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Salinity management in the coastal region of the Netherlands: A historical perspective

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ABSTRACT

In coastal regions of the Netherlands, various aspects of salinity were recognized and dealt with throughout history: causes of salinization and sodification, desalinization, soil structure deterioration and rehabilitation, crop salt tolerance/intolerance, and soil and crop management. Originally, experience of water managers and farmers formed the basis. From 1850 onward, first mainly chemical analysis, later combined with physico-chemical concepts, and still later also analyses of flow and transport processes, and plant physiology were used to transform traditional opinions into scientific understanding. In the 20th century, salinization and sodification arose from natural floods (1906, 1916, 1953) and strategic wartime inundations (1939/1940, 1944/1945), and in the context of creation of the Zuiderzee Works and the Delta Works. J.M. van Bemmelen (1830–1911) pioneered diagnosis of salinity and the study of acid sulfate soils, while D.J. Hissink (1874–1956) understood sodicity and promoted application of gypsum. These early studies were amplified, respectively, by C. Nobel and S. Smeding on monitoring salinity, by A.J. Zuur and B. Verhoeven on desalinization, by W.H. van der Molen and G.H. Bolt on ion exchange, and by K. Zijlstra and C. van den Berg on salinity tolerance/intolerance. In the period 1923–1940, the civil engineer J.P. Mazure studied seepage from saline open water into lower lying land and diffusion and convection of salts into and out of lake bottoms.

1. Introduction

It is a great pleasure to be able to contribute to the AGWAT special issue honoring Dr. James D. Oster.

Jim's initial research experience in the early sixties at Purdue University, under the guidance of the soil physical-chemist Philip F. Low, laid a solid base for his career. In 1965 he moved to Riverside, where soil scientists, plant physiologists, and agricultural engineers were taking the pressing problems of irrigation agriculture very seriously. He effectively operated at the border of soil physics and soil chemistry, thereby leaning toward the chemistry. In the early part of his career he bravely faced the difficult problems of conceptualization, modeling, and measurement, while more recently the emphasis has been on drawing and advocating conclusions of relevance to practice, both regarding agricultural productivity and environmental norms. I got to know Jim in his period of transition from pure scientist to expert in irrigated agriculture. In the years 1973–1976 at the US Salinity Laboratory, I found him of great help in identifying problems in saline plant root zones worth tackling. Moreover, our families had and still have pleasant contacts.

In this paper, I will show that the early contributors to salinity research in the Netherlands shared with Jim Oster a keen interest in applying sound principles and methods to problems of practical agriculture. The salinity problems in the humid, coastal region of the Netherlands arise from seawater flooding or intrusion. In many respects the problems are quite different from those in the semi-arid south-western USA, where Jim has been active. Yet the same scientific principles can be used to understand and deal with the problems.

North Sea water contains of the order of 35 g of salt per kg, of which about 19 g per kg is chloride; it is high in Na^+, Mg^{2-}, Cl^- and SO_4^{2-}, and low in K^+ and Ca^{2+}. The high salt concentration, and thus low osmotic potential, limits the availability of the water. Flooding by seawater causes displacement of Ca from the soil adsorption complex by Na. After leaching of the salt by rainfall or irrigation, the combination of a high fraction Na in the adsorption complex and the low salt concentration leaves the soil vulnerable to slaking. In other words, normally the availability of the water is restored quite rapidly, but if proper measures are not taken, the

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problematic soil structure may last for years. Both aspects were recognized throughout history, at first vaguely, but from the late 19th century onward very clearly.

Following a historical overview of salinity problems in the Netherlands in Section 2, I will discuss in Sections 3 and 4 the early research concerning the two main problems. Response to salinity by crops and vegetations will be considered in Section 5. The emphasis will be on developments till about 1960, around the time both Jim and I got started in soil science.

2. History of salinity problems

There must be another strange secret hidden in salt. It is not only in our tears but also in the sea.
Poet/artist Khalil Gibran (1863–1931)

2.1. Rising sea levels during the Holocene

Living conditions in the coastal area during the Holocene have received much attention recently (Vos et al., 2011; Bazelmans et al., 2012; Nieuwhof, 2010). Despite occasional storm floods, the tidal flats appear to have been densely inhabited. Archeologists originally believed that import of food from higher ground was the basis for living there, but gradually they are learning that local growing of crops and animal husbandry were widely practiced (Cappers and Raemaekers, 2008). Probably overpopulation, poor drainage, and loss of soil fertility were the reasons to leave the higher ground and settle on the fertile tidal flats. Archeologists have shown experimentally that crops can be grown on the sandy clays located at the highest points of the salt marsh (Körber-Grohne, 1967; Van Zeist, 1974; Van Zeist et al., 1976; Bottema et al., 1980), although the risk of crop failures may have been high, especially in the stages of germination and full grown crop. To protect people and animals from floods, dwelling mounds, called 'wierde' in the province Groningen and 'terp' in the province Friesland, were built. To protect cropped fields, dikes were built already much earlier than was believed till recently. Remains of dikes in the 'terps' at Peins-Oost and Dongium-Heringa in NE Friesland have been dated, respectively, 1st century BC and 2nd century AD (Bazelmans, 2005; Bazelmans et al., 2012).

Using dikes to create new farm land evolved over the centuries. St-Annaland is a small village on the island Tholen in the province Zeeland. In the poem 'History of St-Annaland', the Dutch poet, diplomat, gentleman farmer Jacob Cats (1577–1660) described how farms expanded:

Siet, aenwas is een dingh, dat sonder ons gevoelen
Komt stijgen uijt de see en aen den oever spoelen.
Al schijnt het eerst maer sant en niet dan enckel blick,
Het neemt gedurigh toe en wert ten lesten slick.
En daerna wast er gras; een stel van hondert schapen,
Die kander naderhant haer noodigh voetsel raepen,
Totdat het op het lest verandert sijnen naem
En even mettertijt tot dijcken is bequaem.

This poem describes the sedimentation along the coast causing potentially new land to rise out of the sea, first mere sand, then on top of that more valuable mud, on which grass begins to grow, providing feed for a flock of a hundred sheep, and finally it changes its name to 'schor' (=marshland) and is ready for embankment. This method of acquiring new farm land was abandoned in the mid-20th century when the requirements for the outer dikes became so stringent that it was no longer practical to move farther outward several times in a century.

While the sea level was rising, fresh groundwater from melting polar ice caps and precipitation was overrun by saline groundwater from tidal and storm flooding. Thereby, the accumulated fresh groundwater was often spoiled by unstable penetration of saline groundwater, a process that is much faster than diffusion. However in recent decades, it became also clear that in many coastal regions around the world, both below the land and the sea bottom, fresh groundwater was in many places protected by layers with low permeability (Post et al., 2000, 2013). Variable density induced effects in flow of groundwater were pioneered in the Netherlands by Badon Ghyben (1889) and Lorentz (1913). They are not further considered in this paper.

2.2. Storm floods

There was not only gain of new land, but also loss as a result of storm floods and strategic wartime inundations (see Section 2.4). A series of large floods, starting with All Saint's Flood in 1170 and ending with St. Lucia's Flood (Great Storm in the UK) in 1287, caused large changes in the coastal regions of the Netherlands, among them the start of the transition of Lake Flevo or Almere to the Zuiderzee. The Chronicle of Wittewierum is an impressive historical document of life in the northern, coastal region of the Netherlands in the 13th century (Jansen and Janse, 1991). It was written by two successive Abbots of the Premonstratensian (Norbertiner) Bloemhof Abbey at Wittewierum, a still existing hamlet about 20 km northeast of the city of Groningen. In particular the second Abbot, named Menko, describes in detail the living conditions. The impact of a series of storms in the winter 1248/1249 is described by him as follows (Jansen and Janse, 1991; pp. 376–377, text in Latin and Dutch; the following is my translation from the Dutch text):

Since this punishment came toward the end of the winter [the last of a series of storms, in early February 1249], the water, that had risen higher and higher, receded only slowly and in the lower lying areas one could hardly plow around St. Ludgers Day [March 26]; yet the soil was then, by the action of the salt and the frosty nights that made the soil sturdy, easy to till and looked fertile. The farmers were pleased that their work was eased by the looseness of the soil, and almost everywhere more was planted than normally. O, blindness and ignorance of the human race, that by its supposed knowledge and shrewdness ends up in a trap set by itself. For if less had been plowed and planted, one would have saved the seed and then it would have well served the sustenance of the people. The animals, tired from all the work, were devalued; if they had been spared in the spring, the revenue of the sale and the wasted seed would have contributed a lot to the sustenance of the people. The seed that was planted at first nicely showed its first leaves, but in essence it was barren; it did not have living sap but rather withering salt. The more the sun was shining, the more the salt came to the surface, and as a result for the people both the seed and the efforts got lost, thus increasing their punishment. Because of the lack of grass, some sent their livestock to Drenthe or elsewhere to find food. For increased punishment, much of the livestock died. And there was no place where anyone could escape God's punishment, according to the word: 'If I ascend into heaven, Thou art there; if I descend into hell, Thou art present, etc.' (Psalm 138.8-vulgate).

Indeed, a very clear diagnosis and a threat of severe punishment for those who act irresponsibly! The diagnosis nearly matches accounts of the damage to crops and soil structure about 500 years later by Ponse (1808). In 1793 Hendrik Ponse, farmer at Geervliet and member of the regional agricultural committee, sent a response to a querie to the 'Oekonomische Tak van de Maatschappij der Wetenschappen binnen Haarlem [Oeconomic Branch of the Society of Sciences at Haarlem]'. He related experiences with desalinization, crop response, and farm management following a 1776 storm flood. He got little response, but following a 1808 storm flood he

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Table 1
Hectares flooded in the major storm floods in the period 1877–1953.

Year	1877	1881	1883	1889	1894	1906	1911	1916	1953
Groningen	2768		400						
Friesland	1321					1200		3015	
Overijssel	28,745	12,110	15,560	9955	7910	11,885		7557	
Gelderland	17,400	13,000	15,000	14,000	1150	5200		14,600	
Utrecht	7800	8060	7000	7235	7800	3390	547	9750	
North-Holland	230				20			17,765	[a]250
South-Holland	2715	2394	3074	3622	7670	830	2292	3445	53,488
Zeeland	300		35	70	330	4750	410		37,094
North Brabant	7600	7500	8000	7720	5700	10,085	8035	12,610	45,680
Total	68,879	43,064	49,069	42,902	30,580	37,340	11,284	68,742	136,512

[a] On the wadden island Texel.

was advised to publish his report. The resulting 33-page pamphlet (Ponse, 1808) started with a 16-page introduction by Geervliet Clergyman J. van Lokhorst and ended with a 4-page affirmation by fellow-farmers Arij Hoogendijk and Pieter Verwal. Presumably encouraged by the response to this pamphlet, 17 years later Ponse published the pamphlet 'Instructions for farmers whose lands by the storm flood on 3rd, 4th and 5th February 1825 were inundated with salt water: in order to restore the lands by the least costly means to their former fertility or at least to avoid using the wrong means for repair' (in Dutch).

Usually it was a particular storm or wartime inundation that motivated new civil engineering and agricultural projects, and related research, including soil salinity research. Table 1 shows the hectares flooded in the major storm floods in the period 1877–1953 (Anon., 1961):

- Those in Groningen, and part of those in Friesland, were in polders bordering the Wadden Sea in the north. Generally in that region the response was to make the dikes higher and stronger. Traditionally, when sedimentation near the outer dike had advanced far enough, a new polder was reclaimed by building a new dike farther outward. But, as pointed out already in Section 2.1, with the modern safety standards for the outer dikes this is no longer practical.
- The others in Friesland and those in Overijssel, Gelderland, Utrecht, and North-Holland were along the coasts of the former Zuiderzee (except the one in 1953 at the wadden island Texel): these floods motivated the Zuiderzee Works (1920–1975) discussed in Section 2.3 below.
- Those in South-Holland, Zeeland and North-Brabant were in the south-western delta: these floods motivated the Delta Works (1958–1997) discussed in Section 2.5 below.

Since the middle of the 19th century, the Dutch have had the ambition to shorten the North Sea coast and thereby reduce the risk of floods and the costs of building and maintaining dikes. The 20th century Zuiderzee and Delta Works were important steps in that direction. It is also only after 1850 that the first steps were taken to transform traditional opinions about causes, consequences and remedies of soil salinity into scientific understanding. As usual, the key contributions were made by exceptional individuals. I like to introduce three of them.

The agricultural chemist Adolf Eduard Mayer (1843–1942) was born, grew up, and was educated in Germany. In 1876 he became Professor of Agricultural Chemistry and Technology and Director of the Agricultural Experiment Station at Wageningen. He is most known for his early work on tobacco mosaic disease, which, together with later work by Iwanowski and Beijerinck, led to the discovery of viruses. Following the 1877 storm flood, Mayer (1877) followed desalinization in the field. He also studied the effect of salinization and subsequent leaching with fresh water on the hydraulic conductivity in the laboratory (Mayer, 1879). To his surprise, he found that deterioration of soil structure was not a direct, immediate consequence of salinization, but occurred in the phase of desalinization (see Section 4.1). Till then it was commonly believed that damage to soil structure occurred during flooding.

Jakob Maarten van Bemmelen (1830–1911) studied chemistry at Leiden, where in 1854 he was awarded a doctorate degree on styptic substances, that can be extracted from the tree fern *Cibotium cumingii* (Lorentz, 1911). In the period 1852–1860, as assistant of Petrus Jan van Kerckhoff (1813–1876), Professor of Chemistry at Groningen, he became involved in chemical analysis of soil samples. Van Bemmelen (1863) showed that the calcium carbonate content of the soils in the Dollard region in north-east Groningen decreased with the age of the polders. In a description of the harmful consequences of possible strategic inundations by seawater (see Section 2.4) in the province of Groningen, he drew inspiration from experiences following the 1825 and 1863 storm floods (Van Bemmelen, 1874). In the 1870s, he also became involved in the analysis of samples of soils and lake bottoms in the western part of the Netherlands. After more than 10 years of combining research in soil chemistry with teaching and administrative positions in secondary schools, in 1874 he was appointed Professor of Inorganic Chemistry at Leiden. Motivated by the 1825 and 1877 storm floods and the need for more fertile farmland, in the late 19th century numerous plans were put forward to tame the Zuiderzee. Van Bemmelen (1880, 1886, 1890) used his experience from Groningen to analyze samples from the bottom of the Zuiderzee and thereby got a first impression of the nature of the soils of the future Zuiderzee polders (see Section 2.3). He paid much attention to the presence of gypsum and iron sulfides, which may lead to acid sulfate soils if these sediments are drained.

David Jacobus Hissink (1874–1956) was the chief organizer of pre-World War II soil salinity research in the Netherlands. In 1899 he received a doctoral degree in physical chemistry at the University of Amsterdam, with a thesis on compound crystals of sodium nitrate and potassium nitrate and of sodium nitrate and silver nitrate. He started his career as chemist working on Delhi tobacco at 's Lands Plantentuin (the Botanical Garden) at Buitenzorg, now Bogor, Indonesia (1899–1903). Later in the Netherlands he held successive positions at State Agricultural Research Stations (SARS): as soil scientist and from 12 January 1904 as Director at Goes in the province of Zeeland (1903–1907); as Director at Wageningen (1907–1916); as Director of the Department of Soil Science (1916–1926), later Institute of Soil Science (1926–1939), at Groningen.

Following up on the pioneering studies of van Bemmelen, Hissink monitored and interpreted the consequences of the March 1906 storm flood in the province Zeeland (Hissink, 1907a). Already in June 1906 he published a literature review of the chemical and physical effects of salt water on the soil (Hissink, 1906). This early experience with salinity caused by flooding by seawater became a

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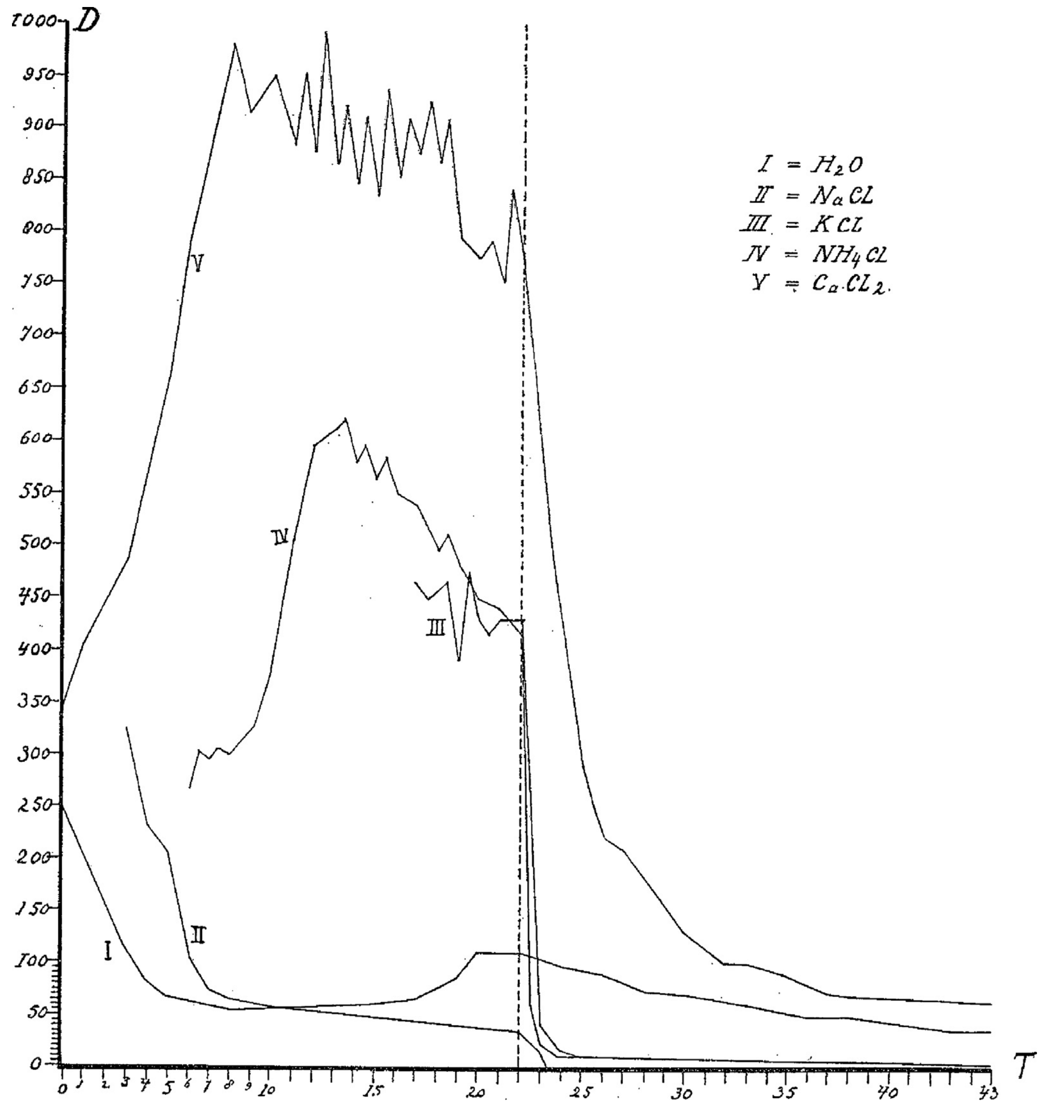

Fig. 1. The influence of different salt solutions on the permeability of the soil (Hissink, 1907b). *T* on the horizontal axis is time in days. *D* on the vertical axes is amount of fluid in grams per day flowing through a standardized column of soil. Before *T* = 22 different columns are percolated by different fluids, after *T* = 22 all columns are percolated with distilled water.
Source: Figure in Hissink (1907b).

lifelong interest. Hissink (1907a) realized that ion exchange might be the key to understanding the cause of the damage and finding means of remediation. He immediately started to experiment with leaching of soil columns by different aqueous solutions (Hissink, 1907b): see Fig. 1. A visit in June 1908 with R. Gans, Director of the Laboratorium für Bodenkunde der Königl.-Preuss. Geol. Landesanstalt at Berlin, convinced him further that ion exchange was the key process in salinization and desalinization (Hissink, 1909). Gans was studying the ion exchange in artificial zeolites, in relation to their use in water purification. Evidently, Hissink was not aware of Mayer's 1879 paper, until Zuur drew his attention to it nearly half a century later (Hissink, 1954).

2.3. Zuiderzee works 1920–1975

In the area of the current IJsselmeer (Lake IJssel) and the Flevopolders, in Roman times was found the fresh-water Flevomeer (Lake Flevo), later known as Almere. In the Middle Ages, the inland lake gradually evolved into the Zuiderzee, which stood in open connection with the North Sea. Up to about 1600 the Zuiderzee was only slightly brackish and it is reasonable, following Volker and Van der Molen (1991), to take the year 1638 as the starting point of the salinization of the sediments of the Zuiderzee.

The 1916 Zuiderzee Storm Flood led to an intensive monitoring of the salinity status of the Waterland and Anna Paulowna polders in North Holland by agricultural engineers C. Nobel and Sikke Smeding (1889–1967) (Smeding, 1919–1920, 1921; Nobel, 1921). The *A*-, *B*-, and *C*-values introduced by Nobel (1921) and Smeding (1921) to describe, respectively, the water content, the salt content, and the salt concentration became standard in the Dutch literature: see Section 3.2. Nobel was head of the extension service in North Holland and the first Director (1896–1917) of the Agricultural Winter School at Schagen. Smeding started as his deputy and succeeded him in 1917. About ten years later, the development of the Flevopolders became the focus for the rest of Smeding's career.

The 1916 Zuiderzee Storm Flood led parliament in 1918, after some delay due to the First World War (1914–1918), to approve the plan for the Zuiderzee Works drawn up by civil engineer and politician Cornelis Lely (1854–1929). Fig. 2 gives an overview of the Zuiderzee Works (ZZW), consisting of the Afsluitdijk (1932) – a 32 km enclosure dam that closed off the tidal inlet of the Zuiderzee

Project	Length of dike (km)	Construction of dikes	Size of polder (ha)	Polder fully drained
Amsteldiepdijk	2,5	1920-1924		
Afsluitdijk	32	1927-1932		
Pilot polder Andijk	1,9	1926-1927	40	August 27, 1927
Wieringermeer polder	18	1927-1929	20,000	August 31, 1930
Noordoostpolder	55	1936-1940	48,000	September 9, 1942
Eastern Flevoland polder	90	1950-1956	54,000	June 29, 1957
Southern Flevoland polder	70	1959-1967	43,000	May 29, 1968
Houtribdijk	28	1963-1975		

Fig. 2. Zuiderzee Works.

Source: Wikipedia.

– and the four successive Flevopolders. After the completion of the Afsluitdijk, the brackish Zuiderzee gradually changed into the fresh-water IJsselmeer. Salt transport across the sediment–lake interface was an important component in the salt balance of the lake and led to a slow desalinization of the sediments of the IJsselmeer: see Sections 3.3 and 3.4 for details on this. The principles of reclamation of the Flevopolders were worked out in the Andijker Pilotpolder (1926, 40 ha) and in the first full-scale polder, the Wieringermeer polder (1930, 20,000 ha). In these first two polders the initial soil condition was very saline. For the Noordoostpolder (1942, 48,000 ha), Eastern Flevoland polder (1957, 54,000 ha), and Southern Flevoland polder (1968, 43,000 ha) the desalinization of the lake sediments since the 1932 completion of the Afsluitdijk lasted progressively longer and thus reached to larger depth. The later the reclamation, the less saline was the initial condition of the polders. After decades of deliberation, the original plan to also reclaim the Markermeer was finally abandoned in 2003. The transformation of the large Zuiderzee to what are now the Flevopolders and the relatively small IJsselmeer and Markermeer inspired a lot of novel research.

The Hydraulic Department of the Government Board of the ZZW, with a staff of mainly civil engineers trained at the Technical University Delft, was responsible for the building of the Afsluitdijk, the sluices connecting the IJsselmeer to the Waddenzee, the dikes surrounding the individual polders, and the pumping stations linking the surface water system of the polders to the IJsselmeer (Mazure, 1963).

In the period 1923–1940, Jannes Pieter Mazure (1899–1990) worked on a variety of problems related to the civil engineering aspects of the ZZW. He started his career with an assignment at the Government Commission Zuiderzee. The retired physicist Hendrik Anton Lorentz (1853–1928; 1902 Nobel Price of Physics Laureate) was the chairman of this Commission studying changes in tidal flow patterns and resulting flood levels caused by the planned Afsluitdijk. Lorentz had a decisive influence in this exercise, requiring formulation of a sound fluid dynamics based theory, collection of real world hydraulic parameters, massive computations, and real world verification. Similar approaches were used by Mazure in his later work. His analysis of seepage underneath dikes (Mazure, 1932) was an improvement of the earlier analysis by Burgers (1926).

The physicist J.M. Burgers (1895–1981) is best known to soil physicists via the Burgers equation, which has been a valuable approximation of the Richards equation for movement of water in unsaturated soils. The 1926 paper appears to be the only one Burgers wrote on porous media. However, he (co-)supervised several PhD dissertations related to water management, hydrology, and soil mechanics, including Mazure's 1937 dissertation on the calculation of tides and storm floods on tidal rivers.

Mazure also analyzed the effect of the gradually decreasing salinity of the IJsselmeer on the salinity of the lake bottom prior to reclamation (Mazure, 1936): see Section 3.3 for the details. In the 1940s Mazure's attention gradually shifted to the construction of buildings, and this continued after his appointment at TU Delft, first as Professor of Applied Mechanics (1950–1956) and later as Professor of Building Construction (1956–1968). To the general public he became mainly known as a left-of-center politician, being involved in the peace movement and serving as Member (1958–1969), and for a while as President (1966–1969), of the (Dutch) Senate (Lichtenberg, 1992).

The agricultural and soil science research needed in the new polders was organized jointly by S. Smeding, at first as an advisor and later in various leadership positions at the ZZW, and D.J. Hissink, Director of the Soil Science Institute (SSI) at Groningen. The main participants in the study of various aspects of soil salinity were, in order of appearance, chemist/soil chemist J. van der Spek (SSI), agriculturist/soil microbiologist G.W. Harmsen (ZZW, later SARS-microbiology), chemist/drainage engineer S.B. Hooghoudt (SSI), agriculturist/soil scientist A.J. Zuur (SSI, later ZZW), plant physiologist K. Zijlstra (SARS-botany), and agriculturist/plant ecologist W. Feekes (ZZW, later SARS-botany, later again ZZW).

In the Dollard-region in the North-East corner of the Netherlands, a lot of land was lost to the sea in the Middle Ages. Later much of this was gradually reclaimed, resulting in polders of a wide range of ages. To get an idea of how the soils in the new Flevopolders would evolve in the course of time, Hissink (1935a) studied the soils in nine Dollard polders ranging in ages from 6 to approximately 400 years. In effect, he expanded upon the earlier study by Van Bemmelen (1863). Hissink determined the evolution of bulk density, cracking, water regime, aeration, content of organic matter and calcium carbonate, base exchange status, pH, and soil fertility status. To reconstruct the settlement, he used a novel technique based on the bulk density profiles, with the then existing marine foreland as reference: see Raats (1998) for an interpretation in terms of the modern continuum theory of mixtures.

Important areas of interest for Hissink, Van der Spek, Harmsen and Zuur were ion exchange, chemical reactions, and biogeochemical transformations. When, following the 1916 storm flood, in 1918 the soil structure was still a problem in the Anna Paulowna Polder, Hissink was the first in the Netherlands to experiment with gypsum as an amendment. Somewhat to his surprise gypsum amendment was never needed during reclamation of the Flevopolders. However, gypsum amendment was needed and much practiced following the Second World War inundations and the 1953 storm flood, when poor soil structure was again a major problem: see Section 4 for details regarding the resolution of this mystery.

Studies of field drainage in the Andijker Pilot Polder and the Wieringermeer were for the chemist Symen Baren Hooghoudt (1901–1953) the start of his evolution to drainage engineer: see Raats and Van der Ploeg (2013) for an overview of Hooghoudt's career.

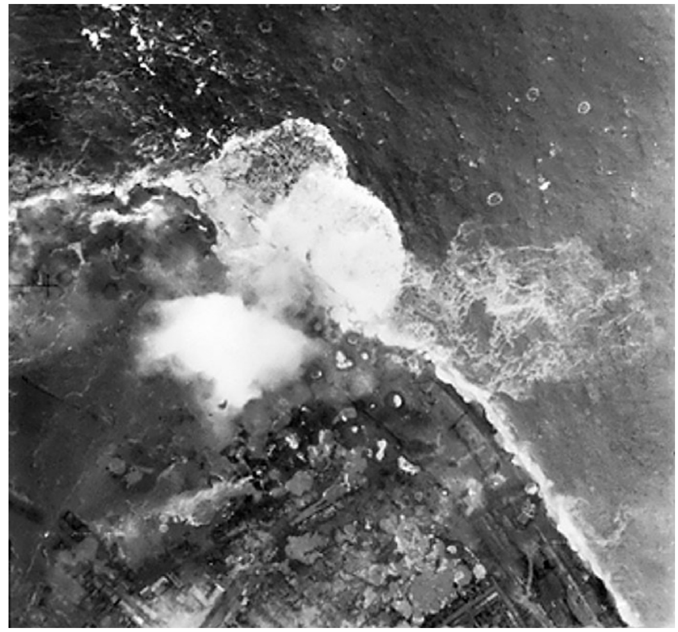

Fig. 3. An aerial photograph of bombs exploding on a dike at the island Walcheren during a RAF Bomber Command raid, 3 October 1944.
Source: Imperial War Museum, Identification Code 4700-11 C 4669.

At Wageningen University, Albert Jan Zuur (1902–1961) studied economic aspects of Dutch agriculture. Nevertheless his entire further career was in soil science. His original responsibility was to study the process of desalinization in the new polders, first in the Andijker Pilot Polder (Zuur, 1932) and later in the Wieringermeer Polder (Zuur, 1938). Following a suggestion by the civil engineer J.F. Ligtenberg, he explored in detail the novel idea to regard the chloride as a tracer to unravel the downward and upward movement of the water in the soil profile. See Section 3.2 for an analysis of the concepts used in these early studies of the desalinization process. Zuur (1936) also made a detailed soil map of the Wieringermeer Polder, which, together with determinations of the hydraulic conductivity by Hooghoudt, was used as a basis for designing the drainage system. Zuur remained active in reclamation research in the Flevopolders and combined this from 1951 onward with an extraordinary professorship at Wageningen Agricultural University.

The biological aspects were outside the expertise of Hissink's group and came from Smeding's ZZW group and other SARS groups at Groningen. For a discussion of the contributions by Harmsen on soil microbes, Feekes and Bakker on natural vegetation, and Zijlstra and Van den Berg on crops, I refer to Section 5.

2.4. Strategic inundations

Strategic inundations were contemplated and often actually used throughout Dutch history. For example, they played an important role in the Eighty Years' War (1568–1648), the war resulting in the independence of the Northern Netherlands from the Spanish Empire. During the Twelve Years' Truce (1609–1621), Jacob Cats and his family were active by reclaiming a large area that had been flooded for decades in the south-west of the province of Zeeland. As mentioned earlier, Van Bemmelen (1874) described the potential damage from strategic inundations with salt water.

Strategic inundations were widely used in the Netherlands during World War II in the period 1939–1945 by, respectively, the Dutch, German, and Allied Armed Forces (Fig. 3). During a visit

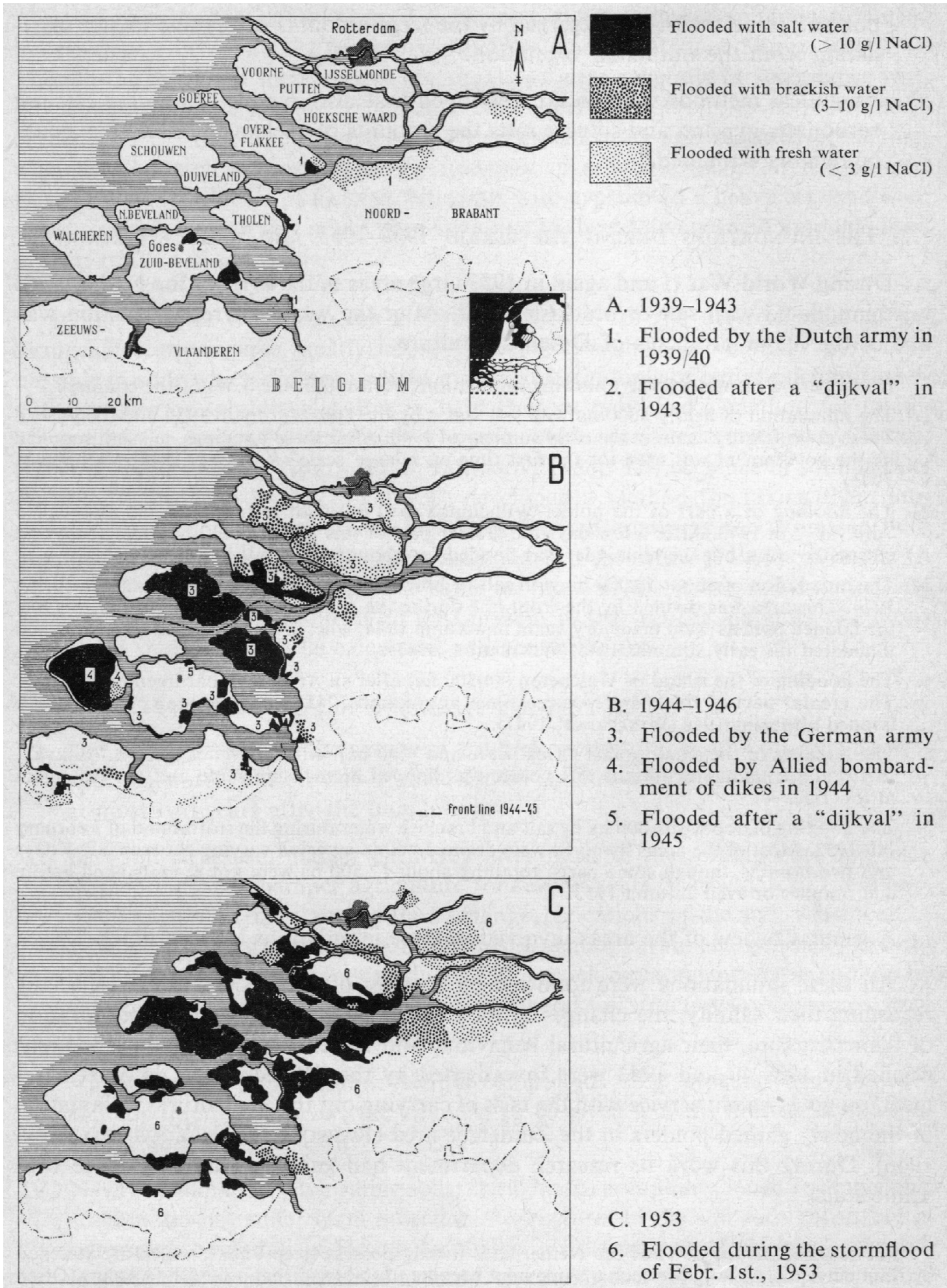

Fig. 4. Flooding in the south-west of the Netherlands in the period 1939–1953. 'Dijkval' refers to failure after a dike becomes water saturated.
Source: Fig. 1 in Van der Molen (1957).

to the Netherlands, Watson (1947) learned that approximately 78,150 ha was inundated with salt water, of which 23,250 ha grassland, 53,600 ha arable land, and 1300 ha horticultural land. The inundations with salt water were mainly in the estuary of the Scheldt in the southwest of the Netherlands, in the provinces of Zeeland and South Holland (Fig. 4). In Zeeland about one-third of the cultivated land was flooded. Watson also learned that 143,000 ha was inundated with fresh water, of which 93,100 ha grassland, 47,550 ha arable land, and 2350 ha horticultural land. The main damage after inundation with fresh water was loss of crops, including fruit trees. Comparison with Table 1 given earlier shows that the total area flooded was of the same order as that of the largest storm floods. During World War II, there were also two small, natural floods in 1943 and 1944.

The inundations with salt water led to a lot of activity. Already during the war, Smeding of the Directorate Wieringermeer (Noordoostpolder Works) and his staff launched, in cooperation with the Agricultural Advisory Service, a program of monitoring, research, and advisory activities in the flooded regions. The preliminary results of the monitoring and research of soils near Kruiningen in the region Zuid-Beveland in the province Zeeland (see Fig. 4) flooded in 1939 and 1940 became available in the month following liberation in May 1945 (DirWM-NOPworks, 1945). It included contributions by B. Verhoeven on desalinization, by A.J. Zuur on content

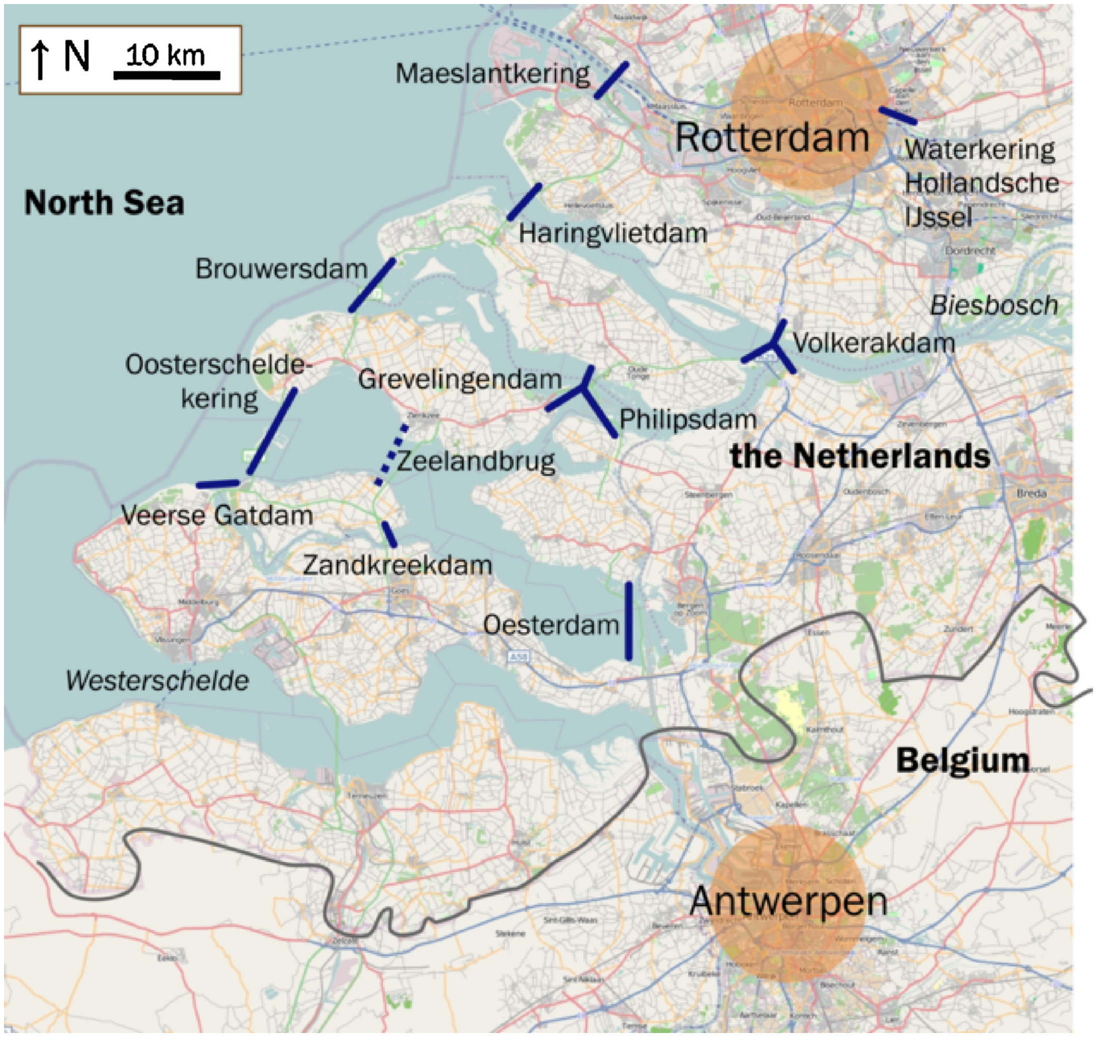

Fig. 5. Delta Works.

Source: Wikipedia.

of exchangeable sodium and the influence of gypsum amendment on this, by G.W. Harmsen on effectiveness of amendments of organic matter and sulfur in comparison with amendment of gypsum, and by A.J. Louwes and W.A. Bosma on soil tillage and crop management.

Also already during the war, in July and August of 1944 three meetings were held at Rotterdam in which experience from earlier reclamation projects was presented by experts to personnel of the agricultural extension service in the inundated regions of the south-west of the Netherlands (DirWM-NOPworks, 1946), with contributions by A.J. Zuur on salinity monitoring and desalinization, by W.R. Domingo on cation exchange and gypsum amendment, by G.W. Harmsen on microbiology, and by W.A. Bosma on soil tillage and crop management.

An intensive monitoring and research program was carried out in the years following the war, in which personnel of the Directorate Wieringermeer and of the Agricultural Research Station and Soil Science Institute T.N.O. at Groningen were the main participants. This resulted in a series of about a dozen publications in 'Verslagen van Landbouwkundige Onderzoekingen (Reports of Agricultural Researches)'. Among these were thorough treatments of crop response to salinity (Van den Berg, 1950, 1952), of monitoring of the progress of leaching of NaCl (Verhoeven, 1953), and of cation exchange following flooding by seawater and regeneration by natural processes and by various soil management practices, especially amendments of gypsum (Van der Molen, 1957).

2.5. Delta Works 1958–1997

The 1953 storm flood has been by far the major post-Second World War disaster in the Netherlands, with more than 1800 people losing their life. Due to the nature of the storm and most likely also thanks to the Zuiderzee Works, the damage was restricted to the south-west of the country: see Table 1 listing the major storm floods in the period 1877–1953. Just like the 1916 storm flood provided the final impetus for the Zuiderzee Works, the 1953 storm flood led to the ambitious, costly Delta Works (Borger et al., 2011).

The Delta Works consist of a series of dams and flood barriers: see Fig. 5 for an overview. Public pressure caused several changes of the plans in the execution phase. Initially, the plan was to close the Oosterschelde and thereby create a freshwater Lake Zeeland. Ernst (1969) used Mazure's approach for a prognosis of diffusion from the lake bed. However, the original plan met with fierce opposition from environmentalists and fishermen and had to be abandoned. While construction of a dam had started already in 1960, it was not until 1979 that parliament agreed to finally realize the novel type of storm surge barrier, completed in 1986, with gates that can be closed when necessary (http://www.deltawerken.com/Dam-or-barrier/426.html).

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The Brouwersdam was finished in 1971. In 1974 it was decided to keep the Grevelingen Lake saline by means of a sluice in the dam. This was completed in 1978.

The dams and storm surge barriers contribute first of all to safety of life and property, but also to a reduction of costs of dikes and to the interests of environmentalists, recreation, and fishermen in maintaining a saline environment. Unlike in the earlier planning of the IJsselmeer as part of the Zuiderzee Works, in the Delta Works there was no room for a fresh water reservoir.

3. Modeling of sodium chloride: salinization and desalinization

3.1. Preliminaries

This section mainly concerns pre-Second World War concepts and methods to describe salinization and desalinization, with emphasis on sodium chloride. In Section 3.2 the compositional variables and storage functions used in early Dutch salinity studies are introduced and analyzed. In Sections 3.3–3.5 early models of diffusive and convective–diffusive transport are discussed.

As a base of reference for the early concepts and methods, it is a convenient to first introduce in this subsection the simplest equations for flow of water and transport of solutes that are *now* commonly used. In the context of this paper, it is sufficient to just consider one-dimensional flow of water and transport of solutes.

The flow of water can be described by

$$\frac{\partial\theta}{\partial t} = -\frac{\partial\theta v}{\partial z} - \lambda_w, \tag{1a}$$

$$\theta v = -K[\theta]\frac{\partial h}{\partial z} + K[\theta], \tag{1b}$$

where t is the time [T], z is the vertical coordinate [L], taken positive in the downward direction, θ is the volumetric water content [L^3/L^3], v is the water velocity [L/T], θv is the volumetric water flux [L^3/(L^{2}T) = L/T], λ_w is the volumetric rate of water uptake [L^3/(L^{3}T) = 1/T], h is the pressure head [L], and K is the hydraulic conductivity [L/T].

The transport of an inert solute can be described by:

$$\frac{\partial\theta c}{\partial t} = -\frac{\partial F}{\partial z} - \lambda_s, \tag{2a}$$

$$F = -D[\theta, v]\frac{\partial c}{\partial z} + \theta v c, \tag{2b}$$

where c is the solute concentration in the fluid phase [M/L^3], F is the salt mass flux [M/(L^{2}T)], λ_s is the rate of salt uptake [M/(L^{3}T)], and $D[\theta, v]$ is the salt dispersion coefficient [L^2/T], which reduces to the salt diffusivity $D[\theta]$ if $v = 0$. On the right hand side of (2b), the first term is the diffusive/dispersive component and the second term the convective component of the salt flux.

Dispersion of solutes in porous media was pioneered in the 1950s by fluid dynamicists, and by chemical, petroleum, and civil engineers. The civil engineer Gerard de Josselin de Jong (1915–2012) of the Laboratory of Soil Mechanics and the Technical University at Delft played a key role with his experiments showing that the transversal dispersion coefficient is much smaller than the longitudinal one and his formulation of the first theory accounting for this. Quite recently, Schotting et al. (2006) published a collection of his most important papers. In the Netherlands, it was not until the 1960s that dispersion was introduced in soil salinity research and, therefore, the dispersion phenomenon is beyond the scope of this paper.

Eqs. (1a), (1b), (2a) and (2b) will be used in Section 3.2 to interpret the storage functions, and serve as a base of comparison for the earliest models of diffusive solute transport in Section 3.3 and of convective-diffusive transport in Sections 3.4 and 3.5.

3.2. Compositional variables and storage functions used in early Dutch salinity studies

Let ρ_b, ρ_w, and ρ_s denote, respectively, the soil bulk mass densities of the dry soil, the water, and the salt, i.e. densities per unit volume of soil [M/L^3]. In the earliest quantitive descriptions of the salinity status, Van Bemmelen (1880, 1890) and Hissink (1907b) used the mass densities ratio ρ_s/ρ_b, expressed as a percentage. The bulk mass densities ρ_w and ρ_s can be written as products of the volume fraction θ of the liquid phase and the respective phase densities γ_w and γ_s of the water and the salt [M/L^3]:

$$\rho_w = \theta\gamma_w, \tag{3a}$$

$$\rho_s = \theta\gamma_s. \tag{3b}$$

To describe the salinity status, Nobel (1921) and Smeding (1921) introduced the water content A in g per 100 g dry soil, the salt content B in g per 100 g dry soil and the salt concentration C in g per 1000 g water (≈1 l water) defined by:

$$A = 100\frac{\rho_w}{\rho_b} = 100\frac{\theta\gamma_w}{\rho_b}, \tag{4a}$$

$$B = 100\frac{\rho_s}{\rho_b} = 100\frac{\theta\gamma_s}{\rho_b}, \tag{4b}$$

$$C = 1000\frac{B}{A} = 1000\frac{\gamma_s}{\gamma_w}. \tag{4c}$$

In line with the practical Dutch literature, in this subsection I use the symbol C rather than c. In addition to these A-, B- and C-values, Zuur (1938) introduced the storages per unit area $W(a \leftrightarrow b)$ of water and $Z(a \leftrightarrow b)$ of salt in the layer between depths $z = a$ and $z = b$ defined by:

$$W(a \leftrightarrow b) = \int_a^b \rho_w dz = \int_a^b \frac{A\rho_b}{100}dz, \tag{5a}$$

$$Z(a \leftrightarrow b) = \int_a^b \rho_s dz = \int_a^b \frac{B\rho_b}{100}dz. \tag{5b}$$

Zuur (1938) also defined the changes VW and VZ in the time interval $t_1 \to t_2$ of the storages of water and salt in the layer between $z = a \leftrightarrow b$ by (the letter V denotes the Dutch word 'verschil' meaning 'difference')

$$VW(a \leftrightarrow b, t_1 \to t_2) = W[a \leftrightarrow b, t_2] - W[a \leftrightarrow b, t_1], \tag{6a}$$

$$VZ(a \leftrightarrow b, t_1 \to t_2) = Za \leftrightarrow b, [t_2] - Z[a \leftrightarrow b, t_1]. \tag{6b}$$

To describe the salinity status following the flood of March 12, 1906 in the Province Zeeland, Hissink (1907b) used variables closely related to B and $Z(a \leftrightarrow b)$, namely mass of salt expressed as percentage of mass of dry soil and mass of salt per hectare in a particular layer. Following the 1916 flood in the Province North-Holland, Nobel (1921) and Smeding (1921) introduced the C-value, in view of its relevance for salinity response of crops and other vegetations, including effect on seed germination.

Zuur (1938) introduced the storages $W(a \leftrightarrow b)$ and $Z(a \leftrightarrow b)$ defined in Eqs. (5a) and (5b) and the change in storages $VW(a \leftrightarrow b, t_1 \to t_2)$ and $VZ(a \leftrightarrow b, t_1 \to t_2)$ defined in Eqs. (6a) and (6b) to describe the desalinization in the Wieringermeer. As mentioned before, following a suggestion by the civil engineer J.F. Ligtenberg, Zuur (1938) explored the idea to regard the chloride as a tracer to unravel the movement of the water and for that purpose introduced the set of variables defined in Eqs. (5a), (5b), (6a) and (6b). He did not introduce differential balance equations like (1a) and (1b) for the water and (2a) and (2b) for the salt. However, I will now show that nevertheless he verbally made use of concepts that emerge when these differential balance equations are integrated spatially and temporally.

Integration of (1a) and (2a) with respect to depth between $z=a$ and $z=b$, and using (3a) and (5a) in the first and (3b) and (5b) in the second of these, gives:

$$\frac{d}{dt}\int_a^b \theta dz = \gamma_w^{-1}\frac{d}{dt}W(a\leftrightarrow b) = (\theta v)_{|b} - (\theta v)_{|a} - \int_a^b \lambda_w dz, \tag{7a}$$

$$\frac{d}{dt}\int_a^b \theta C dz = \frac{1000}{\gamma_w}\frac{d}{dt}Z(a\leftrightarrow b) = F_{|b} - F_{|a} - \int_a^b \lambda_s dz. \tag{7b}$$

Integration of (7a) and (7b) with respect to time between $t=t_1$ and $t=t_2$ gives:

$$VW(a\leftrightarrow b, t_1\to t_2)$$
$$= \gamma_w\int_{t_1}^{t_2}[(\theta v)_{|b} - (\theta v)_{|a}]dt - \gamma_w\int_{t_1}^{t_2}\int_a^b \lambda_w dz dt, \tag{8a}$$

$$VZ(a\leftrightarrow b, t_1\to t_2)$$
$$= \frac{\gamma_w}{1000}\int_{t_1}^{t_2}[F_{|b} - F_{|a}]dt - \frac{\gamma_w}{1000}\int_{t_1}^{t_2}\int_a^b \lambda_s dz dt. \tag{8b}$$

Zuur (1938) showed that special cases of (8a) and (8b) can be used to interpret observations on water content and salinity profiles in the course of time and to infer components of the integral water and salt balances. He dealt with leaching by downward flow, capillary rise by upward flow and the difference of desalinization between clay and sand. Fig. 6 shows the desalinization in the 20,000 ha Wieringermeer polder in the first six years. The main reason for the slow desalinization of the north-eastern part was the upward seepage of saline water from the subsoil.

Verhoeven (1950, 1953) studied desalinization in the southwest of the Netherlands following the military inundations in 1944 and 1945. He made use of the concepts introduced by Zuur (1938). He payed much attention to experimental errors and to spatial variability. He distinguished clearly between (1) local variability associated with soil physical properties, soil structural features such as large pores and cracks, uptake of water by plant roots, and soil surface topography (Fig. 7a), and (2) field scale variability associated soil types and patterns of flow to ditches and drain (Fig. 7b). Verhoeven separately treated the salt and water conditions during summer and during winter. In the Dutch climate, generally leaching of salt occurs during winter, while during summer capillary rise may partly undo the leaching achieved in the previous winter. Often, at the end of the summer the salt concentration C is much higher than in the previous spring, but in the following winter this will be more than offset, so that annually there will be net leaching.

3.3. *Early diffusive model for transport in porous media*

As part of an analysis of the water and salt balances of the IJsselmeer, Mazure (1936) analyzed the diffusion of salt in the lake bottom. His point of departure is the vertical diffusion of salt in a column of an aqueous solution in terms of the salt mass balance and Fick's law for the salt flux, written as

$$\epsilon\frac{\partial c}{\partial t} = \frac{\partial q}{\partial z} \tag{9a}$$

and

$$q = \epsilon k'\frac{\partial c}{\partial z}, \tag{9b}$$

where q is the salt flux [M/(L^{2}T], taken positive in the upward direction, ϵ is the constant porosity [L^3/L^3], and $\epsilon k'$ is the effective diffusion coefficient [L^2/T] given by

$$\epsilon k' = \epsilon k\cos^{-2}\alpha, \tag{9c}$$

where k is the diffusion coefficient at the pore scale [L^2]/T] and $\cos^{-2}\alpha$ is the tortuosity factor, in which α represents the average deviation of the direction of the diffusive flux at the pore scale from the vertical direction. In effect, Mazure used Eqs. (2a) and (2b) with constant $\theta=\epsilon=$ constant, $F=-q$, $\lambda_s=0$, $v=0$ and $D=\epsilon k'=\epsilon k\cos^{-2}\alpha$ for diffusion of salt in a column of aqueous solution representing a lake bottom. Mazure estimated that for densely packed sands the angle $\alpha=45°$, so that $k'=0.5k$. Measurements of k' by Zuur at the Soil Science Institute (Groningen), mentioned by both Mazure (1936) and Zuur (1938), gave values of 0.61 cm^2 day^{-1} in the temperature range of 16–26 °C, comparing well with the value of k of about 1.24 cm^2 day^{-1} for sodium chloride in water at 21 °C listed in 'International Critical Tables'. Introducing (9b) into (9a) gives:

$$\frac{\partial c}{\partial t} = k'\frac{\partial^2 c}{\partial z^2}. \tag{9d}$$

Eqs. (9a)–(9d) are, as far as I know, *the earliest physico-mathematical model for diffusion of a solute in a porous medium.*

Mazure (1936) solved (9d) for the initial and boundary conditions:

$$c(t=0, z>0) = c_0 \tag{10a}$$

and

$$c(t>0, z=0) = c_1 \tag{10b}$$

and gave the resulting expressions for concentration difference $c(z, t)-c_1$, flux $q(z, t)$, the rate of desalinization $q(z=0, t)$, cumulative desalinization $Q(z=0,t) = \int_0^t q(z=0,t)dt$:

$$c(z,t) - c_1 = (c_0 - c_1)\frac{2}{\sqrt{\pi}}\int_0^{\frac{z}{2\sqrt{k't}}}\exp(-\xi^2)d\xi, \tag{11a}$$

$$q(z,t) = \frac{\epsilon(c_0-c_1)\sqrt{k'}}{\sqrt{\pi t}}\exp\left(\frac{-z^2}{4k't}\right), \tag{11b}$$

$$q(z=0,t) = \frac{\epsilon(c_0-c_1)\sqrt{k'}}{\sqrt{\pi t}}, \tag{11c}$$

$$Q(z=0,t) = \frac{2}{\sqrt{\pi}}\epsilon(c_0-c_1)\sqrt{k't}. \tag{11d}$$

Dividing both sides of (11d) by $\epsilon(c_0-c_1)$ gives:

$$\frac{Q(z=0,t)}{\epsilon(c_0-c_1)} = \frac{2}{\sqrt{\pi}}\sqrt{k't} := L. \tag{12}$$

Equation (12) shows that the cumulative desalinization $Q(z=0, t)$ is the amount of salt that is removed if the concentration is lowered from c_0 to c_1 in a soil column of length $L = \frac{2}{\sqrt{\pi}}\sqrt{k't}$.

Elimination of t from (11c) and (12) shows that the rate of desalinization $q(z=0, t)$ is inversely proportional to the cumulative desalinization $Q(z=0, t)$:

$$q(z=0,t) = \frac{dQ(z=0,t)}{dt} = \frac{2\epsilon^2(c_0-c_1)^2k'}{\pi Q(h=0,t)}. \tag{13}$$

Mazure uses this expression to find an approximate expression for the rate of desalinization $q(z=0, t)$ for situations in which the concentration of the lake water reduces gradually from c_0 to c_1. The approximation in effect amounts to the assumption that the rate of desalinization at time t depends only on the instantaneous values of the lake water concentration $c_1(z=0, t)$ and the cumulative desalinization $Q(z=0, t)$. Of course in reality the details of the

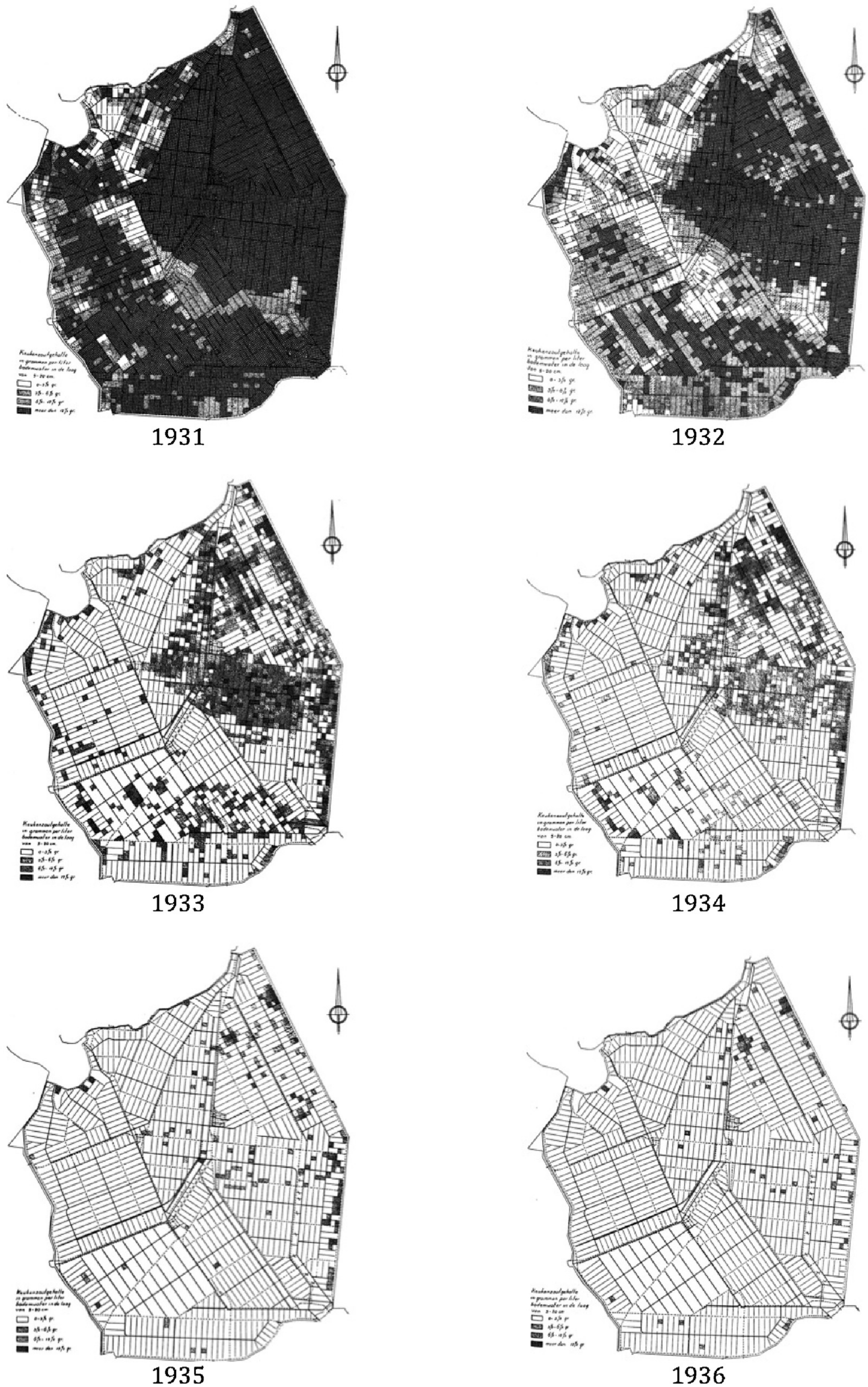

Fig. 6. Desalinization of the Wieringermeer polders in the years 1931–1936, expressed as spring time NaCl concentration in the layer 5–20 cm depth. The concentration *C* ranged from more than 12.5 g per liter in the black areas to less than 3.5 g per liter in the white areas and in between these values in the gray areas.

Source: Adapted from Maps 5 to 10 in Zuur (1938).

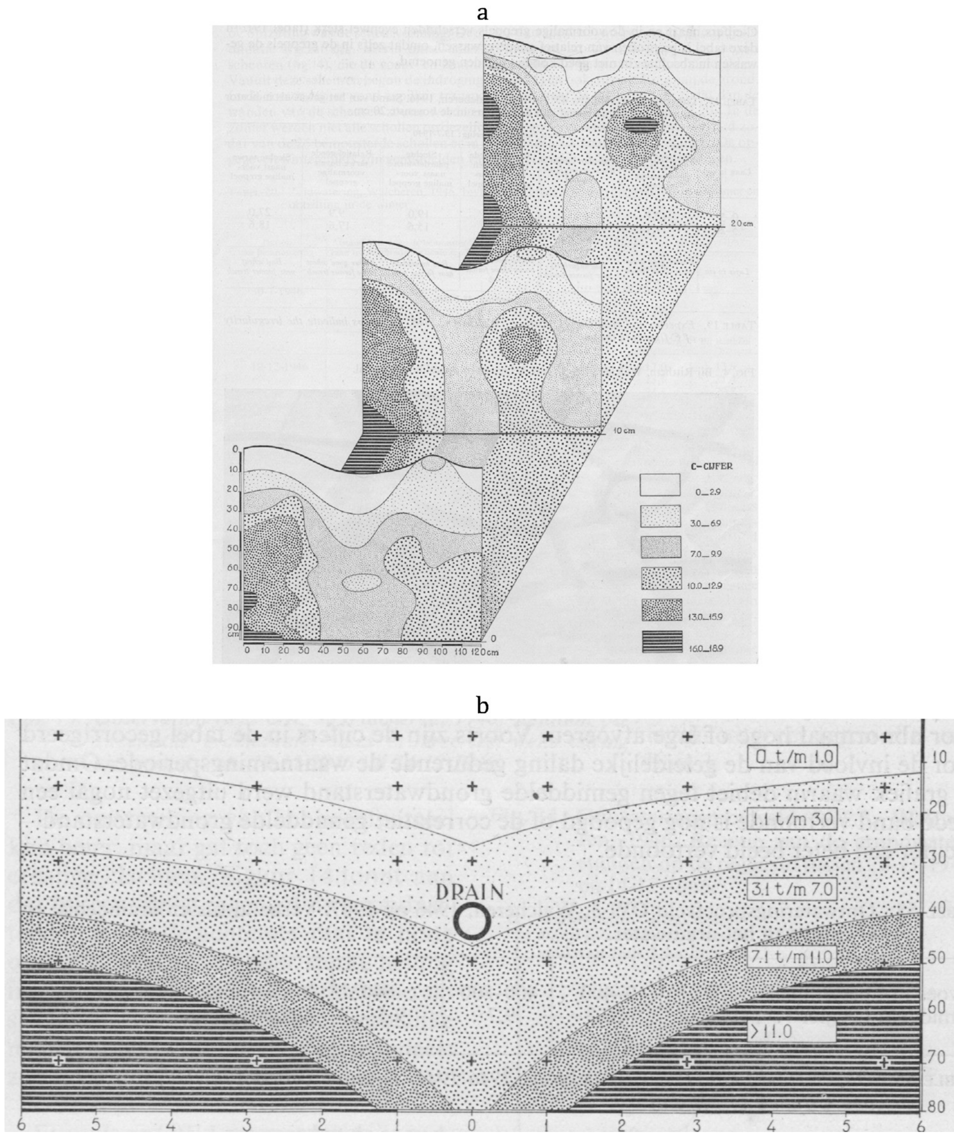

Fig. 7. Typical distributions of *C*-values: (a) at short distances in soil block of 1.2 m × 1.0 m × 0.2 m in Oost-Beveland polder, 01-05-1947; (b) at the scale of 12 m spacing of drains and 0.8 m soil profile depth at the island of Walcheren, 22 March 1947.
Source: Adapted from Figs. 3 and 15 in Verhoeven (1953).

distribution of the salt, which depends on the history of the entire desalinization process, will also play a role.

This is a very early (1936!) example of time condensation. In soil physics and hydrology, time condensation is often used to approximate falling rates of evaporation (Gardner and Gardner, 1969) or infiltration (Sherman, 1943; Reeves and Miller, 1975) resulting from variable boundary conditions at the soil surface.

An expression analogous to Eq. (12) can now be derived for situations in which the concentration of the lake water reduces gradually from c_0 to c_1. Integration of (13), regarding not only Q but also c_1 as a function of t, gives:

$$Q^2 = \frac{4}{\pi}\epsilon^2 k' \int_0^t (c_0 - c_1)^2 dt. \tag{14}$$

If at time $t = T$ the lake water concentration has dropped to an the ultimate constant value $c_1(0, t > T) = c_e$, it is convenient to split (14) in the two parts:

$$\left(\frac{Q}{\epsilon(c_0 - c_e)}\right)^2 = \frac{4}{\pi}k' \int_0^t \left(\frac{c_0 - c_1}{c_0 - c_e}\right)^2 dt \quad \text{for} \quad t < T \tag{15a}$$

and

$$\left(\frac{Q}{\epsilon(c_0 - c_e)}\right)^2 = \frac{4}{\pi}k'\left(\int_0^T \left(\frac{c_0 - c_1}{c_0 - c_e}\right)^2 dt + \tau\right) \text{for } t = T + \tau > T. \tag{15b}$$

Setting

$$\int_0^T \left(\frac{c_0 - c_1}{c_0 - c_e}\right)^2 dt = T' < T, \tag{16}$$

Eq. (15b) can be cast in a form similar to (12)

$$\frac{Q(z=0,t)}{\epsilon(c_0 - c_e)} = \frac{2}{\sqrt{\pi}}\sqrt{k'(T' + \tau)} = \frac{2}{\pi}\sqrt{k't'} := L \quad where$$
$$t' = (T' + \tau) < t = (T = \tau), \tag{17}$$

where L is again the equivalent depth of desalinization

3.4. Early convective-diffusive model for transport in porous media

In a project sponsored by the 'Dienst der Zuiderzeewerken' at the 'Waterloopkundig Laboratorium' at Delft, Klasema et al. (1938) extended the diffusion theory to include upward seepage. For this case, instead of Eq. (9b), the salt flux is given by:

$$q = \epsilon k' \frac{\partial c}{\partial z} - \epsilon v c. \tag{18}$$

Introducing (18) into the mass balance, Eq. (19) gives the convection–diffusion equation:

$$\frac{\partial c}{\partial t} = k' \frac{\partial^2 c}{\partial z^2} - v \frac{\partial c}{\partial z}. \tag{19}$$

As far as I know, Eqs. (9a), (18) and (19) are *the earliest physico-mathematical model for combined upward diffusion and convection of a solute in a porous medium.*

We are interested in the solution of (19) subject to the boundary conditions

$$c(t = 0, z \to \infty) = c_\infty \tag{20a}$$

and

$$c(t > 0, z = 0) = 0 \tag{20b}$$

and the initial condition

$$c(t = 0, z > 0) = (c_0 - c_\infty)\exp\left(-\frac{v}{k'}z\right). \tag{21}$$

The initial condition (21) represents the equilibrium profile resulting from the boundary conditions

$$c(-\infty < t \le 0, z \to -\infty) = c_\infty \tag{22a}$$

and

$$c(-\infty < t \le 0, z = 0) = c_0. \tag{22b}$$

Klasema et al. (1938) gave the following solution derived by J.M. Burgers of TU Delft:

$$c - c_\infty = (c_0 - c_\infty)\frac{2}{\pi} exp\left(-\frac{v}{k'}h - \frac{v^2 t}{4k'}\right)\int_0^\infty \times \exp - (k' p^2 t)\frac{p}{p^2 + (v^2/(4k'^2))}\sin(ph)\,dp \tag{23}$$

As was mentioned in Section 2.3, in 1932 the tidal inlet to the Zuiderzee was closed off by a dam and in a few years the brackish Zuiderzee changed into the fresh-water IJsselmeer. The lake bottom then started to desalinize. Direct comparison of observations with the theory is difficult, since the water velocity v is not easily measured. In fact, Klasema et al. (1938) used Eq. (23) to infer from the observed salinity distributions the velocity v of the water. That way reasonable agreement between observed and predicted salinity profiles was obtained.

Klasema et al. (1938) explicitly attributed Eq. (23) to J.M. Burgers of TU Delft. Recall that Burgers was supervisor of the PhD thesis of Muzure. It may well be that Burgers was instrumental in the entire formulation of the early models for diffusive and the convective–diffusive transport in porous media. However, so far I have not come across direct evidence for this.

Volker and Van der Molen (1991) showed the integral solution (23) agrees with an analytical solution derived by Misra and Mahapatra (1989). They used the model to calculate potential salinization of the bottom of the Zuiderzee for the period 1638–1934. For the solute diffusion coefficient they used the value 0.0146 $\text{m}^{-2}\,\text{year}^{-1}$. For zero flow velocity, the penetration depth $2\sqrt{Dt}$ for the period 1638–1934 is 4.16 m. For the flow velocities they used the values −0.01, −0.005, 0, +0.005, and +0.01 m year^{-1}, corresponding for the period 1638–1934 to displacements of −2.96, −1.48, 0, +1.48, and 2.96 m. The resulting salinity profiles in the top 10 m are in good agreement with profiles reported by Van der Molen (1958). The spatial distribution of the observed salinity profiles are a good indicator of the spatial distribution of the flow velocities. The (upward) flow velocity of −0.01 m year^{-1} over the period 1638–1934 is not sufficient to approach the long-time, steady exponential profile, but a flow velocity of −0.10 m year^{-1} would be.

Van der Molen (1958) noted that in a few scattered places in the Noordoostpolder higher salinities were found at depths of 10–15 m. One such place reflects seepage of water from the former Zuiderzee to lower lying polders along the coast. Another place coincides with a highly permeable Pleistocene deposit reaching the surface. Van der Molen speculated that for that place 'this phenomenon is probably due to convection currents in the bottom of the Zuyder Zee between 1600 and 1931 A.D.'. Specifically he notes that the small difference in density between the fresh water present in the soil and the supernatant seawater is sufficient to cause convection currents (see also Van der Molen, 1989). Already in a 1944 lecture Zuur also speculated on this: see DirWM-NOPworks (1946). With Hans van Duijn and Gert-Jan Pieters of TU Eindhoven, I am currently writing a paper on density stratified, vertical flows.

The small upward or downward flow velocities are also confirmed by the observed salinity profiles in the top meter reflecting the desalinization since the completion of the Afsluitdijk in 1932 (Volker, 1961; Van der Molen, 1958; Volker and Van der Molen, 1991). It was shown by De Vos et al. (2000, 2002) that at an experimental farm in the Noordoostpolder around 1990 upward diffusion of several hundred kg $\text{ha}^{-1}\,\text{year}^{-1}$ was still the major source of chloride in the drainage water, the remainder coming from atmospheric and fertilizer inputs. The desalinization of the sediment in the IJsselmeer meant that, unlike in the Wieringermeer polder, salinity was hardly a problem later on during the reclamations of the Noordoostpolder and the Eastern and Southern Flevoland polders (see Fig. 2).

3.5. Soil salinization from flooding by seawater and desalinization from leaching by rainfall

The pioneering, pre-Second World War analysis of transport in a lake bottom by the civil engineers had only minor influence on the work of Zuur and Verhoeven. In the mid 1950s, Day (1956) and Van der Molen (1956, 1957) were the first to move away from the assumption of purely convective flow. Van der Molen adopted the chromatographic theory of Glueckauf (1949) to account for simultaneous convective and diffusive/dispersive transport. Eugen Glueckauf (1906–1981) was a German-born British expert on nuclear power at the Atomic Energy Research Establishment (AERE) at Harwell, UK (Everett, 1984). In the late 1940s and early 1950s, he wrote numerous papers on chromatography (Ettre and Zlatlis, 1979).

In Appendix A, Glueckauf (1949) gives for the initial condition

$$c(t = 0, z > 0) = 0 \tag{24a}$$

and the boundary condition

$$c(t > 0, z = 0) = c_0 \tag{24b}$$

the following solution of (19), derived by J.H. Tait of the AERE Theoretical Division:

$$c(z, t) = \frac{1}{2}c_0\left[\text{erfc}\left(\frac{z - vt}{2\sqrt{Dt}}\right) + e^{vz/D}\,\text{erfc}\left(\frac{z + vt}{2\sqrt{Dt}}\right)\right]. \tag{24c}$$

Van der Molen (1957) used this solution to describe the salinization of an initially salt-free soil from flooding by seawater with concentration c_0. In his Fig. 32, he showed observed and calculated salinity-depth curves immediately after the inundation of short duration during the 1953 Storm Flood for a light and a heavy soil. He found larger dispersion in the heavy soil, which he attributed to 'rapid passage of part of the penetrating water through existing fissures'.

To describe desalinization from leaching by rainfall, for the initial condition

$$c(t=0, z>0) = c_0 \tag{25a}$$

and the boundary condition

$$c(t>0, z=0) = 0, \tag{25b}$$

Van der Molen (1956, 1957) derived by analogy the following solution of (19)

$$c(z,t) = \frac{1}{2} c_0 \left[\operatorname{erfc}\left(\frac{vt-z}{2\sqrt{Dt}}\right) - e^{vz/D} \operatorname{erfc}\left(\frac{vt+z}{2\sqrt{Dt}}\right) \right]. \tag{25c}$$

Van der Molen (1956) used (25c) to interpret field observations following the Second World War inundations.

4. Ion exchange and biochemical reactions in soils flooded by seawater

4.1. Deterioration and restoration of soil structure following flooding by seawater

Invariably damage to soil structure was recognized by authors recording experiences of farmers and their own observations following flooding of farm land (Jansen and Janse, 1991; Ponse, 1808; Mayer, 1877; Van Bemmelen, 1874; Hissink, 1907a; Smeding, 1919–1920, 1921; Nobel, 1921). As noted earlier, Hissink studied ion exchange and chemical reactions in soils flooded by seawater already in the years 1906–1909. He understood that flooding by seawater transforms a calcium clay rapidly in a sodium–magnesium clay and that, due to the low solubility of calcium carbonate, during reclamation the reverse process is slow. Following the 1916 Stormflood in the Anna Paulowna Polder, in the fall of 1918 the soil structure was still poor. Hissink then suggested a field experiment comparing amendments of calcium carbonate, calcium oxide, and gypsum. The plots treated with gypsum showed improved soil structure, notably in wet years (Hissink, 1923).

In the 1920s, Hissink introduced the total capacity T and the base saturation S of the soil exchange complex, expressed in milligram-equivalents per 100 g of soil. In the 1920s and 1930s, soil acidity was a hot topic and Hissink sought to relate soil pH to the degree of base saturation $V = 100S/T$, expressed as percentage, and the amount $T - S$ of cations the soil can still adsorb: see (Bolt, 1997) for an analysis of the pre-Second World War European and American literature on soil pH. In the 1920–1930s, Hissink and his coworkers worked out in detail methods to determine T, S and V, $T - S$, including soils with a high content of $CaCO_3$: for a brief discussion and numerous references see Hissink (1936).

To characterize the salinity status of soils that had been flooded or recently reclaimed from tidal areas or lake bottoms, Hissink (1935a,b, 1938) used the relative proportions of the exchangeable bases Ca, Mg, K and Na. North Sea water contains of the order of 35 g of salt per kg, of which about 19 g per kg is chloride; it is high in $Na^+ = 0.469$, $Mg^{2-} = 0.0528$, $Cl^- = 0.546$ and $SO_4^{2-} = 0.0282$, and low in $K^+ = 0.0102$ and $Ca^{2+} = 0.0103$, all in mol/kg. The composition of the exchange complex just after draining reflects equilibration with seawater, resulting in a magnesium–sodium clay with the relative proportions of 25–40 Ca, 45–30 Mg, 8 K, and 20 Na exchangeable bases (Hissink, 1938). The leaching of the sodium will change the magnesium–sodium clay within a few years into a calcium–magnesium clay with typical relative proportions of 71 Ca, 21 Mg, 6 K, and 2 Na. In the following 100 years the relative proportion of Mg on the exchange complex further declines, so that one ends up with a calcium clay. All along the $CaCO_3$ content declines and eventually the relative proportion of exchangeable Ca will also decline, leading to an increase of the relatively proportion of Mg and a decline of the pH. Hissink (1920, 1938) speculated that, at this stage, slow diffusion from the interior of soil particles is the main source of Mg. In the Dollard polders of ages ranging from 6 to 400 years, Hissink (1935a, 1936, 1938) convincingly showed this temporal evolution of the composition of the exchange complex.

The models for ion transport and exchange used by Hissink and his coworkers were conceptual and served well to give qualitative descriptions of field observations. In the mid-1950s more quantitative physico-mathematical models that combined transport and ion exchange processes were introduced. After Van der Molen (1956, 1957) had moved away from the assumption of purely convective transport in the description of NaCL accumulation (salinization) and removal (desalinization), he continued by combining this description of convective/diffusive transport with a treatment of linear and nonlinear ion exchange (Van der Molen, 1957). He adopted the chromatographic theory of Glueckauf (1949) to account for both diffusion/dispersion and ion exchange. For the replacement of Na by Ca, he showed that the nonlinear exchange leads to a traveling, gradual front of constant shape. Van der Molen (1957) cited a 1954 private communication from Glueckauf as the source of the solution for a quadratic exchange isotherm. Such power law isotherms are usually attributed to Freundlich (1909). However, Sposito (1981) pointed out that two decades earlier Van Bemmelen (1888) already introduced them in soil science, and he suggested to refer to them as van Bemmelen–Freundlich isotherms. Earlier, Ribble and Davis (1955) had used a simpler chromatographic theory, namely the kinematic wave model of De Vault (1943). For the exchange of sodium by calcium, the absence of diffusion led Ribble to the not quite satisfactory prediction of a sharp front.

My first exposure to ion exchange in soils was in the late 1950s in the lectures by Gerard (Jerry) Hendrik Bolt. He studied at Wageningen in the 1940s and, following his 1954 PhD at Cornell University and a brief interlude at DuPont in Wilmington, Delaware, returned to Wageningen in 1957, the year I elected to major in soil science. His inaugural lecture dealt with adsorption equilibria in soils (Bolt, 1957). Ion exchange in soils was one the many topics he introduced in the Wageningen curriculum. Among others, this later resulted in his review paper on cation exchange equations in soil science (Bolt, 1967) and contributions in three books he (co-)edited (Bolt and Bruggenwert, 1976; Bolt, 1979; Bolt et al., 1990). The 1979 book also includes a chapter on ion exchange chromatography. These books have had a decisive influence on soil physical chemistry and solute transport in the Netherlands and beyond.

4.2. Reduction and oxidation processes in the absence or presence of carbonates

Seawater is rich in sulfate and this is reflected in the aquatic sediments of tidal flats. Transformations of sulfur species are a combination of reductive and oxidative chemical and bacterial processes. Under anaerobic conditions, sulfate-reducing bacteria will oxidize organic matter, thereby producing hydrogen sulfide (H_2S). A relatively rapid reaction of the H_2S with iron oxide, in which again bacteria are involved, produces elemental sulfur (S) and ferrous mono-sulfide (FeS). The FeS is responsible for the black color of anaerobic muds. A relatively slow reaction will combine the S and FeS to produce pyrite (FeS_2), whereby the black color gradually disappears. Drainage of the mud leads to access of oxygen and oxidation of the reduced sulfur species, forming sulfuric acid (H_2SO_4) and iron hydroxide ($Fe(OH)_3$). If FeS is still present in the mud, then during drainage the black color gradually disappears from the surface downward.

If the sulfuric acid is not somehow neutralized, there remains a soil with an extremely low pH, a so-called acid–sulfate soil. In the Netherlands these soils are called cat clay. Pioneering studies of cat clays in the IJ and Haarlemmermeer Polders were done by Van Bemmelen (1886). Hissink (1920, 1924) and Van der Spek (1934, 1950) found acid sulfate soils in many other places. During a tour of the Gulf and Atlantic coastal areas of the USA, Edelman and Van Staveren (1958) regularly came across acid sulfate soils.

If calcium carbonate ($CaCO_3$) is present, it will neutralize the H_2SO_4, resulting in gypsum:

$$4H_2SO_4 + 4CaCO_3 \rightarrow 4CaSO_4 + 4H_2O + 4CO_2.$$

In the new Flevopolders, the simultaneous presence of sufficient sulfur species, at least initially, and in most places abundant $CaCO_3$ led to natural gypsum production (Zuur, 1952). This meant that during the reclamation process gypsum was available to stimulate by its high solubility the conversion of the initial magnesium–sodium soil into a calcium–magnesium soil and that gypsum amendment was not needed.

The above is an outline of the bio-geochemical reactions involving sulfate that gradually evolved. There are a lot of further details and all that was certainly not clear from the beginning. For a long time it remained a mystery why, unlike flooded farm land, newly reclaimed land seldom shows severe soil structure problems. Van Bemmelen (1886), Hissink (1920, 1924) and Van der Spek (1934) were aware of the above reaction. Nevertheless, led by his early experience with farm land flooded by seawater, Hissink for a long time believed that the also naturally formed, but less soluble, calcium bicarbonate played an important role and that therefore stimulation of CO_2 production was needed. It appears that the focus was so much on acid sulfate soils, that the closely related beneficial process of gypsum formation was not recognized. But eventually, experience in the Wieringermeer clearly showed that the sulfate from seawater in calcium carbonate rich soils led to naturally formed gypsum (Zuur, 1936; Zuur and De Bakker, 1936; Harmsen, 1932; Harmsen et al., 1954), whereas in the absence of calcium carbonate it led to acid sulfate soil (cat clay). Soon it was realized that this newly formed gypsum in the 'new' polders had the same effect as the gypsum amendments required on 'old' land after flooding with seawater. Evidently, just before his 1939 retirement Hissink (1938) had also fully accepted the importance of natural formation of gypsum in new polders. Van der Molen (1957) gave an example of the changes in ionic composition by the formation of gypsum in a newly drained mud without vegetation.

In the Flevopolders only in a few places conditions during sedimentation had been such that the calcium carbonate was largely removed during the sedimentation process, so that drainage would lead to acid sulfate soil (cat clay). It turned out to be a problem mainly in the first of the four Flevopolders, the Wieringermeer Polder (Zuur, 1936). In some of these places mixing with soil rich in $CaCO_3$ from another layer in the soil profile neutralized the acidity; only for approximately 565 ha in the 20,000 ha polder such soil rich in $CaCO_3$ had to be brought in from elsewhere.

After reclamation of a new polder the native sulfate gradually leaches out of the soil profile and after that flooding by seawater may require gypsum amendments during remediation. This was the case in most places inundated by saline water just before and during the Second World War. Only repeated flooding might bring in sufficient new, sulfate rich sediment. This was the case following the strategic inundation of the island Walcheren at the end of the Second World War (see Section 2.4).

In contrast to recommendations two decades earlier, Verhoeven (1965) shows data in support of early gypsum treatment, before the bulk of the salt has been leached.

5. Response of crops and natural vegetation to salinity

The early literature pays much attention to response of crops and vegetations to salinity (Jansen and Janse, 1991; Ponse, 1808; Mayer, 1877; Hissink, 1907a; Smeding, 1919–1920, 1921; Nobel, 1921), but much of it is rather qualitative. Perhaps most influential for later work has been the introduction of the *A*-, *B*- and *C*-values by Nobel (1921) and Smeding (1921), with the suggestion that it is the *C*-value that determines the response.

In the fall of 1921, A.C. van der Have approached the State ARS at Groningen regarding problems with poor growth of crops at many places in the province of Zeeland. The suspected cause was high salinity, particularly in dry periods. However, after a site visit and analysis of soil samples, Hissink and Zijlstra (1922) concluded that the presence of dry sandy layers was a more likely cause. In the analysis of this problem, use was made of the *A*-, *B*- and *C*-values.

The plant physiologist Dr. Klaas Zijlstra was in the period 1917–1939 head of the botanical section at the State ARS at Groningen. His main interests were plant root growth and functioning, winter hardiness of wheat, and establishment and botanical composition of permanent meadows. The 1922 paper with Hissink introduced him to the problems of drought and salinity. In the period 1929–1933, Zijlstra studied germination and growth of a large number of species in water cultures of various salinities. The purpose of these experiments was to determine how far soil desalinization should have progressed to more or less assure that crop seeding was justified and a specific crop would not fail. Due to a 1939 reorganization, in 1940 Zijlstra moved to Wageningen, where in 1944 bombings part of his data were destroyed. Although the original aim of the germination experiments was to determine the risks of salinity in the Wieringermeer Polder and the planned later IJsselmeer Polders, the strategic inundations of the Second World War had widened the interest in the subject. Therefore it was decided to still publish what remained of the data (Zijlstra, 1946).

The germination experiments were done with six different culture solutions: Van der Crone culture solution (1 g KNO_3, 0.5 g $MgSO_4$, 0.25 g $Fe_3(PO_4)_2$, 0.5 g $CaSO_4$, and 0.25 g $Ca_3(PO_4)_2$ per liter), Van der Crone culture solution plus artificial seawater (25.83 g NaCl, 3.10 g $MgCl_2$, 2.11 g $MgSO_4$, 1.27 g $CaSO_4$ per liter), four solutions consisting of Van der Crone culture solutions and dilutions of the artificial seawater such that these dilutions contained, respectively, 15, 10, 5 and 1 g NaCl per liter. The six resulting culture solutions were referred to as 0, 1, 5, 10, 15, and 25.8, containing respectively 2 (Van der Crone), 3.27, 8.36, 14.73, 21.10, and 34.87 (Van der Crone + seawater) g salts per liter. Table 2 shows the percentages germination for the six culture solutions after a certain number of days.

The low concentrations (0, 1, 5 and 10) have little influence on the final percentage of germination, except for strawberry clover and smooth-stalked meadow-grass. The summer wheat and perennial rye-grass are performing the best, with, respectively, still 60% and 33% germination in seawater.

Zijlstra (1946) also shows for all ten species the percentages germination at certain instants during the experiment. Generally, the higher the salt concentration, the more the germination was retarded.

To compensate the loss of much of the data on crop growth, Zijlstra (1946) included 23 photos, most of them showing clear effects. In general salinity causes retardation of germination and restriction of growth. For particular species, the varieties adapted

Table 2
Percentages germination for six culture solutions after a certain number of days.

Species	Salinity						Days
	0	1	5	10	15	25.8	
Spring wheat	97	97	96	100	89	60	13
Green pea	97	97	97	83	47	2	13
White clover	84	81	79	74	31	1	22
Strawberry clover	59	58	45	39	24	1	22
Perennial rey-grass	91	88	88	86	84	33	39
Rough-stalked meadow-grass	98	97	97	96	88	0	39
Smooth-stalked meadow-grass	69	54	42	37	1	0	23
Timothy-grass	88	89	84	75	5	0	23
Meadow fescue	92	92	95	88	91	0	24
Meadow barley grass	97	98	96	96	96	0	23

to the tidal flat environment were found to be much less sensitive to salinity. Fig. 8 shows an example.

The agriculturist/botanist Willem Feekes (1907–1979) made detailed studies of pioneer natural vegetations in the Zuiderzee polders. Following his 1930 MSc at Wageningen University, he was for three years a staff member of the 'Commission for botanical research of the Zuiderzee and its environment'. This resulted in a PhD thesis on the development of the natural vegetation in the Wieringermeer polder (Feekes, 1936). Initially mainly algae were found, but soon water, air, birds and men brought in seeds of plants. While 261 naturally dispersed species were found, only about 50 developed socially and of those only a few over large areas. Nitrophilous species dominated and halophytes were soon displaced by glycophytes, showing the importance of nitrogen and the swift leaching of sodium chloride. In the Flevopolders reclaimed later, the initial salinity was progressively lower and this was reflected in the pioneer natural vegetation (Feekes and Bakker, 1954). Eventually Feekes became best known by his work on developmental aspects of wheat, highlighted by the so-called Feekes scale for wheat growth and development stages.

The strategic inundations before and during the Second World War stimulated a lot of research on crop response to salinity. Rowaan (1951) reviewed most work prior to 1944, while Abell (1954) gives an overview for the period 1944–1954. Field studies of crop response were reported for agricultural crops by Van den Berg (1950) and for horticultural crops by Dorsman and Wattel (1951).

Cornelis van den Berg (1912–1991) started out with the State Agricultural Extension Service. In 1940, after passing a state exam

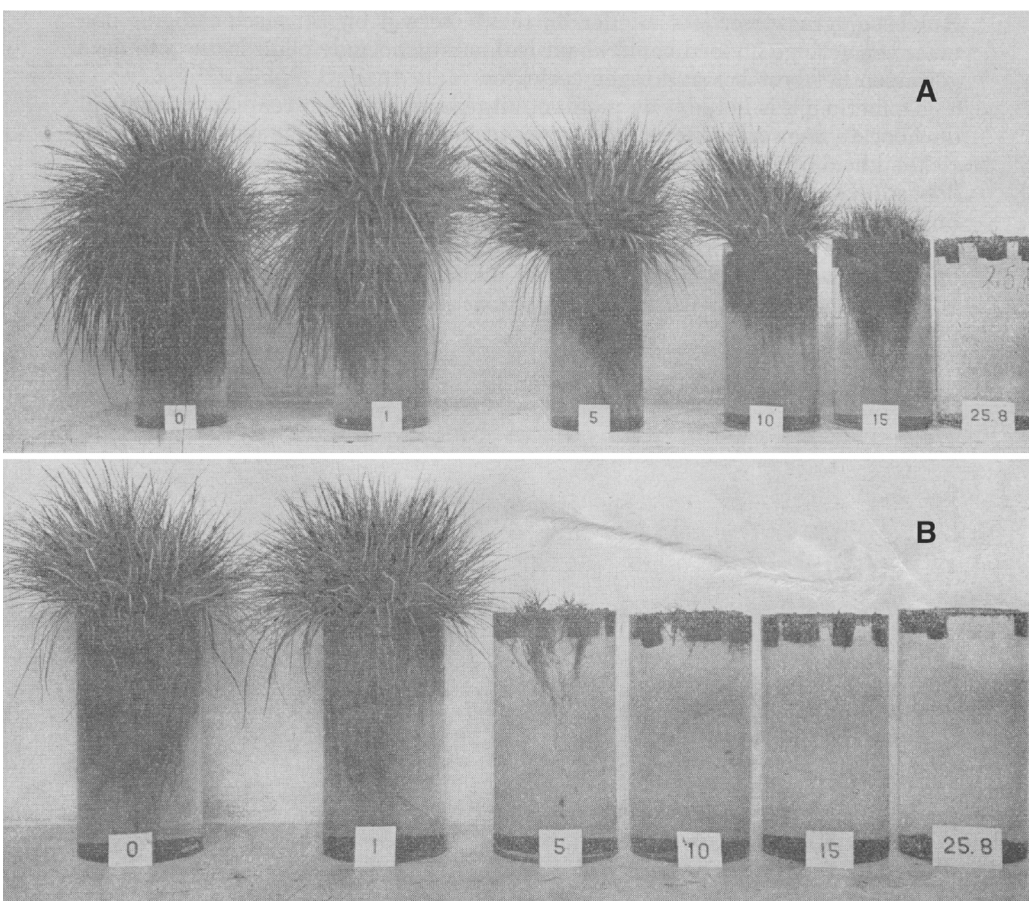

Fig. 8. Red Fescue from A seed collected at a tidal flat, and B commercial seed, both grown in six culture solutions referred to as 0, 1, 5, 10, 15, and 25.8 (see text for explanation).
Source: Adapted from photos 16 and 17 in Zijlstra (1946).

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Table 3
The contents of the cations K, Na, Ca, and Mg, expressed as percentages of the cation-sum in m.e., for nine crops grown on normal marine clay–soils, with the crops arranged in the order of increasing salt sensitivity (Van den Berg, 1952).

Species	Cations			
	K	Na	Ca	Mg
Spring barley	44	9	33	14
Sugar beets	30	33	25	12
Oats	51	12	26	11
Summer wheat	53	2	28	17
Flax	17	13	49	21
Potatoes	21	0	49	30
Horse-beans	25	4	53	17
Peas	15	2	65	18
Red kidney beans	15	1	67	17

equivalent to the required type of high school diploma, he entered Wageningen Agricultural University, where he earned his MSc in 1946. During the Second World War, he was forced to interrupt his study. He went in hiding, worked for the soil improvement firm 'Grontmij' and in 1944/1945 was employed by the Dienst Landbouwherstel (=Agricultural Recovery Service) at Goes in the province of Zeeland. In the period 1946–1956 he was head of the research group at Goes, till 1950 for the Dienst Landbouwherstel and next nominally for the Agricultural Research Station and Soil Science Institute T.N.O. at Groningen. In 1957 he became the founding director of the Institute for Land and Water Management Research (ICW) at Wageningen and held that position till his retirement in 1977. In 1957 the entire water management and salinity research group moved with him from Groningen and Goes to Wageningen. In his PhD thesis, Van den Berg (1952) made an in-depth study of the influence of absorbed salts on growth and yield of agricultural crops on salty soils. I conclude with a few of the highlights of this thesis.

The primary data were observations in 1946, 1947 and 1948 on germination and growth of several crops and on ionic composition of soils and plants in fields with different salinities in the 5–20 cm layer. To extend the range of salinities, in 1947 and 1948 this was complemented with observations in plots that were irrigated with varying quantities of salt water, with six crops growing in every plot of 25 m^2.

During germination the order of sensitivity to salinity was: spring barley < peas < horse-beans < spring wheat < red kidney beans, while for the final yield the order was quite different (Van den Berg, 1950):

$$\text{spring barley} < \text{sugar beats} < \text{oats} < \text{spring wheat} < \text{flax}$$
$$< \text{potatoes} < \text{horse-beans} < \text{peas} < \text{red kidney beans}$$

Salinity retarded crop development: even for spring barley this was very evident from the average number of days after sowing to reach the stages of tillering, shooting and flowering. To study the effect of subsoil salinity on root development, in 1948 peas were grown in 72 pots containing three layers of soil with varying quantities of salt. Root growth was strongly reduced when in the layer 30–60 cm the salinity C, g salt per 100 g water as defined by Eq. (4c), was 6.1 and ceased almost entirely when it was 12.9.

Van den Berg (1952) critically examined the, already at that time, popular idea of high osmotic pressure of the saline soil being the main cause of decrease of crop growth. He concluded that the absorption of salts also plays an important role. Therefore, he payed a lot of attention to the absorption of the various cations and anions and their influence on growth. He found that crop tolerance to salt was closely related to the ability to limit salt accumulation. Table 3 shows, for the cations K, Na, Ca, and Mg, the contents as percentage of the cation-sum in m.e. for nine crops grown on normal marine clay–soils, with the crops arranged in the order of increasing salt sensitivity. Table 3 also shows that the lower the salt sensitivity, the lower is the percentage of calcium in the total of adsorbed cations. Van den Berg (1952) cites several papers that are in line with this. He speculates that the reason is the effect of calcium on the integrity of plasma membranes.

6. Concluding remarks

In the first half of the 20th century, a sequence of serious floods and reclamation projects motivated the collection of a vast amount of field data. While this review is merely exemplary, I hope to have demonstrated that much can be learned from this early Dutch literature. By now, most of it is rarely cited in both the domestic and the international literature. But fortunately, the library of Wageningen Agricultural University and Research Centre (WUR) has made many of the original reports and papers accessible on the Internet, particularly all Wageningen University PhD dissertations. Let us hope that, as far as that is necessary, the contents will eventually pass through the language barrier.

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