The application of the SEAWAT variable density code for the Lake Wieringen project, the Netherlands

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Abstract Advanced regional modelling tools are available to quantify the changes groundwater flow and groundwater quality. The application of these modelling tools is increasingly becoming a part of environmental assessments of large projects. In this paper we examined the application of the SEAWAT variable density model for the impact assessment of the Lake Wieringen Project. Firstly, an assessment is made of the reliability of the predicted salinity trends through comparison with hydrochemical data and surface water data. Secondly, the application of the results of the modelling in the environmental impact assessment of the lake Wieringen Project is described.

Index Terms **groundwater modelling, variable density**

I. Introduction

The Lake Wieringen project comprises the establishment of a brackish water lake with an area of roughly 700 hectares, located on the fringe of the former island of Wieringen and the Wieringermeerpolder in the north of the Netherlands (figure 1). The establishment of the Lake Wieringen aims to increase the socio-economic resilience of the region and make the region less dependent on agriculture as a main source of income.

Because water played an important role in the design of the lake, the plan was underpinned by an integrated water and ecology study. This study aimed to evaluate the effects of the lake on the surrounding land and to optimise the design of the water management system of the lake itself and the surrounding polder. The study included 1) a hydrological study aiming to quantify safety against flooding, 2) an aquatic ecological and surface water quality assessment to predict the future ecological state of the lake [1], and 3) an hydrogeological study aiming to assess the effects of the lake on groundwater levels, groundwater seepage and groundwater quality in the region [2]. This paper describes the latter.

The hydrogeology of the region is characterised by varying occurrence of fresh and saline groundwater. This situation is the result of the geological history and land reclamation and cultivation. In order to understand the impact that the Lake Wieringen will have on groundwater quantity and quality, whilst considering the varying salinity of groundwater, a variable density groundwater model was developed using the SEAWAT code. With this model, the historical and future trends in groundwater salinity were simulated. This was followed by scenario modelling of several design alternatives for the lake.

This paper describes the results of the hydrogeological study and presents an overview of the construction and calibration of a variable density groundwater model using the SEAWAT code. This followed by a description of the modelling results of the autonomous development and the establishment of the Lake Wieringen. The results of the scenario modelling are discussed in terms of reliability and the usability in an Environmental Impact Assessment.

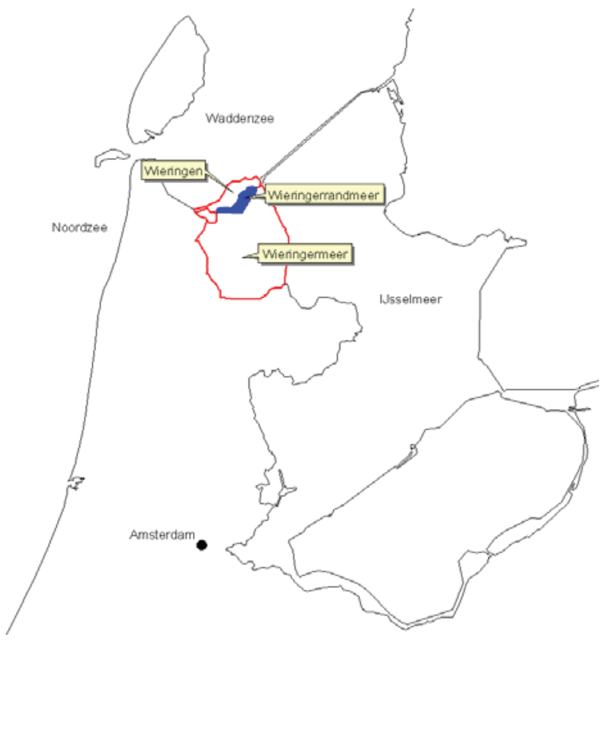

Fig 1: Location of the Wieringermeer and Wieringen

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II. Description of the Wieringermeer region

A. The region's history and its relation to groundwater salinity

From around 2000 years B.C. through to the Middle-ages, a swamp system was located in the region, where peat was formed [3]. During this period fresh water recharged the underlying aquifer. Between the 9th and 12th century, land cultivation, dewatering and peat digging for fuel, led to a land subsidence causing a decline in topographical elevation from several meters above mean sea level to several meters below mean sea level. Remnants of several dikes suggest that the early inhabitants of the region were fighting a continuous battle against the rising sea in the increasingly lower lying land [3]. In that time, several sea inlets existed along the shoreline of Holland through which the sea threatened the peat digging areas in the region.

When during the end of the 12th century and start of the 13th century several storm-floods from the north and east broke away remaining peat and inundated the area, a large inland arm of the Northsea called the Zuiderzee was formed in this region. Due to the occurrence of glacial till deposits, Wieringen is situated on topographically higher ground. The inundation of the Zuiderzee separated Wieringen from land further south and made it an island. At the inundated part of the region, where coarse sands occurred in the underground, saline seawater intruded the aquifer rapidly caused by density induced free convection. At areas where low permeable clay and loam layers occurred in the underground, fresh groundwater is protected from salinisation [4].

During the depression years (1920's to, 1930's) large scale labour projects were undertaken in the Netherlands. One of these projects was the reclamation of Wieringermeerpolder. In 1924, a dike was built between the island and the main land and the Wieringermeerpolder was again land. In the same decade the remainder of the Zuiderzee was disconnected from the Waddenzee through the construction of a dam named the "Afsluitdijk". From then on the Zuiderzee was named the IJsselmeer. Through several decades, the IJsselmeer gradually became a fresh water lake, fed by a tributary of the Rhine.

Hydrogeological investigations undertaken directly following the reclamation of the Wieringermeerpolder showed shallow saline groundwater covering fresh groundwater at a depth of 30 to 50 m below sea level, as a remnant of the period that a fresh water peat system occurred in the region [5].

B. Water management and hydrogeological setting

The occurrence of glacial deposits at Wieringen make that a large part of the rainfall discharges locally in lower parts on the former island. These lower parts are called 'kogen'. Fresh water lenses are developed under the higher areas.

The Wieringermeerpolder is a deep polder with polder drainage levels varying from 4 to 6 meters below average sea level. To facilitate the deep dewatering in the polder, an intensive drainage system was constructed when the polder was established. This drainage system is combined with a separate water inlet system which conveys fresh water from the adjacent IJsselmeer, through the Amstelmeerkanaal, to farmers in the region.

In the region a shallow and deep aquifer can be recognised comprising unconsolidated coarse sand deposited by rivers in the early and late Quaternary. The shallow and deep aquifer are separated by the before mentioned glacial till deposits. At Wieringen these deposits are nearly at the ground surface and the shallow aquifer has a thickness of several meters. South of Wieringen, in the northern half of the Wieringermeerpolder, the moraine deposits are not present and the shallow and deep aquifer are in direct hydraulic connection. Further to the south, the glacial deposits at around 30 meters below ground surface. In the south, the deep aquifer is characterised by several minor aquitards. Figure 2 shows a hydrogeological cross section of the region. It can be seen from this cross section that the occurrence of fresh and saline groundwater is closely related to the hydrogeological structure of the region. Clay layers protect relicts of fresh groundwater present in the underground.

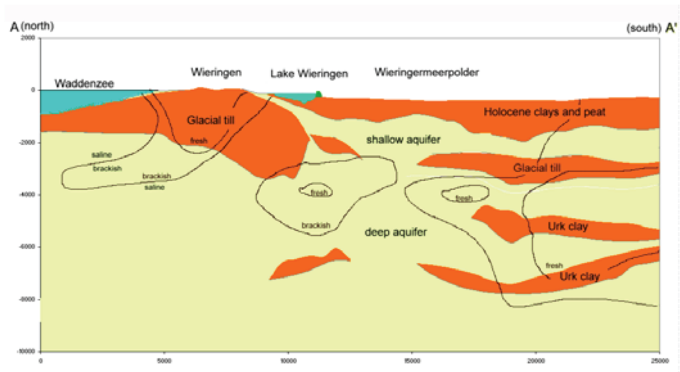

Fig 2: Hydrogeological cross section

III. The project

Figure 3 shows an overview of the proposed Lake Wieringen. The Lake Wieringen project will be undertaken in four phases. In the first phase part of the lake will be built at the Polder Waard-Nieuwland and recreational housing will be realised. In the second phase, the entire Lake Wieringen will be constructed by dredging and construction of a dike. In the last two phases the main infrastructural works will be undertaken (roads and water infrastructure).

The construction of the four phases of the project will be completed around 2025. The design surface water level of the proposed Lake Wieringen in each of the scenario's will be 0.4 meters below mean sea level which is around 4 meters above the present polder surface water level. For this reason, the establishment of the lake is expected to impact both on groundwater flow and salinity patterns. The Lake receives surface water inflow from the IJsselmeer though an inlet construction located in the harbour. Water is discharged to the

Amstelmeer which is located west from the lake.

Fig 3: Layout of the Lake Wieringen

IV. Construction of variable density model and calibration

A. *Model construction*

To assess the effect of the establishment of the Lake Wieringen on groundwater conditions, a variable density groundwater flow and solute transport model was developed using the SEAWAT 2000 code [6]. The SEAWAT code is based around the existing codes MODFLOW 2000 [7], simulating groundwater flow and MT3DMS [8], simulating solute transport. The two models have been coupled and combined with a variable density flow module (the VDF package) that calculates the water pressure field for each time step based on groundwater heads and solute concentration using a linear relationship between solute concentration and density. The darcian flow equation in MODFLOW has been adjusted to account for buoyancy effects.

TABLE I
DETAILS OF NUMERICAL MODEL

Real world	Model representation
Model domain	23 x 32 km^2
Horizontal discretisation	200 x 200 m^2 at boundaries of the model to 50 x 50 m^2 near Lake Wieringen
Vertical discretisation	22 layers
Transmissivity and leakance values	Hydrogeological database REGIS [11] and model calibration
Polder drainage and watersystem	Simulated using RIVER and DRAIN packages. Conductance values are based on soil mapping and model calibration. Chloride values of boundaries are based on average values from measurements
Surface waters	IJsselmeer and Waddenzee are simulated using General Head Boundaries (GHB)
Groundwater recharge	Long term climatic data, crop factors and GIS land use data
Initial heads	Steady state calculation
Initial chloride concentration	Initial chloride concentrations were interpreted from groundwater salinity data from 1930 to present.

The Lake Wieringen-model was based on an earlier model developed for a pre-feasibility assessment using the MOCDENS3D code [9], [10]. Both MOCDENS3D and the SEAWAT codes are based on MODFLOW, facilitating a fairly easy model conversion. The reason to convert the model to SEAWAT 2000 and not use the initial MOCDENS3D model was mainly that SEAWAT is publicly available from the USGS website and comes with extensive documentation. During the construction of the model it was found that SEAWAT 2000 is hardly prone to numerical dispersion and artificial oscillations when using the 3rd order TVD scheme for the advection term for solute transport component. Numerical oscillations are often a challenge in variable density modelling and SEAWAT 2000 was found to be numerically stable even in regions where inversions in the salinity-depth profile occurred. Table 1 shows some details of the Lake Wieringen model.

B. *Temporal discretisation*

Both a steady state model simulating present groundwater flow conditions and a transient model simulating groundwater flow conditions between 1970 and 2150 were built. Steady state conditions were simulated using the interpreted chloride concentration.

The transient model was set up using stress periods with a length of 5 years throughout simulation period. It was attempted to simulate a historical longer period (starting from 1900) to consider the development in salinity pattern over a longer time frame, but calculating time proved to be a limiting factor. In the period 1970 to 2000, boundary conditions are assumed to be constant in time. This period serves to avoid initial numerical transient effects in the chloride field and to verify the predicted salinity trends. From 2000 onwards, sea water levels and recharge are adjusted to account for the effects of Climate Change according to the Middle Scenario for Climate Change as described by the Intergovernmental Panel of Climate Change [12]. The following significant changes in the hydrologic system are adopted for the year 2150 (autonomous developments):

- Sea level rise of 0.9 m;
- Increase in groundwater recharge of 10.5%;
- Soil subsidence of 0.15 m [13].

The soil subsidence is included in the sea level rise term, implying that the head of the General Head Boundary condition is increased with 1.05 m over a time period of 150 years. It is noted that the seasonal changes are not included in the model because of restriction on calculating time. This means that the increase in drought periods (when salinity problems are mostly manifested) can not be directly quantified using this modelling approach.

C. Calibration

The steady-state model was used for calibration against measured groundwater heads and discharge rates measured at the polder pumping stations. The calibration steps involved: 1) adjusting the transmissivity values from the REGIS database to achieve an acceptable difference between measured and calculated heads measured in deep monitoring wells; and 2) adjusting the conductance of the GHB, DRAIN and RIVER packages to achieve an acceptable difference between measured and calculated phreatic groundwater levels and polder discharge rates. This led to an increase in transmissivity values with a factor ranging from 1.5 to 2.5 and conductance values ranging from 60 to 200 m^2/day (corresponding to drainage resistance values ranging from 200 to 700 days).

Figure 4 presents the scatter plots of measured against calculated hydraulic heads and discharge rates.

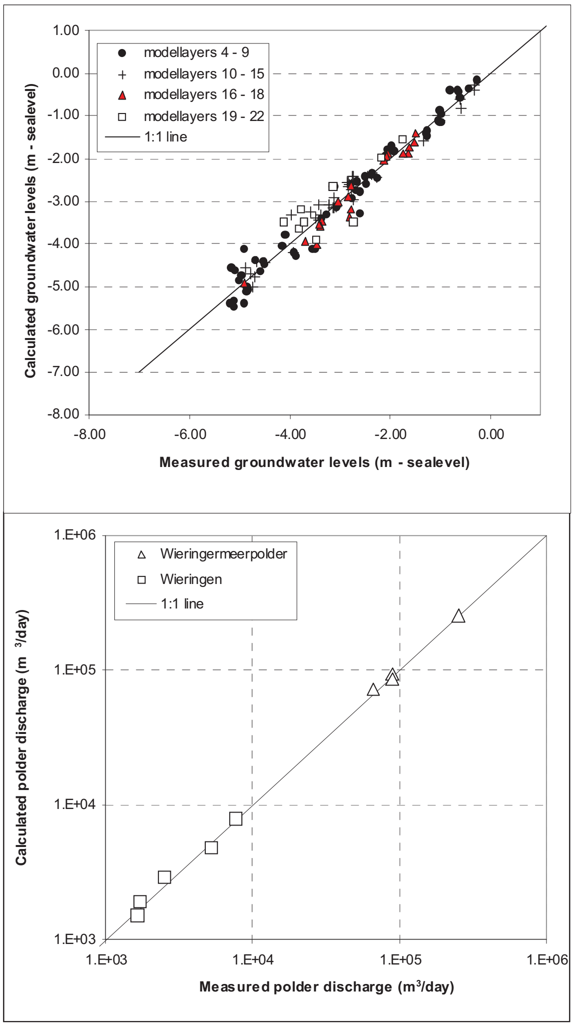

Fig 4: Calibration result

The mean absolute error between measured and calculated heads after calibration varied from around 0.2 meter in the shallow model layers to 0.5 meter in the deeper model layers. The increase in calibration error with depth is probably due to the increasing effect of chloride concentration on the pressure head. The total hydraulic gradient in the model region is around 8 meters which means that the relative error is less than 10 % which was the calibration objective.

The relative error between measured and calculated discharge rates for five pumping stations after calibration was less than 10 % and around 15% for two pumping stations. This calibration result was considered adequate because the error in discharge measurements at pumping stations ranges from 10 to 30%.

V. Results

A. Autonomous development

An important question is what will happen to the groundwater quality when the Lake Wieringen is not constructed. As described, the proposed Lake Wieringen will be completed in 2025. So to make a reliable comparison of the effects of the project, the hydrogeological situation in this year needs to be described and compared to the effects of the Lake Wieringen. Figure 5 shows the predicted salinity of shallow groundwater over 150 years from 2000 onwards. The results indicate that the northern half of the Wieringermeerpolder is characterised by increasing salinity, whilst in the southern half freshening occurs. The increasing salinity in the north is primarily caused by the gradual upward movement of deeper, more saline groundwater, and secondly by rising sea levels. The area where salinisation occurs correlates with the area where the glacial till deposits separating the shallow and aquifer is absent. This indicates that the salinisation process is geologically constraint. Further south, where the till deposits are found at around 30 m depth, horizontal flow of fresh groundwater infiltrated at the IJsselmeer causes freshening.

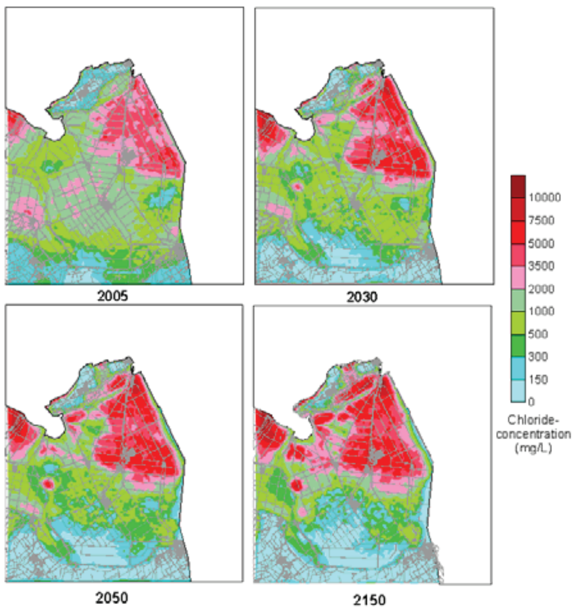

Fig 5: Autonmous salinity development

Apart from changing groundwater quality, modelling predicts that Wieringen will be confronted with increasing groundwater levels. This results in an increased risk for water logging and inundation. Model simulations show these effects will become important from 2050 onwards. Rising groundwater levels are negligible in the Wieringermeerpolder.

B. *Hydrogeological effects of the Lake Wieringen*

The predicted effect that the establishment of the Lake Wieringen will have on shallow groundwater is presented in figure 6. Figure 6 shows that groundwater salinity increases following construction of the Lake.

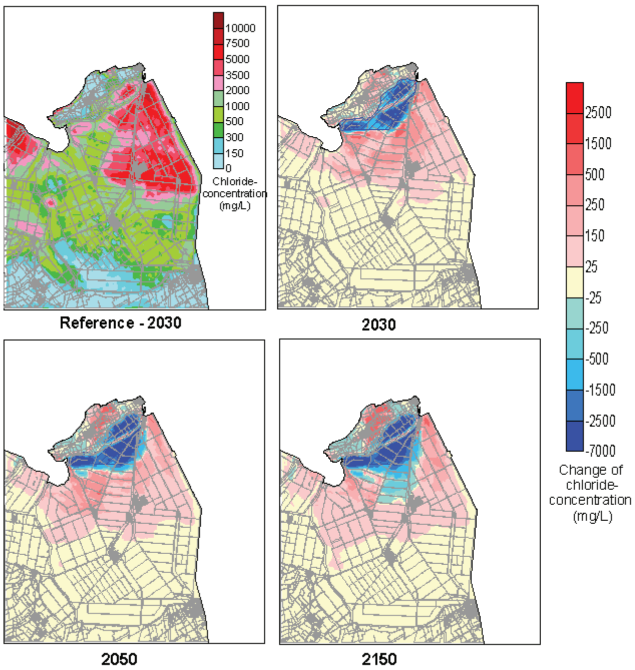

Fig 6: Effects of Lake Wieringen on groundwater salinity

This effect is added to the effects of autonomous development (indicated in figure 5), and of comparable order of magnitude in the area directly surrounding the Lake Wieringen. The salinity of the shallow groundwater is determined by rainfall and by groundwater seepage. The predicted increase in salinity is of comparable order of magnitude to the increased groundwater seepage. This means that the increasing salinisation of shallow groundwater is mainly the result of the increase in groundwater seepage in the polder areas. That is why increasing groundwater salinity is predicted to occur immediately after the lake is constructed.

The model simulations for the years beyond 2050, show that freshening of groundwater occurs. This is due to the infiltration of less saline water from the Lake Wieringen, which will cause a slowly progressing freshening of groundwater in the Wieringermeerpolder. This is a process that will take several centuries before a new equilibrium is reached.

VI. Discussion

A. *Verification of the predicted autonomous development*

In the project area, there are no monitoring wells present that have a reasonable salinity time series data. The absence of groundwater salinity data means that direct calibration of the predicted autonomous development (through comparing measured against simulated chloride concentrations) is not possible. Because (autonomous) salinisation is of great concern, both the agricultural section, nature development, and more recently in the process of implementing the EU groundwater directive, it is essential to how reliable the predictions are from variable density modelling.

To obtain an indication of the reliability of the model's transient predictions, the calculated salinity trends between 1990 and 2000 were compared to the hydrochemical 'signature' of groundwater samples and the trends in surface water salinity.

1) *Salinity trends inferred from major ion chemistry*

Salinising or freshening trends can be identified by analysing groundwater quality. A simple way to determine these trends is to calculate the Base Exchange Index or BEX [14]. BEX is defined by calculating the sum of Na, K and Mg in milli-equivalents corrected by the contribution of sea-salts by the following formula:

$$BEX = (Na + K + Mg) \ -1.0716 \ Cl \, [\, meq/l] \qquad (1)$$

A significantly positive BEX indicates freshening, while a significantly negative BEX indicates salinisation. A neutral BEX indicates adequate flushing with water of constant composition. The BEX is based on the differences in cation exchange between a fresh water intrusion and a salt water intrusion.

Groundwater data from a number monitoring wells was obtained from the Dutch groundwater database DINO and for each groundwater sample taken between 1990 and 2000, the Base Exchange Index (BEX) has been calculated. Subsequently, the trends identified with the Base Exchange Index are compared to the trends calculated with the variable density groundwater model between 1990 and 2000 and shown in figure 7 and summarised in table 2.

Table II
Verification of calculated salinity trends using the Base Exchange Index

		Trend calculated with Seawat		
		Salinising	No Trend	Freshening
BEX trend	Salinising	16	3	11
	No Trend	12	1	3
	Freshening	8	2	22

A reasonable resemblance is found between hydrochemical data and the groundwater model results. Figure 7 shows that the predicted regional groundwater quality trend, which salinisation in the north and freshening in the south of the Wieringermeerpolder corresponds with the trends inferred from the major ion chemistry. Although rather qualitative by nature, this comparison gives a reasonable indication that the trends calculated by the model are reliable.

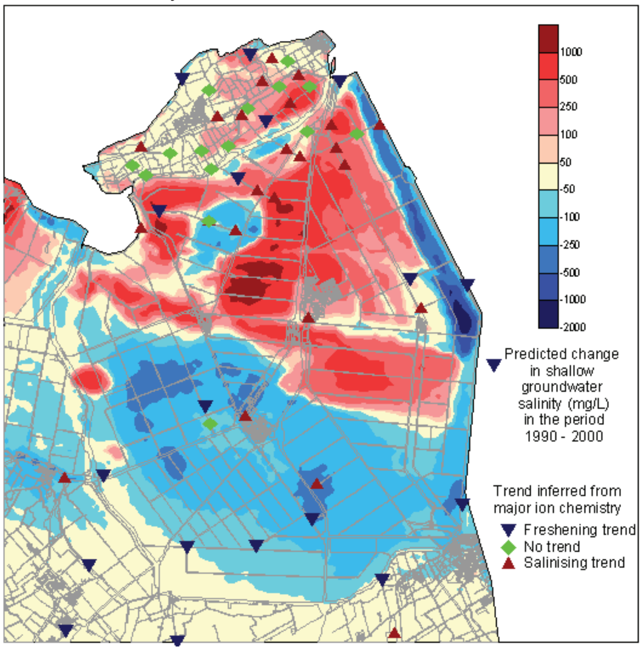

Fig 7: Comparison of autonomous trend with major ion chemistry

2) Salinity trends inferred from surface water data

In contrast to groundwater quality data, there is a reasonable monitoring network present for surface water quality. For each surface water monitoring station, the trend in salinity is calculated using linear regression between 1990 and 2000. Figure 8 shows a comparison between the calculated trends in chloride concentration of the surface water and the phreatic groundwater. Table 3 shows the comparison quantified.

The comparison between trends in surface water and groundwater salinity show that whilst the groundwater model indicates both freshening and salinising of groundwater to occur, the surface water shows only freshening trends.

TABLE III
VERIFICATION OF CALCULATED SALINITY TRENDS USING SURFACE WATER TRENDS

		TREND CALCULATED WITH SEAWAT		
		Salinising	No Trend	Freshening
Surface water trend	Salinising	0	0	1
	No Trend	0	0	1
	Freshening	13	4	16

Obviously, the trends in groundwater and surface water can not directly be compared to each other. The difference between trends in surface water and groundwater can be explained by an increase in flushing of the surface water system with fresh water.

Local farmers take fresh water in from the adjacent IJsselmeer to irrigate their crops and flush the surface water. The water intake may have increased in the area, both to irrigate higher value and more sensitive crops which require more and fresher water, and potentially also the flush the surface water system in response to increasing groundwater salinity. There are no data available on water inlet volumes from the IJsselmeer so this can not be verified. However, the freshening of surface water does indicate that local farmers probably don't really have a problem with salinity yet. This was also confirmed through conversations with local farming organisations.

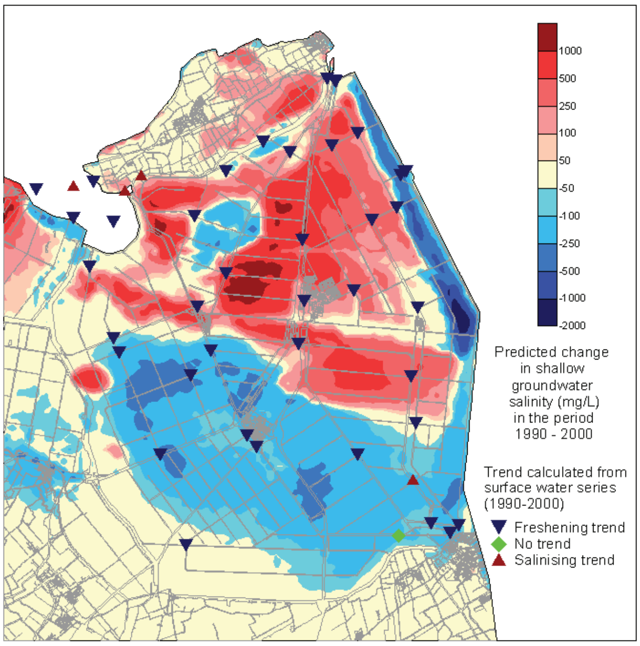

Fig 8: Comparison of autonomous trend with surface water trends

B. Using the modelling results

The result of modelling the proposed Lake Wieringen predict that groundwater levels in the area surrounding the lake will rise and groundwater will become more saline in the near future. Whether this is a negative or positive effect will depend on the type of land use in the area. Most important land uses include agriculture and nature. In order to use the results of the hydrogeological modelling in an Environmental Impact Statement (EIS), the effects on these functions should be described in terms of crop yield, ecological health and inundation risk.

In order to interpretate the hydrogeological effects relating to groundwater quantity aspects (water levels and seepage), the WaterNOOD-code [15] was used. WaterNOOD is a GIS based tool that quantifies agriculture yield and ecological health using calculated groundwater levels, groundwater seepage, soil type and crop type or ecological species. The agricultural yield and ecological health are represented as a percentage of the crop yield or ecological health in an ideal hydrological situation for a certain soil type and land use. The WaterNOOD instrument provides a very powerful tool in quantifying hydrological effects in terms of effects on different functions in an area.

Unfortunately, the WaterNOOD instrument can not be used to translate changes in groundwater quality into agricultural effects and effects on nature. One way of assessing the effect of changing groundwater quality is using salt stress functions developed for typical Dutch crops by Alterra [16]. These salt stress functions describe the relationship between rising salinity and decreasing crop yield. The problem with these relationships is however that salt damage to crops of vegetation occurs when salinity increases in the unsaturated zone around the plant root. The salinity in the unsaturated zone is determined not only by the shallow groundwater salinity but also by precipitation, irrigation and the type of vegetation or crop. One way of dealing with this for irrigated crops is by assuming a constant leaching fraction (that is the fraction of irrigation water that passes the root zone). That way the soil moisture salt stress can be expresses as a salt stress due to chloride concentration in irrigation water. This is illustrated in Figure 9.

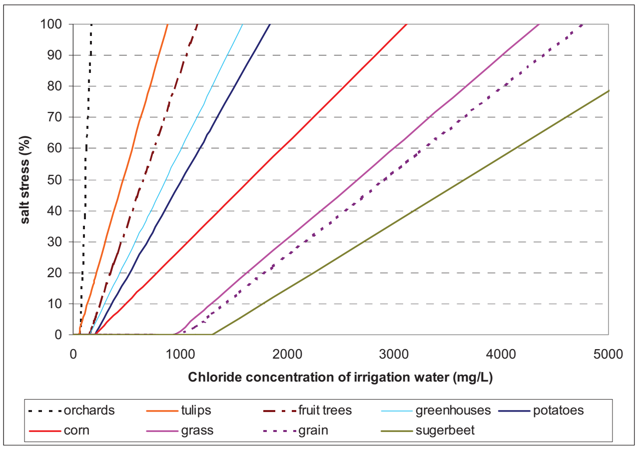

Fig 9: Salt stress functions

Because the Lake Wieringen will provide the agricultural water supply, the results from the variable density modelling were used in SOBEK and solute-balance calculations to investigate the impact of the lake on the surface water quality. Surface water quality has been studied in terms of expected N-P- and Cl-concentrations in 2030. It appeared that polder Waard-Nieuwland, at the low lying part of Wieringen, plays an important role in the surface water quality of Lake Wieringen. In the current situation water is discharged from polder Waard-Nieuwland to the Amstelmeerkanaal (figure 10). In the dry season, water from the Amstelmeerkanaal is used to supply the Wieringermeerpolder.

Calculations indicated that if the additional salt-load from the lower areas of Wieringen caused by the autonomous development is discharging directly to the Lake Wieringen, the level of salinity of the surface water may increase to a level where it will be unusable for agricultural water supply. This information was directly used to optimise the design of the surface water system through deflection of polder discharge aiming to reduce surface water salinity (figure 10).

The calculations show that the increasing salinity levels can mitigated through optimising the surface water system. This is efficient in the area because currently there is already an extensive fresh water infrastructure present in the region.

VII. Conclusions

Presently, very advanced regional modelling tools are available to simulate groundwater flow and groundwater quality. The calibration of especially the quality part of these models is difficult when very few groundwater quality data is available. This means that the reliability of model predictions are hard to verify.

The reliability of the simulated salinity changes were assessed by comparing the predicted changes with hydrochemical data. A reasonable resemblance is found between the salinity trends inferred from the hydrochemical data and the SEAWAT simulations. However, the model predictions are not confirmed by the trends in surface water salinity. This may be caused by an increase in flushing of the surface water system, to counteract the increasing salinity of deeper groundwater.

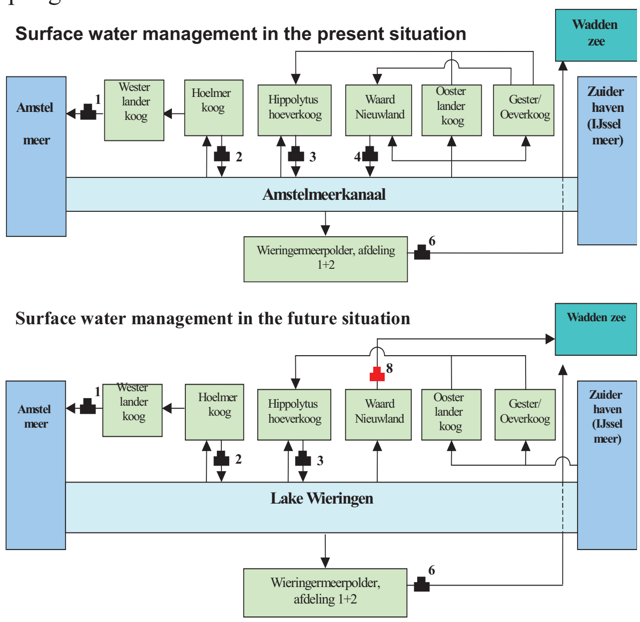

Fig 10: Surface water system in present and future situation. Arrows indicate direction of surface water flow. The symbols next the numbers indicate polder water pumping stations

In order to use the results of the numerical modelling to assess the effects for agriculture and nature, WaterNOOD and a surface water solute balance were employed. Direct translation of the results from numerical groundwater modelling in terms of crop yields and effects for nature is not possible and additional surface water solute balance was required. This is due to the fact that the effects on these land use functions are mainly dependent on salinity changes near the ground surface. This means that the use of variable density modelling on its one, is not sufficient assess the effects of groundwater salinisation in the polder areas of the Netherlands.

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