Engineering and Biological Approaches for Drainage of Irrigated Lands

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Abstract

Irrigated agriculture, contributing two-fifths of global agricultural production from one-fifth cropped area, is under stress due to associated waterlogging and soil salinity problems. Current annual crop productivity losses due to irrigation-induced salinity are estimated at US$ 27 billion for the world and US$ 1.2 billion for India. Of the 6.74 million ha salt-affected lands in India, severely waterlogged saline soils occur in about two million ha area in arid/semiarid alluvial northwestern states and about one million ha each in coastal and black cotton heavy soil (*Vertisol*) regions. The waterlogging and soil salinity-related losses in irrigation commands of India are likely to magnify severalfold with a projected increase of such areas to 13 million ha by 2025 and to 20 million ha by 2050 due to climate change and enforced use of saline/alkali groundwater in northwestern and southern states.

Besides surface drainage, engineering technologies (subsurface drainage (SSD) and tubewell drainage) and biodrainage through high-transpiring trees are extensively applied for control and amelioration of waterlogging and soil salinity. Considering wide-ranging climatic, soil, geohydrological and outlet conditions, drainage problems and solutions are location specific. While watertable control in fresh groundwater regions is commonly achieved by tubewell pumping, subsurface pipe drainage is almost mandatory in waterlogged and saline groundwater regions. In absence of clear guidelines, there often remains considerable ambiguity in the selection of the most appropriate drainage method for any affected area.

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Basic features of SSD, vertical and biodrainage approaches for management of waterlogged saline-irrigated lands have been presented in this chapter. Since SSD is relatively a new technology in India, a major part of the chapter has been devoted to a historical overview on its progression from small manually installed research studies to large mechanically implemented projects. About 62,000 ha waterlogged saline soils have been reclaimed with SSD in India with significant improvement in crop intensity and yields, land value and farmers' income. Monitoring and evaluation of a number of drainage projects have reiterated that high cost, environmental issues relating to disposal of saline drainage effluent and continuous pumping requirement during post-reclamation phase are the major deterrents to the long-term success of this technology.

Similar to SSD, the technical features and scope of tubewell and biodrainage projects and related variant technologies, developed and evaluated for control of waterlogging and soil salinity in India, are also critically reviewed. The presented variants of vertical drainage system include different types of skimming and recharge structures used for selective abstraction of fresh water floating in a thin layer over native saline groundwater and for disposal of excess flood water from agricultural fields, respectively. Finally, a methodology, based on a watertable depth and groundwater salinity linked criterion, has been presented for implementation of SSD, vertical or biodrainage projects specific to different critically waterlogged saline regions of Haryana.

Keywords

Irrigated lands · Engineering approach · Biodrainage · Subsurface drainage · Vertical drainage · Vertisols · Salt-affected lands · Waterlogging · Skimming and recharge structures

18.1 Introduction

The twentieth century ended with impressive accomplishments in diverse fields of human enterprise, but it has still remained a precursor of nearly one and a half billion people going to bed partially hungry. Population growth, economic progress and rising living standards are leading to growing pressure on land and water resources. Irrigated agriculture, contributing about 40% of global agricultural production from 20% of the cultivated area, is under stress for performance. It faces stiff competition from domestic, industrial and recreational sectors in terms of rising water costs, increased environmental restrictions and reduced irrigation supplies. To aggravate the problem, waterlogging and soil salinization, the age-old nemeses of irrigated agriculture, continue to plague crop productivity in canal-irrigated agricultural areas in several countries (Scheumann and Freisem 2002) including India.

Waterlogging, meaning excess soil moisture in the crop root zone, results from the rise of watertable to within 2 m of soil surface due to deep percolation losses from irrigated fields or seepage from surface irrigation network. In arid and semiarid regions having shallow saline groundwater and high evaporative demand, waterlogging often leads to secondary soil salinity. Saline soils have high concentration of soluble salts ($EC_e > 4$ dS m^{-1}, pHs <8.2 and ESP <15) in the root zone which create different levels of salt and moisture (aeration) stresses to limit crop productivity.

About 20–30 million ha irrigated area in the world is severely affected by waterlogging, soil salinity and sodicity; additional 60–90 million hectares are slightly to moderately affected (Umali 1993; Smedema et al. 2004). Among the key irrigated countries, India, China, the USA, Egypt, Australia and Pakistan have the maximum irrigated and salt-affected area (Ghassemi et al. 1995). The threat to global crop production due to irrigation-induced salinity is serious, and losses at more than US$ 27 billion per year are substantial (Qadir et al. 2014). In the Indo-Gangetic alluvial plains of Indian subcontinent, waterlogging and salinity have dealt a serious blow to agricultural sustainability and farmers' livelihood (Datta and De Jong 2002; Bhutta and Smedema 2007).

Of 6.74 million ha salt-affected lands in India, severely waterlogged saline soils occur in about two million ha area in arid/semiarid northwestern states of Haryana, Punjab, Rajasthan and Gujarat and one million ha each in the coastal and black cotton *Vertisol* regions. The rise of watertable to within 2.0 m depth from soil surface restricts the movement of salts applied with irrigation water and also increases the salinity of groundwater. In arid and semiarid regions having high evaporation rates and inadequate drainage, salts are brought up to soil surface and redistributed unfavourably in the root zone by capillary rise to turn it to a saline soil (Fig. 18.1). It is projected that about 13 million ha area in irrigation commands of India will be affected by waterlogging and soil salinity by 2025; increasing use of saline/alkali groundwater in several northwestern and southern states and the impending climate change may further accentuate the hazard to over 20 million ha by 2050 (TERI 1997; Anonymous 2015).

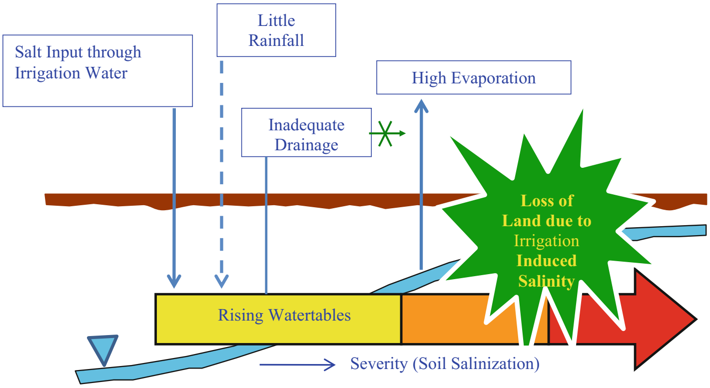


Fig. 18.1 Schematic diagram for development of irrigation-induced soil salinity

The level of reduction in crop yields in an affected area is governed by topography, availability of good-quality irrigation water and depth and salinity status of groundwater and soil. There are earlier reports of 38–77% yield losses of paddy, wheat, cotton and sugarcane due to waterlogging and 40–63% due to high soil salinity and consequent 82–97% reduction in net income in different irrigation commands of India (Joshi 1994) and 58% reduction in net income of cotton in Turkey (Umali 1993). ICAR-CSSRI has estimated the annual crop production and monetary losses due to soil salinity in India as 5.66 million tonnes and INR 80 billion (US$ 1.2 billion), respectively (Sharma et al. 2015).

On-farm or project-level preventive measures like land levelling, micro-irrigation systems, optimizing water allowance, canal lining, establishing biodraining trees alongside of canals, changing cropping pattern and improving surface drainage set-up can be effective to combat or delay waterlogging and soil salinity if implemented before the development of these problems. Curative measures in some form of artificial drainage become inevitable once irrigation-induced waterlogging and soil salinity are developed over large areas.

Though references on land drainage are available in several century-old Indian, Greek, the Netherland, Egyptian, Roman and other western scriptures, this has evolved as an acknowledged technique for watertable and salinity control and for reclaiming agricultural lands since the early twentieth century. Drainage systems are man-made systems that are only implemented when natural drainage is not sufficient to sustain agricultural productivity. Areas with limited natural drainage requiring artificial drainage are usually located in coastal plains, river valleys and inland humid regions where rainfall exceeds evaporation or in arid to semiarid regions where inefficient use and distribution of irrigation water usually lead to waterlogging and secondary salinization.

The drainage methods and techniques vary from one agroecological and socio-economical setting to another (Schwab et al. 1987; Madramootoo and Ochs 1997). Besides surface drainage, other artificial engineering interventions for control of waterlogging and soil salinity in irrigated lands include horizontal subsurface drainage (also called *relief* drains) and vertical subsurface drainage by tubewells, both having a number of variant technologies. Besides these techniques, biodrainage, utilizing the inherent ability of certain deep-rooted trees like *Eucalyptus* to remove excess soil water through rapid transpiration, has been successfully applied for prevention of waterlogging and salinity build-up in irrigated areas in India and several other countries, especially Australia. Both engineering (subsurface drainage and tubewell drainage) and biological (biodrainage) drainage approaches have been applied extensively for control and amelioration of waterlogging and soil salinity in different countries including India. There are, however, no clear guidelines for selection of a drainage method appropriate for any affected area with specific hydrogeological characteristics.

This chapter presents basic features of horizontal subsurface, vertical and biodrainage approaches for management of waterlogging and soil salinity in irrigated lands and progress of these technologies and their variants in India. Finally, a case study is presented for identification of critical and potentially critical waterlogged saline areas of Haryana, most suitable for reclamation through SSD, vertical or biodrainage measures based on a watertable depth and groundwater salinity linked criterion. Surface drainage, though a basic component of any land development and reclamation plan, is not included in this chapter considering the level of socio-economic, environmental and political complexities involved in introducing new surface drainage systems or suggesting modifications in the existing ones.

18.2 Features and Scope of Drainage Systems

All engineering drainage systems have components of field drains and main drainage systems. The field drainage system controls the groundwater level in the field by transferring the excess rain or irrigation water to the main drainage systems which finally dispose it to the outlets of the drainage basins. Field drainage systems can be either surface or subsurface drainage systems. Surface drainage systems consisting of open ditches are most needed when overland flow or water stagnation occurs on the soil surface. Conventional solutions to combat waterlogging and salinity are vertical and horizontal subsurface drainage systems consisting, respectively, of the pumping tubewells or horizontal buried pipes installed at a design slope. While watertable control in fresh groundwater regions is commonly achieved by tubewell pumping, horizontal pipe drainage is almost mandatory in waterlogged and saline groundwater regions. A number of variants of horizontal subsurface drainage system like interceptor drains and pipe less mole drains and of tubewell drainage like different types of skimming wells and recharge structures are commonly used for watertable and or salinity control.

In humid regions the primary goal of agricultural drainage is to lower the water content of the root zone to provide adequate aeration following excessive rainfall or irrigation. A secondary goal is to improve access and trafficability for timely planting and harvesting operations. Open drainage systems are the most common for such conditions but are increasingly being used in combination with subsurface drainage to lower groundwater levels quickly after rainstorms or at the end of the rainy season.

In arid and semiarid regions, the primary goal of agricultural drainage is to remove the accumulated salts from the root zone and to control the secondary salinization by lowering groundwater levels. These goals can be achieved by both pipe and open drains; in most cases pipe drains are the most practical solution. Subsurface pipe drainage systems are further classified as *singular* or *composite* systems. In a singular system, the field drains are buried perforated pipes that discharge into open collector drains. In a composite system, the collector drains also consist of closed or perforated pipes which discharge into an open main drain either by gravity or by pumping.

Most irrigated lands have variable levels of surface drainage in the form of some existing natural drains and a few additionally constructed drains. Subsurface (pipe) drainage systems (Fig. 18.2) are generally used for (i) reclamation of new land with a

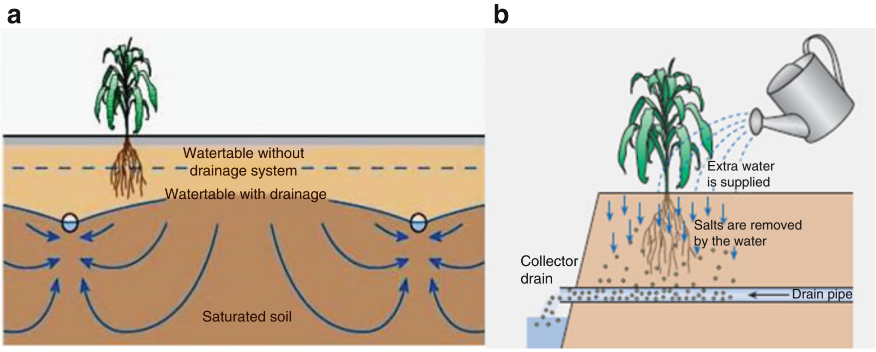


Fig. 18.2 Conceptual diagram of horizontal (pipe) drainage system in irrigated lands. (Figure Courtesy: Nijland et al. 2005)

shallow watertable and/or high soil salinity, (ii) controlling groundwater depth and soil salinity at desired levels and (iii) restoring the productivity of water logged and/or salinized lands to their potential levels. Short-term fluctuations in the watertable are typical in arid and semiarid areas where irrigation is practised. The watertable can rise within a day or two after a surface irrigation and then recede at rates influenced by soil hydraulic properties, irrigation practices, climatic conditions and the depth and spacing of the drains.

A tubewell drainage system consists of a network of shallow or deep tubewells to lower the watertable, including provisions for running the pumps and surface drains to dispose of the excess water. Tubewell drainage is used in areas with a high soil permeability and preferably fresh groundwater that can be reused for irrigation. While all vertical drainage systems continuously need electric or diesel power supply for pumping and horizontal systems dispose drainage effluent under gravity or by pumping, the biodrainage trees dispose excess water through high transpiration using solar energy.

Surface Drainage: Surface drainage is the most important drainage technique in the humid and subhumid zones where overland flow is the major component of excess water movement to major drains or natural streams. The technique normally involves the excavation of open trenches/drains and is most commonly applied on heavier soils where excess rainfall cannot percolate fast through the soil profile to the watertable because of slow infiltration rates. One day water stagnation due to absence of adequate surface drainage measures can result in 2–8% losses of crop yields; the corresponding losses may be as high as 20–48% for 6 days water stagnation (Bhattacharya 2007). A surface drainage coefficient of 5–7 $l\ s^{-1}\ ha^{-1}$ has been reported to provide adequate safety to most sensitive *Kharif* crops against waterlogging in humid regions having ~1000 mm annual rainfall in India. Bhattacharya (2007) also reported that investments on surface drainage are economically viable with yield benefits ranging from 20 to 28% in sugarcane, 20 to 25% in paddy, 32% in gram and 50% in Indian bean.

Subsurface Drainage (SSD) System: SSD has been accepted globally as a viable technology to combat the problem of waterlogging and soil salinity and to ensure the sustainability of irrigated agriculture. It is anticipated that SSD will be needed in 3–5 million ha area in the next 25 years to meet global food requirements (Smedema 2000). While the USA, China and Australia developed and extensively adopted SSD technologies for irrigated lands over the past 80 years (Smedema et al. 2004), Egypt, Pakistan, Turkey and India have been investing heavily on research and development of this technology for the past 40 years (Ritzema and Schultz 2011). Among developing countries, Egypt stands as the country with more than 2.5 million ha area provided with subsurface drainage (Nijland 2000).

Although there have been impressive progress and technical improvements to standardize the SSD technology for improving the productivity of affected irrigated lands, organizational and institutional aspects of drainage projects have also proved to be equally important for its long-term success. High cost, environmental issues relating to disposal of saline drainage effluent and continuous pumping requirement during post-drainage phase in pumped outlet cases are some of the deterrents to long-term success of this technology. There are several reports of serious environmental degradation in terms of increasing levels of river/seawater pollution (salinity, selenium toxicity) and loss of biodiversity due to discharge of polluted drainage water from irrigated lands in Imperial Valley and San Joaquin Valley in California (USA), Aral Sea Basin in Russia, Indus Basin in Pakistan and Murray-Darling Basin in Australia (Cervinka et al. 1999). Involvement of farmers, sharing of construction and operating cost and government subsidy are also vital aspects. Drainage of waterlogged saline soils in low-lying depression areas without a suitable disposal outlet is much more challenging.

Pace of implementation of SSD projects in India and other developing countries has to accelerate significantly to improve productivity potential of waterlogged saline areas and economic wellbeing of resource poor farmers. Preservation and restoring the productivity of irrigated agriculture without environmental degradation is a challenging task and demands regional planning and management perspectives.

Vertical Subsurface Drainage: Vertical subsurface drainage refers to the technique of controlling the watertable and salinity in agricultural areas. It consists of removal of groundwater through pumping, from a single or a multiple well system, an amount of groundwater equal to the drainage requirement. The success of tubewell drainage depends on many factors, including the hydrogeological conditions of the aquifer, physical properties of the overlying fine-textured layers and quality of groundwater being pumped. Enough water has to be removed from the aquifer to produce the required drop in hydraulic head, and for vertical downward flow, the hydraulic conductivity of the overlying layers must be such that the watertable responds sufficiently quickly to the reduced head in the aquifer.

For tubewells to be effective in draining agricultural land, the transmissivity T of an unconfined aquifer ($T = KD$, where K is hydraulic conductivity and D is thickness

Table 18.1 Minimum required thickness of aquifer for tubewell drainage

Mean hydraulic conductivity (m d^{-1})	Minimum required aquifer thickness (m)	Transmissivity (m^2 d^{-1})
43	14	602
26	25	650
17	40	680
13	60	780

McCready (1978)

of aquifer) should be ideally more than 600 m^2 day^{-1} (McCready 1978) to ensure an economic spacing and yield of the wells. For semi-confined aquifers, a further condition is that the hydraulic resistance c of aquitard overlying aquifer ($c = D'/K'$, where D' is thickness and K' is hydraulic conductivity of aquitard) should not be more than 1000 day (Table 18.1).

Early attempts to use a series of pumped wells for land drainage and salinity control were made in the USA and former USSR more than 80 years ago. If the water in the pumped aquifer is of good quality, it can be used for irrigation. The Indus Plains of Pakistan is a notable example of using 3800 public tubewells and over 200,000 low capacity private tubewells for land drainage, salinity control and supply of irrigation water, though with limited long-term success, as a part of Salinity Control and Reclamation Projects (SCARPs) implemented during 1960–1995 (Qureshi and Berrett-Lennard 1998). A review of studies and experiments with tubewell drainage in various countries shows that this technique cannot be regarded as a substitute for the horizontal SSD system. For instance, there are many areas like lower Sindh in Pakistan where tubewells would not function in absence of favourable aquifers. Unlike the other SSD systems, tubewell drainage is not economically feasible in small areas because of the too much water drained out of the area that consists of groundwater flowing in from surrounding areas.

Though Mohtadullah (1990) mentioned that tubewells were a better economic choice than horizontal drains for the Indus Basin, it is generally accepted that horizontal drains have lower construction and operation costs (Zhang 1990) for small to medium areas. In saline areas where the groundwater salinity increases substantially with depth, tubewells would provide more saline drainage effluent and over longer period than horizontal subsurface drains. This occurs since the streamlines towards the well occur deeper in the aquifer than those towards pipe drains or ditches (Fig. 18.3), thus posing more serious disposal and related environmental problems. In SSD systems, salinity of groundwater in the drainage area and of drainage water improves after salts from the soil profile and upper groundwater layers had been drained out. This replacement period is much longer in tubewell drainage, where pumping affects much deeper layers of groundwater.

Mole Drainage: Heavy soils of low hydraulic conductivity (< 0.01 m day^{-1}) often require very closely spaced drainage systems (2–4 m spacing) for effective watertable control, making subsurface drainage systems excessively expensive.

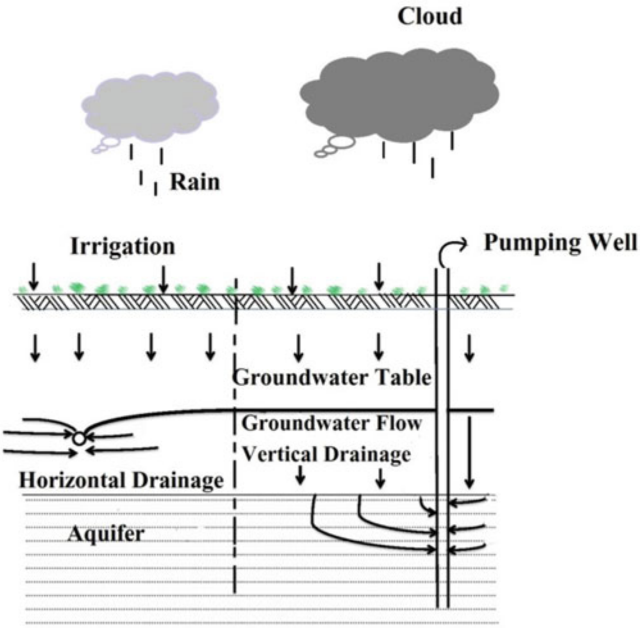


Fig. 18.3 Flow pathways of water and salts in subsurface and tubewell drainage systems

Under such conditions, techniques like mole drains have proven useful alternative to surface drainage (Hopkins and Colac 2002; NRCS 2003). Mole drains are unlined circular channels installed at a depth in the soil profile which function like pipe drains. These are formed in the clay subsoil by pulling a solid cylinder, with a wedge-shaped point, through the soil at a defined slope and depth without digging a trench. During installation, the soil in the vicinity of the mole channel should be moist enough to form a channel but not too dry to break up or too soft to form slurry.

Mole drains are generally installed at 40–60 cm depth and 2–10 m spacing, 4–8 m being the most accepted depth range. Based on a 4-year study involving mole drain spacing of 2–6 m in black cotton *Vertisol soils* in Bhopal region of India, an optimum mole drain spacing of 4 m has been recommended for the soybean crop (Singh and Ramana Rao 2014). The success of mole drainage is dependent upon stability of the mole channel, and it remains open for water entry for a reasonable period of time. Currently mole drainage systems are most commonly used for removing excess water from the surface layers in perched watertable situations in stable clay soils.

The major advantage of mole drains is lower cost for installing drains at very close spacing and shallower depths despite needing frequent renewals after only a few years. Successful application of mole drains as a temporary SSD system for reclaiming saline and saline *sodic* soils has been reported (Spoor et al. 1990), while the scope for extending mole drainage into new areas is provided by Spoor (1994).

Jha and Koga (2002) presented an excellent review of the use of mole drains in combination with subsurface drainage systems in the world.

Interceptor Drains: To protect flat areas from flooding by surface runoff or shallow subsurface outflows from adjacent higher grounds, an interceptor drain can be constructed at the foot of these uplands. For areas of 2–2.5 ha, the interceptor drains can be constructed like terraces and as grassed waterways for large areas. A drain depth of 0.45 m and 0.70 m^2 cross-sectional area are considered minimum values. A silt trap can be constructed on the upslope side of the ditch to prevent clogging of interceptor drains.

Interceptor drains are also used to intercept seepage from canal network which significantly impacts the quantum and distribution of surface and groundwater resources of the area. Canal seepage is influenced by the cross section of canal, nature and quality of canal lining, the hydraulic gradient between the canal and surrounding land, any impermeable layer at or near the canal bed, water depth, flow velocity and sediment load (FAO 1977). However, as per thumb rules, canal seepage is estimated at 20–30% of the canal flow in unlined and 15–20% in lined canals. Open drains, pipe drains and bio-interceptor drains have been used to intercept canal seepage to restrict the damage to a limited area, lessen the degree of damage and allow reuse of the intercepted water. Though open interceptor drains have not been found effective in Pakistan and in Chambal command of India because of poor maintenance and obstructions made in the drain by farmers to store water, limited experience with piped interceptor drains is encouraging.

Biodrainage: It refers to a technique of lowering groundwater in waterlogged areas by raising tree plantations. It is a preventive technique to avoid the development of salinity and waterlogging problem in canal commands. The technique is highly useful when the soil salinization has not still occurred due to rise in groundwater level (Chhabra and Thakur 1998; Jeet Ram et al. 2007; Dagar et al. 2016). For command areas, planting of 100 m or wider belt along the canals on both sides with high water-demanding trees such as *Eucalyptus*, *Populus*, *Leucaena* and *Bambusa* (Singh 2009; Dagar et al. 2016) and grasses such as species of *Spartina*, *Panicum*, *Leptochloa* and *Brachiaria* for the interspaces can be helpful in controlling waterlogging problem. An integrated drainage system comprising of subsurface drains, tree belts (biodrainage), evaporation-cum-fish ponds and agroforestry-based systems seem promising for the amelioration of waterlogged saline soils in areas without adequate outlets in the states of Haryana, Punjab and Rajasthan. Trees along canals help in checking seepage in adjacent agricultural fields.

Selection Criterion of SSD or Tubewell Drainage System

Under the assumption that a reliable source of energy is available for pumping, a methodology for selection of either subsurface (pipe) or tubewell drainage for any waterlogged saline irrigated area, based on depth of watertable, quality of groundwater and aquifer transmissivity as adapted from Bos (2001), is presented in Fig. 18.4. The information on infiltration rate of soil, topography, hydrogeology,

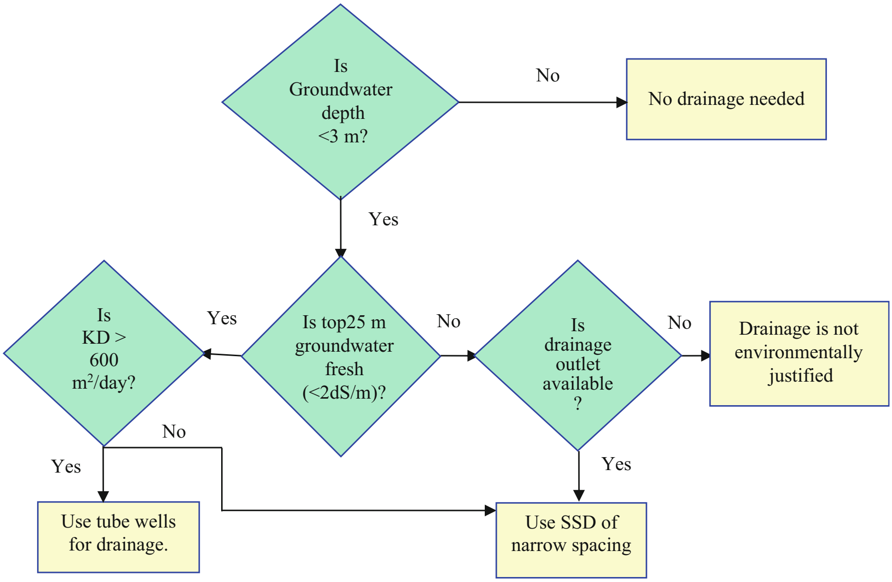


Fig. 18.4 Selection methodology of subsurface drainage method in irrigated land in semi arid climate. (Adapted from Bos 2001)

precipitation, evapotranspiration, irrigation supplies and grown crops is also needed to take a well-considered decision on the selection of either drainage method. No drainage system is needed in the irrigated area if the watertable is deep (at >3.0 m) and thus prevents salt accumulation in the root zone of the irrigated crop. Water balance studies in semiarid areas indicate that deep-percolating irrigation water causes a rising groundwater table if the ratio of potential evapotranspiration and total (irrigation and precipitation) applied water is less than 0.6 (Bos et al. 1991; Bastiaanssen et al. 2001). This emphasizes efficient use of irrigation water applied by surface methods or shifting to micro-irrigation systems to avoid the need for a costly drainage system in future.

If the top (say 25 m) groundwater layer in irrigated semiarid regions is fresh, tubewells will serve the dual purpose of drainage as well as irrigation. For this reason, the salinity of the groundwater should be sufficiently low (< 2 dS m^{-1}), tolerable to most crops without significant yield reduction. If the top layer of the groundwater cannot be used (either directly or mixed with fresh water) and yet needs to be discharged, availability of a drainage outlet is mandatory to consider SSD system. However, the expected benefits of drainage must be weighed carefully against potential damages to downstream users due to discharge of saline drainage water into surface water supplies. If a disposal outlet is available, selecting a horizontal narrow spacing SSD system is recommended to ensure the best possible water quality for downstream users. Flow lines in a SSD system can extend to one-fourth depth of the drain spacing; wide drain spacing is likely to mobilize a much thicker layer of saline groundwater than a close spacing system. If groundwater can be used for irrigation or other purposes, it is still to be ascertained if the transmissivity KD of the aquifer exceeds 600 m^2 day^{-1} to allow continuous pumping by tubewells at 30 l s^{-1} discharge (Kruseman and De Ridder 1971).

18.3 Progress of Subsurface Drainage, Vertical Drainage and Biodrainage Projects in India

As discussed in earlier sections, the productivity of irrigated agriculture can be sustained for a long time with proper leaching practices and adequate drainage to remove the accumulated salts and keep the watertable deep enough to prevent capillary rise of salts into the root zone. Two types of subsurface drainage, horizontal and vertical, are employed to control watertable and/or soil salinity. To control the watertable, it is necessary to attain an equilibrium between the groundwater recharge and draft. Recharge can be reduced by lining of canals and water courses and also by better farm management and judicious use of canal waters. Draft can be regulated by horizontal drainage system consisting of shallow open ditches or pipes laid horizontally at design depths below land surface or by vertical drainage system consisting of open wells, shallow and deep tubewells and related variant technologies. Biodrainage is a biological measure to prevent or delay the development of waterlogging and/or soil salinity in the irrigation commands.

Progress of horizontal subsurface drainage, vertical drainage, biodrainage and related variants and tradeoffs is presented for India in this section.

18.3.1 Subsurface Drainage

Subsurface drainage (SSD) is an effective technology for the amelioration of waterlogged saline-irrigated lands by maintaining watertable below desired depth and draining excess water and salts out of the area. The technology developed by CSSRI during 1980s initially for Haryana has been widely adopted and replicated in Rajasthan, Gujarat, Punjab, Andhra Pradesh, Karnataka and Maharashtra. These research efforts have resulted in the development of a package of practices, consisting of providing appropriate subsurface drainage, leaching of salts and management of saline drainage effluents for reclamation and management of waterlogged saline soils.

A SSD system consists of an underground network of open ditches or filter covered pipe drains installed at designed depth and spacing below the ground surface to remove excess water and salts from the affected fields. It involves three categories of drains: the laterals, the collectors and the main drains. *Lateral drains*, laid parallel to each other at designed spacing, depth and gradients, cover the entire field, accept excess groundwater whenever it rises above drain level and carry it to the *collectors* which further bring it to the main drain. The main drain carries the water to the outlet from where it is disposed out of the area either by gravity or by pumping from a sump well that allows temporary storage of some volume of drainage water. Other components of the system include manholes/inspection chambers, pump house and dewatering pump set. In areas with low soil permeability or high rainfall intensities or where surface water is the main problem, open ditches are preferred. Subsurface drains are preferred in high permeability areas where excessive water in the soil is the main problem.

The most common materials used in the manufacture of lateral drain pipes are clay, concrete and plastic. Clay and concrete pipes (often referred to as tiles), used earlier when PVC pipes were not available, are usually made in lengths of 30 cm and 10 cm internal diameter. The water enters the pipeline through the gaps between the tiles. These have now been totally replaced by PVC pipes which come in smooth and corrugated forms. The length of PVC pipes varies from about 6 m in case of smooth rigid pipes to 200 m in case of corrugated, flexible pipes available in coils which can be joined by sockets. Water entry into smooth pipes is via slit cuts or punched in the walls, while corrugated pipes have small openings in the valley of the corrugations. Perforations of 1–2 mm ϕ are usually provided in about 2–3% of the surface area of the pipe.

The advantage of plastic pipes over clay and concrete is their considerably lighter weight and their productions in larger lengths, thus involving lower transport cost and cheaper installation. The collector and main drains are either of pipes or open ditches. Bigger diameter RCC or PVC pipes joined together with sockets are generally used for collector drains. The joining of laterals to the collector through *manholes* helps in the maintenance of drain lines. The lateral drains are laid at a slope of 0.05–0.1%, while collectors are generally laid at a slope of 0.1%. The *sump* must have adequate storage capacity below the level of entry of the collector drain to avoid the continuous operation of the pump.

Two design variables of a SSD system are drain spacing and drain depth, which control the watertable depth. The depth and spacing of drainage system are governed by rainfall, irrigation, hydrogeology, soil texture and outfall conditions in the affected area. Other factors influencing the watertable height and thus drain spacing include drainage coefficient, representing the volume of water to be drained dependent upon regional water balance of the drainage area, hydraulic properties of soil and aquifer and cross-sectional area of the drains. Several equations relating these factors to drain spacing are available. The depth of lateral drains is influenced by the required watertable levels (for optimum crop production and for preventing soil salinization), the texture of different soil layers and the depth within the reach of available drainage machinery.

In general, the depth of drains may be limited between 1.5 and 2.0 m. The length of lateral drains varies from 200 to 500 m (ideally <300 m) depending on available natural slope and layout of the area. Envelope (filter) materials are provided around the pipe drains to facilitate water flow into the drain and to prevent the entry of soil particles into the drain. In absence of synthetic filters, graded gravel envelopes were used in the 1980s, but these have been replaced by synthetic filters which have considerable advantage over gravel in terms of transportation and installation.

Drainage water is disposed under gravity or by pumping into main drains, stream, canals or evaporation ponds.

18.3.1.1 Manually Installed SSD Projects

Though a few manually installed feasibility studies on SSD were conducted in the past by different research organizations in nonsaline and saline soils in different parts of India, systematic multidisciplinary research on SSD was initiated by CSSRI during early 1980s. A pilot research project on investigations, design, manual installation, monitoring and impact analysis of SSD in terms of watertable control, reduction in soil salinity, improvement in crop yields, cost- benefit analysis and management of saline drainage water was conducted by CSSRI during the period from 1983 to 1995 in 10 ha waterlogged saline area at village Sampla in district Rohtak of Haryana (Rao et al. 1986). About 20 similar pilot studies of 30–120 ha area each were conducted by CSSRI and other state departments during the 1980s and 1990s for amelioration of waterlogged saline soils in the states of Haryana, Rajasthan, Gujarat, Andhra Pradesh and Karnataka.

At most of these sites, the watertable fluctuated between about 1.5 m from ground level during summer to near the surface during monsoon. The initial salinity of groundwater at most sites was more than 10 dS m^{-1}, being as high as 40 dS m^{-1} in extreme cases. In the earlier installations, cement clay tiles were used for laterals and cement concrete pipes for the collectors. However, after 1986, PVC rigid and corrugated pipes are being increasingly used as subsurface drains. Either graded natural gravel or PVC (synthetic) netting (60–75 mesh size) has been used as envelope at these sites. The saline drainage effluent was pumped into surface drains or canal distributaries.

At most sites, drains were installed at about 1.5 m depth; the maximum adopted drain depth being 1.75 m. The average salinity of root zone at all the sites reduced considerably resulting in a good production of a number of crops in hitherto barren highly saline lands. The installation of subsurface drainage has continuously reduced the soil salinity and salinity of drainage water and significantly increased yields of different crops.

The manually installed SSD technology developed by the CSSRI during 1980s initially for Haryana has been widely adopted and replicated through mechanical installation in about 62,000 ha farmers' fields in Rajasthan, Karnataka and Maharashtra Gujarat, Punjab and Andhra Pradesh. This was facilitated in a major way through two international Indo-Dutch projects on land drainage operational at CSSRI during 1983–2001. These research efforts have resulted in the development of a package of practices, consisting of providing appropriate subsurface drainage, leaching of salts, crop production and management of saline drainage effluents for reclamation and management of waterlogged saline soils. Based on the experience of manual subsurface drainage projects, the following observations can be made:

- The reclamation of waterlogged saline soils with subsurface drainage is a technically and economically feasible solution since it leads to considerable increase in cropping intensity and crop yields and shifts to more remunerative cropping pattern.

- Subsurface drains at 65–80 m spacing and 1.5–1.8 m depth can provide adequate watertable and salinity control for potential crop production in waterlogged saline soils. For arid regions of Haryana and Rajasthan, drain spacing up to 100 m can be tried.
- Research output, from field studies and extensive numerical modelling results (Kamra et al. 1991, 1992), contributed to acceptance of shallower drains (1.4–1.8 m) in arid and semiarid regions of India and other countries.
- In areas with suitable outlets, rainwater leaching through drainage during the rainy season is adequate to maintain the favourable salt balance of drained fields. The quality of drainage effluent improves after 1–2 years to levels suitable for possible use in irrigation. After reclamation leaching, the watertable rise due to the suspension of drainage during non-rainy season can contribute up to 50% crop water needs (Rao et al. 1992).
- Reuse of drainage water for irrigation of salt-tolerant crops is an option to handle large volumes of saline drainage effluent. Drainage waters of about 10 dS m^{-1}salinity can be used directly or in conjunction with canal water in blending (mixing) or cyclic (sequential application) mode for irrigation of barley, wheat and mustard in the winter season. Salts added through use of saline drainage water were leached down with monsoon rains or by a pregermination irrigation with canal water (Sharma et al. 1994).
- In inland areas without an outlet, evaporation ponds with the surface area of about 5–10% of the drainage area offer an interim solution for managing saline drainage effluent. The quality of pond water deteriorates with time, and seepage losses can be significant during initial years in ponds constructed in the sandy substratum (Kamra et al. 1996).
- Analysis of financial feasibility of manually installed SSD projects indicated a benefit: Cost ratio of 1.26 and viable internal rate of return of 13.3% (Datta et al. 2000).

18.3.1.2 Mechanically Installed SSD Projects

During the mid-1990s, CSSRI was involved in monitoring and evaluation of two mechanically installed subsurface drainage projects of about 1000 ha each in Gohana and Kalayat blocks of Haryana executed by Department of Agriculture of Government of Haryana with assistance of the Netherlands Government. A number of SSD projects of 800–1200 ha pilot area each have been implemented in about 10,500 ha area in farmers' fields in Haryana where annual potential loss due to waterlogging and soil salinity is estimated at more than INR 10000 million. Besides Haryana, the subsurface drainage technology has been widely adopted and replicated in about 62,000 ha area in India, mainly in Rajasthan, Gujarat, Punjab, Andhra Pradesh, Maharashtra and Karnataka in some of which CSSRI has been/is involved (Table 18.2). About 16,500 ha areas in Chambal irrigation command in Rajasthan

Table 18.2 First estimate of area provided with subsurface drainage in different states under government schemes (needs updating)

State	Irrigation command	Area (ha)
Haryana	Western Yamuna Canal, Bhakra Canal	10,500
Rajasthan	Chambal, Indira Gandhi Nahar Pariyojana	16,500
Maharashtra	Lift irrigation system of Krishna River; Neera canal command, uncommanded	3500[a]
Karnataka	Upper Krishna, Tungabhadra, Malprabha, Ghatprabha	25000[a]
Punjab	Sirhind Canal (Southwest Punjab)	2500
Manual (small projects in different states, including above states)	Andhra Pradesh and Telangana (Nagarjuna Sagar, Krishna Western Delta); Gujarat (Mahi Kadana, Ukai Kakrapar); Kerala (acid sulphate soils); Assam (tea gardens), Madhya Pradesh (Tawa, Chambal, Barma command)	4000
Total		62,000

[a] In addition to above government-supported projects, SSD has been installed in more than 20,000 ha area by local farmers without government support

were provided with SSD with Canadian assistance during the period from 1991 to 2001. A drain spacing of 35–60 m, drain depth of 1.2 m and gravity outlet were the design parameters of the adopted SSD system (Sewa Ram et al. 2000). Extensive monitoring and evaluation indicated 40–50% increase in the yield of soybean and wheat over non-SSD sites resulting in a benefit-cost ratio of 2.6 and an internal rate of return (IRR) of 28% (Sewa Ram et al. 2000). Tejawat (2015) reported that the SSD system is working well after 20 years of installation and bringing in 15–20% additional financial benefits for farmers as compared to non-SSD area.

The implementation of SSD heavy soils of Maharashtra and Karnataka picked up rapidly from 2005 onwards with entry of private sector in SSD projects, almost exponentially with liberal funding under RKVY after 2007. During the past 5 years, CSSRI has been instrumental in getting SSD projects approved and implemented in about 4000 ha waterlogged saline area in Haryana, 2000 ha in Maharashtra and 1000 ha in Karnataka with funding under RKVY and other governmental schemes. More than 3000 ha affected area in Maharashtra and Karnataka has been reclaimed by SSD by farmers themselves without government support with drainage water disposal into open drains under gravity. About 20,000 ha area in Karnataka has been reportedly provided with SSD in a hybrid mode (manual + land shaping machinery like JVC) by different agencies and farmers. Southwest Punjab is in urgent need of SSD and other salinity management technologies like biodrainage and saline fisheries for which comprehensive regional salinity management planning and reclamation are mandatory.

Kamra (2013) summarized the improvement in crop yields in SSD projects implemented in different states of India (Table 18.3). It was reported that SSD increased cropping intensity by 40–50%, farm income by 200–300% resulting from enhanced yields of paddy (> 50%) and of wheat and cotton (> 100%) and by

Table 18.3 Impact of subsurface drainage on crop yields in different states

State	Crop	Crop yield (Mg ha^{-1})		
		Before drainage	After drainage	Increase over pre-drainage (%)
Haryana (3 locations)	Cotton	0.0	1.4–1.8*	**
	Wheat	0.0–3.1	1.9–4.9*	18–112
	Barley	0.0	2.1–4.2*	**
	Paddy	1.4	1.7	21
	Pearl millet	0.88	1.2	39
Andhra Pradesh (2 locations)	Paddy	3.6–3.7	5.2–5.6	45–50
Gujarat (1 location)	Sugarcane	78–104	105–140	35
Karnataka (7 locations)	Paddy	1.4–4.0	3.7–8.4	98–340
	Cotton	3.3	10.4	215
	Sunflower	3.0	7.4	146
	Sorghum	6.8	11.6	70
	Wheat	4.0	6.7	68

*Effect of drain spacing during first year; ** difficult to estimate increase in originally highly saline soil with zero production (> 100%)

Table 18.4 Design parameters of subsurface drainage for different regions of India

Drainage coefficient (mm d^{-1})			Drainage depth (D_d)		Drain spacing (D_s)	
Climate	Range	Optimal	Outlet	D_d (m)	Soil texture	D_s (m)
Arid	1–2	1	Gravity	0.9–1.2	Light	100–150
Semiarid	1–3	2	Pumped	1.2–1.8	Medium	50–100
Subhumid	2–5	3			Heavy	30–50

50–100% in most other crops. The socio-economic analysis of SSD indicated cost-benefit ratio of 1.5, IRR of 20% and employment generation of 128 man-days per ha every year (Kamra and Sharma 2016; Ritzema et al. 2008; Gupta 2002; Datta et al. 2000; Sewa Ram et al. 2000). Further, the finalized design parameters (drainage coefficient, drain spacing and depth) of SSD systems for different regions of India, synthesized from outcome of two Indo-Dutch drainage projects coordinated by CSSRI (Ritzema et al. 2008; Kamra 2013), are presented in Table 18.4.

Bundela et al. (2016) presented a detailed analysis of cost of installation of SSD systems at 50–100 m spacing in coarse- and medium-textured soils (clay $\leq$30%) and at 20–50 m spacing in heavy-textured soils (clay $\geq$30%). The cost of funding of SSD projects has been recommended as INR 74000 ha^{-1} and INR 79000 ha^{-1} for drain spacing (D_s) of 67 m and 60 m, respectively, and pumped outlet in medium-textured soils of Haryana and other northwestern states. Corresponding cost at 30 m drain spacing with a gravity outlet for heavy soils in Maharashtra, Karnataka, Gujarat and other *Vertisol* regions has been recommended at INR 111500 ha^{-1}.

18.3.1.3 Performance of SSD Projects in Haryana State

Out of 10,584 ha area provided with SSD over the last two decades in Haryana, more than 8000 ha has been installed in the past 12 years. Currently, CSSRI is associated with design, monitoring and evaluation of five SSD projects implemented by Haryana Operational Pilot Project (HOPP) of Ministry of Agriculture in 600–1000 ha area in Rohtak, Jhajjar, Jind and Sonepat districts. The basic design parameters of SSD projects in Haryana include a drainage coefficient of 1.5 mm day^{-1}, lateral drain spacing of 60–67 m and 1.5 m depth, corrugated PVC pipes of 75 and 100 mm ϕ for laterals and 160–294 mm ϕ for collectors as per ASTMIDIN standards and geo-synthetic filter with $O_{90} > 300$ on laterals and Nylon sock of 60 mesh on perforated collectors. Brief critical results on the performance of some SSD projects are presented to highlight the salient observations:

- Activities under HOPP are quite comprehensive involving detailed investigations starting from identification of the problem areas, preparation of designs, layout and cost estimates of SSD projects for funding and implementation of the project.
- HOPP has three sets of laser-controlled trencher and bucket excavators (Fig. 18.5) and supporting machines. Each fleet of machines installs subsurface drains in 300–400 ha area depending upon breakdowns or unexpected rains during summer (mid-April to end June) working months when watertable is below 1.5 m.
- Due to less concrete progress on construction of pump house, distribution of pump sets to farmers' societies and farmers' participation in post-reclamation pumping of drainage water, the improvements in crop yields and economic return have remained non-satisfactory at a number of SSD projects in Haryana.
- The technology provides a net present worth of about INR 65000 ha^{-1} with benefit-cost ratio of 1.76 and internal rate of return 20%. The material and mechanical installation costs cover about 60% and 40% of the total cost.

Despite above bottlenecks in efficient pumping of drainage water, significant improvement in watertable control, reduction in soil salinity and improvement in crop yields were observed in selected blocks of certain SSD projects where pumping was initiated either by HOPP or individual farmer's efforts. Pathan (2015) used EM38 technique to evaluate the effectiveness of SSD in improving soil salinity in

Fig. 18.5 Subsurface drainage machinery being used in Haryana

38 ha area of block JD 4 at Siwanamal SSD site in Jind district where adequate pumping had been done by a farmer. GPS-coordinated EM38 surveys were conducted during 2015 to measure apparent electrical conductivity (EC_a) at 50 m × 50 m grid and correlated with salinity analysis of collected soil samples at selected locations. EM survey results of 2015 were compared with similar EM survey conducted by CSSRI in the same block during 2012 (before installation of SSD) to evaluate the impact of SSD on salinity distribution in 60 cm soil profiles. EC_e maps of composite 0–60 cm soil depth for JD 4 (pumping) block are presented for 2012 and 2015 in Fig. 18.6, while differences in salinity levels in different depth zones are presented in Table 18.5.

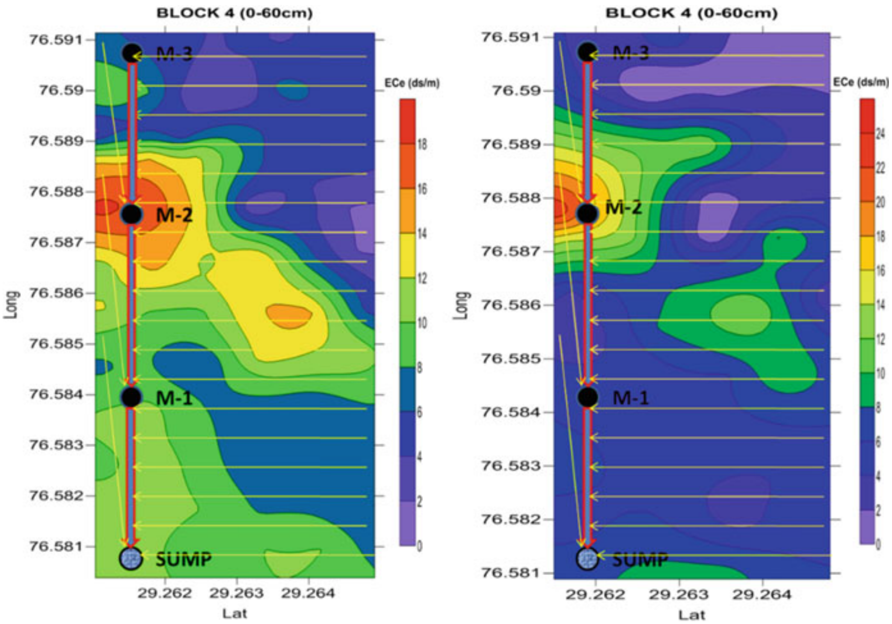


Fig. 18.6 Spatial map of improvement in soil salinity in 0–60 cm depth in JD 4 block of Siwanamal before (2012) and after (2015) installation of SSD

Table 18.5 Improvement in percent area under different soil salinity levels in block JD 4 at Siwanamal SSD site

		EC_e <4 dS m^{-1}	EC_e 4–8 dS m^{-1}	EC_e 8–16 dS m^{-1}	EC_e >16 dS m^{-1}
Depth	Year	Area %	Area %	Area %	Area %
0–15 cm	2012	01.3	21.8	66.2	10.7
	2015	20.5	54.3	23.2	2.0
0–30 cm	2012	02.9	25.4	63.9	7.7
	2015	17.6	37.2	35.6	9.6
0–60 cm	2012	06.6	34.6	56.4	2.4
	2015	18.7	46.0	30.0	5.3

Table 18.6 Pumping status and crop yields in different SSD blocks at Siwanamal SSD (2015–2016)

Drainage block No.	Pumping status	Yield (Mg ha^{-1})	
		Rice	Wheat
JD 1	No	1.5–2.0	1.0–1.5
JD 6	No	2.0–2.5	2.5–3.0
JD 2	Functioning	4.0–4.5	3.5–4.0
JD 4	Functioning	4.5–5.0	4.0–4.5
JD 3	Partial	3.5–4.0	2.5–3.0
JD 5	Partial	3.5–4.0	4.0–4.5
JD 7	Partial	3.5–4.0	3.0–3.5

Table 18.7 Benefit-cost ratio of major crops before and after SSD at Banmandori (district Fatehabad, Haryana)

Crop	Benefit-cost ratio		Percent increase
	After drainage	Before drainage	
Rice	1.42	0.92	54.3
Wheat	1.26	0.85	32.7
Cotton	1.13	0.82	37.6
Mustard	1.22	0.87	40.3

It can be seen that 98.7% and 97.1% area having more than 4 dS m^{-1} salinity in 0–15 cm and 0–30 cm layer during 2012 reduced, respectively, to 79.5% and 82.4% area during 2015 due to SSD activities. Similarly, the area having more than 8 dS m^{-1} salinity in 0–60 cm zone reduced from 58.8% to 35.3% during the same period.

Overall status of SSD project and crop yields of rice (CSR 30) and wheat (Pusa 1121) during 2015–2016 is summarized in Table 18.6. It is seen that the yields of rice and wheat crops in functional (pumping) blocks (JD 2 and JD 4) are almost double over those in non-pumping blocks (JD 1 and JD 6), while the yields of partially functional blocks fall in between the two extremes. There is widespread awareness about the effectiveness of SSD in ameliorating waterlogged saline soils, and it is expected that with efforts of farmers themselves, the crop yields in fully and partially functional blocks will rise to the levels of normal soils. Similar results have been reported for other SSD sites in Haryana (Kamra and Sharma 2016).

For another SSD site of 277 ha at Banmandori in Fatehabad district of Haryana, Raju et al. (2015) presented an economic analysis on gross income, total cost and net income before and after implementation of SSD. The benefit-cost ratio for different crops (Table 18.7) indicate that benefit-cost ratio was less than one for all crops before drainage which improved to 1.42 for rice, 1.26 for wheat, 1.13 for cotton and 1.22 for mustard after introduction of SSD. An increase of 32–54% in benefit-cost ratio due to SSD indicates the worthiness of the technology for reclaiming waterlogged saline soils for the study area in Haryana. It is to be mentioned that farmers insist on going for paddy crop in waterlogged saline areas of Haryana due to not only better benefit-cost ratio but also because of more favourable marketing policies for paddy than other *Kharif* crops.

The operational cost of the drainage system in northwestern states is mainly due to pumping of the drainage effluent. After 1 or 2 years of operation of the drainage system, the quality of drainage effluent improves to a level where it can be reused for irrigation. High costs, socio-economic and environmental issues relating to disposal of saline drainage effluent, need of community participation for system operation and existing institutional/organizational constraints are the major deterrents to rapidly increase the pace of reclamation projects (Ritzema et al. 2008). Involvement of farmers, sharing of construction and operating cost and government subsidy are vital to the success of SSD technology. Adoption of this technology is quite slow keeping in view the quantum of the problem and despite tangible benefits in terms of productivity gains and on-farm employment generation. Major institutional and organizational changes and new business models are needed for expediting the implementation of SSD projects, especially in northwestern Indian states.

18.3.1.4 Disposal and Management of Saline Drainage Water

Subsurface drainage waters generally contain high concentrations of soluble salts and plant nutrients and may sometimes also contain potentially toxic trace elements and pesticides. The disposal and storage of such waters can have remarkable impacts on the degradation of surface and groundwater quality; a threat to aquatic organisms, wildlife and plants; and potential risk to public health (Heuperman et al. 2002). Discharge of drainage water from irrigated lands in the San Joaquin Valley in California (USA) into the Kesterson Reservoir resulted in problems of selenium toxicity in the biota (Cervinka et al. 1999).

Depending on the location, hydrology and topography of the drainage basin, the possible methods for disposing saline drainage water in Northwest India include (i) disposal into regional surface drainage system which is ultimately linked with major rivers flowing through the region, (ii) pumping into the canal distributaries that carry high flow discharge for most of the year and (iii) disposal into evaporation ponds in land-locked depression areas not having a suitable drainage outlet. Options of disposal of saline drainage water into canal distributaries are covered briefly here while of biodrainage are covered separately in another section of this chapter. Details on other alternatives like evaporation ponds, reuse for cropping or agroforestry, shallow watertable management, saline aquaculture and the use of salt-tolerant varieties can be found in Kamra (2015). The large-scale drainage disposal and reuse programs, however, will need substantial infrastructural changes and consideration of maintaining a favourable basin-level salt regime.

18.3.1.5 River Discharge with and Without Dilution

Disposal of the drainage water into rivers or canal can deal with large volumes and may be a practical medium-term solution for the inland sites. Discharge to the river system is inexpensive, but the disposal of large volumes of saline drainage effluent through this mode is likely to become increasingly difficult due to environmental restrictions imposed by downstream users. The maximum drain discharge generally occurs during the rainy season when the irrigation demands are relatively less, and consequently large volumes of saline drainage water can be discharged into the river

Table 18.8 Allowable subsurface drain discharge and drainable area into Yamuna River

	Drain discharge $m^3\ s^{-1}$ using drainage water of EC_d		Drainable area (ha) using drainage water of EC_d	
Month	6 ($dS\ m^{-1}$)	10 ($dS\ m^{-1}$)	6 ($dS\ m^{-1}$)	10 ($dS\ m^{-1}$)
June	0.9	0.5	5000	3000
July	25.4	14.4	146,000	83,000
August	47.6	27.0	274,000	156,000
September	6.5	3.7	37,000	21,000
October	3.0	1.7	17,000	10,000

EC_d is electrical conductivity of drainage water

system. This will necessitate establishment of numeric water quality standards for various points along the river, monitoring and modelling of spatial and temporal water quality trends and provisions for diverting saline drainage waters produced away from the surface drain/canal/river.

During the monsoon (July to September) season, the flow of the Yamuna River exceeds 1000 $m^3\ s^{-1}$, and its salinity is less than 0.2 $dS\ m^{-1}$, while the salinity of water flowing in the surface drains is also low at 1.2 $dS\ m^{-1}$. In a case study on the disposal of drain discharge into the Yamuna River during June to October, UNDP (1985) estimated the volume of SSD water of 6 and 10 $dS\ m^{-1}$ that could be discharged safely in Yamuna without exceeding the salinity of river water after mixing beyond 0.75 $dS\ m^{-1}$. Based on 80% frequency discharges of the river at Wazirabad (Delhi) and of Surface Drain No. 2 and 8 of Haryana, allowable discharge of subsurface drainage water was calculated.

Assuming a subsurface drainage surplus of 1.5 m ha^{-1} day^{-1} during the monsoon period, the area that could evacuate its drain discharge into the river was calculated (Table 18.8). It is seen that 83,000 ha and 156,000 ha critically waterlogged area in Haryana can evacuate 10 $dS\ m^{-1}$ drainage water in Yamuna River during July and August, respectively. It was also reported that in the winter months, low river flows (< 50 $m^3\ s^{-1}$) reduce the disposal capacity considerably. The disposal requirements during this period can be reduced through interventions like shallow watertable management and the reuse of drainage water.

18.3.2 Vertical Drainage

As discussed in an earlier section, vertical drainage is a technique of controlling the watertable and salinity in agricultural areas. It consists of pumping, from a series of wells, an amount of groundwater equal to the drainable surplus. Tubewell drainage enables the watertable to be lowered to a much greater depth than horizontal drainage system. If the water in the pumped well is of good quality, it can be used for irrigation. However, if the pumped water quality is not of good quality, then its disposal and management is much more difficult than other drainage systems.

As a general guideline, it can be stated that vertical drainage systems cannot be used to control waterlogging if groundwater is saline and the salinity increases with depth. However, some variants of vertical drainage systems, called groundwater skimming structures, can be used in a limited way to pump out water from thin layers of fresh water floating over saline groundwater in coastal and inland-irrigated areas. In this paper, basic features of a few skimming structures and other vertical drainage variants like open well and groundwater recharge wells are discussed in the context of Indian conditions.

18.3.2.1 Groundwater Skimming Structures

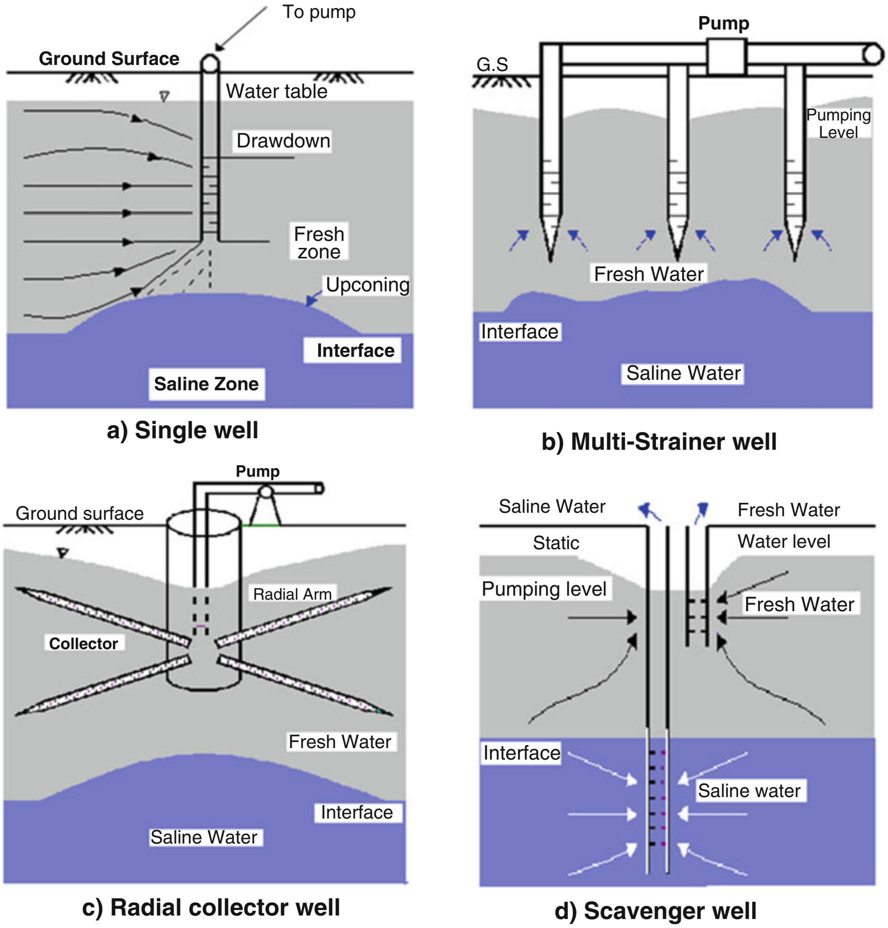
Excessive pumping of fresh groundwater to meet increasing domestic, irrigation and industrial requirement is causing extensive seawater intrusion problems in coastal areas or groundwater salinization in several inland-irrigated regions of India. A 2–3 % mixing with seawater renders fresh water inappropriate for human consumption and for irrigation, while a 4% mixing is enough to destroy a freshwater resource (Custodio 1997). The local effect of such activities is a gradual deterioration in pumped groundwater quality due to up-coning or rise of relatively more saline groundwater of deeper layers to within the domain of pumping wells. Under these conditions, it is imperative not to disturb the saline water but to selectively skim fresh water accumulated over the native saline groundwater by tubewells or some modified forms of vertical drainage and by enhancing groundwater recharge.

Various skimming well configurations such as single, multi-strainer, radial collector and scavenger wells (Fig. 18.7) are possible to selectively abstract fresh water from thin layers overlying saline groundwater. The basic concept of all skimming structures is to modify the flow lines in such a way to maximize horizontal contribution of aquifer zones of acceptable quality to pumped water (Sufi et al. 1998).

(i) *Single Well*

A single well (Fig. 18.7a) is commonly used in unconfined aquifers in most parts of India. While using these wells in saline groundwater regions, well penetration is kept deep into the freshwater layer with a large gap between the bottom of the well and the fresh-saline water interface. As a general rule, the depth of the well-considered safe for extracting fresh water by a strainer tubewell without disturbing the saline water is 1/3rd of the total depth of the freshwater zone. Single tubewell-based drainage projects were executed during the 1980s and 1990s at Masitawali in Indira Gandhi Nahar Pariyojana (IGNP) (Hooja et al. 1995), Ghaggar depression areas in Rajasthan and in Fatehabad branch area of Haryana for watertable control in the vicinity of canal distributaries. In Rajasthan, the water quality was deteriorating with depth, while in Haryana the vertical drainage projects were commissioned to lower watertable in waterlogged areas.

The waterlogged project sites in Haryana were mostly selected along the canal distributaries and irrigation channels where a layer of fresh water floated over deeper saline water zone. A number of pilot projects involving single tubewell-type structures were implemented by Haryana State Minor Irrigation and Tubewell Corporation (HSMITC) (Table 18.9). Strainer tubewells of 6–10 l s^{-1} were used at most sites, while at some sites cavity tubewells were used. The pumped water of



a) Single well b) Multi-Strainer well c) Radial collector well d) Scavenger well

Fig. 18.7 Different types of fresh water skimming wells

acceptable quality was discharged into nearby distributaries to successful lowering of watertable and enabling farmers to get normal crop yields. Continuous pumping of years in a few projects caused negligible increase in pumped water salinity.

Ironically such projects have not been implemented in later years, perhaps due to lack of proper guidelines (as discussed in this paper) for selection of subsurface drainage or tubewell drainage in waterlogged saline areas.

(ii) *Multi-strainer Well*

A multi-strainer well (Fig. 18.7b), with relatively shallower penetration than single well, can be used for watertable control with diminished *up-coning* in freshwater layers of restricted depth. The system consists of closely spaced interconnected wells, each of low capacity, pumped by a central suction pump.

Table 18.9 Vertical drainage schemes executed by HSMITC in Haryana, India, and impact on watertable control

S. No.	Scheme	District	Cost (million INR*)	Period	Watertable decline (m)
1	Narwana area (11 drainage tubewells, 88 ha area)	Jind	1.99	1985–1992	1.00–4.00
2	Rori area (8 shallow tubewells, 70 ha area)	Sirsa	2.10	1985–1992	1.90–3.00
3	Fatehabadbranch (50 drainage tubewells)	Fatehabad	6.10	1995–1996	0.44–3.20
4	Kishangarh sub-branch/link channel (50 drainage tubewells)	Hisar	6.10	1995–1996	0.95–1.90
5	Jui feeder/canal (15 drainage tubewells)	Bhiwani	1.83	1996–1997	0.65–2.18

*1 US$ = 72 INR

Such structures are reported to be extensively used close to canals/distributaries in Punjab in India (Shakya 2002) and in the Indus Plains of Pakistan (Sufi et al. 1998; Mazhar Saeed et al. 2003) and also for draining foundation pits.

A multiple well point system was installed and evaluated for tapping floating thin layer of good-quality water near a canal distributary without creating turbulence in the lower saline water zone in 100 ha project area in Golewala in Faridkot district of Punjab, India (Shakya 2002). It consisted of a number of well points arranged in a line and interconnected to each other through a horizontal pipe line (lateral) installed at about 0.7–1.0 m below ground level to be pumped centrally by one pumping unit (Fig. 18.8). The total discharge from the system was divided equally over the well points so that the requirement of prime mover will be the same as is required by single well.

The above design was further improved (Shakya 2002) to include a siphon system for automatic pumping of water brought by laterals to a centrally located sump of 2 m depth. The moment the water is lowered in the sump through pumping, groundwater starts moving from well points to the sump under siphon action. Length of the lateral should be limited to 350 m to minimize priming problems. There are reports on the use of these systems in marginally saline regions of Haryana, Rajasthan, Andhra Pradesh and Tamil Nadu in India. Air leakage and priming problems have been reported from most of these studies. Sufi et al. (1998) reported that the double-strainer skimming well to be the most promising skimming technique for the studied area in Pakistan.

(iii) *Radial Collector Well*

Radial collector wells consisting of an open well and input radial drains on one or more sides (Fig. 18.7c) involve shallower penetration than a single vertical well operating at the same discharge. Since the radial drains collect water from shallow depths, up-coning of saline water from lower depths is prevented. Large diameter

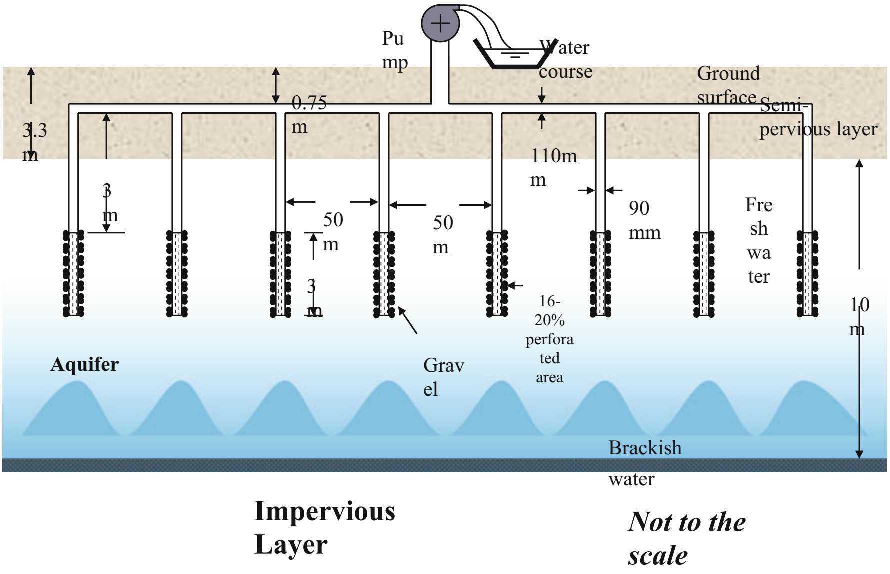


Fig. 18.8 Schematic diagram of multiwell point system installed at Golewala (Shakya 2002)

Fig. 18.9 Installation of radial collector D*oruvu* wells at Bapatla (Andhra Pradesh), India

open skimming wells experimented at Hisar in Haryana (Kumar and Singh 1995) and at Luni-Ki-Dhani in Rajasthan (Hooja et al. 1995) and a drain line-sump-based *Doruvu* technology embarked on a large scale in coastal sandy soils of Andhra Pradesh (Raghu Babu et al. 2004) are the local variants of radial collector wells.

About 0.174 million ha coastal sandy area in Andhra Pradesh and 0.68 million ha in Tamil Nadu, having 700–1200 mm annual rain, is characterized by existence of 8–10-m-thick sandy layer of fresh water followed by a clay layer saturated with saline water. Radial collector well-type *Doruvu* skimming structures (Fig. 18.9) consist of an open well of 1.2–1.5 m diameter with radial subsurface drains (at 2.4–4.0 m depth and of 30–40 m length on two sides) for skimming of fresh groundwater. The system yields a discharge of 5–15 $\mathrm{l\ s^{-1}}$ or more depending upon the number of arms and nature of sand and can operate in combination with sprinkler/drip system. Pumping tests indicated 90 m as the safe spacing between two skimming wells. Such structures can meet *rabi* crop water demand of 2 ha area using sprinklers and have 1.7 benefit-cost ratio and 30% internal rate of return

(NATP 2006). The tracer studies revealed that radial arms contribute 80% of pumped water, while the remaining 20% comes from the bottom of the well.

The D*oruvu* technology was found to increase the farmers' income by 25–40% due to enhanced crop yield, but a major deterrent for large-scale adoption among small and marginal farmers had been the high cost and lack of optimal designs and layouts for sustained supply of fresh water. The technology has been widely adopted in Guntur and Prakasam districts of Andhra Pradesh. Horizontal drilling of radial drains needs to be standardized for sandy soils to reduce the cost of installation of these structures.

(iv) *Scavenger Wells*

Scavenger wells (Fig. 18.7d) involve simultaneous abstraction of fresh and saline waters through two wells having screens in different quality zones, for controlling the rise of interface. The scavenger wells have been tested in the lower Indus Basin of Pakistan (Sufi et al. 1998) and have shown their potential in skimming of fresh water. Despite apparent problem of disposal of saline water, the scope of scavenger wells needs testing for cases involving two cavity wells (non-strainer tubewells common in saline groundwater regions of Indo-Gangetic plains) installed at different depths or a combination of a strainer and a cavity wells. Geological, hydrological and geochemical characteristics of the aquifers must be studied in an integrated way to study the hydraulics and evaluate the performance of these skimming structures. In interconnected layers, the pumping from lower saline zone is likely to increase the fresh water recharge potential of upper zone.

Based on the principle of scavenger wells (Fig. 18.7d), Kamra et al. (2006) installed and evaluated the performance of a skimming cum recharge structure constructed at a downstream location prone to runoff flooding at village Jagsi in district Jind of Haryana. The system consisted of two cavity tubewells, installed at 7 m and 40 m depth in the respective fresh and saline groundwater zones, which could be operated separately or together to obtain water of different qualities. A recharge chamber of 6 m × 2.5 m × 2 m size and containing a graded filter of fine sand, coarse sand, gravel and boulders was constructed close by to facilitate recharging of one or both cavities with filtered runoff during rainy season or excess canal water. The objective was to increase the availability of good water in upper cavity or improve the quality of lower cavity for possible use at time of water scarcity. General improvement was reported in the groundwater regime of area due to combined effect of the natural and imposed recharge interventions. The estimated recharge rates through injection in cavity wells were low at about one-third of the pumping rates under shallow groundwater conditions.

18.3.2.2 Groundwater Recharge Wells

The sustainability of highly productive but water-intensive rice-wheat cropping system in Haryana and Punjab is getting threatened due to alarming decline of watertable, increase in pumping cost and deterioration in groundwater quality. The rate of groundwater decline can be slowed down by change in cropping pattern or by enhancing groundwater recharge (GR). Besides raising groundwater level, GR also helps in utilizing flood water that goes waste or causes damage to standing crops and also in improving groundwater quality. About two-third area of Haryana and one-third each of Punjab and Gujarat are underlain with saline groundwater, a major part by high residual sodium carbonate (RSC) waters. For such and areas having problems of fluoride contamination, groundwater recharge structures can help in improving water quality by dilution.

Under two Ministry of Water Resources (GOI) funded projects, CSSRI developed the design of small groundwater recharge (GR) wells (shafts and cavities) and installed and monitored such structures at 60 low-lying farmers' fields in declining watertable and poor-quality groundwater alluvium regions of Haryana (38), Punjab (5), UP (5) and Gujarat (12) during 2008–2012. In these and earlier works on groundwater recharge of CSSRI (Kaledhonkar et al. 2003; Kamra 2013), the groundwater recharge structures consisted of a bore well (for carrying water to subsurface sandy zones) coupled to a recharge filter consisting of layers of coarse sand, small gravel and boulders in a small brick masonry chamber. Selection of recharge structures of different designs, depths and costs was based on hydrogeological investigations and quantum of potential runoff water available at specific locations. Despite semiarid climate at selected sites, there are depression areas where water accumulates during rainy season and can be recharged to groundwater as a local vertical drainage system to save crops from submergence due to heavy rain.

Of all tested recharge structures under these projects, recharge cavity (Fig. 18.10) has been found to be the most effective and practical for individual farmers' needs (Kamra 2013). It consists of a conventional cavity pumping well coupled with a recharge filter and hence can be used also for occasional pumping. It is constructed by drilling a bore hole until a sandy layer is found below a clay layer. A blind PVC

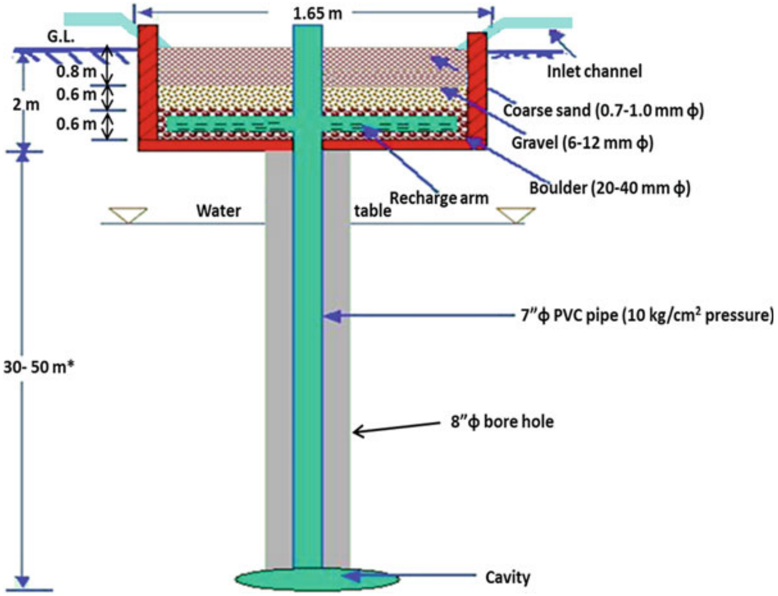


Fig. 18.10 Design features of a groundwater recharge cavity tubewell

casing pipe of 7–9 inch ϕ (7 inch in Fig. 18.10) is drilled into the clay layer, and sand is pumped out until a stable cavity is developed below the clay layer. To safeguard against clogging, the surface runoff is first passed through a recharge filter consisting, respectively, of 0.8 m, 0.6 m and 0.6 m thick layers of coarse sand, small gravel and boulders in a small brick masonry chamber as per details provided in Fig. 18.10.

GR wells, having intake rate of 4–6 litre sec^{-1}, were found effective in augmenting groundwater, improving its quality and enhancing the farmers' income by saving submerged crops. The structures helped in reducing flood volumes to save transplanted rice in the lowest 1–2 ha area at certain sites in Haryana and Punjab resulting in a net saving of 25,000/ from rice only. Recharge wells in Gujarat also resulted in prolonged availability and improvement in quality of groundwater that facilitated increase in income of INR 30000–75,000 ha^{-1} in mango, papaya and banana plantations. The payback period of 30–45 m deep recharge structures and costing INR 30000–50,000 ha^{-1} (2008 prices) was estimated as 1–2 years. The field observations in a farmer's field in Karnal district during heavy rains of August 2012 clearly indicated a recharge structure to be essential for saving maize crop from adverse effect of prolonged water submergence.

Groundwater recharge structures also provided impressive perceptible benefits like improvement in salinity, alkalinity and fluoride concentration at selected sites in four states. The clogging of the recharge filter is a major constraint in the performance of recharge structures. Kumar et al. (2012) reported that the thickness of upper sand layer of recharge filter was the primary factor influencing clogging, while size of gravel in the middle layer also influenced effectiveness of sand as a filter. Practical effective designs of recharge filters and quality of water being recharged are the focus of current research at CSSRI.

18.3.3 Biodrainage

Biodrainage refers to a technique of lowering groundwater in waterlogged areas by making use of evapotranspiration power of plants, especially of trees. It is a preventive technique to avoid the development of salinity and waterlogging problem in canal commands. The technique is highly useful when the soil salinization has not still occurred to a serious level in canal commands due to rise in groundwater level (Chhabra and Thakur 1998; Heuperman et al. 2002; Jeet Ram et al. 2007, 2011; Dagar et al. 2016). Strip plantations of *Eucalyptus tereticornis* prevented the development of shallow watertables and salinity, while adjacent fields lacking tree cover recorded an upward movement of water (Jeet Ram et al. 2007, 2011; Dagar et al. 2016). Dagar (2011, 2014) reported *Casuarina glauca*, *Acacia ampliceps*, *Terminalia arjuna*, *Pongamia pinnata* and *Syzygium cuminii* as other species suitable for block plantations in waterlogged areas.

Fast-growing species, like cloned *Eucalyptus*, poplar and bamboo having high water consumption under excess soil moisture conditions, are suitable for biodrainage (Jeet Ram et al. 2007; Dagar 2014). Of these, *Eucalyptus tereticornis*, a fast-growing deep-rooted tree species, is most commonly used for lowering of watertable and seepage control from canals in waterlogged areas. So far, *Eucalyptus* has been found as the most efficient species for lowering down of watertable (Dagar et al. 2016). A major factor determining the sustainability of biodrainage projects is attainment of long-term salt-balance in the soil profile in shallow saline groundwater regions. The water use and transpiration capacity of trees and other crops decrease with increase in water salinity; it reduced to one-half of potential at 8 dS m^{-1} water salinity in *Eucalyptus* species as compared to normal water (Oster et al. 1999).

Jeet Ram et al. (2011) evaluated the performance of clonal *Eucalyptus tereticornis* planted on field boundaries in a 5 ha land-locked waterlogged area surrounded on three sides by canal branches at Puthi, Hisar district in Haryana (India). The paired row strip plantations at 1 m × 1 m spacing on field boundaries 66 m apart at plant density of 300 plants ha^{-1} were monitored through 22 observation wells for groundwater use and watertable control. These plantations resulted in lowering of shallow groundwater by 0.85 m in 3 years and by ~ 2 m after 5 years. It was also reported that in area planted with *Eucalyptus* trees, wheat yield was 2.15 Mg ha^{-1} as compared to 0.64 Mg ha^{-1} in nearby fields without tree plantations. Dagar et al. (2016) further compared different density of strip plantations and concluded that spacing of 1 m × 1 m is profitable and ideal for strip plantation on acre line to lower down the watertable. This has been adopted by farmers in quite large area in Punjab and Haryana (Fig. 18.11). In another trial (Patil et al. 2005), biodrainage proved an effective option to intercept seepage by trees planted along a canal and water courses. Species such as *Acacia nilotica*, *Dalbergia sissoo*, *Sesbania grandiflora* and *Casurina equisetifolia* intercepted, respectively, 86%, 84%, 72% and 72% of canal seepage in saline Vertisols regions of India.

Fig. 18.11 Biodrainage through strip plantations of *Eucalyptus tereticornis* on field boundaries on farmers' fields in Haryana. (Photos: JC Dagar and Surender Lathwal, DFO Haryana Forest Department)

For canal command areas, planting of 100 m or wider belts of high water-demanding trees such as *Eucalyptus*, *Populus*, *Leucaena* and *Bambusa* along the canal and grasses such as *Spartina*, *Panicum*, *Leptochloa*, *Brachiaria*, *Phragmites*, *Panicum* and *Paspalum* for the interspaces have been recommended for controlling the waterlogging problem (Singh 2009; Dagar 2014). Of late, combined applications of biodrainage and suitable land modifications are being explored to productively utilize the waterlogged salt-affected soils. Heuperman et al. (2002), however, reported apprehensions on the long-term success of biodrainage in controlling harmful build-up of root zone salinity in canal commands without additional drainage measures. This advocates research and pilot studies on the scope of this technology in combination with other drainage or salinity management measures like subsurface drains, evaporation - cum - fish ponds and agroforestry-based systems. Such integrated drainage measures seem promising for the reclamation of waterlogged saline soils in areas without adequate drainage outlets in the states of Haryana, Punjab and Rajasthan.

18.4 Identification of Areas Suitable for Different Drainage Methods in Haryana

Kamra and Sharma (2016) reported that shallow watertable existed within 1.5 m in more than 50,000 ha area in Haryana in 2013 which had almost turned into waste land, while additional 3,80,000 ha area under 1.5–3.0 m watertable depth was potentially waterlogged saline land. Under ICAR-Emeritus Scientist scheme entitled 'Developing a regional framework and guidelines for effective operation and governance of subsurface drainage projects in Haryana' of the senior author operational at CSSRI, Karnal, CGWB data of November 2015 has been further synthesized in the form of GIS maps and watertable depth and groundwater quality for waterlogged regions of Haryana. These maps have been overlaid by surface elevation and surface drainage network maps to identify priority areas for implementation of SSD, biodrainage and vertical drainage projects. Brief results on watertable depth and groundwater quality for November 2015 are presented in Fig. 18.12 and Tables 18.10 and 18.11, respectively.

Most of the critically waterlogged (WTD < 1.5 m) and potentially waterlogged (WTD 1.5– 3.0 m) areas occur in arid and semiarid regions in central inland depression basin of Haryana encompassing Jhajjar, Rohtak, Sonipat, Jind, Fatehabad, Bhiwani, Kaithal and Hisar districts. Out of 74,595 ha critically (0–1.5 m) waterlogged area, above seven districts account for 62% or 46,415 ha area, while remaining 38% ha area falls in Ambala and Yamuna Nagar districts which have relatively higher annual rainfall and consequently less susceptibility to soil salinization and a few other districts in south and northwest Haryana.

Similarly, about 334,902 ha (83%) out of total 403,890 ha potentially waterlogged lands (watertable 1.5–3.0 m) of Haryana occur in above seven districts. Districts Jhajjar, Rohtak and Sonepat have the highest percentage of waterlogged area; Rohtak and Jhajjar have watertable within 3.0 m depth in 53% and 45% area,

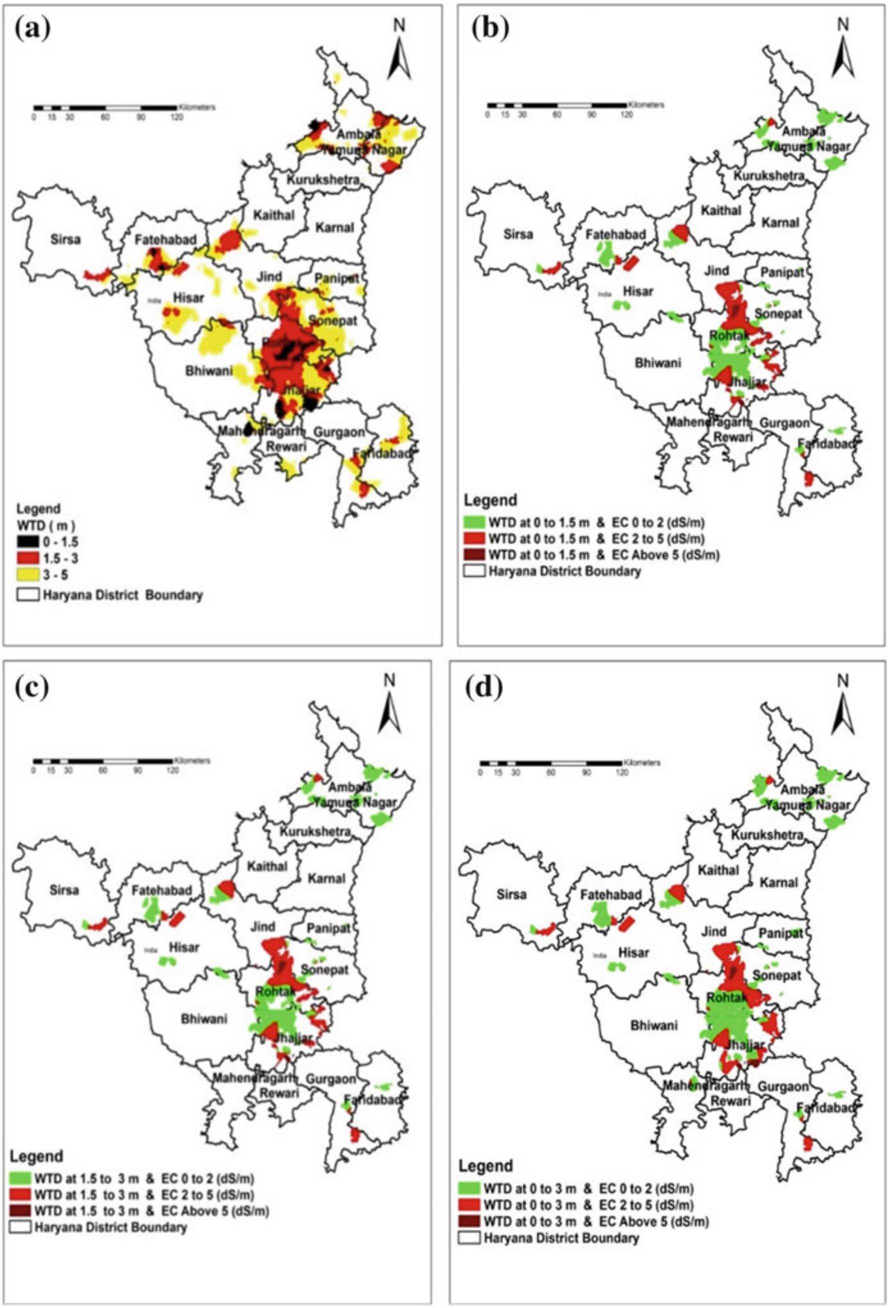


Fig. 18.12 (**a**) Shallow watertable depth WTD (**a**) and associated groundwater salinity regions for 0–1.5 m (**b**), 1.5– 3.0 m (**c**) and 0.0–3.0 m (**d**) depth areas of Haryana

Table 18.10 Area under different watertable depths in different districts of Haryana (November, 2015)

District	Geographical area × 100 (ha)	Area (ha) under watertable depth			% District area under watertable depth		
		0–1.5 m	1.5–3.0 m	0–3.0 m	0–1.5 m	1.5–3.0 m	0–3.0 m
Central Haryana							
Jhajjar	2111.9	26,530	69,424	95,954	12.6	32.9	45.5
Rohtak	1685.1	9020	80,850	89,870	5.4	48.0	53.4
Sonepat	2213.4	–	78,191	78,191	0.0	35.3	35.3
Jind	2732.0	–	42,326	42,326	0.0	15.5	15.5
Fatehabad	2398.0	9613	19,533	29,146	4.0	08.1	12.1
Bhiwani	4632.6	–	19,112	19,112	0.0	04.1	04.1
Kaithal	2299.7	1252	8759	10,011	0.5	03.8	04.3
Hisar	4166.8	–	16,707	16,707	0.0	04.0	04.0
Total (central Haryana)	22239.5	46,415 (62.2)[a]	334,902 (82.9)[a]	381,317 (79.7)[a]	2.1 (1.05)[a]	15.1 (7.6)[a]	17.2 (8.7)[a]
Kandi (Ambala, Panchkula, Yamunangar) and remaining other districts							
Total (other districts)	21773.13	28,180 (37.8)[a]	68,988 (17.1)[a]	97,168 (20.3)[a]	1.3 (0.6)[a]	3.2 (1.6)[a]	4.5 (2.2)[a]
Grand total	44012.63	74,595	403,890	478,485	1.7	9.2	10.9

[a] % of state area

Table 18.11 Status of area under shallow watertable depths and different groundwater salinity (EC_{gw} in dS m^{-1}) in Haryana (Nov. 2015)

District	Area (ha) under WTD (0–1.5 m)			Area (ha) under WTD (0–3.0 m)		
	$EC_{gw} = 0$–2 dS m^{-1}	$EC_{gw} = 2$–5 dS m^{-1}	$EC_{gw} => 5$ dS m^{-1}	$EC_{gw} = 0$–2 dS m^{-1}	$EC_{gw} = 2$–5 dS m^{-1}	$EC_{gw} => 5$ dS m^{-1}
Jhajjar	8200	16,330	2000	43,740	48,180	4030
Rohtak	19,580	6270	–	64,650	40,060	2010
Sonepat	–	–	–	9080	20,600	2830
Jind	–	–	–	9910	23,450	–
Gurgaon	–	–	2350	3090	7030	2350
Mahendragarh	5410	970		5410	970	–
Hisar	–	–	–	7940	8770	–
Ambala	5420	–	–	26,310	2680	–
Bhiwani	70	–	–	12,270	2540	–
Fatehabad	4070	–	–	18,920	1780	–
Yamuna Nagar	140	–	–	20,170	–	–
Panipat	2640	–	–	4020	–	–
Sirsa	–	–	–	2320	6510	
Faridabad	–	–	–	3310	–	–
Total (Haryana)	46,159 (1.0)*	23,570 (0.5)	4350 (0.1)	232,770 (5.3)	133,260 (3.0)	11,220 (0.26)

*Figures in parenthesis in district or Haryana rows indicate % of district or state area, respectively.

while Sonepat, Jind and Fatehabad have such conditions in 35%, 15% and 12% area of respective districts. Assuming 80% of critical waterlogged saline area and 10% of potentially waterlogged area are to be in need of improved drainage, it is estimated that 70,000 ha area need subsurface drainage in these districts, a major part in Rohtak, Jhajjar and Sonepat districts. These are rough estimates, and exact figures may differ depending upon public investments made on implementing/improving existing surface drainage network in coming decades.

For selecting priority areas for implementation of SSD, vertical and biodrainage projects, salinity of groundwater and availability of a suitable outlet for drainage water are other requisites besides shallow watertable conditions. Maps of groundwater salinity were superimposed on watertable depth map (Fig. 18.12a) to derive maps (Fig. 18.12b–d) and areas (Table 18.11) having shallow watertable depth (0–1.5 m and 0–3.0 m) and having salinity from 0–2.0 dS m^{-1}, 2–5 dS m^{-1} and more than 5 dS m^{-1}.

It is seen that out of 46,415 ha critically waterlogged (WTD < 1.5 m) area in Haryana, 2000 ha in Jhajjar has $EC_{gw} > 5$, while 16,330 ha in Jhajjar and 6270 ha in Rohtak district have EC_{gw} of 2–5 dS m^{-1}. Similarly, about 1.1 lakh ha (1 lakh = 100 thousand) area in four districts of Jhajjar, Rohtak, Sonepat and Jind districts have WTD of 1.5–3.0 m and groundwater salinity of 2–5 dS m^{-1}, while 6870 ha area in first three districts have EC_{gw} more than 5 dS m^{-1}, highlighting more severe waterlogging and soil salinity problem needing urgent remedial measures like SSD projects. Other issues like availability of canal water for leaching and suitable outlet for disposal of drainage water are being considered in the above-mentioned project along with above aspects to suggest priority areas for implementation of SSD projects in Haryana.

Similarly, out of 74,595 ha area having watertable at 0–1.5 m depth, 46,159 ha have good-quality groundwater with $EC_{gw} < 2.0$ dS/m which are ideal sites for biodrainage. About 60% of such areas are distributed in Jhajjar and Rohtak districts in central Haryana followed by a few other districts like Mahendragarh, Ambala and Fatehabad. Similarly, out of 478,485 ha area having watertable between 0 and 3.0 m depth, about 50% (232,770 ha) has good-quality groundwater with $EC_{gw} < 2.0$ dS m^{-1}. Those areas in central Haryana having watertable within 0–3 m and groundwater salinity 0–2 dS m^{-1} sites are suitable for biodrainage, while those in other parts of Haryana are recommended for biodrainage, and some forms of vertical drainage provided aquifers in those areas have transmissivity of more than 600 m^2 d^{-1}. All above and other issues like availability of drainage outlets for disposal of saline effluents from SSD projects are being integrated to identify priority locations for implementation of SSD, vertical drainage and biodrainage projects for amelioration of waterlogged saline lands in Haryana.

18.5 Summary and Recommendations

Performance of irrigated agriculture, contributing about two-fifth of global agricultural production from less than one-fifth cultivated area, is getting degraded severally by the problems of waterlogging and soil salinization. Current annual losses in crop productivity due to irrigation-induced salinity are estimated at US$ 27 billion for the world and US$ 1.2 billion for India having 6.74 million salt-affected soils. It is projected that 13 million ha area in irrigation commands of India will be affected by waterlogging and soil salinity by 2025 and over 20 million areas by 2050 due to climate change and enforced increasing use of saline/alkali groundwater in several northwestern and southern states.

Preservation and restoring the productivity of irrigated agriculture without environmental degradation is a challenging task and demands regional planning and management perspectives. Though a number of preventive on-farm and project-level water management measures are recommended, improved drainage conditions become inevitable once irrigation-induced salinity develops over large areas. Besides surface drainage, engineering technologies like subsurface drainage (SSD) and tubewell drainage (and associated variants) and biological approaches like biodrainage through high-transpiring trees have been applied extensively for control and amelioration of waterlogging and soil salinity in different countries including India. While watertable control in fresh groundwater regions is commonly achieved by tubewell pumping, horizontal pipe drainage is almost mandatory in waterlogged and saline groundwater regions. There are, however, no clear guidelines for the selection of particular drainage methods appropriate for any affected area with specific hydrogeological characteristics.

Basic features of SSD and related interceptor and mole drains and vertical and biodrainage approaches for management of waterlogged saline-irrigated lands have been presented along with preliminary guidelines adopted in the past for selection of SSD or vertical drainage system. A major part includes critical review of SSD, vertical and biodrainage projects and related variant technologies developed and evaluated for different agroecological regions of India. The presented variants of vertical drainage system include different types of skimming and recharge structures used for selective abstraction of fresh water floating in a thin layer over native saline groundwater and for disposal of excess flood water from agricultural fields, respectively.

Finally, a case study is presented for the identification of critical and potentially critical waterlogged saline areas of Haryana, most suitable for reclamation through SSD, vertical or biodrainage measures. Selection of sites for appropriate drainage approaches is based on a watertable depth (WTD) and groundwater salinity (EC_{gw}) linked criterion: SSD (WT~ 0–1.5 m; EC_{gw} >2 dS m^{-1}), tubewell drainage (WTD ~ 0–3 m; EC_{gw}, 0–2 dS m^{-1}) and biodrainage (WTD ~ 0–1.5 m; EC_{gw} 0–2 dS m^{-1}).

Land drainage deserves more recognition than it has received so far in India. It is important to recognize significant benefits of land drainage on crop yields and sustainability of irrigated agriculture. Following salient observations and recommendations are synthesized on the effectiveness and scope of SSD, vertical drainage and biodrainage approaches for irrigated lands of India:

(a) *Subsurface Drainage (SSD) Technology*

1. SSD is a technically feasible, cost-effective and socially acceptable technology for reclamation of irrigated waterlogged saline lands. The technology, introduced systematically by CSSRI during early 1980s in Haryana, has

resulted in implementation of mechanically installed large SSD projects in about 62,000 ha area in different states in India.

2. SSD can result in 40–50% increase in cropping intensity, 50–150% increase in yields of different crops and 2–3-fold increase in farmers' income in 2–4 years from hitherto non−/less-productive lands. The technology can result in a benefit-cost ratio of 1.5, IRR of 20% and employment generation of 128 man-days per ha every year.
3. The estimated cost of SSD systems for Haryana and other northwestern states (60 m drain spacing, 1.5–2.0 m drain depth and pumped outlet) is INR 79000 ha^{-1}. Corresponding cost at 30 m spacing, 0.8–1.2 m depth and a gravity outlet for heavy soils in Maharashtra, Karnataka, Gujarat and other *Vertisol* regions, is recommended at INR 1,11,500 ha^{-1}.
4. The operational cost of SSD system in NW states is mainly due to pumping of the drainage effluent. After 1–2 years of operation of the drainage system, the quality of drainage effluent improves to a level that it can be reused for irrigation.
5. High cost, environmental issues relating to disposal of saline drainage effluent and continuous pumping requirement during post-drainage phase are some of the deterrents to long-term success of this technology. Involvement of farmers, sharing of construction and operating cost and government subsidy are other vital aspects.
6. Extensive waterlogged saline areas in alluvial regions of central Haryana, South-west Punjab and Northern Rajasthan urgently need SSD and other technologies like vertical drainage, biodrainage, salt-tolerant crop varieties, micro-irrigation in horticulture crops and saline fisheries.
7. These states must prepare regional master plans with clearly identified areas for implementation of different amelioration technologies and related fund requirement.
8. The methodology proposed in this chapter for identification of areas for priority implementation of SSD, biodrainage and vertical drainage projects in Haryana may be refined further to incorporate environmental aspects for disposal of saline drainage effluent.
9. The concerned states must also procure additional drainage machinery and develop outsourcing mechanisms in PPP modes to enhance the pace of implementation of SSD projects.
10. Regional salinity management and planning requires accelerated application of monitoring systems based on EM38, GPS, GIS, remote sensing and mathematical models.

(b) *Vertical Drainage System*

As a broad principle, vertical drainage systems cannot be used to control waterlogging if groundwater is saline and salinity increases with depth. However, skimming structures, based on the principles of vertical drainage, have proved successful in a limited way to pump out fresh water floating in thin layer over saline groundwater in coastal and inland irrigated areas.

1. A series of single tubewell projects have been successfully implemented to lower watertable in vicinity of canal distributaries in Haryana and Rajasthan during the 1990s. These projects have not been implemented in later years because of ambiguity and lack of guidelines for selection of appropriate drainage method for waterlogged areas.
2. Multiple strainer wells, reported successful to skim fresh water close to canals/distributaries in Punjab in India and in Indus Plains of Pakistan, have not been replicated at other locations in India because of lack of guidelines for selection of appropriate sites for such systems.
3. Radial collector well-type structures have considerable scope in coastal sandy soils for skimming of fresh water from thin sandy zones. The cost of the system can be considerably reduced by standardizing the techniques for horizontal drilling of drains in sandy soil.
4. Pilot projects on scavenger wells, tested successfully to pump simultaneously fresh and saline water from two groundwater quality depth zones in lower Indus Basin of Pakistan and other countries, also need to be evaluated under well-defined hydrogeological conditions in India.
5. Individual farmer-based recharge wells are effective to work as a local drainage system to save crops from submergence due to heavy rains in low-lying sections of inland areas, besides augmenting groundwater and improve quality.
6. Incorporation of small and less costly recharge filters in the abandoned dug-wells can contribute to significantly enhance groundwater recharge and consequent reduction in flood damage to crops. Issues relating to effective designs of recharge filters and quality of recharging water need to be taken care for implementing recharge projects over large areas.

(c) *Biodrainage*

1. Biodrainage is a biological approach to prevent development of salinity and waterlogging in canal commands. It is effective only when soil salinization due to watertable rise has not reached a serious level. Moreover, in bowl-shaped watersheds where drainage is not feasible, biodrainage helps in lowering down of watertable, and farmers may cultivate their fields particularly after rainy season.
2. *Eucalyptus tereticornis* is the most common species for lowering of watertable and seepage control from canals in waterlogged areas. The paired row strip plantations of this species, on field boundaries at plant density of 300 plants ha^{-1}, resulted in lowering of shallow groundwater by 0.85 m in 3 years and by ~ 2 m after 5 years in shallow groundwater regions of Haryana. Whenever crop cultivation is not feasible, the block plantations or trees in wider rows (row-to-row distance 4–5 m) in agroforestry mode may be grown, which will help in lowering down of watertable at faster rate, and agroforestry crops can be cultivated in interspaces successfully at least during initial 3 years of plantations (Dagar et al. 2016).
3. For command areas, planting of 100 m or wider belts of high water-demanding trees such as *Eucalyptus*, *Populus*, *Leucaena*, *Acacia* and

Bambusa along the canal and interspace grasses have been recommended for controlling the waterlogging problem. Research efforts are needed to find out exact size of belt required to be raised along with canals for effective control of seepage depending upon nature of soil of the canal area and species to be grown.

4. A major factor determining the sustainability of biodrainage projects is attainment of long-term salt balance in the soil profile in shallow saline groundwater regions. These studies need to be conducted further.

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