Groundwater flow systems theory: an unexpected outcome of early cable tool drilling in the Turner Valley oil field

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Introduction

The Theory of Groundwater Flow Systems (Tóth, 1963) originated in Alberta, Canada in response to early cable tool drilling data from oil wells in the Turner Valley (Fig. 1), 50 km southwest of Calgary, Alberta.

In the 1920s drilling was done with cable tool rigs without fluid circulation, while almost all other drilling methods used since apply mud or air circulation. The cable tool rig allowed a constant observation of the behaviour of the water level in the borehole with increasing drilling depth. Drilling on hills encountered water levels that decreased with depth once the groundwater table had been reached (Fig. 2). In valleys the water levels rose with drilling depth and turned artesian (flowing). At the shoulder of valleys the water level did not change substantially. This behaviour was puzzling but was finally explained in the 1960s by applying Hubbert's (1940) Force Potential, which up to this time had been widely considered as an absurd opinion within hydrogeology. Thus Hubbert's theoretical development and analytical model of flow within a vertical cross-section (Fig. 3) was confirmed by actual field measurements in the Turner Valley oilfield.

Fig. 1 Topography at Turner Valley, Alberta, Canada. Canada. Water level data from the Turner Valley Oilfield gave rise to the Theory of Groundwater Flow Systems (picture: K.U. Weyer, 20070621)

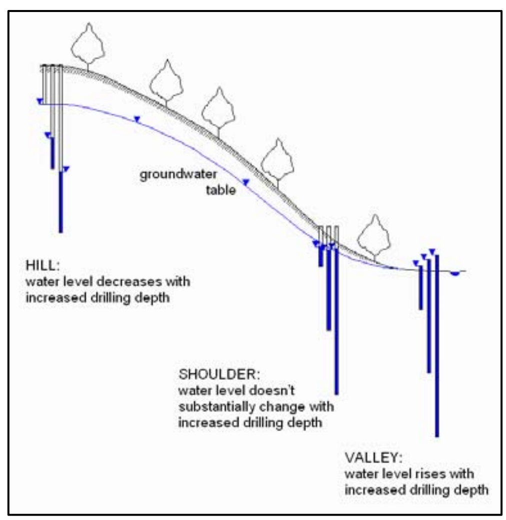

Fig. 2 Schematic depiction of piezometer nests indicating the depth distribution of heads as found by cable tool drilling in the Turner Valley oil field.

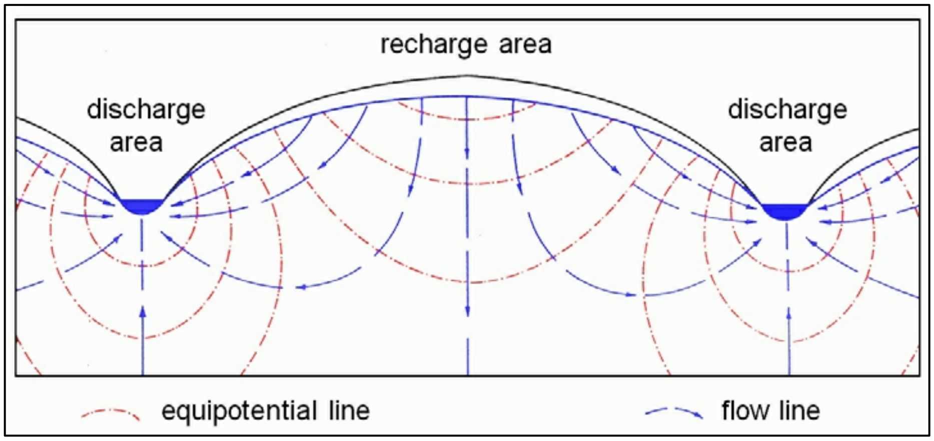

Fig 3

Energy fields (equipotential lines, small dashes) and flow field (flow lines, long dashes) of groundwater flow through homogeneous and isotropic rock in a cross-section between two valleys (after Hubbert, 1940, Fig. 45)

In Fig. 3, recharge areas occur in the elevated portion of the cross-section and discharge areas in the lowlands (valleys). The vertical flow lines under the top of the recharge area and in the middle of the discharge areas indicate hydraulic boundaries between flow systems. In undisturbed conditions, water does not penetrate from one flow system to another; the hydraulic boundary acts as an impenetrable divide.

Inception of Groundwater Flow Systems Theory

In an attempt to explain additional hydrogeological field evidence, analytical calculations by Tóth (1963) led to the formulation of the principles of Groundwater Flow Systems.

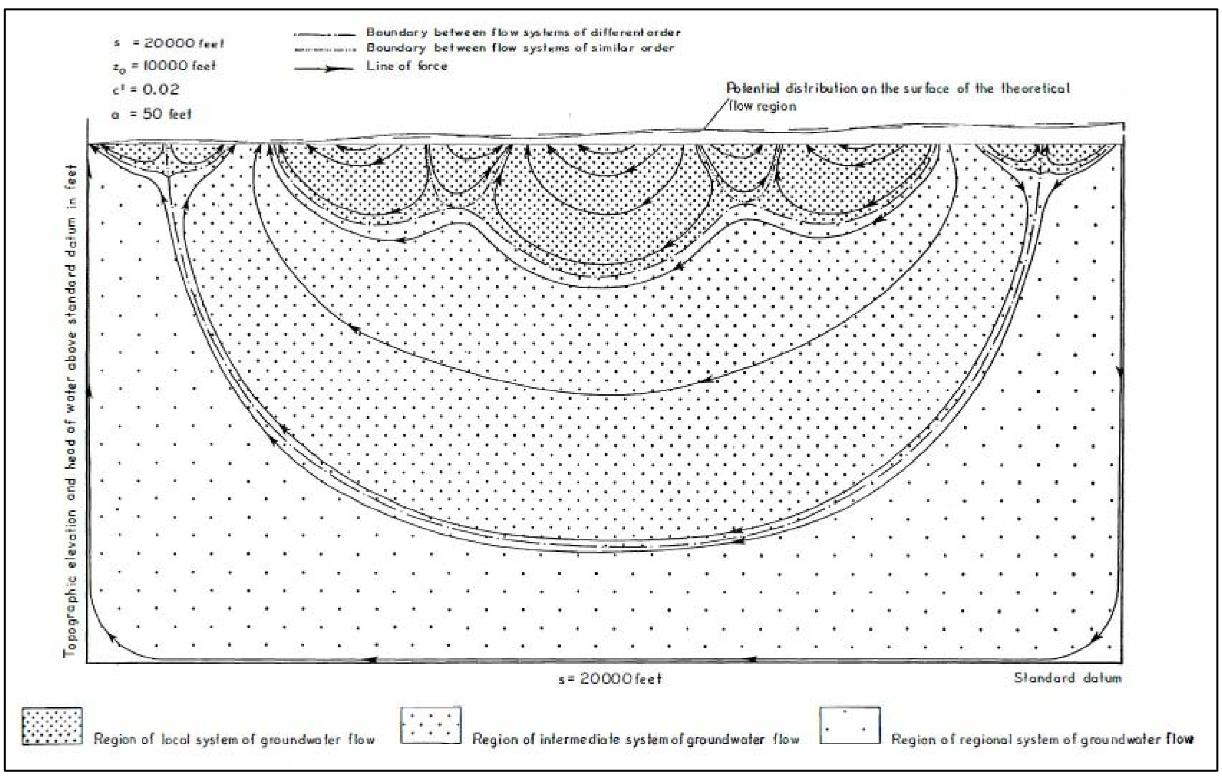

Fig. 4 Analytical model by Tóth [1963]: analytical calculation of groundwater flow systems in a cross-section with homogeneous and isotropic lithology.

Within Tóth's analytical model (Fig. 4), the total elevation gain from the valley to the uppermost hill was taken as approximately 150 m over about 6.5 km; the amplitude between hills and valleys was assumed to be approximately 15 m. The calculations were done analytically in a rectangular field with the undulating boundary condition assigned as the upper boundary to the rectangular field of analytical calculations.

Based on the pattern and discharge points of the flow lines obtained (Fig. 4), Tóth (1963) classified the flow lines of the flow systems into three parts. Local flow systems migrate between neighbouring hills and valleys. In this case, the one intermediate system flows from the second-last hill and discharges into the second-last valley. The regional flow system originates from the highest hill and discharges into the deepest valley. It is remarkable that in his model the intermediate flow system reaches a depth of about 2400 m and the regional system a depth of about 3000 m, the lower boundary of the analytical model. Both depth are well within the depth range of oil fields.

Another important observation is that within flow systems, the direction of groundwater flow could be opposite to the direction of the slope of the groundwater table. This eliminated the use of simple Darcy equations to determine flow directions at greater depth, or the use of the hydrologic triangles to determine the flow direction of groundwater and also the concept of the determination of flow directions by use of pressure values based on the weight of the water column above the point of consideration (as is sometimes assumed in reservoir engineering).

What happened in the development of the Theory of Groundwater Flow Systems is an instructive example of the mutual interplay and reinforcement of theoretical development (Hubbert, 1940), field water level data from oil boreholes in the Turner Valley, and subsequently, additional applications of mathematical models. It becomes obvious that not only can the mathematical model verify and give meaning to the field data, but available field data also can confirm the validity of mathematical models.

In an effort to further understand groundwater flow pattern, Freeze and Witherspoon (1966, 1967) determined the effect of topography and geologic structures of differing permeabilities upon groundwater flow pattern by simulating groundwater flow systems in 2D-vertical geologic cross-sections using early numerical computer models.

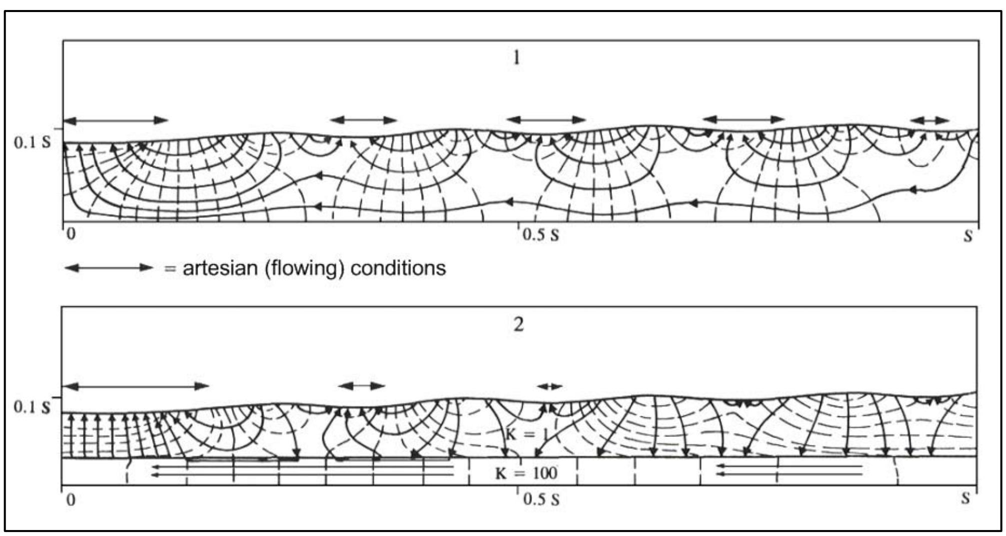

Fig. 5 Mathematical models by Freeze and Witherspoon [1967]: effect of [1] topography and [2] a buried higher-permeable layer upon groundwater flow pattern and location of recharge and discharge areas.

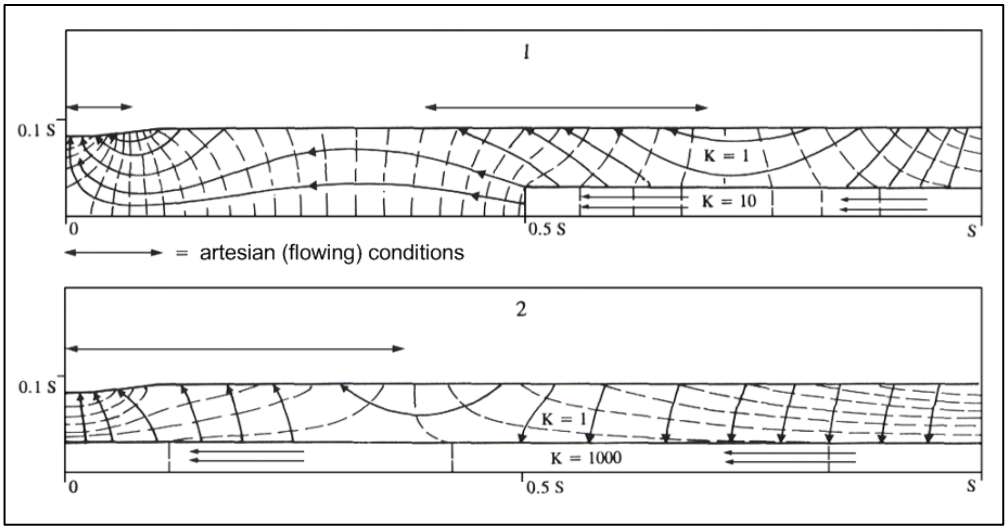

Fig. 6 Mathematical models by Freeze and Witherspoon [1967]: Effect of a buried higher-permeable layer [1,2] upon groundwater flow pattern and location of recharge and discharge areas.

To achieve generally valid results, contrast permeabilities (using relative values), dimensionless distance and dimensionless depth [S] were applied in the numerical model calculations. When using contrast permeabilities, the flow lines are defined properly, but no information is retrieved as to the velocity or amount of groundwater flow. The dimensionless length and depth show that similar flow patterns may exist for models of 1, 10 or 50 km length. Also, the location of the aquifer under the aquitard (which is a natural situation in many areas) concentrates the flow into the aquifer, delivering it from the highland area to the lowland area (valley).

Within these mathematical models, geologic layers are homogeneous and isotropic. Again, flow lines show the occurrence of local, intermediate, and regional flow systems (Figure 5 [1]). Evaluating the flow lines in Figure 5 [2] shows approximately twice as much water flows within the aquitard (down from recharge areas and up towards the discharge area) as within the aquifer (lateral flow only). Figure 6 [2] shows the same pattern of approximately twice as much water flowing through the aquitard (vertically down and up) as flows laterally in the aquifer.

In all four figures, the double-sided lateral arrows indicate areas of artesian (flowing) conditions which means areas of upward flow and discharge.

Penetration Depth of Groundwater Flow Systems

In Fig. 4, Tóth shows local flow systems penetrating up to 900 m depth. The one intermediate system penetrated up to 2400 m depth. The regional flow system originating from the highest hill penetrated to a depth of over 3000 m - the lower limit of the mathematical model. Considering the dimensionless lengths and depths used by Freeze & Witherspoon (1967) in their numerical models, penetration depths there could be between 100 m and 5 km, assuming the lengths to be 1 km or 50 km. Similar penetration depths of 5 to 6 km (Fig. 7) are shown by Tóth (2009).

Hubbert (1953) showed that the force fields of fresh groundwater determine the migration behaviour of oil and gas in the subsurface. This also applies to the storage of CO2. Hence the knowledge of groundwater flow systems at greater depth, and their force fields, is a cornerstone to understand and determine the migration behaviour of hydrocarbons and CO2 in the subsurface.

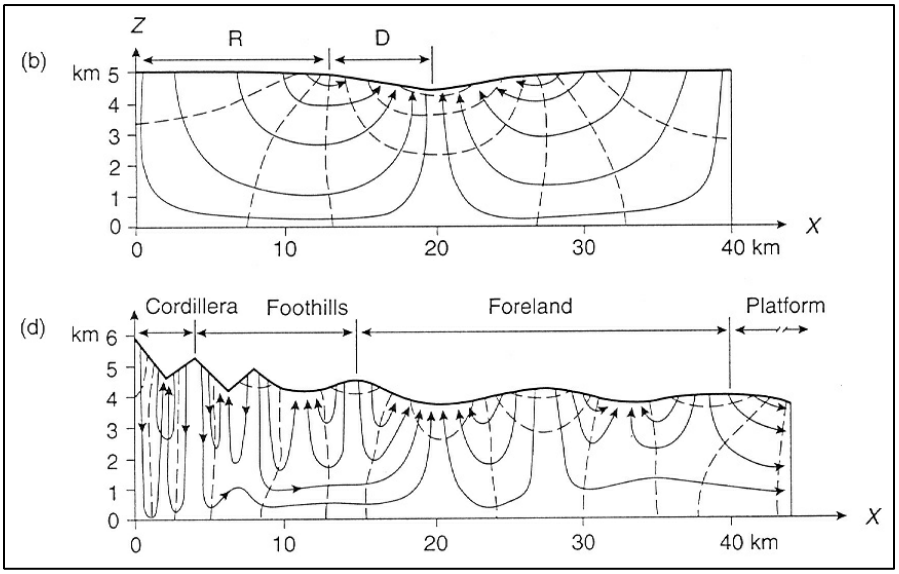

Fig. 7

Schematics of groundwater flow patterns for common types of regional landforms: (b) intracratonic basin with broad uplands; (d) cordillera-cum-foreland.

The schematic topography in case (d) is similar to the situation in Alberta, Canada. All cross-sections are devoid of heterogeneities. The cross-sections have been selected from Tóth (2009), Fig. 3.14..

Conclusions

- Water level data in oil boreholes of the Turner Valley oil field gave rise to the Theory of Groundwater Flow Systems when they were interpreted within the realm of Hubbert's Force Potential.
- The penetration depth of groundwater flow systems reaches depths of several kilometres, well within the depth reach of oil fields and carbon storage in reservoirs and saline aquifers.
- The development of the Theory of Groundwater Flow Systems is an instructive example of the mutual interplay and reinforcement of theoretical development, field data, and the subsequent additional applications of mathematical models. Not only can the mathematical model verify and give meaning to the field data, but available field data can also confirm the validity of mathematical models of fluid flow in the subsurface if the models have a base in physics.

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