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PAPER

What is the Ghijben-Herzberg principle and who formulated it?

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Abstract

It has been suggested in a number of historical notes that it was neither Willem Badon Ghijben nor Alexander Herzberg who formulated the famous principle now carrying their name, which relates the water-table elevation to the depth of the freshwater–saltwater interface in coastal aquifers. In this paper, a systematic review of the literature pre-dating the publication of their work is presented. The aim is to establish to what extent these previous works captured the essence of the Ghijben-Herzberg principle, that is, the combination of a correct conceptual model of the hydrogeological conditions with a quantitative relationship. It was found that references to coastal fresh groundwater reserves can be traced back to Roman times, while the earliest detailed descriptions of a freshwater lens that could be found dates from the eighteenth century. The correct understanding of the hydrostatic equilibrium between fresh and salt groundwater is evident in works from the early nineteenth century. However, it was Badon Ghijben and Herzberg who combined this with the correct understanding of the groundwater conditions of a freshwater lens. It was further found that Herzberg had already recorded his findings in 1888 in a hand-written report, confirming speculation that such a report might exist.

Keywords Coastal aquifers · Groundwater density/viscosity · History of hydrogeology · Salt-water/fresh-water relations · Island hydrology

Introduction

The Ghijben-Herzberg principle relates the water-table elevation to the depth of the interface between freshwater and saltwater in a coastal aquifer. It has been named after Willem Badon Ghijben and Alexander Herzberg. Badon Ghijben was a Dutch military engineer, who was tasked with securing a source of freshwater for the defence works of the city of Amsterdam (Netherlands) to be used during times of emergency (De Vries 1994). Herzberg was a German engineer, who worked on the first central water supply on the island of Norderney, an important spa at the time, and some of the other northern German islands. Their papers (Drabbe and Badon Ghijben 1889; Herzberg 1901) are now among the most well-known in groundwater hydrology.

It has been pointed out in a number of historical notes though that it was neither Badon Ghijben nor Herzberg who were the first to formulate this relationship (Carlston 1963; Davis 1978). It was Carlston (1963) who attributed Joseph Du Commun (1828) for having been the first to recognise the principle. The Dutch mining engineer Johan Heinrich Steggewentz wrote in his PhD thesis on tidal oscillations in groundwater (Steggewentz 1933): "The principle of Badon Ghijben was not formulated by Badon Ghijben". This suggests that he also already knew of works predating Badon Ghijben's formulation, but in the remainder of his thesis, he does not elaborate further on the subject, leaving the reader in the dark about what he meant exactly.

However, a letter sent to the royal Prussian administration in Aurich, Germany, on 19 September 1912 by Alexander Herzberg shows that even he himself was involved in the debate about the discovery of the principle. He had been prompted to write the letter after he had been shown a pre-print of Konrad Keilhack's first edition of his book on

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groundwater and springs (Keilhack 1912), in which it was written that Badon Ghijben had formulated the relationship between freshwater and subsurface seawater in 1889 and that Herzberg had independently done so as well, but only 12 years later in his 1901 publication. In the letter he writes that, although he does not attribute a great significance to there being a mistake, he would like to establish his priority beyond any doubt. He asks the government to send him a copy of a report attached to the contract made in 1888 by his firm Börner & Co. about the expansion of the public water supply on the island of Norderney (Herzberg 1888). He had been unable to find the document in the firm's own archives, and Herzberg needed the addendum report to prove that he had already published the principle around the same time as Badon Ghijben.

Indeed, the report that he was referring to is present in the state archive of Lower Saxony in Aurich and was reviewed by the authors of this paper on December 13, 2017. It is a hand-written document in the "Kurrent" (German cursive) writing style, and is signed on behalf of Börner & Co. by A. Herzberg in May 1888. Badon Ghijben (and his army superior J. Drabbe) finished their publication in July 1887. In the second edition of his textbook (Keilhack 1917), a footnote is included on page 163 that dates Herzberg's report to 1886, so 2 years before Herzberg actually signed off on it but 1 year before Badon Ghijben. It is tempting to speculate that this might have been an act of patriotism, or it might have simply been a mistake, but in any case, it is clear that Herzberg and Badon Ghijben developed their ideas around virtually the same time.

In this paper, it will be demonstrated that the existence of freshwater lenses in aquifers and the hydrostatic equilibrium between freshwater and saltwater had already been documented in the scientific literature well before the year 1887 and even before Du Commun's publication in 1828. To solve the mystery as to who should be credited for the discovery of what has become known as the Ghijben-Herzberg principle, the first question to be answered is what the principle exactly entails. The ingenuity of the Drabbe and Badon Ghijben (1889) and Herzberg (1901) papers is that they combined conceptual understanding of the hydrogeological conditions of a freshwater lens, which cannot be seen by the human eye, with a quantitative, generalizable relationship between the elevation of the water table (h) and the depth of the interface below sea level (z):

$$z = \frac{\rho_{\mathrm{f}}}{\rho_{\mathrm{s}} - \rho_{\mathrm{f}}} h = \alpha h \quad (1)$$

where ρ_{f} is the density of freshwater, and ρ_{s} is the density of seawater. Using typical values for the densities of freshwater and seawater, the parameter α takes a value of around 40 in many coastal regions.

The objective of this paper is to determine if there are any works prior to the now-famous publications by Badon Ghijben and Herzberg that combine these two elements—that is, the correct conceptual model in combination with the quantitative expression. Parallel to this paper, annotated English translations of the original Drabbe and Badon Ghijben (1889) and Herzberg 1901 papers have been published in this issue of *Hydrogeology Journal* (Houben 2018; Post 2018), which are intended to give a larger readership access to these classical and often-cited (but perhaps not as often-read) works.

Earliest works

There is no doubt that humans dwelling along the coast knew of fresh groundwater long before it became documented. Davis (1978) argued that Pliny the Elder should be credited for the discovery of the hydrostatic equilibrium between freshwater and seawater. However, when consulting the English translation of Pliny's natural history (Bostock and Riley 1893), it is clear that Pliny was referring to freshwater which emerged from springs and apparently persisted as a layer on the sea surface. Badon Ghijben and Herzberg specifically studied subsurface freshwater.

Also dating back to ancient times (around 40 BC), Caesar's *De Bello Alexandrino* (On the Alexalndrine War) might be the first written account of coastal fresh groundwater reserves. The story accounts how the Alexandrian commander Ganymedes ordered his men to divert seawater into the canals of the city (of Alexandria) to contaminate the drinking water resources in the downstream quarters that were occupied by Caesar's troops. When fear broke out, Caesar reassured his men by declaring that: "Nam puteis fossis aquam dulce posse reperiri affirmabat: omnia enim littora naturaliter aquae dulcis venas habere.", which in English reads (paraphrased from Way 1955):

> "He confirmed that freshwater can be found in wells and trenches, inasmuch all seashores naturally possess veins of freshwater."

The account then continues as follows (paraphrased from Way 1955):

> "Whereupon, the business being once undertaken with unanimous enthusiasm for the task, in the course of that one night, a great quantity of freshwater was discovered. Thus the laborious machinations and supreme efforts of the Alexandrians were countered by a few hours' work."

Caesar's work was known by later scholars. It is cited, for example in the Dutch textbook by Lulofs (1750) on the physical geography of the Earth, and by le Francq van Berkhey (1769–1771) in his book on the natural history of Holland. The origins of fresh groundwater were then still debated. A view still established at the time was that fresh springs and rivers could originate from seawater. This idea can be traced back to Greek philosophers like Thales (ca. 624–546 BC) and Hippon (ca. 450 BC) who had postulated that the ocean extended under the land, and that fresh springs and rivers formed as steam from evaporating underground seawater rose to the surface and condensed (Brutsaert 2005; Diels 1891). Another theory was that seawater could lose its salt by filtration by the soil, which appears in "De rerum natura" by the Roman philosopher and poet Lucretius (99 BC to ca. 55 BC). The following passage is from the first English translation of the work (Johnson 1872):

> "And thus the atoms that embrine the sea
> May from its liquid elements be strained,
> The fluent waters, percolating earth,
> Rise sweet and freshened in the sandy trench,
> Its acrid salts involved and left behind."

le Francq van Berkhey (1769–1771) did not dispute Lucretius, but in his book he weighed it against an alternative theory by Jean-Baptiste Labat (Labat 1724). This French clergyman and scientist published a remarkable description of a veneer of freshwater overlying saltwater in his account of his journey across the Caribbean. In 1705 he visited L'Ile d'Aves, today known by the name of Isla Aves (Spanish for Island of Birds; Fig. 1), which is part of a group of islands in the Caribbean Sea known as the Federal Dependencies of Venezuela. The rocky islet has no surface water except for some pools of brackish water.

Labat (1724) gives an account of ways to find freshwater, and makes the point that people that would die of thirst on such a location are "truly simple-minded" because one can find water for drinking everywhere. The key is, Labat continues, to find a place that sticks out 5 or 6 ft (feet refers to the French "pied de roi", measuring approximately 32.5 cm) above the point where large waves no longer reach, and one does not need to dig deeper than 10 or 12 "pouces" (a pouce is one-twelfth of a pied de roi) to find water. It will be "perfectly fresh" and especially if one has the patience to let any sand settle one will have "beautiful and good water". He warns though that the wells dug this way will not last for a long time, because "…in less than a quarter of an hour, one will see the water rise and become salty at the same time."

He then continues to provide a physical explanation for his observations (Labat 1724):

> "The physicists will immediately see the reasons for the change that this water experiences, but because we are not all physicists, one has to explain it to those that do not know, after having assured them, that what I am advocating here is not metaphysical speculation, but a real and constant fact, which I have experienced multiple times.
> Everyone knows that fresh water is much lighter than seawater, because the latter is charged with foreign particles, which are not found in the former. … The rainwater that passes through the sand onto which it has fallen, will encounter saltwater, and will easily float on top of it, because it is much less heavy, and at the same time this lightness prevents it from mixing, it is clear that it has to maintain its freshness. … when one has taken out the freshwater, the water that is salty will rise soon, to take the place occupied by the freshwater, and in that way restore the equilibrium, and the level that has to exist between it and the surface of the sea."

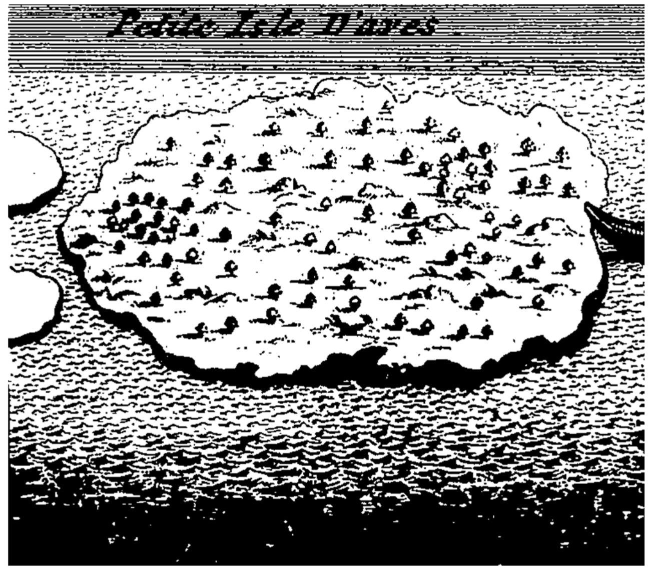

Fig. 1 Labat's depiction of Isla Aves (Labat 1724). No groundwater features are shown

He ends his account by saying that if the castaway Serrano, who allegedly survived 8 years on a small island without water, "… had known about this secret, he would not have had so much trouble surviving on his rock, and would not have to have drunk turtle blood to quench his thirst." He thus mixes empirical observations and physical explanations with witty remarks. His book *Nouveau voyage aux isles de l'Amérique* became very popular but was never translated into English. This is probably the reason that this accurate conceptualisation of a fresh–saltwater groundwater system, albeit qualitative still, has remained unnoticed for such a long time.

An early account from the English literature was published by Page (1784). He described how a well was sunk to a depth of 12 ft at Landguard Fort on the coast of England (UK) near Ipswich in the year 1782, and how he was surprised that at depth it still contained freshwater. Given the closeness to the sea, Page (1784) did not expect to find any fresh groundwater at all. With some effort the hole was dug down to a depth of 16 ft, corresponding to the lowest level at spring low-tide. There the water became saline, and the bottom part of the well was backfilled to 12 ft, after which it successfully produced freshwater. Page (1784) contended that seawater will penetrate a certain distance inland from the coast at depths below the low-tide mark, and that above this level the water is in constant motion depending on the rise and fall of the tides. He then writes:

> "It is probably not so easy to account for a body of freshwater being to the depth of twelve feet in the sand, and in the same line, a few feet deeper, the water should be entirely salt, and that they do not mix together. Whether the greater specific gravity of the saltwater is sufficient to prevent a mixture with the fresh upon a higher line, I cannot venture to say; but the fact of there being a separation is beyond a doubt, and the depths may be ascertained to a great degree of accuracy."

It is difficult to infer from these lines how well Page (1784) understood the pressure equilibrium between freshwater and saltwater, but he deserves recognition for his description of an interface and the mention of the possible role of the saltwater's higher specific gravity (Mather 2012).

The nineteenth century

A few decades later John Storer and Gavin Inglis were engaged in a scientific discourse (Inglis 1817; Storer 1815, 1817) about a well that had been drilled in the harbour of Bridlington, along the Yorkshire coast of England. This well was known to provide an artesian supply of freshwater at high tide, and started flowing when the seawater rose to a level of 49–50 in below the top of the well. Based on the synchronicity between the well flow and the sea tide, Storer (1815) contended that:

> "The appearances seem not to admit of any satisfactory explanation, without supposing some mode of subterranean communication, by which the water of the sea, and that of the spring in question, are brought into actual contact, so as to exert a reciprocal action."

More support for this assertion came from the fact that the well discharge became more erratic during heavy storms when there was strong wave action. Storer (1815) supposed that the freshwater in the harbour extended offshore below a clay layer and discharged further out from the coast where the seafloor dropped off and the rock below the clay layer was in direct contact with the sea. His thinking was that groundwater discharge would more difficult during high tide, thus causing a rise of the water level on land. His correct understanding of the hydrostatic equilibrium between fresh and saltwater is reflected by the sentence:

> "… the issue of a body of fresh water, through a fissure in rock forming the bed of the sea, would meet with more or less resistance at different times of the tide; because the two columns of fluid in meeting, would act upon one another in the ratio of the altitude of each, taking into the account the difference of their specific gravity; and thus, if there is any approach to an equilibrium, an operation would result, analogous to the flux and reflux of the tide, near the mouth of rivers."

Inglis (1817) contested the interpretation by Storer (1815) and argued that the specific gravity of seawater was not enough to produce a column of freshwater rising high above the level of the sea to explain the observations.

> "I beg leave to differ from the Doctor in supposing the rise of the fresh water above the level of the tide to proceed from these waters coming into actual contact, upon the principle of two liquids of different specific gravities in an inverted syphon. … The well-known specific gravity of the German Ocean does not so far exceed that of pure spring water as to equal a column of 49 to 50 inches of superior altitude"

Inglis (1817) noted that the clay layer extending below the seafloor would not be a rigid stratum, but that it would compress and stretch depending on the pressure exerted by the seawater above. This, Inglis (1817) reasoned, was the reason for the observed fluctuations of the water levels in the well. In that sense, he already acknowledged the role of elastic storage changes in the interpretation of tidal pressure propagation in aquifers well before the publication of the classical paper by Jacob (1940).

The analogy of the inverted siphon (Fig. 2) used by Inglis (1817) was also used by Du Commun (1828). As was pointed out by Carlston (1963), the calculation described by Du Commun (1828) is essentially an expression of the formula for the hydrostatic equilibrium written in words rather than as an equation. Indeed, he should therefore be credited for this, although Inglis (1817) estimate of the maximum freshwater column height could have been attributed a similar status if he had been more explicit about how he calculated the reported figure. Du Commun (1828) correctly formulated the hydrostatic equilibrium between fresh- and saltwater, but the implications that he perceived are clearly incorrect:

> "…it follows, that if the junction of the two different kinds of water should take place at five thousand feet, or one mile, below the surface, the fresh water should

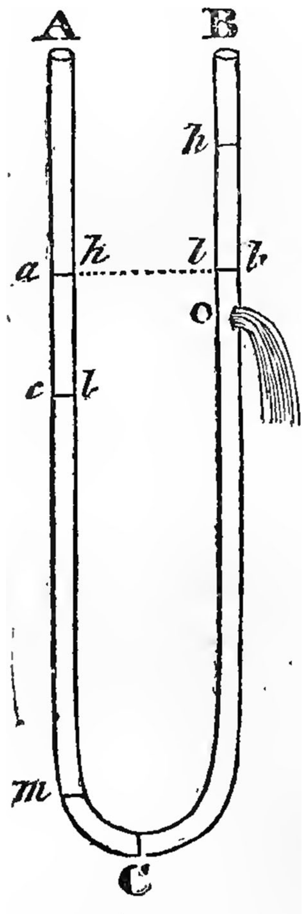

Fig. 2 The inverted siphon as pictured by Du Commun (1828)

rise at one hundred and fifty feet; if at fifty thousand feet, or ten miles, as one thousand five hundred feet, &c. This I think may account for the springs on high ground, and even at the top of insulated mountains."

In other words, Du Commun (1828) attributes the higher level of freshwater on land to the counter pressure exerted by the column of seawater, meaning that he mixed up the cause and effect of this phenomenon. The correct view is that the recharge causes a water table above sea level. The pressure generated by the water column rising above sea level is what determines the position of the intruded seawater.

Yet another scholar who used the analogy of an inverted siphon was the French military geographer and geologist Émile Le Puillon de Boblaye, who visited the Peloponnesus peninsula in Greece in 1829 and was struck by the numerous coastal springs that always appeared to occur at the same elevation above sea level (Boblaye 1833). He attributed this to the counter-pressure exerted by the higher-density seawater. He found evidence for this assertion in a lake named Ino:

"It is a circular hole with a diameter of 12 to 15 feet, right in the middle of a dense limestone, which, like everywhere in the Peloponnesus, is fractured and tilted. The distance to the sea is no more than 300 to 450 feet, and its height over it a mere 6 feet. Although its depth is unknown (within 90 feet the bottom could not be reached), it is filled to the rim with a hardly brackish water during all seasons of the year. Thus it seems as if the lake can be held for the one arm of an inverted siphon, of which the other one has its opening beneath the sea, at a depth, which, according to the density differences between saline and fresh water, and according to the height of the lake of 6 feet, measures 231 feet."

From these numbers he seems to have assumed a value for α (Eq. 1) of ca. 38. The analogy between this description and that by Du Commun (1828) is remarkable. This quantitative expression of the hydrostatic equilibrium between freshwater and seawater also found its way into German textbooks. In his book on chemical and physical geology, Bischof (1847) included the description by Boblaye (1833), which means that the hydrostatic principle applied to fresh- and salt groundwater was part of the mainstream scientific literature in Germany by the mid-nineteenth century.

Herzberg seems to have been unaware of the Bischof (1847) textbook, which is perhaps not surprising, given that he was trained as a building engineer, and not as a geologist. As his letter to the Prussian government in Aurich already showed, he was convinced that he was the first to have formulated the principle in his 1888 report. The report contains a sketch of a freshwater lens (Fig. 3), and the famous equation that relates the water-table elevation to the thickness of the lens. This shows that Herzberg had discovered the principle in his previous work on the German islands and was actively using it to predict the thickness of freshwater lenses. In fact, Herzberg's conceptual model of a lens of freshwater floating on saline groundwater was in the public domain in 1890 or even earlier, as a communication in the *Journal für Gasbeleuchtung und Wasserversorgung* from that year summarised a talk on his findings on Norderney that Herzberg delivered, in the words of the author, "some time ago" (Anonymous 1890).

Just like Herzberg could in principle have read about the hydrostatic equilibrium in German textbooks, Badon-Ghijben could have learned about Labat's observations through the books of Lulofs (1750) and le Francq van Berkhey (1769–1771). In fact, the latter book was directly relevant for Badon Ghijben as it also discussed the salinity of the groundwater in Amsterdam and its surroundings. After all, Badon Ghijben was tasked with finding fresh groundwater and he provided an extensive review of the available data at the time (Drabbe and Badon Ghijben 1889). In any case, Badon Ghijben himself felt that his equation was not at all groundbreaking. During a discussion that followed after a presentation by Pennink (1904) in which Ribbius took exception to the

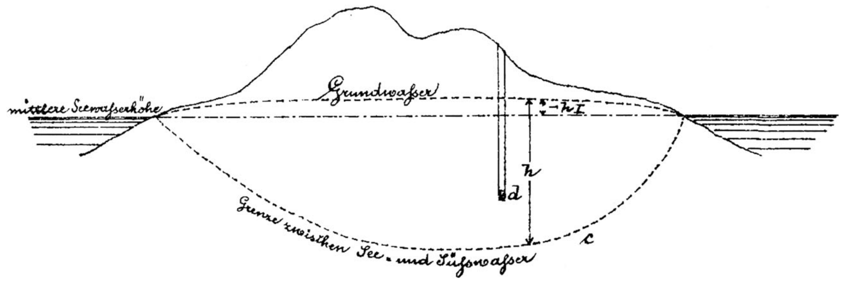

Fig. 3 Sketch from the Herzberg (1888) report. "Mittlere Seewasserhöhe" (mean sea level), Grundwasser (groundwater), Grenze zwischen See- und Süßwasser (boundary between sea and freshwater)

fact that Pennink spoke of the "theory of Herzberg" (see also Ribbius 1903), Badon Ghijben responded to the accolades he received by saying:

> "When I wrote those sentences, it did not cross my mind for a moment, that I was announcing something new. On the contrary, I believe that the matter is as clear as a day, and that all we have to do is remember the simple physics lessons, which dealt with the law of communicating vessels."

A footnote in the original article actually alludes to the fact that Badon Ghijben based his thinking on the analogy with seawater that intruded into locks in rivers in contact with the sea, which had been studied by Conrad (1881). Based on this analogy Badon Ghijben correctly inferred that part of the freshwater beneath the coastal dunes flowed out to sea, and that part of it flowed inland to the low-lying polder area where water levels were maintained at a lower elevation than that of the water table in the dunes. He also recognised that seawater must be flowing inland beneath the freshwater lens. It is not entirely clear how Badon Ghijben pictured the shape of the freshwater body, as he did not include a sketch of the freshwater lens like Herzberg did. Nor did he have water table or salinity measurements from the dunes at his disposal, but it is clear that he understood how the principle could be used in a predictive sense to estimate the depth of the fresh–saltwater interface.

After 1888

A noteworthy footnote appeared in the minutes of a lecture by the German philosopher Hermann Alexander Diels delivered at a meeting of the Royal Prussian Academy of Sciences in Berlin in June 1891. In discussing the Greek ideas about the origin of freshwater springs, he quoted a certain Mr. Möbius, who recounted from his personal experience (Diels 1891):

> "It is an old observation that beach dwellers of the western Baltic Sea area that the water in their wells rises with the seawater when there are easterly winds and falls with westerly winds, which push the seawater away from the coast. This phenomenon is easy to explain. The freshwater column of the beach well and the saltwater on the coast are related to each other like the water columns of communicating tubes. The connection between the two is mediated by the groundwater of the beach. The well water is pushed back by the rising seawater and is therefore lifted up. The heavier seawater stays beneath the lighter freshwater and is flushed back into the sea by it as soon as the sea level falls."

There appears to be no connection to Herzberg, but the timing of this publication is certainly interesting.

And just as Badon Ghijben and Herzberg were not the first to develop ideas about the relationship between fresh and saline groundwater, they were also not the last. Palmer (1957) recounts of Professor Carl Andrews: in Hawaii who, unaware of the publications by Drabbe and Badon Ghijben (1889) and Herzberg (1901), worked out the quantitative equilibrium relationship between fresh and saline groundwater in his Master's thesis (see also Wentworth 1951). The idea that freshwater and seawater exerted a pressure on each other came from Arthur D. Alexander, but the mathematical relationship between the elevation of the water table and the depth of the interface was Andrew's (Palmer 1957).

Concluding remarks

Davis (1978) argued that the Ghijben-Herzberg principle was a historical misnomer, because others had formulated the hydrostatic pressure equilibrium before them. Indeed, several authors expressed a correct understanding of the freshwater–seawater relation in coastal aquifers. The eighteenth century description by Labat (1724) is likely the first to include the correct physical interpretation of lenses of fresh groundwater, but does not yet cast it in quantitative terms. This was provided during the nineteenth century by Du Commun (1828) and Boblaye (1833), or perhaps even Storer (1815) and Inglis (1817), yet none of these authors made the connection with the shape of a freshwater lens.

It is to the credit of Badon Ghijben and Herzberg that they combined the quantitative hydrostatic equilibrium relationship with a correct conceptual understanding. This provided a generic theory that could be used and was adopted quickly elsewhere. Perhaps Herzberg deserves more credit than Badon Ghijben because he provided more detail in his report, such as a sketch that clearly illustrates the lens shape and a comparison between the predicted and observed thickness of the lens. These elements are missing from Badon Ghijben's work, but it is clear that he understood that the pressure exerted by the column of freshwater above sea level determined the depth to the saltwater, and not the other way around like Du Commun put forward. It therefore seems safe to keep referring to the Ghijben-Herzberg principle, at least until the next historical note uncovers previously unknown works from before their day.

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