Combating Waterlogging in IGNP Areas in Thar Desert (India): Case Studies on Biodrainage

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Abstract

Indira Gandhi Nahar Pariyojana/Project (IGNP) in the *Thar Desert* is one of the largest irrigation projects in the world. As a result of this initiative, 1.86 million hectare area has come under cultivation. Although irrigation has greatly increased the agricultural production potential, it has also rendered vast tracts of land under waterlogged category (leading to salinization as well) on account of seepage and deep percolation losses from the irrigation network and lack of a proper drainage system. The concept of biodrainage, removal of groundwater through evapotranspiration, has emerged as an effective way to tackle this problem. Such an approach is economical and eco-friendly. However, more research is required to fully understand the implications, especially at farm level. The policy to control the problems associated with waterlogging and salinization should include biodrainage, reduced water allowance, efficient irrigation, and conjunctive uses.

Introduction

Irrigation of agricultural land has a long and well-documented history. It has a remarkable impact on agricultural development all over the world with increased production and better supply of food, fiber, bioenergy, and bio-industrial feedstock needs. Irrigation with poor drainage creates waterlogging and increases groundwater salinity. The waterlogged areas existing now are the results of negligence and improper drainage management. The history of the Assyrian civilization in Mesopotamia is an example where whole population was forced to abandon a region because of rising groundwater tables and salinity (Jacobsen and Adams 1958).

In India, net irrigated area increased from 22.5 Mha in 1951 to 93.95 Mha in 2002 (Dash et al. 2005). Similarly, the area of degraded land has also changed with time which has been estimated differently by different agencies. In this context, the efforts have been made for integration and streamlining of land based and remotely sensed

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J.C. Dagar, P.S. Minhas (eds.), *Agroforestry for the Management of Waterlogged Saline Soils and Poor-quality Waters*, Advances in Agroforestry 13, DOI 10.1007/978-81-322-2659-8_7

revised databases in the geographical information system environment so that a harmonized database is made available for use by the planning departments. According to NAAS (2010), the area under salt-affected soils is 6.64 Mha, and waterlogged soil due to surface ponding is 0.88 Mha. The area under subsurface waterlogging (4.75 Mha) has been excluded. Rajasthan is the largest state in India, with 27.24 Mha of cultivable area, of which nearly 60 % is classified as desert (GoR 2012). The ambitious project of the government to bring water in this state through interlinking of rivers Ravi (6.9 × 109 m^3 of water) and Beas (2.3 × 109 m^3 of water) and developing storage reservoirs and extensive canal systems has led to intensification of agriculture but with the associated problems of waterlogging and salinity (CAD 2007, 2009; IWMI 2007). In this chapter, an analysis is presented in context of combating these twin problems through biodrainage approach.

Indira Gandhi Nahar Project (IGNP)

IGNP occupies the northwestern and far western parts of the *Thar* Desert in Rajasthan (India). It is one of the biggest projects of its kind in the world aiming at transforming desert wasteland into agriculturally productive area with the objectives of drought proofing, providing drinking water, improvement of environment, development and protection of animal wealth, and increasing agricultural production. The project was conceived as a canal project for irrigating desolate land in the desert area. As per Indus Water Treaty, India got the exclusive right to use waters of the three rivers, namely, Ravi, Beas, and Sutlej. Rajasthan got a share of 10.6 billion cubic meters (BCM) from the surplus water to develop the desert area. Out of 10.6 BCM of water, 9.36 BCM was allocated for meeting the irrigation, drinking purpose, and industrial requirements of the area. The balance 1.24 BCM has been allocated for *Gang, Bhakra*, and *Sidhmukh* canal systems. The canal system in IGNP is enormous. The main canal, Indira Gandhi Mukhya Nahar (IGMN), has a total length of 445 km with 9060 km of distribution canals. The project work has been taken up in two stages – Stage I and Stage II (Fig. 1).

IGNP Stage I: It consists of head reach of the project, comprising 204 km long feeder canal originating from the Harike Barrage in Punjab, 189 km long main canal (from Masitawali head to Pugal head), and 3400 km long distribution system.

IGNP Stage II: It consists of lower reaches of the project comprising 256 km long main canal starting from Pugal head of the main canal (Bikaner) up to its tail and near Mohangarh (Jaisalmer). It has a long distribution system of 5780 km with a culturable command area (CCA) of 1.41 Mha at 80 % intensity of irrigation in flow and 60 % intensity under lift systems (CCA of 0.54 Mha).

The area is unique in many aspects like climate, soil, and landforms. Shifting sand dunes, scantly and uneven distribution of rainfall, extreme temperature (<0 °C in winter to > 50 °C in summer), and frequent occurrence of drought make the Indian desert one of the most inhospitable for agriculture. Annual mean rainfall varies in between 200 and 300 mm which is highly variable (>45 %) in nature. Daily potential evaporation rate rises to 12 mm day^{-1} in summer, when high wind speed, high temperature, and low humidity produce a desiccating environment. The underground water present in most of the places is brackish, deep (150 m), and unfit for human consumption.

Landforms and Physiography

The area falls in the hot western region of Rajasthan in which about 60 % of the area is covered by sand dunes which range from small, bare, and fairly mobile drifts to a few meters tall to large, semi stable longitudinal, parabolic, and transverse dunes over 50 m tall (Rahmani 1989, Cloudsley-Thompson 1977). Within the IGNP area, five main landform types: (1) younger alluvial plan, (2) flat older alluvial plain, (3) sandy undulating older alluvial plain, (4) sand dunes and inter-dunal plain, and (5) saline depressions were identified (Singh and Kar 1991). Soils of IGNP area fall into two broad geographic zones:

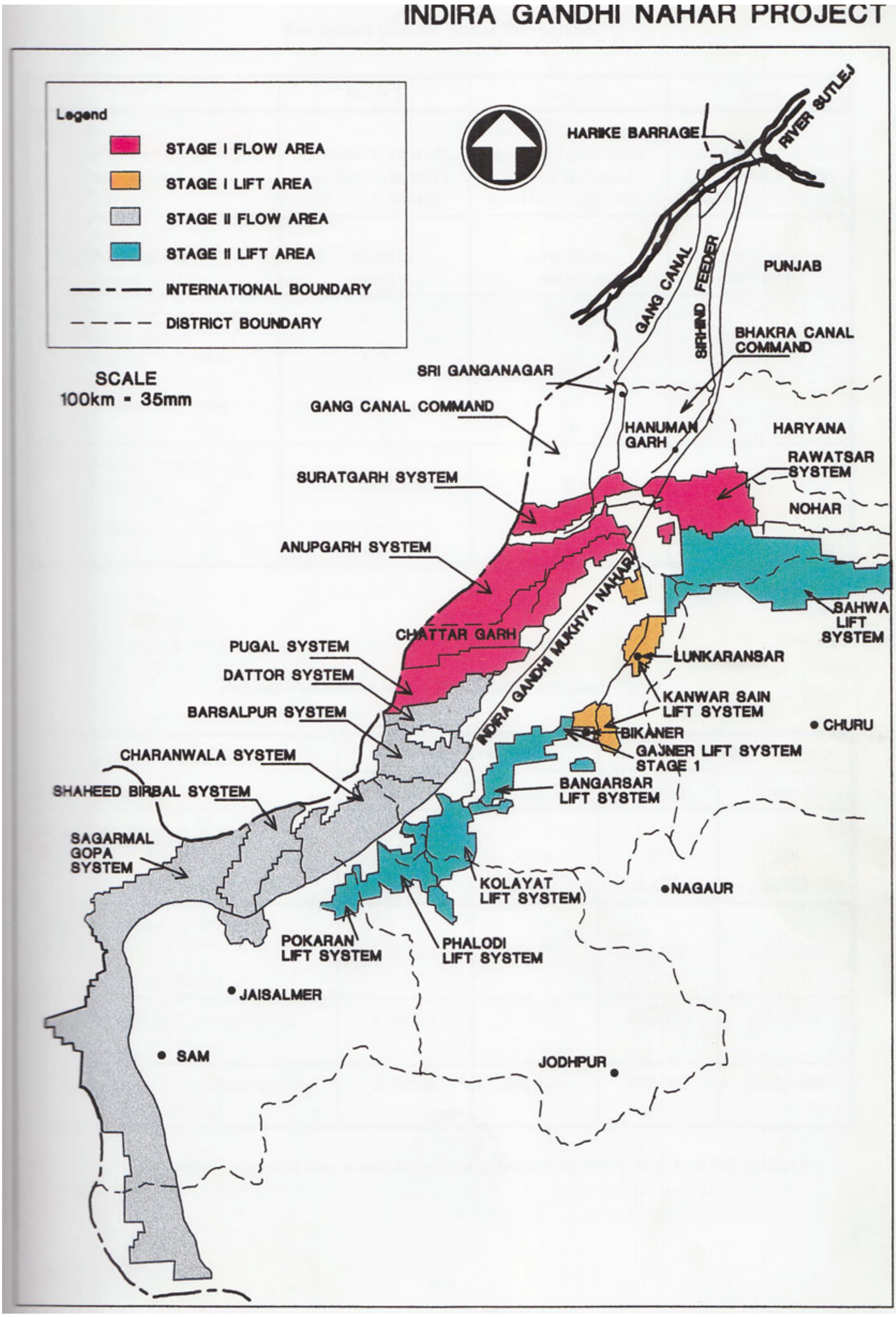

Fig. 1 Layout of IGNP areas in Rajasthan (India)

1. The area north of Pugal branch command, which consists mainly of soils that have developed on late quaternary to recent marine flood plains, with substantial additions of aeolian sand
2. The area south of Pugal branch including Stage II area, the soils of which comprise mainly late quaternary drift sand

The area largely consists of desert plains, sandy plains, and dunes of various types with an underlying impervious layer of calcareous accumulations and rocks. The depth of this layer is up to 15 m below ground level in Stage I and rises toward southwest. In Stage II, it occurs almost on the surface. The most worrying feature is the presence of shale/clay, hard compact friable carbonate nodules, and lime-coated gravel with clay at varying depths with poor infiltration rate and behaving as an impervious barrier. In about 30–35 % of the area under Stage II, the depth down to these hydrological barriers is less than 10 m, being shallower in lift areas and becoming deeper toward the international boundary (CAD 1997, 1999). The hard pan acts as a hydrological barrier to vertical groundwater flow and is not continuous on a regional basis. Perched aquifers are likely to exist where the barrier layer is of particularly low vertical permeability and where it occurs within a shallow depth of ground surface. About 33.4 % flow in command and 76.4 % in lift command (excluding the Sahwa lift area) are prone to waterlogging due to the presence of the hardpan layer.

Causes of Waterlogging in IGNP

IGNP is a boon to the northwestern arid part of India. However, improper and overuse of water coupled with seepage from the canal has created the problem of waterlogging and salinity in the area and has become a major problem to augment agricultural productivity. The conditions those have led to waterlogging in command areas include seepage losses from the conveyance and distribution system, excess water accumulation in lowland, recharge of groundwater table, inadequate drainage, etc. Seepage from the canal, in combination with relatively impervious layers at shallow depth in the profile, resulted in the formation of a perched water body (Kapoor and Denecke 2001). The major causative factors responsible for the development of waterlogging and secondary soil salinization in command area of IGNP have been described by Hooja et al. (1994). These include (1) more incidence of flooding in Ghaggar plains in Rajasthan; (2) inundation of Ghaggar depressions through the use of Ghaggar diversion channel; (3) high water allowances; (4) inefficient lining material; (5) uncontrolled supply of direct outlets from the main and branched canals; (6) over irrigation, surface wild flooding, and growing high water requiring crops by the farmers in the head reaches of the canal systems; and (7) hydrological barrier (hard pan) in subsurface layer. Above changes have induced the recharge component to the groundwater system by various degrees, and in the absence of compensating natural subsurface outflow from the system, the excess water became stagnant on impervious layer resulting in rising water tables. As a result of rising water table, heavy load of salt is left in the profile, rendering the soil saline. Initially the crop yields were marginally reduced, but in the subsequent years, land became completely unproductive.

Water Level Changes Due to Irrigation

Prior to the introduction of canal irrigation, the groundwater levels in the area were very deep varying from 40 and 50 m below the surface. With the introduction of irrigation, the groundwater table started rising. During 1981–1992, the average water table rise in Stage I was 0.92 m year^{-1}. In Stage II of the project, the groundwater table before the advent of irrigation generally ranged between 20 and 100 m below surface. With irrigation it has been rising, though not at the same rate as Stage I. Shrivastava et al. (2013) analyzed the groundwater scenario of IGNP and observed that the earliest groundwater levels during 1952–1972 showed a general rise of 0.42 m year^{-1} which was mainly due to advent of irrigation and groundwater flow from upper reaches, where irrigation was in full swing. During the period 1972–1982, there was a substantial rise in water table up to 1.17 m year^{-1} which was attributed mainly to the return flow of irrigation and filling of depressions through Ghaggar diversion channel in Stage I of IGNP. The net rise in water table reduced to 0.76 m year^{-1} during 1982–1992 in some of the areas, but a large area came under potentially sensitive and critical categories (water level between 1.50 m and 6.00 m below ground level). During the period 1992–1994, the water level depleted drastically due to scanty rainfall and less availability of water in canal system which resulted in the reduction of waterlogged condition significantly. The analysis of groundwater data for the year 1995–1997 revealed rising trend ranging from 0.30 to 0.70 m year^{-1} due to continuous recharge owing to seepage from canal system, return flow of irrigation, etc. The analysis of water level data during the year 1999–2000 revealed that the shallow water table had declined due to scanty rainfall (drought year) and nonavailability of water in the canal.

An analysis of development of waterlogging since 2000–2001 in the IGNP command areas is shown in Table 1. During the year 2002–2005, the average fluctuation of water level showed a declining trend in Stage I and rising trend in Stage II of IGNP command, respectively. However, the water levels in the vicinity of canal had shown declining trend. From the year 2005–2007, the average fluctuation of water level in Stage I as well as Stage II showed an overall rising trend in IGNP command. The water levels in the vicinity of canals had also shown marginally rising trend. During the period 2007–2008, the average fluctuation of water level was −0.09 m in Stage I and −0.02 m in Stage II. This shows an overall marginally depleting trend in IGNP command. However, the fluctuation of water levels in the vicinity of canal of Stage II was −0.12 m year^{-1} showing declining trend (Table 1). The overall increase or reduction in the waterlogged area, critical area, and potentially sensitive area is attributed to the variation in rainfall, availability of water in canal system, and return flow of irrigation.

Impact of Waterlogging

Rise of the water table closer to the surface and inundation of the low-lying areas have caused submergence of agricultural lands, village common lands, villages/habitations besides causing damages to road communication, and public utilities and constraints in the choice of crops and loss of production (Sharma et al. 2009). By the end of year 1997–1998, a total CCA of 514,000 ha (56 % of the total area) in Stage I and about 23,000 ha (about 13 %) in Stage II had become potentially sensitive to waterlogging (CAD 2007). As per estimations of NAAS (2010) in districts of Ganganagar, Hanumangarh, and Jaisalmer, exclusively saline and sodic areas are 36,000 ha and 61,000 ha, respectively.

The analysis of water samples collected from various sources (accumulated seepage lakes (*Tals*), auger bores, and profile pits) of waterlogged and salt-affected soils of IGNP area from different villages near Hanumangarh and Bikaner (29°00′N and 29°35′N latitude and 74°00′E and 74°40′ E longitude) showed a wide variation in electrical conductivity (ECiw); and high to very high ECiw (93.4–102.6 dS m^{-1}) was found in severely affected waterlogged areas of Masitanwali and Bhairusari villages apparently due to prolonged salt accumulation (Mondal and Sharma 2011). The ECiw of water samples collected from profile pits and auger bores (1.7–22.0 dS m^{-1}) and drainage water (3.2–30.6 dS m^{-1}) suggesting its safe reuse after mixing with good quality irrigation water. The transportation of salts from higher to lower elevation through the coarse sandy mass facilitates in development of poor water quality in *Tals* and inter-dunal seepage lakes. The higher EC of water sample (22.2 dS m^{-1}) from profile pit in *Dabli Kalan* village was due to the presence of highly saline *Tal* close to profile pit. The ionic composition of water samples showed significant contribution of sodium (8.2–1935 me L^{-1}), calcium plus magnesium (2.0–370 me L^{-1}) cations for development of high to very high soil salinity. Among anions, chloride and sulfate contributed significantly for the development of salinity. The sandy soil texture in most places enhanced upward movement

Table 1 Status of waterlogging in IGNP command (year wise)

	Total area (000 ha)							
	00–01[a]	01–02	02–03	03–04	04–05	05–06	06–07	07–08
	Potentially sensitive area (water table within 2–6 m)							
Stage I	225.1	179.1	164.3	195.0	168.7	196.8	202.1	181.2
Stage II	12.18	18.3	24.5	13.5	16.0	18.8	15.9	11.8
Total	237.3	197.4	188.9	208.5	184.7	215.4	218.0	193.1
	Critical area (water table within 1–2 m)							
Stage I	13.4	11.3	8.7	9.2	10.6	11.2	16.9	12.5
Stage II	2.2	1.2	0.4	0.3	0.5	1.1	2.6	1.1
Total	15.6	12.6	9.2	9.5	11.1	12.3	19.4	13.6
	Waterlogged area (water table within 0–1 m)							
Stage I	12.7	10.1	5.7	2.5	2.9	3.1	6.8	1.8
Stage II	0.3	0.1	0.0	0.0	0.0	0.5	0.8	0.3
Total	13.0	10.2	5.7	2.5	2.9	3.6	7.6	2.1

Source: CAD (2009)
[a]Denotes years 2000–2001 onwards

of water table and capillary rise of salts to develop secondary soil salinity within the root zone. Such process occurring continuously for longer period produces severe salinization in form of salt efflorescence/salt crust at surface with no agriculture operation. The analysis of soil samples from different pedons showed moderate (ECe 9.3 dS m^{-1}) to very high salinity (ECe 40.3 dS m^{-1}) in IGNP area.

The waterlogging and soil salinity had greatly affected the yield of different crops in the region. According to a World Bank study, India loses 1.2–2.0 million Mg of food grain production every year due to waterlogging (Prasad and Biswas 1999). The average cotton crop yields are low at 1300 kg ha^{-1} as compared to about 1500 kg ha^{-1} in normal soils under Stage I. The same trend was with cluster bean, wheat, mustard, and chickpea. The chickpea yields due to waterlogging and soil salinity reduced up to 50 %. The net returns of cotton and wheat were lowered by about 25 % and 46 %, respectively. In a survey conducted by IWMI (2007), it was emphasized that waterlogging (28 % of respondents) and soil salinity (26 % of respondents) are major problems in IGNP with a lot of area submerged under pools of water. On an average, the additional expenditure due to waterlogging and soil salinity on practices like field preparation enhanced seed rate, and fertilizer applications increased to the tune of INR 1095 ha^{-1}.

Biodrainage in Solving Waterlogging Problems

Many measures for controlling the waterlogging in IGNP area have been planned by the department of IGNP. These includes (a) reduction in excess supplies of water allowance in Stage I till the irrigation in Stage II develops considerably, (b) increase in irrigation area, (c) reduction in number of days of running canal, (d) removal of excess of outlets and correction of over-sized outlets and direct outlets, (e) remedial measures in canal to control seepage through damaged lining, (f) installing shallow skimming wells along with infiltration gallery, and (g) installation of subsurface pipe drainage system.

The usefulness of various techniques in mitigating the problems of waterlogging and salinization or combating the adverse effects of waterlogging has been discussed by many workers (Mann and Chatterji 1978, Chatterji 1985, Shankarnarayan and Sarkar 1985, Chatterji and Saxena 1988). These include construction of open drainage, horizontal subsurface drainage, vertical drainage, soil management, artificial recharge, growing aquatic cash crops, etc. (Sharma 1999). Physical drainage works require expensive capital investment, operation, and maintenance and also generate drainage effluent. Disposal of these effluents is considered unacceptable because downstream users in the catchment rely on these river systems for their water supplies. Greenhouse gas emissions caused during pumping may also be disapproved in a changing climate scenario.

To overcome these issues, biodrainage, i.e., the use of vegetation to manage water fluxes in the landscape has recently attracted interest in drainage and environmental management circles. Following requirements are desired to be fulfilled for effective biodrainage systems: (1) the annual quantity of water removed from the groundwater should equal the quantity of recharge; (2) the quantity of minerals removed annually should be nearly equal to the quantity of mineral import; (3) afforestation or agroforestry should be economically comparable with that from other alternative uses of land. If it is not so, afforestation may still be justified, on considerations of the environmental and drainage benefits; (4) under ideal situation, trees in afforestation area on full development should be able to draw most of their requirement of water from the groundwater table, so that surface irrigation water can be put to other productive uses; (5) when the water table approaches the root zone of trees, the quality of groundwater should be tolerable by the plant species, otherwise the trees would need to be supplied irrigation water; (6) for effective biodrainage system, the groundwater table must be lowered in the irrigated area to a minimum critical depth (say 2 m bg^{-1}) at the farthest point from the edge of the plantation area.

The researchers in India (Hooja et al. 1995, Kapoor 2001, Kapoor and Denecke 2001, Tewari et al. 1997) and abroad (Bhutta and Choudhry 2000, Zhang et al. 1999, Stirzaker et al. 1999) reported that trees could be used to manage rise in water table. When the water table surface comes up sufficiently high and is within the reach of roots of trees in plantations, the trees start drawing water from the groundwater reservoir through the process of transpiration. The root systems of trees could intercept saturated zone or unsaturated capillary fringe above water table to control shallow water table. These plants are known as *phreatophytes*. The unsaturated top soil zones are intercepted by root systems of plants mainly following rainfall or irrigation to remove water from soil profile by controlling recharge. This process of withdrawal of groundwater by plantations is termed biodrainage.

The term biodrainage is relatively new, although the use of vegetation to dry out soil profiles has been known for a long time. One of the earliest documented observations of water table lowering beneath a tree plantation was recorded by Heuperman et al. (1984). The first documented use of the term biodrainage can be attributed to Gafni (1994). Prior to that date, Heuperman (1992) used the term *bio-pumping* to describe the use of trees for water table control. Another term relating to the *bio* aspect of soil water removal is *bio-disposal*, which refers to the use of plants for final disposal of excess drainage water (Denecke 2000). The term biodrainage has attracted interest in drainage and environmental management circles about 10–15 years back due to its eco-friendly nature. The driving force behind the biodrainage concept is the consumptive water use of plants. The rates of transpiration and groundwater uptake by trees underlain by relatively shallow (5–8 m below surface) water tables were very high. It exceeded by a factor 3–6 (1200–2300 mm $year^{-1}$) as compared to pasture (~400 mm $year^{-1}$) (Greenwood et al. 1985).

Lowering of the Raised Groundwater Table

Biodrainage helps in lowering down the groundwater table underneath the plantation area. Large variation in capacity of trees to grow and transpire water has been reported by different workers because of the many factors, influencing the rate of transpiration. Tewari et al. (1997) suggested the suitability of tree species for waterlogged soils on the basis of salinity hazard in IGNP areas. On waterlogged area with lesser salinity, plantations of the recommended tree species, viz., *Eucalyptus camaldulensis*, *Populus casale*, *Phoenix* spp., and *Acacia nilotica*, may be done by making mounds at a spacing of 10 m × 5 m. The width and height of these mounds are recommended as 1.5 m and 1.2 m, respectively. No irrigation is recommended for the plants in such areas. However, in waterlogged area with considerable salinity, narrow plantations with

4 m×4 m are recommended. The suitable tree species which may tolerate high salinity and waterlogging are *Tamarix articulata*, *Prosopis juliflora*, *Acacia nilotica* and *Salvadora oleoides*. Apart from tree species, the shrubs like Saji (*Haloxylon recurvum*) and Lana (*Haloxylon salicornicum*) may also be dribbled for their rehabilitation.

Eucalyptus species are generally considered to be effective for biodrainage purposes. *Eucalyptus camaldulensis* is a hardy tree that grows under a wide range of climatic conditions and soil types in this area. *Eucalyptus* grows fast and has good water consumption capacity when the water is available in sufficient quantity (Alvares 1982). Some provenances of the species tolerate saline conditions quite well. The study conducted in 25 ha waterlogged area in IGNP revealed that in an unplanted area (14.7 ha in 1991), surface water was removed from pools mostly by surface evaporation. Over the period 1991–1997, the water table fell about 10 m. During the same period, the water transpired by the trees was estimated to the tune of 20.6 m (Heuperman et al. 2002).

The impact of block plantations of *E. tereticornis* on reclamation of waterlogged areas was found effective at the Indira Gandhi Nahar Project (IGNP) site in Rajasthan, India (Kapoor 2014). The groundwater table underneath the strip plantations remained lower than that in the adjacent fields. The drawdown of water in IGNP area by the tree plantations established along the canal was reported to the tune of 14 m in 6 years (Kapoor 2001). However, Jeet Ram et al. (2011) working at Puthi research plot in Hisar (Haryana), northwest India, reported that the drawdown in groundwater table was 0.85 m in 3 years. The main reasons for the difference in drawdown of groundwater table at the two sites (IGNP and Puthi research plot) were the design and density of plantations and the sources of recharge of groundwater. IGNP had block plantation of 160 m width with the density of 1000 plants ha^{-1}, and the sources of recharge of groundwater were only rainwater and seepage from canal. Whereas Puthi had strip plantations of 1 m×1 m width on acre line with a density of only 300 plants ha^{-1} and the sources of recharge of groundwater were rainwater, seepage from the canals and irrigation applied to agricultural crops between the strip plantations. Therefore, at the Puthi research plot, the relatively higher recharge of groundwater from many sources and the relatively lower discharge of groundwater due to less number of trees ha^{-1} resulted in less drawdown of the groundwater table.

Besides lowering the water table, *Eucalyptus* fetches high price and provides fuel wood. Strip plantations of clonal *E. tereticornis* also worked as bio-pumps and helped in reducing water table. The drawdown curve of groundwater table due to *E. tereticornis* was similar to the cone of depression of a pumping well (Heuperman 1992, Jeet Ram et al. 2007). Heuperman (1999) estimated annual water use in desert area of Rajasthan by *Eucalyptus* species to the tune of 3.44 m (density of 1900 trees ha^{-1}). Cramer et al. (1999), however, reported that *Casuarina glauca* could extract groundwater more than *Eucalyptus camaldulensis* planted at similar densities. Heuperman and Kapoor (2003) observed the average annual rate of transpiration as high as 3446 mm from a 25 ha mixed plantation (*Eucalyptus camaldulensis, Acacia nilotica, Prosopis cineraria* and *Ziziphus* spp.) in the IGNP area of Rajasthan during 1991–1997. The water removal rate was estimated as equivalent to a vertical drainage network with 500 m well spacing with a 33 m^3 h^{-1} pumping rate. They estimated that a forest cover of 1, 77,000 ha (10 % of the total irrigable area in IGNP) would be able to transpire the estimated annual groundwater recharge of 2.6 BCM. Jeet Ram et al. (2011) reported that transpiration value depends on variation in radiation, temperature, and vapor pressure gradient prevailing during the period. The average rate of transpiration in *E. tereticornis* trees ranged from 44.5 to 56.3 l d^{-1} tree^{-1} in May, 30.5 to 34.0 in July, 24.1 to 28.3 in October, and 14.8 to 16.2 l d^{-1} tree^{-1} in January. The overall average rate of transpiration in the 5-year-old *E. tereticornis* was 30.9 l day^{-1} tree^{-1}, which was 268 mm annum^{-1} by 240 trees ha^{-1} against the mean annual rainfall of 212 mm. The discharge of groundwater by the strip plantations of clonal

E. tereticornis was 1.3 times more than the recharge by rainfall resulting in reclamation of waterlogged areas.

Lowering of water table and associated soil improvement by *Eucalyptus* plantations increased the wheat grain yield by 3.4 times as compared to non-planted agricultural fields and resulted in reclamation of waterlogged areas (Jeet Ram et al. 2011). A close relationship between growth and transpiration rates has been observed by Calder (1992) and Delzon and Loustau (2005). *Eucalyptus* plantation improved overall surface soil properties. Lowering of water table by *Eucalyptus* induced higher root activities and secretion of organic acids in the surface layers. The average steady-state infiltration rate in fields with plantation was 8.3 mm h^{-1}, whereas it was only 5.1 mm h^{-1} in fields without plantation.

Bala et al. (2014) made an attempt to study the removal of excess water from the land through biodrainage and to increase vegetation cover and productivity of a waterlogged area of IGNP. They tried four species on raised bunds (60 cm high, 60 cm wide, and 2 m apart) prepared in waterlogged (inundated water of 15–25 cm) area to provide comfortable root zone for young seedlings. Among the four species tried, the performance of *E. rudis* was best with respect to growth, biomass, transpiration rate, and overall biodrainage potential. *E. rudis* maintained uniform transpiration and photosynthesis rate throughout the year. Groundwater table has receded from 25 cm to 145 cm in *E. rudis* plot compared to 90 cm, 70 cm, and 60 cm in *Corymbia tessellaris, E. camaldulensis* and *E. fastigata*, respectively, within a period of four and half year. Soil working at the site resulted in heavy regeneration of *Eucalyptus camaldulensis*. The regenerated plants were mostly concentrated between 6 and 10 m from the tree trunk of the mother trees situated at the edge of the experimental site. Apart from the planted ones, some species like *Prosopis juliflora*, *Tamarix dioica*, *Saccharum munja* (tall grass) and *Arundo donax* (grass) also have come up in the area. The number of *A. donax* has reduced gradually with recession of groundwater table in the experimental plot. With the lowering of groundwater level, other species started growing in the area as natural succession. Population of *S. munja* was highest followed by *P. juliflora* and *T. dioica.* The total biomass per tree in *P. juliflora* was recorded as 110 kg. The contribution of the roots to the total biomass was 25 %, and *S. munja* and *T. dioica* accumulated a total biomass of 76.5 kg and 73.2 kg per bush, respectively.

Biomass Production and Carbon Sequestration

In a study in IGNP, 5-year-old subirrigated plantations produced dry biomass of 185 Mg ha^{-1}. The utilizable biomass production was 29 Mg ha^{-1} $year^{-1}$. *Acacia nilotica*, *Dalbergia sissoo*, *Tecomella undulata* and *Ziziphus mauritiana* are other species that have performed well in plantations along leaking canals in arid conditions. Under waterlogged saline soils in IGNP area in Lakhuwali, Hanumangarh, Rajasthan, Soni et al. (2012) reported that among the three dominant species in waterlogged salinity, the above ground biomass was highest in *Acacia nilotica* (132.1 Mg ha^{-1}) followed by *Eucalyptus* spp. (77.6 Mg ha^{-1}) and *Acacia tortilis* (40.6 Mg ha^{-1}). Maximum carbon storage was observed by *A. nilotica* (66.5 Mg ha^{-1}) followed by *Eucalyptus* spp. (38.8 Mg ha^{-1}).

Several techniques, viz., double ridge mound (DRM) and circular dished mound (CDM), were developed for the establishment of trees and shrubs in waterlogged saline-alkali soils of IGNP area in Jodhpur district of Rajasthan (Arya et al. 2006). Both mound practices, viz., CDM and DRM, recorded higher survival and growth as compared to control during 36 months of establishment. There was no difference in height of all the three shrub species between CDM and DRM structures. However, for crown diameter, CDM structure exhibited higher growth as compared to DRM structure. Among shrubs, *Suaeda nudiflora* was the best species on the basis of survival and growth followed by *Atriplex lentiformis* and *Atriplex stocksii*. Among trees, *Acacia colei* also showed potential by maintaining 89 % survival on DRM in a drought year.

Salt Balance

Salt balance is one of the most important issues to be addressed before biodrainage can be promoted as an appropriate drainage management technology. The water quality of Indus river system is basically good having low salinity (TSS ~125 ppm). However, due to the large volume of water introduced in the landscape of IGNP system, it increases salt import significantly. When the irrigation water is removed by means of evaporation or by growing plants, the salts remain within the area unless it is removed either by natural or through artificial means. To maintain the salt balance in soil, two mechanisms can be considered in soil-plant systems: (a) salt balance through removal of salts from the vegetation root zone by leaching and (b) removal of salts used by the vegetation through grazing or harvesting of plant matter for its further use. The former is achieved through the concept of leaching fraction on the basis of amount of salt to be leached through root zone. The latter mechanism however needs some elaboration as it is often mentioned in biodrainage related information.

The important aspects to be considered in the salt balance analysis are (1) mineral content in supply (irrigation or ground) water and (2) mineral content in plant biomass. In high-salinity environments, salt uptake by the plants might be negligible in relation to the salts present in the soil. However, under low-salinity scenarios, the salt balance might be achieved between the applied and removal of salt by the plants. This option needs to be critically reviewed. The studies conducted by various researchers showed that the salt uptake by plants is negligible compared to the total salt applied through irrigation water (Hoffman 1990, Chhabra and Thakur 1998, Dash et al. 2007, Heuperman 1999, NIAB 1997, Pessarakli and Szabolcs 1999) and thus leave behind the salts in soil. Schulz (1994) measured average dry matter yields of *Atriplex nummularia* of 0.6 kg plant^{-1} per year^{-1} across a range of applied irrigation salinities (100–10,000 mg L^{-1}, NaCl-dominant water) over a 3-year period. At planting densities of 10,000 bushes ha^{-1}, the salt export in the leaves (considering the major ions) would be between 350 and 433 kg ha^{-1} year^{-1} against the salt application of 1 Mg ha^{-1}year^{-1} and 100 Mg ha^{-1} year^{-1}, respectively, for low- and high-salinity treatment. This suggests that with the low-salinity irrigation water, the plants made a significant contribution to salt removal, but with the higher-salinity values, salt balance control by vegetation was not possible. Lambert and Turner (2000) present data on sodium and chloride accumulation in different components of 22-year-old plantations. The salt balance study on 22 years old plantations of *Eucalyptus grandis* showed an uptake of 14 kg ha^{-1} year^{-1} salt (predominantly Na and Cl). These quantities are small in relation to the salt inputs of 65 kg ha^{-1} year^{-1} in the plantations. As a whole, the potential for export of salt through plant harvesting does not look promising. Salt balance through the removal of vegetation has only been reported for situations with very low salt input/freshwater supplies such as channel seepage.

Conclusions

There are conclusive evidences to suggest that appropriate tree stands have the ability to lower water tables in areas having the problem of rise in water table. This is either on account of reduction in recharge of water or direct extraction of water from the saturated zone or a combination of both. There are also some indications of harvesting of salts from soil by vegetation and plantations. In IGNP areas in Thar Desert, growing of trees in afforestation and other projects have shown its positive impact and supported the concept of biodrainage in combating the problems of waterlogging and associated salinity. Although several studies from IGNP areas in Rajasthan have led to identification of tree species – their plantation density, salt-loving vegetation, etc. – more research efforts on the biodrainage aspects are required for a better understanding and wider adoption. Suggested aspects are:

- Undertaking field measurements of trees in the area and their effect on water table depth

and soil and groundwater salinity from farmers' fields
- Pre- and post-monsoon measurement of salt content of plant samples at periodical intervals
- Studies on transpiration rates of planted tree species and its relationship with pan evaporation
- Screening of salt tolerant tree species
- Investigations on the salt sensitiveness of different tree species and salt balance between the tree and the growing medium
- Economic assessments on biodrainage and other approaches to combat waterlogging in specific situations

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