SALINISATION OF THE NORTHERN COASTEL AREA OF THE NETHERLANDS DUE TO LAND SUBSIDENCE AND SEA LEVEL RISE

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ABSTRACT

Exfiltration of brackish to saline groundwater takes place at the northern coastal area of the Netherlands (Northwest Friesland). This situation patterns for the coastal part of the Netherlands that is situated under the sea level. Land subsidence in the study area due to salt exploitation and future sea level rise is increasing the exfiltration of brackish groundwater causing serious salinisation problems for agriculture. Surface water will not be suitable for irrigation anymore and salt damage to crops can occur when salt groundwater reaches the root zone.
Salinisation problems can be controlled by means of fine tuning of surface water management. The most sustainable water management plan of this coastal area was composed with the help of numerical models and field measurements. That implies that surface water levels have to be increased at most parts of the area to limit the salinisation of surface water and root zone. Other measures such as increasing the distance between ditches and drain tubes also appear to be effective to increase fresh rainwater lenses in order to avoid salt damage to crops.

Key words: salinisation of groundwater and surface water, land subsidence, sea level rise, modeling, brackish-fresh groundwater interface

INTRODUCTION

At the northern coastal area of the Netherlands (Northwest Friesland) salt is exploitated at a depth of 2000 meters causing a land subsidence up to 40 centimeters. To compensate the relative rise of the groundwater table, the local Water Board Wetterskip Fryslan lowered the surface water level equal to this land subsidence. As a consequence, deep brackish to saline groundwater cones up towards the surface and salinisation of the shallow groundwater and surface water takes place. The water board decided the make alternative plans in order to reduce the salinisation of the shallow water system. Salinisation of the root zone and surface water in this area is a major problem for agriculture. Surface water will not be suitable for irrigation anymore and salt damage to crops can occur when salt groundwater reaches the root zone.
TNO was asked to calculate the effects of different scenarios on the salinisation of the groundwater and surface water system. The model code MOCDENS3D was used and field measurements of the brackish-fresh groundwater interface were executed. In this paper the method, results and conclusions of this investigation are described.

DESCRIPTION OF INVESTIGATION AREA

The study area is located in the province of Friesland (The Netherlands) at the northern coast of the Waddenzee (figure 1). During the Holocene, before the embankment and isolation from the sea, this area was an estuary where marine clay and fine sand were deposited resulting in a cover layer of at least 8 meter to 25 meter. Below this cover layer a sequence of aquifers and semi-permeable layers of clastic sediments is found. Groundwater on a regional scale is flowing through these layers. The hydraulic head in the first aquifer at most of the area is higher than the surface water level and phreatic groundwater level in the cover layer. Therefore groundwater from the first and second aquifer is exfiltrating in the polders where surface water levels of –1.0 to –2.0 meters below sea level are maintained.
This exfiltrating groundwater is brackish to salt. It has its origin from transgressions during the Holocene when seawater was infiltrated to great depth. Nowadays intrusion of seawater is taking place but at slower rates. However, the intrusion will be accelerated due to future sea level rise.
All available measurements of the chloride concentration of groundwater were inter- and extrapolated to produce a 3-dimensional chloride map. This was needed as initial condition for the density dependent groundwater flow simulations (TNO, 2005). Figure 2 shows the chloride concentration of a depth of 25 meter below sea level. At this depth the concentration varies from 2500 mg/l inland to 6000 mg/l at the coastal zone.

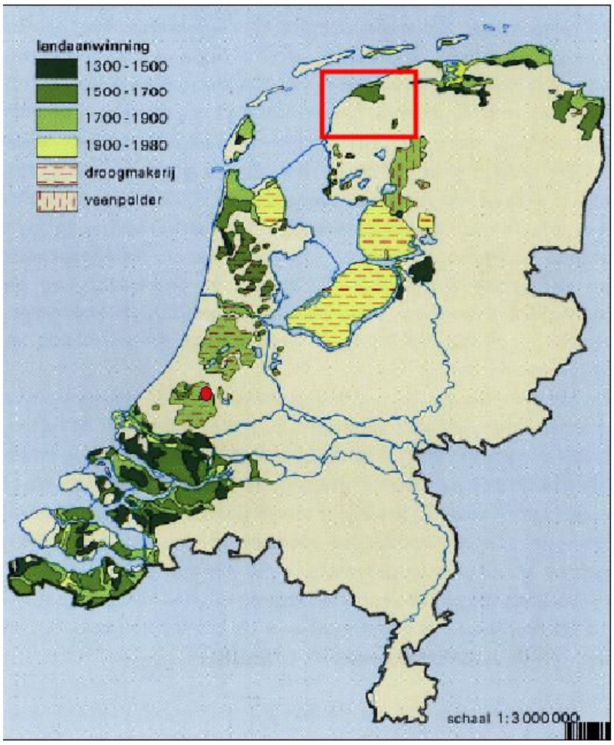

FIGURE 1. Location of the study area and the reclamation period of polders in the Netherlands

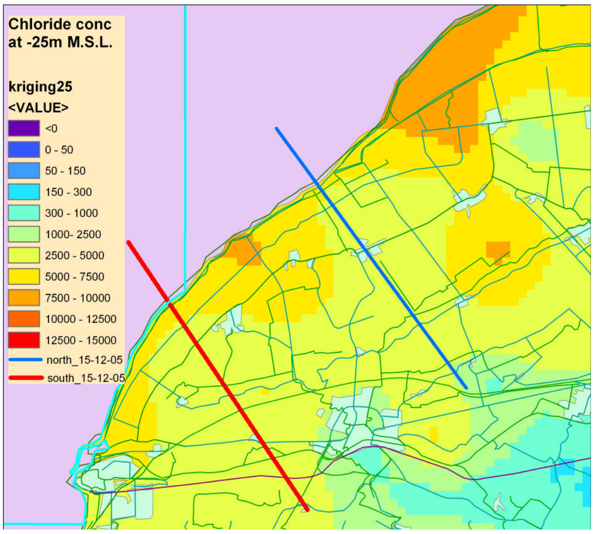

FIGURE 2. Chloride concentration of groundwater at a depth of 25 meters below sea level

METHOD

The model code MOCDENS3D (Oude Essink, 2001, 2004) was used to simulate density dependent groundwater flow and coupled salt transport at two different scales. For two transects perpendicular to the coastline the regional groundwater system is modeled. Various local scale models are set up to simulate the dynamics of the fresh-brackish groundwater interface.

The regional model is used to calculate the effect of surface water level changes, sea level rise and land subsidence on groundwater level, exfiltration rates, salinisation of groundwater and surface water system at a regional scale.

The local model is used to calculate the effects of exfiltration rate, surface water level, drainage characteristics on the dynamics of the fresh-brackish groundwater interface.

Description of MOCDENS3D

To quantify changes in this coastal groundwater flow regime, the processes transient variable-density groundwater flow and coupled solute transport in three dimensions are modeled. The modular variable-density groundwater flow and solute transport code MOCDENS3D has been used. It is based on MODFLOW (MCDonald & Harbaugh, 1988) and MOC3D (Konikow et al., 1996), which has been adapted for density differences. MODFLOW (U.S. Geological Survey public domain) is the most widely used computer code for groundwater flow in porous media. Advective and hydrodynamic dispersive solute transport processes through porous media are modeled by a particle tracking technique in combination with the finite difference method, respectively. As chloride is the major conservative negative ion in Dutch coastal groundwater, the discussion about salinisation is focused on that predominant solute.

Regional Transect Modeling

For two transects perpendicular to the coastline the following geohydrological characteristics were put into the model.

- Length of transect = 10km, thickness of groundwater system = 300m
- Geohydrological schematization from surface to depth (k=hor. permeability, d=thickness of layer)
  - Cover layer of peat and clay; k=0.3m/d; d=8m (transect 1) en d=21m (transect 2)
  - First aquifer; k=2m/d; d=6m (transect 1) en d=4m (transect 2)
  - Semi permeable layer; k=0.06m/d; d=10m (transect 1) en d=20m (transect 2)
  - Second aquifer =25m/d; d=6 (transect 1) en d=8m (transect 2)
  - Semi permeable layer =0.1m/d; d=0m (transect 1) en d=2m (transect 2)
  - Third aquifer =26m/d; d=175m (transect 1) en d=150m (transect 2)
  - Fourth aquifer =20m/d; d=95m (transect 1) en d=95m (transect 2)
  - Anisotropy is 1/3
- Salt transport
  - Effective porosity = 30%
  - Longitudinal dispersivity: α_L=1m; α_{TH}=α_{TV}=transversal disp.=1/10*α_L
  - Molecular diffusion: $D_{mol}=8.64*10^{-5}$ m^2/d.
- Model discretisation:
  - 200 columns, cell size Δx=50m
  - 100 layer, upper 50 layers d= Δz=1m, lower 50 layers d= Δz=5m
  - The flow time step to recalculate flow equation is set to 1 month
  - simulated period is 30 years
  - 9 particles each model cell to calculate advective transport
  - hydrostatic pressure at vertical boundaries
  - impermeable base at -300m below sea level

Local Model

For two different soil types the following geohydrological characteristics were put into the model:

- Length of transect = 170m, thickness of groundwater system = 10m
- Geohydrological schematization from surface to depth (k=hor. permeability, d=thickness of layer)
  - Soil type silty clay:
    - layer 1=0.05m/d, thickness=1.4m
    - layer 2=0.2m/d, thickness =1.6m
    - layer 3=0.5m/d, thickness =7.0m
  - Soil type clay:
    - layer 1=0.05m/d, thickness =1.4m
    - layer 2=0.5m/d, thickness =8.6m
  - Anisotropy is 1/3
- Salt transport
  - Effective porosity = 30%
  - Longitudinal dispersivity: α_L=1m; α_{TH}=α_{TV}=transversal disp.=1/10*α_L
  - Molecular diffusion: $D_{mol}=8.64*10^{-5}$ m^2/d.
- Model discretisation:
  - 170 columns, cell size Δx=1m
  - 50 layers, thickness Δz=0.2m

- The flow time step to recalculate flow equation is set to 10 days
- 9 particles each model cell to calculate advective transport
- Hydrostatic pressure at vertical boundaries
- Fixed head at lower model boundary, 10m below sea level (varies with case)

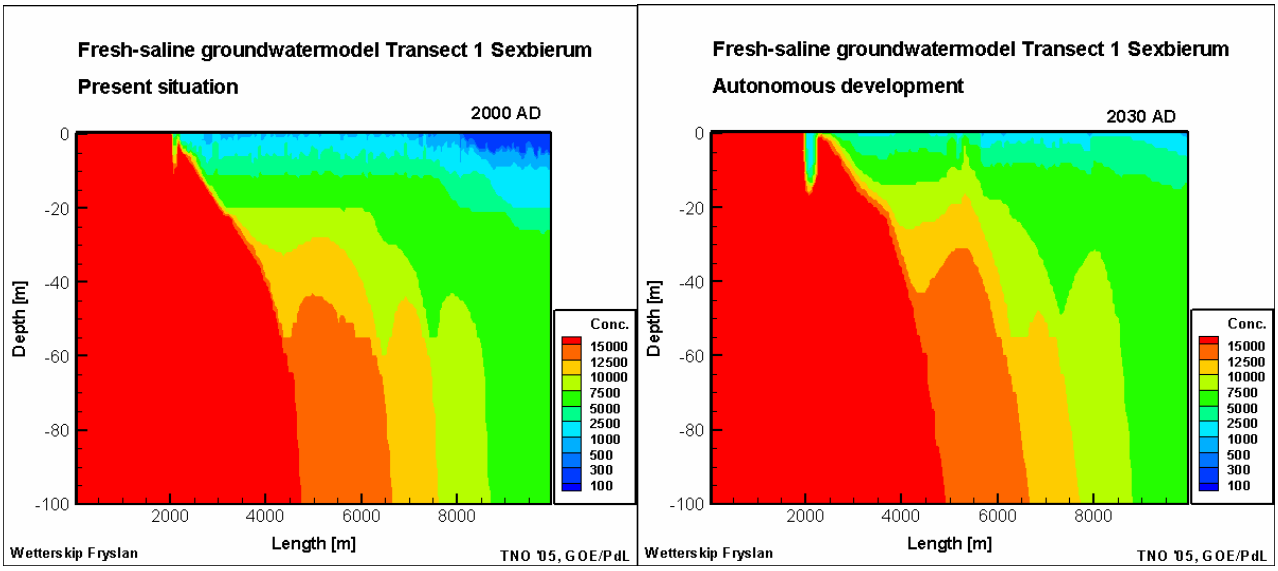

FIGURE 3. Calculated chloride concentration of groundwater at present situation and after 30 years autonomous situation.

RESULTS

Regional Model

The results of transect 1 will be described. At the present situation (2000 AD) the groundwater becomes more saline with depth and the chloride concentration of the groundwater decreases with distance to the coast of the Waddenzee (figure 3). Saline groundwater reaches the surface at ditches where exfiltration rates are high due to low surface water levels. Even higher exfiltration rates are found at locations where the hydraulic resistance for vertical flow is reduced because of the present of sandy sediments in the cover layer (creek deposits). Due to land subsidence caused by salt exploitation, the surface water level is lowered to guarantee sufficient dry conditions for agricultural activities. In the autonomous situation it is estimated that the sea level will rise 18 centimeters for the next 30 years. Exfiltration rates of deeper and more saline groundwater increase as a result of higher hydraulic heads. The model results show that the saline front is moving inland and to the surface (figure 3). At polders where water managers maintain low surface water levels this process is even faster. In the autonomous situation after a period of 30 years salinisation of groundwater and surface water will take place at higher magnitude and in a larger area. The effect of sea level rise reaches to a distance of 8 kilometers to the coast.

TABLE 1. Model results of different scenarios. For the present situation the current values are given, for the different scenarios the difference relative to the present scenario is given. The values are averaged for the whole transect after 30 years.

	Present situation	Sea level rise 18cm next 30 years	Sea level rise and land subsidence, autonomous situation	Scenario 1	Scenario 2
	Current value	Effect	Effect	Effect	Effect
Surface water level	-1.1m below sea level	+0m	-0.30m	+0.10m	+0.26m
Exfiltration rate	0.12mm/d	+0.03mm/d	+0.08mm/d	-0.01mm/d	-0.05mm/d
Cl-conc of shallow groundwater	1700mg/l	+320mg/l	+970mg/l	-232mg/l	-492mg/l
Chloride loads to surface water	600kg/ha/yr	+300kg/ha/yr	+1070kg/ha/yr	+1614kg/ha/yr	-316kg/ha/yr

To compensate wetting effects of land subsidence due to salt exploitation and to reduce salinisation by land subsidence and sea level rise, the water board is redesigning the surface water system into a more sustainable water system. Drainage patterns and surface water levels have to be changed to achieve this. The regional model is used to simulate different water management scenarios. The following two scenarios will be discussed:

- Scenario 1: increase of the surface water level in most of the area, except for a polder called Roptavaart where surface water levels are lowered dramatically in order to attract saline groundwater so the surrounded polders receive less saline groundwater (surface water level Polder Roptavaart is –250 centimeter below sea level).
- Scenario 2: same as scenario 1, except for Polder Roptavaart where surface water levels are at higher elevation in order to reduce salinisation of ground water and surface water in this area (surface water level Polder Roptavaart is –110 centimeter below sea level). In this situation hydrological conditions are no longer suitable for agricultural activities in the Polder Roptavaart.

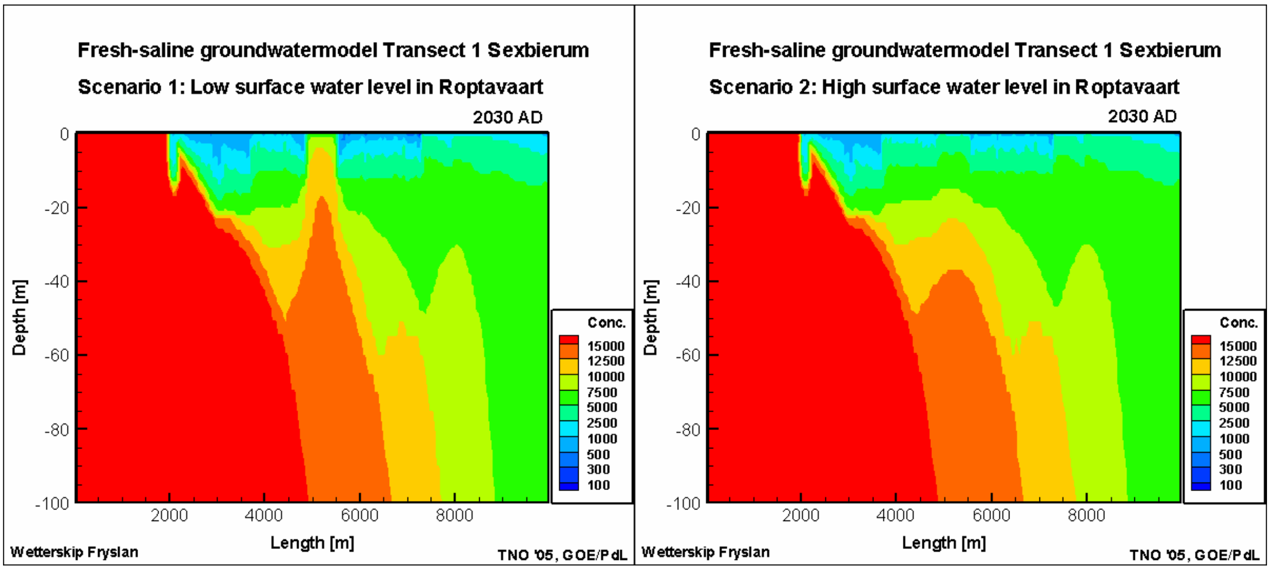

FIGURE 4. Calculated chloride concentration of groundwater scenario 1 and 2 after 30 years

Figure 4 shows the results of these two scenarios after a period of 30 years. Extreme upconing of saline groundwater in Polder Roptavaart is clearly visible for scenario 1. However, the reduction of salinisation in the surrounding of Polder Roptavaart is small as can also be seen in figure 5. The reduction of exfiltration due to extreme low surface water levels in Polder Roptavaart reach only 200-300 meter.

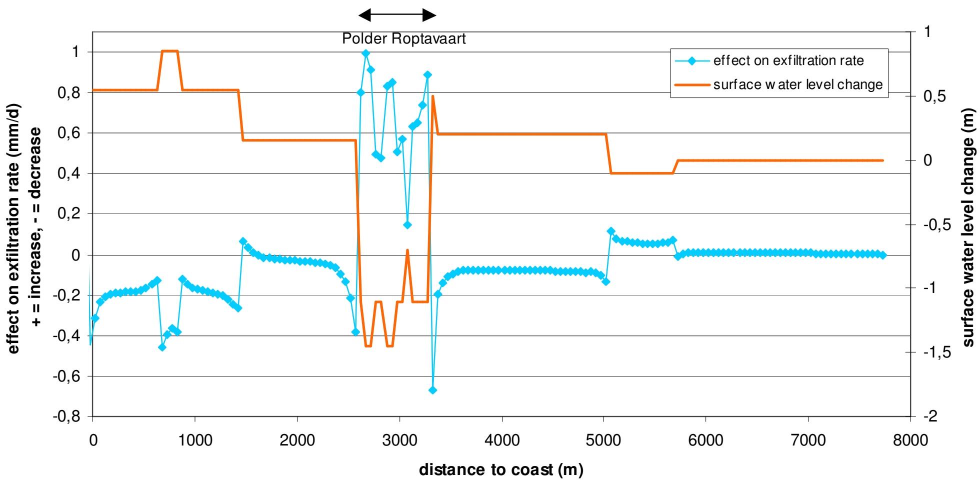

FIGURE 5. Calculated effect of surface water level changes on the exfiltration rate presented in transect 1 perpendicular at the coast (scenario 1)

As a consequence of sea level rise the salinisation of the surface will increase from 600 to 900 kg/ha/yr (table 1). Together with the land subsidence and accompanying surface water level reduction the salinisation process will increase with 1070 kg/ha/yr to an average chloride load of 1670 kg/ha/yr. Scenario 2 will reduce the chloride loads to the surface water while scenario 1 leads to the highest average salinisation. The extreme low surface water levels at Polder Roptavaart cause these high average chloride loads. However, the advantage is that the highest chloride loads are concentrated at one polder.

Local Model

In these brackish groundwater areas near the coast agricultural is possible because of the existence of fresh rainwater lenses. The yearly rainfall surplus in the Netherlands is on average 300 mm/y. In exfiltration areas this amount will be finally discharged to the surface water system. However, the rainwater is temporally stored in the soil, forming fresh rainwater lenses on top of the brackish groundwater (see figure 6). The lens tends to be thicker in winter when more precipitation and less evapotranspiration is taking place than in summer. The exfiltration rate, drainage density, drainage level, hydraulic conductivity of cover layer, meteorological conditions control the dynamics of the fresh rainwater lens.

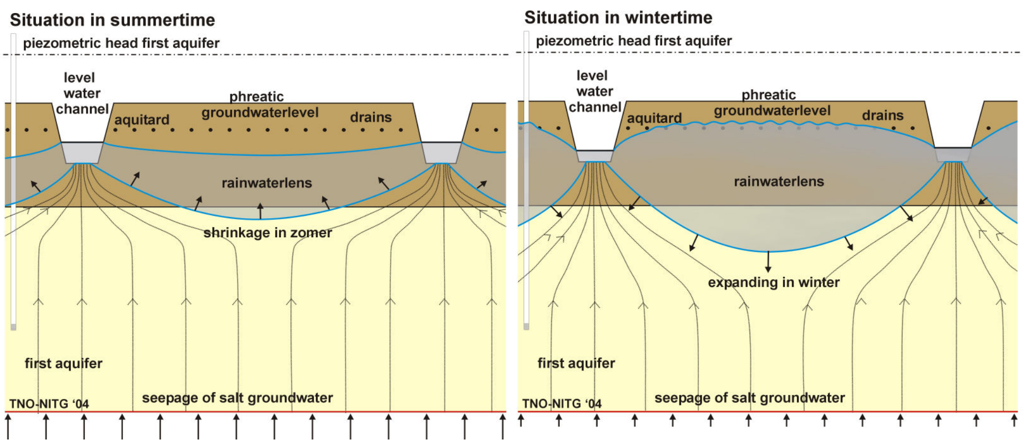

FIGURE 6. The dynamics of the fresh rainwater lens during summer and winter

Measurements in the study area show a large spatial variation of the thickness of the fresh rainwater lens. Two examples of measurements of the interface between brackish groundwater and rainwater are shown in figure 7. The electrical conductivity of the groundwater was measured at depth increments of 10cm. The two profiles are situated only 200 meters from each other while the thickness of the fresh rainwater lens differs much. At parcel 1 the lens varies from 100 cm to 0 cm. At the lowest point in the parcel only brackish groundwater is found. At parcel 2 no brackish groundwater was found while the measurements reach a depth of 3 meters. Both the land surface and surface water level at parcel 2 is 0.5 meter higher than parcel 1. At parcel 2 probably no exfiltration but infiltration of rainwater takes place while the measurements show that brackish groundwater is exfiltrating at the center of the ditch bottom. At the sides of the ditch fresh rain water is exfiltrating, drained from the parcel.

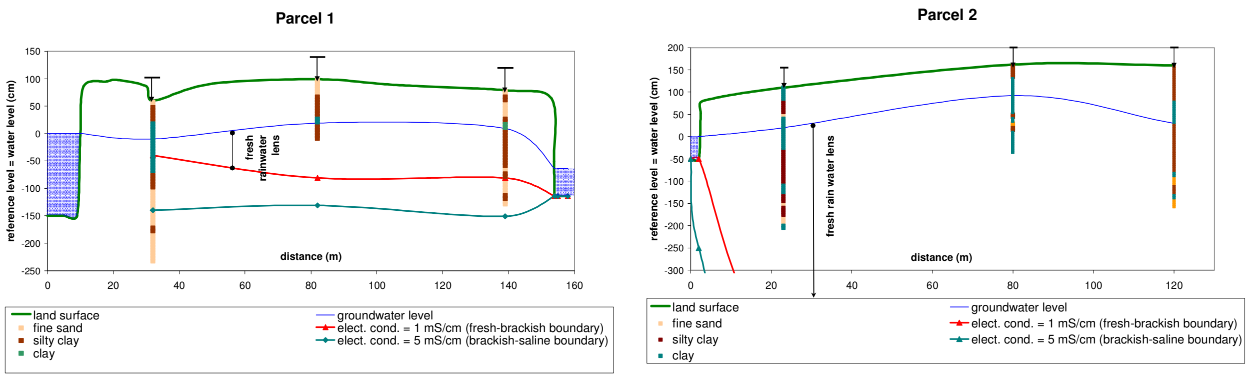

FIGURE 7. Measurements of the interface between fresh rainwater and brackish groundwater (august20th, 2005)

For different cases the dynamics of the fresh rainwater lens was modeled with MOCDENS3D. The calculated temporal variation of the thickness of the lens is shown in figure 8. The effect of the meteorological conditions is clear. The thickness varies from 1.5-3 meter in wet years to 0.5-1.5 meter in dry years.

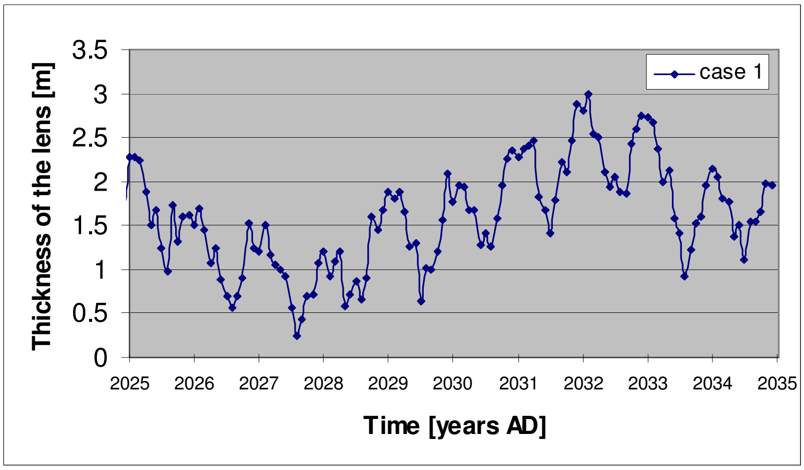

FIGURE 8. Calculated temporal variation of thickness of fresh rainwater lens

Saline groundwater exfiltrates at the ditches, while in the parcel the brackish groundwater is pushed down by the infiltrating rainwater. The effect of drain tubes can clearly be seen in figure 9 where brackish groundwater is attracted. Higher drainage density (reducing distance between ditches) leads to thinner rainwater lenses as can be seen in figure 9c.

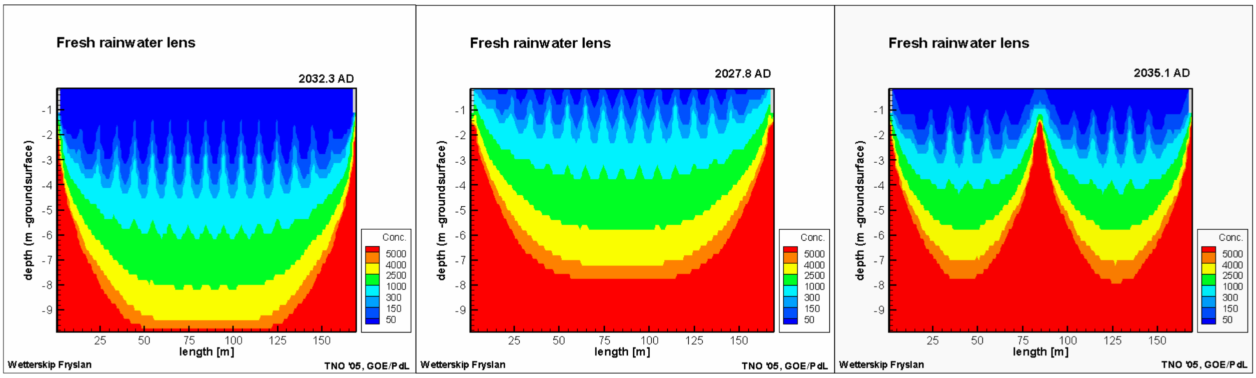

FIGURE 9. Calculated chloride concentration of groundwater between two ditches at two different periods (left: winter, middle: summer). The right picture shows the winter situation in case of reduced distance between the ditches.

For 24 cases per soil type the dynamics of the fresh rainwater lens were simulated and the results are summarized in table 2. The (initial) exfiltration rate has major impact on the thickness of the lens. At average values of 0.3 mm/d the lens has an average thickness of 1.60 m. Reducing this values to 0.1 mm/d leads to an enormous increase of the thickness to average values of 5.35 m while increasing the exfiltration rate to 0.5 mm/d the lens is disappearing in the summer and has average values of 0.13m.

Water management can control the thickness of the lens as can be seen in table 2. Increasing the surface water level with 0.5m (cases 7-9) will increase the lens significantly because the hydraulic head difference is increased and therefore the exfiltration rate. Exfiltration of brackish groundwater in the ditches (case 13) will also be reduced by this measure. Reducing the distance between ditches will reduce the fresh rainwater lens from 1.60m to 1.21m in the 0.3 mm/d exfiltration rate case. More rainwater will be drained and the average groundwater level is lowered causing higher exfiltration rates.

TABLE 2. Calculated thickness of fresh rainwater lens and chloride concentration for different cases for one soil type

Case	Exfil-tration rate	Surface water level change	Drainage level change and distance between drain tubes	Distance between ditches	Drainage resistance	Initial chloride concentration of groundwater	Thickness of fresh rainwater lens (m)					Chloride concentration of shallow groundwater mg/l		Chloride concentration of exfiltrated groundwater mg/l	
	mm/d	m	m	m	d	mg/l	average	winter	summer	max	min	-1.1m	-2.7m	-1.1m	-2.7m
1	0.3	0	0 + 10m	170	5	7500	1.60	1.86	1.35	3.00	0.24	3497	7483	3684	7480
4	0.3	-0.5	0 + 10m	170	5	7500	1.21	1.45	0.98	2.57	0.08	5779	7500	5290	7500
7	0.3	+0.5	+0.5m + 10m	170	5	7500	6.53	6.81	6.24	8.21	5.09	500	500	500	500
10	0.3	0	+0.5m + 6m	170	5	7500	5.60	5.89	5.32	7.44	3.89	2048	7293	2256	7305
13	0.3	0	0 + 10m	85	5	7500	1.21	1.44	0.97	2.52	0.07	3709	7485	3852	7485
19	0.3	0	0 + 10m	170	5	5000	1.50	1.75	1.25	2.84	0.24	3108	4999	3151	4999
20	0.3	0	0 + 10m	170	5	4000	1.46	1.71	1.21	2.83	0.20	2659	4000	2704	4000
16	0.3	0	0 + 10m	170	10	7500	2.61	2.87	2.34	4.11	1.01	3102	7460	3287	7450
17	0.3	0	0 + 10m	170	1	7500	0.63	0.83	0.42	1.85	0.00	4090	7496	4138	7496
18	0.3	0	0 + 10m	170	5	7500	6.64	6.91	6.36	8.42	4.90	469	434	467	456
2	0.1	0	0 + 10m	170	5	7500	5.35	5.62	5.08	7.26	3.57	673	1686	680	1507
5	0.1	-0.5	0 + 10m	170	5	7500	4.07	4.35	3.80	5.86	2.48	4676	7500	3822	7500
8	0.1	+0.5	+0.5m + 10m	170	5	7500	6.25	6.53	5.98	7.87	4.80	500	500	500	500
11	0.1	0	+0.5m + 6m	170	5	7500	6.12	6.40	5.85	7.95	4.42	613	1519	628	1403
14	0.1	0	0 + 10m	85	5	7500	4.52	4.77	4.26	6.17	2.88	686	1676	695	1508
21	0.1	0	0 + 10m	170	5	5000	5.35	5.62	5.08	7.24	3.58	686	1781	693	1601
23	0.1	0	0 + 10m	170	5	4000	5.37	5.64	5.10	7.28	3.61	698	1834	705	1640
3	0.5	0	0 + 10m	170	5	7500	0.13	0.22	0.05	1.10	0.00	5598	7500	5625	7500
6	0.5	-0.5	0 + 10m	170	5	7500	0.12	0.19	0.04	1.02	0.00	6714	7500	6615	7500
9	0.5	+0.5	+0.5m + 10m	170	5	7500	6.92	7.20	6.64	8.40	5.39	495	499	495	498
12	0.5	0	+0.5m + 6m	170	5	7500	5.25	5.53	4.96	7.02	3.55	3415	7499	3497	7499
15	0.5	0	0 + 10m	85	5	7500	0.10	0.17	0.03	0.94	0.00	5484	7500	5539	7500
22	0.5	0	0 + 10m	170	5	5000	0.12	0.21	0.04	1.08	0.00	4167	5000	4135	5000
24	0.5	0	0 + 10m	170	5	4000	0.13	0.21	0.04	1.10	0.00	3466	4000	3437	4000

CONCLUSIONS

Salinisation of the surface water and the root zone is taking place due to exfiltration of brackish groundwater. Sea level rise and land subsidence will accelerate this process significantly. Model results showed that within a period of 30 years the chloride loads to the surface water will be almost three times the present loads and fresh rainwater lenses will reduce in size increasing salt damage to crops.

Salinisation of the shallow water system can be controlled by means of surface water management and so the water board decided the make alternative plans. The most sustainable water management plan of this coastal area was composed with the help of numerical models and field measurements. That implies that surface water levels have to be increased at most parts of the area to limit the salinisation of surface water and root zone. Other measures such as increasing the distance between ditches and drain tubes also appear to be effective to increase fresh rainwater lenses in order to avoid salt damage to crops.

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