Long range regional groundwater flow systems in the Northern Great Plains: (1) Groundwater flow directions within the Midale Formation at the Weyburn carbon sequestration site, Saskatchewan, Canada

K. Udo Weyer & James C. Ellis
WDA Consultants Inc., Calgary, Alberta, Canada

ABSTRACT
Regional groundwater flow patterns have become a basis for judging the environmental effects of subsurface injection of CO_2 in Alberta and Saskatchewan, and waste water disposal in the Athabasca region of Alberta. Presently, however, not much attention has been paid to the type of fluid dynamics used (the mathematical physics of engineering hydraulics with velocity potentials versus Hubbert's force potentials and the integration of field data acquired). This paper evaluates the fluid dynamic concepts and field data presently in use, regionally and locally, at the well-known Weyburn CO_2 sequestration test site in Saskatchewan. As an outcome it recommends an alteration in the concepts, types of investigations, and monitoring procedures in place. The new methods will actually improve the understanding of local and regional fluid dynamic processes, optimize management of injections, and permit the control of possible return flows.

RÉSUMÉ
Les patrons d'écoulement des eaux souterraines sont devenus la base pour évaluer les effets environnementaux de l'injection souterraine de CO_2 en Alberta et en Saskatchewan, ainsi que des bassins d'eaux contaminées dans la région de l'Athabasca en Alberta. Jusqu'à présent, peu d'attention fut portée au type de dynamiques des fluides utilisé (la physique mécanique des milieux continus avec potentiel de vitesse par rapport aux forces potentielles d'Hubbert, ainsi que l'intégration des données de terrains acquises). Cet article évalue le concept de dynamique des fluides ainsi que les données de terrain présentement utilisées régionalement et localement au site d'essais de séquestration de CO_2 de Weyburn en Saskatchewan. Il est suggéré d'apporter un changement dans le concept, le type d'investigations, et les procédures de surveillance présentement mises en place. Les nouvelles méthodes proposées vont permettre d'améliorer la connaissance des processus locaux et régionaux de dynamique des fluides, d'optimiser la gestion de l'injections, et permettre le control possible de retours d'écoulement.

1 INTRODUCTION

A number of practical considerations have put the presumed existence of long range groundwater flow systems into contention in the area of the Northern Great Plains in Canada, such as CO_2 sequestration in Alberta and Saskatchewan, as well as extraction of the Athabasca oil sands and subsurface waste water disposal (Athabasca oil sands and Swan Hills) in Alberta. Thus, in this area, regional groundwater flow has moved beyond the realm of academic studies and became an important component of environmental concerns by industry, governments and the public.

Long range flow systems have been postulated by Downey et al. (1987) with recharge at the outcrop of regional aquifer systems in the Beartooth Mountains, Absaroka Range, and the Big Horn Mountains, all located in Montana within the vicinity of Yellowstone National Park (Figure 1). These mountain chains are of alpine character exceeding 3000 m in elevation. Associated discharge areas from the same aquifer system were presumed to be in South Dakota, North Dakota, Manitoba and Saskatchewan. The assumed flow system [i] of about 1100 km length adheres to Downey at al.'s (1987) postulate. Toop and Tóth (1995) added, within the prairie environment, the Cypress Hills, the Bearspaw Mountains, and the Wood Mountains as additional recharge areas to Downey's et al.'s (1987) concept (see Figure 2).

Long range flow system [ii] was proposed by Bachu (1999) with a length of about 1600 km and was reinforced by Anfort et al. (2001). This paper concerns itself with system [i] only, while system [ii] is addressed in a separate paper in these proceedings (Weyer and Ellis, 2013).

2 GROUNDWATER DYNAMICS

The methods previously applied in the investigations of the above long range systems were based upon chemistry and simplified groundwater dynamics. This paper examines the validity of groundwater dynamic assumptions used by Bachu (1999) and Downey et al. (1987) for recharge and discharge of deep aquifer systems (Figure 3). Deep groundwater flow has been assumed to be recharged as far away as the Big Horn Mountains and Yellowstone National Park in Wyoming (Downey et al., 1987; Hannon, 1987; Bachu and Hitchon, 1996; Khan and Rostron, 2005).

According to the concepts adopted, recharge of the aquifer system occurs only at the mountainous outcrop area while discharge is restricted to the 'downstream'

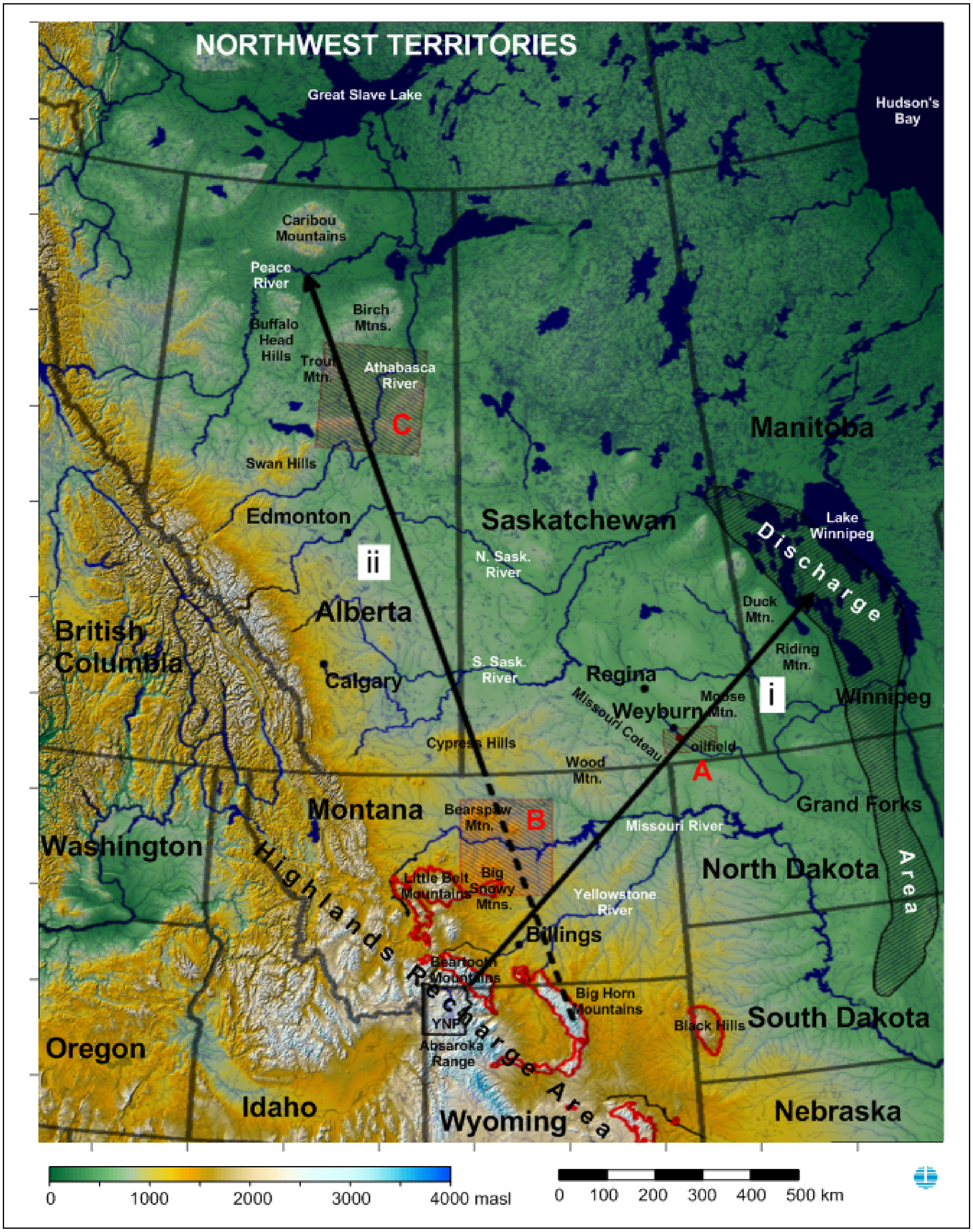

Figure 1. Long range regional groundwater flow systems [i] and [ii] in the prairie provinces and US states proposed by Bachu (1999), Anfort et al. (2001), and Downey et al. (1987). Mountainous outcrops of aquifer systems (after Downey, 1986, Figure 4) are outlined in red. The naming and location of the Highland Recharge areas have been taken from Toop and Tóth (1995). The discharge area, stretching more than 1000 km from north to south, originated with Downey et al. (1987, Figure 6) and was subsequently modified by Toop and Tóth (1995, Figure 13).

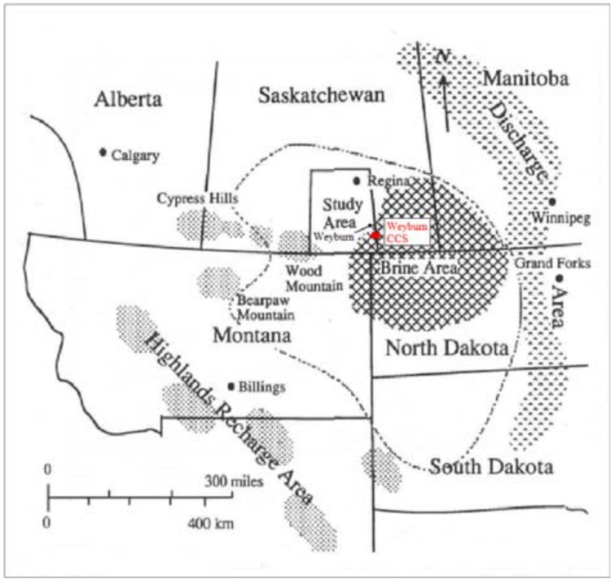

Figure 2. Location of recharge and discharge areas of deep regional groundwater flow after Toop and Tóth (1995, Figure 13). The authors added, within the prairie environment, Cypress Hills, the Bearpaw Mountains, and the Wood Mountains as additional recharge areas to Downey et al.'s (1987) concept and modified the outline of the regional discharge area.

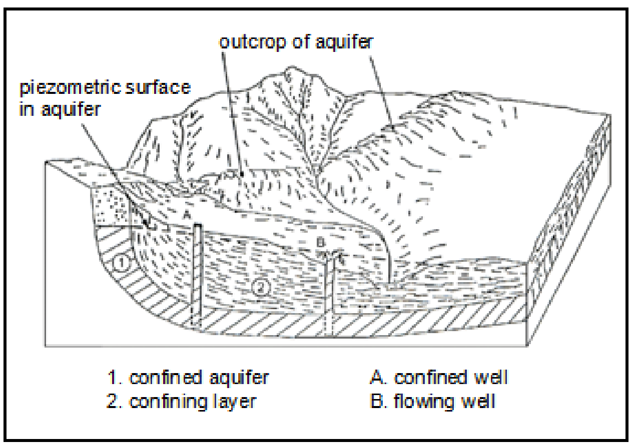

Figure 3. Waltz's (1973, Figure 6.1.3) erroneous concept of regional groundwater flow in artesian aquifers.

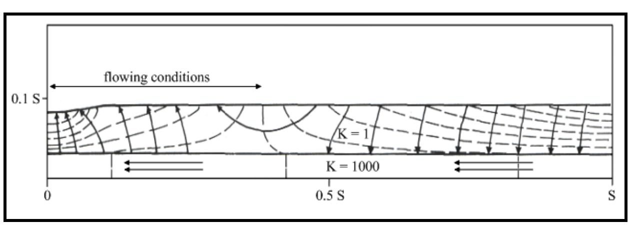

Figure 4. A physics-based concept of regional groundwater flow incorporating aquitards (after Freeze and Witherspoon, 1967, Figure 7[2])

outcrop area of the very same aquifer systems. The overlying 'impermeable' aquitard prevents communication between the aquifer system and the overlying groundwater body and the groundwater table. About 50 years ago this concept was surpassed by the work of Freeze and Witherspoon (1967), which recognized aquitards (and caprocks) as an integral part of groundwater flow systems (Figure 4). Artesian conditions (flowing wells) occur in discharge areas.

The fact that head distributions in aquifers directly reflect the topographical oscillation of the groundwater table (Figure 5) is proof of groundwater flow through aquitards. Under recharge areas the head in the aquifer is lower than the groundwater table; below discharge areas the head in the aquifer is higher than the groundwater table. These configurations have been confirmed by field measurements at many sites worldwide. An example of this type of measurement (Figure 6) has been published by Albinet & Cottez (1969).

By adding the Cypress Hills and the Bearspaw and Wood Mountains to Downey et al.'s (1987) concept of recharge areas, Toop and Tóth (1995) acknowledged that groundwater flow from the groundwater table in these hills and mountains penetrates the aquitards covering the regional aquifer system on its way to the aquifer and the regional discharge area in Manitoba.

Bachu's (1999) and Downey et al.'s (1987) erroneous concept of impermeable aquitards (Figure 3) seems to have led to the postulated long range groundwater flow systems between the upstream and downstream outcrop areas of the same aquifer system. This is the only 'hydraulic' reason why the two long range groundwater flow systems should exist as presumed by their supporters. In applying this concept to CO_2 sequestration at Weyburn, erroneous operational recommendations about subsurface flow were provided (Khan and Rostron, 2005; Rostron and Whittaker, 2011) to industry, governments, and the public which will need to be revisited.

Hubbert's (1940) force potential and the derived gravitationally-driven regional groundwater flow systems are the basis of physically consistent investigations of regional groundwater flow. Thermodynamically, force fields for subsurface fluid flow are arranged in such a way that the total energy consumption within the field is minimized.

Figure 7 shows a greatly-exaggerated (200:1) groundwater table configuration along the postulated groundwater flow system [i] (Figure 1). Contrary to Downey et al.'s (1987) assumptions, recipients of deep regional groundwater flow are the Yellowstone River and the Missouri River as well as their tributaries. Weyburn lies in the wide valley of the Souris River between the Missouri Coteau (including Wood Mountain) and the Moose Mountain (Figure 8). We will test the hydraulic principle of minimization of energy use with the examples of (1) the Weyburn oil field located under the Souris River (Figures 1, 2, and 8) and (2) with the groundwater flow pattern at the Manitoba escarpment just west of the regional discharge area (Figures 1 and 2) postulated by Downey et al. (1987) and adopted by Toop and Tóth (1995).

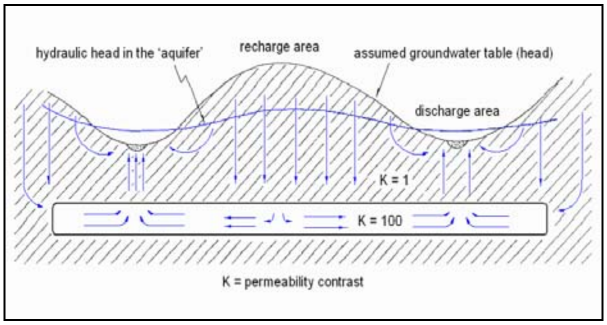

Figure 5 Heads in buried aquifers usually directly reflect the oscillations of the groundwater table (from Weyer, 2006, Figure 10).

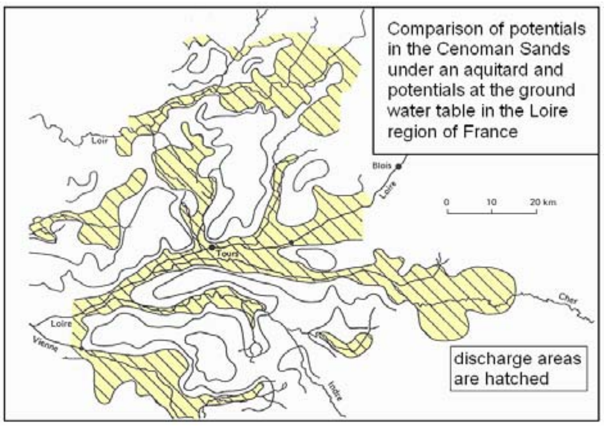

Figure 6. Plan view of groundwater flow systems penetrating an aquitard (after Albinet & Cottez, 1969, Figure 2).

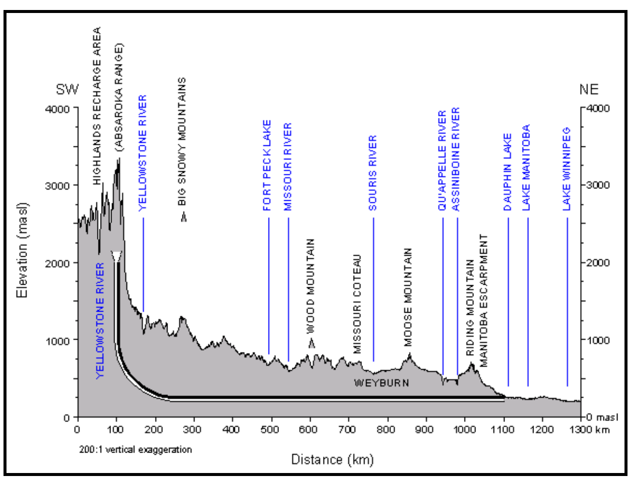

Figure 7. Topographical (groundwater table) cross-section along the postulated long range regional groundwater flow system [i], as shown in Figure 1. Maximum elevations of nearby mountain ranges (recharge areas) are indicated by grey peaks. The black and white 'pipe' schematically represents the regional aquifer system (white) overlain by an aquitard (black).

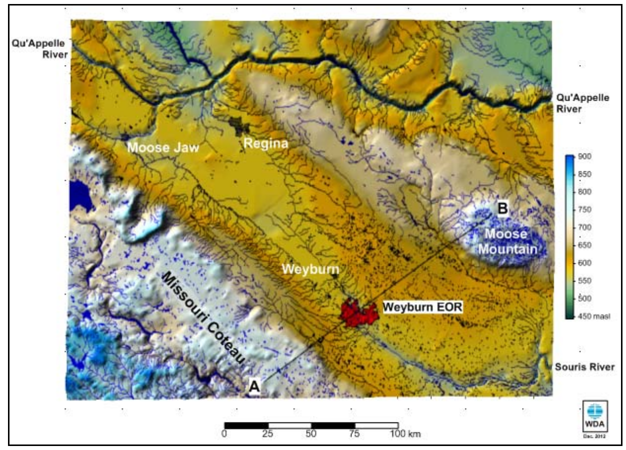

Figure 8. Topography and groundwater table in the Weyburn region. From Weyer (2013).

3 REGIONAL GROUNDWATER DYNAMICS AT THE WEYBURN FIELD

Figure 8 depicts the topography and approximate groundwater table of the region of the Weyburn oil field. The regional recharge areas are the Missouri Coteau with Wood Mountain towards the southwest and, towards the northeast, Moose Mountain and its extension. The discharge areas for regional groundwater flow are the Souris River and Roughbark Creek.

Figure 9 shows the groundwater flow concept presently adopted for CCS and EOR operations at the Weyburn oil field. Groundwater flow in the Mississippian and Midale Formations approaches from the southwest (Figures 1 and 2), passes through the Weyburn oil field and, subsequently, groundwater flow continues laterally northeast towards the large discharge area in Manitoba (Figures 1 and 2). At Weyburn the injected supercritical, and subsequently dissolved, CO_2 is thought to migrate laterally in the same direction. Accordingly, the Watrous aquitard needs to be considered to be impermeable.

Figure 10 indicates the suspected general pattern of groundwater flow systems and flow directions based on the physics of Hubbert's force potential and groundwater flow systems theory. The Watrous aquitard is sufficiently permeable (albeit of low permeability) to allow the passage of significant amounts of groundwater flow. Groundwater would flow from the Missouri Coteau in the southwest and from the Moose Mountain upland in the northeast toward the Weyburn oil field, penetrating the Watrous aquitard upwards and continuing in an upward direction towards the Souris River and Roughbark Creek.

This phenomenon is well known for salty (higher density water) and used to be called 'coning'. The mechanism for upward flow of denser water and brine is a consequence of the physics of Hubbert's (1940) force potential theory and has been elucidated in a field study by Weyer and van Everdingen (1995). Published field data by Hubbert (1967) and Hannon (1987) provide the basis to select the physically valid interpretation and reject the one based on mathematical pseudo-physics and velocity potential of engineering hydraulics (Figures 9,10).

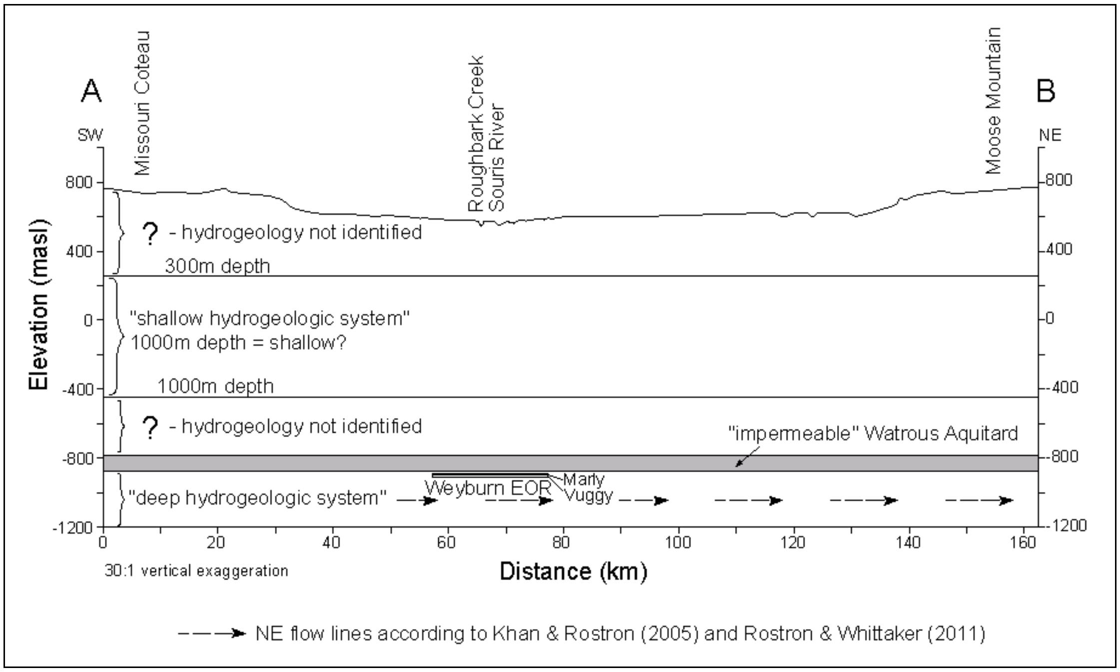

Figure 9. Conceptual hydrogeological framework outlined by Khan and Rostron (2005) and Rostron and Whittaker (2011) for the region of the Weyburn oil field. Below the Watrous aquitard, groundwater supposedly flows in the Midale from southwest to northeast, and does not cross the Watrous aquitard upwards towards Souris River and Roughbark Creek. Groundwater flow in the Mississippian formation (containing the Midale) migrates from southwest under the Wood Mountain and continues towards northeast under the Moose Mountain ridge towards discharge areas in Manitoba. A depth of 300 to 1000 m below surface is considered by the authors to be shallow groundwater. (Diagram taken from Weyer, 2012.)

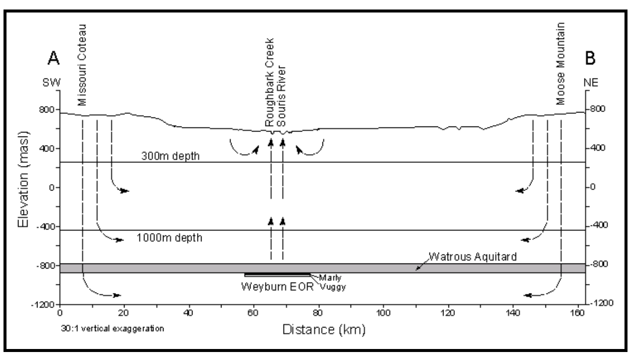

Figure 10. Schematic pattern of groundwater flow at the Weyburn oilfield based on Hubbert's force potential and groundwater flow systems theory. From Weyer (2013).

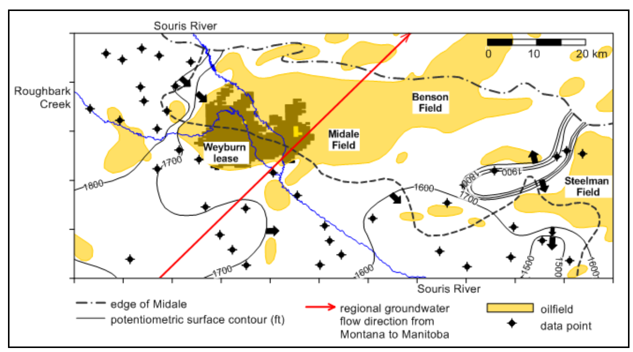

Figure 11. Midale potentiometric surface map (data taken from Hannon 1987, Figure 5). Hannon adopted an unusual interpretation by his concentration of equipotential lines (potentiometric surface contours) in the eastern portion of the map. Box A in Figure 1 shows location of Figure 13.

4 APPLICATION OF PUBLISHED GROUNDWATER FIELD DATA TO THE WEYBURN OIL FIELD

Hubbert (1967, p. 72), based upon exploration data taken by Socony-Mobil, reported a tilt of about 9.5 m/km in a southwards direction for the oil/water interface in the Midale Beds of the Weyburn field. Natural groundwater flow in the Midale formation was thereby directed towards the south, and not towards the northeast as postulated by Khan and Rostron (2005) and Rostron and Whitaker (2011) .

In portions of the Mississippian Formation located southwest of the Weyburn oil field, groundwater flow was generally directed towards the northeast (Figure 11). Hannon's (1987, Figure 6) interpretation of the interplay between the northeast direction of groundwater flow in the area southwest of the Weyburn oil field and the south-directed groundwater flow direction within the Midale layer

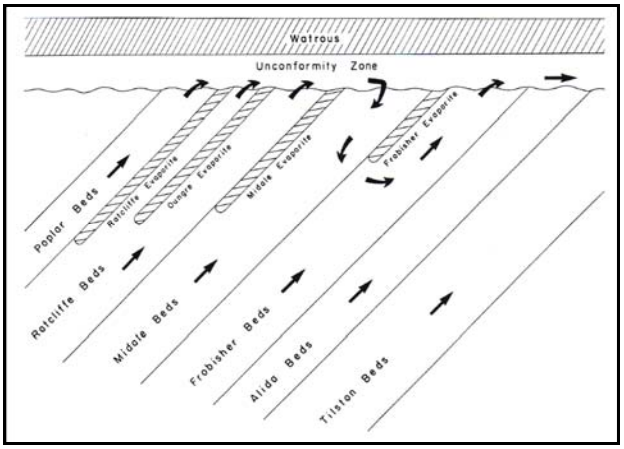

Figure 12. Groundwater flow pattern in Mississippian subcrop, according to Hannon (1987, Figure 6). This interpretation has been based on Downey et al.'s (1987) concept of regional groundwater flow.

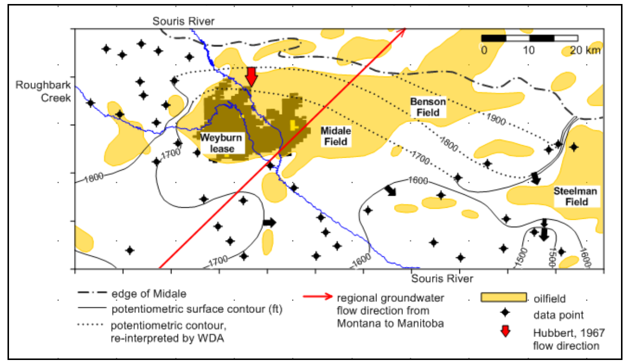

Figure 13. Head distribution in petroleum wells within the Midale formation in the Weyburn area. Fat red arrow: flow direction determined by Hubbert (1967). Dotted lines: re-interpreted head values (modified from Hannon 1987, Fig 5). Long red arrow: flow direction of regional groundwater flow system [i]. Box A in Figure 1 shows location of Figure 13.

of the Mississippian Formation within the oil field is shown in Figure 12. The concept applied by Hannon (1987) contravenes groundwater dynamic principles and is therefore not feasible. Figure 13 provides our reinterpretation of Hannon's equipotential lines which incorporates the head data of Hannon (1987, Figure 6) in a manner consistent with groundwater dynamic principles.

The combination of Hubbert's flow directions (Figure 13: fat red arrow) with the reinterpreted equipotential lines, confirms the natural groundwater flow within the Midale Formation to locations below the Souris River from opposing directions (from both the southwest-positioned Missouri Coteau and the northeast-positioned Moose Mountain ridge). In view of Darcy's law and the continuity equation it follows irrevocably that under natural conditions discharging ground-water moved upward from the Midale layer through the Watrous aquitard to the Souris River and Roughbark Creek as schematically shown in Figure 10.

At Weyburn the deep groundwater flow is intersected by the valleys of the Souris River and Roughbark Creek. The elevation differences between the regional recharge areas of the Moose Mountain ridge to the northeast and the Missouri Coteau to the southwest are up to 230 m and 400 m respectively. Suitable mathematical models have so far not been calculated for the Weyburn CO_2 sequestration site.

Khan and Rostron (2005, p.747) dismissed clear indicators for upward flow from the Weyburn field into the overlying Watrous aquitard because they considered a hydraulic discontinuity "the more likely interpretation of the break" (of vertical pressure data). Hydraulic breaks do not exist in hydraulic force fields, however continual changes do exist (Hubbert, 1940; Weyer, 1978).

Considering that, in the Weyburn field, flow from the north and southwest met under natural pre-pumping conditions, and indicators of upward flow into the Watrous Aquitard have been present, a physics-based judgment would consider the occurrence of salt water coning (upward flow) to be a matter of detailed investigation and monitoring in preparation of the planned long term CO_2 storage. Adjusted post-sequestration groundwater flow systems will resemble the natural pre-production pattern.

5 REGIONAL GROUNDWATER FLOW RECHARGING IN THE HILLS ALONG THE MANITOBA ESCARPMENT

In the province of Manitoba and the states of North and South Dakota, Downey et al.'s (1987) discharge areas (Figures 1 and 2) are located to the east of the Manitoba Escarpment whose southern extension is called the Pembina Escarpment in the Dakotas. To the west of this elongated discharge area are a number of hills along the Manitoba escarpment which are the recharge areas for regional groundwater flow feeding these discharge areas (Figure 14). The elevation differences at Riding Mountain are in the order of 300 m (Figure 15). These elevation differences are sufficient to propel the recharged groundwater to the bottom of the sedimentary layers and up again to discharge areas located east and also west of these hills (compare Figure 14 showing red discharge points of saline water to the east and, in the wider valley of the Assiniboine River, also west of Riding Mountain).

Van Everdingen (1971, Figure 1) also reported discharge with high salinity values east and west of Riding Mountain. We argue that the occurrences of the saline springs are further indicators that the groundwater (and any CO_2 contained) do not flow from the Weyburn area in a northeastern direction towards the Manitoba escarpment but rather towards and into the Souris River and Roughbark Creek. Due to the pattern of the force fields, groundwater and associated or dissolved fluids enter these streams from below and then mixes with the much stronger surface water flow.

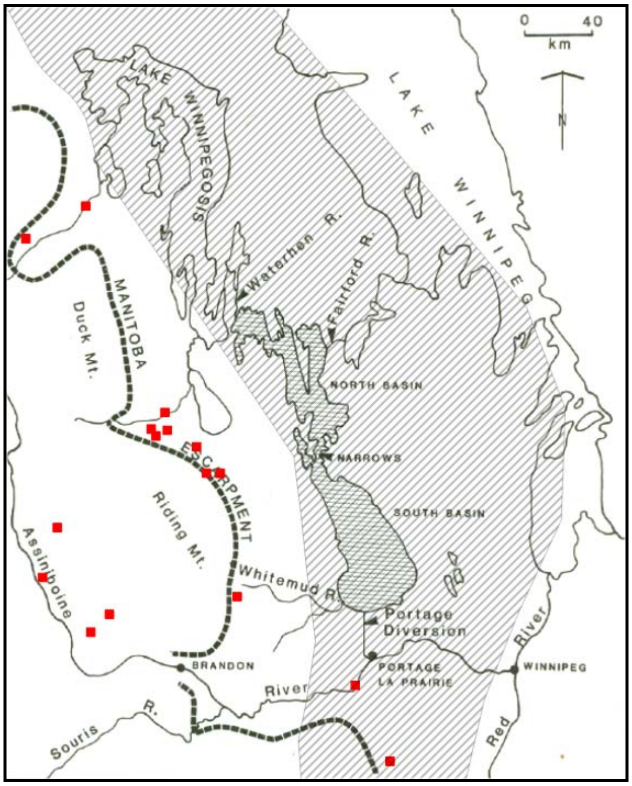

Figure 14. The Manitoba Escarpment (after Last and Teller, 1983, Figure 1). Red squares denote sampling locations (from Rutulis, 1984, Figure 5) with a TDS in excess of 10,000 mg/l. Diagonal shading shows the approximate extent of Toop and Tóth's (1995, Figure 13) discharge area.

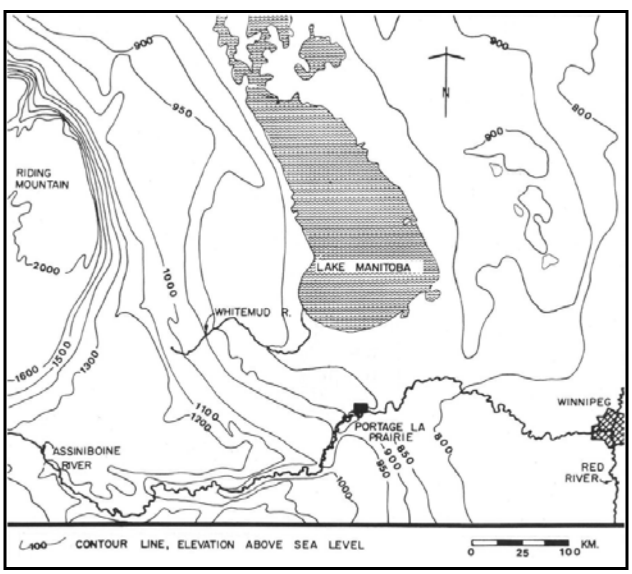

Figure 15. Elevation differences of the Manitoba escarpment at the Riding Mountain. Topography and geographical features taken from Cherry et al. (1971, Figure 2).

CONCLUSIONS

Based upon thermodynamic reasoning and published field data, it became clear that the postulated long range groundwater flow system [i] does 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 system [i] fails that test. At the Weyburn site and at the sites of the Manitoba Escarpments and its southern extension, the Pembina Escarpment, regional groundwater flow recharges in neighbouring hills to penetrate into the deep aquifer systems and discharges in the wider area at valleys and topographical depressions. At the Weyburn CCS site, groundwater flow directions need to be adjusted, proper groundwater dynamic monitoring systems need to be installed, and physically consistent groundwater flow models need to be calculated.

As a conclusion of general nature, it became obvious that investigations of CO_2 sequestration sites need to include physically-consistent studies of regional groundwater flow systems based upon Hubbert's force potential and groundwater flow systems theory and not on the methodologies of engineering hydraulics.

ACKNOWLEDGEMENTS

The authors would like to acknowledge the contribution of R. Sasseville in translating the abstract text into French.

REFERENCES

(star [*] denotes papers available from http://www.wda-consultants.com/papers.htm)

Albinet, M. and Cottez S. 1969. Utilisation et interprétation des cartes de différences de pression entre nappes superposés, *Chronique d'Hydrogéologie*, B.R.G.M., 12: 43–48.

Anfort, S.J., Bachu, S., and Bentley, L.R. 2001. Regional-scale hydrogeology of the Upper Devonian-Lower Cretaceous sedimentary succession, south-central Alberta basin, Canada, *AAPG Bulletin,* 85(4): 637-660.

Bachu, S. 1999. Flow systems in the Alberta basin: Patterns, types and driving mechanisms, *Bulletin of Canadian Petroleum Geology*, 47: 455-474.

Bachu, S., and Hitchon, B. 1996. Regional-scale flow of formation waters in the Williston Basin, *AAPG Bulletin* 80(2): 248-264.

Cherry, J.A., Beswick, B.T., Clister, W.E. and Lutchman, M. 1971. Flow patterns and hydrochemistry of two shallow groundwater regimes In the Lake Agassiz basin, southern Manitoba. In: *Geoscience Studies In Manitoba,* edited by Turnock, A.C., Geological Assn. of Canada, Special Paper Number 9: 321-332.

Downey, J.S. 1986. Geohydrology of bedrock aquifers in the northern Great Plains in parts of Montana, North Dakota, South Dakota, and Wyoming, *USGS Professional Paper 75*, no. 1402-E.

Downey, J.S., Busby, J.F., and Dinwiddie, G.A. 1987. Regional aquifers and petroleum in the Williston Basin region of the United States. In: *Williston Basin: Anatomy of a Cratonic Oil Province,* edited by Longman, M.W., Rocky Mountain Association of Geologists, Denver, Colorado, United States, 299-312.

Freeze, R.A. and Witherspoon, P.A. 1967. Theoretical analysis of regional groundwater flow: 2. Effect of water table configuration and subsurface permeability variation, *Water Resources Research*, 4(3): 581-590.

Hannon, N. 1987. Subsurface water flow patterns in the Canadian sector of the Williston Basin. In: *Williston Basin: Anatomy of a Cratonic Oil Province*, edited by Longman, M.W., Rocky Mountain Association of Geologists, Denver, Colorado, United States, 313-321.

Hubbert, M.K., 1940. The theory of groundwater motion. *Journal of Geology*, 48(8): 785-944.

Hubbert, M.K. 1967. Application of hydrodynamics to oil exploration, *Proceedings of the 7th World Petroleum Congress, Mexico*, Volume 1B: Latest Developments within the Oil Industry: 59-75.

Khan, D.K. and Rostron, B.J. 2005. Regional hydrogeological investigation around the IEA Weyburn CO2 monitoring and storage project site, *Proceedings of the 7th International Conference on Greenhouse Gas Control Technologies (GHGT-7),* vol. 1: 741-750.

Last, W.M. and Teller, J.T. 1983. Holocene climate and hydrology of the Lake Manitoba Basin. In: *Glacial Lake Agassiz*, edited by Teller, J.T. and Clayton, L., Geological Association of Canada Special Paper 26, St. John's, Nfld.

Rostron, B. and Whittaker, S. 2011. 10+ years of the IEA-GHG Weyburn-Midale CO_2 monitoring and storage project: Successes and lessons learned from multiple hydrogeological investigations. *Energy Procedia*, 4: 3636-3643.

Rutulis, M., 1984. Dakota aquifer system in the province of Manitoba. In: *Geohydrology of the Dakota Aquifer*, edited by Jorgensen, D.G. and Signor, D.C., Proceedings of the 1st C.V. Theis Conference on Geohydrology. National Water Well Association Pub., Worthington, Ohio.

Toop, D.C. and Tóth, J. 1995. Hydrogeological characterization of formation waters using ionic ratios, South-Central Saskatchewan. In: *7th International Williston Basin Symposium*, edited by Hunter, L.D. and Schalla, R.A. Billings, Montana, Montana Geological Society, 313-319.

van Everdingen, R. O. 1971. Surface-water composition in southern Manitoba reflecting discharge of saline subsurface waters and subsurface solution of evaporites. Geoscience Studies in Manitoba. *Geological Association of Canada Special Paper Number 9*, 343-352.

Waltz, J.P. 1973. Ground Water. In: *Introduction to physical hydrology*, edited by Chorley, R.J., Methuen & Co. Ltd., London, 122-130.

Weyer, K.U. 1978*. Hydraulic forces in permeable media. *Mémoires du B.R.G.M.*, 91: 285-297

Weyer, K.U. 2006*. Hydrogeology of shallow and deep seated groundwater flow systems: Basic principles of groundwater flow, consultant's report, 21 p.

Weyer, K.U. 2012*. Applying Gravitational Forces to the Weyburn CO2 Sequestration: Expanding Hydraulic Research and Applications for the Benefit of Future Generations, poster presented at the *IEA GHG Joint Network Meeting, Santa Fe, NM*, June 19-21, 2012

Weyer K.U., 2013. Regional groundwater flow pattern in the Northern Great Plains area and their effect on CO2 sequestration at Weyburn, Saskatchewan, Canada. Procedia Earth and Planetary Science, 7, p. 896-899

Weyer, K.U. and van Everdingen, D.A. 1995*. Industrial waste disposal site Münchehagen: Confinement of dissolved contaminants by discharging saline water. Paper for *Solutions '95*, Congress of International Association of Hydrogeologists, Edmonton, Alberta, Canada, 9 p.

Weyer, K.U. and Ellis, J.C. 2013 (this volume). Long range regional groundwater flow systems in the Northern Great Plains: (2) Physics of regional groundwater flow in Alberta. *Proceedings of GeoMontreal 2013*, Montreal, QC, Canada, Sep 29-Oct 3, 2013.