Seasonal Groundwater Turnover in the North and South of Sweden

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Abstract

Nutrient leakage from agricultural areas in Sweden mainly occurs during the autumn in the south and during the spring in the north. The infiltration of nutrients also reaches greater depths in the south. An occurring "seasonal groundwater turnover" similar to that in lakes is the suggested mechanism. This thermal convection results from changing temperatures (densities). The 10°C groundwater in southern Sweden becomes denser as it is cooled from the surface in the autumn, while the corresponding convection in the north occurs during the spring. Performed simulations show how seasonal temperature variations, under certain conditions, initiate and drive thermal convection.

Introduction

Nutrient loss to groundwater leads to overfeeding of lakes and watercourses, which has a negative impact on flora and fauna. By understanding the mechanisms behind the leakage, fertilising could be done more effectively. Such knowledge would also be helpful in preventing and counteracting other types of groundwater contamination. Our hypothesis is that nutrient leakage into groundwater is caused by thermally driven groundwater convection (Fig.1).

The maximum density of water occurs at a temperature of near 4°C. Thus, a density increase of the groundwater occurs by heating from about 3°C in the north of Sweden (springtime) and by cooling from about 10°C in the south (autumn). The depth of the leakage depends on the size of the thermal gradient. This hypothesis consequently explains both why the nutrient leakage occurs during different seasons in the north and south of Sweden and also why the leakage reaches greater depths in the south.

Thermal convection in lakes, the seasonal turnover, is well understood. The driving force of this phenomenon is thermal convection and the temperature dependent density and viscosity of water. This mechanism is here applied as a "seasonal groundwater turnover". The turnover occurs in different time of the year in the north and south of Sweden, depending on correspondingly different groundwater temperatures.

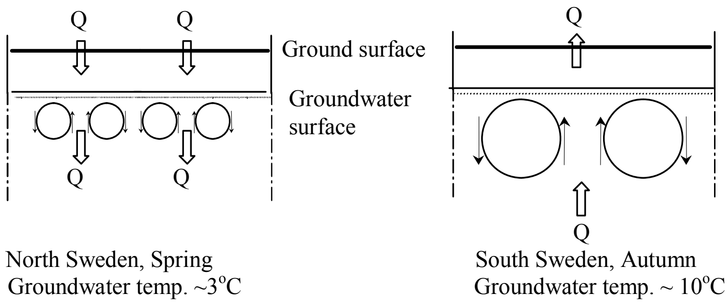

Figure 1. Outline of how heating or cooling drives groundwater convection. Groundwater mixing reaches to greater depths in the south of Sweden since the groundwater mean temperature deviates more from the maximum density water temperature (4°C).

Thermal Convection

Blake et al. (1984) provide the mathematical formulation of the thermal convection in porous media near 4°C. The Boussinesq approximation of temperature dependent density cannot be used in this case since the density function of the groundwater is not linear close to the density maximum of 3.98°C. Therefore, a better, nonlinear approximation is that of Goren (1966) and Moore and Weiss (1973), see Eq.(1).

$$\rho = \rho_0 (1 - \gamma (T - T_0)^2) \quad (1)$$

where ρ0 is the maximum density of the water at T0=3.98°C and $\gamma = 8 \times 10^{-6}$ (°C^{-2}). This approximation is valid in the temperature range of 0°C and 10°C. The momentum conservation is given by;

$$\frac{\partial u}{\partial y} - \frac{\partial v}{\partial x} = -2 \frac{K \gamma g}{\upsilon} (T - 3.98) \frac{\partial T}{\partial x} \quad (2)$$

where υ is the kinematic viscosity, μ/ρ0. The dynamic viscosity of a fluid, μ, is a second order function of temperature between 0°C and 10°C. The viscosity function is derived from tabled values.

The Rayleigh Number (Ra) is the balance between buoyancy force and viscous force, (Kundu, 1990). According to Nield and Bejan (1999) Ra for porous media can be written as:

$$Ra = \frac{g K \gamma (T - T_o)^2 H}{\alpha \upsilon} \quad (3)$$

The general critical Rayleigh number, $Ra_c=4\pi^2$, indicates that convection occurs for $Ra>Ra_c$, i.e. when the solution of the boundary problem is unstable. The instability is the driving force of the convection.

Thermally driven convection could be triggered and partly driven by horizontal groundwater flow. Convection then starts at a lower Ra number. This phenomenon has been the subject of detailed studies in the field of aquifer thermal energy storage (Claesson et al., 1985). Nield and Bejan (1999) analysed Ra for different boundary conditions and showed that it was possible to get lower critical Ra numbers than the general $Ra_c=40$ at undisturbed ground water conditions.

The Nusselt (Nu) number is defined as the ratio between actual heat transfer and conductive heat transfer;

$$Nu = \frac{Q}{kL(T_H - T_C)/H} \tag{4}$$

where k is the thermal conductivity of water saturated porous matrix and Q the overall heat transfer rate. Thus, convective heat transfer entails Nu>1. In performed calculations Nu was used to verify the stability of the numerical simulations.

Simulations

The FLUENT model (Versteeg et al., 1995) was used to simulate groundwater convection. Initially steady state solutions were used to confine the problem for climatic data of southern and northern Sweden. Transient solutions were used to evaluate the time needed to establish stable convection patterns. The influence of obstacles (frost lenses) in the soil was also simulated.

Results

An initial horizontal velocity $V_i=10^{-9}$ m/s was used as a standard disturbance in all the performed simulations. The size of the simulated control volume (10x5 m) was held fixed while the mesh size was varied from 0.15 m to 0.025 m. The expected result was that the numerical solution would converge like the solution in Blake (1984), but some of the solutions were unstable, see Table 1. This matter was also observed by Elder (1966), for mesh size 0.05m and Ra=90.

The permeability, and thus Ra, was varied to investigate the limits for stable convection in a 10x1 m control volume. Table 1 shows that Ra>19, i.e. well below Ra_c, results in stable convection, which was also observed by Nield and Bejan (1999).

Several different control volumes with different depths were simulated for the $V_i=10^{-9}$ m/s, $K=6.7\cdot10^{10}$ m^2, $T_H=10^oC$, $T_C=4^oC$. Fig. 2 shows the result of the numerical simulation under assumed standard conditions. The simulations showed stable convection for depths down to 6 m, except for the 4 m deep control volume, see Table 1. For depths>7 m the temperature gradient is too small to drive the convection.

Transient solutions for climatic conditions in southern Sweden show that 250 days was required to obtain fully developed convection i.e. 10 times more than in the north.

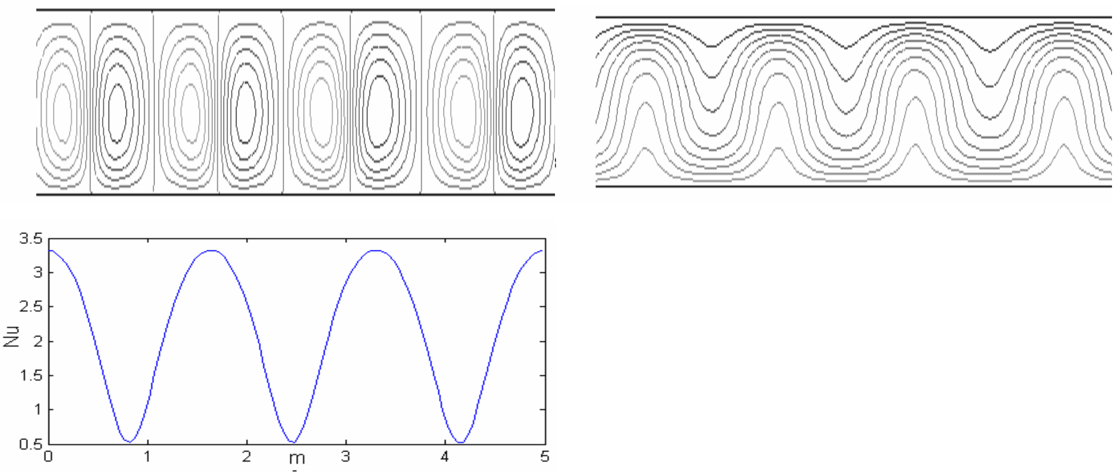

Figure 2 Numerical steady-state solution for half a 10x1 m control volume shows 8 symmetrical convection rolls acting in pairs. $V_i= 10^{-9}$m/s, Ra=19, $K=6.7\cdot10^{-10}$ m^2, $T_H=10$ ^oC, $T_C=4^oC$, Nu= 2.14. *Upper graph*: Streamlines; *Middle graph*: isotherms. *Lower graph* Nusselt number.

For the north of Sweden, a control volume size of 5x 0.5 m was used and a mesh size of 0.025 m was sufficient to achieve converged solutions. The permeability was varied to investigate the limits for stable convection in a 5x0.5 m control volume. Stable convection was obtained for permeability values greater than 2.41 10^{-9} m^2 which corresponds to a soil with 2 mm grain size, see Table 1.

Convection depths between 0.1 m and 1 m were simulated for $V_i=10^{-9}$ m/s, $K=6.1\cdot10^{-9}$ m^2 (3 mm grain size), $T_H=4^oC$, and $T_C=0^oC$. The simulations showed stable convection for depths between 0.2 m and 0.9 m. For a 1.0 m deep control volume the temperature gradient was too small to drive the convection. For a 0.1 m control volume the Ra number was too low for convection to occur at this permeability.

Table 1. Summary of numerical results of convection in the south.

L (m)	H (m)	Mesh size (m)	K ($\cdot 10^{-9}$) (m^2)	Grain size (mm)	Ra (-)	Nu (-)	No. rolls (-)
			Part 1				
10	1	0.150	0.67	1	19	1.97	12
10	1	0.100	0.67	1	19	2.05	12
10	1	0.050	0.67	1	19	2.14	12
10	1	0.025	0.67	1	19	2.14	12
			Part 2				
10	1	0.05	2.71	2.00	76	5.2	26
10	1	0.05	2.07	1.75	59	4.42	22
10	1	0.05	1.52	1.50	43	3.61	18
10	1	0.05	1.06	1.25	30	2.92	16
10	1	0.05	0.67	1.00	19	2.14	12
10	1	0.05	0.38	0.75	11	1.16	-
10	1	0.05	0.17	0.50	5	1.16	-
			Part 3				
10	1	0.05	0.67	1	19	2.14	12
10	2	0.10	0.67	1	38	1.66	8
10	3	0.10	0.67	1	57	1.42	8
10	4	0.10	0.67	1	76	-	-
10	5	0.10	0.67	1	95	1.17	4
10	6	0.10	0.67	1	114	1.11	4
10	7	0.10	0.67	1	134	-	-
10	8	0.10	0.67	1	153	-	-
			North				
5	0.5	0.1	6.09	3	38	1.24	10
5	0.5	0.05	6.09	3	38	1.41	14
5	0.5	0.025	6.09	3	38	1.36	18
5	0.5	0.0125	6.09	3	38	1.36	18
5	0.5	0.025	0.67	1	4	0.21	
5	0.5	0.025	2.71	2	17	0.7	12
5	0.5	0.025	6.09	3	38	1.36	18
5	0.5	0.025	16.90	5	106	1.68	20
5	0.1	0.0005	6.09	3	8	2.63	
5	0.2	0.01	6.09	3	15	1.43	26
5	0.3	0.015	6.09	3	23	1.67	20
5	0.4	0.02	6.09	3	31	1.54	18
5	0.5	0.025	6.09	3	38	1.36	18
5	0.6	0.025	6.09	3	46	1.34	14
5	0.7	0.025	6.09	3	54	1	16
5	0.8	0.025	6.09	3	61	1.13	14
5	0.9	0.025	6.09	3	69	1.14	10
5	1	0.025	6.09	3	77		

In some cases, see Table 1, stable convection occurred though the Nu<1, which indicates that the convective transport reduces the heat transfer. In a 5x0.8 m control volume the effect of three large obstacles was studied, for $K=6.0\cdot10^{-9}$ m^2, $T_H=4^oC$, and $T_C=0^oC$, $V_i=10^{-9}$ m/s. The large obstacles forced the convection rolls to change size and shape. Obstacles with a constant wall temperature, $T_w=0^oC$ for a frost lens, generated a different convection pattern from that of an obstacle without own temperature. The time required to obtain fully develop a steady convection pattern was about 22 days.

Discussion and Conclusions

The hypothesis was that thermally driven groundwater convection would explain the differences in nutrient leakage. This hypothesis was verified for the south of Sweden.

The number of convection cells increased with permeability and decreased with the depth of the control volume. Convection cells occur at Ra>19 providing an initial small horizontal ground water velocity, which does not distort the convection cells. The required horizontal water velocity (disturbance) is so small that convection is likely to occur in nature, due to seasonal temperature changes, provided that the groundwater temperature is 10^{o}C and Ra >19, and a soil permeability greater than approximately $7 \cdot 10^{-10}$ m^2.

Obtained results show that thermally driven convection also occurs in the north. This is however not sufficient to explain the infiltration in fine grained material. It was shown that obstacles like frost lenses in the ground change but not hinder the occurring convection pattern. The time required to establish stable convection patterns is about 22 days.

Performed simulations show that the required grain size for convection to occur is considerably greater than that in typical agricultural soils. Consequently, the temperature differences in the north of Sweden cannot drive groundwater convection in such soils. Still vertical groundwater movements exist.

Possible explanations to vertical groundwater movements in fine grained soils:

1. Unstable groundwater convection or oscillating convection cells.
2. Infiltration of rain and melt water.
3. Pressure induced convection because of partly melted frost in the ground i.e. the pressure below the frost layer forces the groundwater to the ground surface.
4. The Coriolis force because of Earth's rotation could cause secondary currents in groundwater flow. This effect has so far not been applied on groundwater flow but has been studied by Vadasz (1993).

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