Review of „Numerical assessment of potential impacts of hydraulically fractured Bowland Shale on overlying aquifers"

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Message of the Paper

In most studies it is concluded that contaminants migrate as high as the fractures extent, therefore the hydraulic fracture height is the critical parameter to consider. The authors state that horizontal groundwater flux dilutes the contaminants, such that the amount of upwelling contaminants becomes insignificant under the hydrogeological conditions in central Britain.

Detailed Review

The above paper aims to identify the conditions under which hydraulic fracturing of the Bowland Shale in central Britain could contaminate groundwater in St. Bees Sandstone (600-1000 m depth). This research is carried out using a numerical model of the subsurface up to 3000 m depth and comprises the ten main geological layers, mainly alternating high and low conductivity*1; the Bowland Shale is located at a depth between 2000 and 2500 m. The deep groundwater is over-pressured, i.e. it flows upwards and transports hazardous substances of natural or anthropogenic origin if a conductive pathway*2 exists. During hydraulic fracturing additional over-pressure is applied and upward directed hydraulic pathways are created. The model investigates, how these processes affect the water quality of aquifers that are above the Bowland Shale.

The first state of the model represents natural conditions, analogue to the situation before fracturing. The aquifers are well separated and there is no significant fluid flux between them. Hydraulic fracturing is then applied to the model, this means that hydraulic pathways and overpressure are created. Different scenarios for the fracture heights are applied. Some fractures have a vertical extent of 1850 m, while the highest known fractures have a length of 1100 m (Davies et al., 2012). For the simulated fracture heights, contamination of the St. Bees Sandstone is possible.

In most studies it is concluded that contaminants migrate as high as the fractures extent, therefore the hydraulic fracture height is the critical parameter to consider. The authors state that horizontal groundwater flux dilutes the contaminants, such that the amount of upwelling contaminants becomes insignificant under the observed geological conditions. The authors consider two further scenarios with a higher and lower hydraulic conductivity. Only for lower hydraulic conductivity the shallow groundwater becomes vulnerable.

This may appear as a paradox, but it occurs because a high conductivity is correlated with a high horizontal groundwater flow velocity. Here, the horizontal groundwater flow carries contaminants away from the fracture, and natural water from the respective aquifer flows upwards. The authors conclude that the observed and high hydraulic conductivities prevent upward flow of contaminants from the Bowland Shale horizon, even in case of very long hydraulic fractures.

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It has to be emphasized that the model simulates the impact of just one well that is hydraulically fractured. The results cannot be directly transferred to commercial field exploitation with multiple wells. Fluid injection by multiple wells could increase general pressure in the Bowland shale (Keranen et al., 2014) and therefore enhance the upward fluid flux.

I have objections to this paper in respect to the scenarios. All three permeability scenarios use an implausible higy hydraulic gradient. This results in implausibly high flow velocities and therefore the barrier efficiency is highly overestimated. The barrier function is significantly lower if the flow velocity is reduced to realistic values.

Critique on flow model

The hydraulic conductivities of the respective layers are derived from field measurements in the respective depth, the horizontal hydraulic gradient of 5‰ is derived from literature data on shallow aquifers (<100 m) and is assigned to the entire model. Therefore a significant horizontal hydraulic flux establishes in the model. This flux replaces the fluid in the fractures that originates from lower layers with formation water and therefore inhibits the upwelling of contaminants.

I have two objections that this removal mechanism is largely overestimated. First of all, the authors only apply a flow vector perpendicular to the fracture, but with equal probability the flow vector may have the same direction. In the latter case the upward migrating contaminants would hardly be removed. This should be considered as worst case scenario.

As second, and more important point, the applied velocities appear far too high. The effective transport velocity is calculated by equation 1:

$$v_t = \Delta I_x \, K_h \, \frac{1}{\theta}$$

ΔI_x = horizontal hydraulic gradient, K_h = horizontal hydraulic permeability, θ = effective porosity of the respective layers.

Table 1: Horizontal hydraulic permeabilities and porosities as applied by Cai and Ofterdinger (2014) for the thee conductivity cases: low, reference, high. The porosity is identical for all cases. The transport velocities are calculated for a hydraulic gradient of 5‰. Velocities higher than 10 cm/y are marked bold.

	permeability m/s			porosity	transport velocity m/y		
	low	reference	high	reference	low	reference	high
Mercia Mudstone Group	1.00E-08	1.00E-07	1.00E-06	0.1	1.6E-2	1.6E-1	1.6E+0
Sherwood Sandstone Group	1.20E-06	1.20E-05	1.20E-04	0.23	**8.2E-1**	**8.2E+0**	**8.2E+1**
St. Bees Sandstone	8.10E-08	8.10E-07	8.10E-06	0.15	8.5E-2	**8.5E-1**	**8.5E+0**
Manchester Marl	1.00E-09	1.00E-08	1.00E-07	0.15	1.1E-3	1.1E-2	1.1E-1
Collyhurst Sandstone	7.90E-06	7.90E-05	7.90E-04	0.26	**4.8E+0**	**4.8E+1**	**4.8E+2**
Lower Coal Measures	1.70E-10	1.70E-09	1.70E-08	0.1	2.7E-4	2.7E-3	2.7E-2
Millstone Grit Group	7.90E-09	7.90E-08	7.90E-07	0.08	1.6E-2	**1.6E-1**	**1.6E+0**
Bowland Shale	6.00E-09	6.00E-08	6.00E-07	0.03	3.2E-2	**3.2E-1**	**3.2E+0**
Pendleside Limestone	1.60E-07	1.60E-06	1.60E-05	0.01	**2.5E+0**	**2.5E+1**	**2.5E+2**
Worston Shale	6.00E-09	6.00E-08	6.00E-07	0.03	3.2E-2	**3.2E-1**	**3.2E+0**

The resulting velocities appear far too high. The highest transport velocity is simulated in the Collyhurst sandstone for the high conductivity case. The velocity is 480 m/y and comparable to near surface velocities in the vicinity of a big waterworks (Wiese and Nützmann, 2009). It is not realistic for a deep aquifer. Garven (1995) analyses different processes that induce deep fluid flow in the subsurface. The highest velocities are between 0.1 and 100 m/y and occur for geologic processes that are not relevant for Great Britain. Consequently velocities below 0.1 m/y are considered within a realistic scale.

Garven (1995) analyses different processes that are responsible for the high groundwater flow. None of these is relevant to the Bowland shale area. Furthermore, it should be considered, that high fluxes equilibrate different hydraulic potentials and therefore typically correspond to low hydraulic gradients (Flewelling and Sharma 2014), at least in case of long existing pathways (Rozell, 2014), which is the case for the horizontal flow under consideration.

Cai and Ofterdinger (2014) apply a hydraulic gradient of 5‰ which is derived from shallow aquifers with a depths below 100 m (Schürch and Buckley 2002, Schürch et al., 2004). Shallow aquifers typically show high hydraulic gradients since they are affected by groundwater recharge and topography. Deep aquifers in contrast show less recharge and the topographic impact is much smaller. Deep aquifers also have much larger scales. On a distance of 500 km a 5‰ it would require an equivalent height difference of 2500 m water column, which is not realistic for the British Islands.

The horizontal hydraulic transport velocities as simulated by Cai and Ofterdinger (2014) are above a realistic scale. Therefore the removal mechanism for upwelling contaminants is overestimated. The Collyhurst sandstone, which represents the most effective barrier shows unplausibly high horizontal transport velocities for all three conductivity cases. For the reference and the high permeability case the velocity is unplausibly high in 7 of 10 layers. The interpretation that the horizontal flux acts as effective barrier for upwelling contaminants through hydraulic active fractures is not plausible.

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*1 conductivity: A high conductivity level means water (and other fluids) can flow easily through the rock, a low conductivity level means that a rock can be impermeable to water and other fluids.

*2 conductive pathway: a region with high permeability, but low spatial extent, such as an open fault or fracture.