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# Implication of density-dependent flow on numerical modelling of SW-GW interactions

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**Abstract:** With the growing interest in the last decades in the modelling of hydrogeological processes involved in the water resources management, it has been recognized that the assumption of constant-properties water is no longer adequate in the analysis and simulation of the flow considered in these cases. In recent years, many studies used simplistic approaches that may not represent the aquifer flow dynamics realistically by not accounting for changing fluid density. This study explore the importance of understanding the impact of density-dependent flow on SW-GW interactions. To this aim two synthetic models was developed at large and small scales and various scenarios were defined to explore the impact of density-dependent flow on drivers including river and aquifer salinity ratio, hydraulic gradient and river geometry. The results shows that simplifying by excluding density-dependent flow leads to overestimation of solute mass accumulation, and eventually groundwater salinity and limited freshwater lens. Also, the simulated model without density-dependent flow is not able to represent the unsaturated zone properly. However, these impacts are limited to the river banks. In the small scale, when simulated with density-dependent flow, large salinity ratio between river and aquifer can significantly influence both solute and flow dynamics. Moreover, mixed-convention was observed when hydraulic gradient was towards river. Overall, it was concluded that density-dependent flow play an essential role in SW-GW interaction and needs to be taken in to account where the river and aquifer have significant salinity difference, particularly at the vicinity of the river banks.

***Keywords**:* SW-GW interaction; numerical modelling; density-dependent flow.

## 1 INTRODUCTION

In hydraulically-connected SW-GW systems, the flow is considered to be a direct function of the head difference between the surface water body (river, lake or wetland) and the groundwater aquifer and of the hydraulic conductivity of the semi-permeable river sediments. In fact, the great majority of hydrogeological studies have addressed the problem of groundwater flow by considering the water as having constant density and the flow as being driven by pressure differences only, referred as hydraulic-dependent flow. Most of the studies on SW-GW interactions have focused on hydraulic-driven flows (Kollet and Maxwell, 2006, Meire et al., 2010, Partington et al., 2011, Alaghmand et al., 2013). This is the most common approach to analyze flow and solute dynamics. However, it can only be reliable when there is not significant density difference between the two domains.

Fluid density decreases with increasing temperature, increases with increasing salinity and increases with increasing pressure due to fluid (Graf and Therrien, 2005). Density-dependent flow is a term which applies to the behavior of water transport in accordance to the changes in the density of water (Holzbecher, 1998). For instance, when salinity of the groundwater becomes considerable high, density-dependent flow becomes dominant, and therefore, may lead to formation of mixed-convection (Schincariol, 1997). Mixed-convection is a combination of forced (density-dependent) and free (hydraulic-dependent) convections, which is the general case of convection when a flow is determined by the non-uniform density distribution of a fluid medium in a gravity field. In fact, this is where density differences complicate the aquifer flow patterns and velocity fields (Oldenburg and Pruess, 1995, Woods et al., 2003). Therefore, solute transport models for use in these settings must account for density-dependent flow, solute advection, diffusion and dispersion (Murgulet and Tick, 2016). Density-dependent flow is important in a number of natural systems including upcoming below wells (Diersch, 1984, Reilly, 1987), seawater intrusion in coastal regions (Cheng, 2001, Werner et al., 2013) and waste disposal in deep salt formations (Kolditz, 1998, Oldenburg, 1995) or saline disposal basins and salt lakes (Liu, 1996, Simmons, 2002, Wooding, 1997).

To date, many studies have been conducted for the simulation of SW-GW interactions without taking density difference into account. Thus, there is a need for a numerical model that accounts for the effects of salt concentrations on the water density and flow. The consequences of this simplifying assumption are not completely known. The question is to what extent density-dependent flow impacts the SW-GW interactions process. We know that SW-GW simulation using density-dependent mode is time-consuming and computationally challenging. Hence, we intend to quantify the implication of density-dependent flow in SW-GW interactions numerical modeling. And to see when it is essential to include it or under what circumstances this could be simplified. We have designed various scenarios to investigate whether simulating using density-dependent mode can significantly increase the accuracy of the results. Therefore, all the scenarios are to be run with and without density-dependent mode

## 2 NUMERICAL MODELLING

HydroGeoSphere (HGS) model (Therrien et al., 2006) was selected for this study because of the hydrological processes involved. Two conceptual models were developed in order to study the role of density-dependent flow over two different scales including large and small scales. Latter consists of cross-section of a river-floodplain system with 20, 10 and 10 m dimensions in x, y and z direction, respectively. The river was represented in a rectangular shape, 2 m depth and 4 m width. The second conceptual model is identical to the first one, except, the width (x-direction) is 200 m. Moreover, to isolate the effect of aquifer heterogeneity on the SW-GW interactions and focus of the role of density-dependent flow, a simple homogenous conceptual model was used. Figure 1 illustrates the conceptual model.

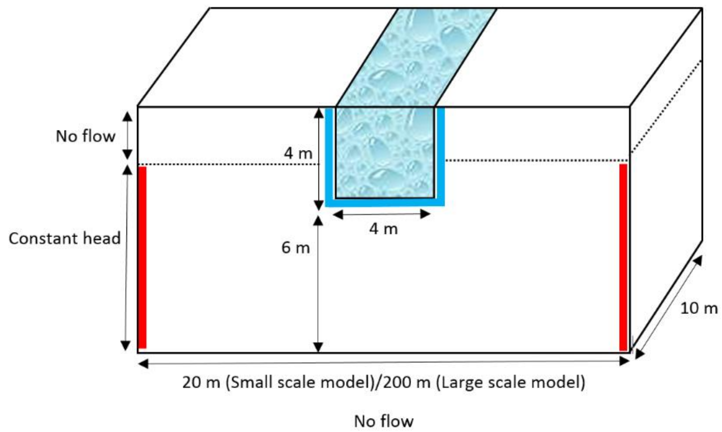



**Figure 1.** Conceptual model with boundary conditions and dimensions. The dimensions and boundary conditions are symmetrical. Note that the figure is not drawn to scale. Fresh and saline solute transport boundary conditions are shown in blue and red, respectively.

The model was a steady model for a period of 20,000 days. No hydraulic gradient was imposed and all the analyses were conducted in steady state. The first scenario, base-case scenario (BC), included salinity ratio of 0.01 for fresh river and 1 for saline groundwater. Scenario BC was designed to represent the model in a simplest way. Therefore, it didn't include ET, recharge from rainfall, pumping and injecting. Moreover, number of scenarios were defined in order to study the impact of density-dependent flow on various parameters and drivers involved in SW-GW interactions. These include salinity ratio (river/floodplain), flow regime (hydraulic gradient) and river dimensions (width/depth ratio). All the scenarios were simulated with and without density-dependent mode. Note that models with density dependent flow and without density-dependent flow are referred as DD and NDD hereafter, respectively. See Table 1 for an overview of the scenarios.

**Table 1.** Selected values for the model parameters

| Scenarios | Salinity ratio | River W/D | Flow regime |
|---|---|---|---|
| Base-case (BC) | 0.01/1 | 4/4 | no hydraulic gradient (7 m head) |
| Salinity ratio (SR) | 0.01/0.5 & 0.01/2 | 4/4 | no hydraulic gradient (7 m head) |
| Losing river (LR) | 0.01/1 | 4/4 | losing river (1% hydraulic gradient) |
| Gaining river (GR) | 0.01/1 | 4/4 | gaining river (1% hydraulic gradient) |
| River dimension (RD) | 0.01/1 | 2/8 & 8/2 | no hydraulic gradient (9 m head) |

## 3 RESULTS AND DISCUSSION

### 3.1 Impact of density-dependent flow in large scale

Spatial variations of fluid density can potentially play an important role in contaminant migration within various geological media. For instance, when there is a saline body of liquid with significant contrast in density overlies a less saline layer of the fluid, the system is potentially unstable and density-dependent flow may take place. Means, the denser liquid, due to gravity, moves towards to bottom and subsequently the less dense fluid tends upwards, which levels out the density stratification and eventually stabilizes the system. This causes continuous circular movements of fluid until reaching an equilibrium density. Scenario BC was simulated at the large scale to examine the impact of density-flow on salinity distribution. As shown in Figure 2, the results indicate two different patterns. It seems excluding density-dependent flow limits the salinity transport at the vicinity of the river bank, in this case less than 5 m from the river bank. Moreover, moving from river to the floodplain aquifer, density-dependent flow leads to larger intermediate zone (between fresh and saline groundwater, shown in green and yellow), and therefore, more gradual conversion from fresh to saline zone. This pattern is sudden under no density-dependent flow.

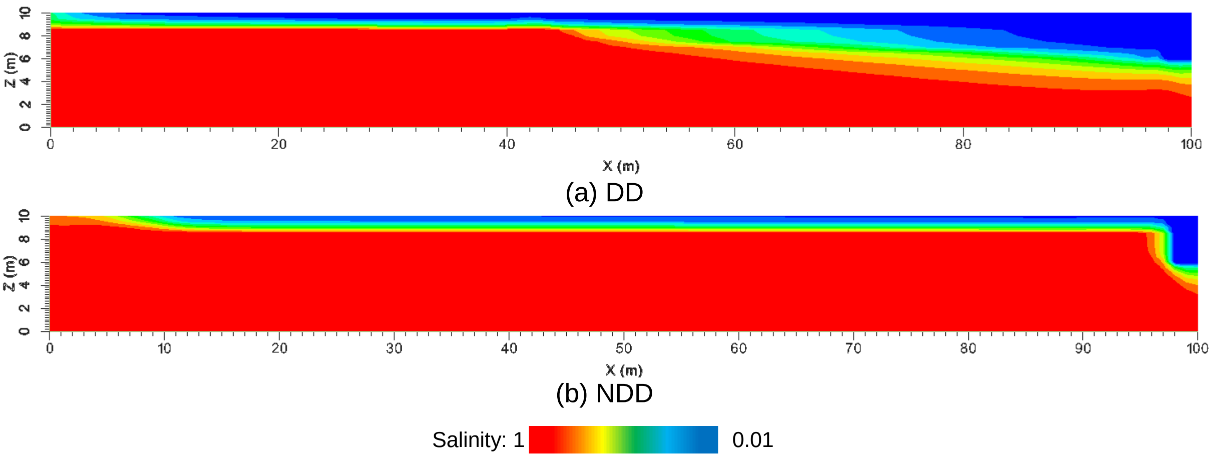
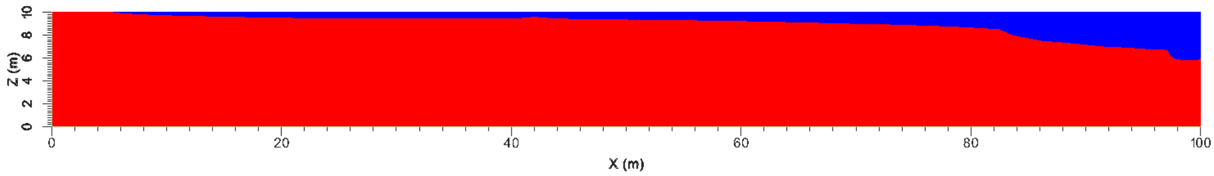
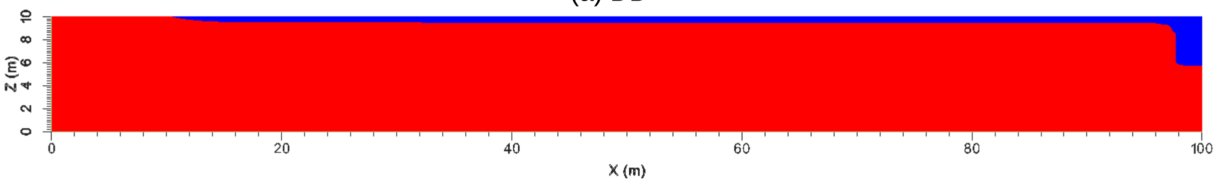



**Figure 2.** Simulated salinity distribution in the large scale model for Scenario BC.

In Figure 3, it can be seen that under same conditions, density-dependent flow can lead to larger freshwater lens (salinity less than 0.1). Since there is no hydraulic gradient imposed on the model (8 m head at both river and groundwater sides), the difference in freshwater lens size is solely due to density-dependent flow. This is particularly important when studying solute exchange at the river banks, seawater intrusion, freshwater availability for riparian vegetation, utilization of freshwater lens and etc.




(a) DD




(b) NDD

**Figure 3.** Conceptual model with boundary conditions and dimensions. The dimensions and boundary conditions are symmetrical. Note that the figure is not drawn to scale. Fresh and saline solute transport boundary conditions are shown in blue and red, respectively.

The larger freshwater lens means overall less saline aquifer and less accumulated solute mass. No density-dependent flow shows 10% less solute mass accumulated in the model. However, majority (up to 90%) of the difference appears at the 20 m distance from the river bank. Again, it seems density-dependent flow play an important role in solute mass balance of the groundwater aquifer. A total of 10 observation wells were defined along the floodplain aquifer to record the modelled groundwater salinity from depth 0.5 m to 8 m. among these four of them are shown in Figure 4. Once more, the results highlight that the main impact of density-dependent flow occurs at the vicinity of the river bank, which is consistent with the above mentioned results. For instance, the groundwater salinity at the observation wells under both conditions are almost the same throughout the floodplain aquifer with exception of two closest to the river. At the location of x=90 and x=95 a significant difference in groundwater salinity profiles can be detected

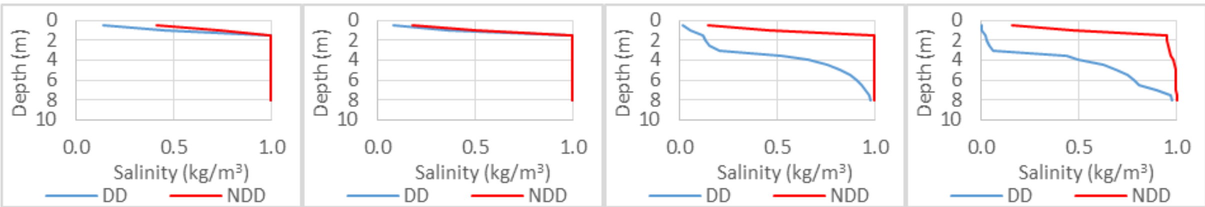



**Figure 4.** Groundwater salinity profile at the location of observation wells.

### 3.2 Impact of density-dependent flow in small scale

As discussed in section 1, the most noticeable impact of density-dependent flow takes place at the vicinity of the river bank. Therefore, the small scale model was defined to look at the solute dynamic in more detail. Figure 5 shows how density-dependent flow results in significantly different solute distribution pattern. The difference can be seen in terms of groundwater salinity, freshwater lens size and solute mass accumulation. These can be interpreted same as section 1, means, overall less saline floodplain aquifer, less accumulated solute mass and larger freshwater lens as result of density-dependent flow. Darcy velocity vectors are shown in Figure 5. It can be seen that under the density-dependent flow, solute dynamic is significantly driven by solute density. Naturally, in arid and semi-arid region where groundwater is shallow and ET rate is higher than rainfall, saline unsaturated zone can be formed. Since, there is no ET imposed on the model, forming a saline unsaturated zone seems unrealistic in Figure 5b. This shows that in case of simplifying, by excluding density-dependent flow, the solute dynamic would be a function of flow dynamic rather than salinity concentration. Thus, when the objective is to investigate the solute dynamic in the unsaturated zone, simulating the process without density-dependent flow may lead to overestimation of solute mass accumulation, particularly in small scale. For example, the results show 18% difference in total solute mass, which up to 90% of that is attributed to the unsaturated zone.

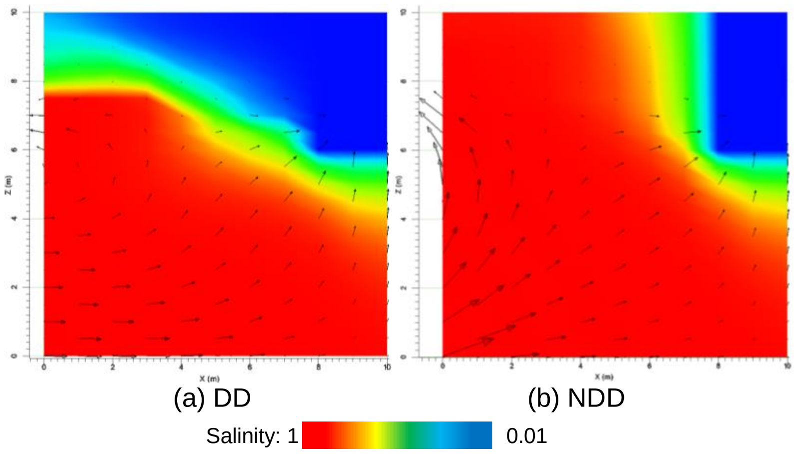
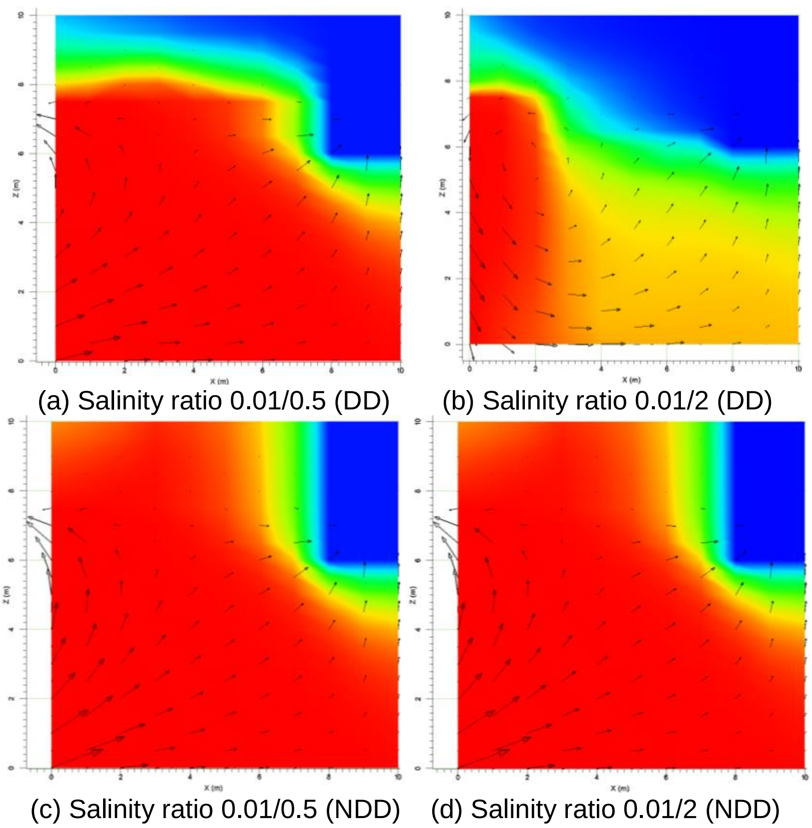



**Figure 5.** Simulated salinity distribution in the small scale model for base-case scenario (BC). Dotted black line represents the groundwater table.

### 3.2.1 Density-dependent flow vs river and floodplain aquifer salinity ratio

Three river and groundwater salinity ratios were modelled including 0.01/0. 5 (SR1), 0.01/1 (BC) and 0.01/2 (SR2). Given Figure 6, it is clear that salinity distribution without density-dependent flow is independent from salinity ratio and is dominantly a function of flow dynamic. Therefore, Darcy velocity vectors are identical in Figures 6c and 6d. On the other hand, high salinity ratio may change the flow dynamic as well as salinity distribution pattern. This can be observed by comparing Figures 6a and 6b. It seems when the interaction occurs between two water components with very high salinity difference (in this 200 times), more complex flow and solute dynamics may follow (see Darcy velocity vectors). Moreover, when the salinity ratio between the SW and GW is relatively lower (in this case 50 times), the impact of density-dependent flow on flow dynamic may be insignificant (see Darcy velocity vectors in Figures 6a, 6b and 6c). However, the dominant impact of density-dependent flow on salinity distribution and forming a distinct unsaturated zone still takes place. Means, when the salinity ratio is small the impact on salinity distribution is limited to the top layer where unsaturated zone exists.



Salinity: 0.5 0.01 Salinity: 2 0.01

**Figure 6.** Simulated salinity distribution in the small scale model for salinity ratio scenario (SR).

### 3.2.2 Density-dependent flow vs river and floodplain flow regime

Hydraulic gradient is the dominant driver in SW-GW interactions process, particularly, when the two domains are connected and the river bed has high-hydraulic conductivity. Therefore, Scenario FR were defined to explore the role of density-dependent flow on solute dynamic in gaining and losing rivers. Therefore, 1% slope where imposed on the model to simulate the scenarios. Note that Scenario BC doesn't include any hydraulic gradient (7 m head at both sides). Figure 7a shows that when the hydraulic gradient is towards the river, a mixed-convection occurs. In fact, both hydraulic gradient and density-dependent flow impact the process. In unsaturated zone hydraulic gradient overcomes the density-dependent flow and forms more saline zone due to more solute influx. In saturated zone density-dependent flow seems to play the dominant role. This can be seen by comparing Figures 7a and 5a. On the other hand, no significant difference is observed between no-hydraulic gradient and gaining river in no-density-dependent- flow condition (See Figures 5b and 7b). Furthermore, a 1% hydraulic gradient towards the floodplain aquifer was imposed on losing river scenario, as shown in Figures 7c and 7d. Given Figure 7c, combination of hydraulic gradient and density-dependent flow leads to the largest freshwater lens and consequently least saline aquifer. However, density-dependent flow is more prominent driver since the hydraulic gradient itself is not able to form same pattern. This can be seen in Figure 7d where significant overestimation of salinity in unsaturated zone takes place due to lack of density-dependent flow.

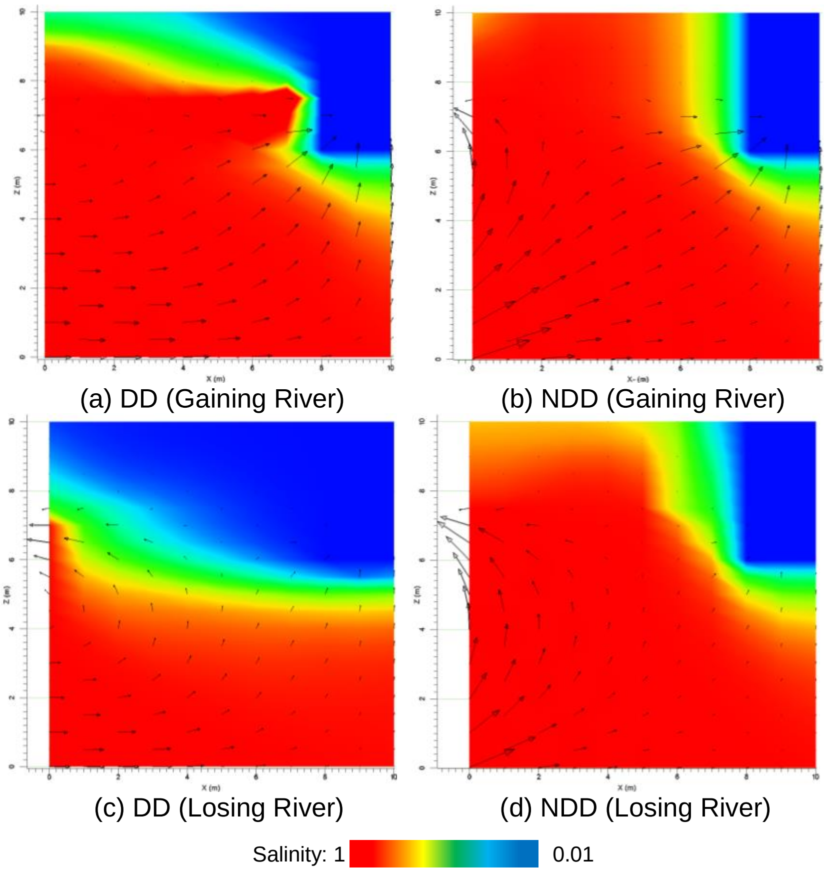



**Figure 7.** Simulated salinity distribution in the small scale model for gaining and losing scenario.

### 3.2.3 Density-dependent flow vs river geometry

River dimension play an important role on SW-GW interactions. In fact, flow, and consequently solute mass, exchanges occur at the river bed and banks. Particularly, when the river and floodplain are hydraulically connected, when there is no hydraulic gradient or river is gaining, majority of flow and solute exchange take place at the river banks. In this regard, besides scenario BC where river cross section is represented by a constant head boundary, where w= 4 m and depth= 4 m, two other scenarios were defined with 2/8 and 8/2 width/depth ratios. In order to isolate the impact of density-dependent flow, same groundwater head was imposed to the model, 9 m head at both sides. The results are demonstrated in Figure 8. Considering Figure 8, it appears density-dependent flow play more significant role in deep river compare to the shallow one. In fact, for the same river cross section area, deeper river generates relatively larger freshwater lens. This can be due to the fact that the interface between the two domains is larger (8 m compare to 2 m), as can be seen through Darcy velocity vectors. Therefore, more interaction occurs at the river bank in deep river, which consequently leads to more flow and solute mass exchange.

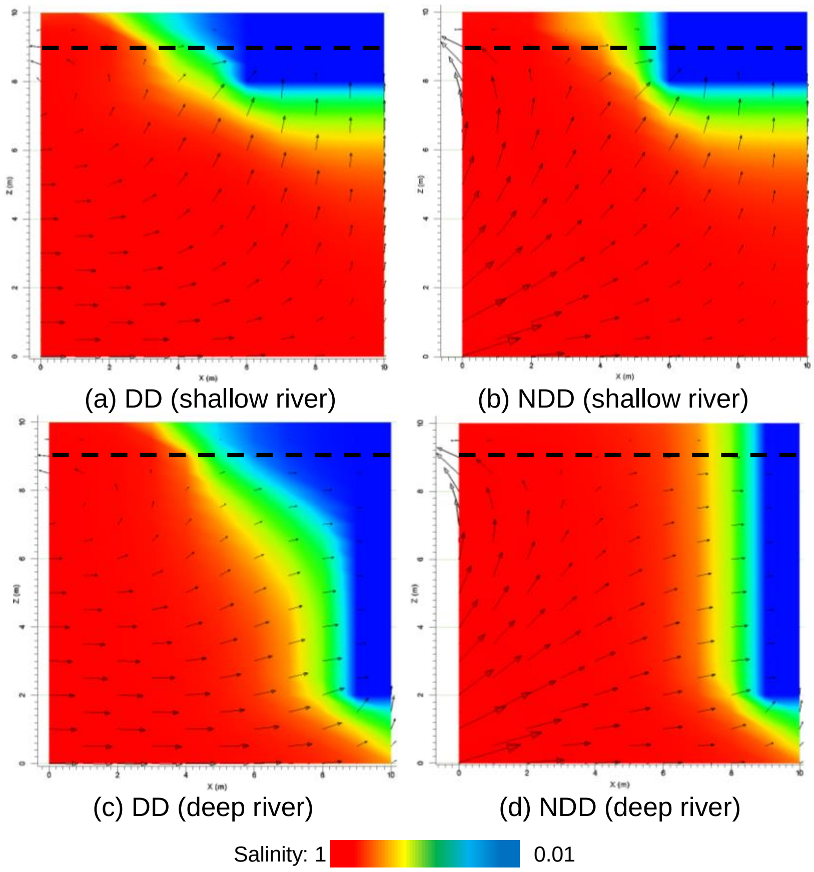



**Figure 8.** Simulated salinity distribution in the small scale model for river dimension scenario (RD). Dotted black line represent the groundwater table.

## 4 CONCLUSIONS

We have presented a synthetic modeling study to investigate the implications of density-dependent flow in numerical modelling of SW-GW interactions. It was aimed to examine when it is essential to include density-dependent flow or under what circumstances this could be simplified. Our analyses were based on a homogeneous saline floodplain aquifer adjacent to a fresh river at both large and small scales. To this aim a fully-integrated variably saturated surface-subsurface flow and solute transport model was used. We tested the impact of density-dependent flow on solute and flow dynamics, particularly in terms of solute mass accumulation, groundwater salinity and freshwater lens extent. In summary, this study demonstrates the following key points:

- At the large scale, excluding the density-dependent flow limits the salinity transport to the vicinity of the river bank and leads to smaller freshwater lens and underestimation of unsaturated zone. However, density-dependent flow may form larger freshwater lens and overall less saline aquifer and less accumulated solute mass, in this case up to 10% less. The groundwater salinity profile under both conditions are almost the same throughout the floodplain aquifer with exception of the two closest to the river.
- In the small scales under the density-dependent flow, solute dynamic is significantly driven by solute density. If the objective is to explore the solute dynamic in the unsaturated zone,

simulating the process without density-dependent flow may lead to overestimation of solute mass accumulation, particularly in small scale, in this case up to show 18%.

- When the interaction occurs between two water components with very high salinity difference more complex flow and solute dynamics may take place, which is reflected in Darcy velocity vectors. On the other hand, when the salinity ratio is relatively lower, the impact on salinity distribution is limited to the unsaturated zone.
- If surface and subsurface domains are hydraulically connected and there is a hydraulic gradient towards the river, the density-dependent flow leads to a mixed-convection. In this case, hydraulic gradient and density-dependent flow play the dominant roles in unsaturated zone and saturated zone, respectively. In losing river, combination of the hydraulic gradient and density-dependent flow leads to the largest freshwater lens and consequently least saline aquifer. However, density-dependent flow is more prominent driver since the hydraulic gradient itself is not able to form same pattern.
- Density-dependent flow has relatively more impacts on deep river compare to the shallow one. For the same river cross section area, deeper river generates relatively larger freshwater lens.

Note that, since ET and rainfall are not included in this study, as long as the salinity condition is similar, the results of this study can be applicable to various climate conditions including arid, semi-arid and humid areas.

## 5 ACKNOWLEDGEMENTS

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