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PIERRE Mathilde

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Intriguing water imbalance in a constructed tidal marsh

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Directeur de l'option : Hervé Le Treut
Directeur de stage : François Birgand
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Nom et adresse de l'organisme :
North Carolina State University
Biological & Agricultural Engineering
148 D.S. Weaver Labs - Campus Box 7625 Raleigh, NC 27695-7625
United States

Abstract

Wetlands and more specifically salt marshes provide many ecosystem services such as water quality benefits and many restoration projects have been carried out recently in the United States. This study focuses on a constructed marsh on North Carolina coast, and is based on the results of a previous study that focused on quantifying the water quality benefits of the marsh with continuous water quality and flow monitoring. This previous study revealed a very surprising and unexplained water balance in the marsh that could have important consequences for not only the water quality benefits and biodiversity of coastal marshes, but possibly to coastal ocean ecosystems as a whole. This study strived to better understand the functioning of the marsh, and identify mechanisms that could explain the water balance. Many scenarios are suggested and investigated. Some of them were invalidated, others are more likely to explain the water balance and need to be studied more carefully. Collection of additional data in the marsh seems necessary to go further and several new types of measurements are suggested.

Acknowledgement

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Introduction

In 1962, Teal suggested for the first time that tidal marshes along the coast of Georgia, USA, likely played a role in providing food and nutrients to the coastal ocean ecosystems. Several years later, Odum (1968) further stated that 'Most fertile zones in the coastal areas able of supporting expanded fisheries result either from the "upwelling" of nutrients from deep waters or from "**outwelling**" of nutrients and organic detritus from shallow-water nutrient traps such as reefs, banks, seaweeds or sea grass beds, algal mats and salt marshes'. Odum emphasized the particular role of '**salt marshes as "primary production pumps"** that feed large areas of adjacent waters'. While there seems to be a large consensus on the role of the cold, nutrient rich and deep "upwelling" waters to provide nutrients to surface organisms (e.g. Mann and Lazier, 2006), the concept of "outwelling" has not received as much support (e.g. Nixon, 1980; Weinstein and Kreeger, 2002). Many studies have examined the "outwelling" hypothesis, but there has not yet been a firm conclusion on whether, when, and where this phenomenon occurs (reviewed in Weinstein and Kreeger, 2002). This study aims at examining the role groundwater may play in the "outwelling" concept.

Beyond their possible "outwelling" role, the importance of salt marshes for providing biodiversity and a large number of ecosystem services has increasingly been recognized. In addition to the legal protection of existing wetlands, there has been a recent movement of restoring coastal land (often previously under agricultural or forested management) into salt marshes. Such a restored marsh has been designed, built and studied at North Carolina State University under the direction of Drs. Mike Burchell, Robert Evans, Stephen Broome and François Birgand. With habitat restoration, the second main objective was to provide water quality benefits, particularly removing excess nitrate before it reaches the nearby nitrogen sensitive estuaries. The latter is exported from the upstream adjacent agricultural land via subsurface drainage. The marsh was designed such that part of nitrate laden drainage water would be diverted into the marsh, where it would undergo nitrate removal processes. The approach followed was a nutrient mass balance from flow and concentration data obtained on a 15-min basis at the in- and outlet of the restored marsh. This method revealed some unexpected massive seasonal net movements of water, which had major impacts on the net exports of nutrients at the seasonal scale. In fact, Etheridge (2014) found that the studied marsh was a major exporter of all nutrients, but nitrate, and that the exports were closely linked to unexpected and unexplained additional volumes of water part of the year. Were the source and the mechanisms for seasonal excess and deficit of water be deciphered, they could provide a possible model for the "outwelling" concept. This model could then explain where and why nutrient "outwelling" should be expected, on the planet, and this may have some major implications on coastal ecosystems and their management around the globe.

In absence of obvious visible sources or sink of water, the intriguing water balance has been hypothesized to be linked to important groundwater flows. The goal of this study was to investigate the potential role of groundwater in the observed water balance. The method involved further analyzing existing data to generate and test possible scenarios that could explain the water balance, and determine what kind of new data would be needed to validate or not these scenarios.

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1. Presentation of the study

1.1 Introduction

1.1.1 The site: a restored tidal marsh located in very flat lands

The study site is a constructed marsh located in Carteret County, North Carolina (34.82° N 76.61° W). This area is located in the area referred to as the lower coastal plain, part of the larger ensemble of the Coastal Plain of the Eastern US. The region is one of the flattest zones of the US, where "summits" culminate below 2 m above sea-level 7 km inland. The marsh and tidal stream system was constructed as a buffer between a row crop agricultural production facility to the north and the upper reaches of the North River to the south (Figure 1). The agricultural operation grew crops such as corn, soybeans, and wheat and was drained using 1m deep parallel ditches placed 80 m apart. The area was a natural wetland until it was drained and converted to agricultural production in the late 1970's as North River Farms. During the fall of 2005 and the spring of 2006, 6.9 ha of brackish marsh and 1000 m of tidal stream were constructed on a portion of the land (Figure 12). The goal of the marsh construction was to create habitat equivalent to that available in nearby natural marshes, while improving the quality of water reaching the North River estuary.

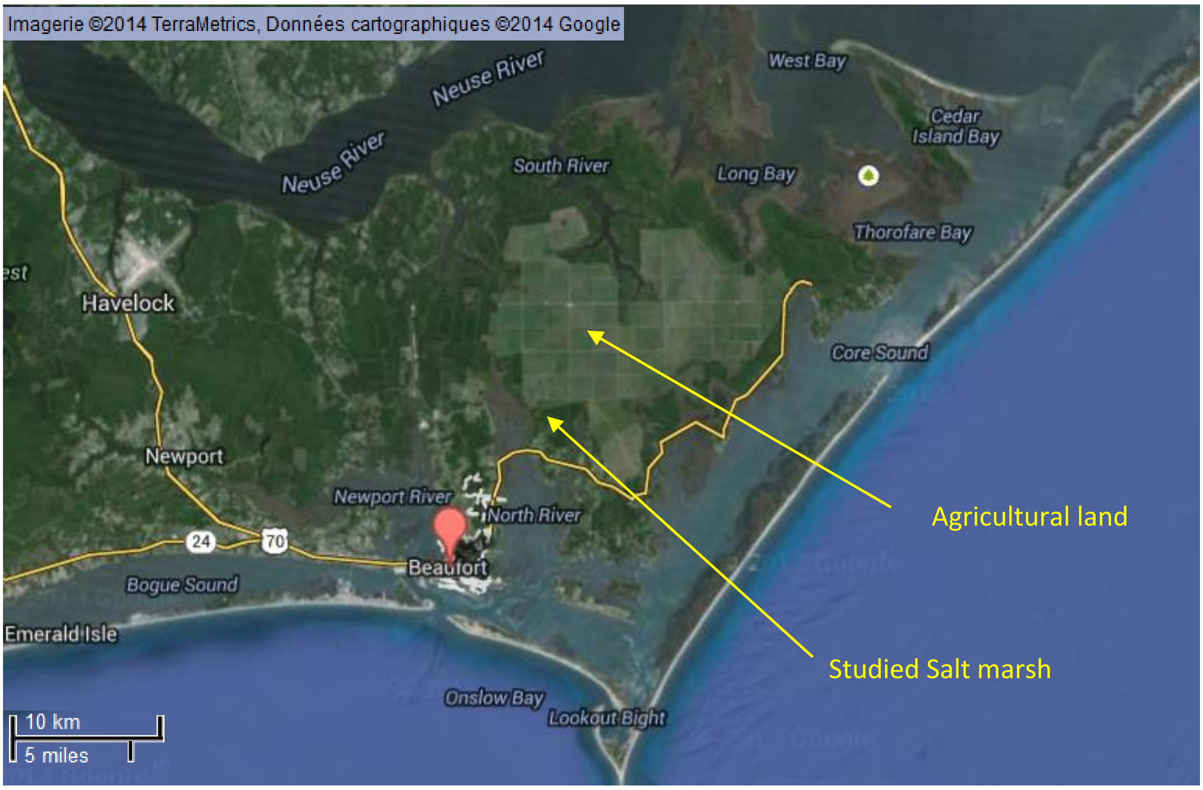


Figure 1 Locations of the agricultural lands, the studied marsh relative to the North Carolina east coast around Beaufort

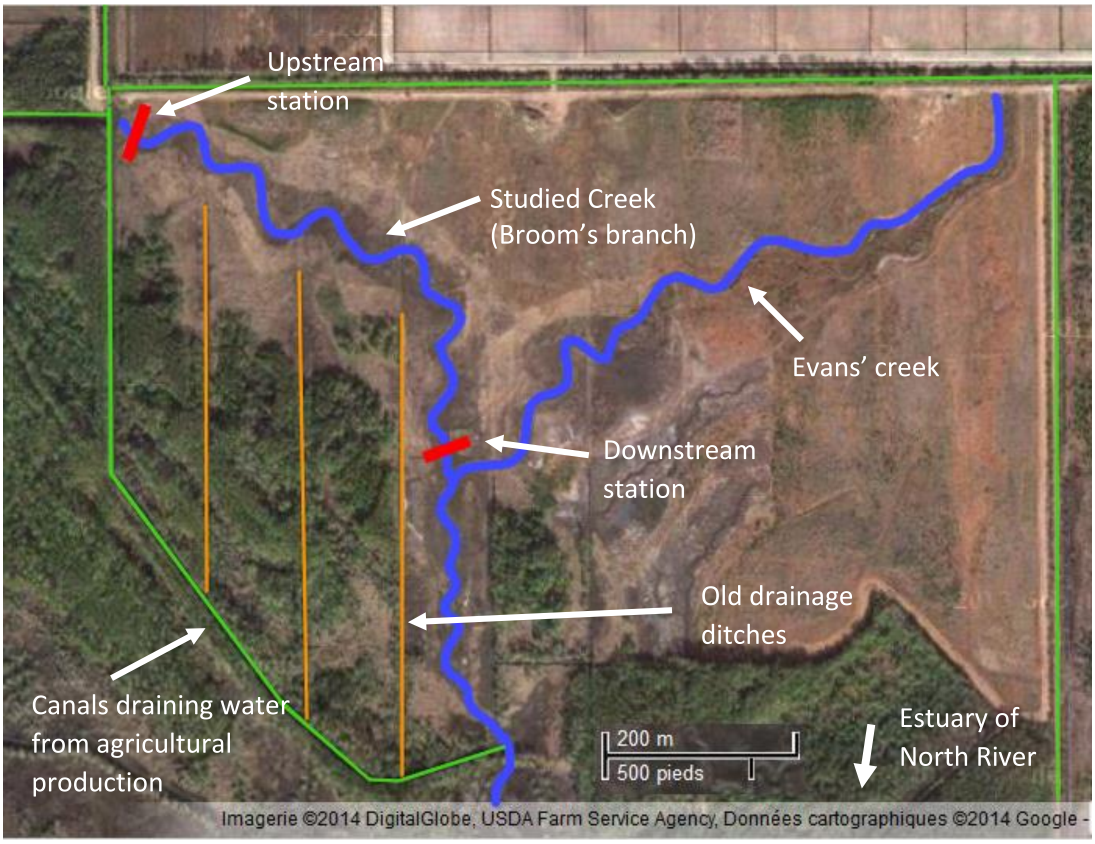


Figure 2 the restored tidal marsh, the monitoring stations and the canals and ditches around.

1.1.2 The original goal of the research: measure the ecosystem services of such a restored marsh with a particular interest in water quality benefit

After the construction/restoration phase per say was done, the ecosystem services of this tidal marsh was studied. A particular emphasis was on examining whether water draining from near-by agricultural land could be "treated" in the marsh, and by how much, before being released to the estuary.

Tidal marshes are considered among the most productive ecosystems in the world, characterized in part by the production of large amounts of organic matter, resulting in strong geochemical gradients at the sediment water interface and within the soil. These and other conditions in tidal marshes are theoretically conducive to eliminate excess nitrate from drainage water via denitrification, i.e. the complete removal of nitrate from the aquatic environment to the atmosphere (Knowles, 1982). However and until now, because of the extreme dynamics of these systems, there had been no report from high frequency long term measurements to assert whether and quantify the magnitude by which, nitrate would be removed/retained. The method chosen to study the water quality benefits of the restored marsh was a water and nutrient mass balance: all water and nutrients flowing in and out being measured, the differences would yield the net effect of the marsh on water and material fluxes.

1.2 Methods

1.2.1 The marsh and its hydraulic functioning

A portion of drainage water from the agricultural land was diverted into the constructed marsh with the hope that biogeochemical processes occurring in the constructed system would remove a portion of the nutrients before the water reached the sensitive estuarine ecosystem. A portion of the drainage water flowing in a large canal just west of the site was diverted into one of the constructed streams, Broome's Branch, by a low level rock weir. This constructed tidal stream discharged to the estuary, but was linked to the same drainage canal at the southern end of the project, creating a hydraulic loop. Drainage from the agricultural production also entered the constructed system through Evans' Creek which transitioned from a freshwater stream at its northernmost point to a brackish stream a few hundred meters northeast of its confluence with Broome's Branch.

The focus of this research was specifically on the tidal marsh portion of the project identified along Broome's Branch (Figure 2). An upstream/downstream monitoring design was used to calculate a mass balance for the portion of the constructed system located between the two monitoring stations. This 660 m reach of tidal stream was chosen as there were no known major inputs of surface water in the adjacent 5.6 ha of brackish marsh other than through the two monitoring stations.

Ground level is higher in the northern part of the creek so freshwater from agricultural production flows towards the sea. However, because of tides, water can flow from the sea to the northern part of the marsh, and even estuarine water can flow back up through the agricultural canal and enter the marsh by its northern end (Figure 3). Old drainage ditches which are no longer used have been plugged to prevent short circuiting, although one cannot rule out that during high tides, some short circuiting could have occurred.

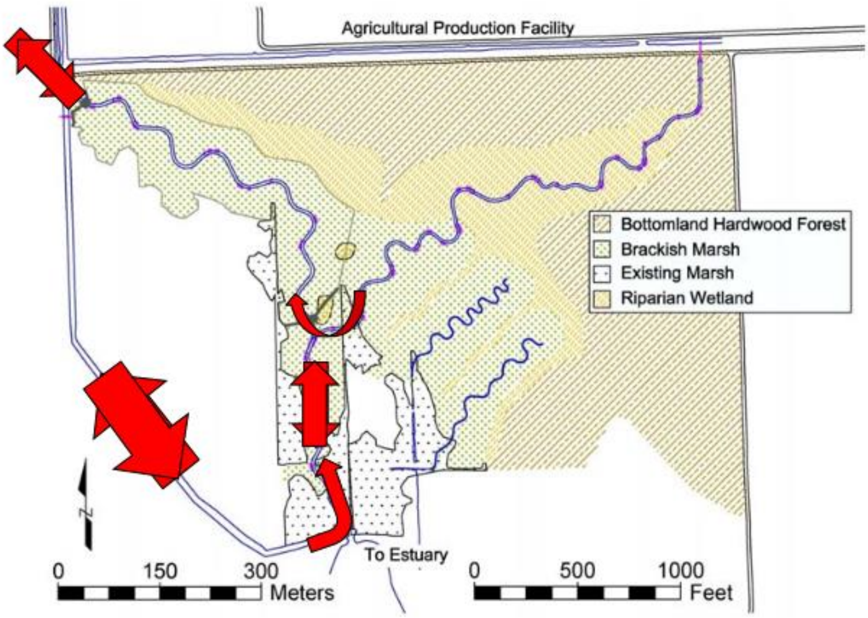


Figure 3 Water movement in the marsh

1.2.2 Flow measurement methods

Flow through each monitoring station was calculated using the continuity equation ($Q = VA$) from 15-min data. Five-meter long trapezoidal flumes fitted with ramps were installed at each monitoring station to funnel bidirectional flow over a section of known and constant geometry to lower uncertainties in measurements of velocity (V) and wetted cross sectional area (A). The velocity was calculated thanks to a Doppler velocimeter, that had been previously calibrated to the mean velocity of the water following published methods (Morlock et al., 2002; Birgand et al., 2005; ISO 15769, 2010).

1.2.3 Additional Water elevation data

Data on the sea level at Beaufort from the NOAA (National Oceanic and Atmospheric Administration) was obtained.

Water table stage across three transects (Figure 4) in the tidal marsh was also available although some data turned out to be unreliable.

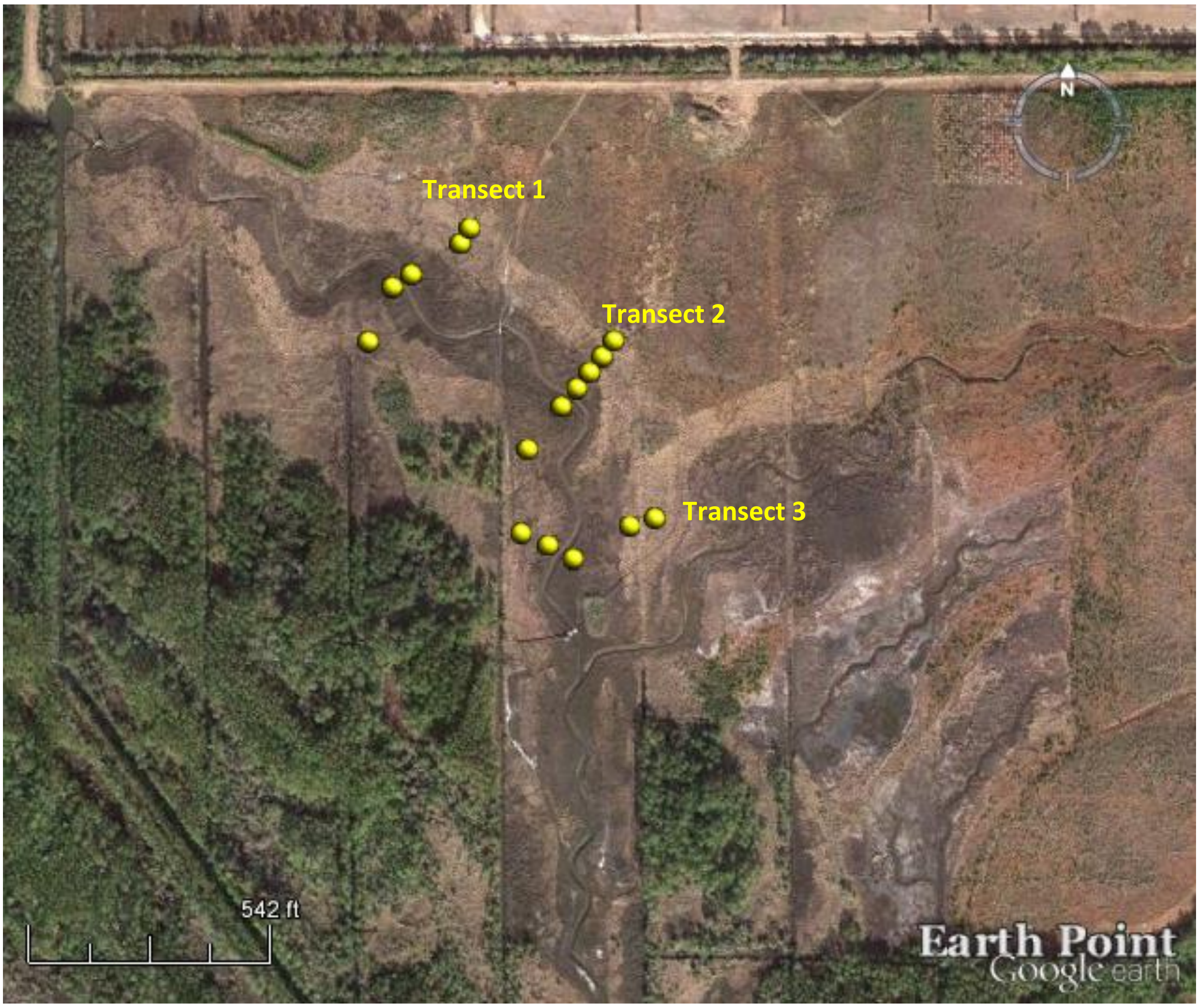


Figure 4 Location of the measurements of the water table in the restored tidal marsh

1.3 Main results

1.3.1 Unexpected Water balance

To calculate the water balance, the convention of positive values was used for all fluxes entering the marsh or imports, and negative values for those exiting the marsh or exports (Figure 5).

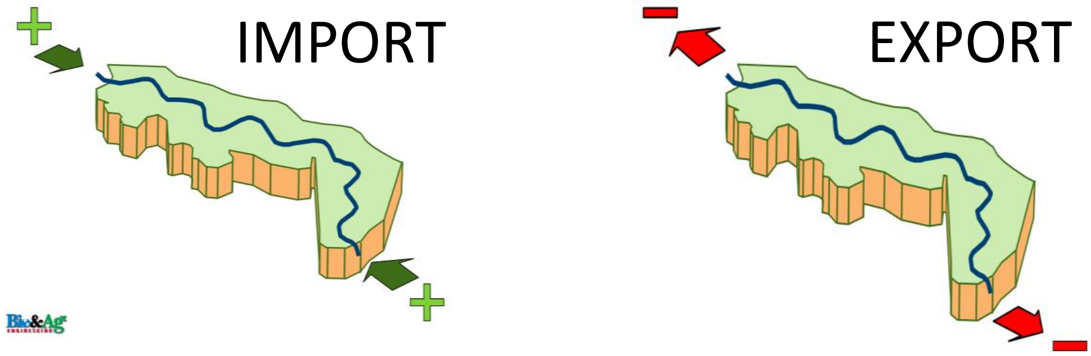


Figure 5 convention used for imports versus exports at both stations

Overall, the direction of the net import/export of water was expected to generally follow the climatic balance, i.e. Rainfall (R) minus EvapoTranspiration (ET), provided that soil storage could modify this to some extent but not the general direction. For example, in late fall and early winter, where R-ET<0, one would expect a net water export. Reversely in late spring and early summer when the ET>R, it was expected that the atmospheric losses would be compensated by water from the estuary essentially irrigating the marsh, hence net imports of water. Generally opposite trends were observed (Figure 6)…!

Figure 6 Expected and observed imports and exports due to rainfall and ET

1.3.2 Uncertainties

We naturally wondered if this result could be due to uncertainties on flow measurements. Our first feeling was that it was really unlikely that uncertainties could explain the water balance as the water balance would first have to be biased toward export and then suddenly be biased towards import, etc…

Birgand et al (2005) described the limitations of the Doppler method and suggested methods to reduce the uncertainty of the measurements. The monitoring stations were designed as suggested to reduce uncertainty and the Doppler velocity was not directly used as the mean velocity but was calibrated thanks to manual velocity data.

However, many uncertainties are very difficult to estimate, such as the ones due to the turbulence in the creek, the difference of velocity along the vertical axis, the intensity of the Doppler signal that can be diminished by important concentration of suspended solids, etc… However, the calibration of the velocity with manual data should diminish these uncertainties. Besides, one can expect that if there is an uncertainty of this kind when the water flows in the creek at high tide, it would be compensated by the opposite uncertainty when the water flows out of the creek at low tide.

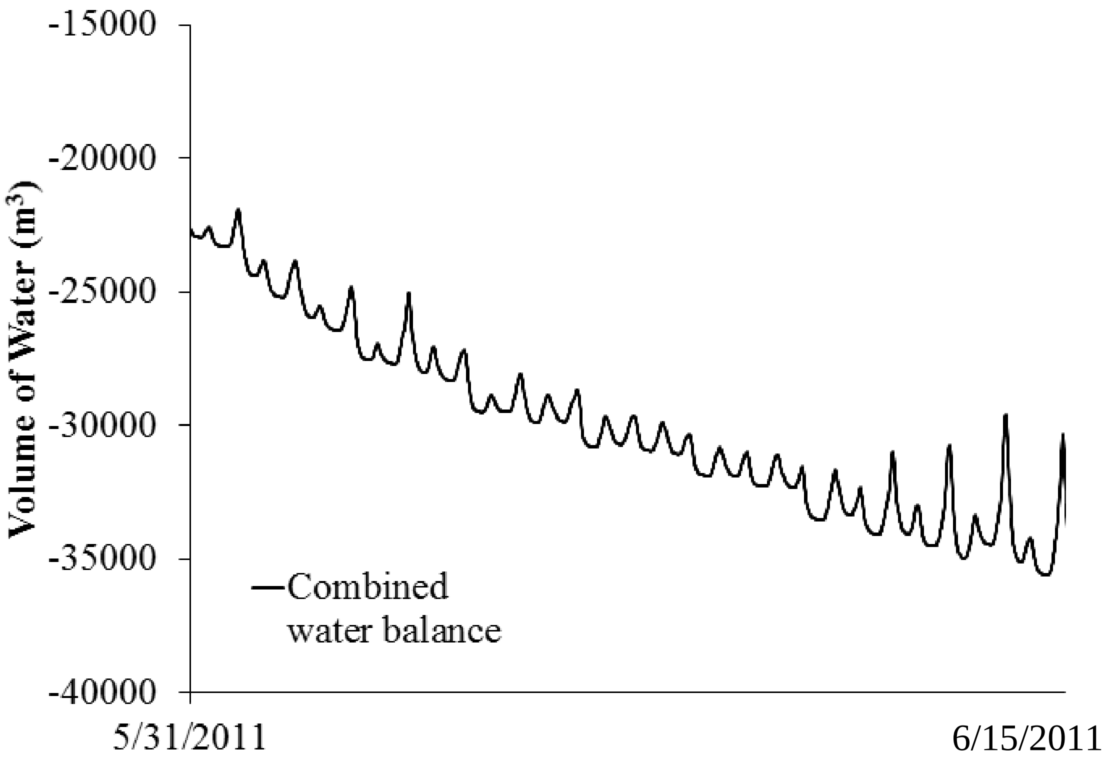


Figure 7 Water balance of the creek. During some tidal cycle, the export can represent up to a third of the total volume of water exchanged during the cycle

As explained by Birgand and al (2005) the velocity should not be systematically biased after calibration, but the area of the flow section could still be biased. The uncertainty on the measurement of the water stage using the pressure at the bottom of the creek is commonly accepted to be about 1 cm (Benoist et Birgand, 2002). The structure where the flux is measured has a trapezoidal shape so the uncertainty depends on the stage of the water. If we estimate the uncertainty on the flow section for the average stage of the creek (0.419m), it is 0.0294 m^2, and it represents 3.9% of the section. This uncertainty is not significant enough to explain the water balance. As one can see on Figure 7, some exports after a tidal cycle can represent much more than a few percent of the total water balance during the tidal cycle.

Although the uncertainty on the water balance was not calculated precisely because of its complexity and should be estimated more carefully in the future, it seems unlikely that it could explain the different trends in the water balance and account for significant volumes of water.

2. Understanding the problem

2.1 Methods

Etheridge (2014) has shown that the overall seasonal water balance did not affect nitrate dissipation values in the marsh (again, the original goal of the project), as nitrate penetrated in the marsh in pulses and generally resided for less than 8 days. However, Etheridge did show that the overall balance for all other parameters were greatly affected by the water balance. Etheridge did not have the time in his dissertation to further analyze and investigate these observations. The first aim of this internship was to layout existing data to open the possibility to draw and test scenarios, which could explain the observations. One of the challenges was to plot on a single layout, relevant and complementary information. Two approaches were used to achieve this goal:

- Display the data on graphs
- Create videos that could display all the data we had, at the same time, in a way that was easy to understand

To display the graphs we simply used excel. To create the videos, we used the language "R" and run a code that could create images representing the data at each time step. Then we used a software called Jpg Video to compile all the images and create a video.

We first created videos representing the water table elevation. We have data for 3 different transects. These videos allowed us to notice that the water table was moving with each tide, but also that some of our data were not reliable because it led to some unrealistic water table shape. Looking more carefully at our water table data we realized that the data were probably not properly calibrated for some periods of time and some wells and that we only had reliable data for 2012.

We then created videos displaying complementary data. These videos can be seen at this web address: http://www.dailymotion.com/video/x1uh9ag_january-april-2011_shortfilms. Each video has a similar 2 rows and 4 columns layout (Figure 8). In the top row in the left panel, stages and cross section areas in the creek at the upstream and downstream station are represented along with the water table level along with transect 1 (the closest to the upstream station, Figure 4). In the right panel of the top row is represented a schematic map of the marsh onto which the direction and magnitude of the flow at both stations have been represented by two arrows of variable size. The color of the arrows indicates the salinity of the water, when available. On the bottom row, from the left to the right panel are represented the cumulative rainfall, the instantaneous water balance zoomed over 5 days, the water balance scaled over months and the sea level at Beaufort, located at the coastline 13.7 km from the site.

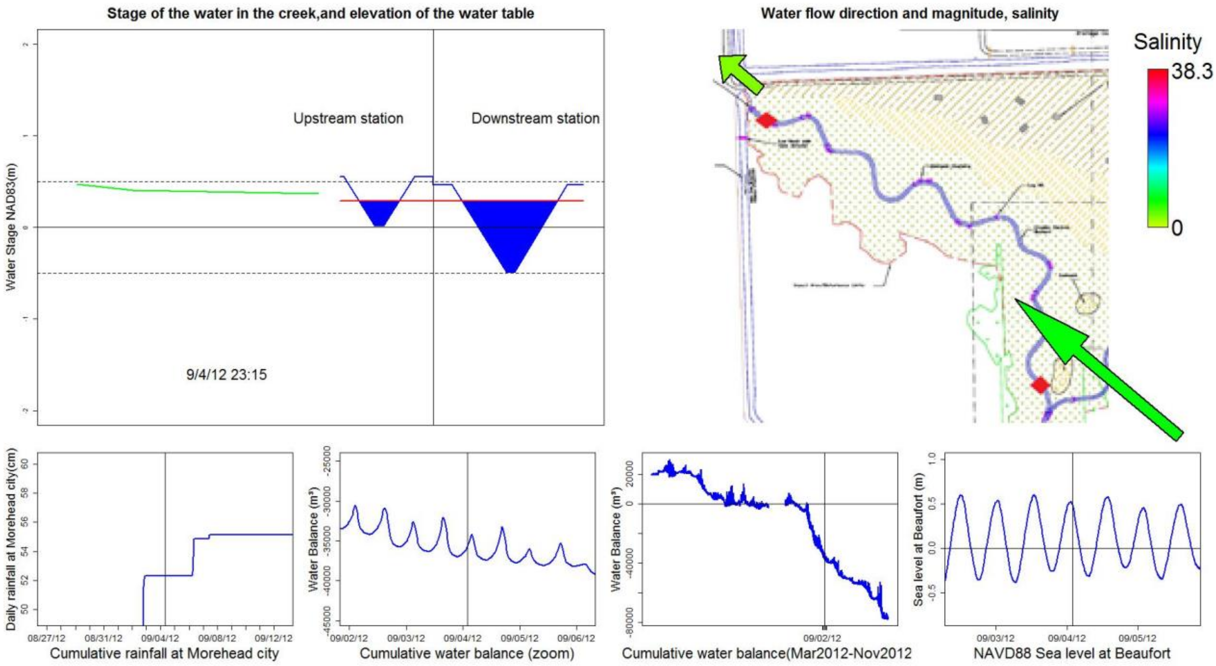


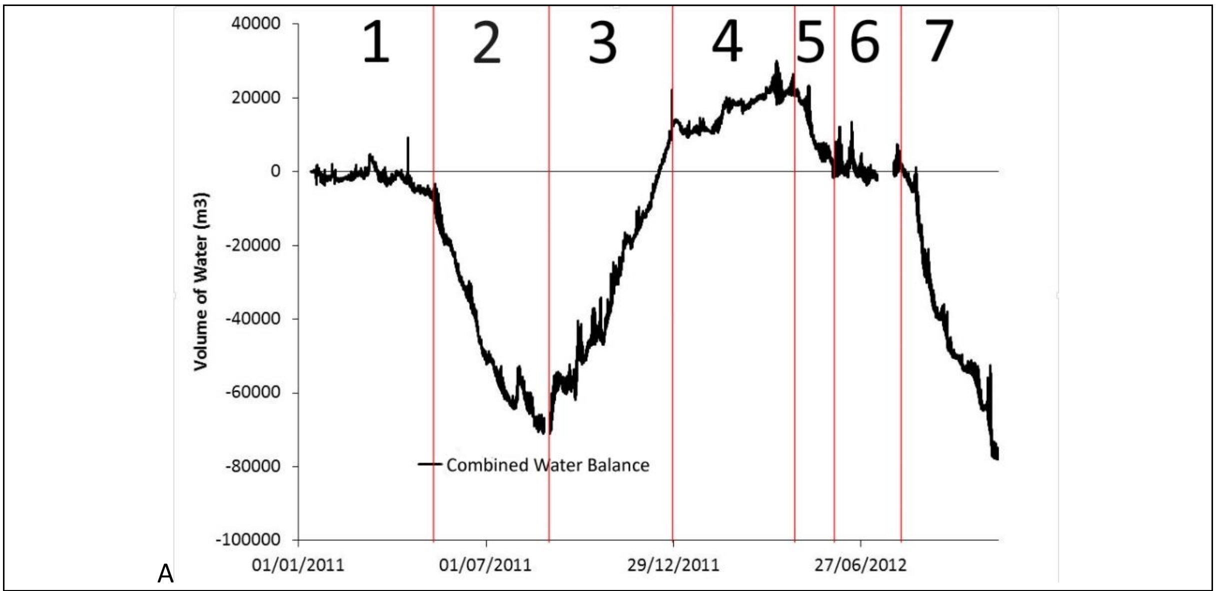
Figure 8 example frame of the videos created to visually analyze the data. Details of the layout in text.

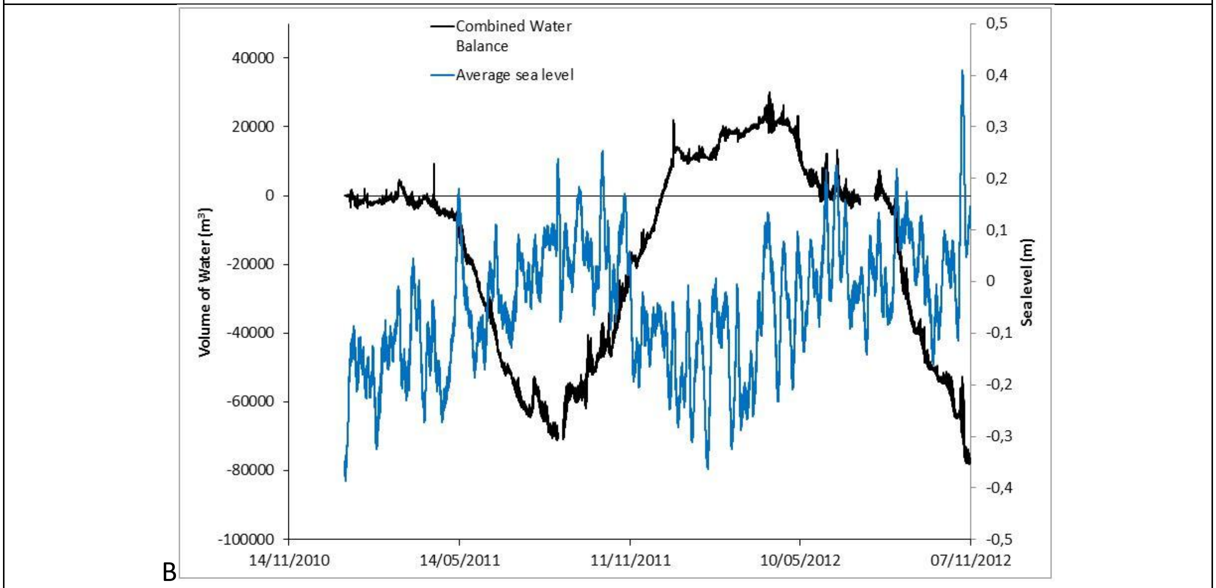
The videos are complementary to graphs because they allowed to put the tidal daily fluctuations in their relationships with rainfall and seasonal weather and tidal patterns. The graphical tools were instrumental to define several typologies at the seasonal and rainfall event scales.

2.2 Seasonal timescale: different phases in the water balance

Looking at the different graphs one can notice several phases in the water balance. One cannot observe the same phases in 2011 and 2012, the phenomenon does not seem to be periodical.

We defined several phases in the water balance, depending on whether the balance showed a net import, a net export or was neutral. For each of the identified phases, the corresponding patterns for rainfall, ET, and sea level were analyzed (Figure 9).





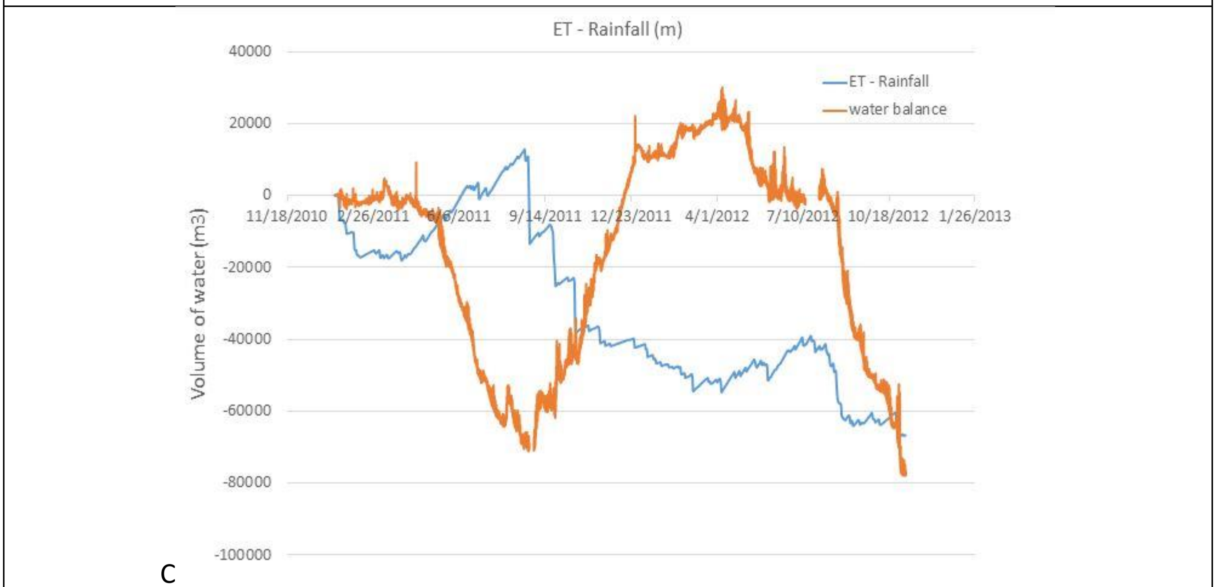


Figure 9: (A) Identified seasonal phases in the water balance; (B) Water balance and average sea level over 3 days at Beaufort; (C) water and climatic PET-rainfall balances

- Phase 1. From January 2011 to May 2011 : neutral balance

During this period, there is as much water imported as exported so the cumulated water budget is balanced. Evapotranspiration is approximately balanced by rainfalls. There are fluctuations of the sea level but the average sea level is relatively low although increasing.

- Phase 2. From June 2011 to August 2011 : net export

Evapotranspiration is higher than rainfall. The average sea level increases. At the same time the creek exports water. Between May 15th and August 31st, there is an average export of 665 m^3/day or 11.7 mm/day (over the marsh area) from the creek.

- Phase 3. End of August 2011 to end of December 2011: net import

This phase seems to be triggered by hurricane Irene at the end of August. There are three important storms or hurricanes during this phase with a total rainfall of about 450 mm. During this period one can see large imports and exports, resulting in a very large net import. The average sea level is relatively high around large fluctuations.

During this period, the stage in the creek is sometimes very high, consequently surface leaks or by passes are not impossible. The magnitude of imports are somewhat uncertain during these short periods. The average rate of import is 616 m^3/day or 10.8 mm/day.

However, in December 2011, there is a regular import of water and no rain. The sea level is relatively low and the creek is empty at the upstream station at low tide. The average import during this period is 972 m^3/day.

- Phase 4. January 2012 to March 2012: net import of lower magnitude (Average: 143 m^3/day or 2.5 mm/d). The average sea level is low.
- Phase 5. April 2012 to May 2012: significant net export. The average sea level fluctuates but seems to increase.
- Phase 6. June 2012 to July 2012: Approximately balanced. High sea level.
- Phase 7.August 2012 to December 2012: large net export (Average 865 m^3/day or 15.2 mm/day). High sea level.

The fluctuations of the average sea level and the water balance seem to follow opposite trends (Figure 9), it suggests that they could be linked.

2.3 Small timescale

2.3.1 Understanding the system

The videos and the zooms on the graphs were instrumental to better understand how the system worked.

- The videos revealed that the stage of the creek varies with tides, with a little delay compared to Beaufort Sea level. When displayed on the same graph the average sea level and the average stage of the creek (Figure 10) over a few days, one sees that the average stage of the creek also depends on the sea level. So the marsh is strongly influenced, and expectedly so, by tides and sea level variations.

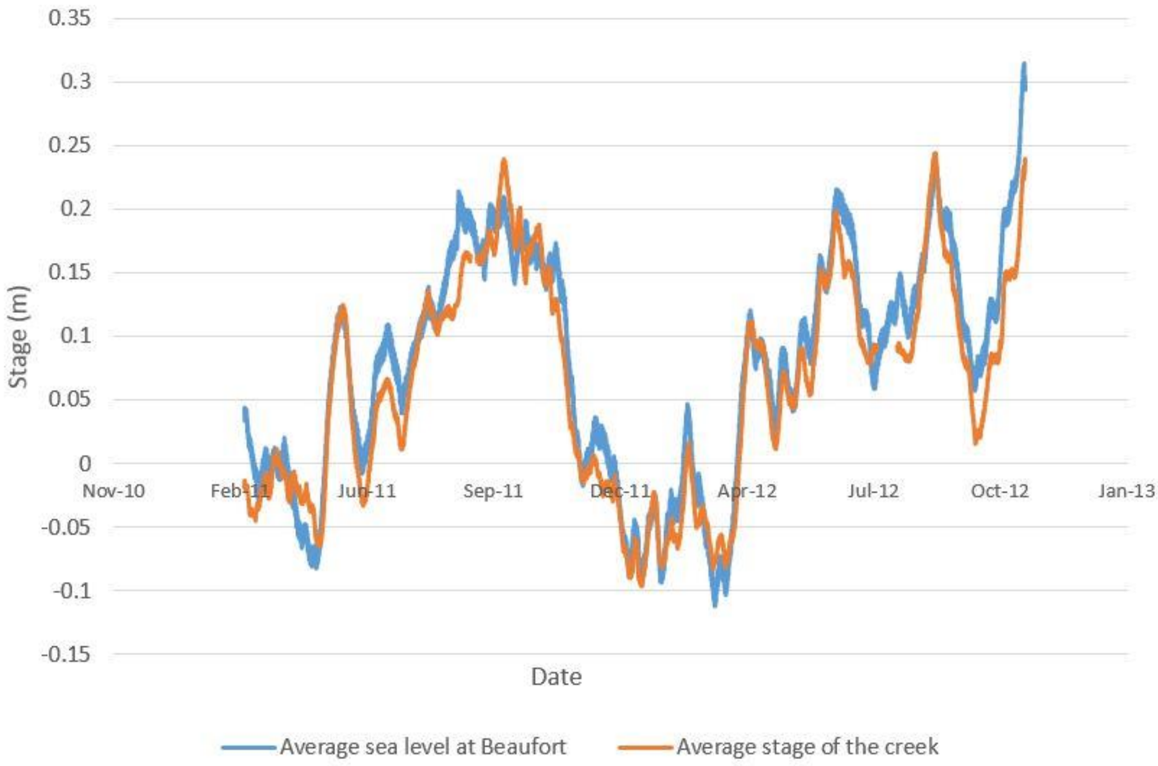


Figure 10 Comparison of moving averages at Beaufort and the studied creek. Averages over 15 days.

- Seasonal imports and exports result from small increments at the end of every tidal cycle and the more so at the end of the daily high tides, as tides are asymmetric during the day (Figure 11).

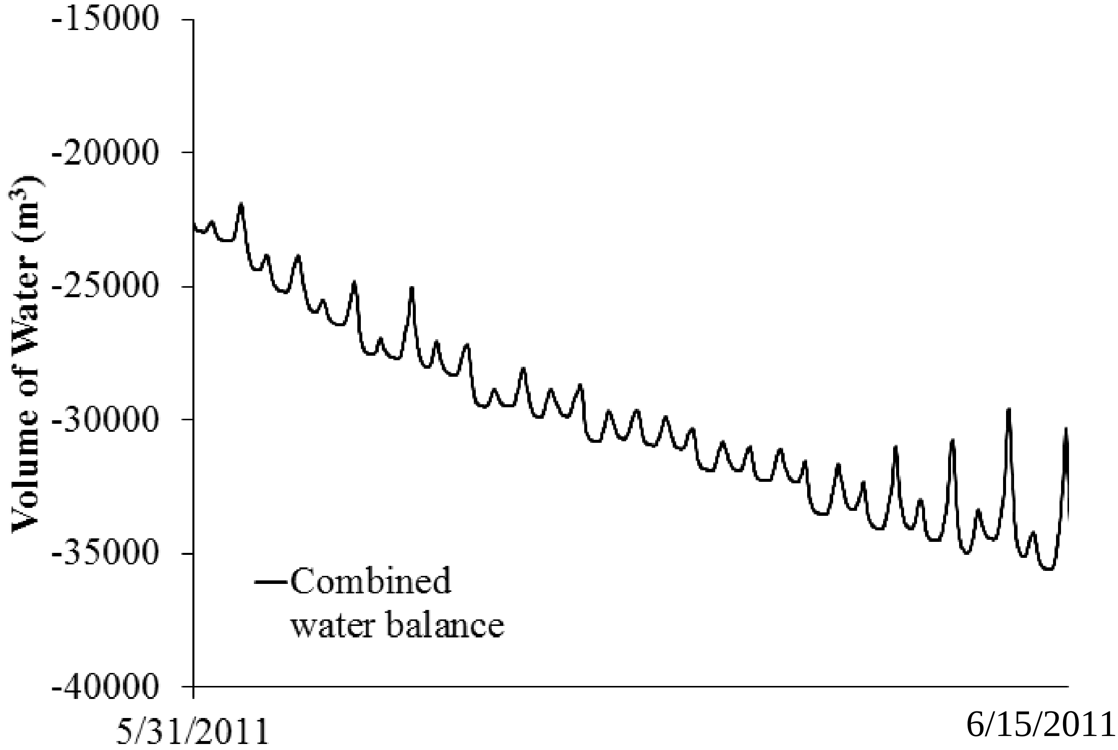


Figure 11 Combined water balance of the creek. Some water is imported and then exported during each tidal cycle

- During flowing tide, water from the estuary flows upstream into the marsh, increasing stage and salinity of water. Some water infiltrates laterally into the soil, essentially sub-irrigating the marsh. Flooding does not occur at every tide but is a rather rarer event. During ebbing tide, lower level in the creek generate subsurface drainage back from the soil to the creek.
- After important rainfalls one can notice that there are important imports of water at the upstream station and exports at the downstream station.
- After important rainfalls the salinity of the water in the creek decreases because of freshwater coming from the rain and upstream drainage waters
- Sometimes, after dry periods the salinity in the creek is higher than the salinity in the sea, and can reach 42 g/L. This is probably due to evapotranspiration.
- When sea level is high, the imports and exports of water to the creek are more important, as flooding can occur, generating much more ebb and flow.
- Because the marsh is connected upstream and downstream the original collector canal, a hydraulic loop exists and flow can, only at the upstream station, change direction several times during flooding tides.
- It is quicker for the water to go through the canal than going through the creek because the creek is sinuous. So during high tides, at the upstream station water first comes from the sea through the canal and temporarily fills the marsh at both stations at the same time.

2.3.2 Typology of rainfalls

Impact on the flow at the upstream station

- Some rainfalls have an important impact on the volume of water imported at the upstream station and exported at the downstream station because rainfall water from the agricultural land flows toward the sea through the tidal creek.
- Others have less or no impact.

One can see on Figure 12 the two different kinds of rainfall.

Large events (over 75 mm in less than 24 hours) generate large sudden drainage pulses which enter the marsh forcing unidirectional flow for sometimes over 48 hours. Interestingly, during these large events, which are short in time by nature, the overall water balance is relatively unaffected, the inputs from upstream generally correspond to the output from downstream. This suggests that the observed seasonal water imbalance are not due to sudden discrepancies during these large events. This also shows that the method used to measure flow did not show large uncertainties. Much smaller rainfall events (less than 30 mm/d) usually generated much smaller drainage volumes and the marsh kept its bidirectional functioning.

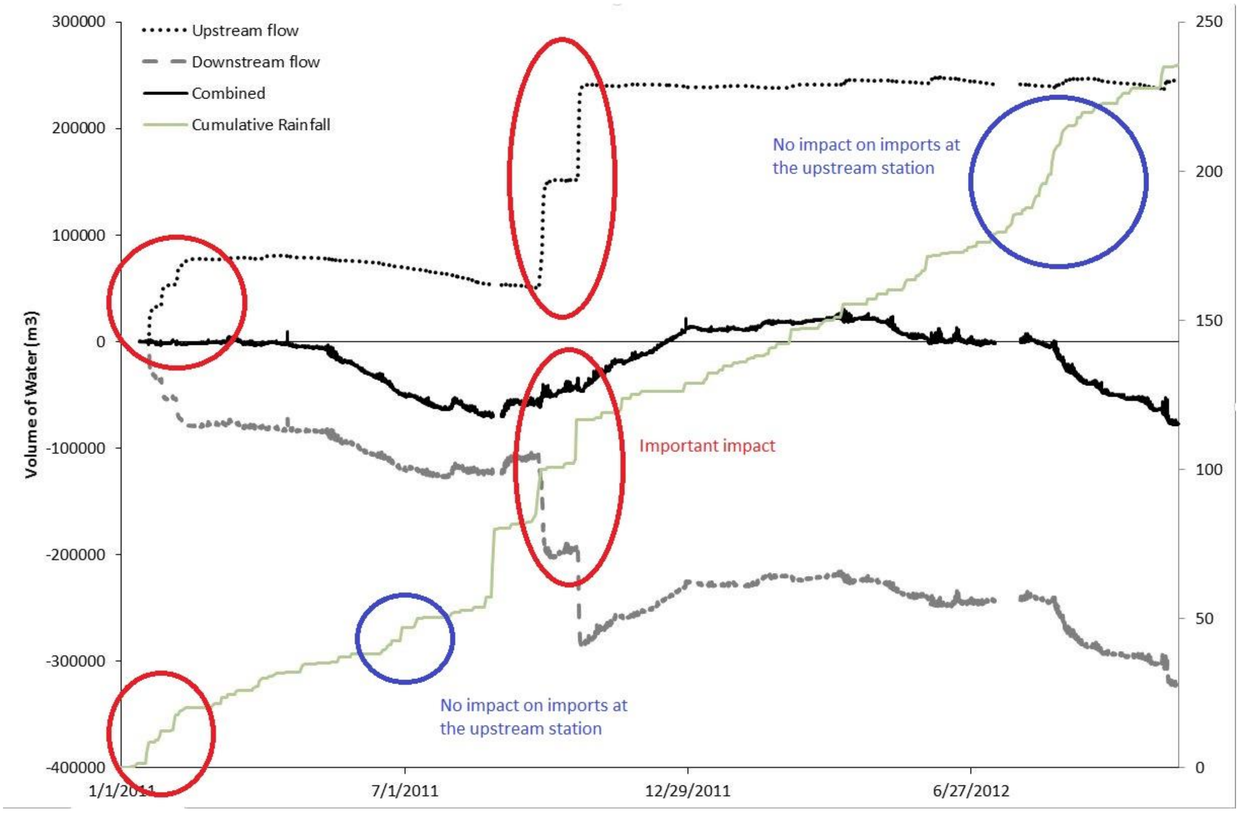


Figure 12 Impact of rainfalls on the upstream and downstream flows. Some rainfalls have an important impact, other rainfalls are as heavy but have a limited impact.

Impact on combined water balance:

- Some rainfalls are followed by an import, export or both. But one cannot say if those exports/imports are due to rainfall. There is no standard reaction of the system. The different reactions that have been observed :
- Little export and then import (especially observed during the import phase)
- Just export
- Other reactions…

- Or no significant effect

Just after the important storms of the import phase, one can see little exports and then big imports. If one looks at the water table elevation and water stage in the creek data, one can notice that there is first a little increase in water table but then the stage of the creek increases very rapidly because a lot of water is coming from the farm, and then the water table increases. A few hours later than the peak of the stage in the creek, one can see a peak in the water table. This suggest that the imports could be due to an infiltration of water in the aquifer after important storms.

2.3.3 Typology of high tides events

Most of increases in sea level are simultaneous with an increase of tidal imports and exports (Figure 13 and Figure 14, very clear on the period of Figure 14). This phenomenon is not surprising because when sea level is high, the stage of the water in the tidal creek is higher and the area occupied by the water is more important because of the trapezoidal shape of the creek. So when the stage varies, more volume has to be imported or exported.

However, during the import phase (August 2011-January 2012), this reaction is less pronounced and other phenomena like rainfalls seem to play a more important role in the magnitude of imports and exports.

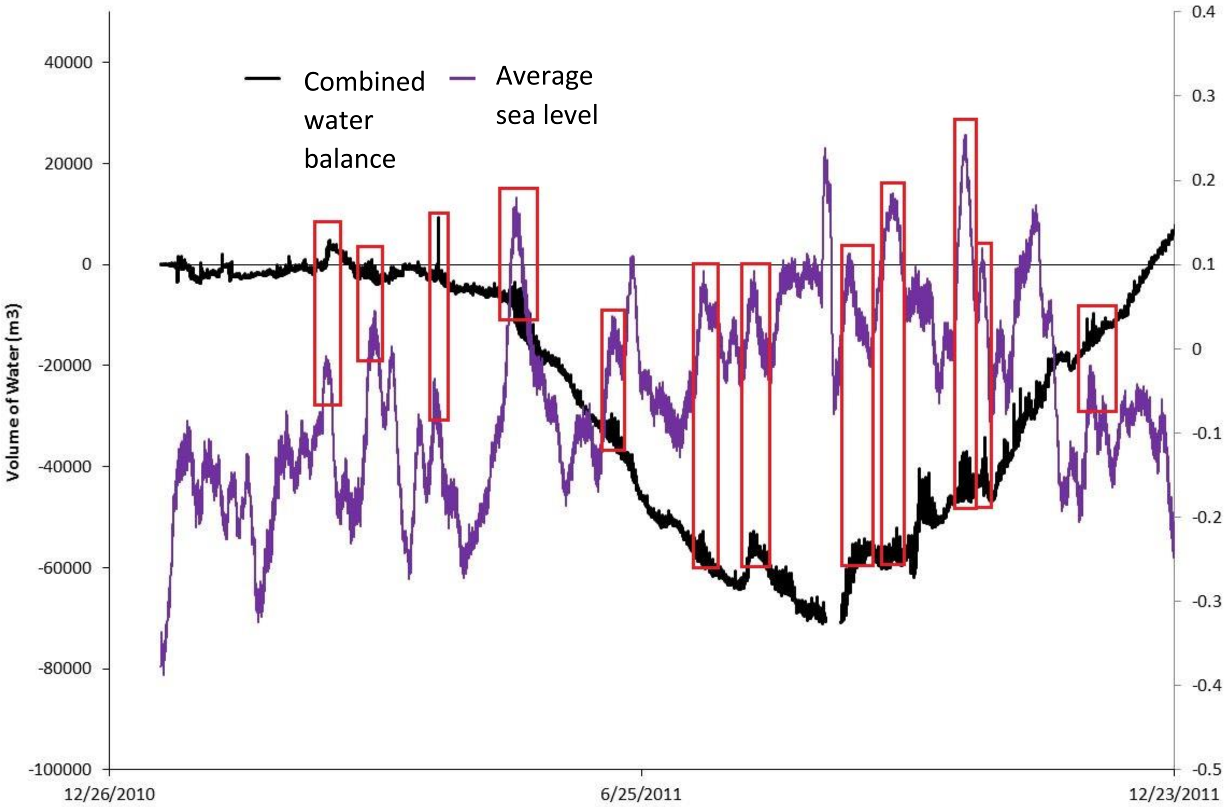


Figure 13 Correlation between high sea level and magnitude of tidal imports/exports between January 2011 and December 2011.

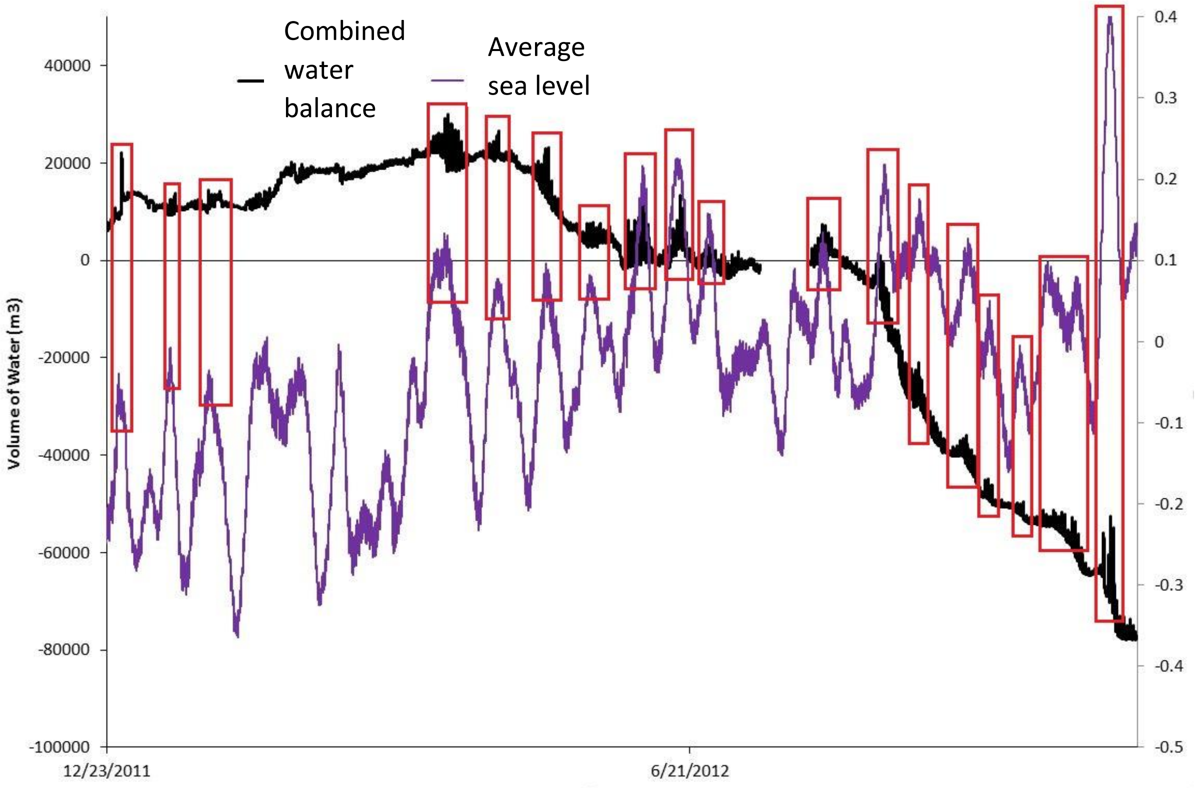


Figure 14 Correlation between high sea level and magnitude of tidal imports/exports between December 2011 and November 2012.

The graphs and videos allowed us to better understand the hydraulic functioning. Most of our observations seem coherent with what was expected and logical, except the water balance. It confirms us that the measurements of the flow are coherent: the creek imports water with high tide and exports water with low tide (there is no error in the direction of the flow). We also know that the water table is connected to the creek, there is no impervious soil that isolates the aquifer from the creek. The marsh is also strongly influenced by the sea level. Finally, particular events like rainfalls and high sea level seem to perturb the water balance, but don't seem to be responsible for the global water balance. Indeed, during the end of phase 3, there is no particular event and one can still observe a very regular import, result of small imports during each tidal cycle.

3. Scenarios

Reminder: Hydrogeology (Appendix 1).

3.1 Can these volumes be stored in the creek?

First, one can imagine that the volumes of water imported and exported to the creek could just be stored in the creek. The magnitude of these exchanges is about 70 000 m^3. However, Etheridge (2013) evaluated the volume stored in the creek (Figure 15), depending on the stage of the water at the downstream station. This graph shows us that the volume of the creek is much lower than 70 000 m^3, knowing that the maximum estimation of 20 000 m^3 is very rarely reached, just during few floods.

If we take into account the water that is stored in the creek in our water balance (Figure 16) the result is not so different from the original water balance.

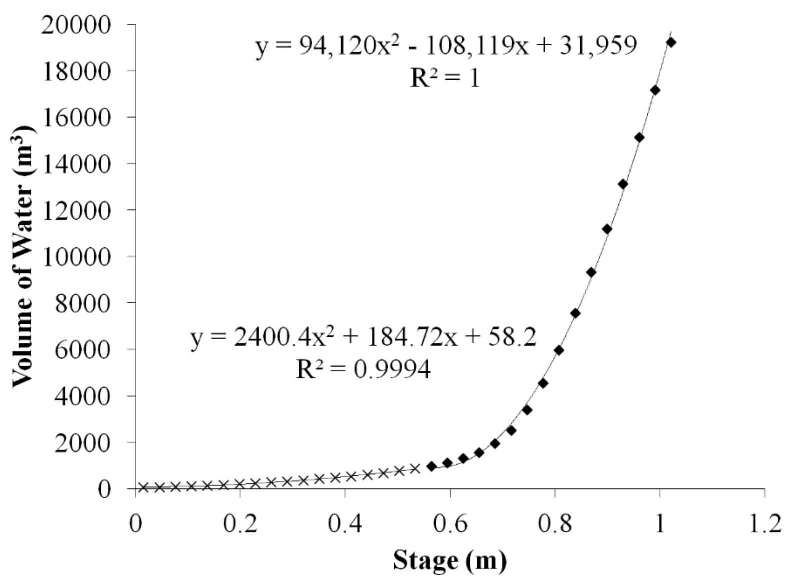


Figure 15 Relationship of stage at the downstream station to the volume of water in the marsh for stages below bankfull and stages above bankfull. These relationships should only be used when the stage is 0.83 m and below.

If the water is not stored, it has to go somewhere. Considering that the water balance is not biased and that if leaks happened, they just happened during some very rare events when the stage was high, the water either has to be evaporated, to come from rainfalls, or to go to the soil profile.

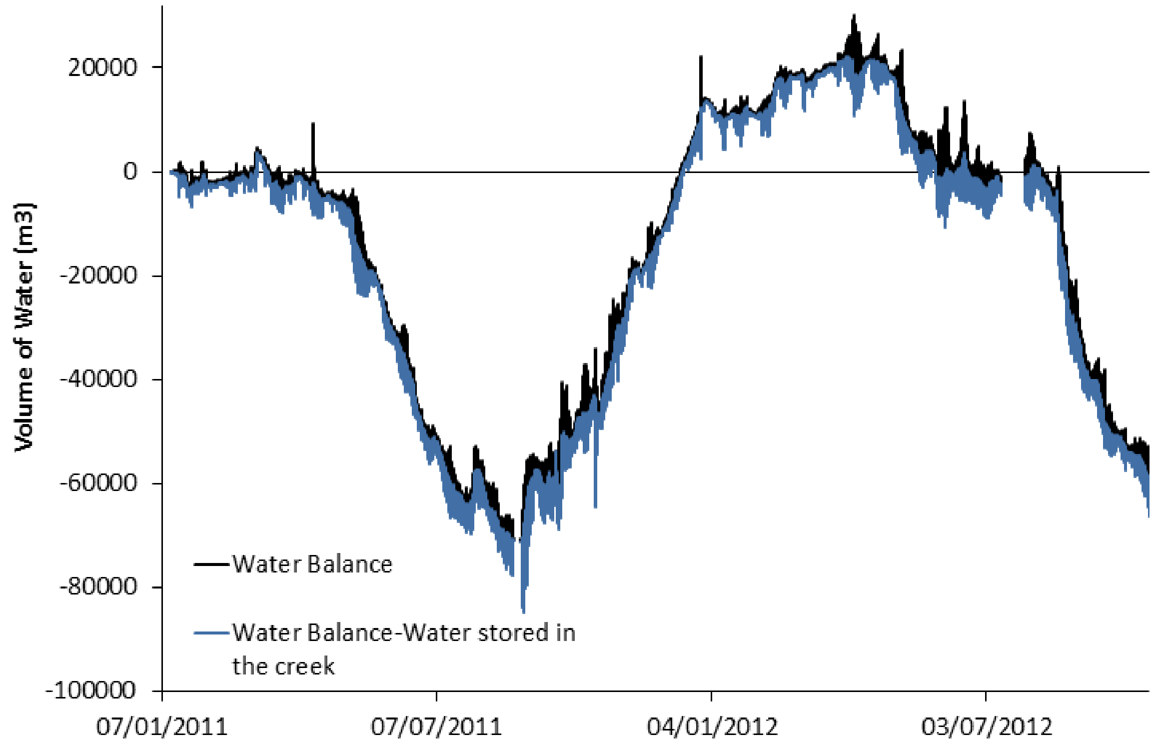


Figure 16 Combined water balance, and combined water balance minus the volume stored in the creek.

3.2 Can one observe gradients between the creek and the water table that would explain the water balance?

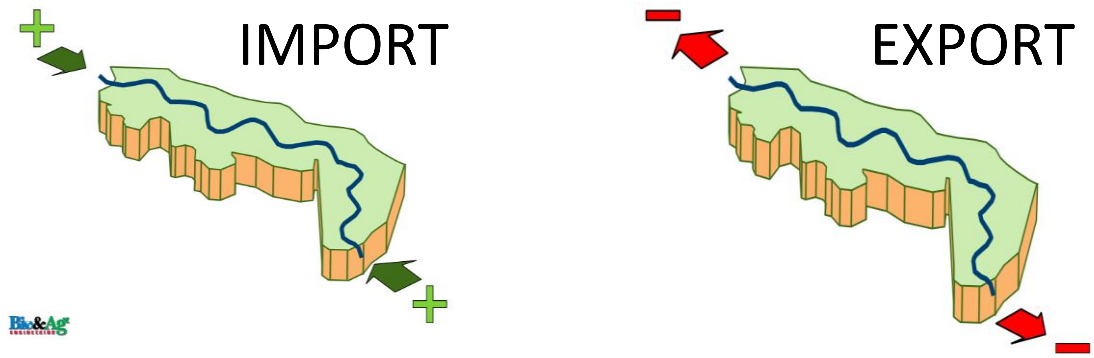


Figure 17 Reminder of the convention used for imports versus exports at both stations

After these first observations, we know that the water has to go somewhere. A quick calculation shows that the imports and exports cannot be only due to evapotranspiration (ET) and rainfall on the creek, because ET is higher during the summer so we should expect an import to the creek instead of an export during the summer, to compensate this loss. Besides, if ET on the creek was responsible for the import, we would have to evaporate about 1m per day which is not realistic.

Consequently, most of the water imported and exported has to go and come from the water table or underlying aquifer.

Using the available water table data, a natural question was to check if the elevation of the water table could explain the imports and export. We expected the water table elevation to be generally higher in the soil profile compared to the stage in the creek during the export phases. The resulting excess drainage would then correspond to the export. Reversely, the imports would have to be associated with lower water tables in the soil profile as the creek would behave as a 'losing creek'. (Figure 18).

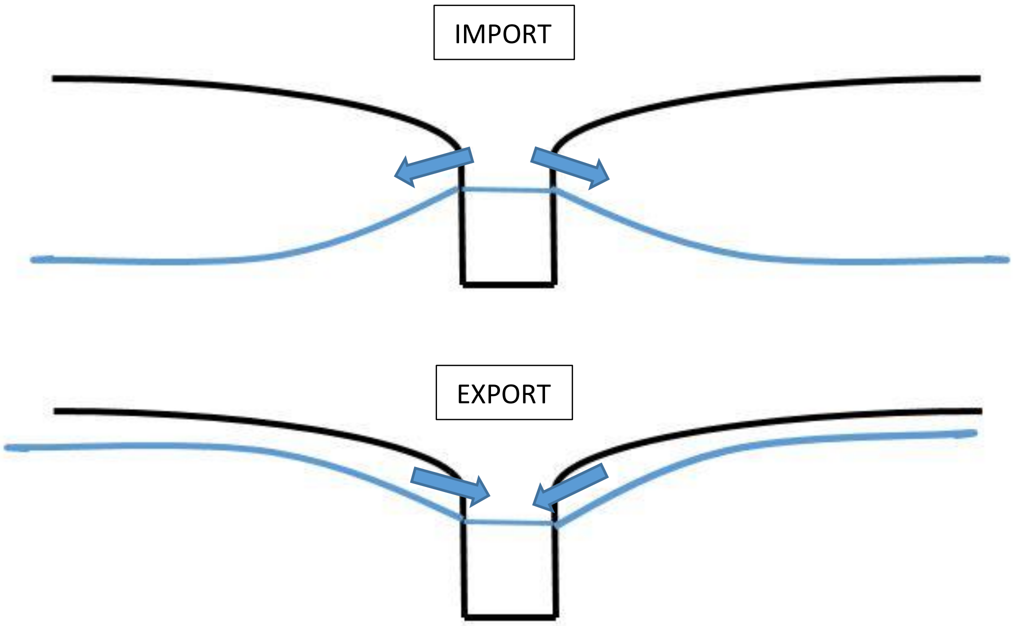


Figure 18 Mechanisms expected during import (low water table compared to the stage of the creek: the water infiltrates into the water table) and export (high water table compared to the stage of the creek: the creek drains the water table).

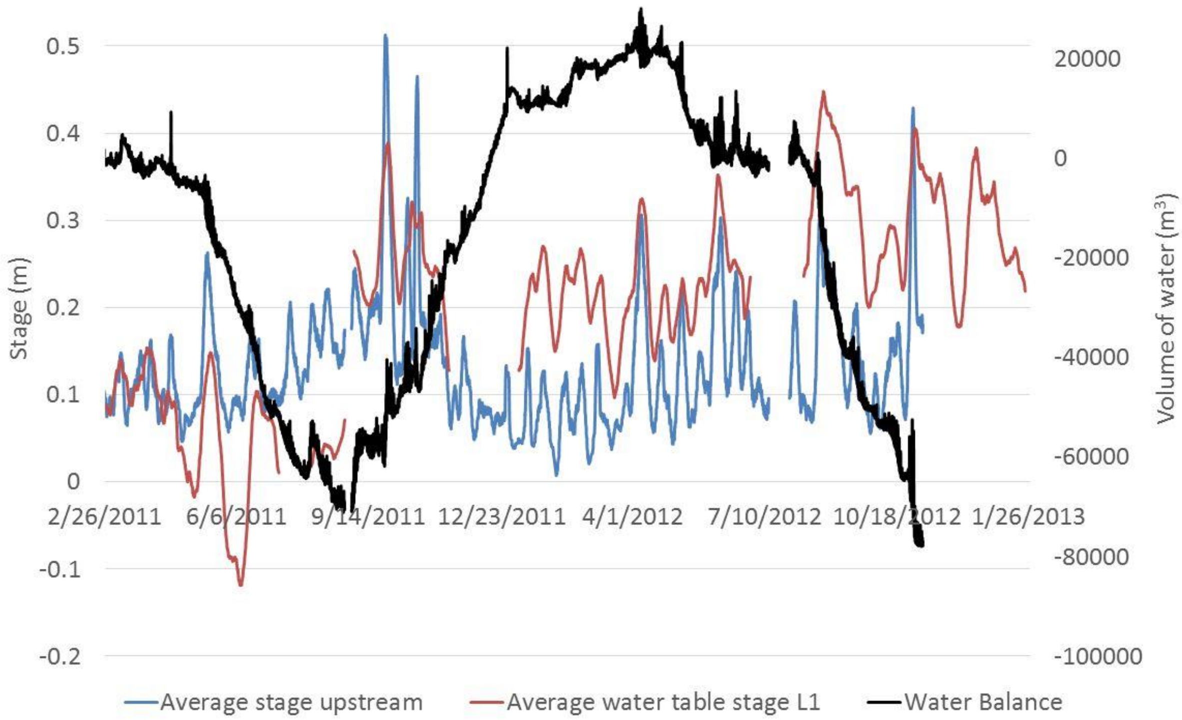


Figure 19 the stage of the water table is higher than the creek except during the first important export: there is no correlation between the water balance and the position of the water table compared to the creek.

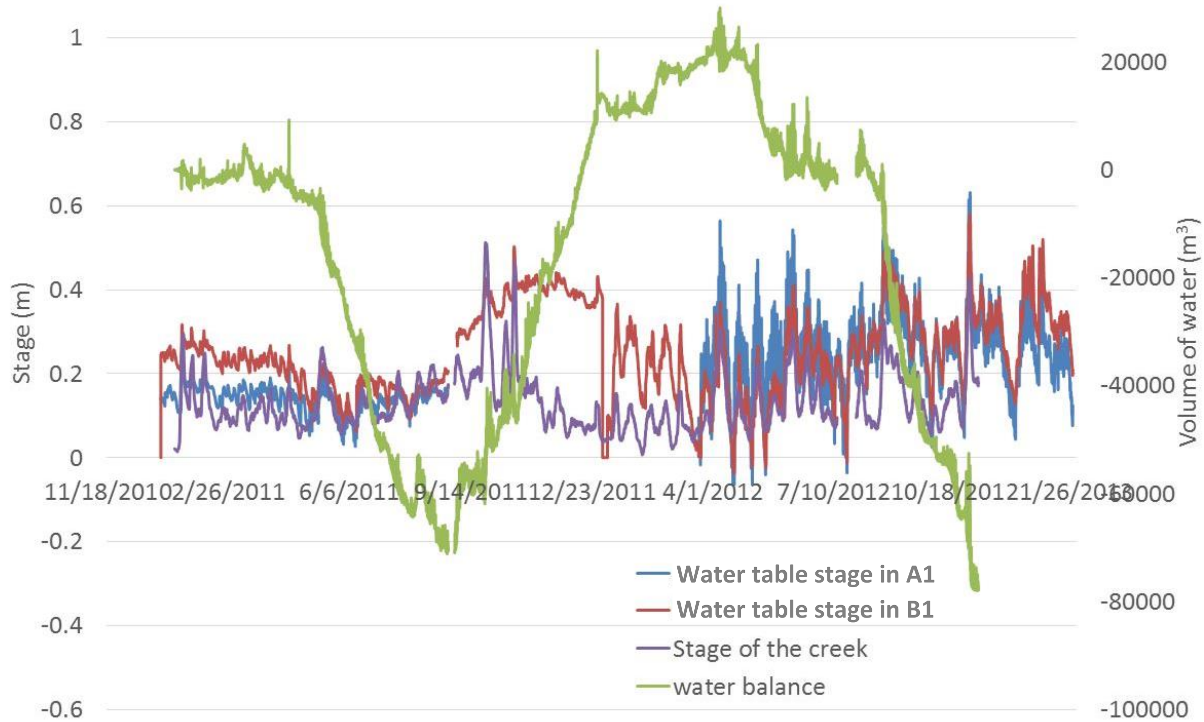


Figure 20 On the werstern side of transect 1 there is no correlation between the water balance and the position of the watertable.

On Figure 19 one can see that the water table is higher than the stage of the creek, except during phase 2 (first export phase). It does not correspond to what we would expect. On Figure 20 one can see that the water table is above the stage of the creek for most of the year, so it would imply an export of water. Moreover, there is a period on Figure 20 (phase 3, important import) when the water table seems to be “disconnected” from the creek because the stage of the water table is much higher than the one in the creek. However, if one zooms on this period, one can clearly see the influence of tides on the water table elevation. Moreover, if one compare A1 and B1 (Figure 20) one can see that most of the time A1 is lower than B1 which means that the water should flow toward the creek, even when there is an import.

Consequently it is difficult to make any meaningful conclusion, especially because of the very uncertain quality of the water table data. Nonetheless, in the available data deemed acceptable, we do not see any logic between the direction of the flow that we have on the water balance and the one we should expect from the water table data.

3.3 Is there a leak to other ditches?

3.3.1 Where could the leak appear?

There could be surface or groundwater leaks between the creek and other creeks canals or ditches surrounding the studied creek. On Figure 2 one can see that there are a lot of legacy ditches or canals in the vicinity of the creek:

- On the western part of the marsh, the historical drainage canal is used to evacuate most of the drained water from the farm, the remainder is diverted into the restored marsh.

- Another collector drainage canal borders the north sides of the marsh and evacuates drainage water from agricultural land to the north.
- Old drainage ditches on the western part of the marsh, although partially filled with soil when the marsh was constructed, could be still influenced by tides and drain some water.
- Evans' creek, on the eastern part of the marsh is another constructed creek but is an unlikely escape route.

Consequently the creek is surrounded by canals. Some of them could drain the water of the marsh (the northern and western canals) because they are deep. The old ditches are not likely to drain a lot of water as they were filled with soil. These canals are also influenced by tides.

<u>Surface leak</u>: When the water level in the creek is particularly high, higher than the top of the trapezoidal structure, there could be some errors in the volume measurements, because some water could flow outside of the trapezoidal structures where we measure the flow.

To prevent this uncertainty, a system was installed to prevent water from flowing outside of the structure. In spite of this system, it is possible that during some rare events when we have a very high water stage in the creek, the water balance could miss some flows.

However, these leaks would be isolated cases and could account for very specific and time-limited imports or exports but not for the general behavior.

<u>Groundwater leak</u>: One can imagine that if there is a hydraulic head gradient between the different creeks, canals and ditches a groundwater leak could appear.

To have an estimation of the volume of water that could be exchanged between those canals and creeks one can consider that the discharge Q= A * v where A is the area where the water would leak, and v the velocity of the water. One can take A= 500m x 1m (approximately 500m long and 1m deep). We can evaluate v thanks to Darcy's law that is used to calculate the velocity of water between two points in porous media (G. de Marsily, 1986)

Darcy's law: $v = K * \frac{\Delta h}{\Delta x}$ where K is the hydraulic conductivity of the porous media, Δh the difference of hydraulic head between two points and Δx the distance between those two points.

3.3.2 What distance, gradient and conductivity do we need to explain exports?

The conductivity of the marsh was measured using the auger hole method and for the top layer of the soil. The measurements gave a value of K around 10^{-6} m/s, 10^{-7} m/s.

This conductivity is very low and probably represents the conductivity of the top layer, the organic soil that was added when the marsh was constructed.

The soil in this area is supposed to be composed of either Deloss fine sandy loam or Leon sand (US Department of Agriculture, Web Soil Survey). The capacity of the most limiting layer to transmit water ranges from 4 10^{-6} m/s to 4 10^{-5} m/s.

The creek is approximately 650m long (with curves). The length of the bottom of the creek and the edge, at the downstream station is 6.6 m. This is probably a high estimation for the rest of the creek because the creek gets smaller towards the upstream station. It represent an area of approximately

650m*6.6m≈ 4300 m^2. However the water doesn't always reach the top of the creek and this area is not always wet. If we consider that the average surface of the wetted area is half of this area because of tides, we have 2150 m^2.

Depending on the period we would need a velocity of water of: 0.31m/day, 0.29m/day (phase 3 of Figure 9), 0.45 m/day (end of phase 3), 0.067 m/day (phase 4) or 0.40 m/day (phase 7).

If we consider that K=10^{-4} m/s, and the average length between the creek and other canals is about 200m, we could need a gradient between 10.4 m to 1.55m.

Of course this is not a precise estimation because the geography of the site is very complex and it is not easy to estimate properly this gradient, with a lot of unknown parameters. This estimation gives us a value for the hydraulic gradient which doesn't seem realistic. However, if K was underestimated and if its real value was 10^{-3} m/s which seems unlikely considering the data from the US Department of Agriculture (Web Soil Survey) but is still a reasonable value if there was a layer of sand under the Deloss of Leon sand soil, we would need gradients ranging from 1.04m to 0.155m which is more realistic. Besides, the distance between the creek and the other ditches is a rough estimate and could be overestimated.

Our estimation of the different parameters is really rough so it is very difficult to estimate precisely the gradient that we need. To estimate it properly we would have to estimate the transmissivity between the creek and another canal or ditches thanks to a 3D model and more precise conductivity data. Although the average values of parameters that we choose seem to require important hydraulic gradients, we cannot dismiss this scenario with certainty.

3.3.3 What gradient could explain the leak?

If there is a groundwater leak between the creek and other ditches, there is a gradient of hydraulic conductivity.

One could imagine different kind of gradients.

- *Gradient due to a high water stage after rainfalls*

After a rainfall, a lot of water comes from the farm which is located in the north of the marsh, because the soil of the marsh is drained using ditches. So one can imagine that there is a higher water stage in Evans' creek and the northern canal if they receive more drained water. The drainage water coming to the north western inlet of the marsh is diverted to the studied creek thanks to a little weir, so there could be a gradient between the creek that receives the rainfall water and the canal that just receives water from the sea.

However, these gradients would always be of the same type (creek higher than the canal and ditches or Evans' creek higher or lower than the studied creek) and they would not explain the change in the observed imbalances (export and then import and export again). Besides these gradients are present over very short periods (just after rainfalls), and they would disappear quickly as the water is redistributed between the creeks and canals and mixes with sea water. The imports and exports don't appear only after rainfalls so they could not explain all the water imbalances.

- *Gradient due to tides*

One can imagine that there is a gradient created with tides. The western canal, the old drainage ditches and the creek are all influenced by tides and because the creek is sinuous, the sea water takes more time to reach the upstream station through the creek than it does through the western canal. So one could imagine that it creates a small gradient between the creek and the canal and the old drainage ditches. However, another gradient is created in the other direction when the water flows back to the sea: the water leaves the canal more quickly than it leaves the creek. So those two gradients would probably compensate one another.

We ran a simulation using FEFLOW (Diersch, 2002) to verify if this mechanism could explain imports or exports.

Figure 21 represents the simulation domain (20mx50m) and the mesh. The simulation was run with saturated conditions which is an approximation but considerably reduces the simulation time. The initial conditions for this simulation were 1m for hydraulic head. The hydraulic head boundary conditions were two different sinusoids on each side of the domain, representing the stage of the canal and the stage of the creek that vary with tides. The variation of the stage of the creek is delayed compared to the stage of the canal.

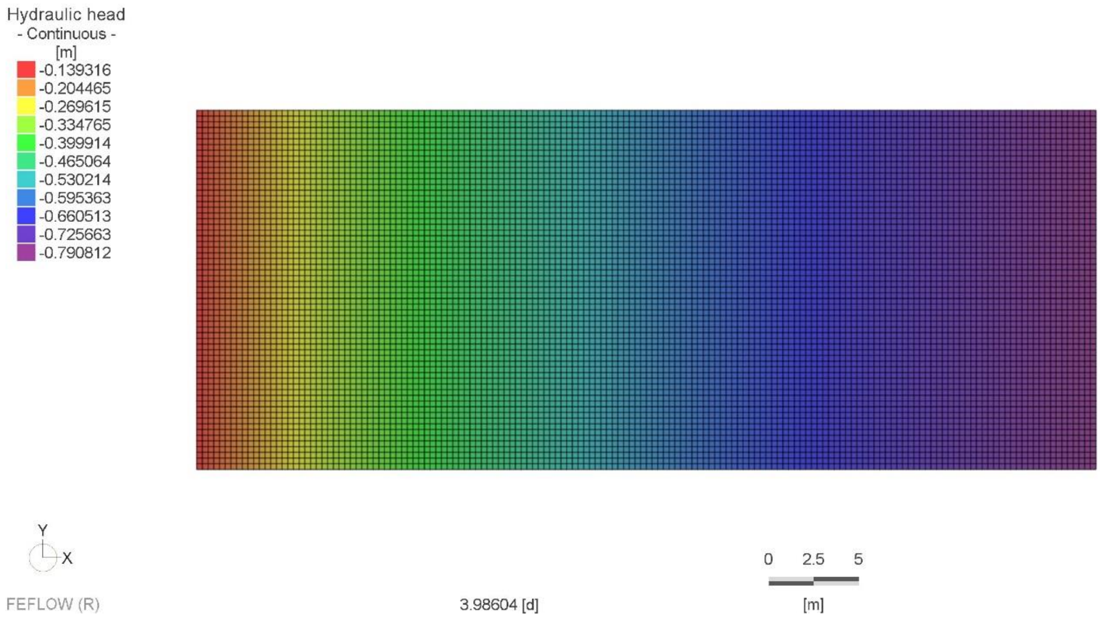


*Figure 21 2D vertical simulation of two creeks with sinusoidal variations of the stage with a delay of 0.2 days between the two, in a 20*50 m domain, tides between -1m and 1m, K=1m/d, initial conditions h=0m.*

The resulted water budget on the right side of the domain which represent the creek is displayed on Figure 22. One can notice that the creek alternatively imports and exports water but the global budget is balanced.

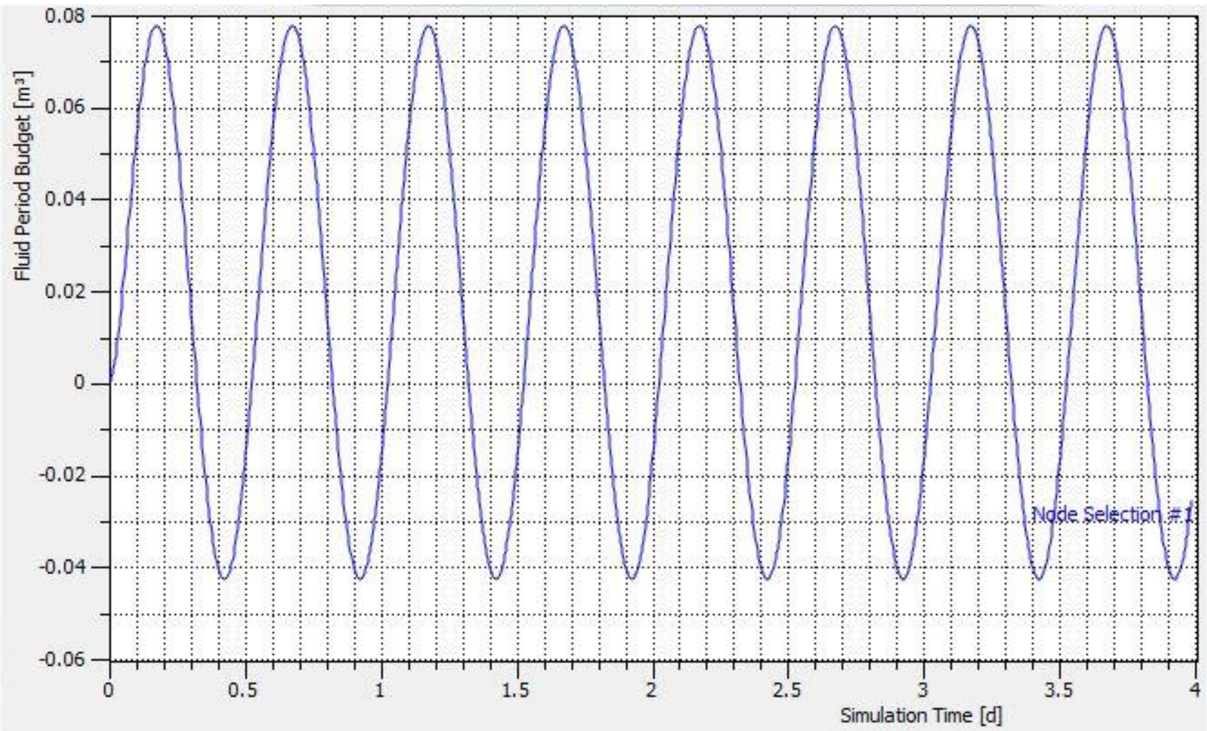


Figure 22 Water budget of the creek with saturated conditions: there are imports and exports due to tides but no global imbalance.

This simulation shows that this scenario does not seem to be an explanation for the observed water balance.

Besides, we can hardly imagine a reason why the flow would change direction during the year.

- *Gradient when the creek is empty at low tide*

Finally one can imagine another kind of gradients. Because the western canal is a bit deeper than the creek, when the sea level is particularly low and the creek is empty at low tide, one can imagine that some water will remain in the soil at the bottom of the creek and if the stage of the water in the western canal is lower than the bottom of the creek, there will be an hydraulic gradient. This gradient could create an import of water in the creek as the aquifer is recharged at high tide.

However, this scenario could just explain a certain type of import, when the sea level and the level in the creek are low (for instance during the end of phase 3 or phase 4) and could not explain the whole water balance.

We ran a simulation to verify if this scenario could explain significant imports. This simulation needs to be run with unsaturated conditions as the water in the top of the aquifer can pour into the canal at low tide.

The domain of the simulation is 100m large and 20m deep. We just took into account the domain between the two creeks, considering that the rest of the marsh does not have an effect on this mechanism. The shape of the domain can be seen on Figure 23. The canal is situated on the left side of the domain and is 2m wide and 2m deep. The creek is on the right side of the domain and is 1m wide, 1m deep.

The initial condition for hydraulic head was 19m on the whole domain (and consequently fully saturated between 0 and 19m). Boundary conditions were a fixed hydraulic head on the edge and bottom of the creek and canal, and a no-flow BC on the other limits of the domain. We used sinusoidal fluctuations for the stage of the creek, between 18m and 20m. The stage of the creek was delayed compared to the canal and its stage could not go under 19m (as the bottom of the creek is at 19m). The porosity was 0.4 and the hydraulic conductivity 10^{-4} m/s. The saturation after 365 days can be seen on Figure 23. The water budget of the canal and the creek is displayed on Figure 24.

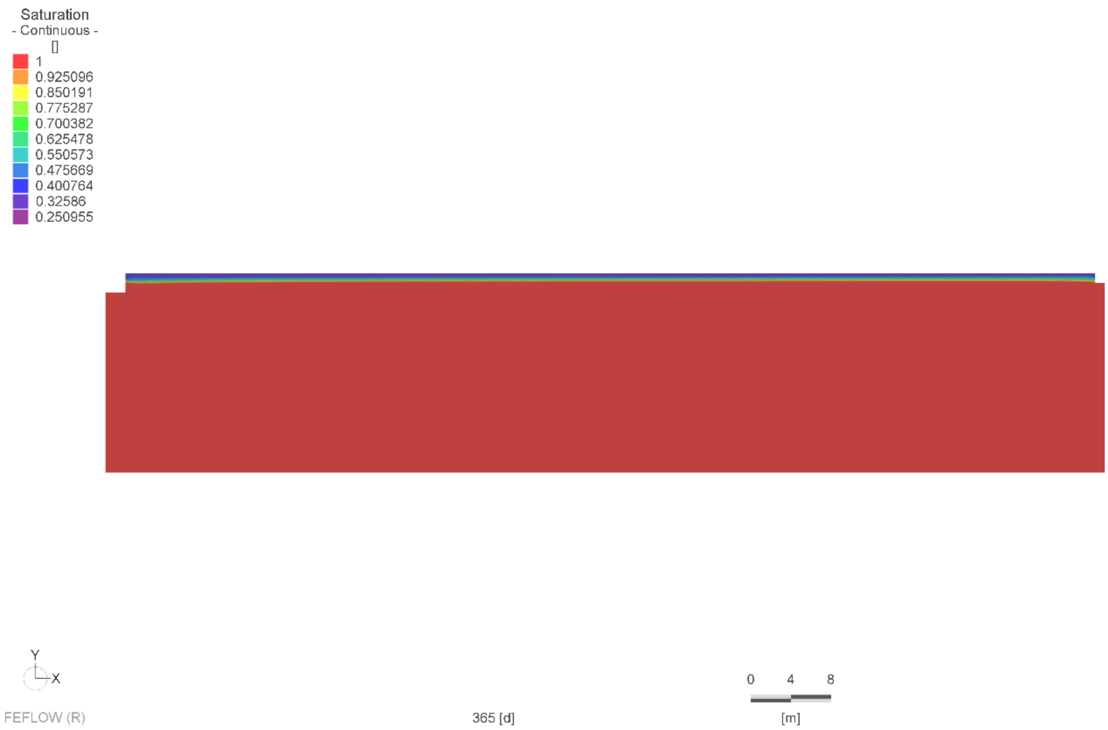


Figure 23 Saturation after 365 days of a 2D vertical simulation of two creeks in unsaturated conditions.

On Figure 24, one can see that some water is imported from the creek to the aquifer and that some water is exported from the aquifer to the canal. The average rate of import / export is 0.188 m^3/day. The creek is about 500m long (if we do not consider the sinuosity) so it could import about 94 m^3/day. This estimation is below the import that we observe in phase 3 and 4 and besides the geography of the site is very complex and only a very short portion of the creek is that close from the canal. If the creek is further, the import is smaller as the gradient is smaller.

Consequently, this scenario could not explain the imports that we observed as it is not significant enough.

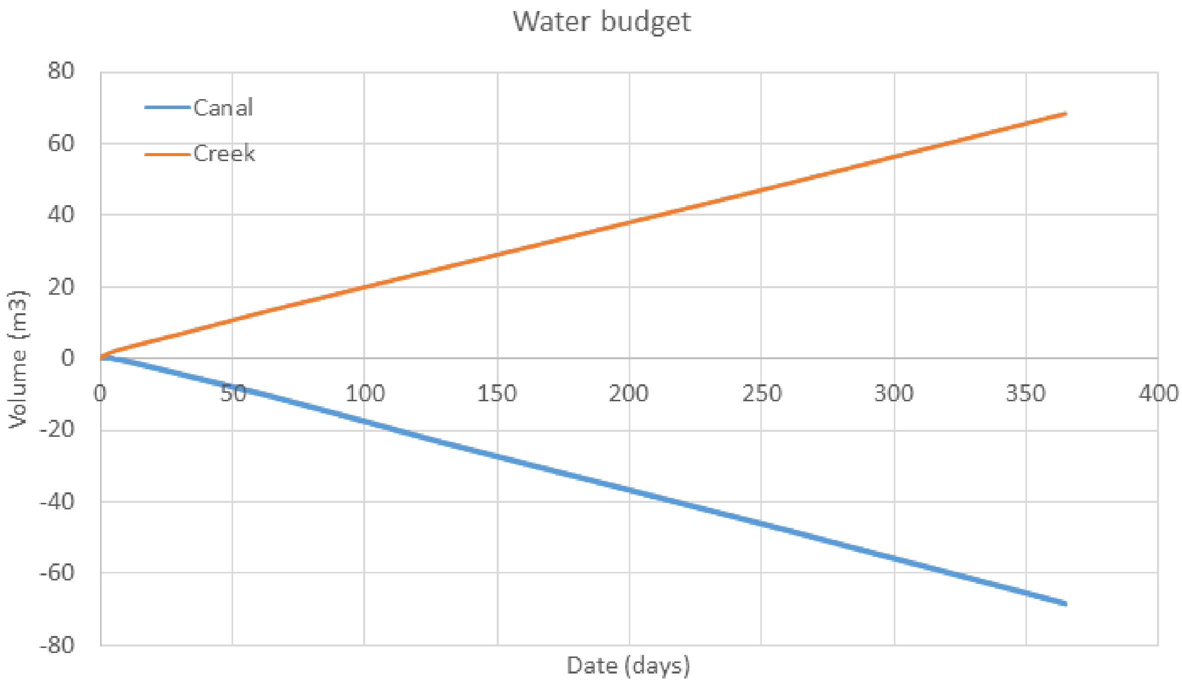


Figure 24 Cumulated water budget of the creek and the canal after 365 days of simulation: the creek imports water and the canal exports water.

3.4 Could the water balance be explained by local storage of water?

3.4.1 Could we explain these exchanges with water table elevation data-Rainfall-ET?

One could consider that these exchanges of water be very local, and due to the water budget of the aquifer in the marsh. The observed water balance and the unexpected export of water in the spring and summer would be due to a delay in the export of water from the marsh.

If this scenario happens, one should expect to see the water table higher than the stage of the water in the creek when there is an export and lower when there is an import. As we observed it in paragraph 3.2, this is not the case, but one cannot eliminate this possibility because our water table data was not always reliable.

3.4.2 Simulation of the marsh

We ran a 2D simulation in Feflow to determine if exports and imports could be explained by local storage of water. The geography of the site is very complex, so we just used a simple 2D confined aquifer, 200m long, 20m deep. On the left side of the aquifer, there is a 1m wide, 1m deep creek. We considered the creek in the middle of a 400m large marsh but we just simulate one side of the marsh as it is symmetric. The domain is shown on Figure 25.

Figure 25 Shape of the domain (400m x 20m) representing the marsh in the simulation, with half of a creek on the left side

The boundary conditions that were used in this simulation are:

- no flow on the bottom, right side and left side (except the creek)
- Hydraulic head boundary conditions on the edge and bottom of the creek, representing the stage of the creek
- Fluid-Flux boundary condition on the top of the aquifer, representing the recharge.

The hydraulic head in the creek was the real stage measured in the creek. The recharge was real daily recharge minus the monthly average evapotranspiration.

Initial conditions were first chosen so that the hydraulic head in the aquifer was equal to the hydraulic head in the creek, h=0m.

We ran a simulation with saturated conditions but we tried to better represent the unconfined aquifer modifying the specific storage coefficient, as explained in appendix 2. The drainable porosity of the aquifer we used was 0,15. It is an estimation because we don't have any data on that. Specific storage was 0.0001 m^{-1}.

We first ran this simulation with $K=10^{-6}$m/s. However, we found that the hydraulic head in the aquifer (representing the stage of the water in the aquifer) was very high (almost 4m): the water could not escape from the aquifer because of the low hydraulic conductivity. This elevation is not realistic for the water table because it is too high compared to the values we obtained in our measurements and higher than the elevation of the ground.

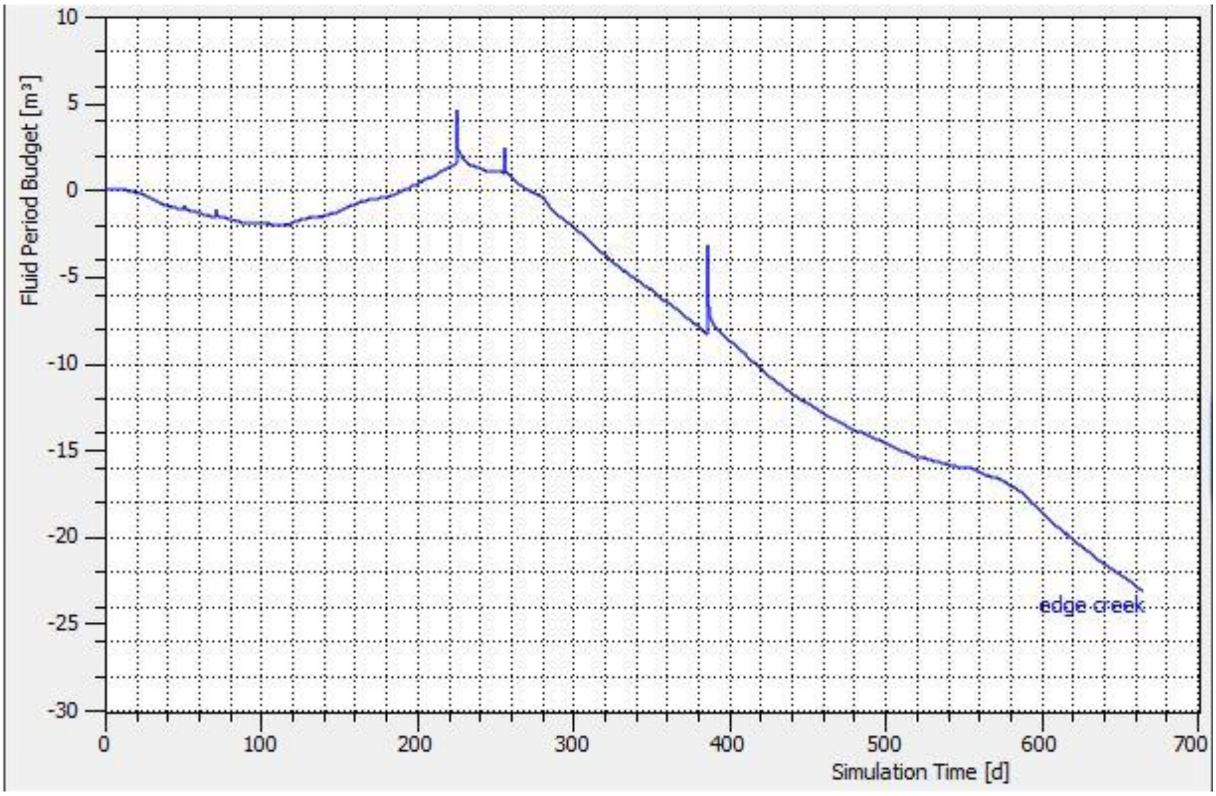


Figure 26 Cumulated water balance of a simulation of the marsh with real water stage, rainfall and ET data, with K=10⁻⁶ m/s. Peaks are due to an error in input data for some time steps but do not seem to influence the general result.

Then, we ran the same simulation with $K=10^{-4}$m/s. The maximum hydraulic head that we obtained in the aquifer was about 0.9m which is more realistic. So we used this value of K for the next simulations.

Figure 27 Cumulated water balance of a simulation of the marsh with real water stage, rainfall and ET data, with $K=10^{-4}$ m/s.

On Figure 26 and Figure 27 one can observe the water budget on the edge and bottom of the creek. In the second simulation, one can notice that the magnitude of the flux is more important. It is due to the fact that less water is stored in the marsh.

However, in both cases, there is no significant delay between the water balance and the recharge (Figure 28). Consequently, this scenario does not seem to explain the delay in the water balance.

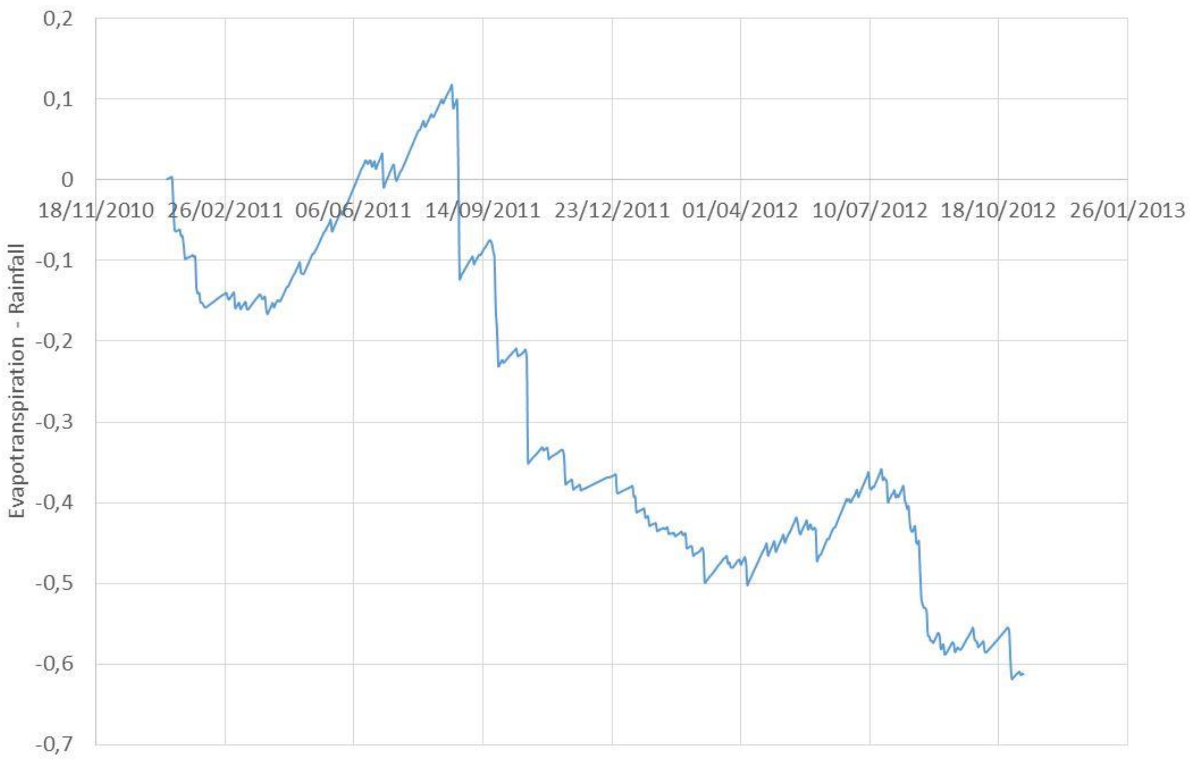


Figure 28 Cumulated ET minus rainfall. Recharge used in the simulation.

3.5 Could the water balance be explained by regional flows or movements of the saltwater wedge?

3.5.1 What is the saltwater wedge?

Reminder: What is the saltwater wedge (Appendix 3).

3.5.2 Movement of the saltwater wedge:

- Due to seasonal recharge

The saltwater wedge can move seasonally because of the variation of thickness of the freshwater lens above it (Michael, 2005). One can imagine that the seasonal movement of the saltwater wedge could induce an import or an export of water to the marsh.

One can expect that during the spring and the summer, the water table is thinner, so the saltwater wedge moves toward the land and push the saltwater wedge up. One could expect an export of water through the creek (Figure 29).

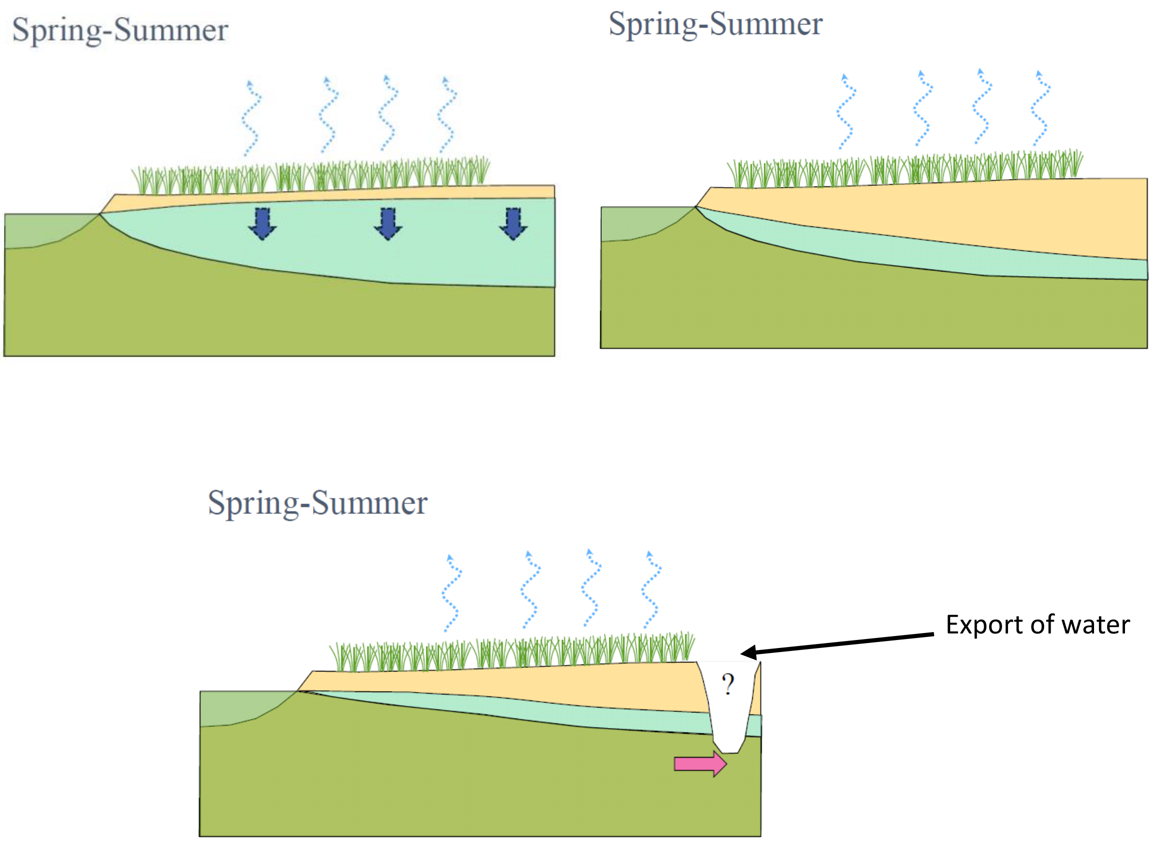


Figure 29 Mechanism that could be expected during the spring and summer when ET is high to explain the export phase.

During the fall and the winter one could expect that the water table is thicker and pushes the saltwater wedge toward the sea. One could expect that this movement could “suck” the water in the creek (Figure 30).

However, one can hardly imagine that those scenarios would work. First, because one can wonder why in the spring and summer the infiltration of the water from the creek to the aquifer would not be

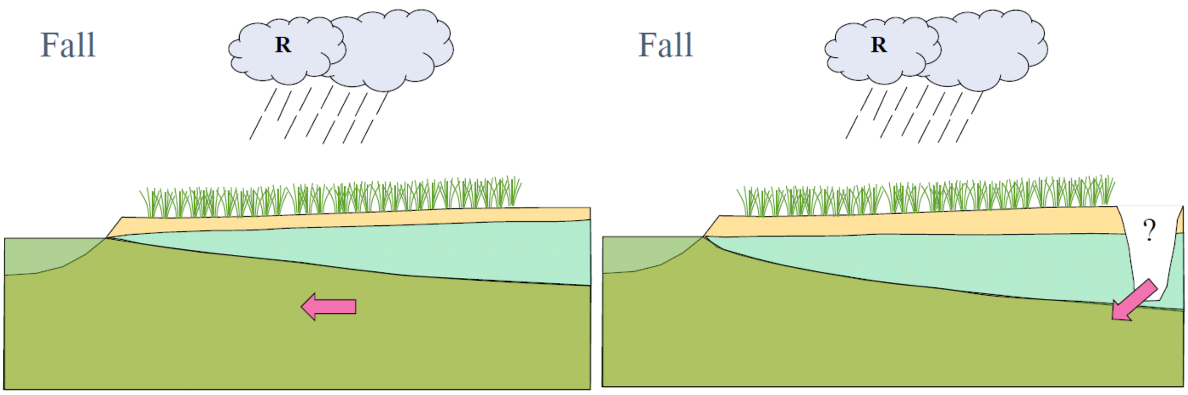


Figure 30 Mechanism that could be expected during fall and winter to explain the import phase

predominant, and in the winter, why the drainage of the thick water table would not be dominant too. Second, those scenarios could probably not explain the volumes of water that are exported and imported. We export and then import and export again about 70 000 m^3 of water. It represents about 64 cm of water on the area of the marsh.

During the spring and summer of 2011, the maximum cumulated ET is less than 30 cm, so the volume of water that could move to replace this lack of water could be 0.3m maximum over the marsh area. One can hardly imagine that this movement could induce a 0.64 m of exports to the creek.

The scenario for the winter doesn't seem realistic either. The maximum cumulated rain is about 0.6m, and the imports are about 80000 m3. One can hardly imagine how the movement of the saltwater wedge could "suck" as much water as the rainfall that pushes it.

Considering that this scenario is highly unlikely, we didn't try to simulate it and focused on other scenarios.

- Due to variations of sea level

Looking at the water balance and the average sea level variation Figure 31, one can notice that when the average sea level increases, the creek exports water and when the average sea level decreases the creek imports water.

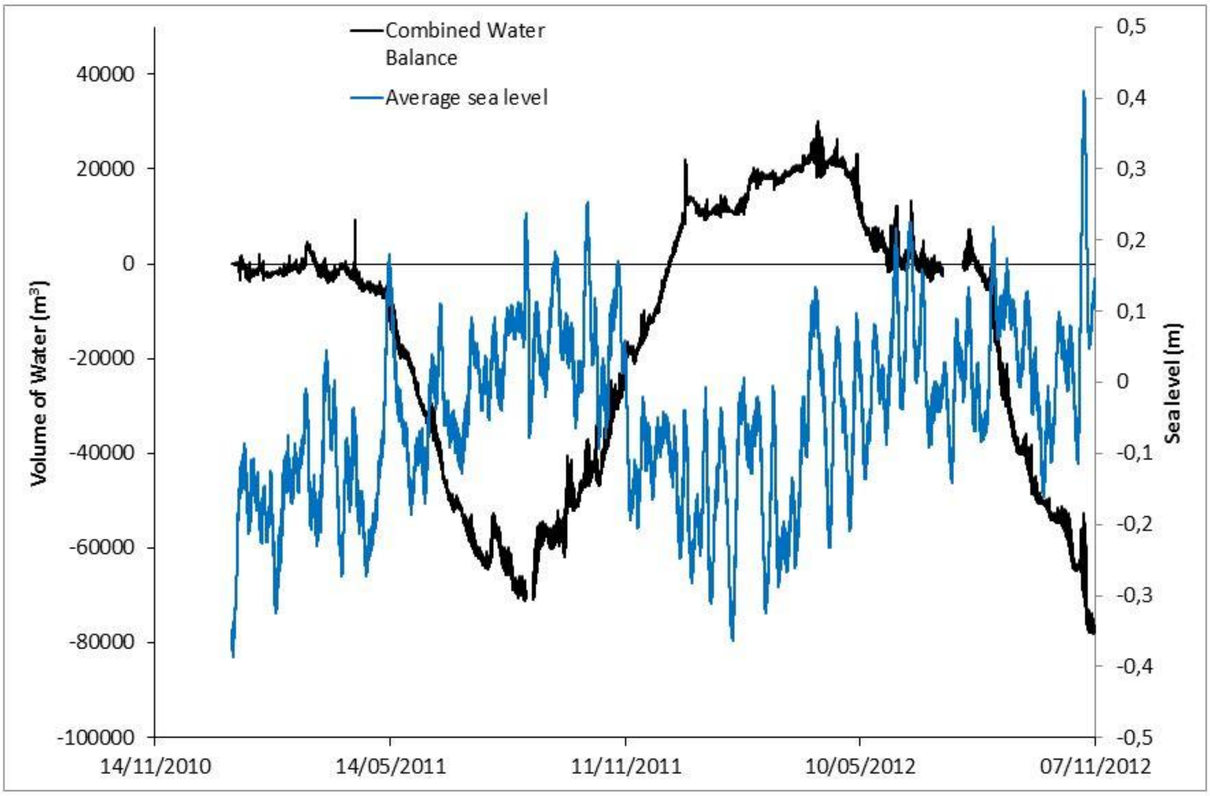


Figure 31 Combined water balance of the creek and average sea level at Beaufort over 3 days

When the sea level increases, the saltwater wedge is supposed to move further inland because the pressure in the saltwater increases (Figure 32). One could imagine that some water could be exported out of the creek. On the contrary, when the sea level decreases, the pressure of the saltwater along the saltwater interface decreases so the wedge moves back toward the sea (Figure 33), some water could be sucked from the creek.

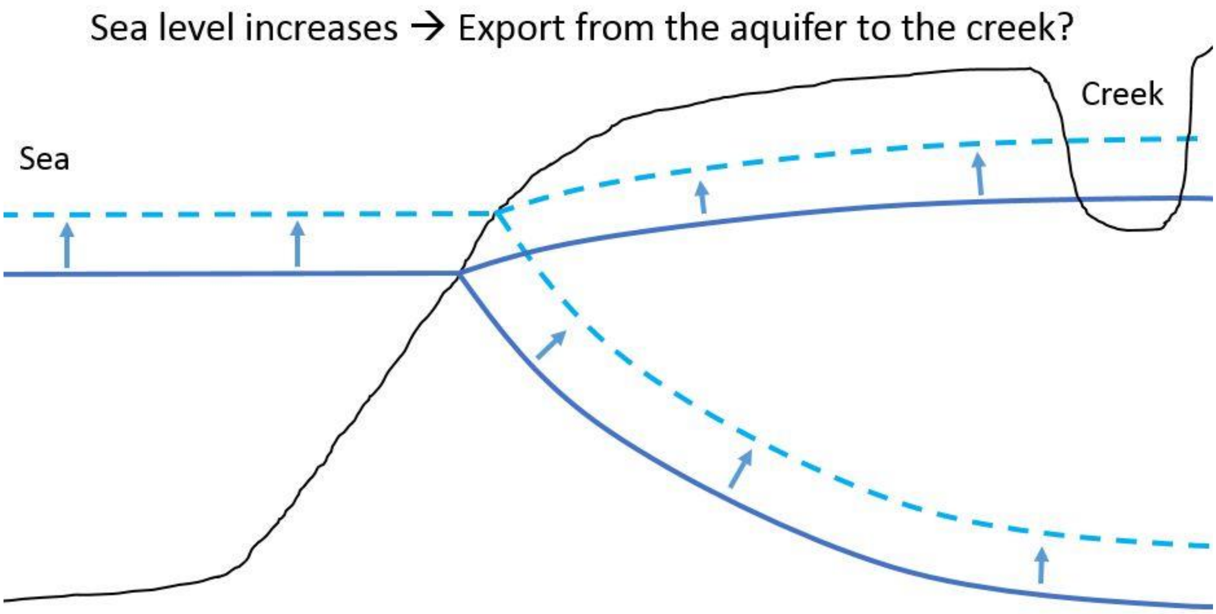


Figure 32 Movement of the saltwater wedge when the sea level increases

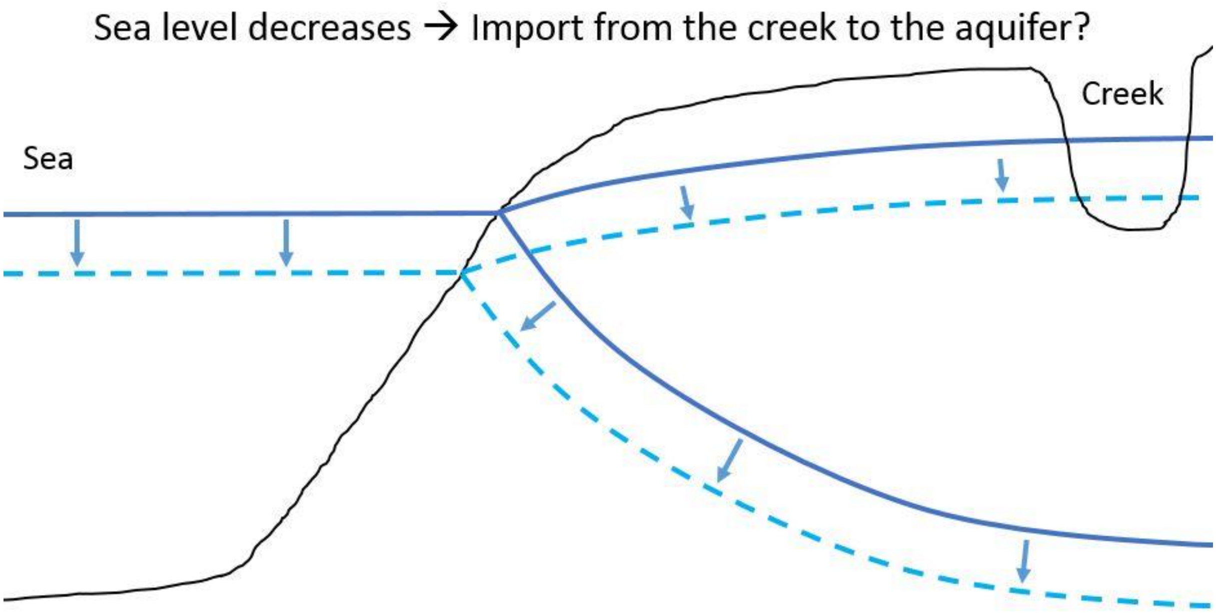


Figure 33 Movement of the saltwater wedge when the sea level decreases

However, if one tries to estimate the volumes of water that could be sucked or that would infiltrate, one realizes that this possibility could not explain the water balance. As we said before, to explain imports or exports we would need at least 64 cm of water over the whole marsh. If we look at Figure 31 one can notice that the seasonal average of the sea level varies by about 40 cm. So the saltwater wedge could vary by 40cm maximum. To calculate the volume that it would represent, one has to take into account the porosity of the soil (we chose 40%, reasonable for this type of soil, Das, 2008). The volume would be about 16cm over the marsh area so about 17400 m^3, very low compared what we observed.

Besides, one could expect that the stage in the creek adapt more quickly to the sea level rise than the saltwater wedge does, so the effect on the water balance could be the contrary: an import when the sea level rises and an export when it decreases.

3.5.3 Scenario with intersection of the saltwater wedge

The idea of this scenario would be that the saltwater wedge from the sea would sometimes intersect the creek. Two different mechanisms could be induced depending on whether or not the saltwater wedge intersects the creek.

- *Infiltration of salt water when water table is thick*

The water of the tidal creek is frequently salted because of the import of seawater with tides. So if the water table is thick enough, we would have high density salt water above freshwater. Consequently, saltwater from the creek would infiltrate into the soil (Figure 34), and to compensate this loss the creek would import water.

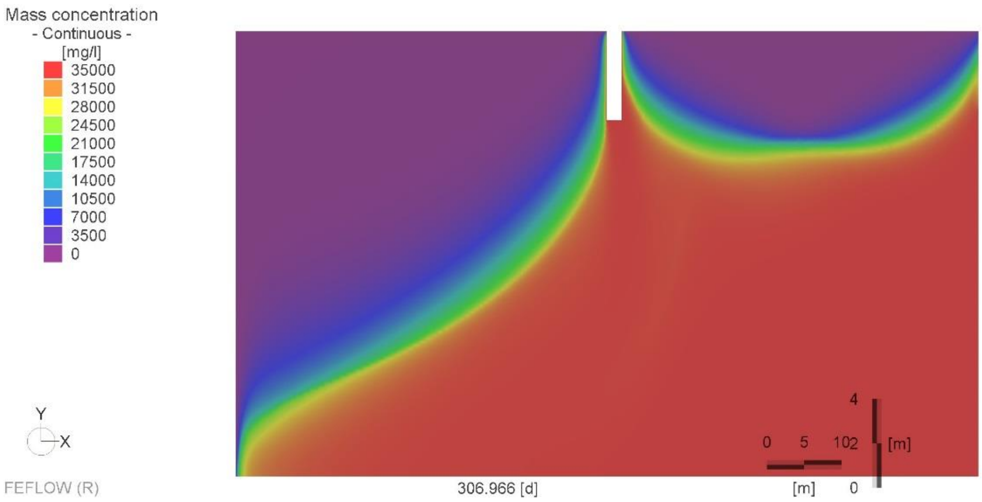


Figure 34 Simulation of a saltwater wedge and infiltration of saltwater from a creek in FEFlow. Boundary conditions on the creek and the right side: hydraulic head and concentration of salt (35 g/L). Flux of freshwater coming from the left boundary of the domain and the top.

- *Export of salt groundwater when the water table is thin*

If the water table is not thick enough, the saltwater-freshwater interface would intersect the tidal creek. When we simulated sea water intrusion into the aquifer, with a very simple 2D geometry for instance the Henry problem (Henry, 1959, Abarca et al, 2006), we see that a convection cell of saltwater is created under the saltwater-freshwater interface. If the tidal creek intersect the saltwater wedge

(Figure 35), one can imagine that the saltwater convection cell would create some exports from groundwater to the creek which would induce an export of water from the creek.

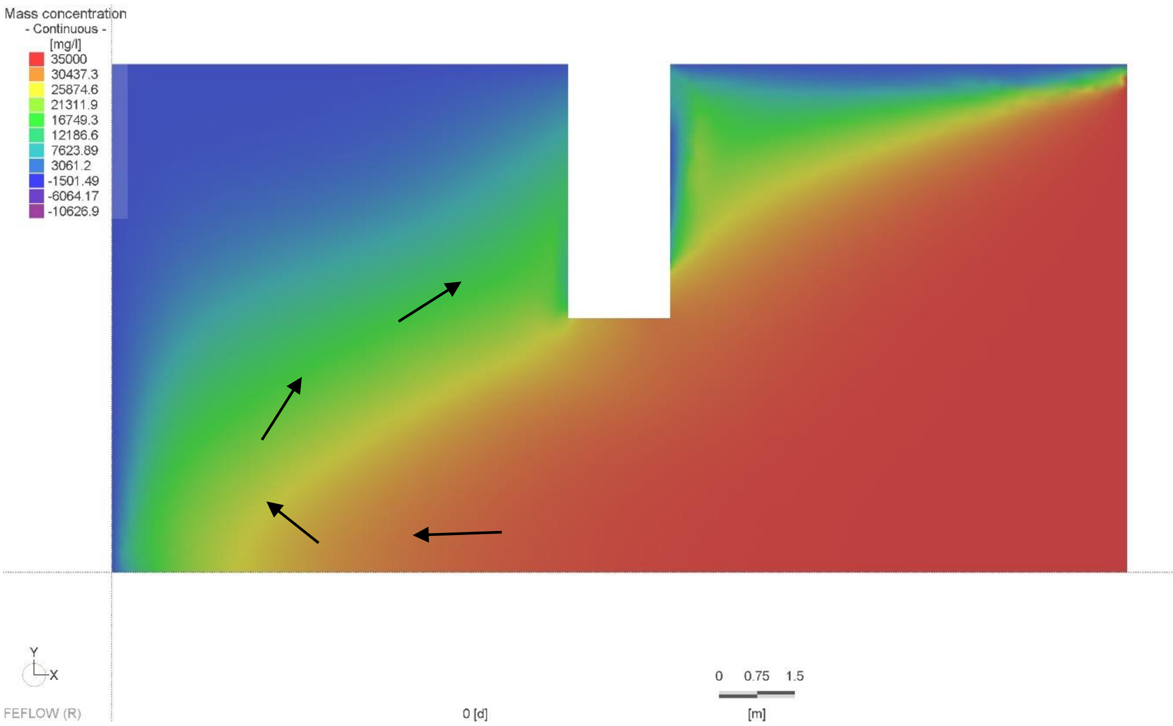


Figure 35 Tidal creek which intersects the freshwater-saltwater interface. Arrows represent the movement of saltwater.

These two mechanisms could explain some imports and exports. Moreover, the large import of water happens during the winter (when the water table is thick) and the export phase seems to happen during the summer, when water table is thin. Which is coherent with these processes.

However, the tidal creek is not very deep (about -0.49 m), so it is really unlikely that it intersects the saltwater wedge. One can try to estimate the position of the wedge knowing the hydraulic conductivity, the recharge of the water table and the distance to the sea. The higher the conductivity, the shallower the wedge is. But if we use a high estimate of conductivity (10^{-3} m/s), estimating the recharge and that the marsh is about 1.3 km from the estuary (Appendix 3), the wedge should be 93m under the sea level. So the saltwater wedge could not intersect the creek. Besides, the creek is surrounded by a deeper canal in the western and southern part so if there was a very shallow saltwater wedge from the sea it would probably be intersected by the canal around.

However, the configuration of the interface could be very different from the classic Ghyben-Herzberg interface because this area is very flat and frequently flooded. Besides, there is probably saltwater infiltration through the bottom of the creek and the canals and saltwater wedges coming from canals and ditches. However, we don't have any reliable data of the salinity in the marsh.

Some devices can measure the resistivity of the water up to 20m (the aquifer is probably about 20m deep) and the resistivity depends on the salinity of the water. These devices are easy to use and can be used from the surface (no need to dig wells). Measuring the resistivity thanks to this kind of device would allow us to know if there is a shallow saltwater wedge from the sea or from other canals, or other important salinity gradients that could induce convection cells.

3.5.4 Regional flows

As previously stated, we expect the water table to be high in the winter when rainfall amounts are significant and low in the summer when ET is high. In the winter, water would be drained by the creek and in the summer the water in the creek would infiltrate into the ground. However, one could imagine that this phenomenon could be delayed by regional flows. Indeed, the water in the water table comes from local rainfalls but also regional rainfalls, as groundwater escapes to the sea.

Marshes as other low-lands can often act as discharge areas for large aquifers, like the "playas" in arid zones and the Sebkhas in Arabic (Gutiérrez Elorza et al, 2005).

North Carolina Coastal plain is composed of several aquifers separated by confining units (Winner et al, 1989) : the Yorktown, Pungo, Castle Hayne, Beaufort, Peedee, Black Creek, Upper and Lower Cape Fear aquifers. These aquifers are made of an unconfined part, where rainfall water recharges the aquifer and then as the aquifers go deeper in the ground, they are trapped between two confining units. These aquifers discharge along the continent. However, there is no precise location for discharge in hydrogeological maps of North Carolina (Winner et al, 1989) and the studied salt marsh could be a discharge zone for an aquifer.

The groundwater discharge could induce an export from the creek. As the recharge of the aquifer depends on ET and rainfall in the recharge zone, one could expect to observe seasonal variations in the exports of the creek and a delay between the recharge and the discharge. The delay would not be the travel time through the aquifer, but it would be the time needed to transmit the pressure from the recharge zone to the discharge zone. One can estimate this time using the time needed to reach near-steady state in large aquifer. Rousseau-Gueutin (2013) estimated this time to

$$t = \frac{3S_u L_u}{T} * (L_c + \frac{L_u}{2})$$

Where T is the transmissivity, L_u the length of the unconfined part of the aquifer, L_c the length of the confined part and S_u the storativity of the unconfined aquifer.

We did not have enough data on the characteristics of the aquifers to estimate properly the delay that could appear after the recharge but this scenario should be further investigated with an estimation of the delay, and measurements of the hydraulic head at different depths in the marsh to determine if there are vertical hydraulic gradients due to a regional discharge.

Conclusion

After this study, the observations in the marsh are still very surprising and even more intriguing: the observed water balance is unexpected and there is no obvious explanation for these net seasonal imports or exports of flow. This study has shown that some scenarios are very unlikely or cannot explain the water balance and other scenarios would need to be investigated further with new data and models. We have shown that the water cannot be stored in the creek, that there is no obvious hydraulic gradients between the creek and the aquifer that could explain the imports and exports. Besides, a leak between the creek and other ditches is unlikely to explain the water balance because the volumes of water that would be involved are not significant enough. The conclusion is the same for scenarios implying saltwater wedges. However, our simulations were basic 2D simulations and did not take into account all the complexity of the marsh, and several scenarios might be combined to better explain the observed water balance. Consequently further measurements should be conducted to better understand the functioning of the marsh. First, measurements of the salinity in the marsh soil profile could be conducted. It would provide a better understanding of the groundwater flows and the density gradients that could appear in the marsh and create convection cells. Second, new water table elevation and water balance measurements should be conducted. The large imports and exports could be recurrent or very unique, but simultaneous water table elevation and water balance data could shed light on the global dynamic of the marsh and might answer questions we were not able to answer because of unreliable water table data. Third, the water flow measurements should be continued in the creek and if possible also in the canals in the vicinity of the creek. Were the same water balance in other canals to be observed, it would imply that the mechanism explaining the water balance would probably be regional. Were the result to be totally different, the water balance would correspond to a local phenomenon involving leaks between creeks and canals, or specific characteristics of the creek (soil type, topography, water inlets, etc…). Besides, the water stage in the canals around the creek would help determine if a leak due to a hydraulic head gradient would be realistic or not. Finally, the regional flows scenario seems to be the more likely candidate. If new water table data shows a recharge of the aquifer in the spring and summer, delayed compared to the rainfall (which was not the case in our data), the imports and exports may be explained by a delay in the recharge of the surface aquifer. If it is not the case, one could still imagine that there would be a delayed recharge involving no rise in the water table because the creek is surrounded by canals and ditches or because the recharge comes from confined aquifers that discharge along the coast. Hydraulic head data at different depths in the marsh would tell if there is a vertical hydraulic head gradient due to a discharge zone or other large-scale flows.

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Appendix 1: Reminder Hydrogeology: Hydraulic head and Darcy's law

This reminder is based on G. de Marsily, Quantitative hydrology, and Groundwater Hydrology for Engineers.

In hydrogeology, the concept of hydraulic head is commonly used, it is defined by:

$$h = z + \frac{p}{\rho g} + \frac{u^2}{2g}$$

Where z is the elevation, p the pressure, ρ the density, and g the standard gravity and u the velocity in the fluid.
As u is negligible in groundwater flows, $h \approx z + \frac{p}{\rho g}$

If there is a gradient of hydraulic head between two points, the water flows from the point of high hydraulic head to the point of low hydraulic head, and one can calculate the velocity of the water thanks to Darcy's law (empirical law).

Darcy's law:

$$v = K * \frac{\Delta h}{\Delta x}$$

Where v is Darcy's velocity of the water, K is is the hydraulic conductivity of the porous media, Δh the difference of hydraulic head between two points and Δx the distance between those two points.

Darcy's velocity does not represent the real velocity of the water, but the real velocity multiplied by the porosity of the soil.

Darcy's velocity is used to calculate the flow Q of water flowing through an area A:

$$Q = v * A$$

Appendix 2: Simulation of an unconfined aquifers with saturated conditions

In Feflow, one can choose to run a simulation in saturated conditions (the saturation of the soil is 100%) or unsaturated conditions (the saturation of the soil can vary between 0 to 100%). The saturated conditions are usually used to simulate an aquifer that is confined between two impervious layers and is always full of water. In this kind of aquifer, usually the volume of water can vary with the pressure but there is no air in the aquifer. On the contrary, in unsaturated aquifers, there can be air and the saturation of water can be below 100%. The aquifer that we want to simulate is an unconfined, unsaturated aquifer (as it is not full of water to the top). However, using the unsaturated conditions considerably increases the simulation time, because another type of equation (Richards' equations) are used to simulate the unsaturated zone (Feflow user manual, p.47).

In this study, a trick has been used to avoid to simulate the unsaturated zone. We used the saturated conditions but we artificially increased the storage coefficient of the soil on the top of the aquifer, so that it could simulate the storage of the water above the domain (Figure 36). The specific storage describes the change in volumetric water content in an aquifer induced per unit change in hydraulic head under saturated conditions. We want that a change in hydraulic head corresponds to the amount of water that would be added on the top of an unconfined aquifer.

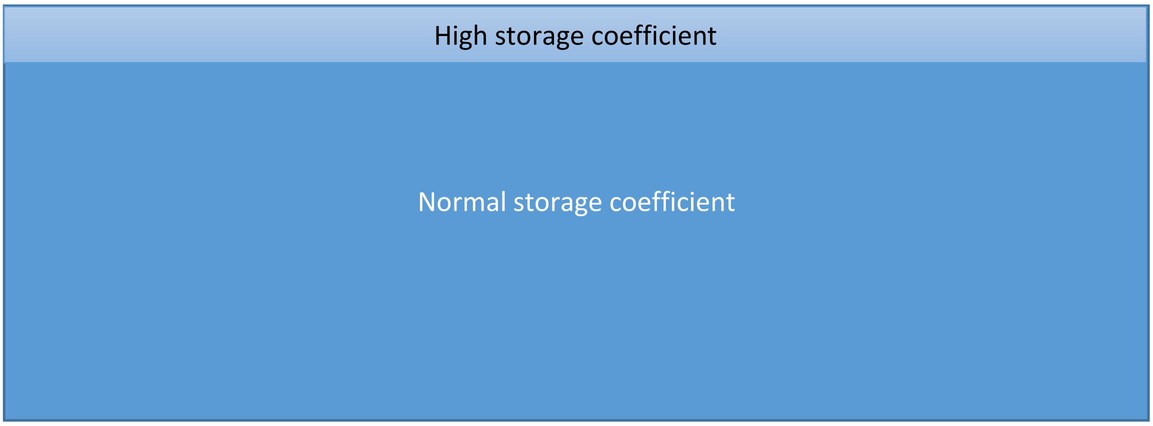

Figure 36 Domain of simulation : the top layer has a higher storage coefficient in order to represent the unsaturated zone

If the drainable porosity of the soil is S, and the specific storage is Ss, we want that if the hydraulic head increases by 1m (the stage of the unconfined water table increases by 1m), the change in volumetric water per surface unit corresponds to 1m*S m^3/m^2 (the volume of water that we would have to add to increase by 1m the stage of the unconfined water table). If e is the thickness of the top layer with a high storage coefficient that stores the water that is supposed to be above the domain in our simulation, we want: S= Ss * e.

However, before using this trick, one need to check if it would give reasonable results. We simulated a problem that has an analytical solution and compared Feflow's solution with the analytical solution.

We simulated a problem with a semi-infinite aquifer and a creek on the left side. The hydraulic head on the creek is set to 0m and at the beginning the hydraulic head on the aquifer is 1m, representing a sudden rainfall. An analytical solution exists for a confined aquifer (G. de Marsily, Quantitative hydrogeology, Groundwater Hydrology for engineers)

We first simulated the problem with a confined aquifer (20m x 500m) and compared the hydraulic head of Feflow's simulation and the analytical solution (Figure 37). The result is very satisfactory.

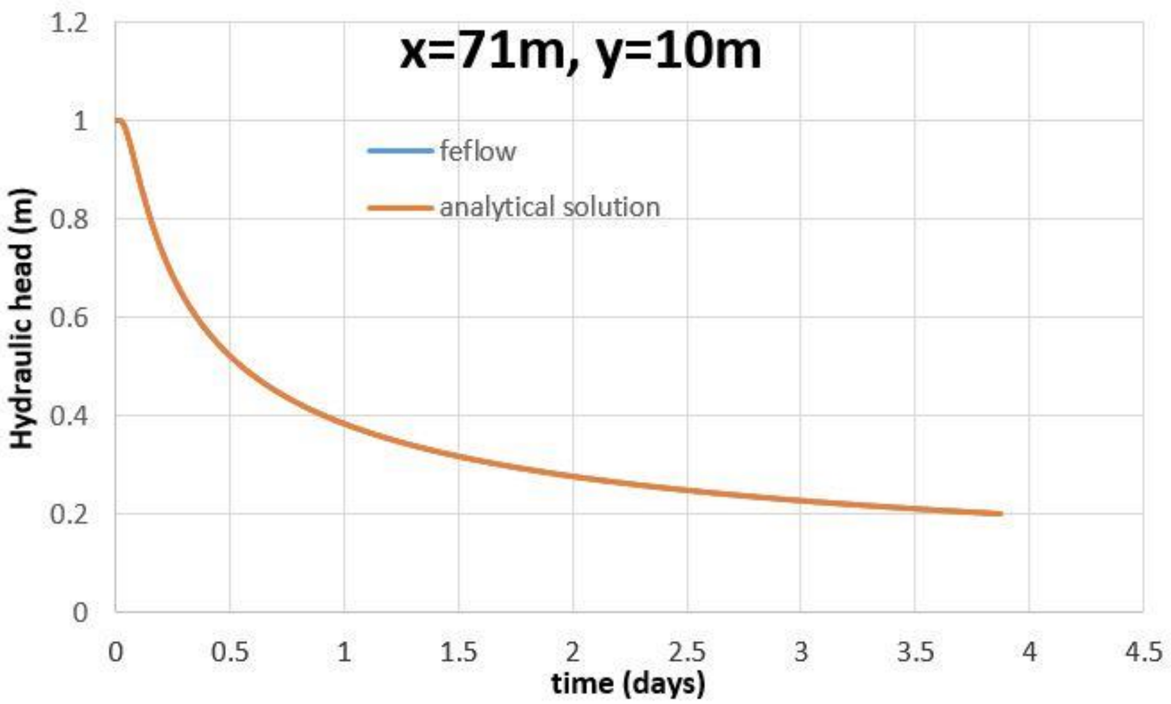

Figure 37 Result of a simulation of a confined aquifer with saturated conditions. Boundary conditions: no-flow except in x=0, h=0. Initial conditions h=1m. K=1m/d.

Then we simulated the same problem with the top layer with a higher storage coefficient. It is supposed to simulate an unsaturated aquifer, so there is no analytical solution for this case (Figure 38). But as all the water is stored in the top layer, at the beginning the aquifer loses water and the hydraulic head drops very quickly as if there was no water on the top (similar to the previous solution) and then it tends toward a solution with a higher storage coefficient because all the water on the top is released. We don't have anything to compare the result with. The solution does not seem to be perfect as the very quick drop probably does not happen in the real unsaturated solution but the result tends to a reasonable solution so we decided to use this trick for future simulation as unsaturated simulations were not possible because of the simulation time required.

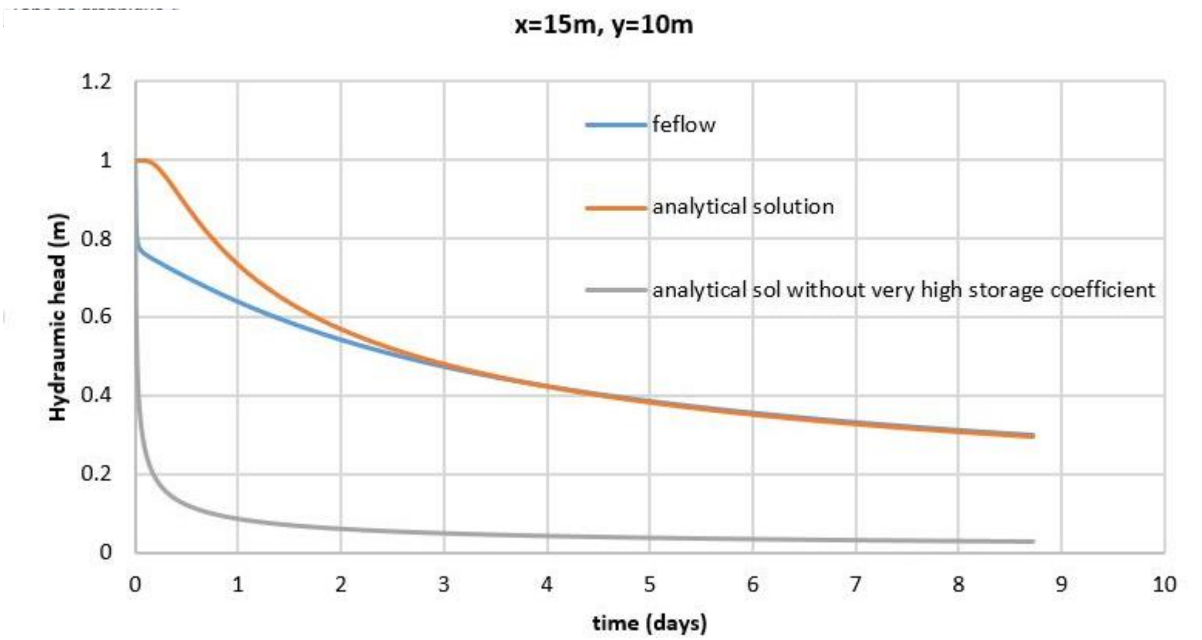

Figure 38 Result of a simulation of an unconfined aquifer using saturated conditions. Boundary conditions: no-flow except in x=0, h=0. Initial conditions h=1m. K=1m/d.

Then, instead of starting with 1m of hydraulic head in the aquifer, we start with 0m and we inject water, simulating the rainfall. The result is displayed on Figure 39. The result is very similar to the previous simulation, it confirms that the boundary condition with injection of water at the top of the aquifer works and represents what we want to simulate.

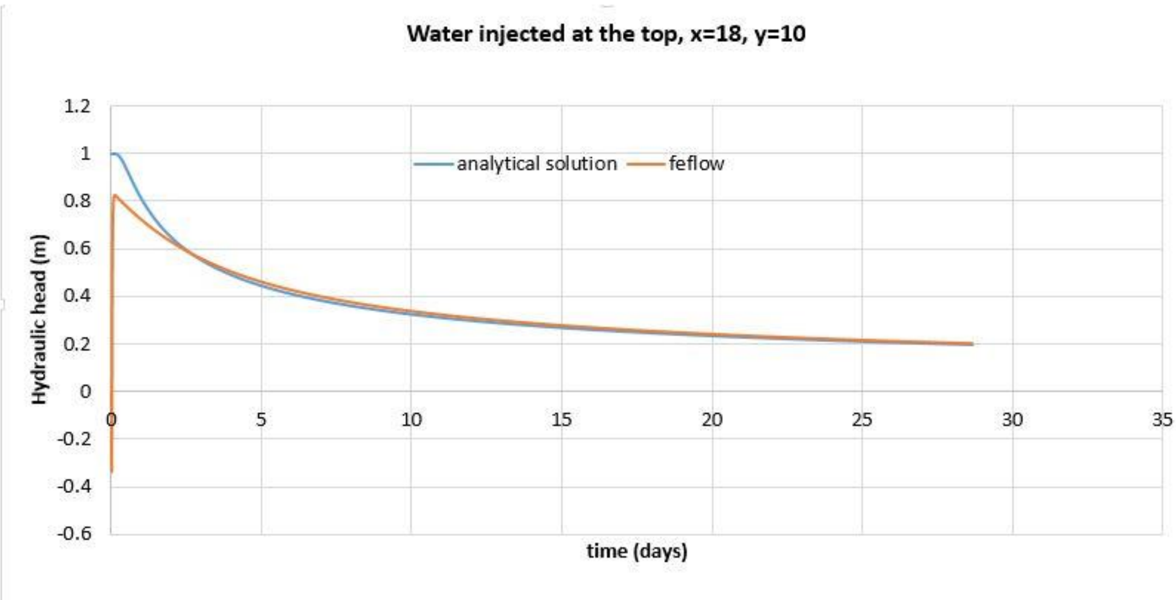

Figure 39 Result of a simulation of an unconfined aquifer using saturated conditions. Boundary conditions: no-flow except in x=0, h=0 and in y=20m, water was injected during the first time steps. Initial conditions h=0m. K=1m/d.

Appendix 3: What is the saltwater wedge?

This reminder is based on G. de Marsily, Groundwater Hydrology for Engineers.

Along the coast, the saltwater from the sea can infiltrate in the soil of the continent, in the freshwater aquifer. The aquifer is recharged with freshwater from the continent and the rainfalls.

As saltwater has a higher salinity than freshwater it also has a higher density. Consequently the saltwater goes under the freshwater. However, the aquifer is recharged with freshwater that escapes to the sea and pushes the saltwater wedge (Figure 40). The position of the saltwater wedge depends on the recharge of the aquifer, the difference of density between the freshwater and the saltwater and the hydraulic conductivity of the soil.

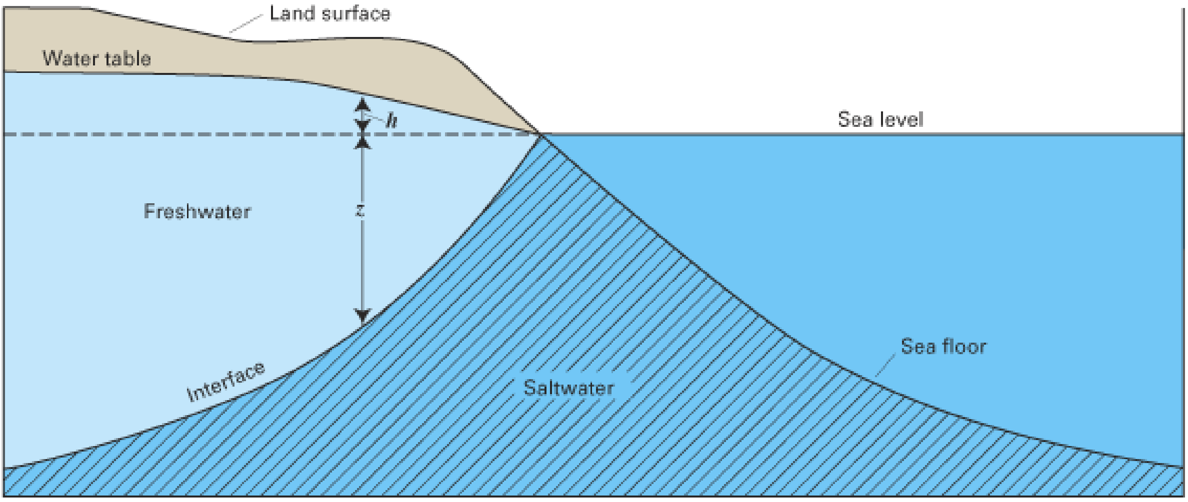

Figure 40 Saltwater intrusion in coastal aquifers

The Ghyben-Herzberg formula gives the position of the wedge depending on the elevation of the water table. For a common value of saltwater density : Z= 40*h, where Z is the distance between the position of the saltwater-freshwater interface and the sea level, and h the distance between the sea level and the top of the water table.

One can estimate the theoretical position of the saltwater wedge knowing the recharge, the density of saltwater and the hydraulic conductivity of the soil (Pryet, 2012):

$$z(x) = \sqrt{\frac{\alpha}{\alpha+1} * \left(-\frac{r}{K}x^2 + 2\frac{rL}{K}x\right)}$$

Where K is the hydraulic conductivity, α is the buoyancy ratio, $\alpha = \frac{\rho_s - \rho_f}{\rho_f}$ (ρ_f is the density of freshwater, ρ_s the density of seawater), r is the recharge from rainfalls (volume per surface unit), x the distance from the sea, L the length of the land that recharges the aquifer.