Drainage Principles and Applications

ILRI Publication 16
Second Edition (Completely Revised)

Drainage Principles and Applications

H.P. Ritzema (Editor-in-Chief)

International Institute for Land Reclamation and Improvement,
P.O. Box 45, 6700 AA Wageningen, The Netherlands, 1994

The first edition of this publication was issued in a four-volume series, with the first volume appearing in 1972 and the following three volumes appearing in 1973 and 1974. The second edition has now been completely revised and is published in one volume.

The aims of ILRI are:

- To collect information on land reclamation and improvement from all over the world;
- To disseminate this knowledge through publications, courses, and consultancies;
- To contribute – by supplementary research – towards a better understanding of the land and water problems in developing countries.

ISBN 90 70754 3 39
Printed in The Netherlands

Preface

Thirty-three years ago, the first International Course on Land Drainage was held at ILRI in Wageningen. Since then, almost 1000 participants from more than 100 countries have attended the Course, which provides three months of post-graduate training for professionals engaged in drainage planning, design, and management, and in drainage-related research and training. In the years of its existence, the Course has proved to be the cornerstone of ILRI's efforts to contribute to the development of human resources.

From the beginning, notes of the Course lectures were given to the participants to lend support to the spoken word. Some twenty-five years ago, ILRI decided to publish a selection of these lecture notes to make them available to a wider audience. Accordingly, in 1972, the first volume appeared under the title *Drainage Principles and Applications*. The second, third, and fourth volumes followed in the next two years, forming, with Volume I, a set that comprises some 1200 pages. Since then, *Drainage Principles and Applications* has become one of ILRI's most popular publications, with sales to date of more than 8000 copies worldwide.

In this third edition of the book, the text has been completely revised to bring it up to date with current developments in drainage and drainage technology. The authors of the various chapters have used their lecture-room and field experience to adapt and restructure their material to reflect the changing circumstances in which drainage is practised all over the world. Remarks and suggestions from Course participants have been incorporated into the new material. New figures and a new lay-out have been used to improve the presentation. In addition, ILRI received a vast measure of cooperation from other Dutch organizations, which kindly made their research and field experts available to lecture in the Course alongside ILRI's own lecturers.

To bring more consistency into the discussions of the different aspects of drainage, the four volumes have been consolidated into one large work of twenty-six chapters. The book now includes 550 figures, 140 tables, a list of symbols, a glossary, and an index. It has new chapters on topical drainage issues (e.g. environmental aspects of drainage), drainage structures (e.g. gravity outlets), and the use of statistical analysis for drainage and drainage design. Current drainage practices are thoroughly reviewed, and an extensive bibliography is included. The emphasis of the whole lies upon providing clear explanations of the underlying principles of land drainage, which, wisely applied, will facilitate the type of land use desired by society. Computer applications in drainage, which are based on these principles, are treated at length in other ILRI publications.

The revision of this book was not an easy job. Besides the authors, a large number of ILRI's staff gave much of their time and energy to complete the necessary work. ILRI staff who contributed to the preparation of this third edition were:

Editorial Committee	R. van Aart
	M.G. Bos
	H.M.H. Braun
	K.J. Lenselink
	H.P. Ritzema
Members prior to 1993	J.G. van Alphen
	Th. M. Boers
	R. Kruijne
	N.A. de Ridder†
	G. Zijlstra
Language Editors	M.F.L. Roche
	M.M. Naeff
Drawings	J. van Dijk
Word Processing	J.B.H. van Dillen
Design and Layout	J. van Dijk
	J. van Manen

I want to thank everyone who was involved in the production of this book. It is my belief that their combined efforts will contribute to a better, more sustainable, use of the world's precious land and water resources.

Wageningen, June 1994

M.J.H.P. Pinkers
Director
International Institute for
Land Reclamation and Improvement/ILRI

Contents

8 Subsurface Flow to Drains 263

H.P. Ritzema

9 Seepage and Groundwater Flow 305

N.A. de Ridder and G. Zijlstra

M.G. Bos and W. Wolters

J.W. van Hoorn and J.G. van Alphen

1 Land Drainage: Why and How?

M.G.Bos[1] and Th.M.Boers[1]

1.1 The Need for Land Drainage

The current world population is roughly estimated at 5000 million, half of whom live in developing countries. The average annual growth rate in the world population approximates 2.6%. To produce food and fibre for this growing population, the productivity of the currently cultivated area must be increased and more land must be cultivated.

Land drainage, or the combination of irrigation and land drainage, is one of the most important input factors to maintain or to improve yields per unit of farmed land. Figure 1.1 illustrates the impact of irrigation water management and the control of the watertable.

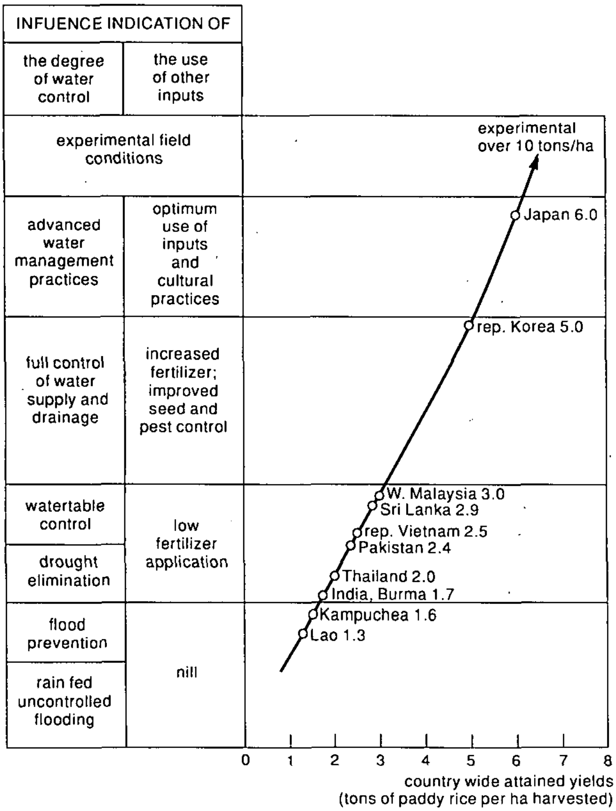

Figure 1.1 Influence of water control, improved management, and additional inputs on yields of paddy rice (FAO 1979)

---

[1] International Institute for Land Reclamation and Improvement

To enlarge the currently cultivated area, more land must be reclaimed than the land that is lost (e.g. to urban development, roads, and land degradation). In some areas, however, land is a limiting resource. In other areas, agriculture cannot expand at the cost of nature.

Land drainage, as a tool to manage groundwater levels, plays an important role in maintaining and improving crop yields:

- It prevents a decrease in the productivity of arable land due to rising watertables and the accumulation of salts in the rootzone;
- A large portion of the land that is currently not being cultivated has problems of waterlogging and salinity. Drainage is the only way to reclaim such land.

The definition of land drainage, as given in the constitution of the International Commission on Irrigation and Drainage/ICID (1979), reads:

> 'Land drainage is the removal of excess surface and subsurface water from the land to enhance crop growth, including the removal of soluble salts from the soil.'

In this publication, we shall adopt the ICID definition because it is generally known and is applicable all over the world. Drainage of agricultural land, as indicated above, is an effective method to maintain a sustainable agricultural system.

1.2 The History of Land Drainage

Records from the old Indus civilizations (i.e. the Mohenjo-Daro and the Harappa) show that around 2500 B.C. the Indus Valley was farmed. Using rainfall and floodwater, the farmers there cultivated wheat, sesame, dates, and cotton. Surplus agricultural produce was traded for commodities imported from neighbouring countries. Irrigation and drainage, occurring as natural processes, were in equilibrium: when the Indus was in high stage, a narrow strip of land along the river was flooded; at low stage, the excess water was drained (Snelgrove 1967).

The situation as sketched for the Indus Valley also existed in other inhabited valleys, but a growing population brought the need for more food and fibre. Man increased his agricultural area by constructing irrigation systems: in Mesopotamia c. 3000 B.C. (Jacobsen and Adams 1958), in China from 2627 B.C. (King 1911, as quoted by Thorne and Peterson 1949), in Egypt c. 3000 B.C. (Gulhati and Smith 1967), and, around the beginning of our era, in North America, Japan, and Peru (Kaneko 1975; Gulhati and Smith 1967).

Although salinity problems may have contributed to the decline of old civilizations (Maierhofer 1962), there is evidence that, in irrigated agriculture, the importance of land drainage and salinity control was understood very early. In Mesopotamia, control of the watertable was based on avoiding an inefficient use of irrigation water and on the cropping practice of weed-fallow in alternate years. The deep-rooted crops *shoq* and *agul* created a deep dry zone which prevented the rise of salts through capillary action (Jacobsen and Adams 1958). During the period from 1122 B.C. to

220 A.D., saline-alkali soils in the North China Plain and in the Wei-Ho Plain were ameliorated with the use of a good irrigation and drainage system, by leaching, by rice planting, and by silting from periodic floods (Wen and Lin 1964).

The oldest known polders and related structures were described by Homer in his *Iliad.* They were found in the Periegesis of Pausanias (Greece). His account is as follows (see Knauss 1991 for details):

> 'In my account of Orchomenos, I explained how the straight road runs at first besides the gully, and afterwards to the left of the flood water. On the plain of the Kaphyai has been made a dyke of earth, which prevents the water from the Orchomenian territory from doing harm to the tilled land of Kaphyai. Inside the dyke flows along another stream, in size big enough to be called a river, and descending into a chasm of the earth it rises again ... (at a place outside the polder).'

In the second century B.C., the Roman Cato referred to the need to remove water from wet fields (Weaver 1964), and there is detailed evidence that during the Roman civilization subsurface drainage was also known. Lucius Inunius Moderatus Columella, who lived in Rome in the first century, wrote twelve books entitled: *'De Re Rustica'* in which he described how land should be made suitable for agriculture (Vučić 1979) as follows:

> 'A swampy soil must first of all be made free of excess water by means of a drain, which may be open or closed. In compact soils, ditches are used; in lighter soils, ditches or closed drains which discharge into ditches. Ditches must have a side slope, otherwise the walls will collapse. A closed drain is made of a ditch, excavated to a depth of three feet, which is filled to a maximum of half this depth with stones or gravel, clean from soil. The ditch is closed by backfilling with soil to the surface. If these materials are not available, bushes may be used, covered with leaves from cypress or pine trees. The outlet of a closed drain into a ditch is made of a large stone on top of two other stones.'.

During the Middle Ages, in the countries around the North Sea, people began to reclaim swamps and lacustrine and maritime lowlands by draining the water through a system of ditches. Land reclamation by gravity drainage was also practised in the Far East, for instance in Japan (Kaneko 1975). The use of the windmill to pump water made it possible to turn deeper lakes into polders, for example the 7000-ha Beemster Polder in The Netherlands in 1612 (Leeghwater 1641). The word polder, which originates from the Dutch language, is used internationally to indicate 'a low-lying area surrounded by a dike, in which the water level can be controlled independently of the outside water'.

During the 16th, 17th, and 18th centuries, drainage techniques spread over Europe, including Russia (Nosenko and Zonn 1976), and to the U.S.A. (Wooten and Jones 1955). The invention of the steam engine early in the 19th century brought a considerable increase in pumping capacity, enabling the reclamation of larger lakes such as the 15 000-ha Haarlemmermeer, southwest of Amsterdam, in 1852.

In the 17th century, the removal of excess water by closed drains, essentially the same as described above by Columella, was introduced in England. In 1810, clay tiles started to be used, and after 1830 concrete pipes made with portland cement (Donnan 1976). The production of drain pipes was first mechanized in England and, from there, it spread over Europe and to the U.S.A. in the mid-19th century (Nosenko and Zonn 1976). Excavating and trenching machines, driven by steam engines, made their advent in 1890, followed in 1906 by the dragline in the U.S.A. (Ogrosky and Mockus 1964).

The invention of the fuel engine in the 20th century has led to the development of high-speed installation of subsurface drains with trenching or trenchless machines. This development was accompanied by a change from clay tiles to thick-walled, smooth, rigid plastic pipes in the 1940's, followed by corrugated PVC and polyethylene tubing in the 1960's. Modern machinery regulates the depth of drains with a laser beam.

The high-speed installation of subsurface drains by modern specialized machines is important in waterlogged areas, where the number of workable days is limited, and in intensively irrigated areas, where fields are cropped throughout the year. In this context, it is good to note that mechanically-installed subsurface drainage systems are not necessarily better than older, but manually-installed systems. There are many examples of old drains that still function satisfactorily, for example a 100-year-old system draining 100 ha, which belongs to the Byelorussian Agricultural Academy in Russia (Nosenko and Zonn 1976).

Since about 1960, the development of new drainage machinery was accompanied by the development of new drain-envelope materials. In north-western Europe, organic filters had been traditionally used. In The Netherlands, for example, pre-wrapped coconut fibre was widely applied. This was later replaced by synthetic envelopes. In the western U.S.A., gravel is more readily available than in Europe, and is used as drain-envelope material. Countries with arid and semi-arid climates similar to the western U.S.A. (e.g. Egypt and Iraq) initially followed the specifications for the design of gravel filters given by the U.S. Bureau of Reclamation/USBR (1978). The high transport cost of gravel, however, guided designers to pre-wrapped pipes in countries like Egypt (Metzger et al. 1992), India (Kumbhare et al. 1992), and Pakistan (Honeyfield and Sial 1992).

1.3 From the Art of Drainage to Engineering Science

As was illustrated in the historical sketch, land drainage was, for centuries, a practice based on local experience, and gradually developed into an art with more general applicability. It was only after the experiments of Darcy in 1856 that theories were developed which allowed land drainage to become an engineering science (Russell 1934; Hooghoudt 1940; Ernst 1962; Kirkham 1972; Chapter 7). And although these theories now form the basis of modern drainage systems, there has always remained an element of art in land drainage. It is not possible to give beforehand a clear-cut theoretical solution for each and every drainage problem: sound engineering judgement on the spot is still needed, and will remain so.

The rapid development of theories from about 1955 to about 1975 is well illustrated by two quotations from Van Schilfgaarde. In 1957 he wrote:

> 'Notwithstanding the great progress of recent years in the development of drainage theory, there still exists a pressing need for a more adequate analytical solution to some of the most common problems confronting the design engineer.'

In 1978, the same author summarized the state of the art for the International Drainage Workshop at Wageningen (Van Schilfgaarde 1979) as:

> 'Not much will be gained from the further refinement of existing drainage theory or from the development of new solutions to abstractly posed problems. The challenge ahead is to imaginatively apply the existing catalogue of tricks to the development of design procedures that are convenient and readily adapted by practising engineers.'

With the increasing popularity of computers, many of these 'tricks' are combined in simulation models and in design models like SWATRE (Feddes et al. 1978; Feddes et al. 1993), SALTMOD (Oosterbaan and Abu Senna 1990), DRAINMOD (Skaggs 1980), SGMP (Boonstra and de Ridder 1981), and DrainCAD (Liu et al. 1990). These models are powerful tools in evaluating the theoretical performance of alternative drainage designs. Nowadays, however, performance is not only viewed from a crop-production perspective, but increasingly from an environmental perspective. Within the drained area, the environmental concern focuses on salinity and on the diversity of plant growth. Downstream of the drained area, environmental problems due to the disposal of drainage effluent rapidly become a major issue.

Currently, about 170 million ha are served by drainage and flood-control systems (Field 1990). In how far the actual performance of these systems can be forecast by the above models, however, is largely unknown. There is a great need for field research in this direction.

The purpose of this manual is, in accordance with the aims of ILRI, to contribute to improving the quality of land drainage by providing drainage engineers with 'tools' for the design and operation of land drainage systems.

1.4 Design Considerations for Land Drainage

In the ICID definition of drainage, 'the removal of excess water' indicates that (land) drainage is an action by man, who must know how much excess water should be removed. Hence, when designing a system for a particular area (Figure 1.2), the drainage engineer must use certain criteria (Chapter 17) to determine whether or not water is in excess. A (ground-)water balance of the area to be drained is the most accurate tool to calculate the volume of water to be drained (Chapter 16).

Before the water balance of the area can be made, a number of surveys must be undertaken, resulting in adequate hydrogeological, hydropedological, and topographic maps (Chapters 2, 3, and 18, respectively). Further, all (sub-)surface water inflows and outflows must be measured or estimated (Chapters 4, 10, and 16). Precipitation

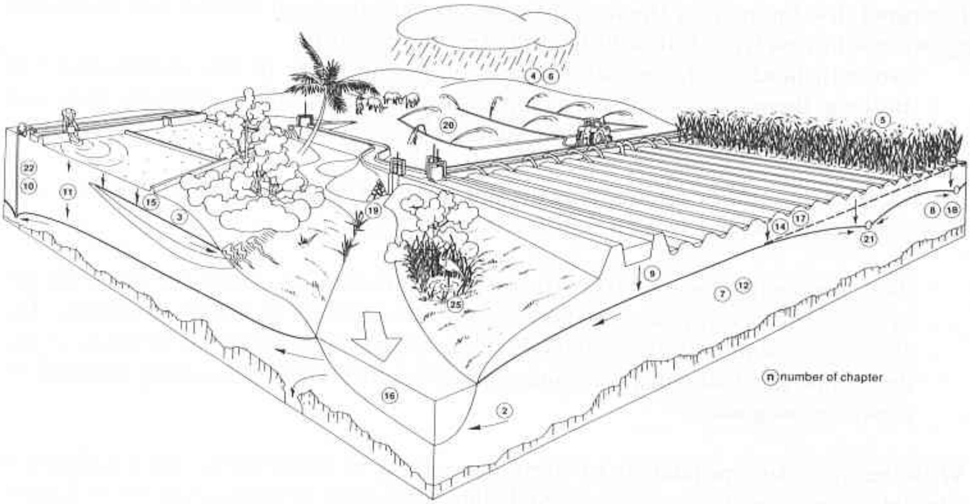

Figure 1.2 The interrelationship between the chapters of this manual

and the relevant evapotranspiration data from the area must be analyzed (Chapters 4, 5, and 6). In addition, all relevant data on the hydraulic properties of the soil should be collected (Chapter 12). The above processes in drainage surveys should be based on a sound theoretical knowledge of a variety of subjects. The importance of this aspect of drainage engineering is stressed by the fact that seventeen of the twenty-six chapters of this book deal with surveys, procedures, and theory.

In some cases, the proper identification of the source of 'excess water' will avoid the construction of a costly drainage system. For example:

- If irrigation water causes waterlogging, the efficiency of water use in the water-supply system and at field level should be studied in detail and improved (Chapters 9 and 14);
- If surface-water inflow from surrounding hills is the major cause of excess water in the area, this water could be intercepted by a hillside drain which diverts the water around the agricultural area (Chapters 19 and 20);
- If the problem is caused by the inflow of (saline) groundwater, this subsurface inflow could be intercepted by a row of tubewells (Chapter 22), which dispose of their effluent into a drain that bypasses the agricultural area;
- If the area is partially inundated because a natural stream has insufficient discharge capacity to drain the area, a reconstruction of the stream channel may solve the drainage problem (Chapter 19).

If, however, the origin of the excess water lies in the agricultural area itself (e.g. from excess rainfall or extra irrigation water that must be applied to satisfy the leaching requirement for salinity control; Chapters 11 and 15), then the installation of drainage facilities within the agricultural area should be considered. Usually, these facilities consist of (Figure 1.3) (i) a drainage outlet, (ii) a main drainage canal, (iii) some collector drains, and (iv) field drains.

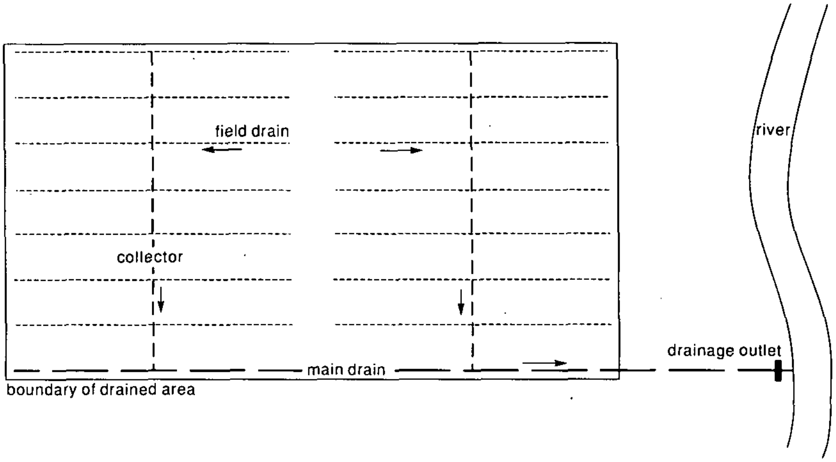

Figure 1.3 Schematic drainage system

The main drainage canal (ii) is often a canalized stream which runs through the lowest parts of the agricultural area. It discharges its water via a pumping station or a tidal gate into a river, a lake, or the sea at a suitable outlet point (i) (Chapters 23 and 24).

Main drainage canals collect water from two or more collector drains. Although collector drains (iii) preferably also run through local low spots, their spacing is often influenced by the optimum size and shape of the area drained by the selected field-drainage system. The layout of the collector drains, however, is still rather flexible since the length of the field drains can be varied, and sub-collector drains can be designed (Chapter 19). The length and spacing of the field or lateral drains (iv) will be as uniform as is applicable. Both collector and field drains can be open drains or pipe drains. They are determined by a wide variety of factors such as topography, soil type, farm size, and the method of field drainage (Chapters 20, 21, and 22).

The three most common techniques used to drain excess water are: a) surface drainage, b) subsurface drainage, and c) tubewell drainage.

a) Surface drainage can be described as (ASAE 1979) 'the removal of excess water from the soil surface in time to prevent damage to crops and to keep water from ponding on the soil surface, or, in surface drains that are crossed by farm equipment, without causing soil erosion'. Surface drainage is a suitable technique where excess water from precipitation cannot infiltrate into the soil and move through the soil to a drain, or cannot move freely over the soil surface to a (natural) channel. This technique will be discussed in Chapter 20;
b) Subsurface drainage is the 'removal of excess soil water in time to prevent damage to crops because of a high groundwater table'. Subsurface field drains can be either open ditches or pipe drains. Pipe drains are installed underground at depths varying from 1 to 3 m. Excess groundwater enters the perforated field drain and flows by gravity to the open or closed collector drain. The basics of groundwater flow will be treated in Chapter 7, followed by a discussion of the flow to subsurface

drains in Chapter 8. The techniques of subsurface drainage will be dealt with in Chapter 21.

c) Tubewell drainage can be described as the 'control of an existing or potential high groundwater table or artesian groundwater condition'. Most tubewell drainage installations consist of a group of wells spaced with sufficient overlap of their individual cones of depression to control the watertable at all points in the area. Flow to pumped wells, and the extent of the cone of depression, will be discussed in Chapter 10. The techniques of tubewell drainage systems will be treated in Chapter 22.

When draining newly-reclaimed clay soils or peat soils, one has to estimate the subsidence to be expected, because this will affect the design. This problem, which can also occur in areas drained by tubewells, is discussed in Chapter 13.

Regardless of the technique used to drain a particular area, it is obvious that it must fit the local need to remove excess water. Nowadays the 'need to remove excess water' is strongly influenced by a concern for the environment. The design and operation of all drainage systems must contribute to the sustainability of agriculture in the drained area and must minimize the pollution of rivers and lakes from agricultural return flow (Chapter 25).

References

ASAE, Surface Drainage Committee 1979. Design and construction of surface drainage systems on farms in humid areas. Engineering Practice EP 302.2, American Society of Agricultural Engineers, Michigan, 9 p.

Boonstra, J. and N.A. de Ridder 1981. Numerical modelling of groundwater basins : a user-oriented manual. ILRI Publication 29, Wageningen. 226 p.

Donnan, W.W. 1976. An overview of drainage worldwide. In: Third National Drainage Symposium; proceedings. ASAE Publication 1-77, St. Joseph, pp. 6-9.

Ernst, L.F. 1962. Grondwaterstromingen in de verzadigde zone en hun berekening bij aanwezigheid van horizontale evenwijdige open leidingen. Verslagen Landbouwkundige Onderzoekingen 67-15. PUDOC, Wageningen, 189 p.

Feddes, R.A., P.J. Kowalik and H. Zaradny 1978. Simulation of field water use and crop yield. Simulation Monographs, PUDOC, Wageningen, 189 p.

Feddes, R.A., M. Menenti, P. Kabat and W.G.M. Bastiaansen 1993. Is large-scale modelling of unsaturated flow with areal average evaporation and surface soil moisture as estimated from remote sensing feasible? Journal Hydrology 143, pp.125-152.

Field, W.P. 1990. World irrigation. Irrigation and Drainage Systems, 4, 2, pp. 91-107.

FAO 1979. The on-farm use of water. FAO Committee on Agriculture, Rome, 22 p.

Gulhati, N.D. and W.Ch. Smith 1967. Irrigated agriculture : a historical review. In: R.M. Hagan, H.R. Haise and T.W. Edminster (eds.), Irrigation of agricultural lands. Agronomy 11, American Society of Agronomy, Madison. pp. 3-11.

Hooghoudt, S.B. 1940. Algemeene beschouwing van het probleem van de detailontwatering en de infiltratie door middel van parallel loopende drains, greppels, slooten en kanalen. Verslagen van landbouwkundige onderzoekingen 46 (14) B, Algemeene Landsdrukkerij, 's-Gravenhage, 193 p.

Honeyfield, H.R. and B.A. Sial 1992. Envelope design for sub-surface drainage system for Fordwah Eastern Sadiqia (South) Project. In: W.F. Vlotman, Proceedings 5th international drainage workshop : subsurface drainage on problematic irrigated soils : sustainability and cost effectiveness. International Waterlogging and Salinity Research Institute, Lahore, pp. 5.26-5.37

ICID 1979. Amendments to the constitution, Agenda of the International Council Meeting at Rabat. International Commission on Irrigation and Drainage, Morocco. ICID, New Delhi, pp. A-156-163.

Jacobsen, Th. and R.M. Adams 1958. Salt and silt in ancient mesopotamian agriculture. Science 128, 3334, pp. 1251-1258.

Kaneko, R. 1975. Agricultural engineering activities in Japan. Irrigation and drainage course, Japan International Cooperation Agency. Uchihara International Agricultural Training Centre, 160 p.

King, F.H. 1911. Farmers of forty centuries, or permanent agriculture in China, Korea and Japan. Rodale, Emmaus, 441 p.

Kirkham, D. 1972. Problems and trends in drainage research, mixed boundary conditions. Soil Science 113, 4, pp. 285-293.

Knauss, J. 1991. Arkadian and Boiotian Orchomenos, centres of Mycenaean hydraulic engineering. Irrigation and Drainage Systems 5, 4, pp. 363-381.

Kumbhare, P.S., K.V. Rao, K.V.G. Rao, H.S. Chauhan and R.J. Oosterbaan 1992. Performance of some synthetic drain filter materials in sandy loam soils. In: W.F. Vlotman, Proceedings 5th international drainage workshop : subsurface drainage on problematic irrigated soils : sustainability and cost effectiveness. International Waterlogging and Salinity Research Institute, Lahore, pp. 5.97-5.104.

Leeghwater, J.A. 1641. In: Haarlemmermeerboek, 1838 13e dr. Amsterdam, 192 p.

Lin, F., P. Campling and P. Pauwels 1990. Drain CAD: a comprehensive and flexible software package for the automation of the drainage design of agricultural drainage systems. User Manual. Center for Irrigation Engineering, Leuven, Belgium. 101. p.

Maierhofer, C.R. 1962. Drainage in irrigation : a world problem I and II. The reclamation era, 48, 3, pp. 73-76 and 4, pp. 103-105.

Metzger, J.F., J. Gallichand, M.H. Amer and J.S.A. Brichieri-Colombi 1992. Experiences with fabric envelope selection in a large subsurface drainage project in Egypt. In: W.F. Vlotman, Proceedings 5th international drainage workshop : subsurface drainage on problematic irrigated soils : sustainability and cost effectiveness. International Waterlogging and Salinity Research Institute, Lahore, pp. 5.77-5.87.

Nosenko, P.P. and I.S. Zonn 1976. Land drainage in the world. ICID Bulletin, 25, 1, pp. 65-70.

Ogrosky, H.O. and V. Mockus 1964. Hydrology of agricultural lands. In: V.T. Chow (ed.), Handbook of applied hydrology. McGraw-Hill, New York, 22, pp. 21-97.

Oosterbaan, R.J. and M. Abu Senna 1990. Using SALTMOD to predict drainage and salinity in the Nile Delta. In: Annual Report 1990, ILRI, Wageningen, pp. 63-74.

Russell, J.L. 1934. Scientific research in soil drainage. Journal Agricultural Science 24, pp. 544-573.

Skaggs, R.W. 1980. Drainmod-reference report: Methods for design and evaluation of drainage water management systems for soils with high water tables. U.S.D.A. Soil Cons. Service, Forth Worth, 190 p.

Snelgrove, A.K. 1967. Geohydrology in the Indus River in West Pakistan. Sind University Press, Hyderabad, 200 p.

Thorne, D.W. and H.B. Peterson 1949. Irrigated soils, their fertility and management. The Blakiston Company, Philadelphia, 288 p.

USBR 1978. Drainage manual. U.S. Department of the Interior, Bureau of Reclamation, Denver, 286 p.

Van Schilfgaarde, J. 1957. Approximate solutions to drainage flow problems. In: J.N. Luthin (ed.), Drainage of Agricultural Lands. Agronomy 7. American Society of Agronomy, Madison, pp. 79-112.

Van Schilfgaarde, J. 1979. Progress and problems in drainage design. In: J. Wesseling (ed.), Proceedings of the International Drainage Workshop. ILRI Publication 25, Wageningen, pp. 633-644.

Vučić, N. 1979. Irrigation of agricultural crops. Faculty of Agriculture, Novi Sad, 567 p.

Weaver, M.M. 1964. History of tile drainage. Weaver, New York, 343 p.

Wen, H.J. and C.L. Lin 1964. The distribution and reclamation of saline-alkali soils of the North China Plain and the Wei-Ho Plain in the period of the Chou-Han Dynasties. Acta Pedologica Sinica 12, 1, pp. 1-9. (In Chinese with English abstract).

Wooten, H.H. and L.A. Jones 1955. The history of our drainage enterprises. In: Water, the Yearbook of agriculture. U.S. Department of Agriculture, Washington, 478-491 p.