Impact of long well screens on monitoring of the freshwater-saltwater transition zone in coastal aquifers

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ABSTRACT
The Magdalen Islands are an archipelago vulnerable to climate change as sea level rise, coastal erosion and changes in precipitation and temperature patterns can impact its freshwater resources. Monitoring the depth of the saline groundwater, located below its freshwater lens, is necessary in order to ensure a sustainable supply. A network of monitoring wells has been installed with long screens across the transition zone between freshwater and saltwater. It has been demonstrated that well screens could lead to a biased observation of the freshwater-saltwater interface caused by vertical flow within the well that changes the position of the interface from its natural elevation. A numerical approach was used to evaluate the presence of a bias within a long-screened monitoring wells and a parametric analysis of the well distance from the coast, screen diameter and length was carried out.

RÉSUMÉ
Les Îles-de-la-Madeleine sont vulnérables aux changements climatiques avec la montée du niveau de la mer, l'érosion côtière et des variations au niveau des précipitations et des températures pourraient affecter ses ressources d'eau douce. Le suivi de la profondeur des eaux souterraines salines est nécessaire afin d'assurer un approvisionnement durable. Un réseau de longs puits d'observation y surveille la zone de transition entre l'eau douce et l'eau salée. Il a été démontré que des puits ouverts profonds pourraient conduire à une observation biaisée de l'interface eau douce – eau salée en raison d'un écoulement vertical à l'intérieur du puits qui modifie la position de l'interface par rapport à son niveau d'origine. Une approche numérique a été utilisée pour évaluer la présence d'un biais à l'intérieur d'un long puits ouverts et une analyse paramétrique de la distance du puits à la côte, du diamètre et de la longueur ouverte a été réalisée.

1 INTRODUCTION

Small saltwater islands often rely on groundwater resources for water supply, which occurs as a buoyant lens-shaped body lying above saltwater. However, such islands are particularly vulnerable to climate change as sea level rise, coastal erosion and changes in precipitation and evapotranspiration patterns can modify the size and shape of the freshwater lens, adversely impacting groundwater resources or requiring adaptation to pumping infrastructure. It is therefore important to monitor the transition zone, where the freshwater progressively mixes with the saltwater, in order to understand the impact of climate change on groundwater resources. One way to do this is to use monitoring wells with long screens that cross the freshwater-saltwater transition zone (also referred as the "interface") where depth is measured by carrying out an electrical conductivity profile. By conducting repeated profiles, it is possible to follow its vertical migration.

On the Magdalen Islands, a groundwater well network has been set up to monitor the interface and to evaluate the impact of climate change on groundwater supply (Lemieux et al., 2017). The monitoring wells have a total length between 60 and 201 meters and have long open sections (between 42 and 189 m) intersecting the transition zone. Electrical conductivity profiles are taken annually to monitor the elevation of the transition zone. The profiles recorded at one of these wells are presented in Figure 1. Two observations can be made from this data. First, the interface elevation quickly increased after the well installation and second, the concentration of the saltwater zone has slowly decreased over the years. These observations suggest that the installation of the well causes a change in local groundwater flow conditions which can lead to a bias in the monitoring of the transition zone.

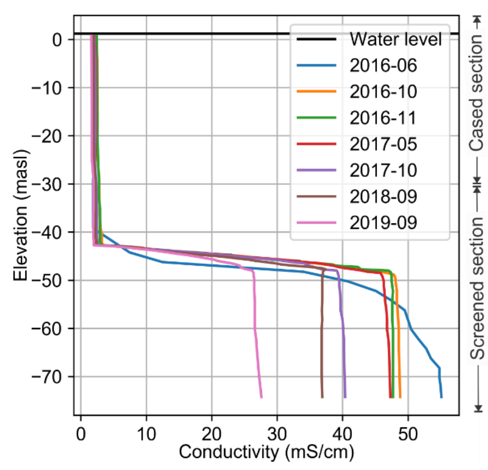

Figure 1. Electrical conductivity profiles from a monitoring well in the Magdalen Islands (F-2). Installation year : 2015.

The effect of long well screens in coastal aquifers is well documented, they introduce a preferential flow path for groundwater which creates a bias in the measured hydraulics heads (Church and Granato, 1996). The well acts as a short circuit by connecting zones with different hydraulic heads, which leads to preferential vertical flow inside the well (Elci et al., 2001). This vertical flow is influenced by the percentage of well penetration into the aquifer. Elci et al. (2001) found that vertical flow starts to increase rapidly with a penetration of 10% of the aquifer and peaks when the well intersects 100% of the aquifer.

A study conducted by Shalev et al. (2009) revealed that long monitoring well screens could lead to a biased measure of the location of the interface. The bias is linked to the vertical flow rate inside the well which is correlated to the vertical hydraulic gradient. It is also strongly affected by the anisotropy in the aquifer's hydraulic conductivity since increased anisotropy leads to an increase of the hydraulic head gradient at the well (Shalev et al, 2009). The known effects of the well are summarized in Figure 2.

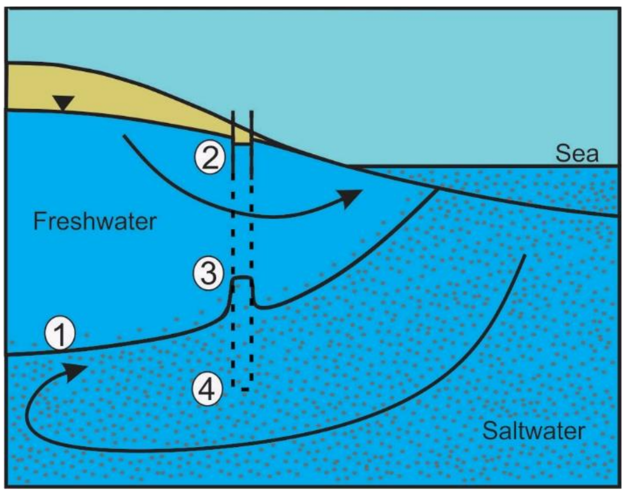

Figure 2. Conceptual model of groundwater flow in a coastal area highlighting 1) the freshwater-saltwater interface, 2) a drop of the water level inside the well, 3) the rise of the interface inside the well and 4) a decrease in the concentration of the saltwater inside the well.

The objectives of this study are to evaluate the bias in the position and shape of the transition zone, along the time scale over which it occurs, for the Magdalen Islands monitoring network, using a numerical model. While the study is designed around the Magdalen Islands site conditions, a parametric analysis is also performed to investigate which and how a broad set of parameters common to many coastal area settings may affect the bias.

2 STUDY AREA

The study site is on the Magdalen Islands, a small archipelago in the Gulf of St-Lawrence approximately 100 km north-east of Prince Edward Island. Four stratigraphic units have been mapped by Brisebois (1981) in the archipelago, the formations of Havre aux Maisons (breccia), Cap au Diable (basalt), Cap-aux-Meules (sandstone and siltstone) and Étang-des-Caps (aeolian sandstone). The Étang-des-Caps formation, composed of poorly cemented and highly permeable red sandstone, is the main aquifer in the archipelago where the municipal wells and the groundwater monitoring network are located. The specific study site is on the island of Grande Entrée which is situated in the north-east of the archipelago. There are 4 monitoring wells on Chemin du Bassin Est identified as F-1 to F-4 (Figure 3). F-1 and F-2 are in the Étang-des-Caps formation while F-3 and F-4 are in a sand valley (Lemieux et al., 2017). The data presented in Figure 1 were collected inside F-2.

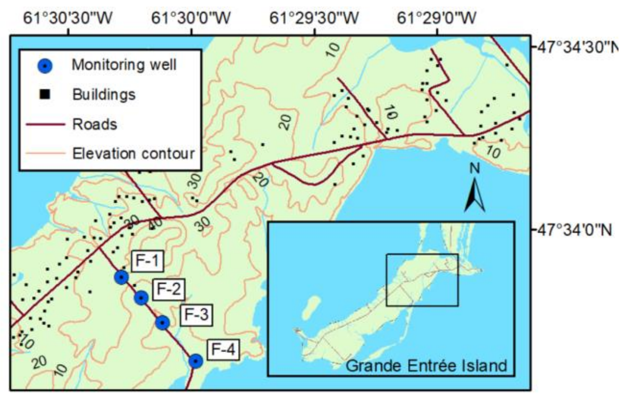

Figure 3. Location of 4 wells from the monitoring network on the Island of Grande Entrée.

3 METHODOLOGY

3.1 Numerical model

To evaluate the bias of the freshwater-saltwater transition zone inside a monitoring well, the 3D numerical model SALTFLOW (Molson and Frind, 2020) is used to simulate coupled density-dependent groundwater flow and mass transport. The 3D model has a length of 800 m, a height of 100 m and a symmetric half-width of 5 m. The 3D model is discretized using a regular grid of 2 m × 1 m × 1 m and a uniform time-step of 10 days to simulate the initial steady-state conditions. The presence of the sand valley is not considered in order to simplify the numerical model. This is justified by the grain size distribution and hydraulic properties of the sand which are very similar to those of the sandstone. The flow and transport boundary conditions are summarized in Figure 4. A fixed concentration representing freshwater total dissolved solids (TDS) of 0 g/L and a recharge rate of 160 mm/year are applied over the land surface. Offshore, a fixed concentration is applied to represent saltwater TDS (35.4 g/L) and the hydraulic head is fixed at 100.1 m because the local sea level is at 0.1 m above mean sea level (Lemieux et al., 2015). This fixed saltwater concentration is automatically switched to a zero-gradient transport boundary where water discharges along the coastline. All other boundaries are set to be impervious for flow and zero-gradient transport. The aquifer parameters, similar to those used by Lemieux et al. (2015), are presented in Table 1. A long transient simulation is carried out until steady-state conditions are reached for heads and TDS concentrations.

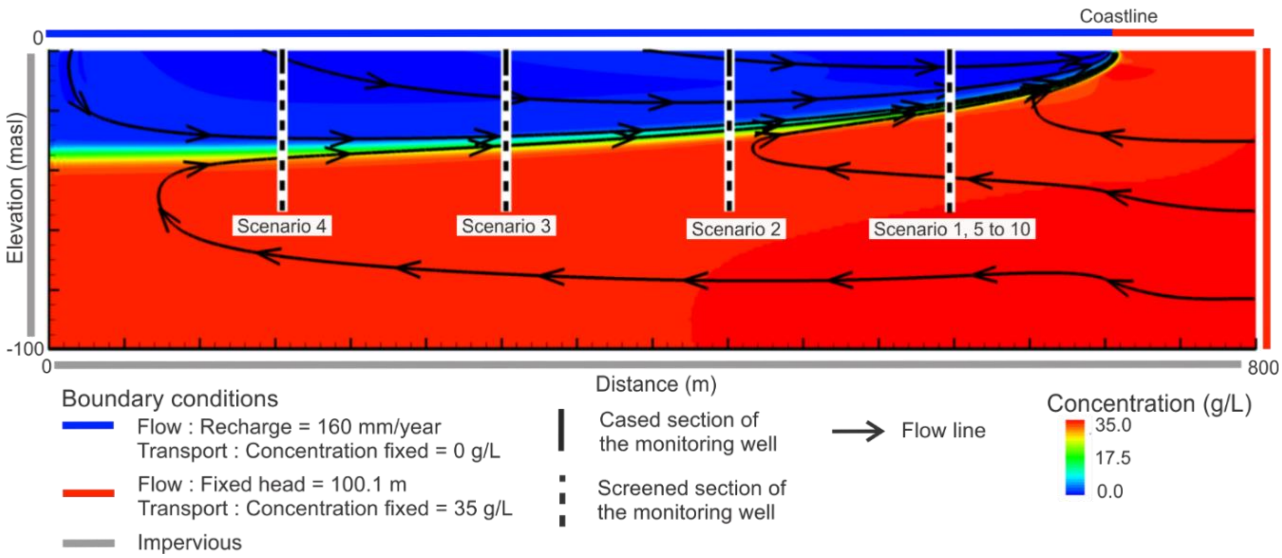

Figure 4. Cross-section of the steady-state simulation without wells, showing boundary conditions and flow lines. (Vertical exaggeration : 2x)

Table 1. Aquifer parameters assumed in the model.

Parameters	Value
Hydraulic conductivity (m/s)	
Horizontal	8.1×10^{-5}
Vertical	8.1×10^{-6}
Porosity	0.3
Specific Storage (m^{-1})	10^{-4}
Dispersivities (m)	
Longitudinal	10
Transverse horizontal	1
Transverse vertical	0.01

The results from the steady-state simulation are then used as the initial conditions for simulations with a monitoring well. The open well is simulated as a high-K 1D line element placed within the y=0 symmetry plane. In the base case simulation (Scenario 1, Table 2), the well is located 100 m from the coastline and has a diameter of 15.64 cm (6 inches). It has a total length of 54 m but is only open from a depth of 8 m to 54 m below the water table for an open length of 46 m. The simulation with the monitoring well is run until a new steady state is reached (which takes on average 5 years) with a uniform time step of 0.1 day.

The initial steady-state TDS concentration profile in the aquifer is extracted before the insertion of the well. This background profile serves as a reference to determine the natural elevation of the interface. New TDS concentration profiles are then extracted from the simulations with the added well. To measure the increase of the interface elevation, a threshold of 50% of the maximum TDS concentration inside the well is used. The vertical flow velocity profiles within the well are also extracted.

A parametric analysis is then carried out to determine which parameters influence the elevation, shape and evolution of the transition zone in the monitoring well. The parameters tested are the distance between the well and the coastline, the well diameter and the length of the screened interval. The tested scenarios are presented in Table 2. The impact of an increasing elevation of the interface in the well on TDS concentrations in the aquifer will also be investigated.

Table 2. Scenarios tested during the parametric analysis and corresponding parameter values.

Scenario	Well distance from the coast (m)	Well diameter[1] (cm)	Well screen length (m)
1	100	7.62	46
2	250	7.62	46
3	400	7.62	46
4	550	7.62	46
5	100	5.08	46
6	100	10.16	46
7	100	12.7	46
8	100	7.62	36
9	100	7.62	56
10	100	7.62	66

[1]Note that because of the domain symmetry along the y=0 plane, only one-half of these full diameters are applied in the model.

4 RESULTS

4.1 Evolution of the TDS concentration profile at the well over time

Concentration profiles at different times are extracted from the base case simulation (Scenario 1) to follow the evolution of the transition zone over time (Figure 5a). Analysis of the different TDS concentration profiles clearly demonstrates an increase of the interface elevation over time. The increase, which reaches 2.6 m after only a week, finally stabilizes at 5.3 m after 5 years. There is also a decrease of the saltwater concentration inside the well over time. After one week, the concentration has already decreased by 3 g/L and eventually stabilizes 5 years after its insertion with a total decrease of almost 7 g/L. The vertical flow velocity profile extracted at each time (Figure 5b) reveals that upward flow is occurring within the well which increases over time. The vertical flow velocity is rather low above the center of the transition zone. Below the inflection point, the vertical velocity increases significantly and reaches a maximum value at an elevation close to -40 masl (meter above sea level). The maximum velocity is 0.01 m/s after a week and eventually stabilizes at 0.014 m/s in this scenario.

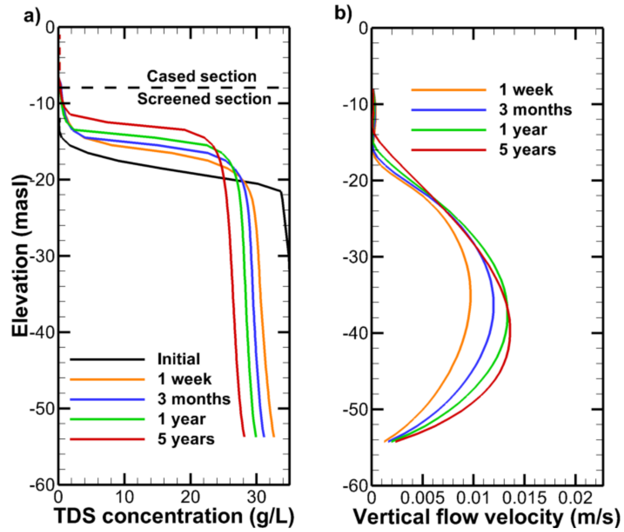

Figure 5. a) TDS concentration profiles over time (Scenario 1) compared to the initial profile without a well and b) comparison of vertical flow velocity profiles over time. A positive velocity indicates upward flow.

4.2 Distance of well from the coast

Figure 6 presents the vertical interface displacement for monitoring wells at different distances from the coast. The interface elevation in the well increases as the distance to the coast decreases, in particular increasing from 0.9 m to 5.8 m when the distance from the coast decreases from 550 m to 100 m. No effect on the saltwater TDS concentration inside the well was detected. The vertical flow profiles were also extracted from the simulations. In each case, the extracted vertical flow velocity is always upward. The vertical flow velocity is highest in the well closest to the coast, increasing from 0.005 m/s to 0.014 m/s when the distance decreases from 550 m to 100 m.

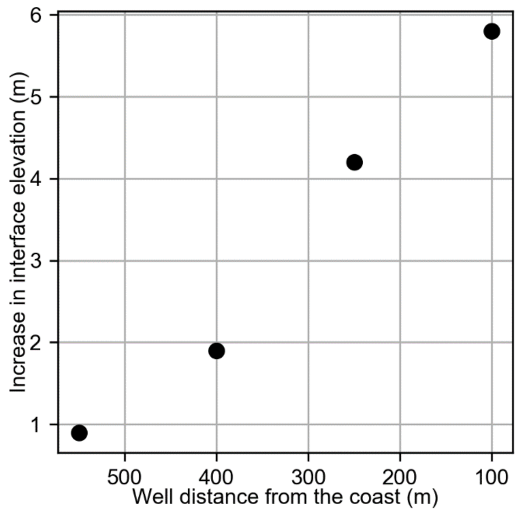

Figure 6. Change in the interface elevation within monitoring wells at different distances from the coast after 5 years (Scenario 1 to 4). (Elevation increase is with respect to the initial steady-state interface elevation without a well).

4.3 Well diameter

The results of the parametric analysis with respect to the well diameter, after a simulation time of 5 years are presented in Figure 7a). The simulated TDS concentration profiles indicate that as the well diameter increases, the vertical displacement of the interface within the well also increases. Specifically, the interface elevation increases from 3.7 m for a well with a diameter of 5.08 cm (2 inches) to 10.3 m for a well with a diameter of 12.7 cm (5 inches).

The well diameter also has an effect on the saltwater TDS concentration, as the decrease from the initial TDS concentration is more significant in larger diameter wells. Specifically, concentrations decreased by 5 g/L for the well with a diameter of 5.08 cm (2 inches) and decreased by 11 g/L for the well with a diameter of 12.7 cm (5 inches).

The vertical flow profiles (Figure 7b) reveal that smaller well diameters lead higher flow velocities within the well. Velocity increases from 0.007 m/s to 0.021 m/s when the diameter decreases from 12.7 cm (5 inches) to 5.08 cm (2 inches). Again, vertical flow within the well is always upward for these simulations.

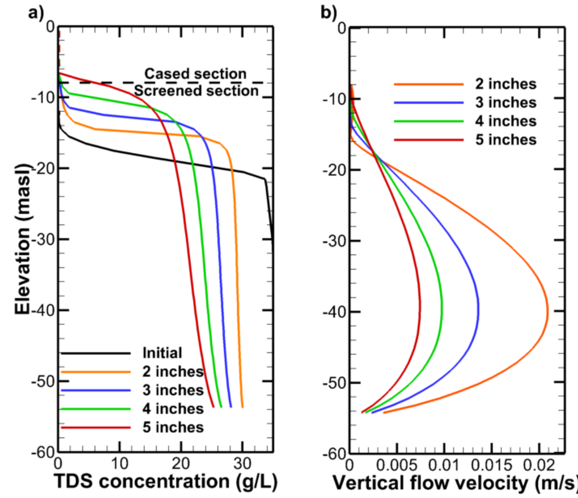

Figure 7. a) Comparison of TDS concentration profiles and b) comparison of vertical flow velocity profiles within different diameter wells, after 5 years (Scenario 1, 5 to 7)

4.4 Well screen length

Results of the parametric analysis with respect to screen length, after a simulation time of 5 years are presented in Figure 8. A linear effect is seen in which the open wells with longer screens induce a greater increase of the interface elevation, increasing by 4.9 m for the well with a length of 36 m to 7.3 m for a well with a length of 66 m. The variation in the length of the well screen has no impact on the saltwater TDS concentration; the decrease in TDS is similar in all cases. Vertical flow profiles extracted from the simulation revealed that the longer screens have higher vertical flow velocities increasing from 0.009 m/s to 0.022 m/s when the screen length increases from 36 m to 66 m.

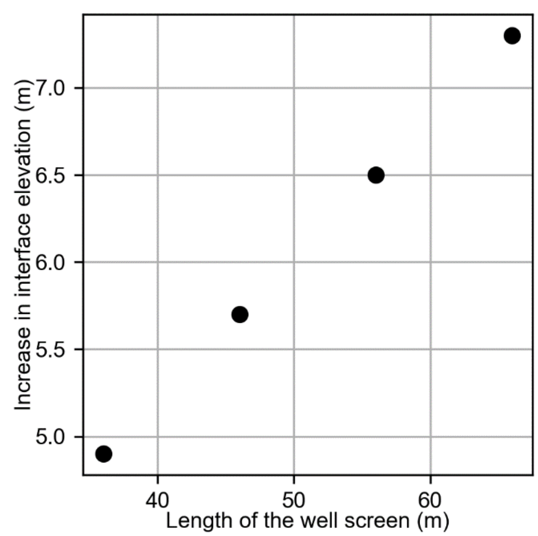

Figure 8. Change in the elevation of the interface for different well screen lengths after 5 years (Scenario 1, 8 to 10). (Elevation increase is with respect to the initial steady-state interface elevation without a well).

4.5 Impact of the monitoring well on the surrounding aquifer

Figure 9 presents in cross-section the simulated flow lines and TDS concentration distribution from Scenario 1 after 5 years, containing a well 100 m from the coast. Compared to the initial flow system without a well (Figure 4), the flow lines from the saltwater zone are now shifted towards the monitoring well. The inflow of water from the aquifer towards the well occurs only in the saltwater zone, until a point of inflection that corresponds to the elevation where vertical flow is highest. Above this point, outflow is outward toward the aquifer resulting in decreasing vertical flow rates within the well. This behavior creates a recirculation zone of somewhat diluted salty groundwater.

The simulation shows that the effects of the open well extend a significant distance into the aquifer, decreasing the aquifer's TDS concentration in a zone with a diameter of approximately 100 m. It also demonstrates that the increase of the interface elevation extends well beyond the monitoring well into the aquifer. The increase of the interface is highlighted by the lowest flow line within the freshwater zone, which closely follows the top of the interface as it rises and passes through the well near the top of the well screen.

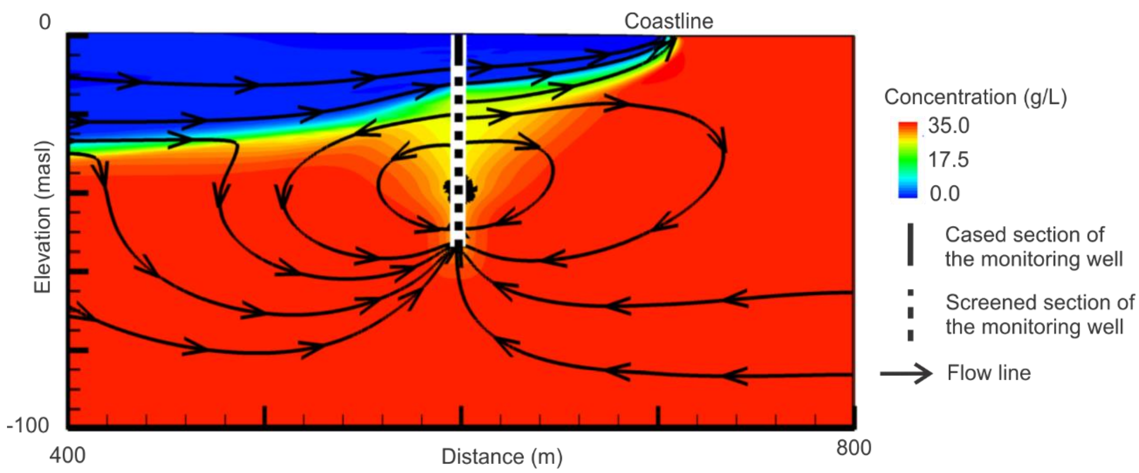

Figure 9. Cross-section of the 3D steady-state flow and transport simulation with an open monitoring well (Scenario 1). Note that the flowlines are based on the 2D (x-z) components of the 3D velocity fields but are nevertheless representative of the true flow patterns within the section. (Vertical exaggeration : 2x)

5 DISCUSSION

The simulated concentration profiles indicate that the construction of a monitoring well instantly changes the equilibrium of the aquifer. It only takes a few days to immediately see a change in the elevation of the interface.

A slow decrease of the TDS concentration then occurs in the saltwater portion of the well until it stabilizes after a few years. This decrease in the salinity of the well is an important phenomenon, as electrical conductivity profiles are often used to derive saltwater properties such as salinity or density (e.g., Post, 2012). Using the lower electrical conductivity values in these wells would yield strongly biased saltwater properties.

The simulated final increase in the elevation of the interface can be quite significant, reaching as much as 4.8 meters in the base case before it finally stabilizes as seen in Scenario 1. This demonstrates that monitoring wells with a long well screen can be unreliable for the monitoring of the interface.

The vertical flow profile extracted from the simulations provided insights on the processes leading to the interface bias caused by the wells. All the simulations revealed an upward flow within the well. This upward flow can be responsible for the displacement of the interface and the decrease of the concentration within the well. Rotzoll (2010) indeed demonstrated that upward vertical flow leads to a rise of the interface in the well, whereas a downward flow leads to a lowering of the interface elevation. Also, Church and Granato (1996) found that upward flow inside a long well screen can lead to a decrease of the concentration of a dissolved solute because of dilution.

The parametric analysis allowed to explore the impact of different parameters of the monitoring well on the interface bias and concentration profiles.

The effect of the distance to the coast is quite important and increases as the monitoring well approaches the coast. This could be explained by the fact that wells which are closer to the coast have a higher vertical hydraulic gradient. The difference in the hydraulic heads of the connected zones is thus greater in these areas. This reveals that more accurate monitoring of the interface can be obtained at greater distances from the coast.

The effects of the well diameter are interesting because of the double effect it creates. A wider well diameter leads to a linearly greater increase in the interface elevation and to lower saltwater TDS concentrations. The well diameter had the most influence on the increase in the interface elevation within the well, with an increase of 10.3 m in the worst case scenario which had a diameter of 5 inch. This means that it would be better to have the smallest well diameter possible to limit the effect that it has on the interface.

The decrease in TDS concentrations in the saltwater portion as the well diameter increases is related to the convection cell shown in Figure 9 which dilutes the saltwater in the well. Volumetric fluxes through the well increase with increasing well diameter which would increase the dilution effect.

The length of the well screen was shown to have an impact on the interface elevation but not on the saltwater TDS concentration. Longer well screens induce greater increases in the interface elevation than shorter ones. This could be explained by the fact that they connect zones with greater hydraulic head differences which would lead to higher vertical flow rates inside the well as demonstrated by Elci et al. (2001). A shorter well can therefore provide a more accurate representation of the position of the interface within the aquifer. These results are consistent with those obtained from Levanon et al. (2013) who demonstrated that shorter well screens limit the vertical flow inside the well and can improve the quality of the monitoring network. These types of wells would thus be more suited to monitor the interface. Monitoring wells should also not extend much deeper than what is needed to determine the position of the interface.

The simulation results for the wells at different distances from the coast reveal that higher flow velocities within the well led to a greater increase of the interface elevation. The same trend was seen in the simulations where different screen lengths were tested. The simulations where the well diameter was varied showed the reverse effect where the highest vertical flow rate was linked to the smallest elevation increase, but a higher velocity in a smaller diameter does not necessarily lead to a greater influx of water. By looking at the volume of water displaced instead of the velocity, the volumetric flow rate actually increases with larger diameter. In particular, the flux increases from 0.000042 m^3/s to 0.000095 m^3/s when the diameter increases from 5.08 cm (2 inches) to 12.7 cm (5 inches). Flow velocities can therefore be misleading in situations where different wells with different diameters are present.

All results from all simulations have been summarized in Figure 10 to illustrate the link between the vertical volumetric flow rate in the well and the increase of the interface elevation within the well. Figure 10 reveals an important correlation between vertical volumetric flow within the well and the increase of the interface elevation. The graph seems to present two trends, one that regroups the scenarios where the well diameter and the distance from the coast were tested and another where different screen lengths where tested.

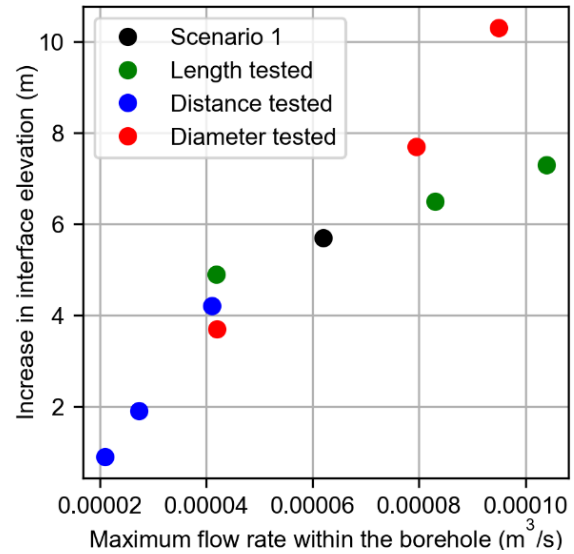

Figure 10. Simulation results of the increase of the interface elevation for different maximum vertical flow rates within the well (Scenario 1 to 10).

6 MODEL LIMITATIONS

The numerical model developed here is a simplification of the field conditions and the results may not accurately represent the specific conditions on the Magdalen Islands. However, they are considered sufficiently realistic to provide a quantitative assessment of the expected bias. The model was developed to explore the effect of installing a screened monitoring well that crosses the transition zone and not to recreate exact conditions from the field. Therefore, the increase in the elevation of the interface obtained in this study may not be exactly representative of field conditions. Local heterogeneity of the aquifer on the site may also have an important effect on the TDS concentration profiles and could lead to differences since this study has assumed homogenous conditions. An example is the sand valley observed on the site that has been neglected to simplify the development of the numerical model. These heterogeneities in the aquifer could affect the groundwater flow paths leading to different results from those obtained here. The relatively narrow width of the model (using a half-domain that is 5 m wide) might also have had an impact on the results, especially noting the conditions where a 100 m zone in the vertical cross-section was shown to be affected by the well. The effect of the tides has also not been introduced in this model which could have an impact on the shape of the TDS concentration profiles within the wells as observed by Shalev et al. (2009). Anisotropy is also an important parameter that was neglected. Recent field investigations were conducted in the field to asses the anisotropy ratio which will later be added to the analysis.

7 CONCLUSION

This study explored the effect of a long well screen on the freshwater-saltwater interface by using field observations and a 3D numerical model. The modelling revealed that the introduction of a long well screen led to an increase of the interface elevation and a decrease in the saltwater TDS concentration inside the well. The investigation found that an upward flow component within the well is responsible for the increase of the interface elevation in the well. Therefore, the measured position of the interface within a monitoring well does not give an accurate representation of the true interface elevation within the aquifer nor is the electric conductivity of the well water representative of the water salinity in the aquifer. These results are supported by field observations in monitoring wells.

Many parameters of the monitoring wells were explored to evaluate their influence on the increase of the interface elevation and on monitored salinity. Wells with wider diameters, longer well screens and which are closer to the coast all showed a greater upward migration in the position of the interface. For the most accurate monitoring of interface elevations, it is therefore critical to properly design the monitoring well, choosing characteristics to limit their effects. The impact of such monitoring wells on the aquifer surrounding the well was also investigated and revealed that introducing a monitoring well shifts groundwater flow lines in the aquifer toward the well and that the TDS concentration also decreases around the well. A link between the magnitude of the vertical volumetric flow rate and the increase of the interface elevation has been found which could be used to estimate the magnitude of an elevation increase on the Magdalen Islands if the vertical flow rate within the well can be measured. This data could be obtained with the help of a flowmeter.

Future work will examine the hydraulic head gradient within the well for the different scenarios. Cumulative impacts of multiple wells in a single simulation will also be investigated. Other parameters will be tested, in particular the anisotropy of the aquifer hydraulic conductivity, which may lead to even greater bias in the measurement of the interface elevation.

8 ACKNOWLEDGMENT

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9 REFERENCES

Brisebois, D. 1981. Lithostratigraphie des strates permo-carbonifères de l'archipel des Îles de la Madeleine (Lithostratigraphy of the Permo-Carboniferous Strata of the Magdalen Islands). Ministère de l'énergie et des ressources du Québec.

Church, P.E. and Granato, G.E. 1996. Bias in ground-water data caused by well-bore flow in long-screen wells. *Ground Water*, 34, (2): 262–273.

Elci, A., Molz, F.J. and Waldrop, W.R. 2001. Implications of observed and simulated ambient flow in monitoring wells. *Ground Water*, 39, (6): 853–862.

Lemieux, J.-M., Dupuis, J.C., Chouteau, M. and Cochand M. 2017. Déploiement du réseau de suivi des eaux souterraines du Québec aux îles de la Madeleine. Département de géologie et de génie géologique, Université Laval, 108 p.

Lemieux, J-M., Hassaoui, J., Molson, J., Therrien, R., Therrien, P., Chouteau, M. and Ouellet, M. 2015. Simulating the impact of climate change on the groundwater resources of the Magdalen Islands, Québec, Canada, *Journal of Hydrology : Regional Studies,* 3, 400–423.

Levanon, E., Yechieli, Y., Shalev, E., Friedman, V. and Gvirtzman, H. 2013. Reliable monitoring of the transition zone between fresh and saline waters in coastal aquifers, *Groundwater Monitoring & Remediation*, 10 p.

Molson, J.-W. and Frind, E. O. 2020. Saltflow, Version 4.0, Dept. of Geology & Geological Engineering, Université Laval, Quebec City, 88 p.

Post, V. E. A., 2012. Electrical conductivity as a proxy for groundwater density in coastal aquifers. *Ground Water*, 50, (5), 785-792

Rotzoll, K. 2010, Effects of groundwater withdrawal on borehole flow and salinity measured in deep monitor wells in Hawai'i-implications for groundwater management. *U.S. Geological Survey Scientific Investigations Report 2010-5058*, 42p.

Shalev, E., Lazar, A., Wollman, S., Kington, S., Yechieli, Y. and Gvirtzman, H. 2009. Biased monitoring of fresh water – salt water mixing zone in coastal aquifers, *Ground Water*, 47, (1): 49-56.