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Regional groundwater flow patterns in the Northern Great Plains area and their effect on CO$_2$ sequestration at Weyburn, Saskatchewan, Canada

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Abstract

Regional groundwater flow patterns in the Northern Great Plains area do not follow the concept proposed by Downey et al. [6] and adopted by Bachu [2,3] for Alberta, and Khan and Rostron [9] for the Weyburn CO$_2$ sequestration site in Saskatchewan. Accordingly, investigations for the migration behaviour of sequestered CO$_2$ in Weyburn and in Alberta should be revisited by applying modern fluid dynamics based on Hubbert’s [1] force potential instead of the methodology of continuum mechanics. Continuum mechanics had been developed in the 19th century for solving practical engineering problems. These methods are not suited for delineating regional groundwater flow patterns and the effect of groundwater flow on CO$_2$ storage.

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1.1 Introduction

Due to new insights into their effect on CO$_2$ sequestration and geological processes, Hubbert’s [1] force potential and the derived gravitational deep-seated regional groundwater flow systems have slowly been taking on more prominence in groundwater dynamic applications and research. Instead of being seen as a static fluid in the deep subsurface, the deep groundwater body is now increasingly seen as a moving fluid (albeit often slow) and as an effective agent of transport and of geologic and chemical change. It is also seen as a provider of gravitational force fields of fresh groundwater at the surface and at greater depth. These force fields are created by the boundary condition of the groundwater table and propel, at the surface and at greater depth, all other fluids such as hydrocarbons, salt water, brine, and both natural and

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Fig. 1. (left) Assumed contemporary regional groundwater flow systems in Alberta and Montana (after Bachu [2, 3]). Regional (black) arrows: gravitational groundwater flow in Upper Devonian layers [2, 3]. Red arrows: ‘inward flow-driven by erosional rebound in the Cretaceous succession’ [3]; double-lined arrows: ‘basin scale flow driven by past tectonic compression in the lower Devonian aquifers’ [3]. after Weyer [4].

Fig. 2. (right) Assumed regional groundwater flow pattern in the Northern Great Plains according to Toop and Tóth [5, Figure 13], based upon Downey et al.[6]. Presumed flow arrow reaches from the area of Yellowstone National Park (assumed Highlands recharge area) to Manitoba (assumed endpoint of regional groundwater flow system [5, 6]). The presumed flow arrow intersects the Weyburn oilfield in Saskatchewan.

sequestered CO₂ (Hubbert [7] p.1960). In this paper, references by Bachu [2, 3] to erosion or tectonically-driven flow (Fig. 1) are ignored as, in our opinion, they are not of significance within present-day regional groundwater flow systems in Alberta or at Weyburn as gravitational forces are dominant by far. The validity of Bachu’s Alberta Basin-wide gravitational flow systems (Fig. 1) is not discussed here.

1.2 Application of legacy concepts to regional groundwater flow in the Northern Great Plains and at Weyburn

In the region of the Northern Great Plains there still exist a number of legacy concepts with respect to subsurface fluid flow (Fig. 1 and 2). The basis for these concepts is that recharge into artesian aquifers needs to take place in surface outcrops of these aquifers in hills as seen in Fig. 3A, while the actual groundwater dynamic flow paths are shown in Fig. 3B which is based on mathematical groundwater flow modeling by Freeze and Witherspoon [8]. Fig. 3B shows the importance of aquitards (in oilfield terminology: caprocks) in securing minimal energy use within force and flow fields by transmitting hydrous flow downwards into the higher permeable aquifer under the recharge area and transmitting the flow back to the surface under the discharge area where artesian (flowing) wells occur. In this constellation twice as much groundwater flows through the aquitard (downwards under the recharge area and upwards under the discharge area) as in the aquifer (lateral flow only). Although for many readers
Fig. 3. (left) Comparison of legacy [7] and modern [8] understanding of the role of aquitards in regional groundwater flow.

Fig. 4. Downey et al.’s [6] regional groundwater system under-flowing the Weyburn CCS site as assumed by Khan and Rostron [9].

this last point may appear unusual, the consequences of applying modern groundwater dynamics are profound in that a great number of legacy assumptions should be revisited in the area of groundwater dependent geological processes and in CO$_2$ sequestration.

In their evaluation of regional groundwater flow in the Northern Great Plains and the Williston Basin, Downey et al. [6] adhered to the legacy concept of Fig. 3A when dealing with Mississippian aquifers. Thereby it is assumed (Fig. 2) that recharge into aquifers under aquitards can only occur in the highland recharge areas of these aquifers (as for example the Bighorn Mountains, and parts of the Beartooth and Absaroka Mountains) and groundwater discharge at the outlets of these aquifers (in South Dakota, North Dakota, Manitoba and Saskatchewan). Similar assumptions (Fig. 4) have been adopted by Khan and Rostron [9] in establishing the groundwater dynamic flow systems at the well-known and exemplary Weyburn test site for CO$_2$ sequestration located in Saskatchewan within the Williston Basin.

Following the lead by Downey et al. [6] and others, the Watrous aquitard overlying the injection Midale aquifer at the Weyburn CO$_2$ sequestration site has been assumed to be impermeable and the groundwater...
flow direction in the injection aquifer has been assumed to be directed northeasterly (Fig. 5) towards regional discharge areas in Manitoba for flow originating in the Montana highland recharge areas in the manner depicted in Fig. 3A. As a consequence of that choice the migration time for sequestered CO$_2$ to the surface in Manitoba has been determined to be in the 400,000 to 600,000 year range.

1.3 Actual flow directions at the Weyburn oil field and their effect on Weyburn CCS

Based on exploration data by Socony-Mobil, Hubbert [11, p.72] identified the Weyburn field as a large hydrodynamic trap for hydrocarbons with groundwater flow in the Midale aquifer directed towards the south, opposing the direction assumed by Khan and Rostron [9]. Applying modern groundwater dynamics to the Weyburn site (Fig. 5: distribution of recharge and discharge areas) indicates that upon cessation of the present EOR and subsequent CCS operations, and recuperation of the groundwater flow fields to preproduction conditions, groundwater flow under the valley bottom will be upward-directed, penetrating the so-called ‘impermeable’ Watrous aquitard (Fig 6). Flow times to water courses at the surface may be in the thousands to ten thousand year range, which is still sufficient to mitigate any undesired effects.

1.4 Conclusions

As a consequence, the groundwater dynamic investigations of the Weyburn field and its associated CO$_2$ sequestration should be revisited by applying Hubbert’s [1] force potential and groundwater flow systems theory. Conclusions previously drawn in this respect were based on unproven assumptions.

References