Earth's Rotation Induces Vertical Ground Water Flow

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Abstract

It is well established that the Coriolis force deflects wind and water currents. However, its influence on groundwater flow is neglected. Earth's rotation causes inertia circles in groundwater that create vortices ending up in different local pressure zones, similar to the high and low pressures in air. High pressure zones in groundwater induce, under certain conditions, a vertical flow to ground surface. This could be the missing link where hydrostatic pressure cannot explain springs in deserts, mountains and on islands in the sea. Here, simulations on the Coriolis force acting on groundwater flow are presented.

Background

Groundwater flows are influenced by the Coriolis force though this effect is generally considered to be small. However, the Coriolis force affects groundwater in the same way as it deflects winds and currents. This means that areas of high pressure and low pressure occur, which induce vertical groundwater flows and may contribute to spring flows.

There are extensive research on how the Coriolis force influence ocean currents and weather systems (Persson, Pedlosky). Larsson (1986) showed that the Coriolis force generates significant secondary currents in open channel flow, which under certain conditions could be applied on groundwater flow. Coriolis induced rotational convection in porous media has been analysed for industrial applications (Vadazs) but not for groundwater flow.

Earth's rotation should amplify existing natural convection and cause secondary currents in groundwater flow. The Coriolis force creates local pressure zones, positive and negative, in aquifers and bedrock fractures. In such positive pressure zones water can be transported up to the ground surface if favourable geological conditions exist. Taylor–

Proudman columns conducting a vertical flow could also occur and deflected groundwater flow would create standing inertia circles or vortices.

In current study the theory and initial numerical simulations are presented. A recently constructed test equipment to verify the Coriolis' effect on groundwater flow is briefly described. The theory includes several research areas that are not usually connected; metrology, rotational convection in porous media, secondary currents, and geostrophic flows and vortices.

Theory

Larsson (1986) showed the importance of secondary currents in river flows even if they only amount about 1 % of the downstream velocity. These currents influence the main velocity distribution and the cross-plane distribution of scalars like heat and concentration of contaminants.

A typical cross-plane flow pattern in a rotating channel is shown in Figure 1. The secondary currents arise because of the Coriolis effect, which accelerates the downstream moving water towards the side wall. As a consequence a lateral pressure gradient is built up. This pressure gradient is fairly uniform in the vertical since it is proportional to the down stream velocity. The result is that the two forces are locally out of balance and a resulting cross-stream flow is induced.

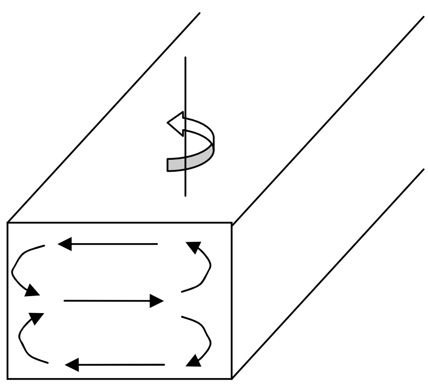

Figure 1. A cross plane flow pattern in a rotating channel

The Coriolis force (F_{cor}) in Eq. (1) is a small component of the general Centrifugal force (F_{cen}) in Eq. (2) (Persson 2005). It is perpendicular to both axis of rotation and the velocity of the moving object.

$$\mathbf{F}_{cor} = -2m\mathbf{\Omega} \times \mathbf{V}_r \quad (1)$$

$$\mathbf{F}_{cen} = \mathbf{\Omega} \times (\mathbf{\Omega} \times \mathbf{E_R}) \quad (2)$$

Here, m is the mass, Ω is the angular velocity, V_r is the velocity of the moving object and E_R is the radius of Earth. The Coriolis force on Earth varies with the latitude (φ) according to Eq. (3).

$$\mathbf{F}_{cor} = -2m\mathbf{\Omega} \sin\varphi \mathbf{V}_r \qquad (3)$$

F_{cor} does not do any work on a rigid body but it deflects motion. One example of the Coriolis Effect on Earth is the inertia oscillations in the oceans. Drifting buoys set in motion by winds tend, when the wind has decreased, to move under inertia and follow approximately inertia circles (Persson, 2005). The inertia circle has a radius (R) and a period of (τ).

$$R = \frac{\mathbf{V}_r}{2\Omega} \qquad \tau = \frac{\pi}{\Omega}$$

Applied on groundwater flow this means, for Earth's angular velocity of $7{,}292 \cdot 10^{-5}$ rad/s and a ground water (pore) velocity of 0.001 m/s, an inertia radius of 6.8 m with a period of almost 12 h. In order to quantify the relative importance of the rotation on a particular problem the non-dimensional Rossby number is often used (Persson YYYY).

$$Ro = \frac{U}{2\Omega \sin(\varphi) L} \qquad (4)$$

where U is the downstream velocity, L is the length, and Ω is the rotation speed. Small Rossby numbers (<xx) imply that the effect of rotation is important, Larsson (1986). Applying Eq.(4) on an aquifer; assuming a pore velocity of 0.001m/s and the length 250 m, at a northern latitude of 65°, the Ro Number gives Ro = 0.03. This value is small and therefore Earth's rotation influences groundwater flows in any given aquifer.

Comment [bn1]: Är detta längden eller bredden? I så fall längden av vad – grundvatten?

Experimental design

The simple experimental setup includes a sand and water filled channel 0.25x0.1x0.25m attached to two vertical volumes filled with water. The constant different water levels, and the corresponding hydrostatic pressure, are set to obtain a suitable and constant water velocity through the porous medium. The water levels on each side of the sand filled channel are kept constant by vertical sewers and a pump to return the water flow. This Darcy flow test setup is placed on a rotating table, with a maximum speed of 6.28 rad/s.

On top of the channel there are 81 drilled holes at equal spaced and plugged with small diameter transparent pipes, through which the static water pressure is observed.

The hydraulic conductivity of the sand was determined by a Darcy test i.e. without rotating the setup. A flow rate of $2.1 \cdot 10^{-5}$ m^3 s^{-1} was obtained for a water pressure difference $\Delta h=0.04$ m. The actual water velocity through the area of 0.25 m^2 is $5.25 \cdot 10^{-7}$ m s^{-1}. The hydraulic conductivity of the sand was determined to 0.007 m s^{-1} and the permeability $6.3 \cdot 10^{-10}$ m^2.

The Rossby number for this problem assuming a rotation velocity of 0.88 rad/s was calculated to $2.75 \cdot 10^{-7}$ by Eq.(4). This is indeed much smaller than necessary to indicate that rotational effects are important in this situation.

In order to detect any effects of the Coriolis Force in this small experimental setup the angular velocity has to be increased so that that the centripetal force in a large aquifer equals that in the experiment. In the assumed aquifer of 250x100x250m (LxWxH) the rotation of Earth creates a pressure of 100 N/m^2 on the walls of the control volume. By using the equation of centripetal force in circular motion Eq.(xx), it was found that an angular velocity of 0.88 rad s^{-1} gives the same pressure in the laboratory test scale.

Before starting up the rotation, a fully developed water velocity must be achieved through the porous media. After that the rotation must go on for a while until a steady state flow is achieved, and measurements were done. To visualize the standing water columns (the static water pressure) the water was dyed with potassium permanganate.

Numerical simulations

The numerical simulations were preformed with the FLUENT model and lab experiments were carried out to validate the model. Thereafter the simulation model was used to investigate the Coriolis effects on groundwater flow in aquifers. It was found that pressure zones, similar to those in weather systems, are built up in aquifers. Coriolis forces acting on faster fluid flows through fractures in bedrock

Comment [bn2]: ???????

Laboratory experiment to verify the simulations

Pressure zones in an aquifer

A control volume in a porous aquifer was rotated $1 \cdot 10^{-5}$ rad /s with the rotation axis in its centre. The porous media has a uniform inertial resistance of $5.3 \cdot 10^4$ m^{-1} and a viscous resistance of $1.5 \cdot 10^9$ m^{-2}, the porosity is 0.35 and the temperature is held at 4°C. Performed calculations show that pressure zones, from -4.8 to +3.5 bar, occurred in the aquifer, see Fig. 2.

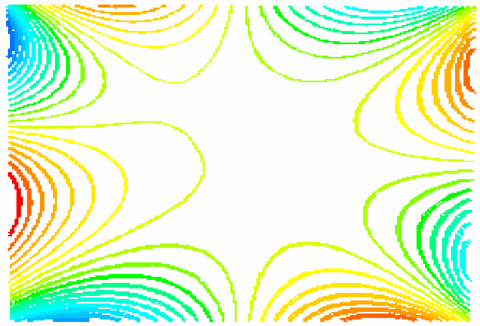

Figure 2. Steady-state pressure distribution in a porous rotating aquifer

Pressure distribution in a rotating fracture

The influence of the Coriolis force on groundwater flow in horizontal rock fractures were also studied. The fracture flow in a 1 mm fracture was analyzed for varying widths and lengths. The groundwater temperature was assumed 5°C and the fracture flow rate 1 kg s^{-1} i.e. a steady-state water velocity of 1 m s^{-1}. An initial water pressure of approximately 1 bar was assumed.

The axis of rotation is set in the direction (0,1,0) an then varied so that origin starts at (0,0, Er), (0,0,- Er) and (Er, 0,0), where Er is the radius of Earth. The results were slightly different depending on the direction of the water velocity (0,0,1).

The first fracture had the dimensions 0.1x0.001x1m. The rotation of Earth causes positive and negative pressure zones with a maximum pressure P_{max}=26 bars in the corners and a minimum pressure P_{min} =-48 bars in the centre.

For larger fracture dimensions (1x0.001x20 m) the axis of rotation in (0,0,Er) gives a pressure range P[-4.3; 7.6] bars. If the axis of rotation is changed to (±Er,0,0) the pressure range is more modest P[0.4; 1.6] bars.

Since 1 bar corresponds to 10 m of water the pressure peaks indicate that vertical flow must occur if there is a channel (fracture) to conduct this flow.

Discussion and Conclusions

Considering the 20x20 m aquifer with the rotational axis in the centre, the area is very small compared to the surface of the Earth, However, by extending the area wide enough positive and negative pressure zones will form in the aquifer.

In smaller fractures great pressures are obtained while larger fractures result in a more modest pressure. The fractures have to be oriented in a favourable direction to the groundwater flow and axis of rotation for maximum pressure. This occurs when the fracture direction lies along the axis of rotation.

Performed simulations show that Earth's rotation causes positive and negative pressure zones in groundwater in both rock fractures and aquifers. During favourable conditions, providing the right channel at the positive pressure zone, enough pressure is built up to result in a vertical water flow upwards to the ground surface.

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