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Salinization in a stratified aquifer induced by heat transfer from well casings

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ABSTRACT

The temperature inside wells used for gas, oil and geothermal energy production, as well as steam injection, is in general significantly higher than the groundwater temperature at shallower depths. While heat loss from these hot wells is known to occur, the extent to which this heat loss may result in density-driven flow and in mixing of surrounding groundwater has not been assessed so far. However, based on the heat and solute effects on density of this arrangement, the induced temperature contrasts in the aquifer due to heat transfer are expected to destabilize the system and result in convection, while existing salt concentration contrasts in an aquifer would act to stabilize the system. To evaluate the degree of impact that may occur under field conditions, free convection in a 50-m-thick aquifer driven by the heat loss from penetrating hot wells was simulated using a 2D axisymmetric SEAWAT model. In particular, the salinization potential of fresh groundwater due to the upward movement of brackish or saline water in a stratified aquifer is studied. To account for a large variety of well applications and configurations, as well as different penetrated aquifer systems, a wide range of well temperatures, from 40 to 100 °C, together with a range of salt concentration (1–35 kg/m^3) contrasts were considered. This large temperature difference with the native groundwater (15 °C) required implementation of a non-linear density equation of state in SEAWAT. We show that density-driven groundwater flow results in a considerable salt mass transport (up to 166,000 kg) to the top of the aquifer in the vicinity of the well (radial distance up to 91 m) over a period of 30 years. Sensitivity analysis showed that density-driven groundwater flow and the upward salt transport was particularly enhanced by the increased heat transport from the well into the aquifer by thermal conduction due to increased well casing temperature, thermal conductivity of the soil, as well as decreased porosity values. Enhanced groundwater flow and salt transport was also observed for increased hydraulic conductivity of the aquifer. While advective salt transport was dominant for lower salt concentration contrasts, under higher salt concentration contrasts transport was controlled by dispersive mixing at the fresh-salt water interface between the two separate convection cells in the fresh and salt water layers. The results of this study indicate heat loss from hot well casings can induce density-driven transport and mixing processes in surrounding groundwater. This process should therefore be considered when monitoring for long-term groundwater quality changes near wells through which hot fluids or gases are transported.

1. Introduction

Oil and gas deposits, as well as exploitable geothermal energy, are typically found in reservoirs well below the depths of exploitable fresh groundwater supplies. Therefore, wells for conventional oil and gas, shale gas and geothermal energy production fully penetrate shallow fresh water aquifers. The temperatures of wellbores during oil production [6], gas production [11], geothermal energy production [13] and hot water or steam injection [50], can be significantly higher (e.g., $T > 40$ °C) than the typical temperatures of the shallow aquifers in moderate climates (10–20 °C). The temperature difference causes heat transfer to the surrounding formations and cooling of the fluid or gas that is flowing inside the well [35]. The resulting temperature at the wellhead is important for operational drilling and injection/production aspects, such as determining viscosity and

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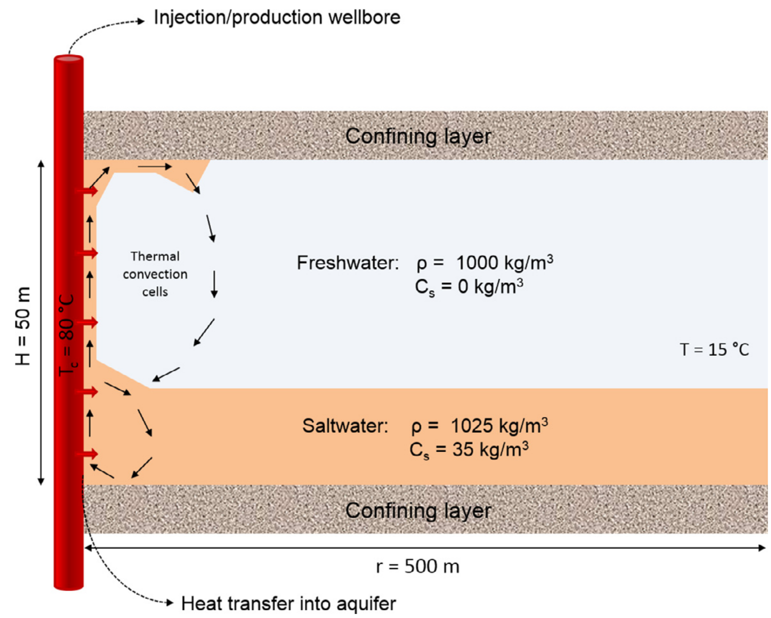

Fig. 1. Thermally induced density-driven flow due to heat transfer from a well to the aquifer and its effect on fresh-salt stratified groundwater (parameter values belong to the reference scenario used in this study).

thereby flowing pressure changes in a heavy-oil well, or estimating steam quality during steam injection. However, to our knowledge, the thermal effects of wellbore heat losses for the aquifers that receive the heat have not been addressed.

Many studies have investigated density-driven flow in porous media under the influence of temperature contrasts in groundwater systems (e.g. [4,15]). This can occur both at large scale, like geothermal convection in geological basins [4], or at small scale such as the upward density-driven flow of injected hot water during high temperature aquifer thermal energy storage (e.g. [2,27,42,44]). In addition to temperature, density-driven groundwater flow is affected by salt concentration contrasts. The effect of salt concentration and temperature gradients on convective flow patterns in thermo-haline systems were studied by [4,17,29,36,39]. A few studies have focused on thermo-haline convection on field scale; e.g. the effect of hypersaline cooling canals on aquifer salinization [16] and the transport of hot, brine water plumes [30].

Thermal convection under the influence of a vertical heat source like a vertical flat plate [3] or long vertical thin blades [32] in a porous medium has been investigated numerically. These geophysical examples suggest that hot wellbores penetrating cooler aquifers could thermally induce density-driven groundwater flow.

In many aquifers, fresh groundwater overlies denser, saline water and salinization by mobilization of the underlying saline water is considered a major threat to fresh groundwater resources and drinking water production [5,34,48]. Local thermally induced density-driven flow in the vicinity of hot well casings could therefore result in mixing and deterioration of the groundwater quality (see Fig. 1). To explore this possibility, we simulated transient temperature and salinity dependent density-driven groundwater flow along a hot wellbore. We used SEAWATv4, and further include a non-linear density equation of state, to apply to various thermal conditions, salt concentration contrasts and aquifer properties.

2. Theory and methodology

2.1. Wellbore heat transmission

Fluid or gas flowing in the wellbore loses heat to its surroundings by thermal conduction due to the difference between wellbore fluid and surrounding aquifer temperature during injection or production operations. The heat transfer from the wellbore is proportional to the thermal resistance of the well system, including the tubing wall, annulus, casing wall and cement sheets. Ramey [35] introduced an approximate, analytical solution for wellbore heat transmission to estimate wellhead temperature as a function of wellbore depth and the operational time. He has developed solutions for fluids and perfect gasses, assuming steady-state fluid flow in the wellbore and transient heat conduction into the formation. An overall heat transfer coefficient was introduced to account for the total thermal resistance of the well system. Other studies introduced methods to account for multiple formation layers with different physical properties [50], for real gas production [11], or for two-phase flow in the wellbore [13]. Wellhead temperature distributions during oil, gas and geothermal energy production, as well as temperature distributions of steam and hot water injection applications, show that the difference between wellbore fluid temperature and surrounding formation at shallow depths can be significant with temperature differences larger than 30 °C [6,11,13,35,50]. However, the effective temperature of the outer well casing may differ from the wellbore fluid temperature, depending on the total thermal resistance of the well system. In general, thermal resistance of steel casings and tubings can be neglected, while insulating materials like cement sheets and annuli filled with liquid or gas have a high thermal resistance. According to Ramey [35], heat transfer through the different thermal resistance elements of the wellbore is considerably faster than heat transfer in the surrounding formation and, therefore, may be assumed as a steady-state solution.

2.2. SEAWAT

We have used SEAWATv4 [10,24] to model density-driven groundwater flow induced by heat transfer from a hot well casing. SEAWATv4 is a coupled version of the simulation programs for groundwater flow, MODFLOW2000 [12] and for multi-species mass transport, MT3DMS [51], together with a variable density and viscosity package. This enables the simulation of variable-density groundwater flow combined with heat and multi-species solute transport. The differential equation for solute transport takes into