Adapting fresh water supply and buffering capacity of the coupled groundwater- surface water system

Work package leader: dr. ir. G.H.P. (Gualbert) Oude Essink

Content

1 Description work package

1.1 Problem definition, aim and central research questions

Surface water quality in Dutch coastal low-lying regions suffers from the combined adverse effects of summer droughts, strong saline groundwater seepage and nutrient fluxes. Ongoing climate change and sea level rise are likely to aggravate these effects and call for adaptation of the fresh water supply - if agriculture and good water quality are to be sustained in these regions (Oude Essink et al., 2010).

Conventional strategies in the Netherlands rely on the intake of fresh surface water from the rivers Rhine and Meuse. This water is used to replenish regional surface water lost to irrigation, evaporation and infiltration to the groundwater system. Large amounts of intake water are used to dilute surface waters and to mitigate the effects of saline groundwater seepage. These conventional strategies may not be robust, as river discharges become more erratic, salt water wedge from the sea intrudes further upstream rivers, water demand intensifies in drier growing seasons and saline groundwater seepage in low-lying areas with controlled water levels increases.

Uncertainty in the spatiotemporal dynamics in the interrelated fresh-saline groundwater and surface water systems on local to regional scale hampers the quantitative evaluation of possible alternative adaptation strategies (Kwadijk et al., 2008). Discharge water rates and the salinity of the discharged water can be extremely variable at a local scale, which makes an accurate quantification very difficult. Yet these processes strongly influence the salinity of surface waters at the scale of water management units like polders (a polder is an area which is protected from water outside the area and which has a controlled water level). The dynamical behaviour of fresh water lenses – vital to sustain agriculture in areas prone to saline groundwater seepage – is highly dependent on spatially variable geological factors and their reaction to climate change is still poorly understood.This work package is focussed on the question: a. how the spatiotemporal patterns in the fresh water availability in ground- and surface water in coastal low-lying regions will change due to climate change and b. what adaptation strategies can be implemented to sustain water-dependent functions in the future. The two PhD-projects in this work package aim at answering these questions:

- Project 2.1 (*Development of a quantitative framework to optimize adaptation strategies to droughts and salinisation in groundwater – surface water systems under climate change*) focuses on the coupled groundwater – surface water system on the local to regional scale. This project aims at understanding the exchanges between fresh and saline groundwater and surface water in dry periods, to understand the controls on spatiotemporal dynamics in the surface water quality. This understanding is paramount to quantitatively evaluate possible adaptation strategies.

- Project 2.2 (*Increasing the robustness and flexibility of fresh water lenses in saline seepage regions under climate stress*) focuses on the future vulnerability of fresh water lenses at different levels, viz. small (lenses in agricultural parcels), medium (lenses in fossil sandy creeks) to large-scale (lenses in dune areas). These lenses as a part of the groundwater system are important in the aim to minimize the reliance of external sources of fresh water under saline and drought conditions. This project starts to establish the reaction of these fresh water systems to climate change and adaptation strategies, to establish key factors, and to extrapolate results to other regions. The research starts with in the Zuidwestelijke Delta and then transferring the results to the Provinces of Noord-Holland and Friesland and the Water Board of Rijnland, and finally possibly to areas outside The Netherlands.

Reference:

Kwadijk J.C.J., A, Jeuken, and Waveren, H. (2008), Climate proofing The Netherlands Water land. Exploratoryinvestigation of tipping points in management and policy of the major water system (in Dutch), Deltares T2447.

Oude Essink, G.H.P., Baaren, E.S., van, De Louw, P.G.B., Effects of climate change on coastal groundwatersystems: a modeling study in the Netherlands, Water Resour. Res. (submitted 2009).

1.2 Interdisciplinarity and coherence between the projects

A number of research disciplines will be combined in the defined projects. Project 2.1 focuses on groundwater hydrology as well as surface water hydrology, and on water quantity as well as water quality. Project 2.2 uses a combination of groundwater hydrology, vadose zone hydrology, soil science and agricultural science. Innovative measuring techniques will be used in both projects to quantify groundwater and surface water fluxes and associated solutes.

The projects in WP-2 are closely interlinked, one focusing on the groundwater system beneath an agricultural parcel, the other on the connection of this system to the surface water system. The two projects together cover the entire groundwater – surface water system in relation to salinisation and droughts. The projects will work together in evaluating possible adaptation strategies to ensure sufficient fresh water in the future on both the local and regional scale. The projects will use results from other work packages and hence other research disciplines. WP-1 is set to translate socioeconomic developments in Europe to projections on the availability of fresh water in the main water system. This data is used as boundary conditions in evaluating possible adaptation strategies. WP-3 uses a biological and ecological approach to investigate the water demand of crops and aquatic ecology. WP-2 and WP-4 together position innovative water technologies in a groundwater - surface water system. KfC theme 6 is aimed at supplying scenarios of the future climate, vital to investigate the effects of different climate projections to the fresh water supply.

1.3 Stakeholders

Stakeholders are those who have to deal with a limited availability of fresh water in a brackish-saline environment under climate change. They can be divided in three groups: 1. agricultural entrepreneurs who need (supplementary) irrigation for new salt sensitive crops or as a risk management strategy for traditional crops; 2. Water boards and Provincial governments dealing with management issues on the scale of polders; and 3. Provincial and national governments who need better knowledge on the hydro(geo)logy of polders, in relation to nation-wide spatial planning of adaptive and mitigative strategies in a brackish-saline environment.

- Water boards (Zeeuwse Eilanden, Hollandse Delta, Delfland, Schieland, Rijnland, Wetterskip Fryslan)
- Provinces (Zeeland, Zuid-Holland, Noord-Holland, Flevoland, Friesland)
- Agricultural NGO’s (LTO, ZLTO, Glaskracht)
- Nature conservation (Natuurmonumenten)

2 Project 2.1 Development of a quantitative framework to optimize adaptation strategies to droughts and salinisation in groundwater – surface water systems under climate change

Project leader: dr ir M. Kok

2.1 Problem definition, aim and central research questions

Problem definition

In coastal regions, like the western part of the Netherlands, fresh water availability and delivery are adversely affected by summer droughts and saline groundwater seepage. Ongoing climate change, land subsidence and sea level rise are likely to aggravate these effects and call for adaptation of the current water management strategies to safeguard the supply of fresh water (Oude Essink *et al.*, 2005; Hoogvliet *et al.*, 2007; Kwadijk *et al.*, 2008).

In the Netherlands, a dense network of subsurface drains, ditches and canals serves to maintain groundwater levels and to discharge excess water. The surface water network is also used to deliver fresh water during periods of drought. Discharge of groundwater into surface water bodies like canals occurs via upward seepage. At the same time, infiltration of surface water results in groundwater recharge. Groundwater and surface water are thus closely linked. Both the exfiltrating and infiltrating water can either be fresh or saline. Many processes, such as groundwater discharge, are spatially variable at a local scale. Discharge rates and the salinity of the discharged water can be extremely variable at the scale of meters, which makes their accurate quantification very difficult (Griffioen *et al.*, 2002; Louw, *et al.*, 2008). Yet these processes do strongly influence the salinity of surface waters at the scale of water management units like polders.

Our present understanding of the response of the coupled groundwater – surface water system is still insufficient (Sophocleous, 2002). The prime reason is that local-scale processes are not captured by regional quantitative models. These models can therefore not be used to make reliable predictions of the future effect of climate change or to assess the suitability of adaptation measures.

Aim

The main objective is to develop a quantitative framework for assessing the volumes and fluxes of water and dissolved salt within the hydrological system. This research project aims to design adaptation strategies to adequately mitigate the adverse effects of climate change in coastal low-lying water systems. Conceptual and mathematical models of the effects of climate change on groundwater – surface water interaction and salinisation will be developed, which will be used to investigate the effectiveness of a variety of possible adaptation measures, both on the local scale (intelligent drainage design, fresh water buffering, level management) and the regional scale (regional water management, flushing, separating discharge and allocation routes).

Central research questions

The central research questions are focused on how groundwater – surface water systems react under climate change at different scales and how optimal adaptation strategies can be optimized:

1. How can groundwater-surface water interaction be quantified and what are the fluxes of water and dissolvedsalt between surface water and groundwater?
2. How can local-scale processes be accounted for in regional models?
3. How much fresh water is really needed to flush salinised water in ditches and canals and is fresh intake waterreally reaching the ditches where it is needed?
4. How will future climate change affect groundwater-surface water interactions and hence the availability of freshwater?
5. What adaptation strategies are best suited to ensure the availability of sufficient fresh water?

2.2 Approach and methodology

The first step in the development of the quantitative models is to integrate all existing knowledge of groundwatersurface water interactions in coastal low-lying areas, particularly in the Netherlands. Recent investigations show that at the local scale sharp gradients in salinity and temperature suggest that fluxes across the sediment-water interface occur at the scale of meters to decimeters (Louw, et al. 2008; Oude Essink et al., 2009). These recent findings call for a re-evaluation of current conceptual models of salt transport between the surface and subsurface compartments of the hydrological system. One component will focus on measurement of surface-groundwater interactions (viz. water and salt fluxes) at the local scale and quantification of its variability using observation wells, flux meters, geophysical techniques (CVES, ERT) and temperature sensors (Anderson, 2005). The purpose is to identify the sources, sinks and pathways of different water types within a water management unit (like a polder) and to determine the dominant processes that control spatiotemporal variations of water salinity.

Secondly, a quantitative framework will be developed to improve the conceptual understanding of the groundwater surface water system. A quantitative framework is paramount in assessing the effects of a changing climate on groundwater-surface water interaction and the salinisation of ditches and canals, and in evaluating possible adaptation strategies. The framework should be designed to be suitable to assess both effects of changing boundary conditions (climate change, societal developments) and the effects of measures to the availability of fresh water in the local and regional water system. Relevant processes include an adequate description of groundwater discharge / recharge and associated solutes (a.o. salt), varying water demands of water users (open field agriculture, glass houses, ecology), hydraulics in ditches and small waterways, fresh water availability in the main water system and regional water management strategies. Various methods for describing the physics of the mechanisms operating at the GW–SW interface as well as current model frameworks (e.g. Kolditz et al., 2008; Sudicky et al., 2006; Langevin et al., 2005) will be reviewed and tested for their applicability to the conditions in the study areas. Part of this research will be conducted in close collaboration with the British and U.S. Geological Surveys.

Effects of climate change on the water demands of the different water users are investigated in collaboration withWP-3. Societal developments and the availability of fresh water in the main water system will be derived from WP-1. Different realisations of future climate conditions, results from calculations using regional climate models, will be made available by KfC research theme 6. These realisations will be downscaled to the appropriate spatial resolution and be used as forcing data in the quantitative framework.

Using the quantitative framework, different adaptation strategies to ensure the availability of fresh water will be evaluated. Which strategy is best suited to mitigate the likely adverse effects of climate change on the availability of fresh water? Which measures are no-regret measures? Which measures are widely applicable, and which are only suitable for specific conditions? Strategies will be selected after consulting the different WPs and in close consultation with the KfC hotspots.

2.3 Scientific deliverables and results

- Four scientific papers in peer-reviewed journals that describe the outcome of the research activities describedabove.
- A review of techniques for effectively incorporating groundwater-surface water interactions in regional-scalemodels
- A model tool that simulates coupled groundwater, surface water and unsaturated zone processes in coastal lowlying water systems
- Model based scenarios of future fresh water availability under the influence of climate change and associated uncertainties in the study areas of the selected case studies
- Report describing adaptation strategies for the selected study areas
- Table of feasible adaptation strategies under different changing boundary conditions for various coastal low-lying water systems

2.4 Integration of general research questions with hotspot-specific questions

In present-day water management it is often unclear what the fresh-water demand in a particular area is and how much water is circulating in the surface water system. With these numbers unknown, future water demands and adaptation measures to climate change are impossible to evaluate. This study aims to investigate and quantify the volumes of water that are present in and are moving between the different compartments of the system, both by collecting field data and by modelling. The expected outcome is a better conceptual and quantitative understanding of the water and chloride balance at a local and regional scale that will allow for a more accurate assessment of the fresh water demand in a region. The aim is also to identify those regions that have sufficient fresh-water resources to become less dependent of external supply of fresh water.

Chloride concentrations in polder areas are highly-variable in both space and time. Saline seepage causes salinization of waterways which necessitates flushing with fresh water in order to ensure sufficient amounts of fresh water for irrigation. Salinity variations in surface waters also have important ecological effects. At present, our understanding of the temporal variations of the salinity of surface water is limited, thus hampering the optimization of the fresh water supply via the surface water network. This project aims to improve our understanding and predictive capabilities of the spatial and temporal varying chloride concentrations in ditches and canals.

The scientific work in this project will partly be done in the cases Haaglanden (Greenhouse Horticulture), Groene Ruggengraat (Groene Hart) and Zuidwestelijke Delta (Fruit cultivation Zuid-Beveland), thus achieving a good connection with specific hotspot-questions.

2.5 Societal deliverables and results

Fresh water is a scarce commodity during dry summers, and is expected to become even scarcer in the future. Before we can decide upon the best adaptation strategy, more must be known about the expected changes of fresh water availability. Insights from this project about future extremes in water scarcity will aid in selecting possible adaptation strategies in the regional water system, given existing uncertainties in the climate response. This project will strive to provide a sound scientific foundation for policy makers to decide on the proper adaptation strategy to sustain water-dependant functions in the future.

2.6 Most important references

1. Post, V.E.A. and B.M. van Breukelen (submitted to Water Resources Research special issue, 2009). Changes in groundwater and baseflow composition due to climate change: Effects of shifts in the seasonal rainfall distribution.
2. Oude Essink, G.H.P., Baaren, E. van, Louw, P.G.B., de, (submitted to Water Resources Research special issue, 2009). Effects of climate change on coastal groundwater systems of the Netherlands.
3. Oude Essink, G.H.P., Louw, de, P.G.B., Stevens, S., de Veen, B., de, Prevo, C., Marconi, V. en Goes, B.J.M.2009, Monitoring campaign in the occurrence of freshwater lenses in the Province of Zeeland, 2007-U-R0925/A,132p.
4. Bosch, S., Wateren-de Hoog, B., Oude Essink, G.H.P., Louw, P., de. 2009. Zou't Verzilten? Stromingen (4),2009.
5. Kolditz O., Delfs J.O, Burger C., Beinhorn M., Park C.H. 2008. Numerical analysis of coupled hydrosystemsbased on an object-oriented compartment approach. Journal of Hydroinformatics 10 (3), 227-244.
6. Louw, P.G.B., Oude Essink, G.H.P., Goes, B.J.M. and Sergi, F., Characterization of Local Rainwater Lenses inAgricultural Areas with Upward Saline Seepage: Monitoring Results, Proceedings Salt Water Intrusion, Naples, Florida, 2008.
7. Hoogvliet, M., et al.. 2007. Inventarisatie van effecten van klimaatverandering op fysiek systeem Hoogheemraadschap van Delfland, TNO rapport 2007-U-R01023/A, in opdracht van Hoogheemraadschap van Delfland, 117 p.
8. Rushton, K. 2007 Representation in regional models of saturated river-aquifer interaction for gaining/losing rivers, Journal of Hydrology 334 (1-2), DOI: 10.1016/j.jhydrol.2006.10.008.
9. Anderson, MP 2005 Heat as a ground water tracer. Ground Water 43 (6), 951-968

10. Langevin C.D., Swain E., Wolfert M. 2005. Simulation of integrated surface-water/ground-water flow and salinity for a coastal wetland and adjacent estuary. Journal of Hydrology 314 (1-4), 212-234.
11. Post, V.E.A. 2005. Fresh and saline groundwater interaction in coastal aquifers: is our technology ready for theproblems ahead? Hydrogeology Journal 13 (1): DOI 10.1007/s10040-004-0417-2
12. Oude Essink, G.H.P., V.E.A. Post, M.J.M Kuijper & B. Minnema 2005. Land Subsidence and sea level rise threaten the coastal aquifer of Zuid-Holland, the Netherlands. In: Groundwater and saline intrusion – Selected papers from the 18th Salt Water Intrusion Meeting. Edited by: Araguas, L., E. Custodio & M. Manzano. IGME, Madrid: 617-624.
13. Sudicky E.A., Park Y.J., Unger A.J.A., Jones J.P., Brook□eld A.E., Colautti D., Therrien R., Graf T. 2006. Simulating complex □ow and contaminant transport dynamics in an integrated surface-subsurface modelling framework. Geological Society of America Abstracts with Programs 38 (7), 258.
14. Griffioen, J., De Louw, P.G.B., Boogaard, H.L., Hendriks, R.F.A., 2002. De achtergrondbelasting van het oppervlaktewatersysteem met N, P en Cl en enkele ecohydrologische parameters in Westelijk Nederland. Tech. Rep. Rapport no NITG 02-166-A, NITG-TNO.
15. Sophocleous, M.A. 2002. Interactions between groundwater and surface water: the state of the science, Hydogeology Journal 10 (1), 52–67.

3 Project 2.2 Increasing the robustness and flexibility of fresh water lenses in saline seepage regions under climate stress

Project leader: dr. ir. Gualbert Oude Essink

3.1 Problem definition, aim and central research questions

Problem definition

Large parts of The Netherlands are at present situated several meters below mean sea level which results in the intrusion of sea water into the groundwater system and the upconing of saline groundwater from deep marine aquifers. The salinisation of Dutch coastal groundwater systems is mainly caused by two ongoing processes of anthropogenic origin for nearly a millennium. The first –drainage of peaty and clayey soil by digging channels and building dikes– is a slow and continuous process, leading to land subsidence by peat oxidation as well as compaction and shrinkage of clay. The greatest land subsidence of this kind occurred in the western and northern parts of the Netherlands. The second process – land reclamation – resulted in a relatively abrupt change in the land surface level, creating the well-known Dutch polders.

In many low-lying coastal provinces (Zeeland, Noord-Holland and Friesland), saline groundwater is often encountered at shallow depths (< 10-15 m). Precipitation surplus lead to the forming of rainwater lenses on top of saline groundwater. The thickness throughout the seasons may have major implications for these fresh water lenses. On top of the climate effects of rainwater lenses depends on factors like recharge, seepage flux, salinity, drainage characteristics. They vary in thickness from > 50 m in dune areas, 5 to 20 m in fossil sandy creeks to < 2 m in agricultural parcels in polder areas with prominent saline seepage. The fresh water availability for drinking water and agricultural purposes depends on these fresh groundwater lenses. Changes in precipitation and evaporation both in quantity and seasonal distribution as well as sea level rise will accelerate saline seepage in the lower lying areas. Moreover, the fresh water lenses will especially vulnerable during summer time, when both precipitation deficits and groundwater extractions for human and agricultural purposes are the largest. It is unclear whether or not these fresh groundwater lenses at different scales (dunes, sandy creeks, saline seepage areas) can cope with ongoing (sustainable) extraction rates under changing climate and socio-economical conditions. Water management in these low-lying areas should anticipate on these changes but the knowledge how to do is inadequate.

Aim

This research project aims to analyse what measurements are effective in mitigating the salinisation due to climate change, sea level rise and increasing need for fresh water. The aim is to increase the availability of fresh water

by creating a robust and flexible buffering capacity of fresh water stored in those fresh water lenses. This project 2.2 of WP-2 partially succeeds the Project Salinisation and freshening of phreatic groundwaters in the Province of Zeeland. Currently, in two other PhD-studies the presence and behaviour of shallow fresh groundwater in areas with saline seepage under present conditions is being studied and monitored at one site in the Province of Zeeland. Here, in this KfC project, four new activities on this fresh water lens research will be added: 1. to assess effects of climate change, sea level rise, land subsidence and socio-economical changes (land-use changes), 2. to up scale local knowledge of presence and dynamics of fresh water lenses and effects of future changes to the coastal area of The Netherlands, 3. to determine measures on a local or sub-regional scale to preserve or increase the fresh water lenses, 4. to make an assessment of the contribution of saline seepage to the nutrient (Nitrogen, Phosphorus) loading of surface waters.

Central research questions

1. How will future climate change affect fresh water lenses in brackish-saline conditions?
2. How can local-scale processes be up scaled to national/regional level and how can these processes be implemented in national/regional-scale models like Netherlands Hydrological modeling Instrument (NHI) or The Deltamodel?
3. What adaptation and/or mitigation strategies are best suited to ensure or increase the availability of sufficient fresh water, in view of the future climatic and socio-economical conditions?
4. Can enough fresh water be stored in sandy creeks to assure that water systems are independent from national fresh water supply?
5. What are the relative contributions of fresh groundwater discharge and saline seepage to nutrient fluxes towards surface water?

3.2 Approach and methodology

The research will be focussed on: a. extensive fieldwork to collect geophysical, hydrological and geohydrological information to better understand the behaviour of fresh water lenses to changing boundary conditions and b. the development of modelling tools, which can be used to predict the impact of sea level rise, climate change and measurements to adapt to and mitigate the salinisation. The field data will also be used to improve the reliability of the modelling tools, considering variable density groundwater flow, coupled salt transport and heat transport.

Precipitation, evapotranspiration, groundwater levels, groundwater outflow from drains and water courses and salinities and nutrient contents of groundwater and surface water will be measured in the study areas of the selected case studies. The focus point will to monitor the effects of changing boundary conditions related to climate change, sea level rise and mitigating measures. Based on these data conceptual models for coupled flow of soil moisture, groundwater (and surface water) will devise and elaborated further in conceptual and mathematical models. Collaboration with project 2.1 in building the modelling tools will be intensified. With these models scenarios for future climate, water level management will be studied. Also new drainage systems and groundwater recovery techniques will be optimized. Two study areas of field scale are proposed (depending on co-funding): one in a polder with vegetable/potato farming where a shallow fresh water lens is used for irrigation; one in a polder fruit tree farming (in the fruit cultivation area of Zuid-Beveland in the South-western Delta) where shallow groundwater is artificially being recharged under a water reservoir. In the latter study area, the focus is on the feasibility of storing fresh water in medium size fresh water lenses in sandy creeks, and its impact on ground- and surface water systems.

To address the research questions above, the following activities are envisaged:

1. Quantification of the effects of changing boundary conditions on fresh water lenses in brackish-saline environments under different hydrogeological conditions. Special attention is given to the shallow fresh water lenses in agriculture plots. The larger fresh water lenses in sandy creeks will be considered together with WP-4. Attention will also be paid to the nutrient concentrations in both the fresh water lenses and saline seepage
2. Estimating tipping points under climate change scenarios: to assess when and under what conditions fresh water lenses will disappear.
3. Quantification of present and future salt damage to crops (relation with WP-3).
4. Finding and testing feasible adaptation and mitigation strategies for sustaining fresh water supply in a saline environment on a local scale
5. Up scaling of effects of future changes of boundary conditions and effects of adaptation and mitigation strategies for sustaining fresh water supply to a regional scale.

3.3 Scientific deliverables and results

1. Four scientific papers in peer-reviewed journals that describe the outcome of the research activities described above.
2. A modelling tool to simulate variable density groundwater flow, coupled solute transport, heat transport and unsaturated zone processes
3. Model based scenarios of future fresh water availability in shallow lenses and sandy creeks under the influence of climate change and associated measures
4. Report describing adaptation strategies for the selected study areas

3.4 Integration of general research questions with hotspot-specific questions

This project will increase our knowledge of the behaviour of vulnerable fresh water resources at different scales in a brackish-saline environment, and their response to climate change. This knowledge is necessary to design no-regret adaptative and mitigative strategies for a robust and flexible self-sufficient fresh water supply under local and regional conditions. Moreover, the study answers the important question of how to continue to farm cultivated crops in a brackish-saline environment.

The core of the research is focussed on small fresh water lenses in the Zeeland, with interest for similar lenses in the Noord-Holland, Fryslan and the Water Board of Rijnland (all depending on co-funding). The sustainment of agriculture in these saline seepage areas is threatened by the combined adverse effects of climate change, sea level rise and land subsidence. Agriculture is now supported by small fresh water lenses, which are replenished during winters and used during the growing season. Expected extremes in the climate make the future existence of these lenses, and hence the agriculture it supports, uncertain. This research will also give preliminary insight into the role of saline seepage as a contributor to nutrient loading of surface waters (relation with WP-2 project 2.1).

In addition, a case study in Haaglanden (Greenhouse Horticulture) is also considered in collaboration with WP-4 (but depending on co-funding). The focus will be on the feasibility of storing fresh water under horticulture infrastructure in the subsurface, and its impact on ground- and surface water systems

3.5 Societal deliverables and results

- Better understanding of the hydrogeology of small, medium to large-scale fresh water lenses.
- Better understanding of the response to climate change of vulnerable fresh water resources in a saline environment.
- Knowledge about no-regret adaptation and mitigation strategies for local and regional self-sufficiency in the fresh water supply.
- Knowledge on how to continue to farm cultivated crops in a saline environment.

3.6 Most important references

1. Oude Essink, G.H.P., Louw, de, P.G.B., Stevens, S., de Veen, B., de, Prevo, C., Marconi, V. en Goes, B.J.M. 2009, Monitoring campaign in the occurrence of freshwater lenses in the Province of Zeeland, 2007-U-R0925/A, 132p.
2. Maas, K. 2007. Influence of climate change on a Ghijben–Herzberg lens, Journal of Hydrol. 347 (1-2), 223-228.
3. Robinson, C. , Gibbes, B. , Li, L. 2006. Driving mechanisms for groundwater flow and salt transport in a subterranean estuary. Geophysical Research Letters (33) 3, L03402.
4. Louw, P. de & Oude Essink, G.H.P., 2006: Salinisation of the Northern coastal area of the Netherlands due to land subsidence and sea level rise. In: Jun Xu, Y. & Singh, V.P. (eds.): Coastal Environmental and Water Quality, AIH Annual Meeting & International Conference, Challenges in Coastal Hydrology and Water Quality, Baton Rouge, Louisiana, 21-24 May, 2006, pp 167-179.
5. Louw, P. de, Oude Essink, G.H.P., Maljaars P. en Wils, R.A., 2006, Monitoring verzilting Dongeradeel, TNO rapport 2006-U-R0177/B, 57 p., november 2006.
6. Roelofsen, F.J., Oude Essink, G.H.P. and Stuurman, R.J. 2005. Haalbaarheidstudie naar Gietwateropslag in de ondergrond; Een studie op basis van systeemrendementen, NITG 05-168-A, 52 p., Utrecht, TNO Bouw en Ondergrond.
7. Schot, P.P., Dekker, S.C. and Poot, A. 2004. The dynamic form of rainwater lenses in drained fens, Journal of Hydrology 293: 74-84.
8. Velde, M., van der, Javaux, M., Vanclooster, M., Clothier, B.E., 2006, El Niño-Southern Oscillation determines the salinity of the freshwater lens under a coral atoll in the Pacific Ocean, Geophysical Research Letters 33 (21), nr L21403
9. Li L., Barry D.A., Stagnitti F., Parlange J.-Y., (1999) Submarine groundwater discharge and associated hemical input to a coastal sea. Water Resources Research 35 (11), 3253-3259.
10. Oude Essink, G.H.P. 1996. Impact of sea level rise on groundwater flow regimes. A sensitivity analysis for the Netherlands. Ph.D. thesis Delft University of Technology. Delft Studies in Integrated Water Management: no. 7 (ISBN 90-407-1330- 8). 428 p.
11. Stuyfzand, P.J. 1993. Hydrochemistry and hydrology of the coastal dune area of the Western Netherlands. Amsterdam, The Netherlands, Vrije Universiteit: 366.
12. Lebbe, L.C. 1983. Mathematical model of the evolution of the fresh-water lens under the dunes and beach with semi-diurnal tides. Proc. 8th Salt Water Intrusion Meeting, Bari, Italy, Geologia Applicata e Idrogeologia, Vol. XVIII, Parte II: 211-226.