Sensitivity of the Amsterdam Water Supply Dunes storages to intake stoppages

Abstract

The storage capacity of the Amsterdam Water Supply (AWD) dune infiltration system is estimated by undertaking scenario analysis using a calibrated, transient MODFLOW-2005 groundwater flow model of the AWD infiltration areas. The primary constraint on utilising groundwater is the ability to physical extract fresh water from the shallow and deep aquifers. The length of time a complete stoppage of infiltration water can be withstood depends on the management decisions made when the intake ceases. Utilising the deep wells immediately, and drawing the levels in the abstraction and storage canals down as slowly as possible to meet production demand, ensures production can be met for a maximum period of 112 days. The risk of upconing of the fresh-saltwater interface and salinization of the deep wells is not a constraint on extraction over a150-day period. Based on these results, it is recommended that the current management strategy for unplanned intake stoppages is updated to allow for immediate utilisation of the deep wells, to maximise both production and environmental outcomes.

Keywords: *dune infiltration, storage, saltwater interface*

1. Introduction

The Amsterdam Water Supply Dunes (AWD), a dune infiltration managed aquifer recharge system in the western coastal Netherlands, has been supplying drinking water to Amsterdam and its surroundings since 1853. Since its inception, many improvements to increase the treatment capability and storage capacity of the system have been introduced. In its current layout, the system can supply 70 million m^3/year of extremely high-quality water to the municipality, while concurrently serving an important environmental conservation function.

The ability of the AWD to meet its water supply and environmental objectives relies on the consistent supply of pre-treated river water from the Rhine. The artificial infiltration supplements precipitation recharge to maintain a fresh-water bubble atop naturally-occurring saltwater found at depths up to 130 m below the ground surface. This freshwater bubble represents the total storage of groundwater available in the AWD. Its utilisation depends on several limiting factors, including the physical ability to extract the water from the shallow and deep aquifers, the quality of the water extracted via pumping from the deep aquifer, the level of the groundwater table required to maintain the dune ecosystem, and environmental licence conditions.

Estimates of the storage of the AWD were calculated in 1967 and 1971, when the layout and management of the dunes were different to the current situation. Since these calculations, there has been no scientific estimate of the dune storage. Current ‘best guess’ estimates suggest the AWD could supply drinking water for a two to three-month period, if all intake of pre-treated water from the Rhine ceased. The question around the storage capacity of the AWD is becoming increasingly important. The likelihood of future intake stoppages is increasing due to both aging pipeline infrastructure and predicted climate change effects on Rhine river water quality. A prolonged stoppage of Rhine water intake represents a serious risk to both the security of Amsterdam's water supply, and endangered flora and fauna in the AWD. To manage this risk, robust estimates of the effective storage capacity and seasonably-varying usable storage volumes in the AWD are required.

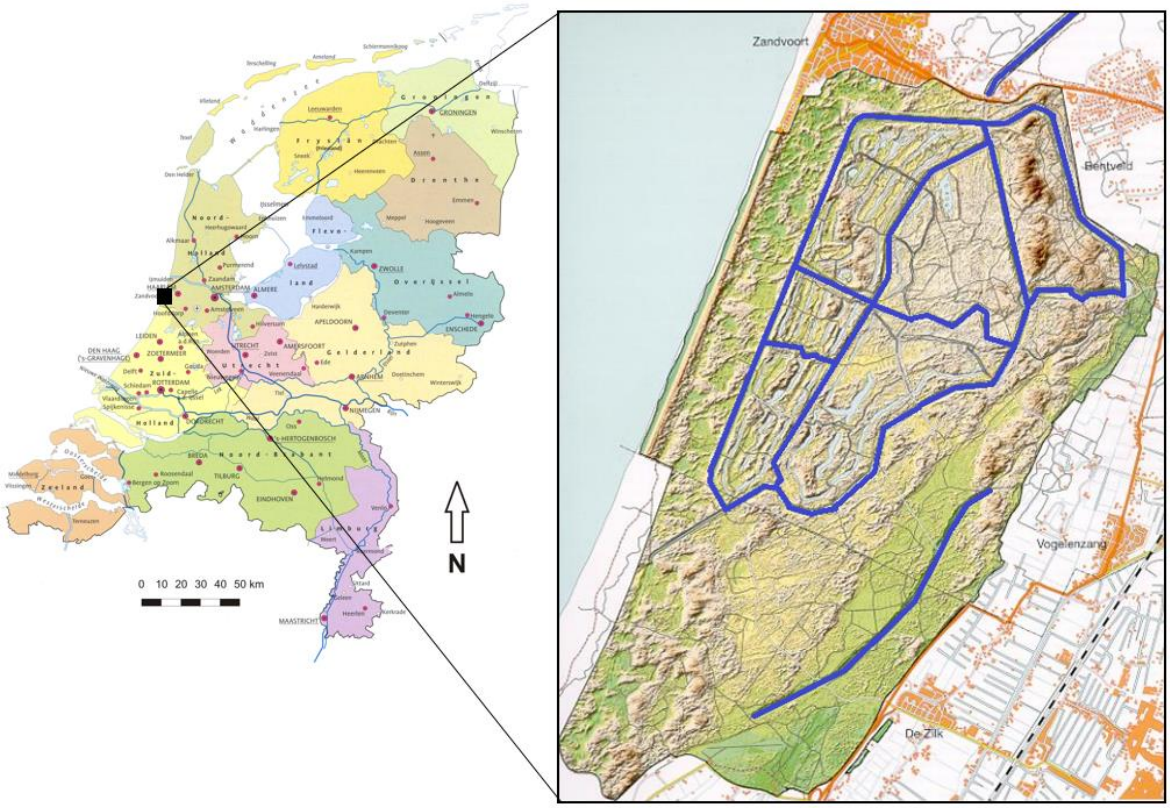

Figure 1 Location of the Amsterdam Water Supply Dune; insert showing the dune area with the abstraction canals highlighted in blue (Smits, 2017)*.*

2. Study Area

Groundwater from the AWD, located south of the city of Zandvoort (Figure 1), has been used to supply potable water to Amsterdam since 1853. Initially, shallow groundwater was extracted via excavated channels under gravity flow. Around 1900 it became necessary to install boreholes to extract deep groundwater from beneath the confining clay layer, to meet increased demand. Abstraction exceeded the natural recharge to the dunes, resulting in lowering of the water table and upconing of saline groundwater to the deep extraction wells. In 1957, the Amsterdam Water Company implemented artificial recharge of the dune system as a solution to increase capacity and prevent over-extraction (De Moel et al., 2006; Olsthoorn and Mosch, 2002).

Surface water is taken from the Lekkanaal, supplied by the River Rhine, with a maximum supply capacity of 88 million m^3/year. Pre-treatment of the Rhine water is undertaken at the WRK production plant near the city of Nieuwegein. Infiltration occurs over an area of approximately 86 hectares containing 40 infiltration ponds, with an average width of 35 m, and a total length of 24.6 km. Infiltrated water is extracted by horizontal drainage pipelines lying between the infiltration ponds, or flows directly to extraction canals. The average residence time is 90 days, with a minimum residence time of 60 days.

Once artificial recharge of the shallow aquifer began in 1957, regular utilisation of the deep aquifer bores ceased, preventing further salinisation of the water supply. The fresh-saltwater interface was pushed downward again to restore the original volume of fresh water (Kamps, 2010). The deep aquifer is used for additional storage and back-up supply during management of the AWD. The deep aquifer system consists of 240 wells, which are managed in groups of around 20 wells each. Abstracted water from the shallow and the deep aquifers undergoes post-treatment at the production plant at Leiduin, and is transported to the Amsterdam municipality.

3. Hydrogeology

The AWD is part of the coastal dune zone of the western Netherlands, which forms an approximately 100 km stretch along the North Sea coast. The dune zone consists of unconsolidated sediments of Quaternary age deposited under aeolian, fluvial, marine, marsh, and glacial conditions (Stuyfzand, 2003) atop the hydrogeological basement. Important formations are the shallow (unconfined/semi-confined), and deep (leaky-confined) aquifers, and the two confining layers. Below NAP -20 m is the deep, Pleistocene-age, leaky-confined aquifer, consisting of deposits of fluvial and aeolian fine sands, underlain by coarse marine and fluvial sands. All extraction wells in the AWD are screened in the deep aquifer. The shallow and deep aquifers are separated by a well-developed aquitard of marine sandy clays and peat deposits, 2 to 4 m thick (Karlsen et al., 2012). Leakage to the deep aquifer has been estimated at 7.5 million m^3, or 200 mm per year.

The deepest aquifer also consists of Pleistocene-age, marine and fluvial sands. A layer of loam, sandy clay and peat forms a confining layer above the aquifer. Successive periods of sea rise and fall during the Quaternary period has resulted in brackish to saline groundwater, present in the Pleistocene sediments, throughout the Netherlands (De Vries, 2007). The fresh-saltwater interface is found within the deepest aquifer.

4. Modelling methodology

The AMWADU model is a MODFLOW-2000 regional ground-water flow model of the AWD and surrounding areas. The initial version of AMWADU was developed by Waternet in 1988 (Olsthoorn and Kamps, 1996). Since then, the model has been progressively refined and calibrated. The most recent calibration was undertaken during 2005, and included measurements from 400 observation wells (Kamps, 2006). The model grid represents 33.6 km in the y-direction and 25.6 km in the x-direction. The grid has a variable spatial discretisation: the infiltration area has a 20 x 20 m grid spacing which 40 increases to 100 x 100 m outside of the infiltration area and 400 x 400 m at the model boundaries. The vertical extent of the model is more than 300 m, and reaches the hydrogeological basement. The model includes seventeen layers: ten aquifer layers and seven aquitard layers. Not all aquitards beneath the AWD are continuous. Where the stratigraphic layers are non-existent, they are modelled by setting the thickness of the representative layer to 0.01 m and the hydraulic conductivity to the value of the layer below.

All lateral boundaries in the first layer are modelled as river boundaries. In the west, the river boundary represents the changing head in the North Sea. The conductance is set to 4,000,000 m^2/day and does not provide resistance to flow. The remaining river boundaries represent the polder areas of the flower farms, and the Haarlemmermeer polder in the east. The infiltration ponds are modelled with the general head boundary package, with the head varying based on measured values for water height in each pond. The abstraction and storage canals are modelled using the river package, also considering measured values for head. The well package is used to model the deep pumping wells. The drain package is used to model the drains.

A MODFLOW-2005 telescopic model was developed for calibration, validation, and scenario analysis. The telescopic model covers the entire watershed of the AWD and extends to the boarder of the Haarlemmermeer Polder in the east. The model grid represents 10 km in the y-direction and 4.9 km in the x-direction with a 20 x 20m grid size within the infiltration area. All boundary conditions and initial parameters were taken from the AMWADU model. The saltwater interface was modelled with the SWI2 package.

5. Model calibration and validation

The initial telescopic model performance was tested against a historical 50 % intake reduction that occurred from 3 to 29 October 2016. The model fit was insufficient to undertake scenario analysis. The primary purpose of the model calibration was to ensure the model accurately represents the volumes that can be extracted from the AWD during an intake stoppage. Calibration of the model for the phreatic aquifer (model layers 1 to 3) considered the spatial distribution of hydraulic conductivity, storage parameters and the resistances of the infiltration ponds and drains using PEST software. The optimum parameter values were determined by comparing modelled and observed groundwater levels, and modelled and measured abstraction from the shallow aquifer.

After calibration, the net discrepancy in the flow budget was -11,000 m^3/day. This is a 40 % improvement compared to the pre-calibration model. The improvement in the water budget is translated to an improvement in the calibrated fit for the head measurements. Overall the calibrated model shows an improved prediction of the shallow water table heads compared to the pre-calibration model. There was little to no change in the modelled heads outside of the infiltration areas, with most residuals varying by less than 0.05 m. Within the infiltration areas, the model fit is improved in most wells in the shallow aquifer by an average of 0.10 to 0.25 m.

The calibrated model was tested against the period June to September 2015, to determine whether the improved model conceptualisation and calibrated parameters are suitable for periods outside the October 2016 intake reduction. A good model fit was achieved for all components in the flow budget, improving confidence in the results of the scenario analysis.

6. Result and Discussions

Prior to this research, the best estimate of the storage capacity of the dunes was 50 days, considering a production demand of 83 million m^3/year (Roebert, 1971). However, this estimate was calculated when the production demand, the layout, and the management of the dunes were quite different to the current situation. The best estimate of the dune storage considering the current layout and management of the AWD is between two and three months (Mosch, 1998).

The results of these modelling scenarios improve this estimate, considering different management options and climate conditions:

- Scenario 1 calculates the storage capacity utilising only the phreatic aquifer, for average precipitation conditions in 2016.
- Scenario 2 calculates the storage capacity utilising both the phreatic aquifer and the deep pumping wells, for the same conditions in Scenario 1.
- Scenario 3 calculates the storage capacity for a historical dry period, 2009.

The calculated storage capacity in days is based on a production demand equal to 70 million m^3/year or 192,000 m^3/day. Following the calculations of gross storage, the main constraints affecting usable storage from the dunes are discussed. The results of all the scenarios, and the constraints, are then used to identify optimal management strategies for future intake stoppages.

Ability to meet production demand

Table 1 compares the results of the scenarios. The results are provided in terms of the capacity of the AWD in days, which is comparable to the previous estimate of two to three months (Mosch, 1998). The modelling shows that the storage capacity of the AWD is greater than previously estimated, with a maximum period of 112 days (Figure 2). Even under dry conditions, the AWD can sustain an intake stoppage of 90 days provided the deep wells are utilised immediately. The results are also provided in terms of total production over the period in which the demand is met. The total production is higher than the demand times the capacity, because in all simulations there is initially a short period of over abstraction.

Total production is then split into the contributing volumes from each component of the surface and groundwater stores. The usable capacity of the storage and abstraction canals is 2 million m^3. The usable surface water volume is limited by the height difference required to sustain flow through the culverts between the canals. In most simulations, the maximum surface water volume is utilised within two to four months.

Table 1 Results of all production scenarios.

Scenario	Minimum canal level reached in # days	Weather conditions	Capacity (days)	Total production (million m^3)	Surface store depletion (million m^3)	Pumped volume (million m^3)	Precipitation recharge (million m^3)	Phreatic usable storage (million m^3)*
1a	90	Normal	4	0.4	0.1	No pumping	0.01	0.3
1b	60		10	1.1	0.5		0.07	0.5
1c	45		47	4.7	2.0		0.5	2.2
2a	90	Normal	92	8.9	2.0	4.5	1.4	1.0
2b	112		112	11.2	2.0	5.5	1.8	1.9
2c	98		98	9.7	2.0	4.1	1.5	2.1
3a	90	Dry	2	0.2	0.07	No pumping	0.04	0.09
3b			90	8.6	2.0	3.6	0.5	2.5

* *Numbers may not add up due to rounding*

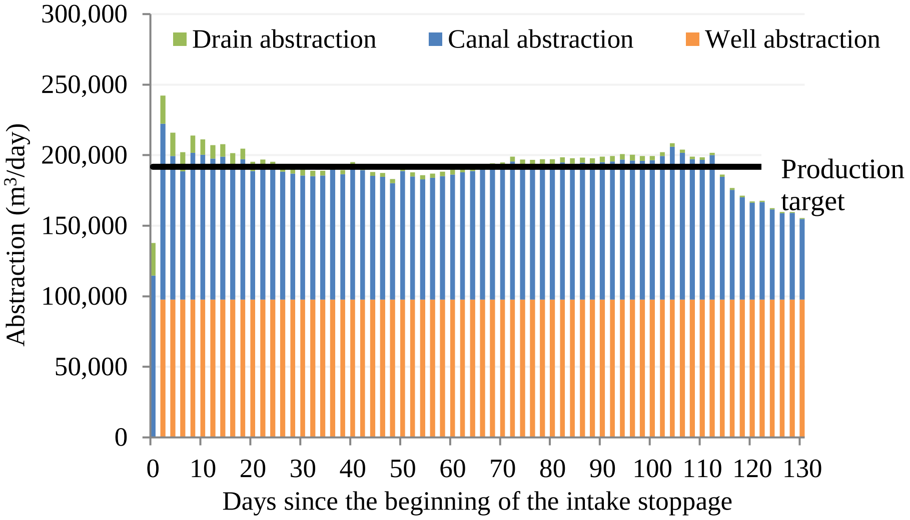

Figure 2 Production from the AWD under Scenario 2b, minimum drawdown of the canal levels.

Extraction from the deep aquifer is limited by the number of pumping wells and the maximum capacity of the pumps. The total pumped volume depends on how quickly the deep wells are utilised when an intake stoppage occurs. The results show that there is a trade-off in exploiting the volumes from the shallow and deep aquifers. Utilising the deep wells immediately reduces the depletion of the shallow aquifer and increases the length of time over which an intake reduction can be withstood. This longer period also maximises the potential that a precipitation event will occur, adding to the volume of recharge that can be exploited. On the other hand, extraction from the deep wells reduces by 5 % the volume abstracted from the shallow aquifer by increasing leakage.

Finally, the contribution of usable storage from the phreatic aquifer is calculated. The usable storage is only calculated for the period in which the demand is met, and is not the total volume of shallow storage that can be abstracted from the AWD with the current infrastructure. Initially the usable storage is high, because artificial infiltration causes mounding of the groundwater table under the infiltration areas. This volume is depleted rapidly, as can be seen from the high discharge from the drains at the beginning of the simulations. As the level of the water table declines, the rate of abstraction from the shallow storage also declines, and is then controlled by the rate of drawdown of the canal levels. Figures 2 shows that abstraction from the shallow aquifer continues once the canals are on the minimum levels, but at rates too low to meet the production demand.

Ecological constraints

A simplified assessment of the vulnerability of the dune slacks to the modelled stoppages considers changes in the wetness zones supporting different communities, as described in Geelen et al. (2016). Changes to the wet zone (depth to groundwater < 0.5 m) the moist zone (depth to groundwater between 0.5 and 1.0 m), and the dry zone (depth to groundwater between 1.0 and 2.0 m) are considered to result in vulnerability to the dune slack communities.

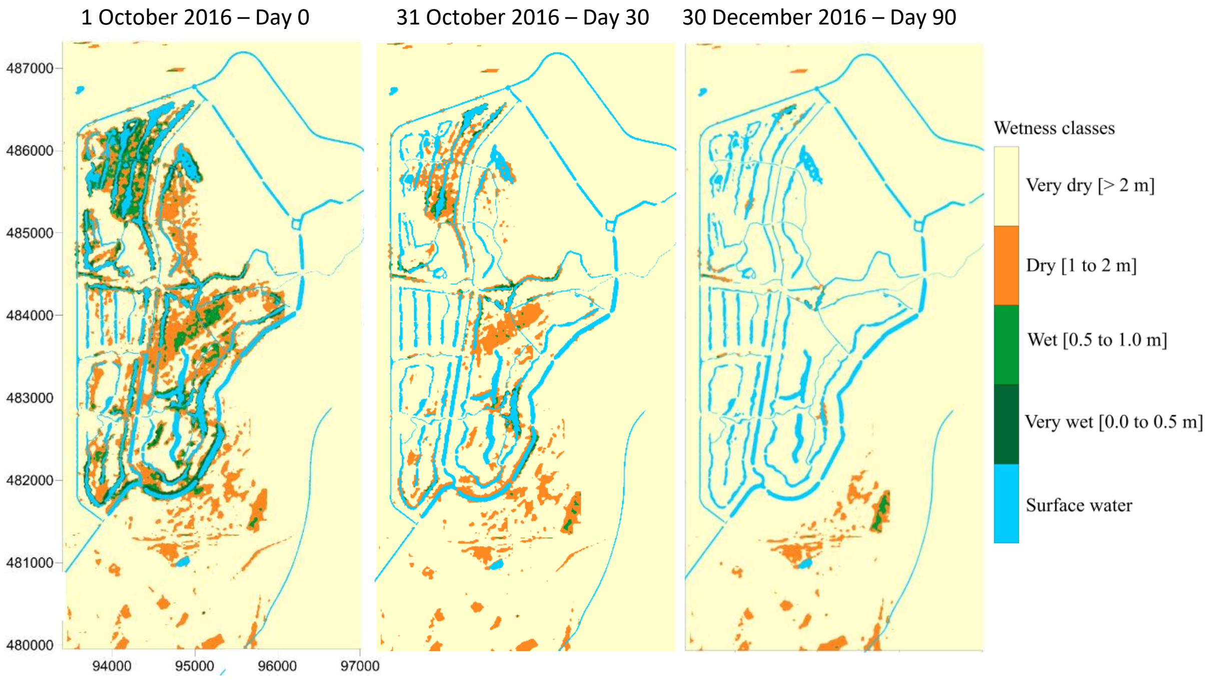

Figure 3 Modelled change in wetness classes between the start and end of the intake stoppage, minimum drawdown of the canal levels, 1 October to 30 December 2016.

The results indicate that the dune slacks are highly vulnerable to intake stoppages in the absence of deep well extraction. Thirty days after artificial infiltration ceases, there is a significant reduction in all three wetness classes. After 90 days without artificial infiltration, virtually all the very wet, wet and dry zones within the infiltration areas have become very dry, with the depth to the water table greater than two metres. A small area of moist dunes remains near the Huppelkanaal, which has a fixed outlet preventing the water level being reduced. Outside of the infiltration areas the wetness classes are largely retained, indicating that the dune slacks in this region are less vulnerable to intake stoppages as the level of the water table does not decline as rapidly. Dry years represent a greater risk to the ecological function of the dunes. A larger, and more rapid drop in the water table affects a greater proportion of the dune slack habitat, and decreases the resilience of the dune slack communities.

Water quality constraints

Salinization of the deep wells is prevented by maintaining the fresh water bubble through artificial recharge, and by limiting extraction. During an intake stoppage, utilisation of the deep wells represents a risk that salinization will re-emerge. Figure shows the spatially distributed movement of the interface after pumping at full capacity for 150 days, the maximum simulation period. Upconing can be seen underneath the pumping well groups of the Rechte-Schusterkanaal and the Nieuwkanaal in the south of the study area, and the Boogkanaal in the north. Less interface movement is seen below the Oosterkanaal well group, and almost no movement under the other well groups. The results match the expectations of the well groups vulnerable to salinization based on the geology of the dunes and historical measurements. The well groups showing an interface rise of more than 3 m are all located in areas were the clay aquitard is not present below the deep aquifer.

The maximum increase in the interface of 5.2 m below the Boogkanaal well group. Pumping near the Boogkanaal began in 1903, and was ceased in 1978 due to the increase in chloride concentration in the wells. During the period of salinization, there were 79 pumping wells extracting a total of 3.6 million m^3/year. The rate of increase in the brackish interface was estimated between 1 and 3 m/year, depending on the total extracted volume (Kooiman, 1983). In this modelling, extraction from the Boogkanaal pumping group was approximately 1 million m^3 over the 150-day simulation period. The modelled rate of increase in the fresh-saltwater interface is therefore higher than historical measurements. No parameters in the deep aquifer were adjusted for this modelling. The ratio of vertical to horizontal hydraulic conductivity was set to 1, which likely overestimates the rise in the interface.

Based on the comparison to historical data and modelling, the modelled increase in the fresh-saltwater interface is reasonable. The measured depth from the well filters in the deep aquifer to the fresh-brackish interface (300 mg/L isoplane) is more than 40 m for all well groups (Kamps, 2010). Dispersion effects, which are not taken into account with the SWI2 package, mean that the rise of the brackish interface will be greater than the rise of the saltwater interface. Historically, the measured rise in the brackish interface under the AWD was around 5 times greater than the rise in the saltwater interface after sustained over abstraction of the deep aquifer (Schuurmans, 1983 in

Olsthoorn and Mosch, 2002). Assuming a similar rise in the brackish interface as was observed during historical salinization periods, these results indicate that there would be little or no increase in chloride concentration in the deep wells after pumping for 150 days. This means that chloride is not a constraint on usable storage during an intake stoppage of this duration.

5. Conclusions

The scenario analysis shows that the AWD can meet production demand during a complete intake stoppage for a maximum of 112 days, if the deep wells are utilised immediately. This represents a 25 % increase on the upper end of the previous estimate of two to three months' capacity. In terms of production, the AWD is more capable of withstanding an intake stoppage than previously believed.

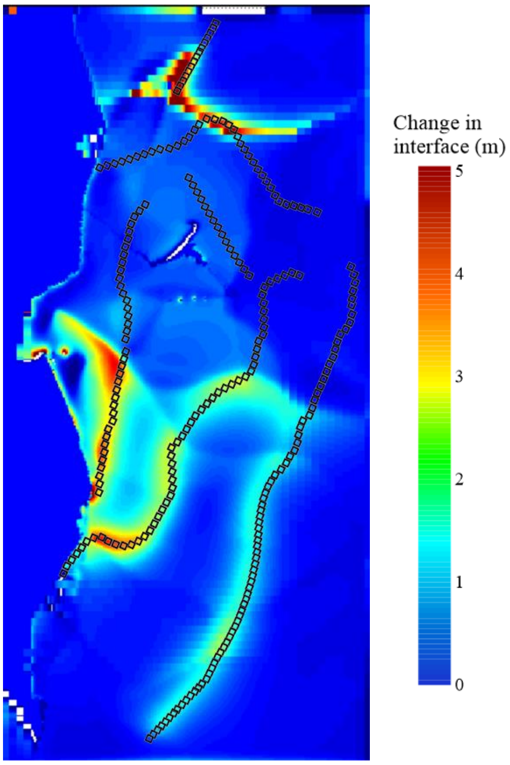

Figure 4 Movement of the fresh-saltwater interface (position at the final time step minus position at the initial time step) with pumping at full capacity for 150 days in 2016

The results show that management decisions over the first days of an intake stoppage are the most important factor in determining how long the AWD can withstand an intake stoppage. Production can be met for 47 days by rapidly drawing down the levels of the canals and depleting the surface water and shallow aquifer store. However, this strategy is extremely risky if an intake stoppage lasts longer than expected. Once the minimum canal levels are reached, drinking water demand from Amsterdam cannot be met with any existing management measures in the AWD. Utilising the deep wells as soon as the intake stoppage occurs results in the greatest period of production. Therefore, the current Waternet management plan does not represent the best strategy in terms of maintaining production. Waiting until the calamity levels are met before beginning deep well extraction foregoes 1.4 million m^3 of production from the deep aquifer. This results in two weeks less production capacity than Scenario 2b, which begins full capacity pumping on the first day of the intake stoppage.

Water quality is not a constraint on the utilisation of the deep wells over 150 days, the maximum period of an intake stoppage considered in this study. The main constraint on production from the deep aquifer is the maximum capacity of the pumping well groups. Drawdown in the deep aquifer after sustained pumping can reduce the discharge from the deep wells, but this can be managed by using variable frequency pumps or by manually increasing discharge through manipulation of the valves between the wells and the collector pipes. The risk of generating brackish water by sustained utilisation of the deep wells, decreasing the size of the freshwater bubble and reducing the available storage, has not been considered in this research. This risk is particularly high if multiple intake stoppages occur leading to successive pumping-induced contractions then recovery of the freshwater bubble.

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