Response to the Editor

hess-2020-270, Flowing wells: history and role as a root of groundwater hydrology

Authors: Xiao-Wei Jiang, John Cherry, and Li Wan

Review conclusion, Special issue handling editor: Okke Batelaan

Dear Authors,

As handling-editor for this special issue I like to thank you for your contribution. We now have received two reviews for your manuscript (MS), and you have replied on their comments. I appreciate the thoughtful comments of the reviewers and your replies. The MS is certainly of interest and value for this special issue.

Having gone over the MS myself, and the raised comments, I do agree with these comments and believe that the paper would become clearer, easier to read and more impactful if you would consider the raised comments in a revised MS.

Especially, I would like to stress the following points:

1. The paper can indeed be shortened and written more concise (referee 1). In addition, I notice some unnecessary repetition in the text. This all requires a very careful re-evaluation of each paragraph and what it adds to the total story (and if not already mentioned before). Some examples (but this is certainly not all) are:

-abstract, line 16 and further is an example of the style of writing that you should try to avoid. Another example is line 46-54, extremely long, difficult to understand sentence.

-the introduction can certainly be shortened; it goes into too much detail of aspects that are later (again) discussed.

-section 2 is noted (referee 1) to benefit from more focus. I would keep it still in the MS but shorten it, and maybe restructure it.

-section 7 is very long and would benefit from trimming.

Response: The title has been modified and many parts, including the abstract, Sect. 1, Sect. 2 and Sect. 7 have been shortened.

Specifically, the sentence starting from line 16 in the abstract has been deleted. Two paragraphs in the introduction part are deleted, including the paragraph with line 46-54. To make it more focus, Section 2 has been shortened and restructured by deleting a subsection.

Some redundant words in Sect. 7 have been deleted.

2. Referee 1 does not agree with the main thesis of the paper that "flowing wells… led to the birth of many fundamental concepts and principles of groundwater hydrology". Although, I can see the merit and value in raising attention for this thesis, I am afraid that the style of presentation of the text and building up the arguments for this thesis have not helped the MS in providing a convincing thesis. Again, the above-mentioned line 46-54 is an example. Reconsidering how in the introduction to state the thesis and in the remaining text to build up the arguments for this thesis, requires some careful restructuring of the text.

Response: Thanks for the suggestion. To make the manuscript logical and convincing, we have modified the title and the abstract, completely rewrote the introduction, shortened section 2, added more references in sections 3, 4 and 7, and improved the language.

We have completely rewrote the first paragraph of the introduction part, deleted paragraphs 2 and 3 which go into too much detail of sections 4 through 7, and modified paragraphs 4 and 5. After deleting two paragraph in the introduction part, the plot showing four threads of evolution of physical hydrogeology stemmed from flowing wells is placed in Fig. 1.

The main thesis of the current manuscript is flowing wells in confined aquifers led to developments of three threads, which are elaborated in sections 4, 5 and 6, and flowing wells in unconfined aquifers have contribution to development of the fourth thread, which are elaborated in section 7. These four sections correspond to "the role in the evolution of groundwater science" in the title. Before introducing the role, we use section 2 to introduce the terminology, and use section 3 to introduce the history. We believe that the slightly modified title corresponds to the structure of the manuscript.

In the section 3, 4 and 7, we added some references in the 1600s and 1700s (Ramassini, 1691; Valniseri, 1726) on early thinking of causes of flowing wells, and some references (King, 1899; Pennink, 1905) at the turn of 20th century on topographically-driven groundwater flow, and the reference of Versluys (1930) which explicitly demonstrated that aquitards are not necessary conditions of flowing wells by calculation based on the analogy between temperature and hydraulic head.

Moreover, we invited Prof. John F Hermance of Brown University to thoroughly edit the manuscript.

3. Referee 2, point 1 and 3. Indeed this are important references, which should be investigated for their value and inclusion in this MS.

Response: Following the suggestion of referee #2, we read de Vries (2007) and learned more on the history of hydrogeology. Following de Vries (2007), we have incorporated such references as Ramassini (1691) from Italy, King (1899) from US and Pennink (1905) from Netherland.

In the process of revising, we found Versluys (1930) from Netherland explicitly demonstrated that aquitards are not necessary conditions of flowing wells by calculation based on the analogy between temperature and hydraulic head, which was 10 years earlier than Hubbert (1940) to explicitly point out a similar statement.

4. Referee 2, point 2, 5 and 6. I believe that in recent decades we start to use to easily the word 'paradigm' to try to stress the importance of a certain 'progress in science'. As it is the goal of all research to make some level of progress, we need to be careful when to use such a word, i.e. inflation of the meaning might occur quickly. I believe that the referee is trying to tell you that *if* you use 'paradigm', you should clearly articulate the arguments why it is a paradigm shift.

Response: The main thesis of the current manuscript is flowing wells in confined aquifers led to developments of three threads of physical hydrogeology (sections 4, 5 and 6), while flowing wells in unconfined aquifers have contribution to the theory of topographically-driven groundwater flow systems, which is one thread of physical hydrogeology (section 7).

In the revision, we rewrote the following paragraph in subsection 7.2 to emphasize why quantitative analysis of topographically-driven groundwater flow systems is a paradigm shift, and how others evaluate this paradigm shift in different words.

"As illustrated above, although horizontal flow dominates when the basin width/depth ratio is high and/or hydraulic conductivity is the deep layer is much higher, vertical components of groundwater flow are widespread in either thick unconfined aquifers or aquitards overlying confined aquifers, which is quite different from the flow pattern shown in Fig. 2.1 and 4. The spatial distribution of groundwater age in thick unconfined aquifers is also more complicated than that in a confined aquifer (Jiang et al., 2010;Jiang et al., 2012). Therefore, quantitative analysis of the topographically-driven groundwater flow systems became a paradigm shift of hydrogeology. This paradigm shift has been expressed by others in similar words. Anderson (2008) comments that “The Tóth model is an important early exploration of the analysis of regional flow systems.” Bredehoeft (2018) points out that “Tóth’s conceptual model of groundwater flow” represents the beginning of a new era in hydrogeology and termed the paradigm shift to be “the Tóth revolution”.

5. Referee 1, point 4 and Referee 2, point 4 both raise the issue of geological vs topographical control. My reading of their comments is that a more critical evaluation of the limitations of this differentiation in your MS, would increase the learnings achieved from your manuscript (i.e. learn from the past is a goal of this special issue).

Response: Freeze and Cherry (1979) gave a comprehensive description of flowing wells in both confined and unconfined aquifers and termed the former to be geologically-controlled and the latter to be topographically-controlled. We agree with the reviewers that in geologically-controlled flowing wells, topography is still the driving force of groundwater flow from the topographic highs to topographic lows.

To avoid confusion, in the revision, we utilize the terms proposed by Toth (1966), confined-flow flowing wells and unconfined-flow flowing wells. We also explicitly point out that “confined-flow flowing wells and unconfined-flow flowing wells as two end members of flowing wells” because different forms of heterogeneity is widespread in the field.

Minor correction: it is ‘Davis and De Wiest’, Wiest with ‘ie’.

Response: Thanks for pointing out the typo.

I look forward to your revised MS.

A list of major changes

1. To make the structure of manuscript clear, the title has been changed to: “Flowing wells: terminology, history and the role in the evolution of groundwater science”. Terminology corresponds to section 2, history corresponds to section 3, and the role in the evolution of groundwater science corresponds to sections 4 through 7.

2. The introduction part has been shortened, and the first paragraph has been completely rewritten.

3. Section 2 has been restructured and shortened.

4. In section 3, the histories of flowing wells in two more countries, Italy and China, are added.

5. In section 4, we add the study of Ramazzini (1691) on flowing wells in Modena, Italy.

6. Section 7 has been significantly revised by deleting some redundant sentences, adding some earlier references on topographically-driven flow (King, 1899; Pennink, 1905) and flowing wells in basins without aquitards (Versluys, 1930) , and rewriting the description of the paradigm shift, i.e., quantitative analysis of topographically-driven flow systems.

7. The conclusions part has been rewritten.

8. The language has been thoroughly improved.

Flowing wells: terminology, history and the role in the evolution of groundwater ~~hydrology~~science

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Abstract

The gushing of water from~~spewing of groundwater in~~ flowing wells attracted public attention and scientific curiosity as early as early as the 17th century ~~is a phenomenon of interest to the public,~~ but little attention has been paid to the influence ~~role~~ of flowing wells on the evolution ~~science~~ of groundwater science. This study ~~reviews~~ asserts that questions posed by ~~answering to problems related to~~ flowing wells since the early 19th century led to the birth of many fundamental concepts and principles of ~~groundwater~~ physical hydrogeology. ~~The concepts stemmed from flowing wells in confined aquifers include permeability and compressibility, while the principles include Darcy's law, role of aquitards on flowing well conditions and the piston flow pattern, steady-state well hydraulics in confined aquifers, and transient well hydraulics towards constant-head wells in confined or leaky aquifers, all of which are applicable even if flowing well conditions have disappeared.~~ Due to the widespread occurrence of flowing wells in basins with regional aquitards, there is a long-lasting misconception that flowing wells ~~must be geologically-controlled~~could only occur in regional confined aquifers. However, the recognition of possible occurrence of flowing wells in unconfined aquifers ~~The occurrence of flowing wells in topographic lows of unconfined aquifers,~~ was anticipated ~~in~~ at the turn of the ~~1940~~ 20th century based on observed increases in hydraulic head with depth in topographic lows of basins without apparent

aquitards. ~~and~~ This was later verified in the 1960s by field and modelling studies~~,~~ — that ~~accompanying with the~~gave birth ~~of~~ to quantitative analysis~~the theory~~ of topographically-driven groundwater flow systems, ~~which has been considered as~~ a paradigm shift in ~~groundwater~~ hydrogeology. ~~Based on studies f~~Following this ~~new~~ paradigm, several preconditions ~~of~~ for flowing wells established~~given~~ in the 19th century ~~have been~~were found ~~to be not~~ unnecessary~~ at all~~. Intermingled in the evolution of flow system concepts are inconsistencies and confusion concerning the use of the term ‘artesian” for which we propose avoidance of this term. This historical perspective of the causes of flowing well conditions and the ~~role~~ influence of flowing wells on groundwater ~~the~~ science ~~of groundwater~~ could lead to a deeper understanding of the evolution of groundwater science~~hydrology~~, and guide future studies on hydraulics of flowing wells.

1 Introduction

The primary motivation for the study of groundwater is its importance ~~role~~ as a resource (Back and Herman, 1997;Freeze and Cherry, 1979). Groundwater from springs was utilized ~~by people~~ in the Middle East ~~about~~ some 10, 000 years ago (Beaumont, 1973), ~~while~~ and produced from shallow flowing wells in the western desert of Egypt in the first millennium B.C. as dug wells reached greater depths (Commander, 2005)~~, which overflow at the surface, was used in northern France as early as 1126 (Margat et al., 2013)~~. However, hydrogeology did not emerge as a distinct science until the 19th century (Fetter, 2004), which corresponds to a period when deeper drilled flowing wells was a substantial source of water supply in Europe {Howden, 2013 #32}. It is acknowledged that the recognition of the great value of flowing wells in Europe in the 18th century stimulated the advancement of water well drilling technology (Davis and De Wiest, 1966), and that the maturation of geological and hydrological sciences in the 19th century led to the birth of hydrogeology in the 19th century (Meyer et al., 1988). ~~pointed out that exploration of flowing wells in Europe in the 18th century was responsible for stimulating the advancement of water well drilling technology.~~However, little attention has been paid to the importance of the scientific questions prompted by flowing wells in the early evolution of groundwater science in the 19th century. ~~It was believed that the emergence of groundwater hydrology (hydrogeology) as a distinct science in the 19th century was a result of the maturation of its mother sciences (geology and hydrology) in the 19th century (Fetter, 2004;Meyer et al., 1988). Although it has been realized that flowing wells have always attracted considerable public interest (Chamberlin, 1885;Freeze and Cherry, 1979;Meiter, 2019), little attention has been paid to the role of flowing wells on the science of groundwater.~~

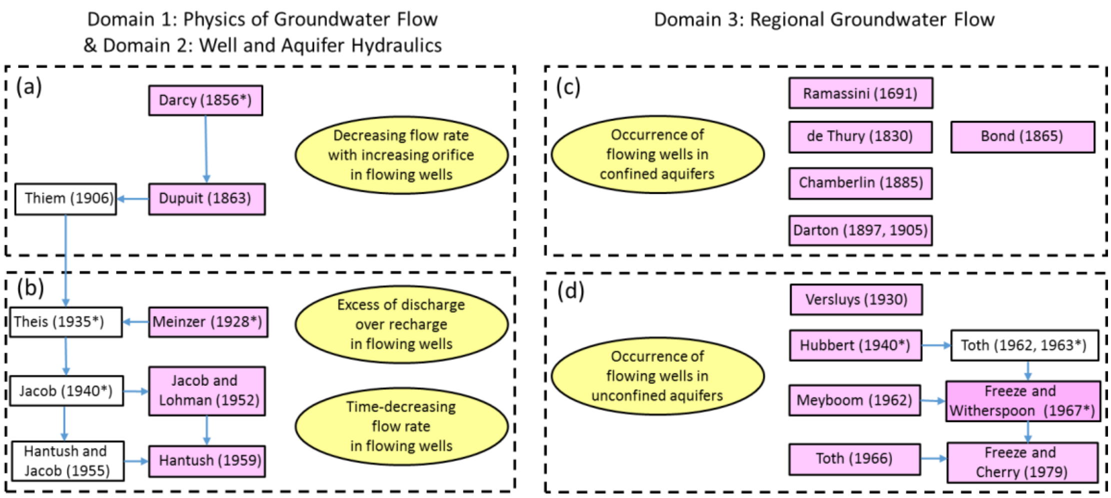
~~Due to the function of providing clean groundwater without pumping,flowing wells were a significant source of water supply for drinking and/or agriculture in Europe and the United States in the 19th century and early 20th century (Howden and Mather, 2013;Konikow, 2013). During this period, in the process of exploring flowing wells and observing the flow rates in flowing wells, field observations of flowing wells led to some fundamental concepts and principles of groundwater hydrology in Europe and the United States. For example, based on field conditions in such regions as Paris, London, Wisconsin, and North and South Dakotas, the qualifying conditions of flowing wells were well recognized (Chamberlin, 1885;Darton, 1905;Bond, 1865;Darton, 1897), which further led to the pattern of piston~~

flow in confined aquifers; inspired by observations of flow rates of flowing wells in Paris, Darcy (1856) identified the controlling factors of flow in subsurface media and Dupuit (1863) established the principles of steady-state groundwater flow (Ritzi and Bobeck, 2008); based on the decreasing discharge in flowing wells with time and the excess of groundwater discharge compared to estimates of groundwater recharge, Meinzer (1928) identified the compressibility of confined aquifers, which constitutes the basis of transient groundwater flow. Probably because these concepts and principles are applicable to non-flowing wells and most developments on well hydraulics since the 1930s were based on pumping in non-flowing wells, it seems that the role of flowing wells on the development of these concepts and principles in history was not realized in current textbooks.

The widespread occurrence of confined aquifers and the accompanying phenomenon of flowing wells in the initial stage of groundwater development made the piston flow pattern and geologically-controlled flowing wells(Fig. 1a) a widely accepted conceptual model in groundwater hydrology. By analyzing the cross-sectional flow pattern from recharge to discharge areas in thick unconfined aquifers, Hubbert (1940) pointed out that a confined aquifer outcrops in the highlands and overlain by impermeable strata in the lowlands as shown in Fig. 1a is by no means a necessary condition for flowing wells, and found that flowing wells could occur in topographic lows without an overlying confining bed (Fig. 1b). In the course of exploring groundwater in the Canadian Prairies, Tóth (Tóth, 1962, 1963, 1966) and Meyboom (1962; 1966) verified the occurrence of topographically-controlled flowing wells in the field and further developed Hubbert's model of topographically-driven groundwater flow from recharge to discharge areas. In the Canadian Prairies, one of the topographically-controlled flowing wells has a well depth of only 9 m (Tóth, 1966). Kasenow (2010) reported a topographically-controlled flowing well in the discharge area of an unconfined aquifer, which was constructed at a depth of only 6.1 m below surface but has a head of around 1.4 m above surface. The principles of topographically-driven groundwater flow systems and the cause of topographically-controlled flowing wells constitute a paradigm shift in groundwater hydrology (Bredehoeft, 2018;Madl-Szonyi, 2008). Unfortunately, topographically-controlled flowing wells, which is a natural consequence of topographically-driven groundwater flow, are described only in very few textbooks (Domenico and Schwartz, 1998;Freeze and Cherry, 1979;Heath, 1983;Kasenow, 2010), the number of which is very limited compared with the large number of groundwater textbooks. In other words, although the concept of flowing well is introduced in almost every groundwater textbook, a complete understanding of the causes of flowing wells is still

~~missing in most textbooks. This also undermines the role of topographically-controlled flowing wells on the paradigm shift from the conceptual model of piston flow to topographically-driven flow.~~

This review aims to demonstrate that flowing wells contributed to not only the birth, but also the evolution of several aspects of hydrogeology. Freeze and Back (1983) divided physical hydrogeology into three domains, i.e., physics of groundwater flow, well ~~and aquifer~~ hydraulics, and regional groundwater flow. Following these domains~~this approach~~, studies directly or indirectly related to flowing wells~~ or bridge classical studies on flowing wells~~ are divided into four threads (Fig. ~~2~~1), ~~which~~ covering all of the three domains. The first three threads shown in Fig. 1~~2a-c~~ ~~are all~~ stem~~med~~ from ~~geologically-controlled~~ flowing wells in *confined aquifers*, while the ~~thread shown in Fig. 2d is~~fourth is from ~~topographically-controlled~~ flowing wells in *unconfined aquifers*. Note that the seven classical studies which were selected by both Freeze and Back (1983) and Anderson (2008) as benchmark papers of ~~groundwater hydrology (~~physical hydrogeology~~)~~ (groundwater hydrology) have been included in the four threads~~,~~. Moreover,~~and~~ four out of the seven papers are directly related to flowing wells, implying that flowing wells can be considered as, at least, one of the roots of physical hydrogeology ~~groundwater hydrology~~. ~~The main aim of this review is to give a clear picture on the history of drilling flowing wells and the role of flowing wells on the evolution of the four threads of physical hydrogeology.~~



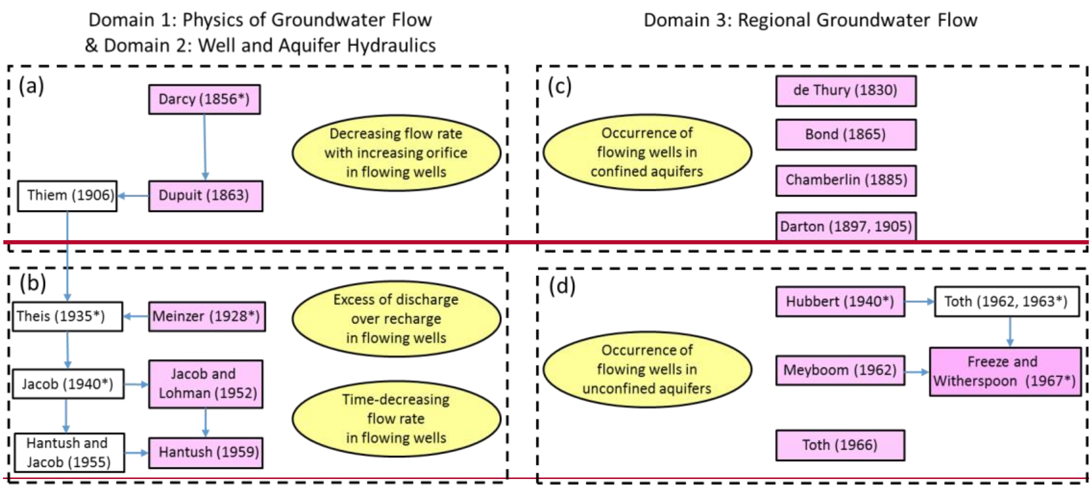


Fig. ~~2~~ 1 Four threads of evolution of physical ~~groundwater~~ hydrogeology stemmed from flowing wells. The yellow ellipses are field phenomena of flowing wells, the purple boxes are papers directly related to flowing wells, and the white boxes are papers less or not directly related to flowing wells but have connections to previous or follow-up studies on flowing wells. The publications labeled with a "*" are ~~included~~ the seven classical studies identified by ~~in~~ both Freeze and Back (1983) and Anderson (2008).

The paper is organized as follows. We first introduce the terms used to represent flowing wells, with conceptual examples of the root difference between confined and unconfined sources for these wells~~, and the evolution of the ambiguous term "artesian well", which was initially used to represent flowing wells in confined aquifers but was later widely used to denote flowing well in both confined and unconfined aquifer, or any well penetrating a confined aquifer~~ (Sect. 2). ~~After introducing~~Sect. 3 summarizes the history of drilling flowing wells in selected regions that ~~had~~ have inspired ~~groundwater~~ hydrogeologists. ~~in Sect. 3,~~ Sect. 4 through 7 then historically sequence the principal hydrogeological publications through which flowing wells played a major role in the evolution of the science as we know it today~~the four threads of evolution of groundwater hydrology rooted from flowing wells are briefly summarized in Sect. 4 through 7, which are sequenced based on the order of earliest publications about each thread~~. Finally, ~~some~~ concluding remarks are given in Sect. 8.

2 Terms related to flowing wells and ~~definitions~~ confusion of "artesian"

2.1 Terms representing flowing wells

~~Photos of flowing wells were used as the cover image or frontispiece of some professional publications (Chamberlin, 1885;Freeze and Back, 1983;Hudak, 2005;Deming, 2002;Younger, 2007),~~

~~which indicates the interest of groundwater professionals in flowing wells.~~ In the groundwater hydrology, hydrogeology or hydrology textbooks available to the authors, we found the phenomenon of a well ~~which~~ that overflows at the surface is defined or at least mentioned in 34 textbooks. The widely used terms include “flowing well”, “artesian well” and “flowing artesian well”, which appear in 17, 15 and 13 textbooks, respectively (sometimes more than one term is used in a book). Other less frequently used terms include “artesian flowing well”, “overflowing well”, and “free flowing well”. For convenience of discussion, we divide these six terms into two categories, those using the term ~~based on whether~~ “artesian”, and those not using “artesian” ~~is shown~~.

The terms “flowing well”, “overflowing well” and “free flowing well” stem purely from the phenomenon of water overflow at the well outlet, presumably at grade level. The term “overflowing well” has been used in Britain since at least as early as the 1820s (Anonymous, 1822), and currently is still widely used in Britain, as found in several textbooks (Hiscock and Bense, 2014;Price, 1996;Rushton, 2003). To the authors’ knowledge, the term “flowing well” was first used in the USGS hydrogeologic report *Requsite and Qualifying Conditions of Artesian Wells* (Chamberlin, 1885) and is currently the one most widely used ~~one~~. The term “free flowing well” can be found in three textbooks available to us (Fitts, 2013;Kruseman and de Ridder, 1990;Nonner, 2003). By including the adjectives “flowing”, “overflowing” or “free flowing”, these terms have clear meaning to represent wells that groundwater could flow out without the aid of ~~do not need~~ pumping.

The number of textbooks that use one or two of the terms “artesian well”, “flowing artesian well” and “artesian flowing well” is as high as 28, indicating the popularity of the adjective “artesian”. The term “~~Artesian~~ artesian well” originates from “well of Artois” ~~derived its name from the place Artois~~ (“Artesia” is the historical Latin name of Artois, an ancient province in northern France) ~~where the first flowing wells were obtained in the 12th century), and gives birth to the terms “flowing artesian well” and “artesian flowing well” by adding the adjective “flowing”~~. It is unquestionable that it was the phenomenon of water overflow at the surface which attracted people’s attention to wells of Artois drilled in 1126 (Fuller, 1906;Norton, 1897). ~~As early as 1805, t~~The ~~name~~term “artesian fountain” was applied in French scientific literature to represent flowing wells in 1805 (Lionnais, 1805), and the term “artesian well” was widely used in France, Britain and the United States in the 1820s and 1830s {Arago, 1835 #65;Buckland, 1836 #87;de Thury, 1830 #88;Garnier, 1822 #64;Storrow, 1835 #92}. ~~Literally~~5). ~~Literally, “artesian well” stands for “well of Artois”. It is unquestionable that it was the phenomenon of~~

~~water overflow at the surface which attracted people's attention to wells of Artois (Fuller, 1906;Norton, 1897).~~ Currently, an artesian well is synonymous with a flowing well in the majority of European textbooks we have inspected~~in Europe~~ (Hendriks, 2010;Kruseman and de Ridder, 1990;Price, 1996;Rushton, 2003;Brassington, 2017;Davie, 2008;de Marsily, 1986;Hölting and Coldewey, 2019) and in at least eight textbooks in North America (Deming, 2002;Domenico and Schwartz, 1998;Driscoll, 1986;Pinder and Celia, 2006;Yeh et al., 2015;Hornberger et al., 2014;Fitts, 2013;Alley and Alley, 2017)~~,~~ ~~the term "artesian well" is synonymous with flowing well~~. Since the late 19th century, the term artesian wells were not restricted to ~~a~~ flowing wells~~, and~~but ~~can be~~were divided into flowing artesian wells and non-flowing artesian wells (Carpenter, 1891;Norton, 1897;Slichter, 1899). In ~~Note that in~~ ten textbooks in North America we inspected (Fetter, 2001;Freeze and Cherry, 1979;Batu, 1998;Kasenow, 2010;LaMoreaux et al., 2009;Mays, 2012;McWhorter and Sunada, 1977;Heath, 1983;Schwartz and Zhang, 2003;Todd and Mays, 2004), the term flowing artesian well is used to represent a flowing well and an artesian well is equivalent to a well penetrating a confined aquifer but not necessarily flowing at the surface ~~an artesian well means a well that derives its water from a confined aquifer, the details of which are discussed in Subsect. 2.2 and 2.3~~.

~~Before 1940s, it was believed that only a confined aquifer has the possibility to have hydraulic head higher than the ground surface elevation, i.e., flowing wells could occur only in confined aquifers. Hubbert (1940) first noted that flowing wells could occur in the discharge area of a homogeneous basin (Fig. 1b, the details can be found in Subsect.7.1). This explanation of the cause of flowing wells was accepted by the USGS (Heath, 1983;Lohman, 1972a;Lohman, 1972b).~~

Due to the widespread occurrence of aquitards, it was initially believed that only a confined aquifer bounded by aquitards has the possibility for the static water level to have hydraulic head higher than the ground surface elevation, i.e., flowing wells could occur only in confined aquifers. Later studies found that flowing wells could also occur in an unconfined aquifer, i.e., a homogeneous aquifer without aquitards (Hubbert, 1940;Tóth, 1966;Versluys, 1930). Because the adjective "artesian" indicates the type of aquifer in Artois, i.e., a confined aquifer, according to the definitions given by the USGS, ~~In Heath (1983) and Lohman (1972b),~~ the term "flowing artesian well" was restricted to flowing wells in confined aquifers (Lohman, 1972b)~~, and~~, and it was explicitly pointed out that "a flowing well does not necessarily indicate artesian conditions" ~~in~~ (Heath, ~~(~~1983).~~,~~ ~~it was explicitly pointed out that "a flowing well does not necessarily indicate artesian conditions".~~ To differentiate ~~the two types of~~ flowing wells in confined and unconfined aquifers~~due to different causes~~, Tóth (1966) defined confined-flow flowing wells and unconfined-flow flowing wells as two end members of flowing wells, while Freeze and Cherry (1979) defined geologically-controlled flowing wells and topographically-controlled flowing wells. As shown in Fig. ~~1~~2, geologically-controlled flowing wells are equivalent to Tóth's confined-flow flowing wells, while topographically-controlled flowing wells correspond to ~~the former develop in confined aquifers and receive recharge at upland outcrops, while the latter occur in the topographic lows of~~ Tóth's unconfined-flow flowing wells~~-aquifers~~. Note that in geologically-controlled flowing wells, topography is still the driving force of groundwater flow from the topographic highs to topographic lows. ~~In the following discussion, we avoid using the confusing adjective term "artesian well". Instead,~~ We ~~following~~use ~~Freeze and Cherry~~Tóth's ~~(1979~~1966) ~~classification~~terminology in the following discussion ~~of flowing wells, we use geologically-controlled flowing wells to represent flowing wells in confined aquifers or leaky aquifers, and topographically-controlled flowing wells for wells in aquifers without a confining bed.~~

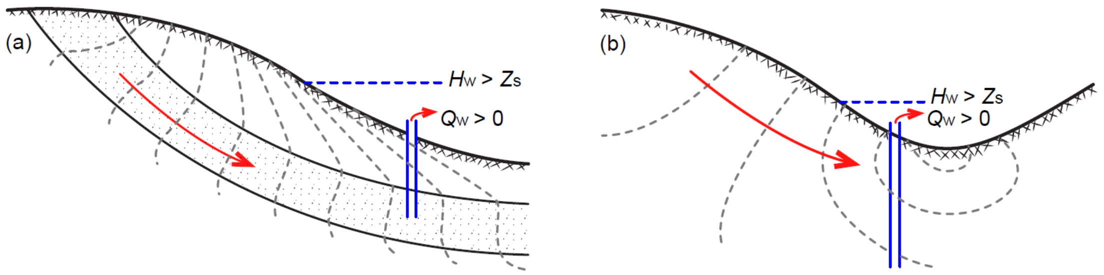


Fig. ~~1~~ 2 (a) Geologically-controlled or confined-flow flowing wells; (~~a~~b) ~~and~~ topographically-controlled or unconfined-flow flowing wells ~~(b) flowing wells~~ (Modified from Freeze and Cherry, 1979). It is assumed that the screened intake for the respective well is at its bottom.

~~2.2 Evolution of "artesian well" and the birth of "flowing artesian well"~~

~~Literally, "artesian well" stands for "well of Artois". It is unquestionable that it was the phenomenon of water overflow at the surface which attracted people's attention to wells of Artois (Fuller, 1906;Norton, 1897). As early as 1805, the name "artesian fountain" was applied in French scientific literature to represent flowing wells (Lionnais, 1805). In later publications, "artesian well" was widely used to represent flowing wells in France and Britain~~ (Arago, 1835;de Thury, 1830;Garnier, 1822;Buckland, 1836)~~. The term "artesian well" was introduced in the United States in 1835 (Storrow, 1835). In Chamberlin (1885), the terms "artesian well", "artesian fountain" and "flowing well" were used~~

~~interchangeably.~~

~~Probably because most artesian wells were much deeper than traditional dug wells, and a driller could not assure a deep well could overflow at the surface before finishing drilling, the term "artesian well" was frequently used to denote a deep well that did not overflow. Chamberlin (1885) condemned such a use, however, in less than 20 years, Chamberlin and Salisbury (1904) pointed out that "*at present time any notably deep well is called artesian, especially if it descends to considerable depths*". Moreover, because deep wells or artesian wells were drilled instead of being dug, artesian wells were also widely used to denote drilled/bored well in the 19th century. Fortunately, such usages were seldom adopted in subsequent years, probably due to the contribution of definitions given in Meinzer (1923b).~~

~~As the geologic conditions governing flowing wells became known, the term "artesian well" was suggested to represent any well in which hydraulic head is higher than the elevation of water table in the 1890s (Carpenter, 1891;Norton, 1897;Slichter, 1899). Norton (1897) insisted that if there are two wells in the same town derived from the same aquifer and rising to the same height, one could overflow at the surface but the other could not just because of slightly higher ground surface, it was preferable to term both wells artesian wells. Such a usage was accepted and popularized by the USGS (Lohman, 1972b;Meinzer, 1923b). In some later publications by authors of the USGS, the term "artesian well" was used equivalently to a well in a confined aquifer (Jacob, 1940, 1946, 1947;Meinzer, 1928;Theis, 1935).~~

~~Since the 19th century, artesian wells were not restricted to a flowing wells and can be divided into flowing artesian wells and non-flowing artesian wells. Although the term "non-flowing artesian well" (or "negative artesian well") was used in the 19th century and early 20th century (Arago, 1835;Norton, 1897;Slichter, 1899;Meinzer, 1928), the adjective "non-flowing" is used only in very limited textbooks (Heath, 1983;Schwartz and Zhang, 2003;Singhal and Gupta, 2010). In the textbooks that define an artesian well to be any well tapping a confined aquifer, an artesian well is by default a non-flowing artesian well (Fetter, 2001;Todd and Mays, 2004;Abdrashitova, 2015;Kasenow, 2010).~~

2.~~3~~ 2 Confusing uses of "artesian" in the literature

The adjective "artesian", which ~~can be traced to the~~was initially used in terms "artesian fountain" and "artesian well", has been applied to such terms as~~ "artesian pressure",~~ "artesian water", ~~and~~ "artesian aquifer", and "artesian pressure". Following the definitions given by the USGS (Lohman, 1972a), and as used in many USGS publications, the term "artesian aquifer" is equivalent to "confined aquifer", "artesian water" refers to groundwater from or within a confined aquiferartesian water and artesian aquifer are equivalent to confined groundwater and confined aquifer, and "artesian pressure" can be considered asis the water pressure in a confined aquifer. An artesian basin was defined by Meinzer (1923a) to be a basin in which water is confined under artesian pressure, implying that the hydraulic head being greater than the elevation of ground surface is not a necessary condition., and an artesian well is a well that derives water from a confined aquifer. Such definitions of artesian well and artesian aquifer can be found in 14 textbooks (Abdrashitova, 2015;Batu, 1998;Fetter, 2001;Heath, 1983;Lohman, 1972a;Mays, 2012;McWhorter and Sunada, 1977;Rudakov, 2014;Schwartz and Zhang, 2003;Sen, 2015;Singhal and Gupta, 2010;Todd and Mays, 2004;Kasenow, 2010;LaMoreaux et al., 2009). Note that the majority of these authors are from the United States and Canada, with four exceptions: Russia (Abdrashitova, 2015) , Ukraine (Rudakov, 2014), India (Singhal and Gupta, 2010) and Turkey (Sen, 2015). The Great Artesian Basin in Australia is one of the largest artesian basins in the world and is well known for its numerous flowing wells in confined aquifers. –In the United States, there are many artesian basins, like the artesian basin of the Dakotas (Darton, 1905;Swenson, 1968), the great Paleozoic artesian basin of the Mississippi Valley region (Meinzer, 1923b), the Roswell artesian basin in New Mexico (Fiedler and Nye, 1933), and the Grand Junction artesian basin in Colorado (Jacob and Lohman, 1952), all of which had many flowing wells in the initial stage of groundwater development, but many of which currently have static water levels significantly below grade. According to Meinzer (1923b), an artesian basin is a geologic structural feature or combination of such features in which water is confined under artesian pressure, implying that the hydraulic head being greater than the elevation of ground surface is not a necessary condition of an artesian basin . In fact, all of these well-known artesian basins have many flowing wells in the initial stage of groundwater development. Therefore, it is difficult to interpret the meaning of the adjective "artesian" in the term "artesian basin".

However, in other 20 textbooks (Alley and Alley, 2017;Bear, 1972, 1979;Brassington, 2017;Davie, 2008;de Marsily, 1986;Deming, 2002;Domenico and Schwartz, 1998;Driscoll, 1986;Hendriks, 2010;Hölting and Coldewey, 2019;Hornberger et al., 2014;Kruseman and de Ridder, 1990;Nonner, 2003;Price, 1996;Fitts, 2013;Pinder and Celia, 2006;Yeh et al., 2015;Rushton, 2003;Dassargues, 2019) that defined one or several of the terms "artesian pressure", "artesian water", "artesian well" and "artesian aquifer", the water level in the artesian well should be higher than the ground surface, and at least part

~~of an artesian aquifers should have hydraulic head above the ground surface. Note that the authors of eight of these books are from the United States~~.

~~Many basins throughout the world were called artesian basins. The Great Artesian Basin in Australia is one of the largest artesian basins in the world and is well known for its numerous flowing wells in confined aquifers. In the United States, many basins were termed artesian basins, for example, the artesian basin of the Dakotas (Darton, 1905;Swenson, 1968), the great Paleozoic artesian basin of the Mississippi Valley region (Meinzer, 1923a), the Rowsell artesian basin in New Mexico (Fiedler and Nye, 1933), and the Grand Junction artesian basin (Jacob and Lohman, 1952). According to Meinzer (1923b), an artesian basin is a geologic structural feature or combination of such features in which water is confined under artesian pressure, implying that the hydraulic head being greater than the elevation of ground surface is not a necessary condition of an artesian basin . In fact, all of these well-known artesian basins have many flowing wells in the initial stage of groundwater development. Therefore, it is difficult to interpret the meaning of the adjective "artesian" in the term "artesian basin".~~

The different meanings of "artesian" caused confusion not only to beginners of ~~groundwater~~ hydrogeology, but also to professional ~~groundwater~~ hydrogeologists~~. The confusion caused by "artesian"~~, which has been realized by some textbook authors. Deming (2002) and Younger (2007) both chose photos of a flowing well for their cover image, but they have quite opposite viewpoints on "artesian". Deming (2002) ~~from the United States~~ held the opinion that "artesian" implies that the hydraulic head is greater than the elevation of ground surface, and defining "artesian aquifer" to be identical to confined aquifer would make the definition not only conceptually useless, but also etymologically incorrect because wells drilled in Artois ~~in 1126~~ could flow spontaneously. On the contrary, Younger (2007) ~~from the United Kindom~~ believed that "artesian" is a synonym of "confined", and pointed out that "artesian" is also widely misused to refer to any well from which water flows without pumping, a phenomenon which is not restricted to confined aquifers. Younger also discouraged further use of "artesian" because it lacks intuitive meaning in modern English.

To sum up, hydrogeologists are keenly interested in flowing wells, but the literature is confusing concerning the qualifier of~~are also confused by the term~~ "artesian". This confusion has likely lea~~d~~ds to the groundwater community ~~underestimation~~ underestimating ~~of~~ the role ~~of~~ that flowing wells have played ~~on~~ in the ~~development~~ evolution of ~~groundwater~~ its ~~hydrology~~science. Given that the meaning of the adjective "artesian" has a few meanings in the literature, the meaning can be unclear unless it is defined in each publication of use. There is no necessity to preserve this term in groundwater science and therefore we propose that its use be avoided. ~~In the following discussion, we avoid using the confusing adjective term "artesian well". Instead, following Freeze and Cherry's (1979) classification of flowing wells, we use geologically-controlled flowing wells to represent flowing wells in confined aquifers or leaky aquifers, and topographically-controlled flowing wells for wells in aquifers without a confining bed.~~

3 The history of drilling flowing well in selected regions

Many of the first deep wells that were drilled encountered static ~~aquifers had~~ hydraulic heads significantly above the local land surface ~~when the first deep wells were drilled~~ (Fetter, 2001). ~~A thorough review on the history of flowing well drilling is beyond the scope the current discussion.~~ Here, we briefly review the history of both shallow and deep flowing well in regions that most directly contributed to the development of modern groundwater science~~inspired hydrogeologists~~.

3.1 France

As early as 1126, ~~the first~~a shallow flowing well tapping the confined fringe of the chalk aquifer was ~~obtained~~ identified in Artois in northern France (Margat et al., 2013). The technique of cable-tool drilling (also called percussion drilling) resulted in drilling of deeper flowing wells in France in the early 19th century. Garnier (1822) published the first technical guidebook on drilling artesian wells. It was stated that with the exception of some provinces, there are few parts of France where artesian wells ~~might~~ are not be ~~procured~~expected. Garnier obtained a prize from the Society for the Encouragement of Industry due to the publication of this book, which reflects the interest of the French government in flowing wells.

According to Arago (1835), most flowing wells up to that time ranged in depth from 36 m to 177 m~~, however, one borehole which was drilled in quest of coal resulted in the formation of a flowing well with a depth of 314 m~~. Between 1833 and 1841, a flowing well with a depth of 548 m was drilled in Grenelle within the Paris Basin. ~~This~~ The water level in this flowing well could rise to a height of 33 m above ground surface in a pipe supported by a wooden scaffolding ~~which was~~ accessible by steps (Fig. 3). In 1855, an article ~~named~~ titled *The Artesian Well at Grenelle, in France* was reproduced in *California Farmer and Journal of Useful Sciences* in the United States (Anonymous, 1855). It was commented that "*This splendid achievement at that date may be looked upon as the pioneer effort, and at the present time and within a very few years, the most astonishing results may be expected.*" In 1861, another flowing well with a depth of 586 m was completed ~~finished~~ in Passy near Paris, which is the last flowing well in Paris ~~that is~~ still in use today. Darcy (1856) and Dupuit (1863) were both inspired by flow rate measurements at different orifices in these deep flowing wells. The details are given in Sect. 5.

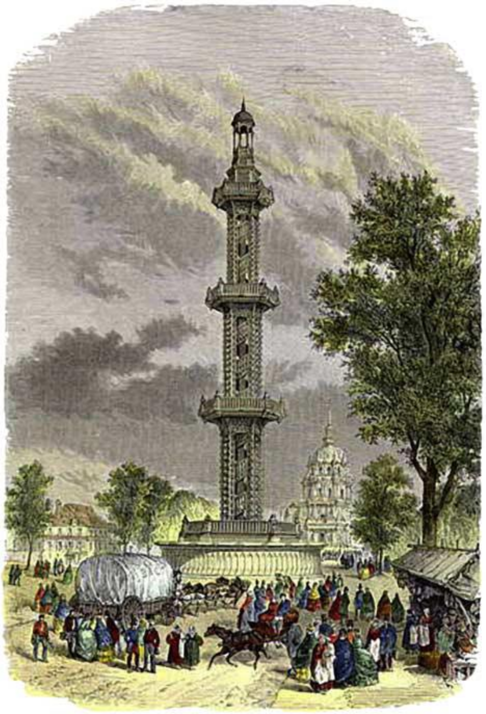


Fig. 3 The wood engraving of the flowing well at Grenelle (uncopyrighted and freely distributed by http://www.antiqueprints.com). The external structure was demolished in 1903 (Ritzi and Bobeck, 2008).

3.2 Italy

According to Norton (1897), nearly equal in antiquity with the flowing wells of Artois are those of Modena in northern Italy, which might have disputed with Artois on the right to provide their name to flowing wells. It was noteworthy that two well-borer's augers were used in the municipal coat of arms, indicating the influence of wells on the town. Giovanni Cassini (1625-1712), referred to flowing wells in Modena and Bologna, and developed one himself at the castle of Urbin (Merdinger, 1955). A shallow flowing well can be obtained by digging to a depth of ~20 m and boring a hole for the next ~1.5 m by using an auger (Biswas, 1970).

Based on the famous flowing wells of Modena, Bernardino Ramazzini (1633–1714) and Antonio Vallisnieri (1661–1730) connected flowing wells to the water cycle and pioneered the theory of artesian water pressure in the late 1600s and early 1700s (Duffy, 2017). The details are to be introduced in Subsect. 4.1.

3.~~2~~ 3 Great Britain

By the end of the 1700s, some shallow flowing wells had been dug in Great Britain. In 1785, a flowing well (artificial spring) with a depth of ~3.7 m was dug ~91 m away from the Darwent River in Derby (Darwin, 1785). One of the first flowing wells near London was completed in 1794 (Buckland, 1836). The successful experiences of water supply from flowing wells led to sinking of more flowing wells.~~In Great Britain,~~ According to ~~James Ryan obtained a patent on boring for minerals and water in 1805, while John Goode obtained a patent on boring for the purpose of obtaining and raising water in 1823~~ (Macintosh, 1827), James Ryan obtained a patent on boring for minerals and water in 1805, while John Goode obtained a patent on boring for the purpose of obtaining and raising water in 1823, indicating that drilling was active in Great Britain in early 19th century. According to an article in *Monthly Magazine and British Register* (Anonymous, 1822), two flowing wells with depths of 32 m and 37 m were drilled in the town of Tottenham in 1821, and many flowing wells had existed for a period of time in various parts of the country by 1822.~~The grant of these patents indicates that Great Britain was active in drilling wells in the early 19th century. In 1807, it was reported that there were flowing wells in the Thames Basin, London (Farey, 1807). According to an article in *Monthly Magazine and British Register* (Anonymous, 1822), many flowing wells had existed for a long time in and near London, and in various parts of the country by 1822, and two flowing wells drilled in a town called Tottenham in 1821 had depths of 32 m and 37 m.~~

The publication of Garnier (1822) in France aroused further interest in flowing wells in Great Britain (Farey, 1823). ~~By 1840, many "artesian wells" had been drilled in the London Basin (Mylne, 1840), although~~ Although many flowing wells had been drilled in the London Basin, many boreholes failed to become flowing wells. ~~because of lack of geological information~~Therefore, Buckland (1836) called for a theory of flowing wells. The experience gained from the costly failures improved understanding of conditions necessary for the success of a flowing well, the details of which are to be discussed in Subsect. 4.1.

3.~~3~~ 4 The United States

Accompanying with the increase in the population due to immigration and Western expansion in the US, there was a higher demand of water resources for drinking and for agriculture. As a result of the increased drilling technology since the 19th century, deep groundwater was utilized by drilling numerous wells, many of which were flowing wells, at least in the initial stage of development.~~To meet the water supply in some cities as well as irrigation demands in farms, numerous flowing wells were drilled in the United States beginning in the 19th century as a direct result of the increased drilling technology.~~ Here, we list some regions where flowing wells were drilled, ~~causing~~ resulting in significant advances in groundwater ~~hydrology~~science.

Development of the Cambrian-Ordovician aquifer system in the northern Midwest can be traced to 1864 when a flowing well with a depth of 217 m was drilled in Chicago (Konikow, 2013). By the end of the 19th century, flowing wells were common in topographically low areas in the Mississippi, Missouri, and Illinois River valleys, near Lake Michigan, and around Lake Winnebago in northeastern Wisconsin (Young, 1992). At the beginning of the 21st century, there were still many flowing wells newly drilled in Michigan (Gaber, 2005). Chamberlin's (1885) classic report ~~was~~ based on the hydrogeologic conditions in Wisconsin~~, and~~ is considered as one of the roots of groundwater science ~~hydrology~~ in Wisconsin (Anderson, 2005). In 1876, a flowing well with a depth of 293 m and an initial flow rate of 3270 m^3/d drilled in Prairie du Chien, Wisconsin~~, which~~ was named *The Greatest Artesian Fountain in America*~~, was drilled in Prairie du Chien, Wisconsin~~ (Meiter, 2019). The photo of this flowing well ~~was used~~served as the frontispiece of Chamberlin (1885) and Freeze and Back (1983), the cover image of Deming (2002), and was also cited in Anderson (2005).

In the Great Plains, interest in groundwater emerged due to the irrigation demands beginning in the 1880s, due to the widespread drought. In early 20th century, flowing wells were common in topographic lows near rivers, for example, in the Arkansas River valley of southeastern Colorado, much of South Dakota, and parts of southeastern North Dakota and northeastern Nebraska in the Missouri River valley (Darton, 1905). In South and North Dakota within the Great Plains, ~~there were about~~some 400 deep wells were drilled into the Dakota sandstone by 1896, of which over 350 were flowing wells (Darton, 1897). Due to the introduction of the jetting method of drilling in around 1900, thousands of small-diameter wells were drilled to the Dakota sandstone during the following two decades. There were about 10,000 deep wells in South Dakota in 1915, and between 6,000 and 8,000 deep wells in North Dakota in 1923 (Meinzer and Hard, 1925). Due to the increased withdrawal of deep groundwater, many flowing wells became non-flowing wells, accompanied by decreasing flow rates in the flowing wells that still flowed. The condition of flowing wells led to improved understanding of the pattern of groundwater circulation in confined aquifers (Darton, 1905), while the changing production ~~imbalance between groundwater~~

discharge and rechargerates led to the birth of the concept of compressibility of confined aquifers and the role of compressibility on production in confined aquifers (Meinzer and Hard, 1925; Meinzer, 1928).

In flowing wells of the Dakota aquifer, it was noted that "*the pressure increases for several hours or even days after the flow is shut off, and when opened the flow decreases in the same way until the normal flow is reached*" (Meinzer, 1928). Several decades later, based on field observations of decreasing flow rate with time in flowing wells in the Grand Junction artesian basin and in the Roswsell artesian basin in New Mexico, constant-drawdown aquifer tests were proposed to obtain hydraulic parameters (Jacob and Lohman, 1952;Hantush, 1959).

3.4 5 Australia

The Great Artesian Basin, which covers 1/5one-fifth of the total area of Australia, is one of the largest and wellbest-known groundwater basins in the world (Ordens et al., 2020). The first shallow flowing well was dug to with a depth of 43 m was dug by using an auger near a spring in New South Wales in 1878, while the first deep machine-drilled flowing well was completed in 1887 at with a depth of 393 m was completed near Cunnamulla, Queensland in 1887 (Williamson, 2013). By the end of the 19th century, there were already around 1000 flowing wells on the continent (van der Gun, 2019). The exploitation discovery of flowing wells and artesian water contributed totriggered the emergence of hydrogeology as a discipline in Australia (Williamson, 2013), and the development of "artesian water" such sources have has played a vital role on in the pastoral industry in the arid and semi-arid regions of Australia (Habermehl, 2020).

Due to the occurrence of intervening aquifers and aquitards, the Great Artesian Basin is a multi-layered confined aquifer system. Although head drawdowns of up to 100 m have been recorded in highly developed areas, hydraulic heads in the Jurassic and Lower Cretaceous aquifers are still above ground surface throughout most of the basin (Habermehl, 2020). In Australia, currently the term "artesian" still implies that a bore will flow naturally (Williamson, 2013). A comprehensive review of the history and recent research status of the basin can be found in Ordens et al. (2020).

3.5 6 Canada

In this subsection we consider the hydrogeology of the Canadian Prairies which has been studied since Since the beginning of the 20th century, the hydrogeology of the Canadian Prairies has been studied. Groundwater in this region is largely obtained from surficial Pleistocene glacial drift and from the underlying bedrock of Tertiary or Cretaceous age. Quaternary glacial deposits and the underlying Tertiary Paskapoo sandstone constitute a thick unconfined aquifer. A similarity between the potentiometric surface and the local topography were widely observed in many parts of the Canadian Prairies (Jones, 1962;Meyboom, 1962;Tóth, 1962;Farvolden, 1961). Due to the occurrence of a large number of flowing wells, either in the glacial drift or in the bedrock, great attention was paid to the relation between topography, geology and areas with flowing wells during basin-scale groundwater surveys (Meyboom, 1966).

The Trochu area in central Alberta, which covers an area of 67 km^2, is representative of the hydrogeology of the Canadian Prairies. There were 10 shallow flowing wells ranging in depth from 9 m to 27 m in topographic lows (Tóth, 1966). Because the glacial deposits have low contents of clay, they are efficient for infiltration of rainfall and evaporation of soil water. ~~Therefore, the Quaternary glacial deposits and the underlying Tertiary Paskapoo sandstone constitute a thick unconfined aquifer.~~ Combined with previous theoretical findings on topographically-driven flow systems (Hubbert, 1940;Tóth, 1962, 1963), these flowing wells in unconfined aquifers were considered to be controlled by topography and are typical manifestations of groundwater discharge (Tóth, 1966). The details are discussed in Sect. 7.

3.7 China

As early as in the 11th century, deep drilling using bamboo pipes was employed in Sichuan Province, China, to reach brines from 100-m-deep boreholes (Vogel, 1993). In the 16th century, a flowing well in Beijing became a site of tourism known as “Manjing” (literal meaning, a well full of water). In the 17th century, due to the success of developing flowing wells for brines, “Ziliujing” (meaning, flowing well) became the name of a town in Sichuan. In 1835, the 1001-meter-deep flowing well at Xinhai was constructed for producing brines and gases (Vogel, 1993). However, these early drilling techniques and experiences of drilling deep flowing wells did not substantially produce follow-on activity in the development of groundwater science in China. In early 1950s, the large demand of groundwater in (semi-)arid regions led to exploration of groundwater and resulted in the establishment of hydrogeology as a distinct discipline in several universities. In late 1950s, the success of drilling some flowing wells led to a campaign of finding more flowing wells for agriculture in many basins of the country. Unfortunately, flowing wells in many basins have disappeared.

One of the most intensively studied groundwater basins is Tthe Ordos Plateau in northwestern China has, composed mainly of a thick Cretaceous sandstone aquifer of Cretaceous age, the thickness of which could be up to around 1000 m thick. Because the overlying thin Quarternary deposits overlying the Cretaceous sandstone have much higher permeability, and there is no continuous aquitard within the Cretaceous sandstone, the Ordos Plateau can be conceptualized considered as a thick unconfined aquifer (Hou et al., 2008;Jiang et al., 2018). As early as the 1950s,Due to the undulating topography, there are numerous topographically-controlled flowing wells several flowing wells were established in deep boreholes drilled intoin the Cretaceous sandstone in topographic lows., and subsequently numerous flowing wells were drilled for agricultural water. For example, in the Wudu lake catchment, on this plateau with with an area of aroundapproximately 200 km^2, there were 15 flowing wells in 2015 (Wang et al., 2015b). In recent years, moreadditional flowing wells have been drilled. The majority of flowing wells in this catchment range in depth from 70 m to 300 m, andwith one well reachingreaching the bottom of the Cretaceous sandstone has at a depth of 800 m.

To reduce costs, The the flowing wells drilled into the Cretaceous sandstone wells have long-screens and are cased only in the very shallow part that correspondings to the Quarternary deposits. These wells provide a prime example to study the hydraulics of flowing wells in a macroscopically homogeneous basin. It is interesting that groundwater collected at the flowing wells has a hydrochemical facies of Na-HCO_3, does not contain NO_3^-, and is depleted in δ^2H and δ^{18}O, all of which are quite different from groundwater in recharge areas (Wang et al., 2015a). Moreover, Mg in groundwater collected from flowing wells has been greatly removed by the process of clay formation, leading to much lower δ^{26}Mg than samples in recharge areas (Zhang et al., 2018a). These hydrochemical and isotopic evidences show that groundwater collected at the outlets of flowing well could represent deep groundwater and is seldom mixed with shallow groundwater (Zhang et al., 2019).The hydraulics of flowing wells in homogeneous basins is introduced in Subsect. 7.3.

4 GeologicallyConfined-controlled flow flowing wells and confined flow bounded by aquitards piston-flow in confined aquifers (1820s1690s-current)

4.1 Conditions of geologicallyconfined-controlled flow flowing wells

Based on his observations of flowing wells in Modena, Italy in 1691, Ramassini plotted a geological section showing the occurrence of flowing wells penetrating a confined aquifer, receiving its water from an underground reservoir at a higher level in the surrounding mountain (Biswas, 1970). Therefore, for the occurrence of flowing wells, Ramassini already suspected the role of topography, or the hydraulic gradient between the well and the underground reservoir in the surrounding mountain (de Vries, 2007). Unfortunately, he thought the source of water in the underground reservoir in the surrounding mountain was more likely to be from the sea. Later, Valniseri argued in 1726 that the source of water in the flowing wells of Modena must be rainfall and snowmelt in the adjacent Apennine Mountains (Duffy, 2017), which was the start of thinking about the simultaneous control of topography and precipitation on flowing wells.

~~Due to the progress of hydrology and geology in the 18th century~~In the evolution of thinking about groundwater, it was universally accepted ~~in~~ by the early 19th century that the water ~~of~~ from flowing wells came from rainfall, which found its way through the pores or fractures of a permeable stratum sandwiched between two water-tight strata at depth~~enclosed between two water-tight strata~~ (Garnier, 1822). de Thury (1830) summarized three conditions of flowing wells ~~in confined aquifers~~. In his words, ~~The~~ the first is to reach a flow of deep water coming from higher basins and passing along the bosom of the earth between compact and impermeable rocks; the second is to afford this deep water the possibility of rising to the surface by using an artificially bored well; and the third is to prevent the spreading of the ascending water into the surrounding sand or rock by inserting tubes into the bored well.

Following the successful drilling of flowing wells in France, the theory of the mechanism~~behind the occurrence~~ of flowing wells ~~was~~ became well understood in Britain. For example, Buckland (1836) ~~illustrated~~ illustrates the cause of two flowing wells in the confined aquifer of the London Basin. The successful experiences coupled with the costly failures of drilling in Britain led to the recognition of three necessary conditions for the success of a flowing well (Bond, 1865). The~~conditions~~se are:

> *"(1) The existence of a porous stratum having a sufficient outcrop on the surface to collect an adequate amount of rainfall, and passing down between two impermeable strata; (2) the level of the outcropping portion of the porous stratum must be above that of the orifice of the well, so as to give a sufficient rise to the water; (3) there must be no outlet in the porous stratum by which its drainage can leak out, either in the shape of a dislocation, by which it can pass into lower strata, or a natural vent, by which it can rise to the surface at a lower level than the well."*

Based on his North American experience within~~in~~ the Wisconsin ~~part~~ portion of the Cambrian-

Ordovician aquifer system, Chamberlain (1885) published *The Requisite and Qualifying Conditions of Artesian Wells* and listed seven conditions of flowing wells~~. The conditions~~, which include:

> "*(1) A pervious stratum to permit the entrance and the passage of the water; (2) A water-tight bed below to prevent the escape of the water downward; (3) A like impervious bed above to prevent escape upward, for the water, being under pressure from the fountain-head, would otherwise find relief in that direction; (4) An inclination of these beds, so that the edge at which the waters enter will be higher than the surface at the well; (5) A suitable exposure of the edge of the porous stratum, so that it may take in a sufficient supply of water; (6) An adequate rain-fall to furnish this supply; (7) An absence of any escape for the water at a lower level than the surface at the well.*"

In fact, the seven prerequisites given by Chamberlain (1885) are inclusive of~~more or less similar to~~ the three conditions given by de Thury (1830) and Bond (1865) several decades earlier. However, Bonds (1865) did not cite de Thury (1830), and Chamberlin (1885) did not cite either Bonds (1865) or de Thury (1830), therefore, we assume their findings were obtained independently. ~~Chamberlin (1885) also pointed out that confining layers are not totally impermeable, which foreshadowed later studies on well hydraulics of leaky aquifers (Hantush, 1959;Hantush and Jacob, 1955;Jacob, 1946) and leakage in sedimentary basins (Swenson, 1968). Chamberlin's report was recognized as the first classic paper on regional groundwater flow in the United States (Bredehoeft et al., 1982).~~

4.2 Confined flow bounded by aquitards

~~4.2 Piston flow in confined aquifers~~

In the late 1890s, Darton (1897) with the USGS investigated the occurrence of flowing wells in the Dakotas and plotted the cross-section of the Dakota aquifer (Fig. 4). By constructing contours of ~~the~~ hydraulic head ~~contours~~ of the Dakota confined aquifer across ~~in~~ South Dakota, which shows the head loss through the confined aquifer, Darton (1905) concluded that groundwater discharged by the flowing wells in the east had flowed hundreds of kilometers horizontally through the ~~confined~~ aquifer from ~~the~~ outcrops in the west. This study popularized the pattern of groundwater flow in a confined aquifer ~~which~~ that outcrops in topographic highs as shown in Fig. ~~1a~~2a. There was also a long-lasting conceptual model for the Great Artesian Basin of Australia that each aquifer can be considered to be laterally continuous across the extent of the basin~~In the Great Artesian Basin of Australia, there was also a long-lasting conceptual model that each aquifer can be considered to be laterally continuous across the extent of the~~

basin (Habermehl, 2020). In the Dakota confined aquifer, vertical leakage into the aquifer from adjacent strata was identified in the 1960s (Swenson, 1968). In Australia, several recent studies also identified vertical connections between aquifers (Pandey et al., 2020;Smerdon and Turnadge, 2015). However, vertical leakage seldom change the direction of groundwater flow within the confined aquifer.

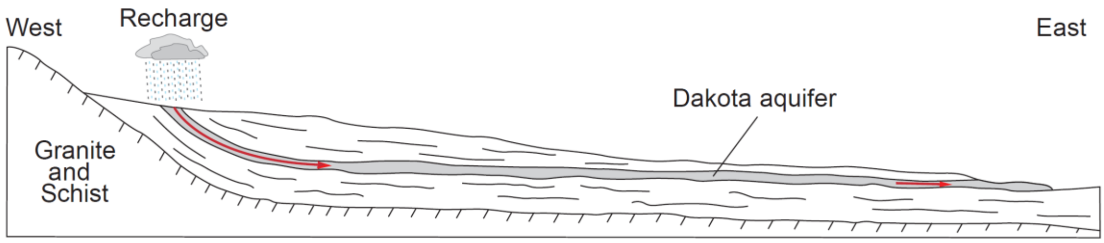


Fig. 4 The profile of the Dakota confined aquifer and the piston confined flow in a confined aquiferbounded by aquitards. (Modified from Darton, 1897)

As shown in Fig. 4, the groundwater flow pattern in a confined aquifer, which is bounded by the adjacent aquitards, is similar to flow through a pipe, . Such a flow pattern and is commonly referred utilized to interpret groundwater age in confined aquifers, which is knownto as piston flow age (Bethke and Johnson, 2008;Hinkle et al., 2010). Because many hydrogeochemical processes are dependent on travel time through the aquifer, hydrochemical facies (Back, 1960; 1966) usually evolve along the flow path within the piston flowbounded by aquitards. Therefore, the piston flow modelsuch a flow pattern, which stemmed from analyzing geologically-controlledconfined-flow flowing wells, is the cornerstone of sampling and analyzing groundwater geochemistry and isotopes in confined aquifers.

5 Darcy's law and steady-state well hydraulics inspired by flowing wells (1850s-1910s)

5.1 The birth of Darcy's law evoked by flowing wells

It is widely known that Darcy's law, which represents the beginning of groundwater hydrology as a quantitative science in 1856 (Freeze and Back, 1983), was established based on sand column experiments. In fact, the sand column experiments were designed to confirm a linear correlation between flow rate and head loss in sands which was first recognized discovered in flowing wells (Brown, 2002;Ritzi and Bobeck, 2008). Because fFlowing wells were important sources of water supply in the Paris Basin since the early 19th century, and this led to flow rates being measured at different elevations of discharge orifices ~~were measured~~ in several flowing wells in the 1840s (Fig. 5)~~, which were called experiments of head loss versus riser pipe height (Ritzi and Bobeck, 2008)~~. In fact, such experiments can be regarded as constant-head (drawdown) tests at multiple discharge orifices in single wells. As shown in Fig. 5a, in either September or November, the flow rates ~~measured in September and November~~ increased linearly as the elevation of discharge orifice decreased. Henry Darcy's interest in ~~was interested by~~ this linear correlation instigated his famous lab experiments with sand column (Brown, 2002;Ritzi and Bobeck, 2008).

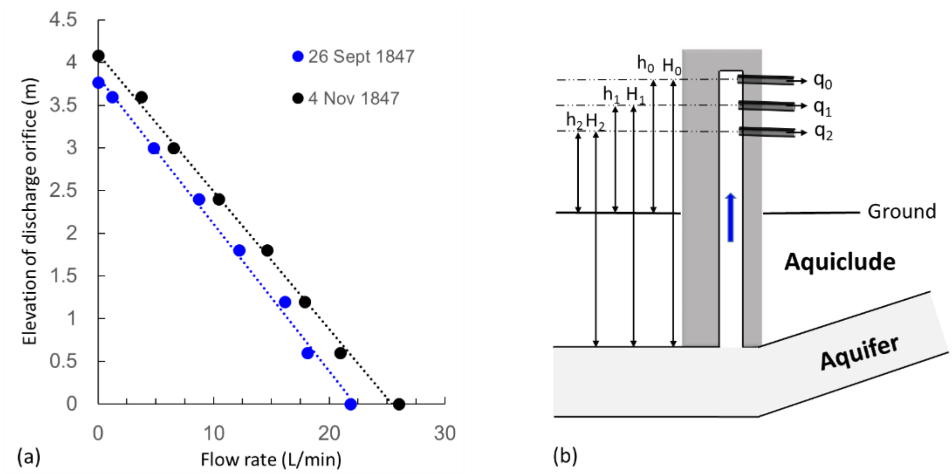


Fig. 5 (a) The change in flow rate with elevation of discharge orifice of a flowing well (data from Darcy, 1856); (b) The device for measuring flow rate (only one discharge orifice is open during measurement). The higher flow rate in November shown in (a) can be a result of higher hydraulic head surrounding the flowing well, probably due to the contribution of groundwater recharge.

Theoretically, the head loss from the recharge area to the discharge orifice can be divided into head loss in the aquifer and head loss along the well pipe. According to the Chezy equation describing head loss at high flow velocities in pipes, head loss in the well pipe should be proportional to the square of flow rate. Based on the linear trend between head loss and flow rate shown in Fig. 5a, it was inferred that the head loss in the short-distance well pipe with high velocities is limited compared with the well loss in the long-distance aquifer with low velocities. To identify the control of flow velocity on head loss, Darcy conducted pipe flow experiments during 1849 and 1851 and proposed equations on the dependence of head loss on flow rate. At low velocity, the head loss was found to be linear to discharge rate, which can be written as

$$h_L = \frac{La}{\pi r^4} q \tag{1}$$

and at high water velocity, the head loss was found to be linear to the square of discharge rate, which can be written as

$$h_L = \frac{Lb}{\pi r^5} q^2 \tag{2}$$

where L is length, r is pipe radius, q is the volume discharge rate, and a and b are empirical coefficients of proportionality. Eq. (1) verified Poiseuille (1841) equation by experiments under completely different circumstances, and Eq. (2) can be considered as another form of the Chezy equation. Note that Eq. (2) led to the co-naming of the Darcy-Weisbach pipe friction formula. About 30 years later, Reynolds (1883) fully quantified the occurrence and differences between laminar and turbulent flow by introducing the Reynolds number.

By assuming that head loss from the recharge area to the discharge orifice occurs in both the aquifer and the well pipe, equations similar to the following forms were obtained:

$$h_1 + \frac{aL'}{\pi r'^4} q_1 + \frac{bH_1}{\pi r^5} q_1^2 \cong h_2 + \frac{aL'}{\pi r'^4} q_2 + \frac{bH_2}{\pi r^5} q_2^2 \tag{3a}$$

$$\left(h_1 - h_2\right) + \frac{b}{\pi r^5}\left(H_1 q_1^2 - H_2 q_2^2\right) \cong -C\left(q_1 - q_2\right) \tag{3b}$$

where L' is flow distance in the aquifer from the recharge area, r' is radius representative of pores in the aquifer, H_1 and H_2 are the lengths of well pipes from the bottom to the discharge orifice, and C is an unnamed constant. The linear relationship between h_1-h_2 and q_1-q_2 shown in Fig. 5a indicates that the second term on the left side of Eq. (3b) is negligible. Therefore, Eq. (3b) changes into

$$h_1 - h_2 \cong -C\left(q_1 - q_2\right) \tag{4}$$

where~~, and~~ C can be interpreted as the slope shown in Fig. 5a.

To ~~further~~ confirm Eq. (4)~~that head loss in aquifers is linear to the velocity~~, in 1855, Darcy conducted the sand column experiments assuming that water flow through sands is similar to water flow through the aquifer and obtained the well-known empirical equation of Darcy' law~~(Darcy, 1856)~~. Note that the coefficient today known as hydraulic conductivity was not named by Darcy.

~~The equation he wrote for fluid motion through sands, with the head loss between two points separated by a distance l, is~~

$$q = ks\frac{h_L}{l} \tag{4}$$

~~where s is the total cross-sectional area perpendicular to flow, and k is a coefficient unnamed by~~

Darcy, today call *k* the hydraulic conductivity. Hubbert (1940) rigorously interpreted hydraulic conductivity and examined Darcy's law in the light of the microscopic Navier-Stokes flow theory, which raised the sophistication of understanding of Darcy's law to a higher level of sophistication.

5.2 Steady-state well hydraulics in confined aquifers: Dupuit equation

In 1850, Jules Dupuit succeeded Henry Darcy as Chief Director for Water and Pavements and started his research on groundwater hydraulics. The field data shown in Fig. 5a triggered Dupuit to quantify the constant *C* in Eq. (3b). Dupuit realized that groundwater flow would radially converge to the flowing well and head loss in the confined aquifer away from the flowing well would form a cone of depression (Fig. 6).

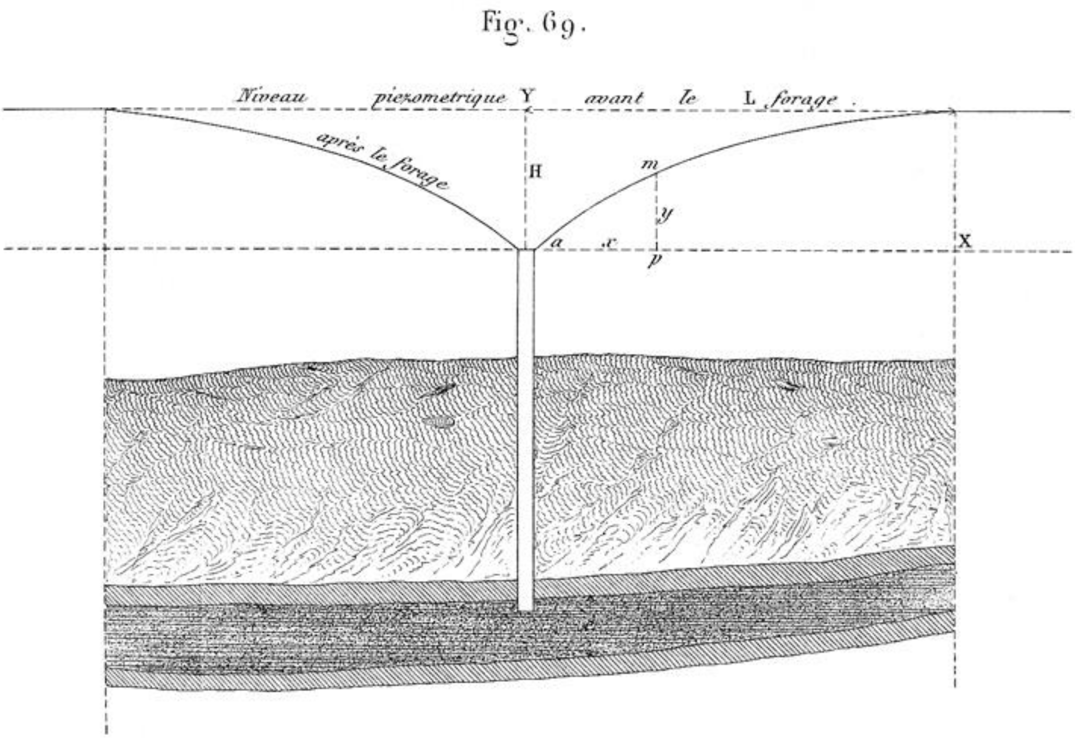


Fig. 6 Plot from Dupuit (1863) showing the radial flow toward a flowing well penetrating a confined aquifer, which caused head loss with a cone of depression in the potentiometric level ("niveau piezometrique"). It is clear that the potentiometric level of the cone of depression is still above the land surface.

In radial flow, Eq. (4)Darcy's law can be rewritten as

$$q = k\left(2\pi xB\right)\frac{dy}{dx} \tag{5}$$

where *B* is the thickness of the confined aquifer, *x* is the radius within the cone of depression, and *y* is the corresponding head with reference to the elevation of the discharge orifice. Dupuit (1863) obtained the following equation by integrating Eq.~~equation~~ (5) from the radius of the well, r_w, to the radius of influence, R:

$$h_0 - h_w = \frac{q}{2\pi kB} \ln\left(\frac{R}{r_w}\right) \tag{6}$$

where h_w is the elevation of the discharge orifice, and h_0 is the hydraulic head at the radius of influence, which equals the initial hydraulic head of the flowing well when the well has been closed for a duration of time. By comparing Eq. (4) and (6), it can be interpreted that $C = \frac{1}{2\pi kB} \ln\left(\frac{R}{r_w}\right)$. Dupuit (1863) explicitly stated that Eq. (6) is supported by the measurements of flow rate versus elevation of discharge orifice of flowing wells reported in Darcy (1856).

Although Eq. (6) was derived based on the hydrogeologic condition of a flowing well in a confined aquifer, it is applicable to non-flowing wells in a confined aquifer. A limitation of the equation is the difficulty of determining the radius of influence in the field. Thiem (1906) improved Eq. (6) by integrating Eq. (5) between two wells within the cone of depression and obtained an equation to determine hydraulic conductivity, which is known as the Thiem equilibrium method. Although the Thiem equation (Thiem, 1906) was introduced in almost all textbooks, Dupuit's pioneering study on steady-state radial flow to a flowing well in confined aquifers (Dupuit, 1863) was seldom mentioned in textbooks.

Dupuit (1863) also derived similar equations for a well in unconfined aquifers by neglecting the vertical hydraulic gradient, which is currently known as Dupuit-Forchheimer approximation. Although the vertical hydraulic gradient is neglected, the Dupuit-Forchheimer approximation is still useful in interpreting regional scale groundwater flow problems (Haitjema and Mitchell-Bruker, 2005).

6 Compressibility of confined aquifers and transient well hydraulics inspired by flowing wells (1920s-current)

6.1 Compressibility of confined aquifers: concepts instigated by flowing wells

In the 1920s, ~~groundwater exploration in the United States had culminated and~~ groundwater resources were ~~already~~ undergoing development in the United States, therefore, much of the effort of the USGS turned toward developing an inventory of wells and their production (Domenico and Schwartz, 1998). The inventory of groundwater resources in the Dakota aquifer indicated that~~, where~~ the number of flowing wells was decreasing.~~ in the 1920s~~, The imbalance between groundwater discharge through flowing wells and groundwater recharge led to significant insight into the role~~theoretical finding~~ of aquifer compressibility (Meinzer, 1928;Meinzer and Hard, 1925).

Groundwater development in the Dakota aquifer started with flowing wells in the 1880s. After active drilling in the 1900s, investigations in the 1910s showed that many flowing wells had stopped flowing. To determine the groundwater budget, a study area of 18 townships near Ellendale, North Dakota (Ranges 48 through 65 West along Township 129 North) with a total of 320 flowing wells supplied by the Dakota sandstone was selected. The rate of discharge through flowing wells was estimated to be close to 3000 gallons per minute during the 38-year period from 1886 to 1923, but the rate of lateral recharge through eastward percolation was inferred to be less than 1000 gallons per minute (Meinzer and Hard, 1925). Although these estimates could be very inaccurate, they were sufficient to demonstrate the excess of discharge through flowing wells over recharge. Meinzer and Hard (1925) concluded that most of the water discharged through the flowing wells was taken out of storage in the sandstone aquifer, indicating that the sandstone aquifer was compressible. It was also observed that the artesian head would increase gradually for some time after a flowing well was shut off, which is a manifestation of elasticity of the aquifer medium (Meinzer and Hard, 1925).

By summarizing these observations of flowing wells, as well as the evidences of compressibility and elasticity of compacted sand, land subsidence in an oil field, water level fluctuations produced by ocean tides, and water level fluctuations produced by railroad trains, Meinzer (1928) concluded that confined aquifers are compressible and elastic. Although geochemical and numerical studies several decades later showed that leakage also contributed to well discharge in the Dakota aquifer (Bredehoeft et al., 1983;Leonard et al., 1983;Swenson, 1968), this did not undermine the role of flowing wells that had intrigued the interest of hydrogeologists.

Several years later, by assuming that discharge of groundwater from storage as head falls is similar to release of heat as temperature decreases, Theis (1935) recognized that confined aquifers possess a property analogous to heat capacity and derived the equation characterizing the transient behavior of hydraulic head due to discharge of a well. Theis's solution was not understood by the groundwater hydrology community until Jacob (1940) defined the coefficient of storage as a combination of vertical compressibility of the porous medium and compressibility of water. Hereafter, numerous efforts were devoted to determining the aquifer parameters using transient well hydraulics and identifying the behavior of drawdown/flow rate in other aquifers (leaky aquifers, unconfined aquifers).

6.2 Transient well hydraulics in flowing ~~wells~~ and non-flowing wells in confined aquifers

In the early 1930s, the high demand for groundwater led to evaluation of groundwater in different parts of the United States and pumping tests using the Thiem equilibrium method were conducted to obtain hydraulic conductivity in several regions (Lohman, 1936;Theis, 1932;Wenzel, 1936). Unfortunately, it was found difficult to consistently obtain aquifer parameters because of the increasing drawdown with time (Wenzel, 1936).

To interpret the time-varying drawdown, Charles Vernon Theis assumed that groundwater flow disturbed by a sink withdrawing water was analogous to heat conduction disturbed by a sink withdrawing heat and resorted to Clarence Isador Lubin, a mathematician at the University of Cincinnati, for the solution of temperature distribution of a uniform plate under two different conditions (White and Clebsch, 1993). The first condition is the introduction of a sink kept at 0 temperature, which corresponds to the constant-drawdown aquifer test problem and is applicable to flowing wells, and the second condition is the introduction of a sink with a uniform heat flow rate, which corresponds to the constant-rate pumping test problem. It was fortunate that the solution of the second problem was readily available in the field of heat conduction (Carslaw, 1921). In this way, Theis (1935) obtained the analytical solution of time-dependent drawdown induced by pumping and opened the door of determining aquifer parameters using transient well hydraulics.

When a flowing well has been shut off for a duration of time, upon reopening, the discharge rate decreases with time, which can be considered as a constant-drawdown aquifer test. Based on Smith (1937) solution to the analogous problem in heat conduction (the first problem raised by Theis), Jacob and Lohman (1952) derived a solution to the constant-drawdown well test problem in a confined aquifer and verified the results based on flowing wells in the Grand Junction artesian basin, Colorado. Several years later, after the classical work on constant-rate pumping problem in leaky aquifers (Hantush and Jacob, 1955), Hantush (1959) derived a solution to the constant-drawdown well hydraulics to a flowing well in leaky aquifers. In fact, constant-drawdown tests can also be carried out in non-flowing wells either by using a specially designed pump or by connecting the well to a pressurized water container at the surface (Mishra and Guyonnet, 1992). Such constant-drawdown tests have been found to be particularly useful in low-permeability aquifers (Jones, 1993;Tavenas et al., 1990;Wilkinson, 1968).

In summary, although the door of transient well hydraulics was directly opened by Theis (1935) based on constant-rate pumping tests, constant-drawdown well tests triggered by flowing wells belong to an indispensable component of transient well hydraulics and are still receiving active attention in the current century (Chang and Chen, 2002;Wen et al., 2011;Tsai and Yeh, 2012;Feng and Zhan, 2019). It is worth noting that current models on transient well hydraulics did not fully account for the relationship between groundwater recharge from precipitation and groundwater discharge in wells, for example, the higher flow rate in November than that in September shown in Fig. 5a can not be explained by current theories.

7 ~~Topographically-controlled~~Unconfined-flow flowing wells and topographically-driven flow systems (~~1940s~~1890s-current)

7.1 Qualitative understanding of topographically-driven flow and unconfined-~~controlled~~ flow flowing wells

At the turn of 20th century, there was initial field evidence of upward groundwater flow below surface water bodies (King, 1899) and increases in hydraulic head with depth in the discharge area (Pennink, 1905) in homogeneous aquifers. These were attributed by ~~(~~Versluys (1930) to the control of topographically-driven groundwater flow who explicitly pointed out that the occurrence of artesian pressure exceeding the land surface corresponds to an increase in hydraulic head with depth, and would necessarily lead to upward groundwater flow. By calculating head distribution based on the analogy between temperature and hydraulic head, Versluys found hydraulic head could increase with depth in homogenous basins and concluded that aquitards are not necessary conditions of flowing wells. Note that due to the poor understanding of potential of subsurface water, Versluys wrongly assumed that pressure head difference is the driving force of groundwater flow.

Based on the principle of the conservation of mass and the laws of thermodynamics, Hubbert (1940) defined the potential of subsurface water and ~~proposed the fundamental rules to~~ obtained graphical solutions of regional groundwater flow in a homogeneous and isotropic aquifer with a symmetrical topography between two streams (Fig. 7). ~~, a cross-sectional flow net was drawn by assuming that groundwater recharge is distributed over the whole air-water interface except for the streams at the valleys. shows that flow lines diverge from recharge areas and converge toward discharge area at the bottoms of valleys.~~ Hubbert (1940) found that flowing wells could occur in topographic lows without an overlying confining bed and pointed out that a confined aquifer outcrops in the highlands and overlain by impermeable strata in the lowlands as shown in Fig. ~~1~~2a is by no means a necessary condition for flowing wells~~, and found that flowing wells could occur in topographic lows without an overlying confining bed (Fig. 1b).~~

~~Fetter (1994) superposed some piezometers onto the equipotential lines, which clearly shows that hydraulic head decreases with well depth in topographic highs near the divide, and increases with well depth in topographic lows near the valley. Moreover, below the streams, hydraulic head in the aquifer is higher than the elevation of ground surface, which constitutes a necessary and sufficient condition of vertical flowing wells.~~ Because there was no aquitard in the studies of Versluys (1930) and Hubbert (1940), the pattern of groundwater flow is mainly controlled by topography. Such flowing wells in homogeneous unconfined aquifers driven by topography ~~were termed~~belong to ~~topographically-controlled~~unconfined-flow flowing wells– (Tóth, 1966)~~(Freeze and Cherry, 1979)~~.

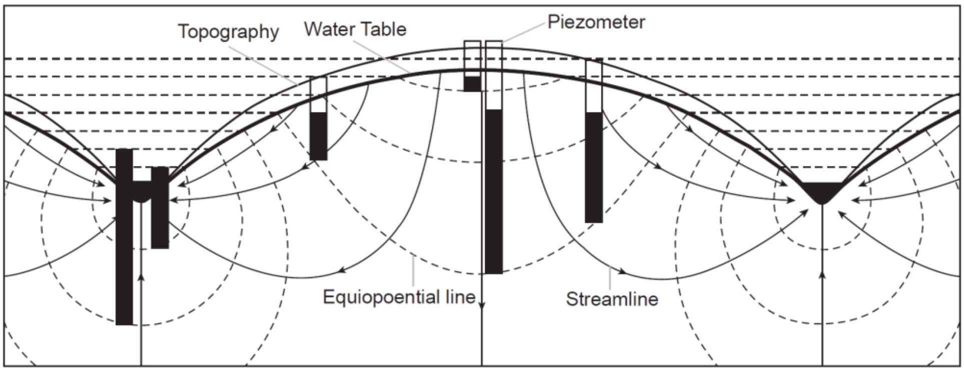


Fig. 7 The flow net of groundwater flow between two river obtained by Hubbert (1940) and the head in selected piezometers (Modified from Fetter, 1994).

7.2 Topographically-driven groundwater flow systems advances from the Canadian Prairie Region in the 1960's

In the 1950s and 1960s, the high demand for water on the Canadian Prairies led to institutional programs of ground water exploration and research. The phenomena ~~anticipated~~ described by King (1899) and Hubbert (1940), like the mean water table closely follows the topography,~~ hydraulic head decreases with well depth in topographic highs (corresponding to recharge areas) and increases with well depth in topographic lows (corresponding to discharge areas),~~ and flowing wells occur in topographic lows, were quite common in the Canadian Prairies (Meyboom, 1962, 1966;Tóth, 1962, 1966). Based on the field observations, two similar but slightly different conceptual models of topographically-induced groundwater flow (Fig. 8) were developed by Tóth (1962) and Meyboom (1962)~~, both of which believed that flowing wells could occur in the discharge area (Fig. 9).~~~~Although Toth and Meyboom had disagreement on some specific details,~~. Because the mean water table which closely follows the topography can be considered as *priori* known, Tóth (1962) solved the Laplace equation for a homogeneous unit basin with a known water table that changes linearly from the divide to the valley. Based on intuitive thinking founded on field observations, Meyboom (1962) considered the permeability difference between the shallow and deep aquifers and qualitatively obtained the flow pattern. ~~t~~They agreed that the combination of the two models "*gives a good description of the unconfined region of groundwater flow in the western Canadian Prairies*"(Tóth, 2005).

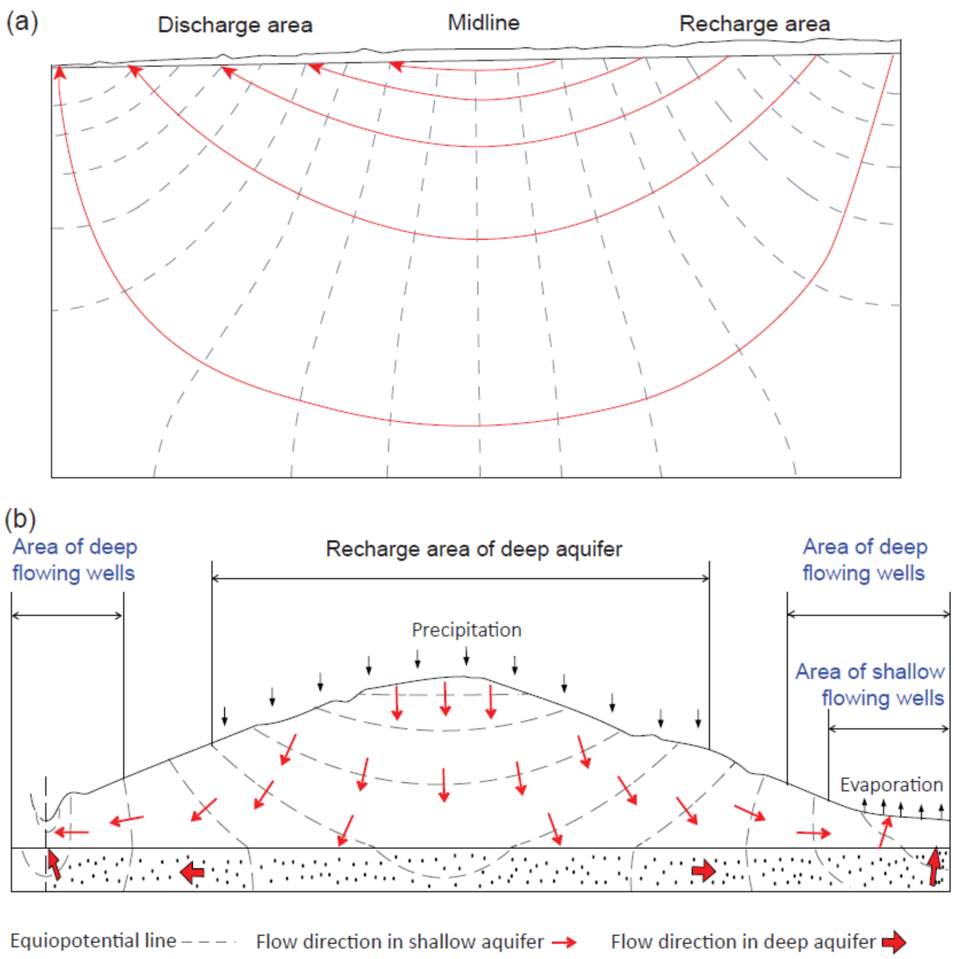


Fig. ~~9~~ 8 Topographically-~~induced~~ driven flow systems: (a) homogeneous basin (Modified from ~~Toth~~Tóth, 1962) and (b) heterogeneous basin with a higher permeability layer in the bottom (Modified from Meyboom, 1962).

According to Tóth (1962), ~~Because the glacial deposits with low permeability are still efficient for~~

~~infiltration of rainfall and evaporation of soil water, Tóth (1962) neglected the permeability difference between glacial materials and the underlying sandstone. By solving the Laplace equation for a homogeneous unit basin with a known water table change linearly from the divide to the valley, Tóth (1962) obtained a cross-sectional flow net (Fig. 9a) slightly different from Hubbert's. It was found that~~ groundwater discharge could cover the entire lower half of the unit basin, and the whole discharge area has higher hydraulic head than the corresponding elevation of water table~~ (the cases shown in Fig. 8h,i,j)~~, which fulfills Meinzer's (1923) definition of "artesian water". To quantify the occurrence of flowing wells in topographic lows of homogeneous unconfined aquifers, Wang et al. (2015b) examined the zone with flowing wells under different water table undulations and basin width/depth ratios. By fixing basin depth, increases in water table undulation and decreases in basin length both lead to increased hydraulic gradient between recharge and discharge areas. Based on the distribution of head exceeding surface (termed artesian head in their paper), it was found that the zone with flowing wells is always within the discharge area and the ratio of its size to the whole basin is proportional to the hydraulic gradient (Fig. 9). Therefore, in homogeneous basins, the hydraulic gradient is the main control factor of flowing wells.

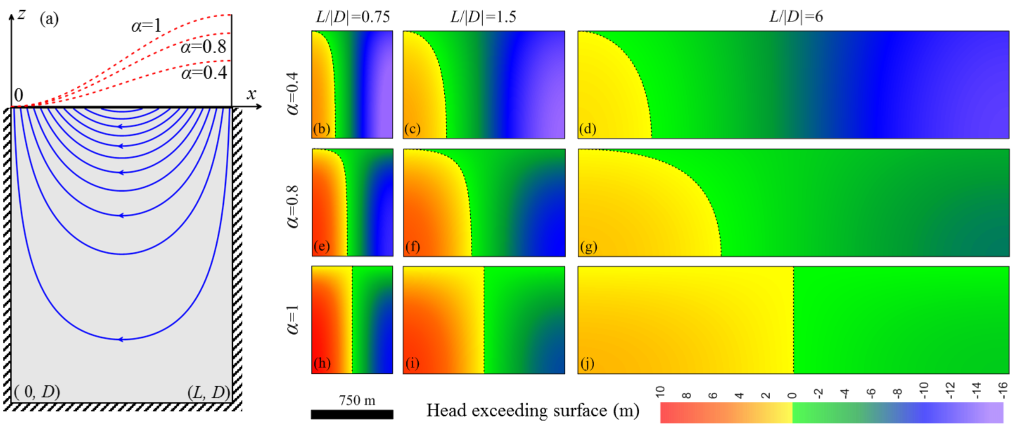


Fig. 9 (a)The geometry of a unit basin with a length of L and depth of $|D|$; (b-j) The distribution of head exceeding surface in the unit basin under different water table undulations (corresponding to different α) and basin length/width ratios ($L/|D|$). (Modified from Wang et al., 2015)

When the undulation of the topography is more complex, ~~In a composite basin whose water table configuration is the superposition of a sinusoidal curve and a linear regional slope~~, Tóth (1963) assumed that the water table configuration can be characterized by the superposition of a sinusoidal curve and a linear regional slope and obtained a flow net showing the simultaneous occurrence of several local flow systems, ~~and~~ one intermediate flow system ~~or~~ and one regional flow system~~s across divides within a large~~

basin. Note that the Canadian Prairies is semi-arid and the impetus for advancing flow systems thinking came from the need to understand terrain patterns of soil salinity, vegetation patterns and groundwater chemistry for which the spatial variations are flow system based. Note that Toth (1963) cited the pattern of cross-sectional groundwater flow inferred from hydrochemical facies in the northern part of the Atlantic Coastal Plain (Back, 1960;Back, 1966) to support his finding. Because Back (1960) and Toth (1963) are not directly related to flowing wells, plots of nested flow systems are not shown here.Several years later, as a PhD student, R. Alan Freeze, who was a protégé of Meyboom, -decided to bringcombined the ideas of Meyboom and TothTóth together in his PhD thesis by numerically simulating steady-state regional groundwater flow in heterogeneous basins with any desired water table configuration (Freeze, 2012). As reported in Freeze and Witherspoon (1967), it was demonstrated that heterogeneity does not affect the topographically-induced flow pattern from recharge to discharge areas (Fig. 10) and confined aquifers need not outcrop to produce flowing well conditions (Fig. 10b and 10c). In fact, Fig. 10 b and 10c indicate that a higher permeability in the lower aquifer could lead to a larger area of flowing wells. Moreover, they found that confined aquifers like those shown inFig. 10b and 10c need not outcrop to produce flowing well conditions. However the computing capabilities at the time limited the permeability contrasts between aquifer and aquitard units to a factor of 100, which is far from what is reality in actual flow systems in the field and these simulations are then to some degree misleading in light of what we now know.

Meyboom (1962) qualitatively plotted the flow net called the "Prairie Profile" (Fig. 9b), which considered the higher permeability of the sandstone than glacial deposits. The profile has large zones of shallow or deep flowing wells as well as large zones of evapotranspiration in the discharge area. Although Toth and Meyboom had disagreement on some specific details, they agreed that the combination of the two models "*gives a good description of the unconfined region of groundwater flow in the western Canadian Prairies*"(Tóth, 2005).

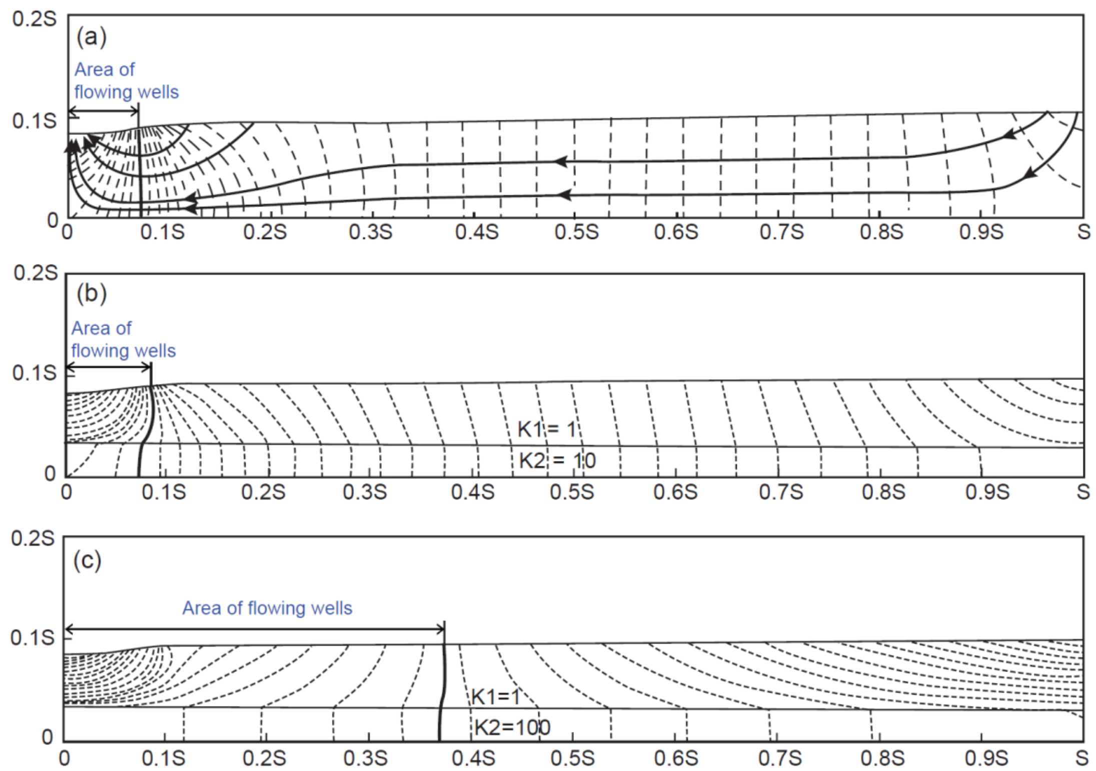


Fig. 10 The distribution of equipotential lines and area of flowing wells in homogeneous (a) and heterogeneous basins (b-c). Also shown in (a) is the streamlines showing the pattern of groundwater flow from the recharge to the discharge area. (Modified from Freeze and Witherspoon, 1967).

~~(Tóth, 2009)As shown in Fig. 7 through 10, the pattern of groundwater flow in thick unconfined aquifers is quite different from that in thin unconfined aquifers as well asin confined aquifers.The spatial distribution of groundwater age in thick unconfined aquifers (Jiang et al., 2010;Jiang et al., 2012) is also more complicated than that in a confined aquifer. the concept of topographically-controlled flowing wells has been included in some textbooks (Domenico and Schwartz, 1998;Freeze and Cherry, 1979;Heath, 1983;Kasenow, 2010;Lohman, 1972b), the number of which is limited compared with the large number of existing groundwater textbooks~~. ~~To quantify the occurrence of flowing wells in topographic lows of unconfined aquifers, Wang et al. (2015b) examined the zone with flowing wells under different water table undulations (characterized by different *α*, which is the ratio of water table undulations to topography undulations) and basin width/depth ratios (*L*/|*D*|, where *L* is the basin length and |*D*| is the basin depth). By fixing |*D*|, increases in *α* and decreases in *L* both lead to increased hydraulic gradient between recharge and discharge areas. Based on the distribution of head exceeding surface (termed artesian head in their paper), it was found that the zone with flowing wells is always within the discharge area and the ratio of~~

its size to the whole basin is proportional to the hydraulic gradient (Fig. 8). Therefore, in homogeneous basins, the hydraulic gradient is the main control factor of flowing wells.

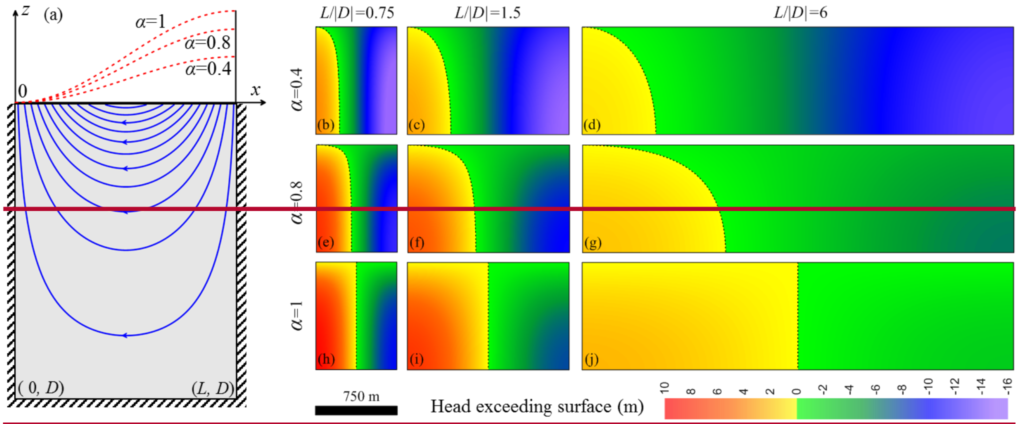


Fig. 8 The geometry of a unit basin with a length of L and depth of $|D|$ (a) and the distribution of head exceeding surface in the unit basin under different water table undulations (corresponding to different α) and basin length/width ratios (b-j). (Modified from Wang et al., 2015)

In the Dakota confined aquifer, vertical leakage into the aquifer from adjacent strata was identified in the 1960s (Swenson, 1968). In Australia, several recent studies also identified vertical connections between aquifers (Pandey et al., 2020;Smerdon and Turnadge, 2015).

As illustrated above, although horizontal flow dominates when the basin width/depth ratio is high and/or hydraulic conductivity is the deep layer is much higher, vertical components of groundwater flow are widespread in either thick unconfined aquifers or aquitards overlying confined aquifers, which is quite different from the flow pattern shown in Fig. 2.1 and 4. The spatial distribution of groundwater age in thick unconfined aquifers is also more complicated than that in a confined aquifer (Jiang et al., 2010;Jiang et al., 2012). Therefore, quantitative analysis of the topographically-driven groundwater flow systems became a paradigm shift of hydrogeology. This paradigm shift has been expressed by others in similar words. Anderson (2008) comments that "*The Tóth model is an important early exploration of the analysis of regional flow systems*." Bredehoeft (2018) points out that "*Tóth's conceptual model of groundwater flow*" represents the beginning of a new era in hydrogeology and termed the paradigm shift to be "*the Tóth revolution*".

In his book about flow systems, Tóth (2009) states that since the 1960s, hydrogeology's basic paradigm has shifted from confined flow in aquifers (aquitard-bound flow) to cross-formational flow in drainage basins, i.e., flow paths change from through a confined aquifer to across aquitards and different depths of aquifers in heterogeneous basins. Although cross-formational flow (inter-aquifer leakage) had already been anticipated by Chamberlin (1885), it was identified in the Dakota artesian basin through aquitards in the 1960s (Swenson, 1968), and was recently identified in the Great Artesian Basin through faults (Pandey et al., 2020;Smerdon and Turnadge, 2015). Moreover, although the concept of flowing wells in the context of aquitard bounding is introduced in almost every groundwater textbook, the concept of unconfined-flow flowing wells in homogeneous basins has been included in few textbooks (Domenico and Schwartz, 1998;Freeze and Cherry, 1979;Heath, 1983;Kasenow, 2010;Lohman, 1972b). Therefore, the acceptance of the new paradigm is a slow process.

7.3 Hydraulics of topographically-controlled flowing wells in unconfined aquifers

The Ordos Plateau in northwestern China has a thick Cretaceous sandstone, the thickness of which could be up to around 1000 m. Because the thin Quartnary deposits overlying the Cretaceous sandstone have much higher permeability, and there is no continuous aquitard within the Cretaceous sandstone, the Ordos Plateau can be considered as a thick unconfined aquifer. Due to the undulating topography, there are numerous topographically-controlled flowing wells drilled into the Cretaceous sandstone. For example, in the Wudu lake catchment with an area of around 200 km^2, there were 15 flowing wells in 2015 (Wang et al., 2015b). In recent years, more flowing wells have been drilled. The majority of flowing wells in this catchment range in depth from 70 m to 300 m, and one well reaching the bottom of the Cretaceous sandstone has a depth of 800 m. The wells have long-screens and are cased only in the very shallow part corresponding to the Quartnary deposits. It is interesting that groundwater collected at the flowing wells has a hydrochemical facies of Na-HCO_3, does not contain NO_3^-, and is depleted in δ^2H and $\delta^{18}O$, all of which are quite different from groundwater in recharge areas (Wang et al., 2015a). Moreover, Mg in groundwater collected from flowing wells has been greatly removed by the process of clay formation, leading to much lower $\delta^{26}Mg$ than samples in recharge areas (Zhang et al., 2018a). These hydrochemical and isotopic evidences show that groundwater collected at the outlets of flowing well could represent deep groundwater and is seldom mixed with shallow groundwater (Zhang et al., 2019).

The steady-state hydraulics of confined-flow flowing wells had been examined by Glee in the 1930s, but the study of unconfined-flow flowing wells is most recent. (Zhang et al., (2018b) simulated To examine the hydraulics of topographically-controlled flowing wells, tthe water exchange between the unconfined aquifer and ~~the~~ a flowing well ~~has been simulated using the revised multi-node well (MNW2) package (Konikow et al., 2009) of MODFLOW by considering a flowing well~~ in a three-dimensional homogeneous unit basin ~~(Zhang et al., 2018b)~~. ~~The hydraulic head of the flowing well, H_w, is set equal to the elevation of the ground surface.~~ As a result of ~~T~~the ~~trend of~~ increasing hydraulic head with depth in the discharge area of the aquifer, ~~results in~~ hydraulic head in the shallow part ~~aquifer~~ is smaller than hydraulic head of the flowing well~~H_w~~, ~~in the shallow part~~ and in the deep part is larger than hydraulic head of the flowing well~~H_w in the deep part~~. Therefore, there is groundwater inflow from the aquifer to the flowing well (Q_{in}) in the deep part, and groundwater outflow from the flowing well to the aquifer (Q_{out}) in the shallow part. ~~If $Q_{in}=Q_{out}$, then flow rate at the well outlet equals 0 (Fig. 11a), which is the same as a non-flowing well in the discharge area as reported in Zinn and Konikow (2007).~~ Because Q_{in} is larger than ~~However, if $Q_{in}>$~~ Q_{out}, flow rate at the well outlet is above 0 (Fig. ~~11b~~11a), which results in water overflow at the surface. In some extreme cases, for example, if the water table coincide with the ground surface, or the shallow part is cased, Q_{out} equals 0 and flow rate at the well outlet is determined by Q_{in} (Fig. ~~11c~~11b). ~~It has also been~~ (Zhang et al., 2018b) found that the simultaneous occurrence of inflow and outflow could also occur in a thick confined aquifer ~~(Zhang et al., 2018b)~~. Therefore, the 3rd condition proposed by both de Thury (1830) and Bond (1865), and the 7th condition given by Chamberlin (1885), is not a necessary condition for flowing wells.

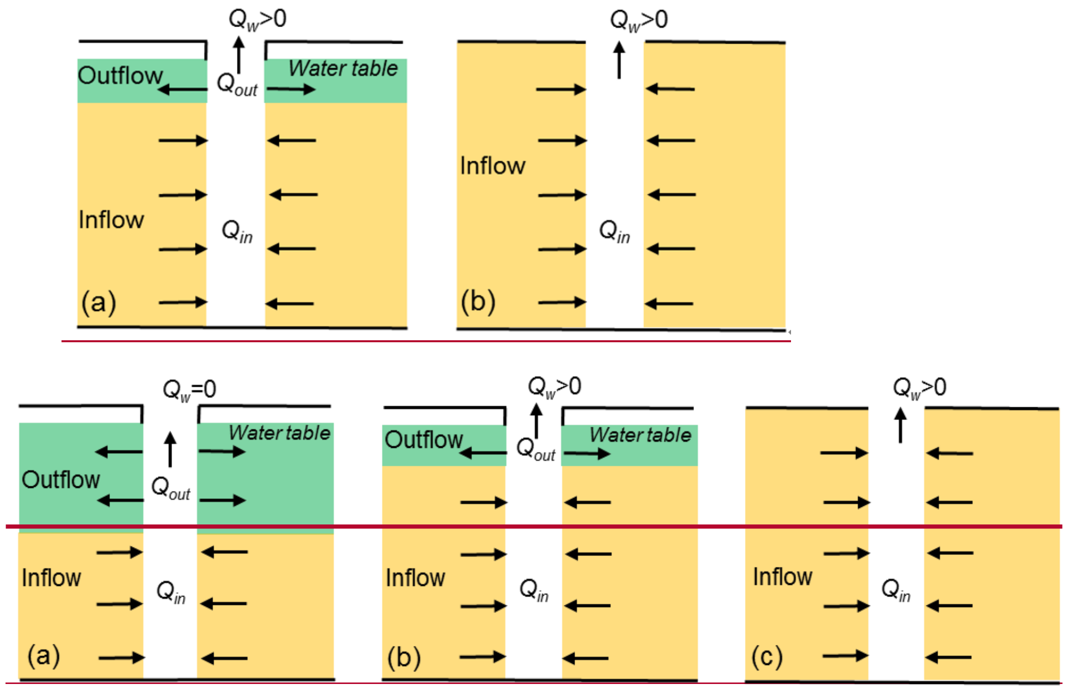


Fig. 11 Conceptual cross-sectional views of flow around ~~non-pumping~~flowing wells ~~in the discharge~~

area of a basin. (a) A non-flowing well with $Q_{in} = Q_{out}$; (b) a flowing well with $Q_{in} > Q_{out}$; (cb) a flowing well with $Q_{in} > Q_{out} = 0$. (Modified from Zhang et al., 2018b)

Based on the plots shown in Fig. 7 through 11, many several qualifying conditions of flowing wells proposed in the 19th century have been found to be not unnecessary conditions since 19401930. The concepts of topographically-controlled flowing wells and topographically-induced groundwater flow systems have led to a paradigm shift of hydrogeology (Bredehoeft, 2018;Tóth, 2005). Although the transient behavior of groundwater flow to geologically-controlled flowing wells in leaky confined aquifer has been studied in the 1950s (Hantush, 1959;Jacob and Lohman, 1952), there is has been no research on the transient groundwater flow to topographically-controlled flowing wells in unconfined aquifers. Moreover, research coupling groundwater recharge from precipitation and groundwater discharge through flowing wells, which is critical to interpret the increased flow rate from September to Novemberwith time as shown in Fig. 5a and the sustainability of flowing wells, is also missing.

8 Conclusions and suggestions

The thread of evolution of nearly all domains of physical hydrogeology connects back to flowing wells. The first recorded recognition of flowing wells was as early as 1126 in northern France, but it was tThe advent of modern cable-tool drilling equipment in Europe in the early 19th century that made flowing wells common in the 19th century. In the textbook by Davis and De Weist (1966), it was pointed out that exploration of flowing wells in Europe in the 18th century was responsible for stimulating the advancement of water well drilling technology. In fact, flowing wells, which represent aBecause flowing wells are spectacular visual evidence natural phenomenon of deep groundwater occurrence, they became the impetus for both qualitative and quantitative, also instigated groundwater the science of groundwater. The pursuit of answers to fundamental questions generated by flowing wells in confined aquifers bounded by aquitards moved the science forward for more than a century since the early 19th century until pumping became the main form of groundwater development. Moreover, it is interesting that since the 1940sturn of 20th century, flowing wells in unconfined aquifers were an impetus for played a significant role on the new paradigm, i.e., a paradigm shift from aquitard-bound flowpiston flow in confined aquifers to cross-formational flow driven by topography in either homogeneous or heterogeneous basins.

Given ~~T~~the spectacular flowing wells in Paris and London in the early 19th century, ~~drew widespread attention to this most noticeable feature of groundwater, which was the early impetus behind the start of groundwater science in the mid 19th century. It~~it was not a coincidence that Darcy (1856) did his monumental laboratory experiments soon after he did pipe flow experiments prompted by flowing wells. He was followed by his colleague Dupuit (1863) to develop the hydraulics of steady flow to wells. The term “flowing well” was introduced by Chamberlain (1885) in his classic USGS report, which provided the first comprehensive explanation of flowing wells using hydrogeological principles. Based on field investigations of the Cambrian-Ordovician aquifer system in Wisconsin, he recognized the role of confining beds in creating flowing well conditions and also that these confining beds are leaky. This was followed soon after by the classic work by Darton (1897, 1905) who studied the regional Dakota aquifer. Meinzer and Hard (1925) and Meinzer (1928) deduced from declining discharge of flowing wells and excess of discharge over recharge that confined aquifers are elastic and have storage capability related to compressibility. This prompted Theis (1935) of the USGS to initiate ~~unsteady~~ transient state well hydraulics for non-leaky aquifers, although leakage recognized decades earlier set the stage for Hantush to pioneer the hydraulics of pumping wells and flowing wells in aquifers with leaky confining beds in the 1950s (Hantush and Jacob, 1955; Hantush, 1959).

The wide occurrence of regional scale confined aquifers showing ubiquitous flowing wells in sedimentary rocks in France, ~~England~~Britain, ~~and~~ the United States and Australia resulted in confined flow in aquifers being a broadly useful conceptualization. However, this resulted in the common misconception that flowing wells must occur in confined aquifers bounded by aquitards~~be geologically-controlled~~, and the confusion of the term “artesian”. ~~In his monumental treatise on the theory of groundwater motion,~~ Versluys (1930) and Hubbert (1940) realized flowing wells can occur in entirely unconfined and homogeneous conditions ~~based~~ controlled only by topography, which was ~~. Hubbert’s concepts of topographically-driven groundwater flow and topographically-controlled flowing wells were further developed~~supported by ~~Toth~~Tóth’s (1962, 1963, 1966) and Freeze and Witherspoon’s (1967) quantitative studies of topographically-driven groundwater flow systems~~and Meyboom (1962, 1966) in the Canadian Prairies~~. An introduction to confined-flow and unconfined-flow flowing wells has been included in the textbook by Freeze and Cherry (1979) and the quantitative analysis of topographically-driven groundwater flow systems has been considered to be a paradigm shift of modern hydrogeology (Bredehoeft, 2018;Madl-Szonyi, 2008;Tóth, 2005). –The misconception that flowing wells must occur in confined aquifers is still impeding the acceptance of the new paradigm, which is reflected by the limited number of textbooks introducing flowing wells in unconfined aquifers. Generally in the earth sciences it takes decades for the acceptance of the importance of a paradigm shift to achieve completeness when completeness is judged by the paradigm being the primary basis for teaching as manifested in what is included in textbooks and groundwater flow systems theory is no exception.Subsequent studies by Freeze and Witherspoon (1967) and Zhang et al. (2018b) found that several qualifying conditions of flowing wells proposed by Chamberlain (1885) are not necessary at all. Although the theory of topographically-driven groundwater flow systems has been considered to be a paradigm shift of modern hydrogeology (Bredehoeft, 2018;Madl-Szonyi, 2008;Tóth, 2005), the misconception that flowing wells must be geologically-controlled is still impeding the acceptance of the new paradigm. Moreover, many modern textbooks still have not fully clarified the differences and implications of the two types of flowing wells, geologically versus topographically controlled.

Although there have been great advances in how we think about groundwater flow systems and the current paradigm is well advanced, it is not yet comprehensive. Based on the summary of the role of flowing wells on in the evolution of many concepts and principles of groundwater hydrology, it is desirable that integrating the root of flowing wells into textbooks and courses of groundwater hydrology would inspire the interest of beginners, and also lead to a deeper understanding of the science of groundwater (Deming, 2016), as well as of the current paradigm shift of hydrogeology. Therefore, consistent terminology and a Avoidance of the term “artesian”, a complete description of confined-flow and purely unconfined-flow both types of flowing wells and their connections to evolution of hydrogeology are expected in future groundwater textbooks. Moreover, because purely confined-flow and purely unconfined-flow are two end members of groundwater flow, a generalized theory on the simultaneous control of aquitards and topography on the occurrence of flowing wells, the pattern of groundwater circulation and hydrogeochemical evolution is expected in future studies.

Although the number of flowing wells has decreased significantly since the 20th century, flowing wells still occur widely in many parts of the world and the overflow of some flowing wells have lasted for more than a century. The aquifer hydraulics behind the sustainability of flowing wells, i.e., coupling groundwater discharge in flowing wells to groundwater recharge from precipitation, deserve further research. Moreover, 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 of

~~flowing wells is expected in the future~~.~~–~~

Code/Data availability

Not apply to the review paper.

Author contribution

XJ and JC prepared the manuscript with contributions from LW.

Competing interests

The authors declare that they have no conflict of interest.

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