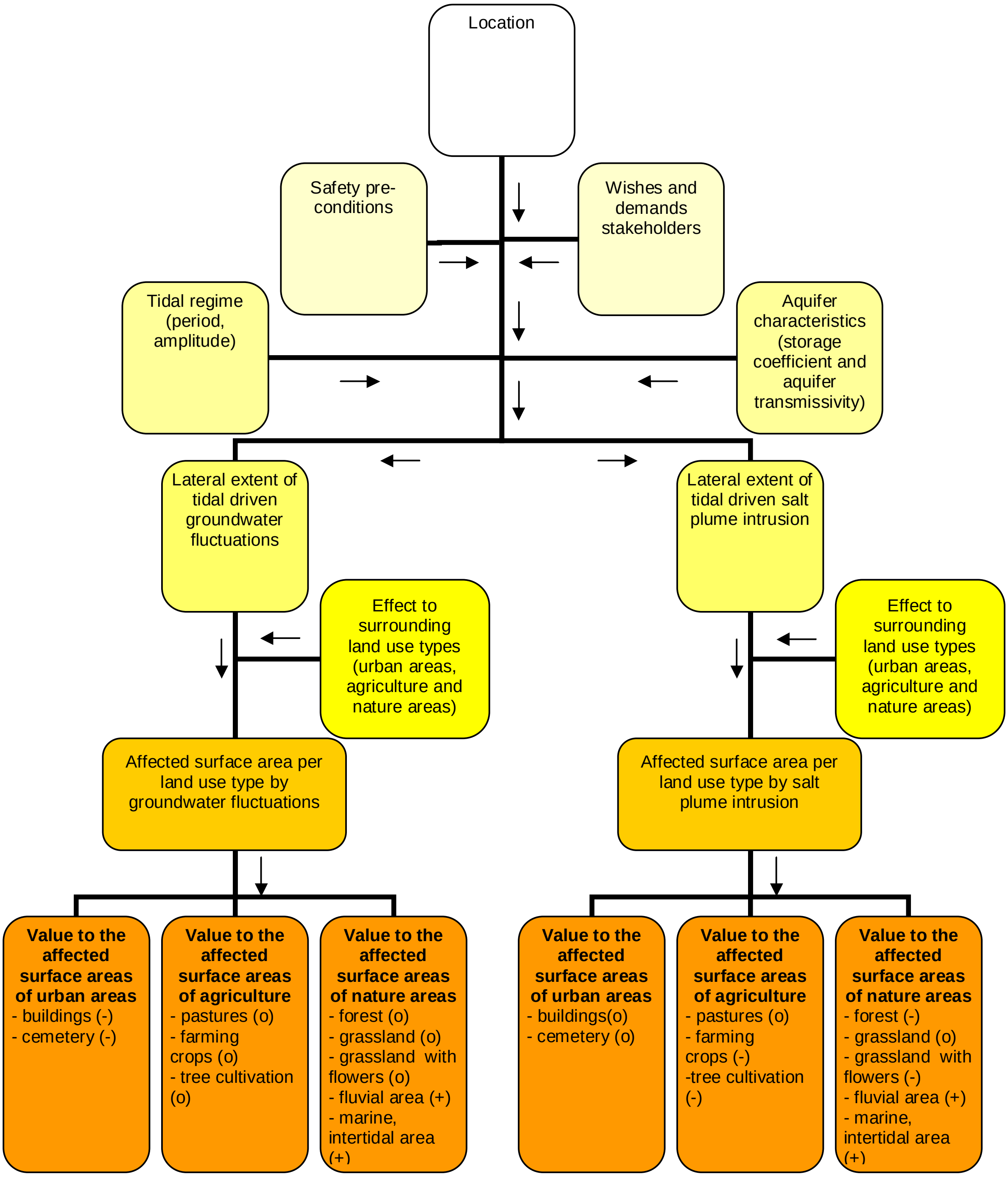


Figure 4.9. Framework to evaluate the location of the restoration of a tidal creek, based on the effects on the surrounding land use. The first step, at the top of the framework is to choose a location for tidal creek restoration. The next step is to determine the wishes and demands of stakeholders at a location and to combine this with the safety preconditions. The following step is to determine the location characteristics. After the location characteristics are obtained, the area of influence can be determined. This can be divided in into the lateral extent of groundwater fluctuations and the lateral extent of salt plume intrusion. After this the land use types that lay within the area of influence are determined, so the surface areas per land use types which are affected, can be calculated. The last step is to combine the quantification of the surface areas with the given value per land use area (+ = positive, o = no effect, - = negative effect). Note: this framework only accounts for effects of tidal energy (and thus not for the effects of wave energy) and for tidal creeks in a semi-humid climate.

5. Application of the framework to the locations

This chapter gives a general description of each of the locations and the geohydrological characteristics to predict the area of influence at the three locations. When assuming that groundwater fluctuations are negligible and not measurable when they are lower than 0.05 m., a lateral extent of tidal driven groundwater fluctuations in Colijnsplaat of 160 m. occurs. This is much smaller than at the locations of Zierikzee and Sint Maartensdijk, which are 625 and 1082 m. respectively. The lateral extent of salt plume has a fixed distance of 60 m. for each location (paragraph 4.1.2).

5.1 General characteristics of the three locations

The three potential locations for the restorations are the creeks close to Zierikzee, Colijnsplaat, and Sint Maartensdijk (figure 5.1), which are all situated in Zeeland in the South West of The Netherlands.

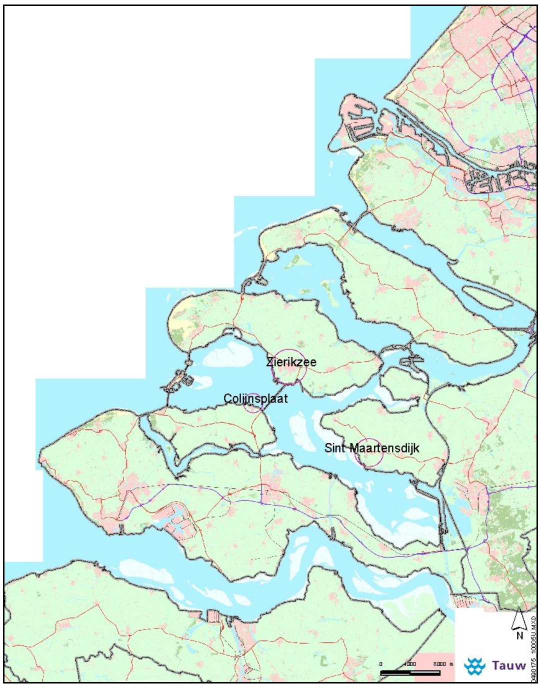


Figure 5.1. The locations of the three possible creek restorations, Zierikzee, Colijnsplaat and Sint Maartensdijk. These locations are all situated in Zeeland in the South West of The Netherlands.

The geohydrological situation of the three locations is best described by comparing it to a confined aquifer. This means that the aquifer is embedded by a top layer and a basis layer, who are both impermeable (figure 5.2). The occurrence of this top layer, however, is depending on the occurrence of creeks. In the occasion that a creek or an old creek system is present, the top impermeable layer is absent and replaced by fluvial sediments (*Hoogendoorn, 1985*).

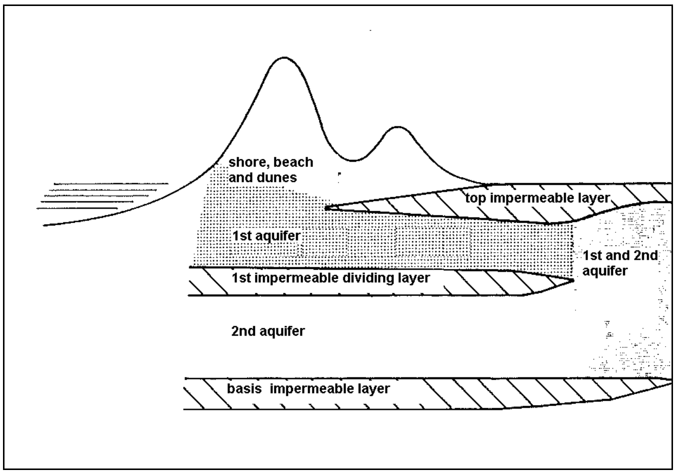


Figure 5.2. Geohydrological schematization of a coastal area with partially an unconfined and partially a confined aquifer (based on *Hoogendoorn, 1985*).

As this research is aimed to investigate the influence of tidal energy to the surrounding land use, only the groundwater flux in the first aquifer is of interest, as it influences the groundwater table. Due to a gradient in the hydraulic head in the aquifer at all the three locations, the groundwater flux is directed land inwards. Therefore the aquifer contains mainly brackish (150 mg/l < Cl^{-1} < 1000 mg/l) and salt (Cl^{-1} > 1000 mg/l) water. However little amounts of fresh water (Cl^{-1} < 150 mg/l) are located at the rooting zone due to the supply of rain (*Cornelissen, 1984*). Furthermore the creeks and drainage channels at the locations are brackish till salt and the seawater in this area is polyhaline (10-17 g/l Cl^{-1}; *Waterschap Zeeuwse Eilanden, 2009*).

The geohydrological parameters that are necessary to predict the lateral extent of the tidal driven groundwater fluctuations and salinity intrusion are given in table 5.1. A detailed geohydrological analysis of the three locations can be found in appendix A.

Table 5.1. The relevant parameters to predict the lateral extent of the tidal driven groundwater fluctuation and salinity intrusion at Zierikzee, Colijnsplaat and Sint Maartensdijk (based on *Cornellissen, 1984* and *Hoogendoorn, 1985*). S_x is the storage coefficient, t_0 is the tidal period (hours), T is the aquifer transmissivity ($m^2.d^{-1}$; hydraulic conductivity times the saturated thickness), h_0 is the tidal amplitude (m) and ψ is the hydraulic head (m in comparison to NAP).

	Zierikzee	Colijnsplaat	Sint Maartensdijk
S_x	0.0175	0.4	0.025
t_0	12	12	12
T	200	300	425
h_0	3.5	3.5	3.5
ψ	- 1.0	- 0.5	- 0.5

5.2 Lateral extent of the tidal driven groundwater fluctuations and salinity intrusion

In this paragraph the prediction of the lateral extent of tidal driven groundwater fluctuations and salt water plume intrusions at the locations is made. It is assumed that the effects are symmetric to both sides of the creek.

5.2.1 Groundwater fluctuations driven by the tidal regime

According to the scientific literature (*Cornellissen, 1984* and *Hoogendoorn, 1985*) groundwater fluctuations are negligible and not measurable when they are lower than 0.05 m. This range will be therefore assigned as the border of the tidal driven groundwater fluctuations in this research. As the tidal efficiency is an exponential formula the range will be set on 0.01. The lateral extent of the groundwater fluctuations at a location will be calculated with the input of table 5.1 and by:

$$h(x,t) = h_0 \exp\left(-x\sqrt{\frac{\pi S_x}{t_0 T}}\right) \quad (6)$$

and

$$TE = \exp\left(-x\sqrt{\frac{\pi S_x}{t_0 T}}\right) \quad (7)$$

The tidal efficiency (formula (7)) at the locations plotted against the distance from the tidal creek (figure 5.3) show that the tidal efficiency decreases faster at Colijnsplaat than at Zierikzee and Sint Maartensdijk. The tidal efficiency of 0.01 at Colijnsplaat is already reached at 246 meters from the creek, while the this point at Zierikzee and Sint Maartensdijk is reached at a greater distance from the creek, namely at 962 m and 1174 m respectively. This corresponds to the findings in paragraph 4.1.1, as Colijnsplaat is a unconfined aquifer and Zierikzee and Sint Maartensdijk are confined aquifers (appendix A). Furthermore figure 5.3 show that the tidal efficiency, decreases exponentially with the distance of the tidal creek.

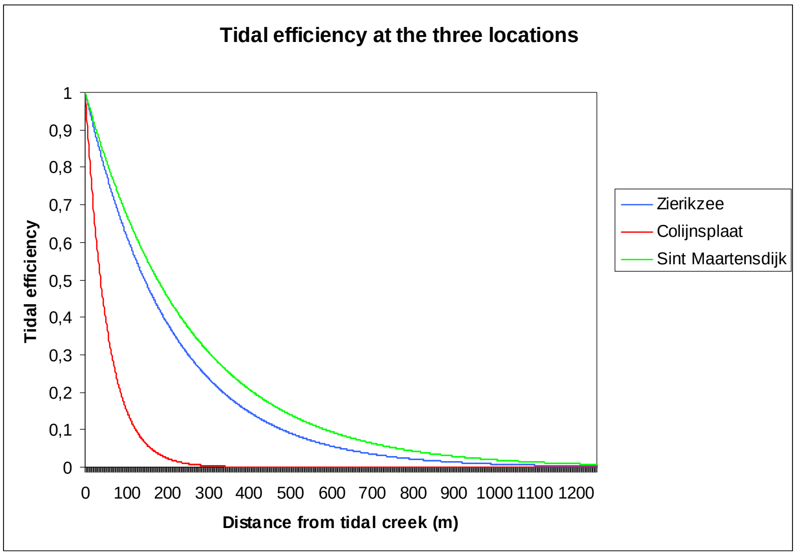
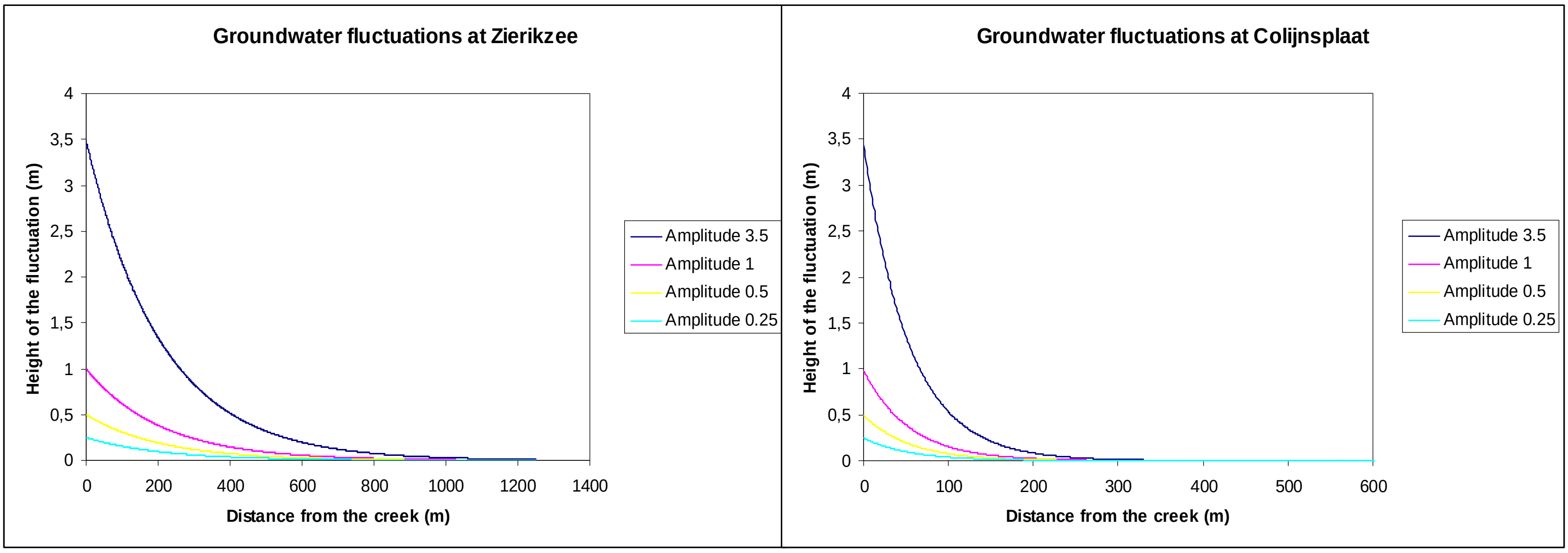
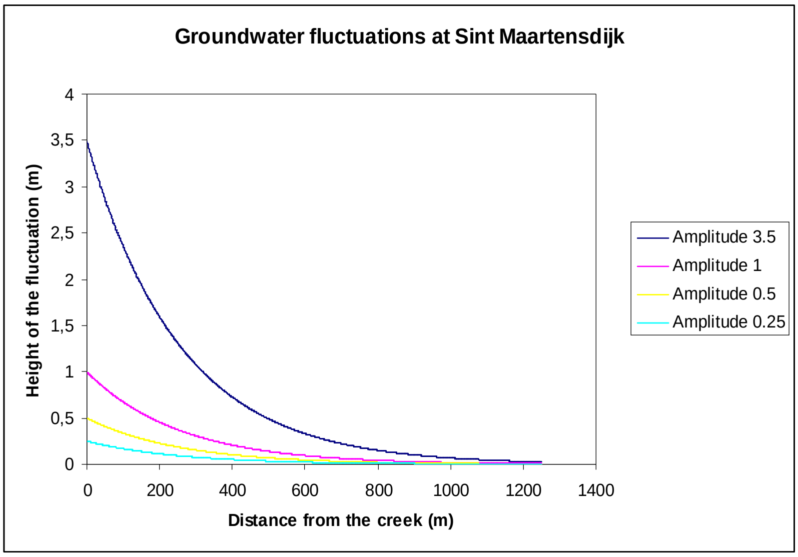


Figure 5.3. The tidal efficiency (formula (7)) at the three different locations plotted against the distance from the tidal creek. Tidal efficiency is the ratio of the amplitude of groundwater fluctuations in the aquifer to the amplitude of tidal fluctuations at the upland-estuary boundary.

Figure 5.4 a, b, c represents the groundwater fluctuations with the different tidal amplitudes of 3.5, 1, 0.5 and 0.25 m at the three locations, using formula (6). The amplitude of 3.5 represents the normal tide, while the amplitude of 1, 0.5 and 0.25 m are options for possible tidal amplitudes which are allowed into the creek when the safety preconditions are taken into account.



a) b)



c)

Figure 5.4 a, b, c. The groundwater fluctuations calculated according formula (6) at the locations. To take the safety preconditions and the wishes and demands of the stakeholders into account, there is chosen to work with different tidal amplitudes, namely with amplitudes of: 3.5, 1, 0.5 and 0.25 m. The amplitude of 3.5 represents the normal tides, while the amplitude of 1, 0.5 and 0.25 m are options for possible tidal amplitudes which are allowed into the creek. a) Groundwater fluctuations at Zierikzee, b) Groundwater fluctuations at Colijnsplaat, c) Groundwater fluctuations at Sint Maartensdijk.

Table 5.2 show the distance between the tidal creek and the presumed boundary regarding the influential lateral extent of the groundwater fluctuations (fluctuations < 0.05 m). It can be seen that for the preferred tidal amplitudes (grey compartments table 5.2) this distance amounts for the locations Zierikzee, Colijnsplaat and Sint Maartensdijk 625 m, 160 m, and 1082 m respectively.

Table 5.2. The distance from the tidal creek to the location where the groundwater fluctuations are less than 0.05 m, for the locations Zierikzee, Colijnsplaat and Sint Maartensdijk, according to formula (6). To take the safety preconditions and the wishes and demands of the stakeholders into account, there is chosen to work with different tidal amplitudes, namely with amplitudes of: 3.5, 1, 0.5 and 0.25 m. The amplitude of 3.5 represents the normal tides, while the amplitude of 1, 0.5 and 0.25 m are options for possible tidal amplitudes which are allowed into the creek. The grey compartments are the preferred tidal amplitudes from the stakeholders, as described in paragraph 4.3.

tidal amplitude (m)	distance border Zierikzee (m)	distance border Colijnsplaat (m)	distance border Sint Maartensdijk (m)
3.5	887	227	1082
1	625	160	763
0.5	481	123	586
0.25	336	86	410

5.2.2 Salt plume intrusion driven by the tidal regime

The intrusion of the salt water plume is only of interest around the groundwater level, as research has shown that the rest of the aquifer is already brackish till salt (*Hoogendoorn, 1985*). Furthermore the land use types are mainly affected by changes in salinity around the groundwater level (*Ursino et al., 2004*). The parameters that influence the intrusion of the salt water plume into the aquifer are the tidal amplitude and period and the hydraulic head (table 5.1).

As there is no free available model to predict the tidal driven intrusion of the salt plume into the surrounding land, the SUTRA model (*Werner et al. 2006*) shall be used as example to predict the salt water intrusion at the three locations. The tidal period at the locations is equal to the tidal period used in the SUTRA model. Furthermore this model shows that when altering the tidal amplitude and the hydraulic head the lateral extent of the salt plume remains fixed. This means that the lateral extent of the salt plume intrusion can be set at 60 meters of the creek (paragraph 4.1.2).

Research from *Narayan et al. (2007), Robinson et al. (2007a), Vaz et al (2008)* showed, while the amplitude and the hydraulic head were different, similar scale for the lateral extent of the tidal driven the salt plume intrusion, which strengthens the made prediction of a fixed distance at 60 meters of the creek.

The salinity content at 60 meters is 1 % of chloride concentration in the tidal creek. Assuming that the tidal creek has the same salinity as the sea (10 -17 g/l Cl^{-1}; *Waterschap Zeeuwse Eilanden, 2009*), this means that the salinity content is between 100 and 170 mg/l Cl^{-1}. The highest salinity of 170 mg/l Cl^{-1}, is still is below the found border of 200 mg/l Cl^{-1} at which most crops and vegetation types starting to lose yield (figure 4.6).

5.3 Surface area and land use type affected by the tidal energy

The figures 5.4, 5.5 and 5.6 and table 5.3, show the region and land use types which are affected by the tidal energy for Zierikzee, Colijnsplaat and Sint Maartensdijk. The tidal amplitudes which are used to predict the groundwater fluctuations are the amplitudes which are preferred by the stakeholders (paragraph 3.3). The border which was used to calculate the surface areas of the groundwater fluctuations is the blue line in the figures 5.4 - 5.6, which represent a groundwater fluctuation of 0.05 m. The main land use types at the three locations that lies within the region coincides with land use types mentioned in chapter 4.2 and are: urban areas, agriculture and nature areas.

5.3.1 Effects at Zierikzee

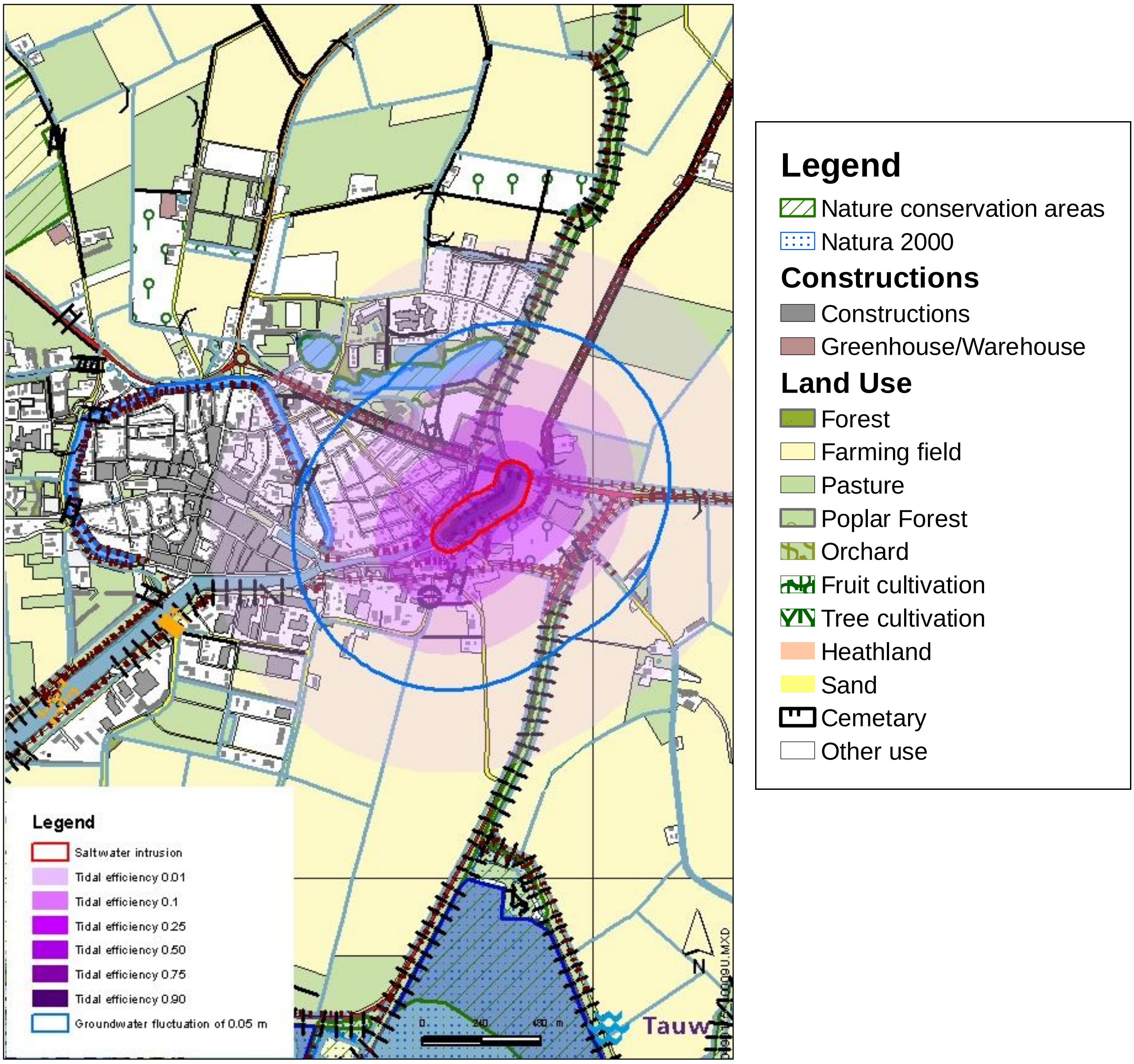


Figure 5.4, Salt water intrusion and the tidal efficiency displayed with an underground of the types of land use at the location of Zierikzee (scale 1:40.000)

5.3.2 Effects at Colijnsplaat

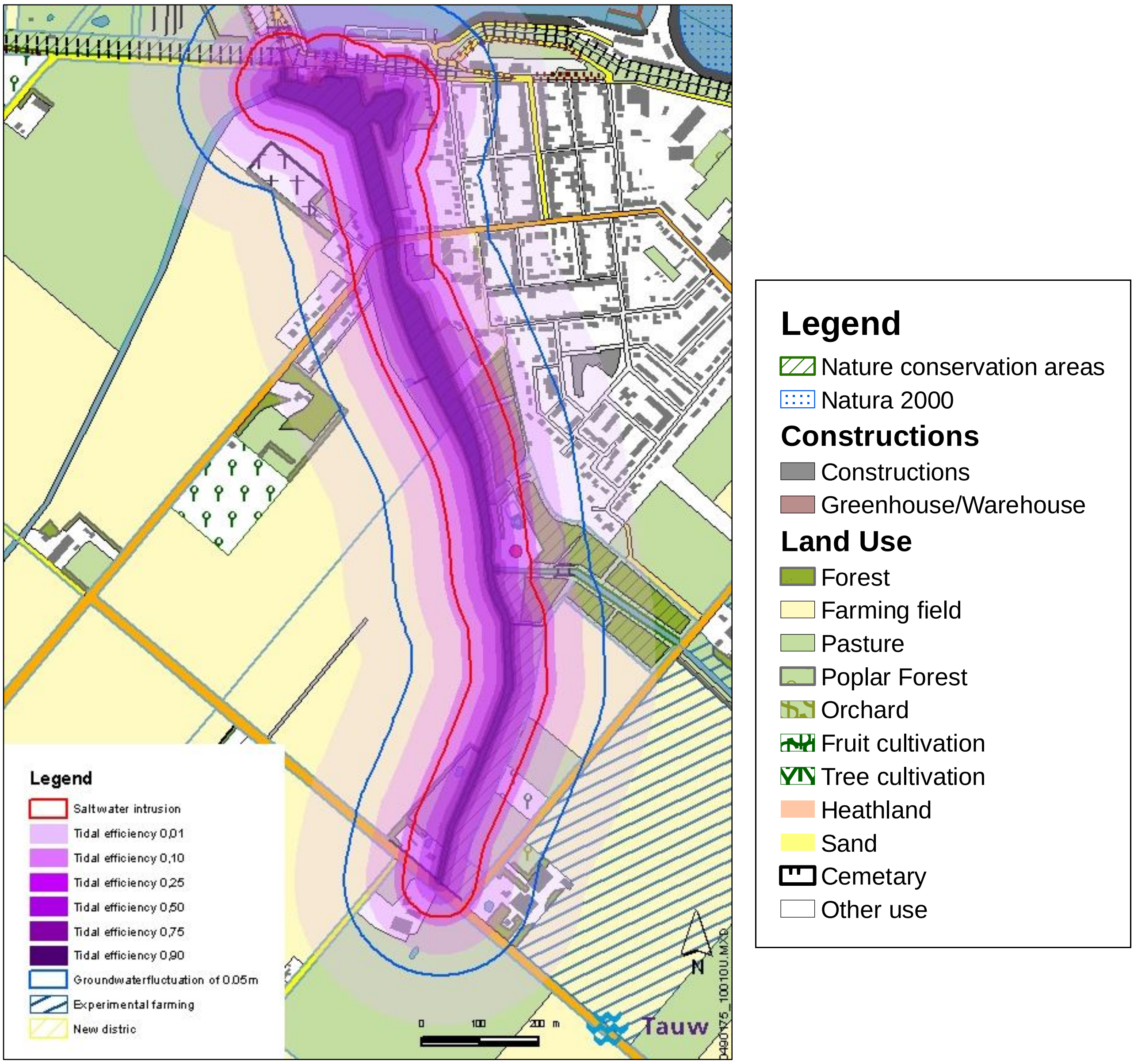


Figure 5.5. Salt water intrusion and the tidal efficiency displayed with an underground of the types of land use at the location of Colijnsplaat (scale 1:12.500)

5.3.3 Effects at Sint Maartensdijk

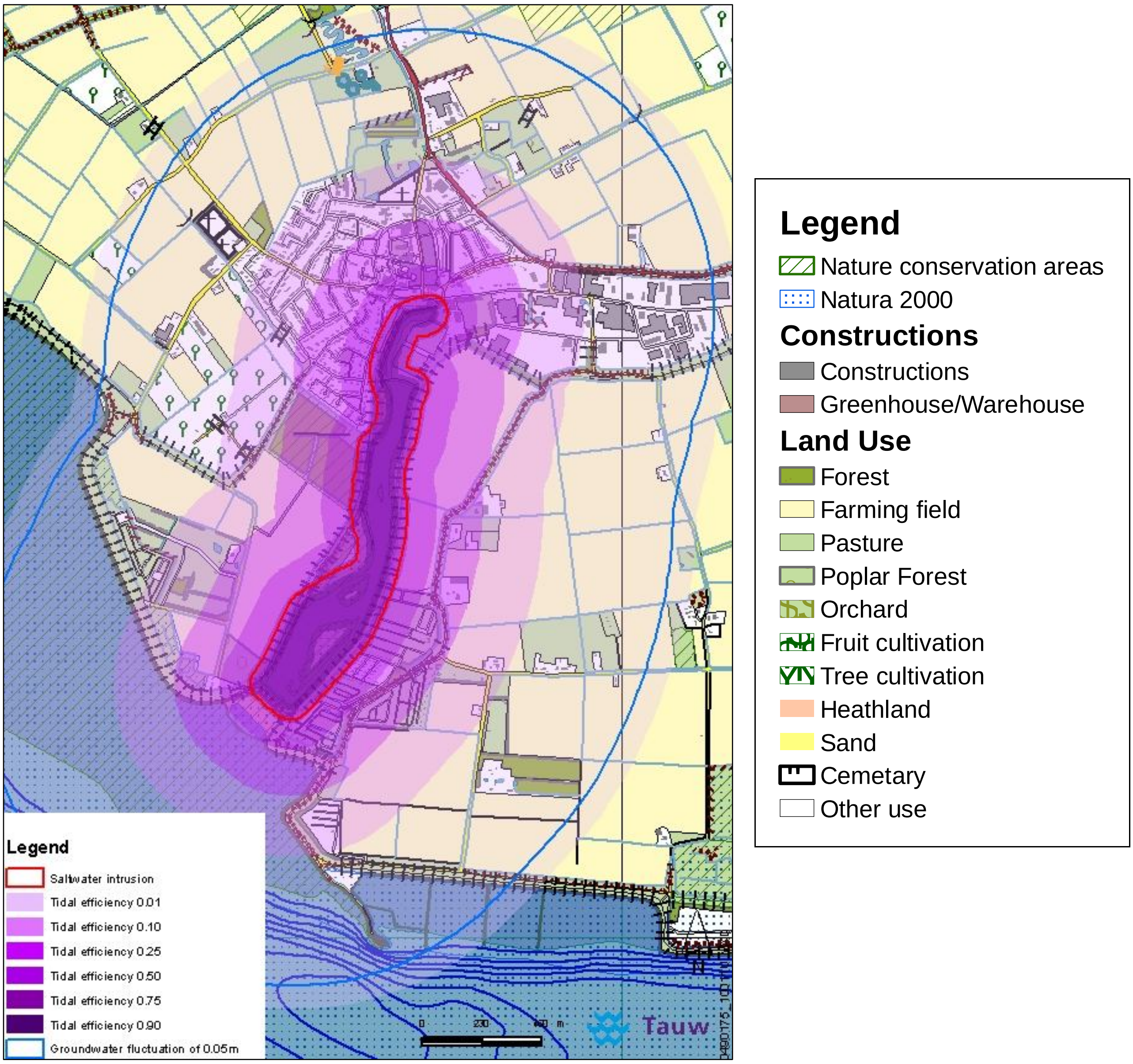


Figure 5.6. Salt water intrusion and the tidal efficiency displayed with an underground of the types of land use at the location of Sint Maartensdijk (scale 1:25.000)

Table 5.3. Surface area (in hectare = 10,000 m^2) of the affected land use types, determined by GIS, divided in three main groups; urban areas, agriculture and nature, by groundwater fluctuations and salt plume intrusion at the locations of Zierikzee, Colijnsplaat and Sint Maartensdijk. The value of the effect from the groundwater fluctuations and salt plume intrusion on the different land use types is given by: + = positive, o = no effect, - = negative effect (based on paragraph 4.2). The tidal amplitudes which are used to predict the groundwater fluctuations are the amplitudes which are preferred by the stakeholders. The border which was used to calculate the surface areas of the groundwater fluctuations is the blue line in the figures 5.4 - 5.6, which represent a groundwater fluctuation of 0.05m.

	Groundwater fluctuations				**Salt plume intrusion**			
	Value to effect	Zierikzee	Colijns-plaat	Sint Maartens-dijk	Value to effect	Zierikzee	Colijns-plaat	Sint Maartens-dijk
Urban area								
buildings	-	10.70	2.70	23.79	o	0.33	0.38	0.30
cemetery	-	1.40	0.74	2.58	o	0.57	0	0
Agriculture								
pasture	o	31.45	14.64	106.56	o	1.24	8.32	10.30
farming crops	o	10.76	17.28*	285.78	-	1.30	4.19	2.35
tree cultivation	o	4.62	0.59	19.12	-	0	0.11	0
Nature								
forest	o	6.30	5.17	24.68	-	0.26	1.75	2.97
grassland	o	0	0	5.03	o	0	0	0
grassland with flowers	o	6.94	3.51	3.00	-	0	2.66	2.98
fluvial area	+	19.31	3.76	20.98	+	0.95	3.77	20.98
marine area	+	0	2.14	0.17	+	0	0.13	0.17

* from this area 3.59 ha is in use by a company who practices experimental farming

5.4 Comparison of the affected surface areas at the locations

Figure 5.3 - 5.6, and table 5.3, makes it easy visible which areas are affected and where problems will occur in case of tidal creek restoration. Focusing at the negative effects in Zierikzee the salt plume intrusion will mainly affect some farming crops and forest areas. The groundwater fluctuations will affect buildings and cemetery. Colijnsplaat will mainly suffer from negative effects caused by salt plume intrusion in farming crops, tree cultivations, forests and grasslands with flowers. The groundwater fluctuations will cause a problem for buildings and cemetery. Sint Maartensdijk will endure negative effects caused by salt plume intrusion in farming crops, forests and grasslands with flower. The groundwater fluctuations will negatively affect buildings and the cemetery.

This means that generally al the locations have the same types of land uses that are negatively affected. However due to the wishes of the stakeholders and to the typical location characteristics the surface areas of the affected land use types differs significantly for the different locations (table 5.3).

6. Discussion

First the method of this research is discussed, followed by a summarization of the lacking data that were not taken into account when predicting lateral extent of groundwater fluctuations. The discussion of prediction of the lateral extent of salinity intrusion is incorporated in the methods section, as this research does not predict the lateral extent itself but uses the SUTRA model as an example (*Werner et al., 2006*). Next the interaction between the salinity intrusion and groundwater fluctuations is discussed. Thereafter the use of the framework is discussed. The last paragraph contains the most important recommendations to improve the framework to evaluate a location for tidal creek restoration.

6.1 Methods

The geohydrological analysis of the soil at the three locations was mainly done by using old Groundwater maps of the location, although newer versions were available. The choice for the older versions is based on the fact that these are based on real data collected with fieldwork, which rate them with a high reliability. The newer versions are based on interpolations of empirical formulas which make them far less reliable.

To predict the lateral extent of the salt plume into the upland, the SUTRA model (*Werner et al. 2006*) is used as example. This can be justified as the parameters used in this model, have a high similarity to the parameters at the three locations. However it is realized that this is by far ideal method to predict the salt plume intrusion. Attempts to use expert knowledge from the “Waterschap Zeeuwse Eilanden” in this matter were not successful, as they were far less detailed and useful as the SUTRA model. There were also no other models freely available to use to predict the lateral extent of the salt plume.

Furthermore there are a few shortcomings to the SUTRA mode that needs to be improved namely as the transportation caused by surface evaporation or evapotranspiration is neglected. Additionally the SUTRA model is not specialized for the non-linearities of unsaturated flow and hence accurate predictions of vadose zone (unsaturated zone of the soil) salinity distributions would require an alternative code. And the SUTRA model does not take influential landscape characteristics as the topography, drainage channels etc. into account. Besides that when predicting the lateral extent of the salt plume and the internal distribution of the isochlors, influential environmental factors like evapotranspiration, temperature and precipitation, are left out.

When predicting the area of influence, symmetry about the creek centreline is assumed for simplicity. However given that the surrounding aquifer and its characteristics differ at each side of the creek, asymmetry occurs. This could lead to a difference in the lateral extent at each side of the creek.

6.2 Lack of data when predicting the affected region

Besides the influence that the tidal energy has on groundwater fluctuations, it also affected by clogging. Clogging is responsible for the development of a lower permeable layer along the upland-estuary interface, and especially in hypohreic zone of water surface bodies (region beneath and lateral to the streambed). Normally the permeability of the upland-estuary interface is controlled by the size of the wash load sediment and the effective pore diameter. However the interaction of fine particles with the porous hypohreic zone of tidal creeks, through surface caking, particle straining and physio-chemical reactions, can clog the sediment pore space (*McDowell-Boyer et al., 1986*), hereby affecting the hydraulic conductivity.

Furthermore there are processes, which occur after the deposition of the fine particles that are able to further alter the permeability of tidal creeks sediments. The discharge of anoxic groundwater into oxic tidal creeks, for example, could cause a reduction to the effective porosity due to the precipitation of metal-(hydro) oxides, like iron and manganese- (hydro) oxides (*Millham et al., 1995*).

Clogging and the post-depositional processes, both occurring due to the tidal energy, affect the hydraulic conductivity of the soil. Research has shown that these processes are responsible for a decrease of the hydraulic conductivity by more than two orders of magnitude (*Schulz et al., 2002*). It is likely that this will modify the nature of the interaction between the surface water in the tidal creek and the groundwater in the upland. These two processes could lead to differences (and especially an over prediction) between the predicted lateral extent of groundwater fluctuations by formula (6) and (7) and the reality.

Furthermore this research excludes for simplicity one important process which is altered by the groundwater fluctuations, and has the potential to affect the land use types, namely: the redox potential. The redox potential has a large influence on the bioavailability on pollutants, like e.g. heavy metals, and is regulated by oxygen availability. Soil oxygen availability is on its turn mainly determined by the soil moisture conditions. Changes in the soil moisture conditions by tidal driven groundwater fluctuations could seriously change the solubility, uptake kinetics and the ability of pollutants to form complexes.

Another point of discussion is the fact that the different anthropogenic landscape characteristics, like drainage channels were not taken into account. Drainage channels are important in agricultural areas to ensure a certain desired groundwater level for optimal crop growth. These channels allow having different groundwater levels, which behave separately, at one region. Furthermore these channels are there to decrease the effects of seepage. This indicates that the drainage channels, which are present in great numbers at the three locations, could seriously decrease the area which is affected by the tidal influence. However the scientific knowledge of the influence of such shallow channels on tidal driven salt intrusion and groundwater fluctuations is not extensive enough to take it into account when predicting affected region. The usage of drainage channels for agricultural purposes to decrease the effect of seepage and to ensure a certain desired groundwater though, could be seen as an indication that it has significant influence on the groundwater level and thus also on tidal driven groundwater fluctuations and salt intrusions.

6.3 Interaction between tidal driven salt plume and groundwater fluctuations

Tidal energy will lead to an intrusion of a dense salt plume in the upper region of the aquifer, which will cause a higher discharge of groundwater through the lower creek bank and through the base of the creek compared to the situation without tidal energy. This means that the tidal energy will change the direction of the groundwater flux, as more groundwater will flow into the creek via the lower creek bank and through the base of the creek. It is likely that such a change in the direction of the groundwater flux will have an effect on the amplitude of the tidal driven groundwater fluctuations, although little scientific literature is available on this topic.

6.4 Framework

The evaluation of a location for the tidal creek restoring with the designed framework uses the quantification of the surface of a certain land type with a given value to evaluate a location and to compare different locations to each other. However the given value is disputable as it is subjective, because what this research designates as negative effect might be valued positive by another party. The given value completely depends on the interest of the researcher and remains thus an ethical question. However this research has tried to value the effect to a certain land use type from the eyes of the stakeholders of the concerned land use type.

Furthermore the given values are disputable as it can be imagined that for example a negatively influenced area of a relatively small surface could have a bigger influence or value as it for example contains a rare species or attributes, than a negatively influenced area of a relatively large surface which contains only common species or attribute.

7. Conclusions and recommendations

7.1 Conclusions

The framework is mainly formed by a literature study and expert meetings and handles the relevant factors concerning evaluating locations for tidal creek restoration: safety preconditions and wishes of stakeholders, which show the possibilities for tidal creek restoration, the lateral extent of groundwater fluctuations and salinity intrusion with their valued effects and the surface area of the affected types of land use, which show the impact of tidal creek restoration.

Safety preconditions in the Netherlands are set by “Wet op de Waterkering” of 1996 and “Waterwet” of 2009 (www.wetten.overheid.nl). In order to ensure these safety standards, the incoming tide via the tidal creek needs to be controlled and damped by water constructions. Tidal creek restoration with the help of a water construction diminishes the wave energy, so the tidal energy is the most important factor from the tidal regime when restoring a tidal creek with a SRT. This research will therefore focus only on the effects of the tidal energy. The wishes of the stakeholders can be set by expert meetings

To predict the lateral extent of groundwater fluctuations and salinity intrusion, landscape analysis is needed to find the relevant parameters. The lateral extent of groundwater fluctuations depends on whether the adjacent aquifer is a confined or unconfined aquifer. Unconfined aquifers (Colijnsplaat; ± 200 m) showed a far less extent of groundwater fluctuations compared to the confined aquifers (Zierikzee, Sint Maartensdijk; ± 1,000 m). Both of the aquifers showed that the amplitude of the groundwater fluctuations decreases exponentially with the distance. The lateral extent of the intrusion of salinity is not depended on locations characteristic, only on the tidal period (which is the same for all the three locations), and has a fixed distance of 60 meters.

The value of the effect is depended on the land use type. The main types of land use in Zeeland can be divided in the following groups: urban areas, agriculture and nature areas. Groundwater fluctuations have especially a negative influence to wooden foundations of constructions in urban areas, due to bacterial decay. The most prominent negative effects of an increase in salinity are on agriculture and most terrestrial nature areas as forests. Finally a quantification of the surface area of a certain land use type with the given valued effect is needed as it makes it able to compare different locations to each other.

Applying the framework to the locations shows that the framework makes it easily visible to see which, how and how much of a land use type is affected, which can help policymakers to make their decision on which location is the “best option” for tidal creek restoration. However this framework is not meant to point out the best location, it just is aimed to be a tool in the evaluating process for policymakers.

7.2 Recommendations

To start with the method used to predict the lateral extent of the tidal driven salt intrusion could be improved. This could be done by improving the SUTRA model or by developing an experiment where the salinity content in the groundwater in the surrounding land around a water body with tidal influences is measured. This could provide more information and could lead to a formula to calculate the salinity content at a certain distance from a water body.

Furthermore more research is needed to gain knowledge of the influence and the development of clogging and post depositional processes caused by the tidal energy. This as it has the power to drastically change the hydraulic conductivity in a region which has an influence on the lateral extent of the groundwater fluctuations. Besides that a sensitivity analyses to formula (6) and (7) could be helpful, as it provides insight in which factors are most influential for the lateral extent of the groundwater fluctuations. Knowledge about the most influential factors determining the lateral extent of groundwater fluctuation is useful when evaluating a location for tidal creek restoration.

Additionally that research to the influence of drainage channels on the lateral extent of salinity and groundwater fluctuations is necessary. This is especially important as the locations contain many drainage channels for agricultural purposes. It is expected that the presence of these drainage channels will cause a much smaller region which is affected by the tidal energy than the outcome of the predictions would show. However lacking of scientific research on this topic makes it impossible to take this into account.

Furthermore more representative and better values can be given to the effects on a land use types, to represent the wishes and demands from the society. This could be done by performing interviews to residents and stakeholders.

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Appendix A. Geohydrological characteristics of the locations

A.1 General characteristic of Zierikzee

Zierikzee is situated in Schouwen-Duiveland (figure 7.3a) and contains important nature conservation areas, like Natura 2000 areas (the whole Oosterschelde) and Water Framework Directive (WFD) bodies. The WFD body is a branch form the tidal creek, which is situated to the North of Zierikzee.

Zierikzee has a semi-diurnal tide (tidal period of 12 hours) which fluctuates generally between NAP + 1.70 - – 1.80 m (*Ministerie van Verkeer en Waterstaat, 2009*). Because Zierikzee contains a harbor, the tidal regime is allowed to enter as far as the pumping station (figure A.1a).

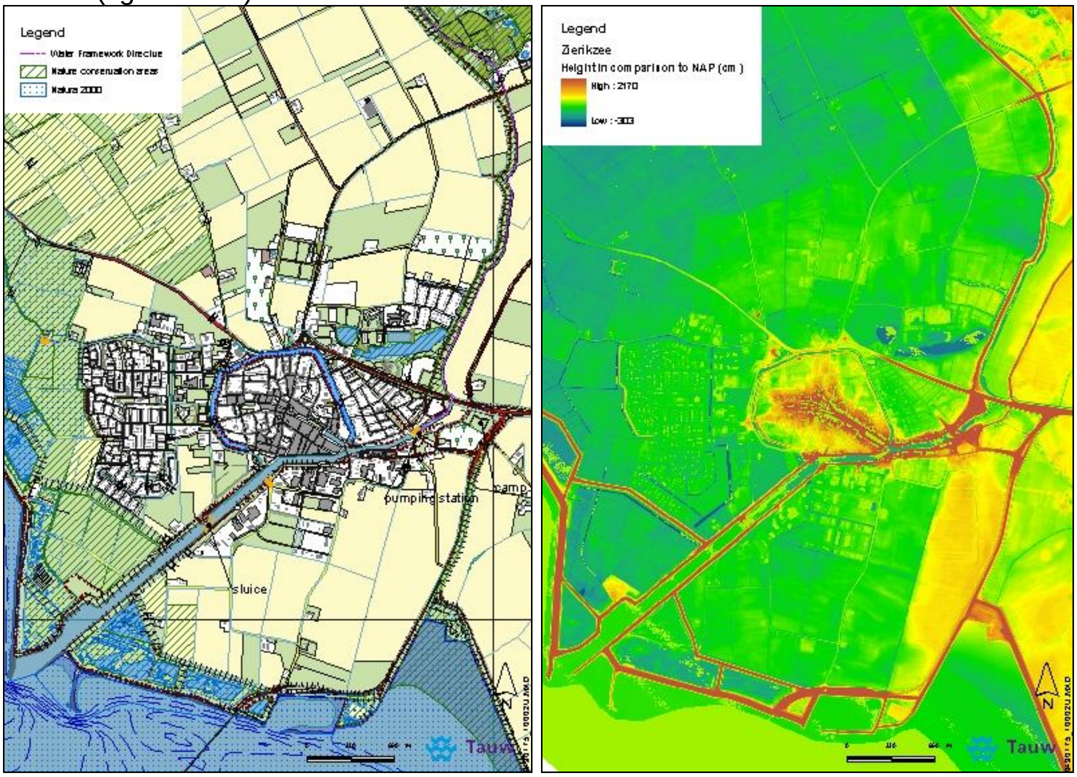

Figure A.1 a. b: a) the region around the tidal creek at Zierikzee, b) height of the ground level of Zierikzee in comparison to the NAP, based on the AHN (Actueel Hoogtebestand Nederland; scale 1:40.000).

A.1.1 Composition of the soil

The height of the ground level around Zierikzee is closely around NAP 0 m (figure A.1b; the green areas lays below NAP 0 m, the yellow areas lays above NAP 0 m). The city of Zierikzee itself lays higher, between NAP + 1 m and + 2 m, and is protected by the dikes. There is a level gradient in the area as the West of Zierikzee lays lower (NAP -1m), than the East of Zierikzee (NAP + 0.5 m).

The general composition of the soil around Zierikzee (table A.1) is formed by a confined aquifer. The impermeable top layer consists of clay and peat holding sediments formed in the Holocene which belongs to the Naaldwijk formation. The thickness of this layer varies from 10 meters to the South of Zierikzee, to 4 meters to the North-East of Zierikzee.

Beneath this layer lays an aquifer which consists of fine sands from the Naaldwijk and Boxtel formation. Generally this aquifer is 120 meters deep, however an impermeable separating layer of clay from the Waalre formation lays to the South of Zierikzee. The basis of this aquifer is formed a layer of clay from the Rupel formation.

Table A.1. General composition of the soil around Zierikzee, in which c = vertical hydraulic resistance, k = hydraulic conductivity

layer (m – NAP)	formation	geohydrological unit	composition	permeability	Storage coefficient*
0 – 4 or 10	formation of Naaldwijk	confining layer	clay	c between 40 or 900 days	-
4 or 10 – 43** or 120	formation of Naaldwijk and Boxtel	aquifer	fine sand	k = 5 m/d	0.002
43 – 47**	formation of Waalre	dividing layer	clay	c = 500 days	-
47 - 120	formation of Naaldwijk and Boxtel	aquifer	fine sand	k = 5 m/d	0.0015
120	formation of Rupel	Basis of aquifer	clay	-	-

* storage coefficient is calculated by the formula of Gun (1979) and only accounts for the confined aquifers, with a unconfined aquifer the storage coefficient corresponds with the effective porosity.
** dividing layer only present to the south of Zierikzee

A.1.2 Groundwater and hydraulic regime

The MHWL (mean highest water level) of the phreatic groundwater around Zierikzee varies between 0.40 and 0.80 m below ground surface, and the MLWL (mean lowest water level) between 0.80 and 1.20 m below ground surface.

The level of the hydraulic head in the aquifer in the main area around Zierikzee lays around NAP -1 m. At the sea side the hydraulic head is just above NAP (0.0 till +0.25 m), which lowers when mitigating land inwards until NAP -1.5 m at the North-West side of Zierikzee. This means that the main groundwater flux in the aquifer is directed northwards from the sea into the land.

A.2 General characteristics of Colijnsplaat

Colijnsplaat is located in Noord-Beveland and contains several nature conservation areas (figure A.2a). The tidal creek that lays just to the west of Colijnsplaat is connected to the sea with a sluice, which remains open during the ebb tides. The creek is designated to be a WFD body. Colijnsplaat has a semi-diurnal tide which fluctuates between NAP + 1.65 - – 1.78 m (*Ministerie van Verkeer en Waterstaat, 2009*).

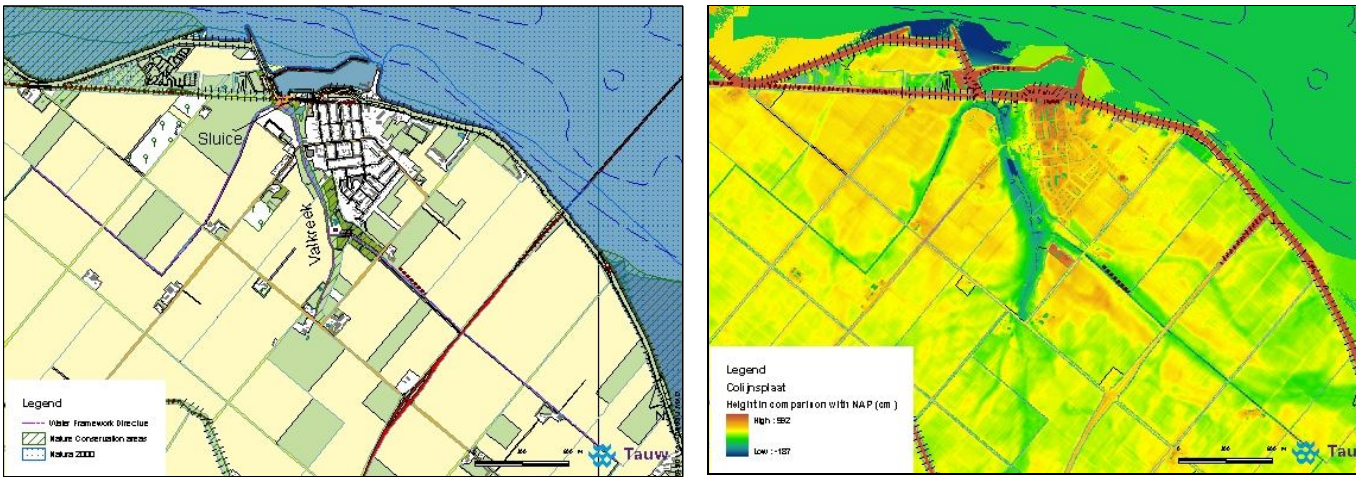

Figure A.2. a,b: a) the region around the tidal creek at Colijnsplaat, b) , height of the ground surface of Colijnsplaat in comparison to the NAP, based on the AHN (scale 1:30.000).

A.2.1 Composition of the soil

The height of the ground level around Colijnsplaat lays between NAP 0 +1 m (figure A.2b; the green areas lays around NAP 0 m, the yellow areas lays around NAP + 1 m) and forms the highest part of Noord-Beveland. Colijnsplaat lays higher, between NAP + 1 and + 2 m, and is protected by the dikes. The higher areas (yellow/orange) present the (old) creek banks which can be found around the creek and are surrounded by the lower lying areas (green). Such a distinct morphological pattern is typical for creeks or rivers. Usually the soil of the creek banks consists of sand or loam and the flooding areas of clay.

The composition of the soil around Colijnsplaat (table A.2) is formed by an unconfined aquifer. The aquifer has a thickness of 55 meter which mainly consists of sands and belongs to the Naaldwijk and Boxtel formation. The aquifer layer is heterogeneous and the size of sand particles ranges from very fine till very coarse. Additionally a few layers of clay are embedded in the aquifer. The basis of this aquifer lays is formed by a layer of mainly of clay and loam which generally has thickness of 5 meters from the Oosterhout formation

Table A.2. General composition of the soil around Colijnsplaat in which k = hydraulic conductivity

layer (m – NAP)	formation	geohydrological unit	composition	permeability	Storage coefficient
0 – 55	formation of Naaldwijk and Boxtel	aquifer	very fine till very coarse sands, embedded with layers of clay	k = 6 m/d	0.4
55 - 60	formation of Oosterhout	basis of aquifer	clay and loam	-	-

A.2.2 Groundwater and hydraulic regime

The phreatic groundwater level in the area of interest around Colijnsplaat has a MHWL between 0.40 and 0.80 m below the ground surface and a MLWL which is lower than 1.20 m below the ground surface.

The aquifer in the region has a hydraulic head level which lays around NAP. There is a slight gradient in the hydraulic head, as the hydraulic head at the sea side (north of Colijnsplaat) is NAP +0.5 m. This slowly decreases until a hydraulic head of NAP -0.5 m at the south of Colijnsplaat is reached. Hence the main groundwater flux in the aquifer is directed to the south and into the land.

A.3 General characteristics of Sint Maartensdijk

Sint Maartensdijk is located in Tholen and contains several nature conservation areas (figure A.3a). Sint Maartensdijk has a semi-diurnal tide which fluctuates generally between NAP + 1.70 - – 1.83 m (*Ministerie van Verkeer en Waterstaat, 2009*).

The tidal creek lays right below Sint Maartensdijk and is sealed of by dikes, so currently no tidal influence occur in the creek. The creek runs to Sint Maartensdijk and is designated as a Natura 2000 area and as part of the "Ecologische Hoofdstructuur".

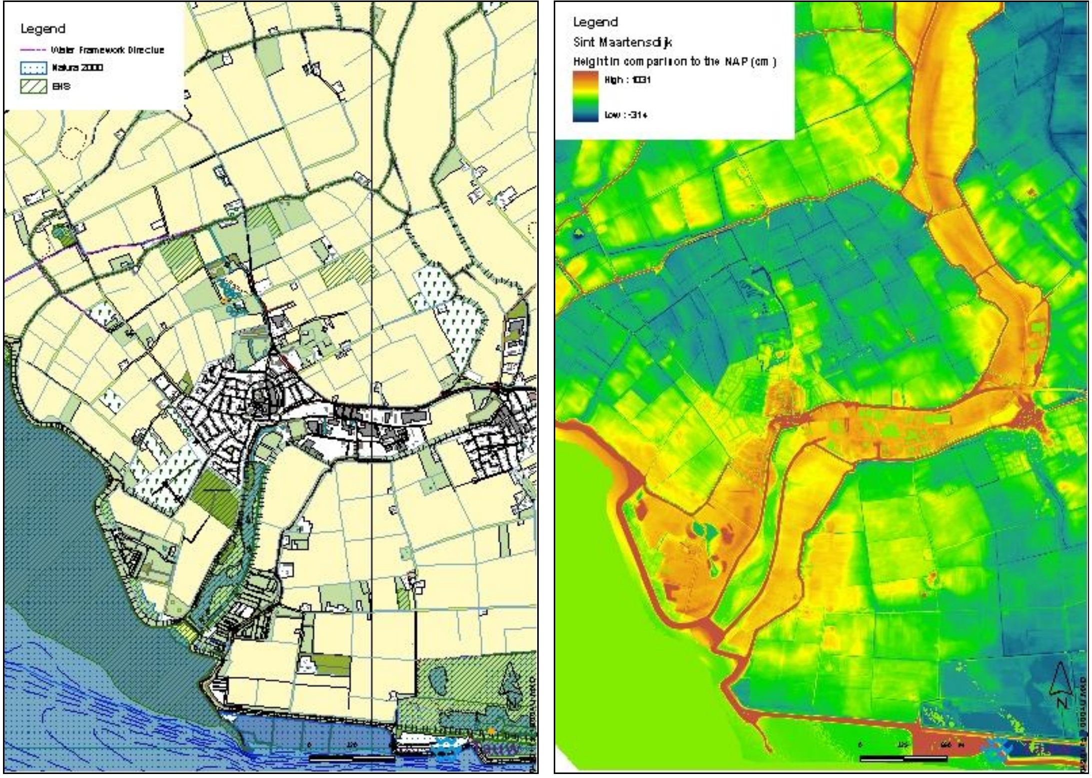

Figure A.3 a,b: a) the region around the tidal creek at Sint Maartensdijk, b) , height of the ground surface of Sint Maartensdijk in comparison to the NAP, based on the AHN (scale 1:40.000).

A.3.1 Composition of the soil

The height of the ground level varies in Sint Maartensdijk (figure A.3b) between NAP -1 (green) and NAP +1 (orange/red) and lays generally higher than the surrounding areas. The higher areas (orande/yellow color) mainly occur around the creek and are formed by the creek bank, which are surrounded by the lower lying areas (blue/green color). This represents a typical pattern for creeks or rivers. Compared to Colijnsplaat the typical creek pattern in Sint Maartensdijk is from a far larger scale.

The creek pattern at Sint Maartensdijk, though, is not so widespread, meaning that the construction of the soil around Sint Maartensdijk can be compared to a confined aquifer (table A.3). The impermeable top layer has a thickness which varies between 5 m to the north of the creek and 8 m to the south of the creek. This layer mainly consists of clay and peat and belongs to the Naaldwijk formation. The impermeable layer, however, is absent at the location where the tidal creek banks and its branches occur (figure A.3b).

The underlying aquifer has a thickness of 70 meter which consists of fine till coarse sands and belongs to the Boxtel and Naaldwijk formation. The basis of the aquifer is formed by impermeable layer of clay and loam which generally has thickness of 3 meters and belongs to the Oosterhout formation.

Table A.3. General composition of the soil around Sint Maartensdijk in which c = vertical hydraulic resistance, k = hydraulic conductivity

layer (m – NAP)	formation	geohydrological unit	composition	permeability	Storage coefficient
0 – 5 or 8*	formation of Naaldwijk	confining layer	clay	c varies between 50 or 80 days	-
0 – 70, 5 or 8 - 71	formation of Naaldwijk and Boxtel	aquifer	fine till coarse sand, embedded with layers of clay	k = 6 m/d	0.0025
71 -75	formation of Oosterhout	basis of aquifer layer	clay	-	-

A.3.2 Groundwater and hydraulic regime

The MHWL of the phreatic groundwater around Sint Maartensdijk varies between 0.40 and 0.80 m below the ground surface, the MLWL is between 0.80 and 1.20 m below the ground surface.

The hydraulic head of the aquifer is the highest to the south, at the sea, namely NAP + 0.5 m, moving land inwards the hydraulic head decreases to NAP -0.5m around Sint Maartensdijk. The lowest hydraulic head (NAP -1.0) of the region lies to west of Sint Maartensdijk. This shows that main groundwater flux is directed northwest.