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Drain for Gain: Managing salinity in irrigated lands - A review

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Abstract

At present, about 299 Mha (or 18%) of the arable and permanent cropped areas worldwide are irrigated and, although drainage is an important component of irrigation, only 22% of these irrigated lands are drained. As a consequence, salinity and waterlogging problems affect about 10-16% of these areas because the natural drainage is not sufficient for controlling soil salinity levels. Additional, artificial drainage is needed to address this problem. Although the total area under irrigation continues to grow, very little is being invested in drainage systems to sustain the investments in irrigation. This is due in part to drainage being at the end of the pipeline where it has to clean up the "mess" that other activities leave behind: i.e. salts brought in by irrigation water, residues of fertilisers and pesticides etc. However, to move towards more reasonable sustainability, drainage has to be given its appropriate role in agricultural water management. In this paper seven reasons why drainage is needed are discussed, followed by seven aspects of why drainage is different than irrigation, and seven challenges to making drainage work. The paper concludes with a three-step approach reversing the negative trends in drainage management that result in salinity build-up in irrigated lands.

Highlights (max 85 characters)

- The low priority of drainage in irrigated agriculture is explained;
- Seven reasons why irrigated agriculture needs drainage are discussed;
- Seven reasons why drainage is different than irrigation are discussed;
- Challenges making drainage work are outlined;
- An approach revising salinity build-up in irrigated lands is presented.

Keywords (max 6)

Drainage; Waterlogging; Agricultural water management

1. Introduction

At present, about 299 Mha (or 18%) of the arable and permanent cropped area worldwide are irrigated (International Commission on Irrigation and Drainage (ICID), 2015), contributing as much as 40% of the gross agricultural output (Faures et al., 2007). However, despite the importance of drainage as a component of irrigation, only about 22 % of these irrigated lands are drained (Schultz et al., 2007). In humid regions drainage is needed to control soil water for better aeration, higher temperatures, and easier workability; by contrast in arid and semi-arid regions its primary function is to prevent irrigation-induced waterlogging and salinization of the soil. In regions with prevailing dry and high evaporative conditions, increased salt concentrations and river depletion have become two inevitable collaterals of irrigated crop production.

Salinity build-up is a slow process so farmers, engineers and government departments all see irrigation as a need for today and salinization as a problem of tomorrow. Thus drainage has a lower priority than other agricultural activities like irrigation, on-farm management, etc. This is due in part to drainage being at the end of the pipeline: to clean up the "mess" other activities leave behind like salts brought in by irrigation water, residues of fertilisers and pesticides, etc. Most people do not like to be reminded of this and therefore ignore it.

On top of this, irrigation needs are changing triggered by land use changes. In the past, large-scale irrigation systems were built to supply water to farmers for a limited number of crops, mainly irrigated by surface water diverted from rivers, streams or lakes. In the last decades there has been a gradual change in land use: urbanisation and non-agricultural uses, including ecosystem services, are increasing. This has changed the demand for water. Global climate change may further exacerbate the pressure on supply and demand through changing temperatures and long-term variation in annual precipitation amounts and regional distribution patterns. In addition to the changing climate, cropping patterns are diversifying and field irrigation methods are changing (De Fraiture et al., 2010). Irrigation water demands are no longer homogeneous and surface water is often supplemented with water from other sources: groundwater extraction, (treated) waste water and/or the re-use of drainage water (Singh, 2014). As a result river basins are closing, water resources are becoming increasingly contested, and stakeholders engage in different ways to influence water policies and intervention programs.

The aforementioned developments have already led to certain changes in water management, however more awareness of the entire system is needed. For example, recent approaches that include multiple water services, have repercussions for the hydraulic design of irrigation and drainage systems (Renault et al., 2007). To optimize water use and control salinity it is important to match rainfall, irrigation and drainage (Van Hoorn and Van Alphen, 2006). In irrigated agriculture, the only agronomically significant criterion for installing drainage is the commercial crop yield. This makes the need for drainage complex as the direct effects of drainage, i.e. controlling the water table and discharge, are mainly determined by the hydrological conditions, the hydraulic properties of the soil, and the physical characteristics of the drainage system (Oosterbaan, 1988). Salinity control is only an indirect effect of drainage, thus water and salt balance analyses are needed to check whether the salt build-up in the root zone stays within acceptable limits (Ayers and Westcot, 1994) and to informed decisions in irrigation and leaching management. For these analyses, the crop tolerance to salinity has to be know. Soil salinity, however, varies in both time and space and the salt tolerance depends upon many plant, soil, water, and environmental parameters. The crop tolerance to salinity is usually expressed as the yield decrease for a given level of soluble salts in the root zone (Maas and Hoffman, 1997). The most common method for measuring soil salinity is to determine the electrical conductivity of the saturation extract (EC_e) in the root zone. Based on an extensive literature review, Maas and Hoffman (1997) concluded that crop yield as a function of average root zone salinity could be described reasonably well with a piecewise linear response function characterized by this salinity “threshold” value below which the yield is not affected, and above which yield decrease linearly with salinity. (Van Genuchten and Gupta, 1993) used the database complied by Maas and Hoffman (1997) to derive a single dimensionless curve to describe the salt tolerance of most crops. More recent studies indicate that the these models overestimate the above mentioned salinity threshold value and nonlinear salinity models are more accurate (Homaee et al., 2002; Saadat and Homaee, 2015). These threshold values for salinity are used to calculate the leaching requirement, which is the fraction of irrigation water entering the soil that must flow effectively through and beyond the root zone to prevent a build-up of salinity resulting from the addition of solutes in the water (Van Hoorn and Van Alphen, 2006). Artificial drainage is needed if the natural hydrological and soil conditions cannot cope with this extra amount of irrigation water. Traditional surface irrigation methods, like basin and furrow irrigation, have field application efficiencies that are generally lower than the leaching requirement; but modern irrigation methods, like sprinkler or drip, can have field application efficiencies that are higher than the required leaching (Brouwer et al., 1989). In light of all the changes in water demand, supply and use, the role of (subsurface) drainage in arid and semi-arid regions has changed from a single-purpose measure for controlling waterlogging and/or salinity to an essential element of integrated water management under multiple land use scenarios (Schultz et al., 2007).

Although subsurface drainage practices have evolved from manual to large-scale mechanized installations (Ritzema et al., 2006), the fundamental design methodology and management criteria have not changed in the last 50 years (Ayars and Evans, 2015). Although the installed systems are technically sound and cost-effective, drainage development has lagged behind irrigation development (Ritzema, 2009). This is mainly because drainage systems tend to be designed and implemented by government, with the users, the majority of whom are small farmers, having little responsibility for them and providing little input. Often, these farmers are poor and do not have the means to invest in drainage themselves. In the traditional top-down approach standardized designs are generally used with little or no consideration of the location-specific conditions and farmers' needs and preferences. Furthermore, the emphasis has been primarily on the technical aspects (physical infrastructure), while the organizational aspects (institutional infrastructure) of the drainage systems have been largely neglected (Scheuman, 1997) . A shift to a more service-oriented approach, which has been promoted since the 1990s, has not gained much of a foothold in practice. A study reviewing the completed and active drainage projects financed by the World Bank identified multiple limitations of the traditional approach, including a lack of an integrated approach, threats to drainage system sustainability, shortcomings in governance and institutional infrastructure, policy and legal constraints, weak participatory planning and inadequate private sector involvement as well as a lack of focus on poverty (World Bank, 2004).

In response to these findings the World Bank developed the Drainage and Integrated Analytical Framework (DRAINFRAME) approach to overcome these limitations (Abdel-Dayem et al., 2004). The application of DRAINFRAME in Egypt and Pakistan has shown that it offers a useful approach and methodology for analysing water management situations in an integrated manner and can offer useful contributions to the project planning cycle (Slootweg et al., 2007). It was also concluded, however, that the approach needs a more systematic elaboration of the stakeholders to ensure their views and preferences are taken into consideration and a reliable methodology for evaluating the institutional setting of water management situations. Furthermore, more attention must be given to satisfying increasingly stringent environmental and water quality criteria, ensuring multi-stakeholder participation and recognition of social benefits and to meeting economic criteria. In order to attain more sustainability, drainage has to be given its appropriate role in agricultural water management in irrigated lands.

To bring drainage back into the lime-light, and inspired by the work of (Scheuman, 1997), the balance of this article discusses seven reasons why drainage is needed, seven aspects of why drainage is different than irrigation and seven challenges to making drainage work. Based on these challenges, I present a three-step approach to stop the negative trend in salinity build-up in irrigated lands.

2. Seven reasons why drainage is needed

2.1 Drainage protects the resource base for food production

In arid and semi-arid regions, drainage can prevent waterlogging and root zone salinity in irrigated lands. In humid and sub-humid regions, drainage removes excess water reducing the risk of crop failure and increases farmer's freedom of crop choice and varieties. And in temperate regions, drainage enables the reclamation of waterlogged areas and optimises growing conditions for crops (Pearce and Dennecke, 2001); (Ritzema et al., 2007). Global arable land and permanent crops spanned 1 371 MHa in 1961 and increased to 1 533 MHa in 2009, but it is expected to reduce again to 1 385 MHa in 2060 as a result of the ongoing urbanization (Ausubel et al., 2013). Thus the increase in agricultural production, needed to feed the growing world population, will have to come – at least in part - from investments in improved irrigation and drainage practices in existing agricultural areas (Schultz and de Wrachien, 2002).

World-wide, salinity and the related waterlogging problems affect about 10–16% of the irrigated lands. The annual rate of land loss due to waterlogging and salinity is about 0.5 Mha per year (Smedema, 2000). The history of ancient Mesopotamia illustrates that salinization when not properly recognized and addressed can be a time bomb waiting to explode upon the agricultural scene (Postel, 1999). To overcome irrigation-induced waterlogging and salinity problems, it is estimated that existing drainage systems will have to be replaced or modernized in about 30 Mha and new systems will have to be installed in another approximately 30 Mha (Ritzema, 2009).

To protect irrigated lands against waterlogging and salinity, (sub)surface drainage systems have been or are being installed. Over the last 50 years, drainage practices have evolved from manual to large-scale mechanized installation (Ritzema et al., 2006). These drainage systems effectively prevent waterlogging and root zone salinity and consequently increase crop yield and rural income. The systems have also proven to be very cost-effective (Ritzema and Schultz, 2011). The recent rise in major food commodity prices will increase the economic returns even further. However, although the installed systems are technically sound and cost-effective, drainage development still lags behind irrigation development and, as a result, a substantial part of irrigated areas suffer from waterlogging and salinity.

2.2 Drainage sustains and increases yield and rural incomes

There is abundant evidence that drainage systems increase yields which, in turn leads to increases in rural incomes. In Egypt, which has one of the largest subsurface drainage programmes in the World (Abdel-Dayem et al., 2007), a nationwide monitoring programme revealed that installation of subsurface drainage resulted in an average 30% decrease in the depth of the groundwater level, a 35 to 50% decrease in the areas affected by soil salinity and increased yields of all crops - beyond expectations - although individual crops reacted differently (Ali et al., 2001). Similar results were obtained for subsurface drainage projects in India where, in the five agro-climatic regions where canal irrigation is most important, crop yields increased significantly: on average 54% for sugarcane, 64% for cotton, 69% for rice and 136% for wheat (Ritzema et al., 2008a). These yield increases were obtained because water tables and soil salinity levels in the drained fields were respectively 25% and 50% lower than in the non-drained fields. Similar results have been recorded in large-scale projects in India: in the RAJAD Project (15 000 ha) in Rajasthan and in HOPP Haryana (12 000 ha) yield increases were between 19 and 28% (Nijland et al., 2005; Sharma and Gupta, 2006). And in Pakistan, subsurface drainage systems effectively control the water table, decrease soil salinity, allow increases in crop yield and crop intensity and decrease the area of abandoned lands (Bhutta et al., 1995). For example in the Mardan SCARP project area (29 500 ha), the groundwater level dropped more than 50% considerably reducing waterlogged conditions (Nijland et al., 2005). In the Khushab (23 400 ha), the Fourth (30 000 ha) and the Swabi SCARP

(22 000 ha) drainage projects, the percentage of abandoned land decreased considerably and the cropping intensity increased about 20% (Ghumman et al., 2012).

The investment costs for these improved growing environments and crop yields have proved to be very cost-effective. In Egypt, the Gross Production Values increased by € 500–550 per hectare and the annual net farm income increased by € 375 per hectare in non-saline areas and by € 200 per hectare in saline areas (Ali et al., 2001). Similar results were reported in India: the installation of subsurface drainage in the RAJAD Project (15,000 ha) proved to be economically sound with the benefit-cost ratio ranging from 1.3 to 2.9, the net present value ranging from € 200 to € 1,050 per hectare, the payback period being just 4 to 7 years and the internal rate of return ranging from 18 to 35% (Gopalakrishnan and Kulkarni, 2007). And in Pakistan the socio-economic benefits per year from 1994 to 2006 have increased by 2.5% for Khushab and Faisalabad, and by about 1.8% per year for Swabi (Ghumman et al., 2012).

2.3 Drainage protects land productivity and irrigation investment

Waterlogging and salinization are serious threats to irrigated agriculture in arid and semi-arid regions as irrigation water, even of good quality, brings huge amounts of salts with it. These salts, if not removed, will accumulate and gradually lead to losses in both land productivity and the investment in irrigation. Well designed and managed drainage projects are the only way to avoid these threats and reap the potential returns on investments in irrigation. Experiences abound to support this proposition, for example a comparison of the situations in Egypt and Pakistan both countries where agriculture depends on irrigation.

In Egypt, which receives irrigation water from the River Nile, 86% of the irrigated lands are drained, compared to only 32% in Pakistan which pulls its irrigation water from the River Indus (ICID, 2015). In Egypt, this has resulted in equilibrium in the overall salt balance of the River Nile: although the majority of the water brought in by the river at Aswan is used for agriculture, all the dissolved salts entering at Aswan are discharged to the Mediterranean Sea (Table 1). In the Nile Valley, between Aswan and Cairo, about 36% of the water released through the Aswan dam is used for irrigation and, because all drainage water is diverted back into the River Nile, the salinity increases in the downstream direction (from 0.3 dS/m in Aswan to 0.47 dS/m in Cairo). The total salt load between Aswan and Cairo, however, remains the same, indicating that the leaching efficiency and drainage systems in the Nile Valley are adequate to keep equilibrium soil salinity.

++ Table 1 Comparison of the water and salt balances of the Nile River in Egypt and the River Indus in Pakistan

By contrast, in Pakistan only 50% of the salts brought in by the River Indus are discharged into the Arabian Sea (Table 1). This means an average annual addition of 16.6 Mt of salt are stored in the Indus Basin (Quereshi and Sarwar, 2009). Of this, only 2.2 Mt are deposited in a series of evaporation ponds located in the desert area outside the irrigated plain in southeast Punjab; the remainder accumulates in the irrigated land and its underlying strata and aquifer. Each year, on average 1 ton of salts is added to each hectare of irrigated land. This accumulation is the main cause of land salinization. About 35–40% of irrigated areas are affected by salinity - 6% moderately and 8% severely. This amounts to 6 Mha out of the 16 Mha of irrigated land in Pakistan being compromised due to inadequate drainage (Ghafoor and Boers, 2003).

2.4 Drainage infrastructure serves urban and industrial areas as well as agriculture

The function of drainage systems in rural and peri-urban areas is changing (Vlotman et al., 2007). Through population growth, the rapid urbanization of rural land and the emergence of mega-cities, drainage systems, preliminarily designed to remove excess water from agricultural lands, nowadays also serve to dispose of wastewater from rural settlements, cities and industry, with severe negative consequences for the quality of the water (Scheuman, 1997). A study conducted in the Red River Basin in Vietnam showed that land use in the traditional rice polders, is gradually changing with the non-agricultural use, mainly villages, farm buildings and local industries, expanding at the expense of agricultural land (Ritzema et al., 2011). The increasing urban and industrial land use requires a 12-18% higher capacity of the drainage system than it was originally designed for and is also negatively affecting the water quality. Especially in the dry season the water becomes polluted, not yet seriously but the decreasing water quality is already affecting the water quality in the adjacent rivers. Thus improved drainage is needed to meet urban and industrial needs. Lack of sufficient drainage will lead to overtaxing old systems, and/or pollution/water quality problems. This increasingly important role for drainage highlights why systematic attention to drainage infrastructure is important.

2.5 Drainage protects human lives and is a buffer against flooding and high groundwater levels

There is an old Chinese saying '*The water can bear the boat and can swallow it too*.' This proverb means that different attitudes toward the water could lead to benefits but can also have negative consequences. The ancient people of China already had a comprehensive understanding of the important role of drainage for coping violent floods (Wu et al., 2013). They understood that the hydrologic functions of storage, infiltration, and groundwater recharge, as well as the volume and frequency of discharges could be used to control and reduce floods. They developed methods to utilize rainwater effectively, to control floods and to maintain a healthy environmental. In today's more complex environment, integrating this traditional philosophy with modern technologies proved to be extremely useful in building urban and rural storm water management systems in China. These experiences in China show that integrating traditional knowledge and advanced philosophy with modern technologies is extremely useful in building sustainable systems in both rural and urban areas.

Floods and waterlogged land are well-known in humid regions, but can also occur in arid and semi-arid regions. In India, forty million hectares of land, roughly one-eighth of the country, are prone to floods caused by the monsoon rains (Gupta et al., 2003). But also irrigation developments, to overcome water shortages in the dry season, can create waterlogging problems where drainage is insufficient. For example, as a result of excessive seepage from the INDP Canal (in fill), some villages had to be abandoned because of waterlogging in north Rajasthan near Hanumangarh (Indo-Dutch Network Project (IDNP), 2002). Not only flooding is a threat, but water quality can also become a threat. In the Ica Valley of Peru, there are signals that pollution of groundwater is occurring with NO_3-concentrations exceeding the EU recommended maximum value (Hepworth et al., 2010). These nitrate concentrations are unlikely to cause a health hazard at present, but if the pollution is not controlled, contamination will continue to increase, potentially to levels hazardous to health. Effective drainage is an important part of controlling such contamination.

2.6 Drainage services improve health conditions by reducing or eliminating water-related vector-borne diseases

The Greeks and Romans realised that malaria (mal'aria = bad air) was associated with stagnant water and swamps and practised various methods of drainage from the 6th century B.C. onwards (Snellen, 1988). For centuries mainly surface drainage systems were used, but in the beginning of the 20th century subsurface drainage also began to play an important role in the battle against vector-borne diseases starting in Central America and the southern states of the USA (Randle, 1940). However, when DDT became available after World War II, the practices of reducing man-made vector contact and eliminating or modifying breeding sites with drainage and other methods was replaced by a single approach: spraying DDT. Initially, this approach was very successful; but in time malaria mosquitoes developed resistance to these insecticides. As a result, engineering measures for reducing water-borne disease risk have come back into the lime-light.

The Dez Irrigation Scheme in Iran is an example where engineering measures to remove stagnant water have proven to be a more sustainable option to control water-related vector-borne diseases (mainly schistosomiasis or bilharzias) than chemical and medical measures (Ritzema and Braun, 2006). Along with this positive information it should be mentioned that lack of maintenance of the engineering measures reduced their effectiveness over the years. While drainage can be very useful in this application, it must be correctly implemented and maintained. A field study carried out in the irrigated rice scheme *Office du Niger* in Mali showed that, because of improper drainage after harvest, mosquito (*An. Gambiaiae s.l.*) breeding quickly re-established on fields where small pools of water remained (Klinkenberg et al., 2002). As in the previous section, experience from ancient times onward indicates that including drainage as part of land management infrastructure has positive impacts for the health of local populations.

2.7 Drainage and the protection of water quality

To sustain irrigated agriculture, salts brought in by the irrigation water have to be evacuated. Thus a certain amount of "over"-irrigation, or leaching, is needed. Often the leaching requirement is less than the irrigation field application efficiency (max 60% for surface irrigation methods, 75% for sprinkler and 90% for drip irrigation). In a well operated irrigation scheme, the leaching fraction will be around 15 to 30% (= concentration factor between 7 and 3) depending on the soil type (El-Guindy, 1989). This extra applied water will dissolve salts in the soil and carry or leach them from the root zone. However, water quality can also be negatively affected by the leaching of nutrients and pesticides from agricultural lands, so here as well drainage must be implemented with care. Experiences from the USA show that controlled drainage (also called Drainage Water Management/DWM) can reduce nitrogen (N) losses (primarily in the nitrate nitrogen [NO_3-N] form) by 18 - 75%, depending on drainage system design, location, soil, and site conditions (Skaggs and Chescheir, 2003). Similar results were obtained in the Netherlands where experiments with controlled drainage resulted in a reduction of nitrogen losses and a positive effect on the quality of the drainage effluent (Ritzema and Stuyt, 2015).

3. Seven aspects why drainage is different than irrigation.

Despite the clear need for drainage in irrigated agriculture, investments in drainage are lacking behind investments in irrigation. This section addresses seven reasons why drainage gets far less attention than irrigation. It is not because drainage is more complicated or more expensive, but has mainly to do with institutional aspects. Let’s find out why drainage is so different.

3.1 Drainage is at the end of the pipeline

Drainage deals with cleaning up the "mess" that multiple other activities have left behind. Drainage water from different locations and/or facilities will have different quality characteristics affecting the surrounding area differently and requiring different means of being handled (Jorjani, 1990). As such drainage, in comparison to irrigation, is off-site for every single entity and therefore, ultimately, somebody else’s problem. Even natural or good quality drainage water makes a significant contribution to the watershed hydrology. Studies conducted in the USA indicate that a considerable part of the precipitation (21%) was recovered through the subsurface drainage system, contributing 47% of the watershed discharge (King et al., 2014). As this drainage water is "polluted" with salts, fertilizers, pesticides, etc., it can have a considerable impact on the water quality in the watershed.

Poor quality water should be separated from good quality water. If drainage water is unsuitable for re-use, it should be disposed of in a sink of lower quality water. But who is, or should be, responsible for this? There are several factors that need to be considered when determining the constraints for the management of surface or subsurface agricultural drainage water, i.e. the volume and quality of drainage water, fluctuations in the flow rate and the chemical concentrations (Madramootoo et al., 1997). Even when irrigation practices are good, many tons of salts are imported. Salts are a hidden cost farmers have to pay and they affect not only the farmers' land, but also downstream constituents. In Andhra Pradesh, India, for example, drain discharge amounts to leach out these salts are small (around 1.0 mm/d), but the salinity of the drainage water is high (between 1.8 to 8.2 dS/m) restricting downstream re-use (IDNP, 2002). The physical location of drainage at the end of the pipeline – where all surrounding use affects it, but no single entity is responsible for it - is a major difference between drainage and irrigation.

3.2 Agreement on and enforcement of rules and regulations is difficult

State regulation of drainage has always been a challenging issue. Compared to irrigation, the enforcement of rules is even more difficult because drainage systems are often designed for extreme rainfall events that may occur only once every 1, 2, 5, 10, etc. years, and salt build-up, the consequence of insufficient drainage, is a slow process. This is in contrast with irrigation where, if a farmer doesn't receive enough water, the crop will suffer directly. In other words: irrigation is a need for today, and drainage a problem of tomorrow.

Once drainage has been provided, exclusion from benefits and enforcement of financial contributions is difficult, if not impossible, at the basin level. When in the 16th century large-scale drainage began in Western Europe, the viability of these projects was often endangered by litigation or violent conflicts with landlords, commoners, cities, or water boards whose interests were harmed by the implementation of such projects. A comparison between the Dutch Republic, England, and France shows that the Dutch developed institutions to deal with these conflicts more efficiently than the others (Van Cruyningen, 2015). The decentralized nature of the Dutch state turned out to be an advantage: Dutch politicians and entrepreneurs were used to compromises, and solutions could be adapted to local circumstances. In more centralized England and France this was more difficult to achieve. This problem still exists in many countries, for example, the establishment of Lakhuwali Drainage Pilot Area in Rajasthan, India was delayed because farmers could not agree among each other on the location of the disposal drains (IDNP, 2002).

3.3 In small-scale irrigated agriculture, drainage is always a joint effort

The water infrastructure in arid and semi-arid conditions is traditionally based on the water supply. Disposal of excess water requires a complementary infrastructure that invariably serves a multitude of users. Drainage therefore requires the cooperation of various stakeholders, which makes it generally more difficult to organize than irrigation. Studies conducted in Egypt, India, Pakistan and Vietnam show that farmers, especially small scale farmers, are willing to cooperate but that an appropriate organizational setting is often lacking (Ritzema, 2009). For example, in the ANGRAU Pilot Area in Konanki, Andhra Pradesh, India, the average farm size is 0.5 ha. Drain spacing varies between 30 and 50 m, thus a field drain always serves more than one plot. The same applies for the Nile delta in Egypt, where the average plot size is 0.4 ha and drain spacing varies between 15 and 60 m (Abdel-Dayem and Ritzema, 1990). Thus farmers have to cooperate, because if only a few farmers drain their fields, their neighbours will also benefit as groundwater flow doesn’t stop at the boundary of a field.

3.4 Boundaries of drainage units usually do not coincide with the boundaries of an irrigation unit

That drainage areas flow beyond irrigation units is a fact that applies at command area scale as well as at field level (Bos and Wolters, 2006). Thus, existing institutional set-ups - often based on irrigation system lay-out - need to be modified as soon as drainage is introduced in the area. In India, irrigation is organised in State Irrigation Departments, sometimes with separate drainage units. Drainage improvements within an irrigation command are entrusted to the Canal Development Authorities (CADAs), but there is not an integrated and centralised organisation for improving drainage and the policy and practices also suffer as they vary with each department (Nijland et al., 2005). In Egypt, water uses and the interlinkage and interdependency between the different water uses is growing exponentially (Van Steenbergen and Abdel Dayem, 2007). Drainage plays a crucial role in these interlinkages, particularly through the re-use policy and practice (as will be explained in Section3.7). The increase in population, on-going urbanization of rural areas and climate change all call for further integration of drainage, irrigation and flood management (Vlotman et al., 2007).

3.5 Disposal of drainage water creates off-site externalities

Drainage water that is discharged back into the river from which it was originally diverted not only has a higher salt content, but is also polluted with residues of fertiliser, pesticides and waste water from villages, cities and industries. For example, in northern Italy, where nitrate losses through the subsurface drainage system on a farm near Bologna were monitored for three years, a high correlation was found between the nitrate losses and the amount of water evacuated through the drainage system (Rossi et al., 1991). The greatest nitrate losses were recorded during winter and early spring when drainage was at its highest. The annual rate of nitrate losses, 214 kg NO_3/ha (50 kg N/ha), was a major contribution to the eutrophication (i.e. the chemical enrichment) of surface water. So, while upstream users benefit from disposal, downstream users, or society as a whole, bear the cost. Thus at basin level, a decentralized water allocation mechanism which is adapted to incorporate sustainable water use and deal with the externalities from upstream-downstream linkages is needed (Pande et al., 2011). This calls for state regulation (Roest et al., 2006).

3.6 High investment costs with immediate benefits versus lower investment but only long-term benefits

Although the investment costs for drainage are only a fraction of the investment costs for irrigation infrastructure (usually between the 10 and 30%), they are still significant and benefits are often only recognized on a long-term basis (Ritzema et al., 2006). As already noted, salinization is often a slow process, and subsistence farmers normally do not have the resources to invest in the next generation (Pearce and Dennecke, 2001). So what about sharing the costs?

A successful model for this can be found in India where investments in surface drainage are in general done by the government with only small contributions from the farmers. For example the subsurface drainage system installed in the Chambal Command in Rajasthan had an installation cost of US $815/ha and an internal rate of return of 28%. The farmers contributed only a small amount however their return rate on investment was around 240% (Ritzema et al., 2008a).

Although the cost-benefit situation for drainage is different and appears more long-term than that for irrigation, innovative approaches can result in affordable investments and positive returns for all parties.

3.7 Reuse of drainage water

The re-use of drainage water is practised worldwide, mostly in arid or semi-arid regions where irrigation water is in short supply, but also in temperate regions, where re-use is practised during the dry summer months (Ritzema and Stuyt, 2015). Re-use can increase a country's available water considerably. In irrigated agriculture, re-use can be practised at farm level, project level, and regional level, often as a combination of official re-use by government and unofficial re-use by individual farmers (Ritzema and Braun, 2006). Drainage water can never be completely re-used, however, because the salts that are imported with the irrigation water have to be exported out of the area. Therefore, much more so than when irrigating with 'fresh' or 'new' water, it is always necessary to make a water and salt balance to calculate the long-term effects of the re-use of drainage water on soil salinity (Van Hoorn and Van Alphen, 2006).

Re-use at farm level can be practised when the drainage water is of good quality (not too many salts). Farmers can pump irrigation water directly from the open drains or use shallow wells to pump groundwater. Re-use at project and regional level is practised when drainage water is pumped back into the larger irrigation system. With this type of re-use, the drainage water is automatically mixed with better-quality irrigation water. The quantity and quality of both the irrigation and drainage water determine how much drainage water can be re-used. Because this type of re-use requires high investment costs (i.e. the construction of pumping stations) and because the effects on soil salinity are difficult to predict, careful planning is a prerequisite for success. Finally, re-use can be practiced at regional or even national level. The question is how to organise this: at field-, project- or basin-level? This calls for state regulation again adding an aspect to drainage that is removed from the direct user of the water.

For examples of these different levels of use and what is involved, we can look at Egypt. In the Nile Delta in Egypt, farmers re-use drainage water by pumping it for irrigation directly from the drains. In the eastern part of the Nile Delta, 15% of the crop water is supplied from groundwater and on-farm re-use (Abdel Gawad et al., 1991). A major disadvantage of this type of re-use is that, because the salinity of the re-used water is often high, it contributes disproportionately to the total salt supply to the crop. For the Eastern Nile Delta, the chloride contribution of the 15% re-used water is about 46% of the total crop chloride supplied through irrigation. The official re-use of drainage water at a regional level is also considerable. Since 1930, 21 pumping stations have been built in the Nile Delta to pump part of the drainage water back into the regional irrigation systems (El-Quosy, 1989). In the 1980s approximately 2.9 x 10^9 m^3/year of drainage water with an average salinity of 1.45 dS/m was pumped back into the irrigation system, totalling approximately 15% of the crop water supply. The re-use at national level, using the River Nile as the main conduct has already been discussed in section 2.3, where we have seen that the River Nile is both used as the main irrigation “canal” as well as the main “drain”. All these re-use options have increased Egypt’s water availability by 20% (Barnes, 2014).

4. Seven challenges to making drainage work

To this point, I have discussed seven reasons why drainage is needed and seven institutional aspects of how drainage is different than other aspects of irrigation. I hope that you are now convinced of why, if we strive for sustainability of water and land use, drainage must be given its appropriate place and role in integrated water management. In my opinion, there are seven challenges to achieving this.

4.1 Establishing an institutional menu for drainage goods and services

Is drainage a public good that should be financed by the general public or is it a private good to be financed by the users/consumers? In reality it is most often a combination of these two, which requires a sound institutional set-up.

In Western Europe, the origin of drainage institutions can be traced back to the Middle Ages, where the earliest forms appeared in the flood-prone areas in the Netherlands (Pant, 2002). Over time these gradually developed into organizations with three main characteristics: (i) most organizations were initiated by the landowners/users and only implemented when the majority of them gave their approval; (ii) organization and management was controlled by the members; (iii) most times the control was exercised by a general assembly based on the one-man–one vote or proportional land area basis. The management of water however is becoming more complex because of the diminishing role of agriculture, increased urban and industrial water use, increasing environmental concerns, the need to integrate water management, the blurring of the private versus public dichotomy and the subsequent diverse and complex funding.

Experiences in Egypt show that applying the principles of the decentralized concept of the Dutch Water Boards in irrigated agriculture faces two major challenges: (i) it requires the transfer of authority and responsibility from the Central Government to the Water Boards, and; (ii) achieving the level to which the Water Boards need to be developed (Oliemans and Kuindersma, 2002). Experiences from a Dutch and Indian collaboration suggests that dissemination of research results in the form of popular information bulletin for policy-makers can help to inform the debate. For example (Boonstra, 2003) produced the popular brochure “Drainage protects irrigation investments” in which the results of seven years of research cooperation between six Indian and Dutch institutes to combat salinity and waterlogging in canal command areas in five States in India are presented in a format that the general public can understand. This brochure helped, but without some form of information or process that brings the various stakeholders around drainage together, it is a challenge to develop the much needed institutional menu for drainage goods and services.

4.2 Investment in drainage infrastructure

The costs of installing large-scale subsurface drainage systems depend on local physical and economic conditions as well as the installation method (Ritzema et al., 2006). As a result the overall cost varies considerably (Ritzema and Schultz, 2011). In Egypt the overall cost per hectare is € 750, in India the cost per hectare in large-scale schemes is around €800 and in Pakistan around € 1,200 per hectare. Note: all prices have been converted to euro (€1.00 = US$ 1.35) at 2007 prices. These investments, despite their differences, proved to be very cost-effective in all cases (Section2.2). Drainage helped increase land productivity, gainful employment of farmers and farm income. Subsurface drainage can be become even more profitable as research shows that the deep drain depths used for irrigated land in some countries are unnecessary for salinity control and there is evidence of the adequacy of shallower drains (Abdel-Dayem and Ritzema, 1990; Ritzema, 2009; Ritzema et al., 2008a; Smedema, 2007).

Thus financial and economic feasibility of drainage in waterlogged and saline areas looks favourable, provided sufficient water is available for leaching and irrigation and that a sustainable solution for the disposal of the low-quality drainage effluent is found. Research has shown that farmers, both male and female, are willing to pay their part of the cost as they clearly see the benefits of drainage (Ritzema et al., 2008a). In reality, however, they are too poor to pay their part of the installation cost. The investments in irrigation are still heavily subsidised by the Government, which makes it extra problematic to obtain cost-recovery for drainage. None the less more shared investment in drainage is needed. The challenge is to involve all beneficiaries, so that not only the farmers have to pay their share but also the other users (or polluters) of the drainage infrastructure. A study in California shows that pricing policies such as a drainage effluent charge can influence investment in and adoption of input conserving technologies such as drip- and sprinkler irrigation methods (Caswell et al., 1990). Finding the organizational frameworks and issues that can trigger the necessary investment in drainage systems is a major challenge that must be addressed.

4.3 Organisation of drainage

In irrigated areas, especially in developing countries, drainage systems are often designed and implemented by government, with the users, very often small farmers, having little input or responsibility and making little contribution. The majority of these farmers are poor and do not have the means to invest in subsurface drainage themselves. In the typical top-down standardized approach, the location-specific conditions and farmers preferences are hardly taken into consideration. Furthermore, the emphasis has traditionally been on the technical aspects (physical infrastructure) of the systems, while the organizational aspects (institutional infrastructure) have been largely neglected. The result has been that the installed systems are not effective and most beneficiaries don't feel ownership, resulting in poor operation and maintenance. A shift to a more service-oriented approach, as promoted since the 1990s, has not gained much of a foothold in practice (Ritzema, 2009). The institutional set-up for drainage is complex and enforcement of rules and regulations is difficult. In contrast to irrigation, where direct benefits to stakeholders are involved, rules and regulations for drainage are much more difficult to enforce. Drainage fees need to be collected and, unlike the irrigation supply system, it is difficult to disconnect uncooperative customers. A case study on participatory research in Vietnam showed that the existing institutional setup, often based on irrigation system layout, needs to be modified or adapted to improve drainage efficiency (Ritzema et al., 2011). In the Ica Valley of Peru, six public and five private organizations are involved in the water management. This legal and institutional framework, however, appears to be inadequate to solve the overexploitation of the (ground)water resources (Hepworth et al., 2010). Finding institutional or organizational arrangements that are culturally acceptable and functionally effective are a fundamental challenge for achieving the proper role of drainage in integrated water management.

4.4 Maintenance of the drainage infrastructure and its financing

Maintenance is the main management task required for keeping drainage systems functioning and playing their appropriate role in regional water management. The overall picture is that maintenance tends to be poor, especially if government is responsible. In addition maintenance involves costs which are often a challenge to cover. Farmers and non-agricultural users are very often not charged for drainage services and, when charges or taxes are imposed, collection is a fundamental problem.

Open field drains have to be cleared of weeds before the growing season, but because they are designed based on a rainstorm that will only occur once every 5 or 10 years it is never clear when the drains have to function. Thus after a few dry years, farmers tend to neglect maintenance and crops are damaged by waterlogging in an above-average wet year. By that time, however, it is too late to clean the drains. Main drainage systems are usually maintained by contractors using specialist machinery to clear gullies, pipework, and storage zones of trash and sediment accumulation. Some of the same challenges related to timing exist for these drains as well. And the subsurface drainage infrastructure is underground thus out of sight; so the frequency of routine maintenance is generally determined by routine rather than needs, and irregular maintenance activities tend to be triggered only by system performance failure (Bray, 2004; Nijland et al., 2005). Clearly, effective functioning of drainage systems depends on good maintenance, and this is a big challenge.

4.5 Participatory drainage management

We have seen that (i) irrigation units do not coincide with drainage units; (ii) farmers that benefit are not the farmers that are negatively affected, and; (iii) exclusion from benefits is difficult. A management framework is needed to ensure full participation of drainage beneficiaries in the management process (Malano, 2000). Effective user participation requires appropriate institutional arrangements to be set up to ensure both accountability between service providers and recipients, and transparent links between cost and level of service provided.

The key element of service oriented management is the service agreement that governs the accountability between the drainage provider and beneficiaries (Dolfing and Snellen, 1999). The service agreement contains several elements describing the service transactions and the accountability mechanisms between service provider and beneficiaries. The cost of providing a drainage service must be clearly linked to the level of service provided by the drainage organization. To do this an asset management programme is needed to identify the long-term maintenance, renewal and modernization requirements of the drainage infrastructure. If the pricing policy is not aimed at charging the full cost of providing the service, any shortfall in revenues must be clearly identified and met by government subsidies.

4.6 Reuse of drainage water

Drainage systems that were traditionally built for rapid removal of all excess water have to be transformed to systems that can better control water levels (Vlotman et al., 2007). Controlled drainage aims, in a three-step approach of decreasing priority, to reduce drainage outflows by: (1) retention of excess rainfall in the soil; (2) storage of remaining excess water in the field or the (field) drainage system, and; (3) controlled removal (Ritzema and Stuyt, 2015). We have seen that the remaining drainage outflow can be re-used to supplement freshwater resources, sometimes only after mixing. There are various options for this, as already discussed in Section 3.7. It can be done directly in the field, through the irrigation system or downstream in the basin. This can occur officially or unofficially. The challenge in this aspect of drainage management is related to the common need to improve the quality of the drainage water before it can be re-used. There are number of ways to accomplish this, for example by legislation to restrict the use of fertilizer and/or manure at farm level (Ritzema, 2007); with subsidies, through advisory services to reduce losses of nitrogen (Christianson et al., 2013); if the farmers have to pay for the quality of their drainage effluent, desalination e.g. by using reverse osmosis membrane technology (Thompson et al., 2013; Uléna et al., 2012). The challenge is to find the best method or combination of methods for achieving the target quality. A participatory approach in defining goals by merging local visions and expert judgment increases goal functionality and robustness when adapting and implementing national goals at local level (Jonsson et al., 2011; Speelman et al., 2011). Whatever approach is decided upon, continuous monitoring of both the quantity and quality of the water is needed to ensure good quality irrigation water (El-Quosy, 1989). This too is a challenge that needs consideration.

4.7 Safe disposal of drainage effluent

We have seen that controlled drainage can reduce outflow, but in the end, the salts brought in by the irrigation water, together with the residues of fertiliser, pesticides and wastewater coming from non-agricultural sources, require safe disposal (Ritzema and Braun, 2006). This is a final challenge to drainage being able to have its place as part of integrated and sustainable water management. Evaporation ponds are sometime used for salt disposal, e.g. in Pakistan, but they are of limited use as only 13% of the salts that are left behind in the Indus Basin are deposited in the ponds which are located in the desert area outside the irrigated plain in southeast Punjab (Quereshi and Sarwar, 2009). Discharging the salts into lakes and/or rivers that eventually reach the sea or ocean seems logical, but the consequences of these higher salt concentrations, not to mention the other (toxic) elements dissolved in the water, require serious consideration.

If the receiving water cannot cope with the amount of salt laden drainage water, a separate facility with a safe outlet, usually the sea, has to be constructed. Two of the best known outfall drains, especially created for the disposal of highly saline drainage water, are the Left Bank Outfall Drain in Pakistan and the Third River in Iraq. The Left Bank Outfall Drain has been constructed to drain approximately 0.5 million ha in the Sind Province of Pakistan (McCready, 1987). The disposal of the drainage effluent back into the River Indus, or one of its branches, is unacceptable because of the high salinity levels: the effluent from subsurface drainage can vary from 4.7 to 15 dS/m and that from tubewells can be twice as saline. Disposal into the river would result in excessively high salinity levels and would make downstream use for irrigation impossible. In Iraq, the Third River, which was completed in 1993, acts as an outfall drain for the area between the Euphrates and the Tigris.

But even disposal to such a "safe" outlet (the sea) can have environmental effects. An example is the eutrophication of the North Sea and Baltic Sea caused by the leaching of minerals from agricultural lands as a result of the excessive use of manure, fertilizers, and pesticides in the North-western European countries bordering these seas (Skogena et al., 2014).

5. Conclusions

I have discussed seven season why drainage is needed to protect and sustain irrigated agriculture, seven institutional aspects of how drainage is different than other aspects of irrigation and seven challenges to give drainage its appropriate place and role in integrated water management. However, despite the clear need for drainage in irrigated agriculture, investments in drainage are lacking behind investments in irrigation. To reverse this trend and allow the benefits of drainage to be more widely realized, a three-step approach is proposed (Ritzema, 2009):

(i) **Balancing top-down against bottom-up**. This requires a participatory approach focusing on societal choices and decentralized management. Participation must occur throughout the complete cycle: from planning, design and installation to operation and maintenance (O&M). Recent approaches, such as participatory learning and action research, including participatory modelling, and communities of practice, can enhance this process (Ritzema et al., 2011). Another key part of this is the need to enhance the link between technical aspects (requiring physical solutions) and organizational aspects (requiring institutional changes).

(ii) **From standardization to flexibility**. Instead of standardized design and implementation practices a much more flexible approach based on location-specific conditions and farmers' preferences is recommended. Integration between the irrigation and drainage networks needs to be improved. The challenge is to find a balance between the individual need for drainage, which varies from field to field, and the fact that drainage at farm level is a collective activity. This calls for better operational control (Ritzema and Stuyt, 2015).

(iii) **Focus on capacity development**. There is ample evidence that capacity building is a prerequisite for success in most drainage projects involving activity by multiple stakeholders (Burns et al., 2015; Ghumman et al., 2012; Van Keulen et al., 2003) A capacity building process, based on the knowledge-creating process of (Nonaka and Takeuchi, 1995), is needed to integrate research, education and advisory services to link the local tacit knowledge of the stakeholders with the explicit knowledge of the researchers to create new knowledge (Ritzema et al., 2008b). This type of applied research is extremely profitable. Experiences from Egypt, India and Pakistan show that the benefits of applied research easily outweigh the costs (Ritzema et al., 2007).

We can conclude that drainage offers great benefits for sustainable resource management, but there are complexities and challenges that we face giving drainage its due place in irrigated agriculture. These challenges can be overcome however and doing so will allow realization of the benefits to land productivity, people, and a more sustainable future.

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List of Tables

Table 1 Comparison of the water and salt balances of the Nile River in Egypt and the River Indus in Pakistan

Location	Discharge ($\times 10^9$ m^3/yr)	Total salt load ($\times 10^9$ kg/yr)
Nile River, Egypt[a]:		
Inflow (Aswan High Dam)	55	11.0
Delta Barrage (Cairo)	35	10.5
Outflow to Mediterranean Sea	14	32.0
Indus River, Pakistan[b]:		
Inflow	181	33.0
Outflow to Arabian Sea	39	16.4

[a] (El-Quosy, 1989) [b] (Quereshi and Sarwar, 2009)

Note: the increase in the total salt load between Cairo and the Mediterranean Sea is due to the leaching of deeper (saline) soil layers and the seepage of saline groundwater (El-Quosy, 1989).