

Long Range Groundwater Flow in the Northern Great Plains of America

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1. Introduction

A number of practical considerations have put the presumed existence of long range groundwater flow into the centre of interest in the area of the Northern Great Plains in Canada, such as CO₂ sequestration in Alberta and Saskatchewan as well as mining of the Athabasca oil sands and subsurface waste disposal (Swan Hills) in Alberta. Thus, in this area, regional groundwater flow has moved from the realm of academic studies to become an important component of environmental concerns by industry, governments and the public.

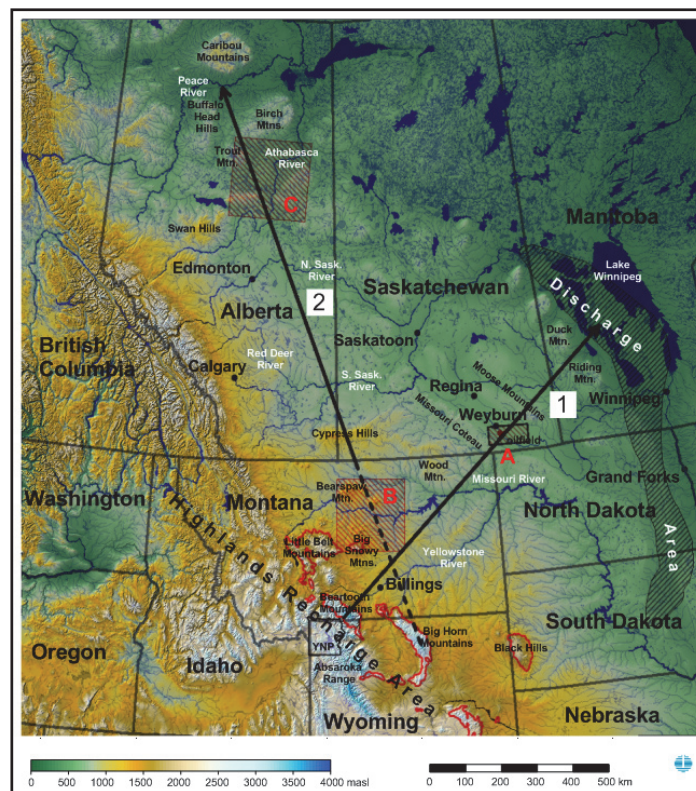


Figure 1. Long range regional groundwater flow systems [1] and [2] in the prairie provinces (Alberta, Saskatchewan and Manitoba) and US states (Montana, North and South Dakota) proposed by *Bachu* [1999], *Anfort et al.* [2001], and *Downey et al.* [1987].

One such long range flow system has been postulated by *Downey et al.* [1987] with recharge into deep aquifer systems in the Beartooth Mountains, Absaroka Range, and the Big Horn Mountains, located off Yellowstone National Park. They are of alpine character exceeding 3000 m in elevation. Associated discharge areas were presumed to be in South Dakota, North Dakota, Manitoba and Saskatchewan. The assumed flow system [1] of about 1100 km length is part of *Downey et al.*'s [1987] postulate.

Long range system [2] is about 1600 km long [*Bachu*, 1999, *Anfort et al.*, 2001] and recharges at the outcrop of the aquifer system in the Big Snowy Anticlinorium and Big Horn Mountains in Montana (Figure

1), and discharges about 1600 km further north into the Peace River. Based on thermodynamical principles and head data, *Weyer* [2012] showed this construct to be physically untenable and contrary to head data provided by *Bachu et al.* [1993].

The methods applied in the investigations of these systems related to chemistry and basic groundwater dynamics. This paper examines the validity of groundwater dynamic assumptions used. The outdated concept applied for recharge and discharge of deep aquifer systems as shown in Figure 2A. Recharge of the aquifer system is assumed to occur only at the mountainous outcrop area while discharge only occurs in the ‘downstream’ outcrop area of the very same aquifer system. The overlying ‘impermeable’ aquitard prevents communication between the aquifer system and the overlying groundwater body and the groundwater table. For about 50 years, the concept has been replaced by *Freeze and Witherspoon* [1967], which recognized aquitards (and caprocks) as an integral part of groundwater flow systems (Figure 2B).

The outdated concept of Figure 2A leads to long range groundwater flow systems between the two outcrop areas of the aquifer system. This is the only ‘hydraulic’ reason why the two long range groundwater flow systems ([1] and [2]) have been postulated by their supporters. In applying this outdated concept to CO₂ sequestration and the mining of the Athabasca oil sands, erroneous operational recommendations were provided to industry, governments, and the public which will need to be revisited [*Weyer*, 2012; 2013].

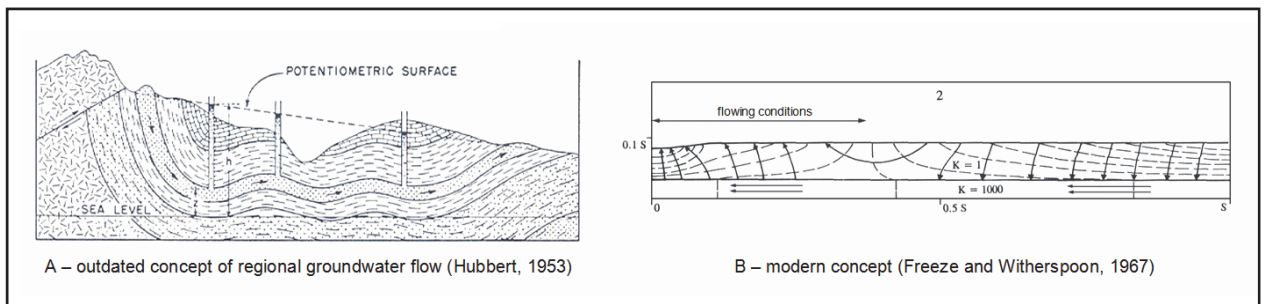


Figure 2. Comparison of outdated [Figure 2A; *Hubbert*, 1953] and modern [Figure 2B; *Freeze and Witherspoon*, 1967] concepts with respect to the role of aquitards in regional groundwater flow.

2. Groundwater dynamics

Hubbert's [1940] force potential and the derived gravitational regional groundwater flow systems are the base of physically consistent investigations of gravitational groundwater flow systems. Force fields for subsurface fluid flow are arranged such that the total energy consumption of the field is minimized. This alone prevents the creation and existence of the two postulated long range flow systems in the Northern Great Plains. In addition, field data published by *Bachu et al.* [1993] for the area of the Athabasca Oil Sands and by *Hubbert* [1967] and *Hannon* [1987] for the Weyburn oil field, showed that groundwater recharge in nearby hills and associated downward flow through aquitards into the regional aquifer system at the Athabasca Oil Sands and at the Weyburn oil field established groundwater flow directions which are opposite to those postulated for groundwater systems [1] and [2] [*Weyer* 2012; 2013]. Space limitations cause us to deal here only with system [1] at the Weyburn oil field.

Figure 3 depicts the topographical and, due to the regional scale chosen, the water table profiles along the assumed groundwater flow system [1] from the highland recharge area in the southwest to the Manitoba discharge area in the northeast with an elevation drop of over 2500 m. The deep groundwater flow will be intercepted by major river valleys such as those of the Yellowstone River, Missouri River, and their

tributaries. We test this process with the example of the Weyburn oil field located under the Souris River between the Missouri Coteau and the Moose Mountains (Figures 1, 3). Figure 4 shows the topography and the regional groundwater table at the Weyburn oil field. Figure 5 indicates the expected groundwater flow systems from the application of Hubbert’s force potential and groundwater flow systems theory.

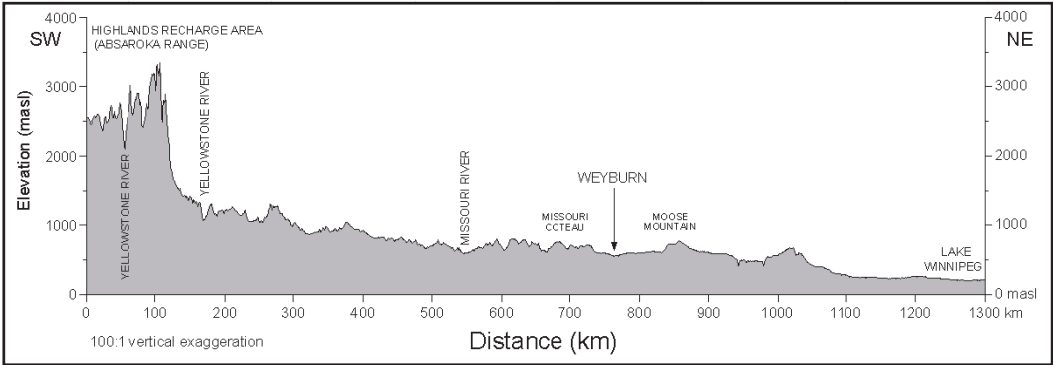


Figure 3. Topography of land surface and groundwater table in a cross-section which runs along the flow arrow [1] in Figure 1.

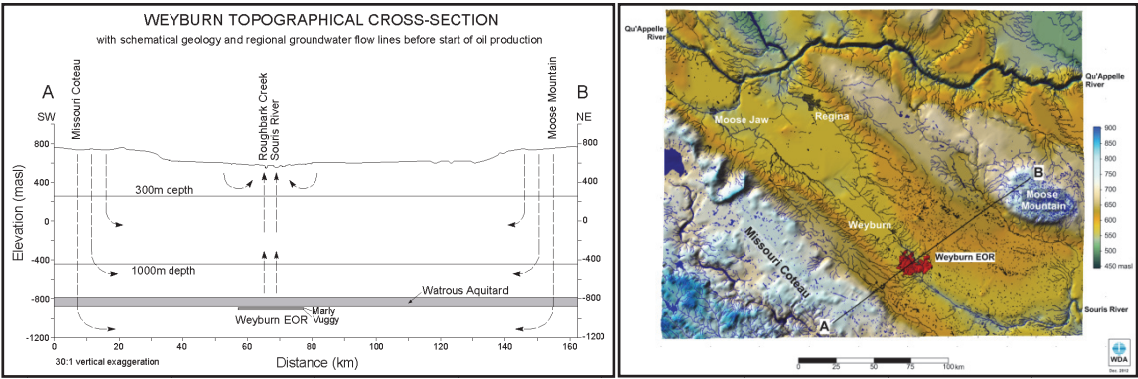


Figure 4. Topography and groundwater table at Weyburn. From Weyer [2013].

Figure 5. Schematic pattern of groundwater flow at the Weyburn oilfield. From Weyer [2013].

3. Interpretation of field data at the Weyburn oil field

Hubbert [1967] and Hannon [1987] provided data on flow direction and head values in the Midale aquifer. These data have been summarized in Figure 6. The combination of Hubbert’s flow directions (red arrow) and Hannon’s head data confirm that groundwater flows within the Midale Formation to a position under the Souris River from both sides. From the groundwater physics involved it follows irrevocably that discharging groundwater moves upward from the Midale to the Souris River as diagrammatically shown in Figure 5.

4. Conclusions

Based upon thermodynamic reasons and field data, it became obvious that the postulated long range groundwater flow systems [1] and [2] do not exist. Any interpretation of regional groundwater flow systems needs to be cross-checked against the unforgiving yardstick of physical causation. The postulated long range groundwater flow systems fail that test.

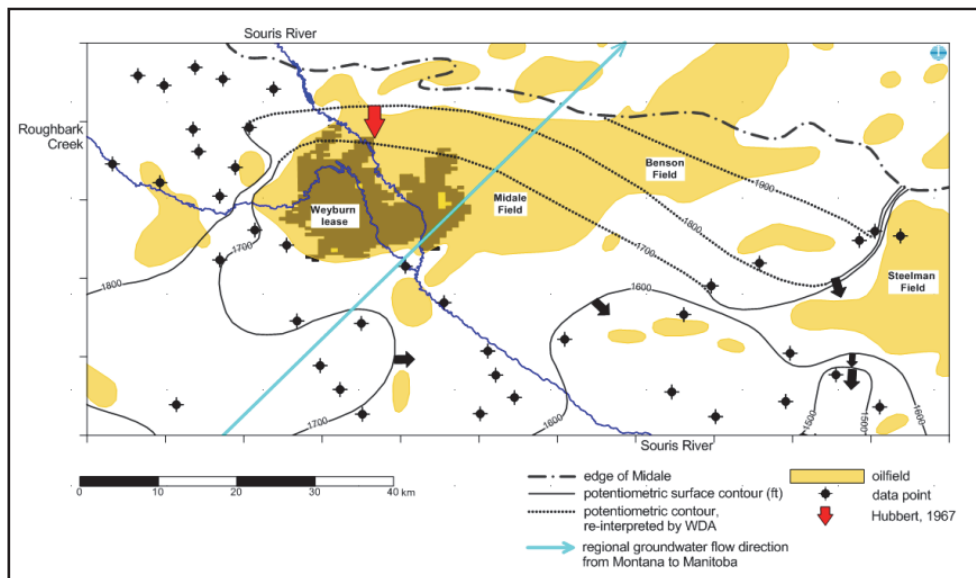
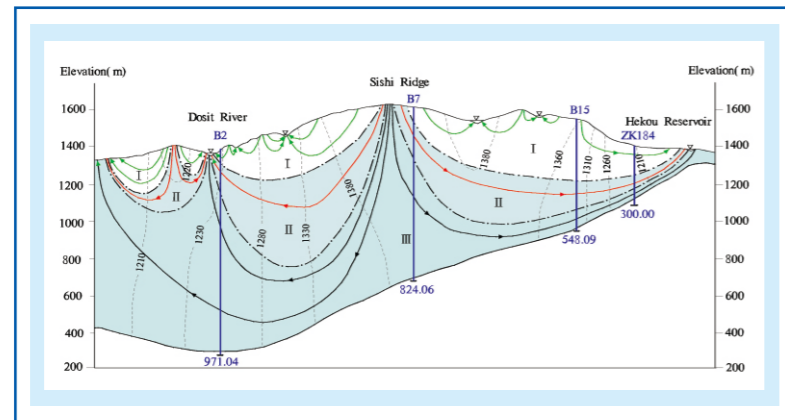


Figure 6. Head distribution within the Midale formation in the Weyburn area. Red arrow: flow direction determined by *Hubbert* [1967]. Dotted lines: interpreted head values given by *Hannon* [1987, Fig 5]. Cyan line: flow direction of system [1]. See box in Figure 1 for location.

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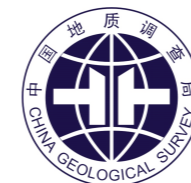
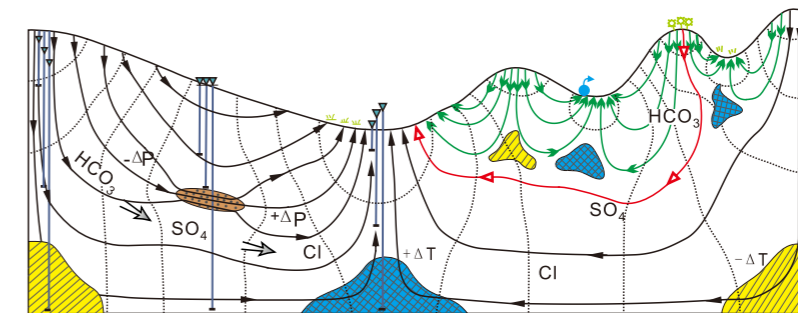
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