Hydrol. Earth Syst. Sci. Discuss.,
https://doi.org/10.5194/hess-2020-270-AC2, 2020

Hydrology and Earth System Sciences
Discussions
Open Access

Interactive comment on "Flowing wells: history and role as a root of groundwater hydrology" *by* Xiao-Wei Jiang et al.

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Received and published: 13 August 2020

Response to Referee #2 (Garth van der Kamp)

This manuscript provides a detailed and global overview of the progress of understanding of flowing wells. In this sense it has the potential to make a worthwhile contribution to the science of hydrogeology and its historical development. Flowing wells have always been, and still are, a topic of wonderment and questioning.

1. In such a historical overview, spanning many countries and two centuries, it is a formidable challenge to recognize and give due credit to all significant contributions, the literature of which may not be easily accessible. In this case the authors would do well to widen their search and in particular to refer to the historical overview by

J. J. de Vries (2007), which describes several pre-1940 examples of what the present paper describes as “topographically-driven” groundwater flow. (History of Groundwater Hydrology. In: The handbook of Groundwater Engineering (Jacques W. Delleur ed.), Chapter 1: p.1.1-1.39. CRC Press, 2007).

Response: Thanks very much for suggesting this reference. We benefit a lot from this reference. We also found more references from the review by de Vries.

2. More generally this manuscript is perhaps over emphasizing the analysis of “topographically-driven” groundwater flow in the 1960’s by Toth and others as a paradigm shift. Such a shift in science is typically defined as, for example “an important change that happens when the usual way of thinking about or doing something is replaced by a new and different way” [https://www.merriamwebster.com/dictionary/paradigm%20shift]. It might be added that in science such a paradigm shift also opens up new and expanded fields of enquiry. Casting historical developments in hydrogeology in terms of paradigm shifts can be a valuable and enlightening exercise by emphasizing when and how new concepts were developed and became accepted. The authors are encouraged to maintain a paradigm perspective.

Response: Thanks for the encouragement of maintaining a paradigm perspective. We will incorporate the referee’s suggestions on the earlier references to alleviate the problem of “over emphasizing” the contributions by Toth and others.

3. With regard to topographically-driven flow the manuscript makes clear that it was recognized very early on, in the 19th century, that the occurrence of flowing wells is dependent on a recharge source of the groundwater at a higher elevation. In other words, topographically-driven groundwater flow (together with various geological configurations) has always been recognized. It was also recognized early on that flowing wells can occur even where there is no overlying low-permeability formation confining an aquifer (See for example the measurement-based flow diagrams published by Pennink

in 1907 as reproduced by de Vries (2007, p. 1-11). As pointed out in the manuscript (L 60) Hubbert noted this (Hubbert, 1940, p.913: “As a matter of fact, in order to have artesian potentials, an aquifer need not be overlain by impermeable material, and it need not out-crop.”)

Response: Thanks very much for the suggestions! We totally agree with the referee’s statement that “the occurrence of flowing wells is dependent on a recharge source of the groundwater at a higher elevation”, which had been realized by Bernardino Ramazzini (1691) and other European researchers in the 1800s, can be considered as an early recognition of topographically-driven groundwater flow. After reading J. J. de Vries (2007a) and J. J. de Vries (2007b), we realize that King (1899) and Pennink (1905) had already described the phenomenon of upward flow in discharge areas, which is critical for flowing wells. This understanding of artesian water was 35 years earlier than Hubbert (1940). We will incorporate them in the revision.

4. Clearly there is a continuum of hydrogeological conditions that can result in flowing wells, varying from highly confined aquifers with distant higher-elevation outcrops to entirely homogeneous surficial aquifers, the latter likely relatively rare. Thus a distinction between “topographically-controlled” and “geologically controlled” flow may not be useful. Incidentally the Paskapoo formation in southern Alberta which inspired Toth’s early analyses is far from constituting “a thick unconfined aquifer (L. 335), but “represents a foreland deposit of a siltstone and mudstone-dominated fluvial system” with interspersed channel deposits of coarse-grained sandstone (Grasby et al., 2008. Can J Earth Sc., 45: 1501-1516, p.1).

Response: We agree with the referee that “there is a continuum of hydrogeological conditions that can result in flowing wells, varying from highly confined aquifers with distant higher-elevation outcrops to entirely homogeneous surficial aquifers”. A similar statement “The variety of hydrologic situations that will give rise to potentials below the ground surface larger than those a few feet above is very great” was given by Hubbert (1940). Hubbert (1940) also pointed out that the extensive textbook illustration of flowing wells in confined aquifers has “obscured a more complete understanding of artesian phenomena”. Therefore, in the classical textbook written by Freeze and Cherry (1979), flowing wells were divided into “geologically-controlled” and “topographically-controlled”.

Freeze and Cherry (1979) pointed out that “The primary control on flowing wells is topography”, implying that geologically-controlled flowing wells, i.e., flowing wells in confined aquifer, are also controlled by topography. Therefore, we agree that a distinction between topographically-controlled and geologically controlled flowing wells is not enough. In fact, we have pointed out in the final sentence of the conclusion that “because geologically-controlled flowing wells usually occur in topographical lows, a generalized theory on the simultaneous control of topography and confining bed on the occurrence and the hydraulics of flowing wells is expected in the future.” We hope the current paper would inspire studies in this field by combining Toth’s “rigorous mathematical description of regional groundwater flow” and classical well hydraulics which assumes a totally flat initial hydraulic head field.

5. Toth and others set off an important change in hydrogeology by introducing rigorous mathematical description of regional groundwater flow, at first by calculus methods, soon followed by numerical modelling. Numerical modeling has become a major and standard tool in hydrogeology. Its introduction by Toth, followed up by Freeze, could indeed be characterized as a paradigm shift, in the sense of doing something in a new and different way, which has also led to new research and discovery. But their analysis and description, as such, of flowing wells occurring without an overlying aquitard does not appear to merit characterization as a paradigm shift because this idea was already present in the literature and was recognized as a logical consequence of Darcy’s Law.
Response: We agree with the reviewer that Toth and others’ analysis and description of flowing wells occurring without an overlying aquitard, which had already been described by Pennink (1905) and Hubbert (1940), does not merit characterization as a paradigm shift. We will avoid the misunderstanding that “Topographically-controlled

flowing well analyzed by Toth and others is a paradigm shift" in the revision. We also totally agree with the referee that the introduction of rigorous mathematical description of regional groundwater flow by Toth and Freeze could be characterized as a paradigm shift. Anderson (2008) made a similar statement that "the Toth model is an important early exploration of the analysis of regional flow systems". Bredehoeft (2018) pointed out that "Toth's conceptual model of groundwater flow" constitutes a paradigm shift. In the current paper, what we want to emphasize is "topographically-driven groundwater flow systems" is a paradigm shift, which is based on Toth's (2005) statement that "The (topographically-driven) groundwater flow system has become a generally accepted paradigm". In our opinion, Toth's term of "topographically-driven groundwater flow systems" is similar to the referee's term of "rigorous mathematical description of regional groundwater flow", Anderson's (2008) term of "the Toth model", and Bredehoeft's term of "Toth's conceptual model of groundwater flow". We will make it clear in the revision. Like all paradigm shifts, the beginning of the paradigm shift began much earlier, based on field evidences, i.e., King (1899) and Pennink (1905) described the phenomenon of increasing head with depth in the discharge area due to topographically-driven groundwater flow, and the mathematical foundation given by Hubert (1940). However, like nearly all important paradigm shifts in the geosciences, more field evidences had to be accumulated until the new paradigm was overwhelming. The first textbook to systematically introduce Toth's mathematical model of regional groundwater flow systems and differentiate "topographically-controlled" between "geologically-controlled" groundwater flow was the one by Freeze and Cherry (1979), which was published 80 years later than King's (1899) first field description.

6. Perhaps a case could be made that the recognition of aquifer compressibility by Meinzer and others, based on analysis of flowing well yields, was the beginning of a paradigm shift in hydrogeology. The manuscript describes how the follow-up work by Theis (1935) and Jacob (1940) led to a widening field of enquiry and understanding of transient groundwater hydraulics, particularly with regard to well hydraulics.

Response: We agree that the recognition of aquifer compressibility by Meinzer and others, based on analysis of flowing well yields, was the beginning of a paradigm shift in hydrogeology. This paradigm shift had been accepted by the groundwater hydrology community since the 1940s. It is interesting that it took much shorter times for this paradigm shift to become well established in groundwater hydrology.

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