Agricultural Water Management 215 (2019) 74–85

Contents lists available at ScienceDirect

Agricultural Water Management

journal homepage: www.elsevier.com/locate/agwat

Groundwater irrigation induced soil sodification and response options

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ARTICLE INFO

Keywords:
Alkali water
Sodic water
Soil amendments
Conjunctive use
Sodic soils
Infiltration problems

ABSTRACT

The continuous surge in irrigation, particularly using groundwater for sustaining food security in many developing countries, has necessitated the utilization of low-quality waters especially in water-scarce arid and semi-arid regions. Inappropriate irrigation with these waters results in land and environment degradation produced by associated salts, sodium and other toxic elements. Generally the soil's sodification process is insidious and build-up of exchangeable-Na is initially gradual. It stabilises at levels governed by sodicity indices of irrigation water, soil type, cropping sequences and agro-climatic conditions. As the soils become sodic, crop productivity declines and ultimately soils can become unsuitable for cropping. As a result, cultivators are forced to opt for tolerant crops, which are typically of less economic value. To minimize harmful effects of sodicity, remedial measures have been developed at the crop, root zone, farm and district/basin levels. These include water quality driven conjunctive uses, chemical amelioration of soils and irrigation waters, mobilising native calcite through phyto-remediation, growing tolerant crops, and other specialised tillage, fertiliser use and irrigation practices. This review seeks to critically analyse the role of these measures and the crop, water and soil factors defining the sodification vis-à-vis infiltration problems. The conclusions provided here are expected to be helpful for a range of stakeholders to promote irrigation with sodic/alkali waters, thereby partly alleviating the forecasted scarcities in water for agriculture.

1. Introduction

Globally, the aquifer withdrawals for irrigation have witnessed a boom during the last few decades, particularly in drought-prone regions. World over, almost 43% of the irrigated area is groundwater-dependent (Shah, 2014), mainly in the agro-economies of South Asia using groundwater at 262 $km^3\ yr^{-1}$ (km^3 = billion m^3), Middle East & North Africa (87 km^3) and East Asia (57 km^3). In terms of ground coverage, the largest groundwater-use areas are in India (39 M ha), followed by China (19 M ha) and USA (17 M ha). Since groundwater provides for a reliable source of water that can be used in a flexible manner, farmers mostly utilize it to support intensive land cultivation and high-value agriculture. However, a typical scenario has emerged in groundwater-irrigated areas revealing the poor quality of underlying aquifers in water scarce areas. Nevertheless, the priorities for high agricultural production and intensification are pushing cultivators to increasingly pump lower quality groundwater for irrigation. The extensive use of saline and alkali ground waters for irrigating food grain, fodder and fuel crops are widespread, particularly in countries such as Bangladesh, China, Egypt, India, Iran, Pakistan, Syria, and the United States (Tanwar, 2003). There is a trade-off associated with extensive pumping of poor-quality groundwater. The better quality aquifers may be at risk from contamination stemming from adjoining poor water-quality zones due to their overexploitation and the resultant fall of groundwater levels.

Irrigation with poor quality groundwater without following the recommended soil–water–crop management strategies has severe impacts on soil health and the environment (Rhoades et al., 1992; Minhas and Gupta, 1992; Minhas and Samra, 2003). The build-up of salts, sodium and other toxic ions in soils leads to a decline in both agricultural productivity and produce quality. Generally the sodification process is insidious and the build-up of exchangeable-Na is initially gradual. It stabilises at levels governed by sodicity indices of irrigation water, soil type, cropping sequences and agro-climatic conditions. When soil's sodicity levels exceed the tolerance thresholds of the prevalent crops, their productivity declines and cultivators are left with no alternative but to opt for less profitable tolerant crops. Ultimately, soils may become unsuitable for cropping. The remedial measures and irrigation strategies that are required at crop, root zone, and farm level when using sodicity inducing waters are different from those using saline waters. Therefore, specialised methods and remedial techniques are advocated to create a favourable soil environment for maximising

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https://doi.org/10.1016/j.agwat.2018.12.030
Received 16 July 2018; Received in revised form 27 December 2018; Accepted 29 December 2018

agriculture productivity at the lowest cost (Hillel, 2000). Moreover, their effective use should be tailored to local hydro-geological and socio-ecological realities.

While the issues related to sustainable use of saline/drainage water are almost global, these have been extensively investigated under field conditions and several critical reviews and comprehensive recommendations are available to overcome salinity problems (Minhas, 1996, 2012; Rhoades, 1999; Tanwar, 2003; Grattan et al., 2015). However, sodic/alkali ground waters exist mainly in the Indian subcontinent and there has been a lack of such an analysis on the impacts of irrigation with these waters on soils and crops. This review highlights the importance of achieving sustainability of agricultural productivity through augmenting the use of sodicity inducing groundwater. This information is expected to enhance the possibilities of sustained irrigation with lower quality waters by offering opening to overcome water shortages for agriculture.

2. Impacts of alkali/sodic irrigation waters on soils and crops

2.1. Chemical impacts – soil sodification

Irrigation water quality is assessed based on the potential of water to cause salinity, sodicity/alkalinity and toxicity hazards. The parameters used for their soluble salt contents are total dissolved salts (TDS) and electrical conductivity (EC). Alkalinity (pH) and sodium (Na) saturation (ESP, exchangeable sodium percent) in soils is a consequence of a higher proportion of Na relative to Ca and Mg and that of carbonates (CO_3 and HCO_3) in irrigation waters. Various indices to determine the sodicity and alkalinity potential of irrigation waters are: sodium adsorption ratio (SAR), adjusted SAR (adj.RNa) and residual sodium carbonate (RSC). These are calculated as:

$$SAR = (Na)/[(Ca + Mg)/2]^{0.5}$$

$$adj.RNa = Na/[(Ca_x + Mg)/2]^{0.5}$$

$$RSC = (CO_3 + HCO_3) - (Ca + Mg)$$

Where concentrations are expressed in milli-equivalent per litre (meq L^{-1}]. Ca_x represents the modified concentration of Ca due to salinity (ionic strength) and HCO_3:Ca ratio (Suarez, 1981; Ayers and Westcot, 1985). Hence, the notations of saline, sodic and alkali are used here for irrigation waters with EC > 2.0 dS m^{-1}, SAR > 10 and RSC > 2.5 meq L^{-1} respectively. Considering no precipitation, early water quality criteria considered that the irrigated soils accumulated sodium on exchange complex in proportion of SAR. In long-term studies (Chauhan et al., 1991), though the SARe (SAR of saturation paste extract) even approached √2 × SARiw after the irrigation of dry season winter crops, these declined considerably following rains received during monsoon season. Therefore, the overall increase in ESP is considerably less than SARiw especially at high levels (SARiw > 20). The factors like soil texture and its salt release characteristics, e.g. calcite content, quantities of applied irrigation water and episodic events of rainfall, associated anions, e.g. SO_4^{2-}, further modify the final ESP build up in soils (Manchanda et al., 1989; Chauhan et al., 1991; Singh et al., 1992; Minhas and Gupta, 1992)

A number of systematic agronomic investigations have evaluated the long-term sodification of soils occurring with sodic/alkali irrigation waters, especially in north-west India (Bajwa et al., 1983, 1986, 1992, 1993; Bajwa and Josan, 1989a,b; Sharma and Mondal, 1981; Sharma and Minhas, 1997a, 2004; Minhas et al., 2007a,b; Choudhary et al.,2011a). With exchange of divalent cations and their release from the inherent calcite and other soil minerals, the initial rates of sodification were found to be slow. However, the chances of soil solutions to concentrate in surface soil get augmented through a 'distilling-out' effect of evapo-transpiration when the water infiltration rates are slowed with increase in sodicity (relative infiltration rate, RIR = 0.3 at an

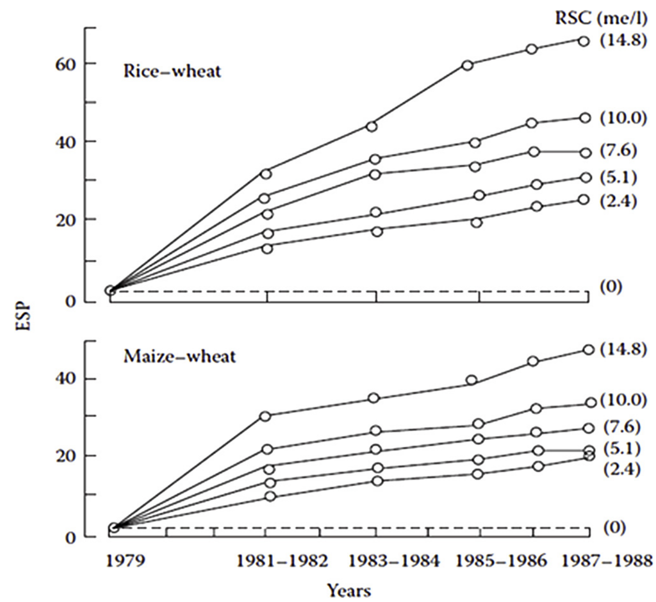

Fig. 1. Periodic build-up in ESP in soils when irrigated with waters having variable residual alkalinity (RSC) in rice-wheat and maize-wheat sequence. Source: Adapted from Bajwa et al (1989a&b).

ESP > 20). Such conditions further increase the sodicity and thereby, steady-state conditions, as were the basis for earlier sodicity indices e.g. adj.SAR by Bower et al. (1968) and Rhoades (1968), are not attained in shorter intervals. Rather, field observations on ESP are usually contrary to those predicted with adj.SAR indices which state that sodification should be lower with increased leaching fractions (LF). Higher quantities of irrigation water to the rice-wheat cropping system (LF 0.6-0.8) resulted in faster sodification, especially of surface soil (ESP 2.4 × SAR) when compared with upland crops such as cotton, maize, and pearl millet in rotation with wheat (Minhas and Gupta, 1992; Minhas and Bjwa, 2001). Thus, rather than 1/√LF that has been most commonly used to define the concentration factors, the general experience is that stabilisation of pH and ESP do occur when a quasi-equilibrium is achieved after alkali water irrigation for about four-five years and their levels usually depend upon cropping sequence and other agro-climatic conditions (Fig. 1). Thereafter, the further sodification slows down.

Minhas and Sharma (2006) analysed a large number of agronomic experiments (n = 100) where irrigation waters in the range of EC = 0.4–10 dS m^{-1}, SAR = 0.6–43, adj.SAR = 0.6–102, adj.RNa = 0.6–57 and RSC = 0–15 meq L^{-1} were applied for longer-term (> 5 years) on light-textured soils (loamy sand to silt loam) for fallow-wheat, cotton-wheat, maize/millet-wheat and rice-wheat rotations. The coefficient of determination for predicting ESP with different indices of sodicity like SAR, adj.SAR, adj.RNa were only R^2 = 0.20–0.32. The predictability improved considerably (Fig. 2; R^2 = 0.69**) when the concentration and dilution factors were included in terms of the annual quantities of alkali waters applied (Diw) as irrigation, the rainfall (Drw) at the site, and the evapo-transpiration demands of the crops grown in sequence (ET), as:

$$ESP = (Diw/Drw)(\sqrt{1 + Drw/ET})(adj.RNa)$$

Considering the diversified situations of agro-climate and soil types from which the data sets were obtained, the overall predictability seems quite satisfactory. It should, however, be mentioned that adj.RNa considers the precipitation of calcite ($CaCO_3$) only. Since ground waters with residual alkalinity also have appreciable contents of chloride and sulphate ions ($Cl + SO_4$:HCO_3 0.3–5.7), these also affect Ca concentrations of soil solutions. Firstly, in the case of calcite-gypsum-controlled system, competition for Ca would allow more HCO_3 to stay in solution (gypsum precipitation would remove Ca and SO_4) and thus

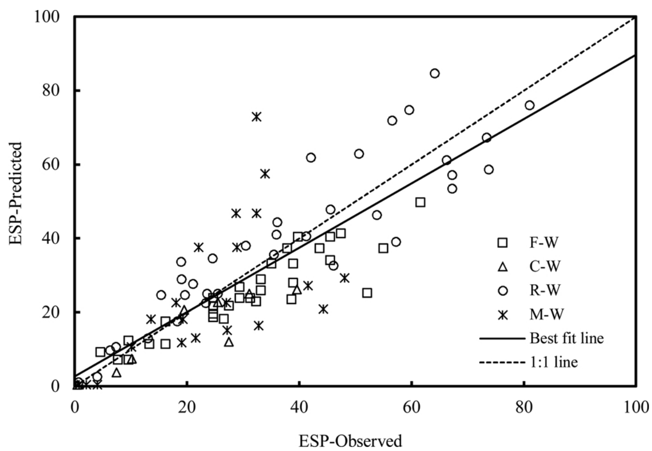

Fig. 2. Observed and predicted ESP using modified value of adj.RNa based upon annual alkali water, rainfall and evapo-transpiration; F–W, C–W, M–W and R–W refer to fallow-wheat, cotton-wheat, maize-wheat and rice-wheat cropping sequence. Source: Minhas and Sharma (2006).

calcite precipitation may be overestimated. Additionally, relatively higher dissolution of gypsum with rainwater during monsoon season than that of calcite should add more Ca to solution. In fact, a critical re-look at the predicted and reported sodicity (ESP) values brought out that the over-predictions were mainly for alkali waters that contained considerable neutral salts (Cl & SO_4) along with residual alkalinity. The presence of neutral salts is also reported to result in the enhanced dissolution of calcite and Ca-primary minerals (Dubey et al., 1988; Nadler and Magaritz, 1991). Since neutral salts are first to be dissolved and displaced with rainwater, the above processes would lead to decline of Na in soil solution and thus cause a decrease in SAR of the soil solution vis-à-vis sodicity in soils. Relatively reduced sodification when SO_4 was the dominant anion following HCO_3 as compared with Cl-dominance in alkali waters was reported by Minhas et al. (2007b).

2.2. Physical impacts – soil infiltration problems

The sodification leads to soil structure deterioration and consequently in manifestation of physical stresses. For example, the formation of surface crust impacts the emergence of seedlings, water stagnation with reduced infiltration causes anoxic conditions, causes impaired root growth with hard setting, and induces dispersion and swelling of clays. These factors ultimately affect water-storage and its movement to roots. Tillage and sowing operations also become more difficult with soil structural deterioration (Oster and Jaywardane, 1998), and restricted water movement into and through soils can induce additional surface retention of salts (Minhas et al., 2004).

Several studies since the 1950s have demonstrated the tendency for swelling, aggregate failures, and increase in dispersion rates with an increase in ESP and a decline in salinity; even non-sodic soils with ESP < 3 may behave like sodic soils at very low electrolyte concentrations (Oster and Schroer, 1979; Shainberg and Letey, 1984; Minhas and Sharma, 1986; Sumner et al., 1998; Oster et al., 1999). There is a salinity–sodicity continuum and highly sodic soils require high salinities for soil stabilization. Soil water intake in terms of infiltration/permeability values should decline in most of the soils when concentration of electrolytes in permeating water is inadequate to compensate for high Na effects. This formed the basis of the earlier water quality criteria which included combinations of EC and SAR to maintain infiltration rates of soils (Ayers and Westcot, 1985). Analogous to SAR, a ratio namely 'CROSS' (cation ratio of soil structural stability) was put forward by Rengasamy and Marchuk (2011) where flocculation value of Mg for soil clays is 0.69 to that of Ca.

Under field situations, rainfall and irrigation water infiltration alternate, especially during the monsoon season. Generally, upland crops suffer the most due to water stagnation problems during the rainy season and soil crusts may form due to beating action of raindrops. After simulating monsoonal rainwater infiltration conditions using deionised water, drastic reductions in hydraulic conductivity were observed even at SAR/ESP around 5, and such reductions were irreversible (Minhas and Sharma, 1986). Field observations (n = 19) further corroborated this where infiltration rates of sandy loam soils irrigated with saline-sodic waters, SSW (EC 2.3–11.0 $dS\,m^{-1}$; SAR 10–28) were monitored to be 8.7 ± 2.6 $cm\,h^{-1}$ with SSW and were reduced to 4.4 ± 1.6 $cm\,h^{-1}$ when deionised water (simulating rainwater, SRW) followed SSW while the values were 2.7 ± 0.8 $cm\,h^{-1}$ with SRW and improved only to 3.3 ± 1.0 $cm\,h^{-1}$ when SSW followed SRW (AICRP-SSW, 1972-2016). Slaking upon wetting and thereafter translocation of dispersed clay particles was also reported to be the main cause of limiting infiltration of rainfall water (Shainberg and Letey, 1984; Oster et al., 1999; Sumner et al., 1998). In a field experiment where wheat-pearl millet crop rotation was irrigated on a sandy loam soil with various EC (6 and 12 $dS\,m^{-1}$) and SAR (10, 20, 30 and 40) waters for 8 years, its steady infiltration rates (IR) declined to 5–10% of the normal soil (Minhas et al., 1994). The recoupment in IR with saline waters was only 22–28 % even though the flocculation values of clays for such illitic soils are 30–40 meq L^{-1}. This finding established that in the monsoonal climate, dispersed colloidal clays get transported with the traction of infiltrating rainwater and the process over the longer periods leads to the formation of subsoil zone which gets enriched with illuviated clays. This zone is below the plow layer where remixing of move-in clay does not occur with tillage operations. The deposited clays lead to development of relatively finer pore sizes and more dead-end pores, lowering the overall porosity. Ultimately this zone becomes a sort of permanent throttle for downward movement of water and thus controls steady-state infiltration rates. Minhas et al. (1999) confirmed this with six cycles of alterations of saline (80 meq L^{-1}; SAR 10, 20 and 30) and simulated rain waters (deionised EC < 0.02 $dS\,m^{-1}$) where the "washed-in" subsoil, as evidenced from depth distributions of hydraulic head and dispersible clay, became restrictive and had major control over K-values (Fig. 3). The calcium released in highly calcareous soil (Calcite 9.7%) showed some effects in alleviating the impacts of high-SAR waters. The quantum of clays that can undergo translocation and their settling depth should depend upon the soil texture and its mineralogy which define their inherent infiltration characteristics and the modifying factors like sodicity level of the soil, its salt release characteristics, among others. For this consequent measurements of K-values with sodic water and followed by de-ionised water (simulating rainwater) should serve as a better diagnostic criterion for infiltration hazards (Minhas, 2010). With simultaneous rising of pH, alkali waters prove more deleterious than those with neutral salts. Sharma and Minhas (1997b) reported that in an illitic sandy loam soil, the effect of SAR for waters with neutral salts (Cl, SO_4) and adj.SAR for water with residual alkalinity on infiltration rates were negative and similar in magnitude. The heavy-textured soils (Surapaneni and Olsson, 2002) and those put under rice-wheat systems are even more prone to an infiltration problem when irrigated with sodic/alkali waters (Bajwa et al., 1983; Minhas and Gupta, 1992).

Although the primary concern has mostly been shown for the water movement into the soils, sodicity also influences the movement of water through the soils, impinging upon salt dynamics. A reduced drainage co-efficient of subsurface soil enriched with moved-in dispersed clays may lead to low anoxic conditions with reduced ODRs (oxygen diffusion rates), while the reduced unsaturated hydraulic conductivity (K(θ) relations) would restrict the water movement vis-à-vis the root water uptake (Minhas et al., 1994). Moreover, the dispersion and movement of clay induces flow through finer pores and results in dead-end pores. These conditions lower the leaching efficiency by holding back salts. Lowering of salts upon leaching in soils irrigated with sodic waters (Singh et al., 1992) and with residual alkalinity (Sharma and Khosla,

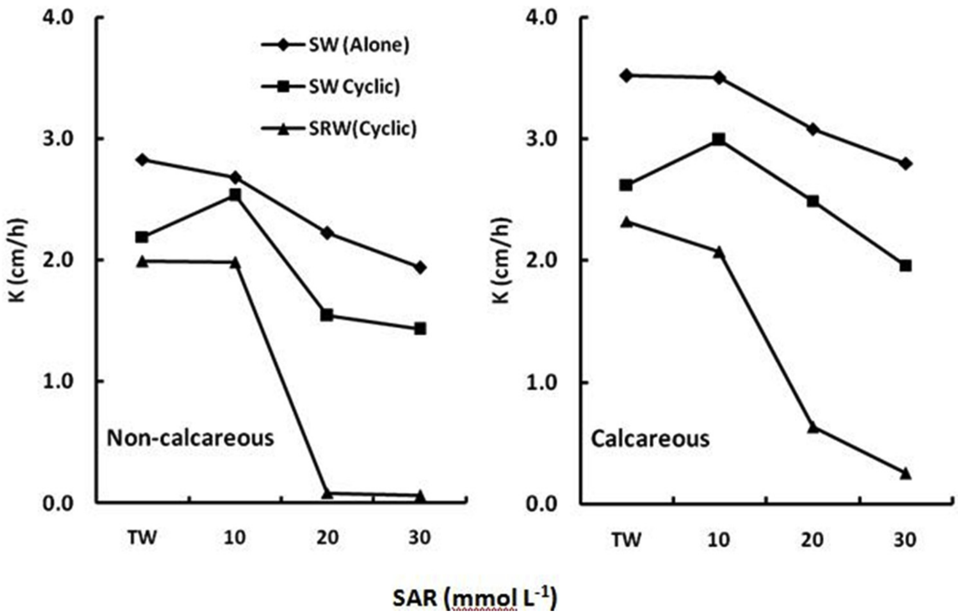

Fig. 3. Saturated hydraulic conductivity (K) after 6 cycles with saline waters (EC 80 meq L^{-1}) of varying SAR (SW) and de-ionised water to simulate rain water (SRW) irrigation in non-calcareous (0.8%) and calcareous (9.7% calcite) soils. Source: Adapted from Minhas et al. (1999).

1984) often leads to an increase in pH, vulnerability to clay dispersion and a sharp decline in infiltration rates. Therefore, these soils required almost double the water (0.9–1.3 cm cm^{-1} soil) for accomplishing the same amount of leaching (80% removal of initial salt) compared with structurally stable saline soils (0.4–1.0 cm cm^{-1}). Studies reveal that the leaching efficiency improved by adding gypsum to the soils irrigated with saline-sodic waters (Singh et al., 1992) but not in soils irrigated with alkali water (Sharma and Khosla, 1984).

2.3. Impacts on crops – productivity

Plant growth and development in soils irrigated with sodic/alkali waters depends on several complex factors like ion-toxicities (e.g. Na, HCO_3, etc.), Ca deficiency with its precipitation as calcite, nutritional imbalance, dispersive behaviour leading to lesser salt leaching and other soil physical constraints. Rhoades et al. (1992) stated that in case Ca in soil solution is > 2 mmol L^{-1}, high SAR will not show adverse effect on most crops, as distinguishable from salinity. Usually the adverse effects of highly saline-sodic water (EC > 4 dS m^{-1}; SAR > 20) on soil structure lead to lesser quantities of monsoon rains to infiltrate into soils, thereby rendering soils saline due to poor leaching of winter season accumulated salts. Therefore, elevated levels of salinity as induced by high SAR (30 and 40 mmol L^{-1}) waters was reported as the main reason for yield decline in pearl millet-wheat rotation when irrigated with waters of various combinations of EC (6 and 12 dS m^{-1}) and SAR (10, 20, 30 and 40 mmol L^{-1}) for 8-years (Singh et al., 1992). Rainfall received during monsoon season further defined the yields of pearl millet (Fig. 4). As expected, the dilution and salt leaching were reduced during low rainfall years while simultaneous water stagnation problems during higher rainfall years affected pearl millet yields and the decline was more at higher SAR of irrigation water. The impacts of high SAR were also more pronounced on black clay loam soil (Minhas and Gupta, 1992) and a shift to water-logging and salinity tolerant crop like Sesbania (*Sesbania sesbans*) was a promising alternative during monsoon rains (Bhu-Dayal et al., 2009).

Earlier examples for viability of alkali water usage were: i) the soils to be irrigated should be deep, have adequate drainage and loamy sand to sandy loam in texture, ii) only winter semi-tolerant crops such as wheat and barley should be grown, and iii) monsoon rainfall during fallow *Kharif* (summer monsoon season) should be at least 400 mm for

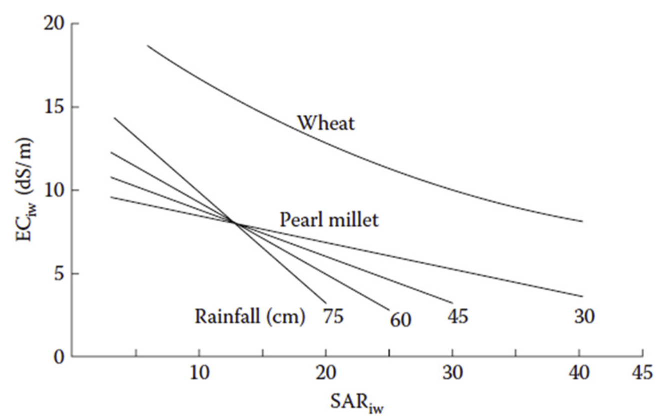

Fig. 4. Predicted salinity of irrigation water, ECiw for 0.75 relative yields of pearl-millet and wheat as affected by SARiw and rainfall. Source: Adapted from Singh et al. (1992).

adequate dissolution of precipitated calcite (Manchanda et al., 1989). However, alkali ground waters are more prevalent in the annual rainfall zone of 500–750 mm where double cropping is regular practice. Several reports have subsequently emerged where the ability of different crops to perform under alkali water irrigated conditions has been evaluated in different agro-ecosystems that are typical to north-western parts of India (Table 1). Maize productivity declined with sodification of a sandy loam soil with irrigation waters of EC (1.15–4.5 dS m^{-1}), RSC (2 and 8 meq L^{-1}) and SAR (11.6–38.5) for 5 years. Relative yield (RY) of maize could be described by the relation; RY = 109.4 − 1.95 ESP. However, the highest ESP (30.5) was within tolerance limits of wheat and thus its yields were not affected (Bajwa et al., 1983). In a similar study with alkali irrigation waters (EC 1.4–1.6 dS m^{-1}, SAR 11.4–19.2, adj.SAR 20.5–41.0), Bajwa and Josan, (1989c) reported sustained crop yields during the initial two years in rice-wheat and pearl millet-wheat rotation. Using quadratic relations between adj.SAR and rice-wheat yields, the estimated values of adj.SAR values for obtaining 90, 75 and 50% of the relative yields were estimated to be < 23, 28 and 32, respectively while the counter values were 10, 28 and 36 for pearl millet-wheat rotation. For another high water requiring crop, sugarcane, after one-year of irrigation with alkali water (EC 1.2 dS m^{-1}; RSC 10 meq

Table 1
Soil pH, sodicity (ESP), infiltration rate and crop yields as affected by longer-term irrigation with alkali waters.

Water quality parameters			Soil texture	*Kharif* crop	No of years	Soil parameter			RY** wheat
EC ($dS\ m^{-1}$)	RSC ($meq\ L^{-1}$)	SAR				pH	ESP	RIR*	
3.2	4.0	21.4	Loamy sand	Maize	10	8.9	36	0.46	0.91
1.5	14.8	19.5	Silt loam	Millet	9	10.0	43	–	0.20
1.4	10.0	15.8	Silt loam	Millet	9	9.6	32	–	0.60
1.4	10.1	13.5	Sandy loam	Rice	6	9.6	46	0.14	0.45
1.4	10.0	15.8	Silt loam	Rice	9	9.7	46	–	0.42
1.5	8.0	11.6	Sandy loam	Maize	5	9.1	20	0.71	0.96
3.0	8.0	25.0	Loam	Maize	5	9.0	28	0.21	0.92
1.2	10.6	10.1	Sandy loam	Cotton	8	9.2	24	–	0.74
2.3	11.3	15.0	Sandy loam	Rice	6	8.7	27	–	0.81
3.6	12.4	15.8	Sandy loam	Dhaincha	5	9.1	41		0.34^{Pt}
2.8	10.6	5.0	Sandy loam	Rice	4	8.5	16	–	0.84(0.73)
2.8	10.0	10.0	Sandy loam	Rice	4	8.6	19	–	0.80(0.70)
1.4	14.9	10.1	Sandy loam	Cotton	6	9.3	41	0.33	0.78^{Sf}
1.4	14.9	10.1	Sandy loam	Cotton	6	9.2	31	0.42	0.85

*RIR represent relative infiltration rate referenced to canal water. **Relative yields averaged over years, ^{Pt}potato, ^{Sf}sunflower. Figure in parenthesis is for rain protected conditions; Data compiled from Bajwa et al. (1983, 1986, 1993) and Bajwa and Josan (1989a,b,c), Choudhary et al. (2006), Choudhary and Ghuman (2008), Chauhan et al (2007), Minhas et al. (1994, 2007a), Sharma et al. (2001).

L^{-1}) and saline-alkali water (EC 3 $dS\ m^{-1}$; RSC 10 $meq\ L^{-1}$), the sugar yield was reduced to 10.2 and 8.3 $Mg\ ha^{-1}$, respectively, while it was 12.2 $Mg\ ha^{-1}$under canal water irrigation. The yields continued to decline further to 0.29 and 0.18 $Mg\ ha^{-1}$towards the end of the 10 year experimentation period (Choudhary et al., 2004). When cotton-wheat (4 years) and following pearl-wheat (7 years) were irrigated with waters of varying residual alkalinity (5 and 10 $meq\ L^{-1}$), salinity (2 and 4 $dS\ m^{-1}$) and sodicity (SAR 10. 20 and 30), yields of *Kharif* crops (cotton/pearl–millet) were reduced by 9–36%; with the effects being more in pearl-millet (Sharma and Minhas, 2004). Overall, wheat yields could be sustained (RY 90%) with waters having EC $\leq$ 4 $dS\ m^{-1}$, SAR $\leq$ 30 and RSC $\leq$ 10 and cotton/pearl millet (RY $>$ 80%) with waters of EC $\leq$ $dS\ m^{-1}$, SAR $\leq$ 20 and RSC $\leq$ 5. The first cotton crop remained unaffected, but the yields declined in subsequent crops of wheat and cotton when a sandy loam soil was irrigated with a saline-sodic water (EC 3.32 $dS\ m^{-1}$, SAR 16.3, SAR adj 18.2; RSC 5.2 $meq\ L^{-1}$) in the Indus basin (Murtaza et al., 2006).

Rainfall plays an important role in areas irrigated with sodic/alkali waters, not only as a substitute for irrigation water and to achieve salt balances, but by being unsaturated with Ca, it also helps in dissolving calcite and other soil minerals. Impacts of rainfall were isolated in rice-wheat rotation when alkali waters of varying RSC (5 and 10 $meq\ L^{-1}$), SAR (adj.RNa 13.6 and 29.2) and $Cl:SO_4$ (4:1 and 1:4) combinations but with similar total salts (30 $meq\ L^{-1}$) were used for irrigation (Minhas et al., 2007b). Relative yields of rice and wheat averaged 56–74 and 81–88% of good-quality water (EC 0.5 $dS\ m^{-1}$; RSC nil) during the initial four years, indicating that the former is more sensitive to irrigation with alkali water. When crops were protected by rain shelters, almost complete mortality of rice crop after two years signified the contribution of monsoonal rainfall in sustaining irrigation with alkali waters. Production functions further brought out that in addition to the sodicity (ESP), salinity simultaneously inhibited growth and defined crop performance, especially for salt sensitive rice crops (threshold EC 1.4 $dS\ m^{-1}$). The impacts of residual alkalinity were comparatively lower when SO_4 was the dominant anion in the irrigation water rather than Cl.

The consensus that emerges from the above evidences is that degradation of soils and productivity losses are aggravated when alkali water is used for rice-wheat systems. Since the viability of this system was questionable, earlier water quality guidelines recommend avoiding rice in crop rotations (Minhas and Gupta, 1992). Minhas and Sharma (2006), while evaluating a large dataset available on the use of waters with residual alkalinity, predicted that crop yields could be sustained with water of adj.RNa ranging from 14–27 $mmol\ L^{-1}$in fallow/millet/maize/cotton-wheat rotation, while the values were about half (6–14 $mmol\ L^{-1}$) for a rice-wheat rotation. Still, the farmers of the afflicted areas prefer the cultivation of rice-wheat. While evaluating the causes of persistence among farmers relying on rice-wheat rotation, Minhas et al. (2004) concluded that in addition to economics, the rice-wheat are prevalent because: i) the establishment of upland crops during *Kharif* is usually difficult because of water stagnation vis-à-vis root aeration problems on these structurally unstable sodified soils, ii) the demand for continuous submergence in rice helps in better and uniform salt leaching than the upland crops where rain water is usually drained-off to avoid its stagnation, iii) rice helps in conjunctive use with canal water since it can be adjusted as and when available due to submergence requirement of rice while its use for upland crops is possible only during dry periods between episodic rain events and iv) if groundwater contain sufficient Ca, i.e., up to 2 $mmol\ L^{-1}$, thus soils are less responsive to gypsum application.

3. Management options for sustaining crop production

The management options leading to sustainable crop productivity with saline-sodic/ alkali irrigation waters should aim at practices that do not allow build-up of root zone sodicity to levels that impair soil productivity; and also those options that help in alleviation of sodicity impacts to promote crop growth. Attempts have therefore been made through conjunctive use of water resources, chemical amelioration of alkali waters/soils, mobilising the native calcite through phyto-remediation, growing sodicity tolerant crops, and other agronomic measures (Minhas and Samra, 2003; Minhas et al., 2004; Sharma and Minhas, 2005; Qadir and Oster, 2004, 2007; Choudhary et al., 2011b; Minhas, 2012). Since these measures may not control sodicity of irrigated soils when executed in isolation, integration of the available crop, irrigation, soils, chemical, and other agronomic practices is desirable.

3.1. Use of Amendments

3.1.1. Soil applied amendments

The degradation of soils with sodification can be alleviated with extraneous input of amendments which either contains Ca (e.g. gypsum) or those that on reaction with calcite release Ca in soil solutions (e.g., sulphur, sulphuric acid, pyrites, etc). The viability of these amendments should be judged from alleviation in soil constraints to improve crop yields versus the cost involved. Since the application of amendments is a recurring need under alkali water-irrigated conditions, the effects of various amendments, their doses, modes, and frequency of

Table 2
Crop responses to gypsum application in alkali water irrigated soils.

Water quality			Soil properties			Grain yield		Gypsum applied	GY with gypsum	
EC (dS m^{-1})	RSC (meq L^{-1})	SAR	pH	ESP	ECe (dS (m^{-1})	*Kharif* (Mg ha^{-1})	*Rabi* (Mg ha^{-1})	(Mg ha^{-1})	*Kharif* (Mg ha^{-1})	*Rabi* (Mg ha^{-1})
Rice-Wheat										
2.6	9.5	20.5	8.3	58	14.9	4.4	2.2	5.6-22.4	5.9-6.1	3.8-4.4
0.85	6.8	8.5	9.5*	26	NA	5.8	4.4[k]	0.7NR	6.1	4.8
0.95	10.3	13.5	9.7*	42	NA	3.6	2.0	0.5NR	6.0	4.9
NA	12.5	NA	9.9*	NA	0.7*	0.6	1.0	2.0-4.0	2.0	2.1-3.7
3.1	9.5	15.4	8.7	21**	2.5	4.0	3.5	0.5NR	4.3	3.8
1.2-2.2	6.7-8.0	7.3-10.6	8.7*	19**	2.6	2.2	2.4	2.5	3.0	2.9
1.7-2.1	9.9-12.5	9.4-10.6	10.0*	49	0.54**	5.5	4.7	0.5NR	6.4	5.7
2.9-3.4	4.6-10	12-19	8.0-8.4	57-78	2.4-3.2	0.3	2.3	1.0NR	0.3	2.9
Sorghum-Wheat #										
3.1	9.5	15.4	8.7	25	7.1	2.8	2.0	1.0-3.5	2.2-2.6	2.1-3.1
2.6	9.5	20.5	8.3	58	14.9	–	0.5	2.2-8.8	–	1.5-3.2

*1:2 soil:water, **SARe, NR denotes gypsum added to neutralize RSC, # Gypsum @ 5 Mg ha^{-1} applied initially. Source: Manchnada et al. (1985), Bajwa and Josan (1989b), Sharam and Mondal (1982), Sharma et al. (2001), Qadir et al. (2001), Choudhary et al. (2011b).

application have been studied at large (Table 2). Early observations suggested that wheat may not respond to applied gypsum when RSC of irrigation water is below 10 meq L^{-1}, soils are light-textured (loamy sand–sandy loam), fields are kept fallow during *Kharif* and annual rainfall is 500–700 mm (AICRP-SSW, 1972–2016). However, with application of gypsum (25% of gypsum requirements, GR) on a degraded soil (pH 10, ESP 92), and with long-term use of alkali water (EC 1.6 dS m^{-1}, RSC 10 meq L^{-1}), grain yield of wheat yield improved from 0.06 (almost nil) to 2.67 Mg ha^{-1}, and to 6.33 Mg ha^{-1} (normal yields of the area) with 100% GR (Manchanda et al., 1985). The *Kharif* crops of guar/pearl millet could be cultivated successfully by maintaining ESP between 15 and 20 with application of gypsum (Sharma and Manchanda, 1989). The site was semi-arid with annual rainfall < 500 mm. Similarly, after two years with gypsum application (100% GR) of both soil and alkali waters, moderate yields of wheat (2.61 Mg ha^{-1}) and mustard (2.0 Mg ha^{-1}) were harvested on an abandoned soil because of irrigation with alkali waters (RSC 7.2–8.9 meq L^{-1}) under an arid climate (Joshi and Dhir, 1991). However, the gypsum @50% GR sufficed for cultivating *Kharif* crops like pearl-millet, urd-bean, mungbean, cowpea and pigeon-pea on a soil (pH 9.6–9.7) irrigated with alkali water (EC 1.93 dS m^{-1}, RSC 12 meq L^{-1}), while additions of 100%GR were required for cluster bean (Yadav and Kumar, 1994). Among the winter crops, mustard responded better to gypsum than wheat and barley. Later reports from the same site (Singh et al., 2008) showed that application of gypsum to neutralise RSC above 2.8 meq L^{-1} increased wheat yield by 53%, pearl millet (88%), mustard (56%), sorghum (98–100%), and sesbania (62%) when RSC of irrigation water was 12 meq L^{-1} and increases in yields were 59, 66, 67, 71–126 and 89% with RSC 16 meq L^{-1}, respectively. The yields of vegetable crops such as potato, tomato, brinjal and cluster bean grown in sequence using an alkali water (RSC 11.6 meq L^{-1}; SAR 14.0) on a long-term basis (15 years) and a sandy-loam soil averaged (3 years each) only 13.41, 1.65, 0.30 and 0.06 Mg ha^{-1} (Phogat et al., 2010). These improved to 21.0, 23.6, 16.7 and 9.6 Mg ha^{-1}, respectively with additions of gypsum @50% neutralisation of RSC and further to 21.3, 31.6, 22.9, 10.5 Mg ha^{-1} with gypsum equalling 100% RSC neutralisation.

Under rice-wheat cropping system irrigated with alkali water (EC 2.6 dS m^{-1}, SAR 20.5, RSC 9.5 meq L^{-1}), Sharma and Mondal (1982) observed wheat productivity to improve with gypsum application, while no response was initially observed in rice. Gypsum to neutralise RSC equivalent of 2.5 and 5.0 meq L^{-1}could sustain yields of wheat and rice receiving irrigation with waters of RSC 8.4 and 13.2 meq L^{-1}, respectively (Bajwa and Josan, 1989a). Similarly, the sustainable yield index (SYI) with application of gypsum @ 50 and 100%GR ranged between 0.57-0.65 and 0.54-0.65 in rice and wheat respectively, indicating that 50%GR is sufficient (Sharma et al., 2001). More pronounced benefits of gypsum (RSC 2.5 meq L^{-1} neutralization) were observed in cane yield of sugarcane (30% increase) that was irrigated with alkali water (RSC 10 meq L^{-1}, SAR 19.8, EC 1.43 dS m^{-1}) as compared with saline-alkali water (RSC 10 meq L^{-1}, SAR 31.2, EC 2.90 dS m^{-1}) where the improvement was about 13% (Choudhary et al., 2004). The effects of gypsum were complemented by FYM (Farmyard manure), especially when alkali water was used. While working with different crop rotations, Sharma et al. (2001) concluded that (i) growth of wheat cultivated after rice mainly depends upon soil pH and its sodicity and therefore it usually respond to gypsum when RSC is > 5 meq L^{-1}; (ii) when fields are kept fallow during *Kharif*, the carried over soil salinity also governs growth of wheat and therefore its response to gypsum remains variable; and (iii) when wheat is grown after sorghum, the interactive effects of ECe, pH and SARe of soils govern its response to gypsum e.g. at a given pH as SARe rises, ECe should be lower. Higher yields of rice and wheat were also observed in a saline-sodic soil when treated with gypsum and irrigated with alkali water in cyclic mode with good water (Murtaza et al., 2013). Therefore, it emerges that gypsum applications are required on a recurring basis to minimise impacts of irrigation water having high residual alkalinity especially in high water demanding rotations like rice-wheat.

Saline-sodic soils developed with high SAR-saline water irrigation are also prone to reduced infiltration and thereby temporary waterlogging, especially during monsoonal season. Therefore, small additions of gypsum may help maintain structural stability and thus avoid water stagnations vis-à-vis aeration problems during rainy season. Application of phospho-gypsum helped in preventing surface crusts and maintained the yields of cotton (5 Mg ha^{-1}) in a soil that was irrigated with saline-sodic water (EC 4.6 dS m^{-1}; SAR 26) for 16-years in Negev region of Israel (Keren et al., 1990). In pearl millet–wheat irrigated with waters of varying SAR (10–40 mmol L^{-1}) but similar salinity (EC 8 dS m^{-1}), gypsum application at 25% GR improved the average yields (1999–2002) of pearl millet by 5–23% (AICRP-SSW, 1972–2016). Response to gypsum was observed mainly during the years when episodic events of rainfall and consequent water stagnation problems occurred during its initial stages, and the overall effects of applied gypsum were higher at SAR of 30 and 40 mmol L^{-1}. The yields of pearl-millet further improved (5–11%) by draining-out the stagnating rainwater after heavy rainfall events. However, the long-term consequences of removing rain-stagnated water needs to be further examined since such a practice could reduce the volume of rainwater for salt leaching.

3.1.2. Mode and time of amendment application

Smaller doses of gypsum to neutralise the RSC (8 meq L^{-1}) of each irrigation was reported to be better in improving the crop yields in maize–wheat system rather than an annual application (Bajwa et al., 1989a). However, in a later experiment with rice-wheat system irrigated with alkali water (RSC 6.8 meq L^{-1}, SAR 8.4), the response to gypsum was at par when applied either annually before rice crop or with each irrigation, while application of gypsum before transplanting was better in rice irrigated with alkali water (RSC 10.3 meq L^{-1}, SAR 13.5). This was ascribed to appreciable sodification during rice growth because of its high irrigation water requirements. Similarly, in pearl millet-wheat crops the application of gypsum before the onset of monsoons was more effective as compared with its application either before wheat crop or with each irrigation (Yadav and Kumar, 1994). When pyrite was applied to amend the deleterious effects of high RSC waters, Chauhan et al. (1986) reported that application before wheat was better than its mixing with irrigation water or its small doses before each irrigation. Longer-term performance of rice and wheat was better when gypsum/pyrite was applied every year compared with its application every 3-years (Minhas et al., 2004). Recently, Murtaza et al. (2015) has reported that a coarse-textured salt-affected soil could be reclaimed with saline-sodic water (EC 3.94 dS m^{-1} SAR 18.2 RSC nil) in combination with gypsum. The grain yield of wheat improved by 9%, 42% and 75% when gypsum applied was 50 and 100%GR and to neutralise 100% RSC of irrigation water, respectively.

3.1.3. Water amelioration techniques

Responses to gypsum application in general show that application at each irrigation was superior or at least as effective in mitigation of the sodicity effects of alkali water irrigation. Therefore, efforts have been made to devise mechanisms for dissolving gypsum in alkali water itself in terms of specially designed 'gypsum beds'. Passing of alkali waters through these beds further eliminates the expense of grinding, bagging and storing mined gypsum before field usage. The beds are designed for specific dissolution of Ca from gypsum and their dimensions depend upon factors like surface area, as defined by the distribution of different sized fragments, the reaction time driven by the velocity with which water would pass through the bed and the ion chemistry of irrigation water (Pal and Poonia, 1979; Pal and Poonia, 1979; Singh et al., 1986). For practical purposes, the Ca^{2+} dissolution through gypsum beds can be as high as 8 meq L^{-1}. When similar doses of gypsum were applied either by ameliorating the alkali water (RSC 9 meq L^{-1}) with gypsum beds or its soil application, the 5-year average crop yields were superior in sorghum-mustard rotations while these were similar in rice-wheat (Minhas et al., 2004). In a similar 5-year field experiment with sorghuM–Wheat, the pyrite bed was more effective in reducing residual alkalinity (14.2 to 8.9 meq L^{-1}) than the gypsum bed (11.2 meq L^{-1}), as indicated by higher crop yields (AICRP-SSW, 1972–2016). The wheat grain yield averaged (4 years) 1.58 Mg ha^{-1} with alkali water and improved to 2.56-2.98 Mg ha^{-1} when soil was amended with gypsum (50–150% GR) and 2.46–3.02 Mg ha^{-1} with pyrite (50–150% GR). The yield was 2.68 and 2.72 Mg ha^{-1} when irrigation water was passed through gypsum and pyrite beds, respectively. However, the highest dry forage production of sorghum (11.78 Mg ha^{-1}) was monitored with pyrite beds whereas production was 5.66, 8.64–11.54, 8.5–11.06 and 10.00 Mg ha^{-1} with alkali water as such, soil applied gypsum (50–150% GR), pyrite (50–150% GR) and gypsum bed, respectively. These results reveal that amelioration of water itself can help in efficient utilization of amendments like gypsum and pyrite, though the availability and economics of the pyrite remains uncertain. Viability of gypsum beds is further evident from many field trials with wheat, mustard and gram on farmer's fields where the BCR (benefit: cost ratio) and IRR (internal rate of return) of these beds was computed to be 2.04 and 40.2%, respectively (AICRP-SSW, 1972–2016). An alternative to beds is to keep the clods of gypsum in water courses/ channels used for irrigation (Qadir et al., 2007; AICRP-SSW, 1972–2016).

Treatment of irrigation water with acid leads to its reaction with HCO_3 and CO_3 to form CO_2 gas plus water as well as it lowers the pH of water which allows for more Ca and Mg to remain in the soil solution and displace Na from exchange sites rather than its precipitation as calcite. Therefore, sulphurous acid generators (SAG) have been developed for producing sulphur dioxide gas (SO_2) through the burning of sulphur in specially designed chambers. SO_2 is later dissolved in 10–15% of irrigation water to produce sulphurous acid (H_2SO_3). The ameliorated waters are then mixed with original alkali water for irrigating the degraded soils (Qadir et al., 2001; Kahlown and Gill, 2003). Studies suggest that RSC of saline-sodic water was decreased from 5.4 to 3.6 meq L^{-1} after SAG treatment, whilst having no impact on SAR/EC (Zia et al., 2006). It was also reported that SAG, sulphuric acid and gypsum were at par in improving rice yields, but the costs involved in SAG and sulphuric acid treatment were about six times greater than gypsum. Therefore, because of economic considerations, SAG's are not becoming popular.

3.1.4. Use of organic/green manures

The beneficial effects of organic/green manure as a source of nutrients and on improvement of soil structure and permeability are well established. In addition to their nutritional benefits, these have multiple benefits in term of bioremediation under sodic soil environments (Qadir et al., 2006). Organic acids produced during their decomposition and the increased pCO_2 in soils help to mobilise the inherent Ca from calcite and other minerals. Moreover, the Ca and other cationic contents of these organic materials also get released on their decomposition. Green manure crops like sesbania also release protons (H^+) during N_2-fixation to lower soil pH and thus help in dissolving calcite (Qadir and Oster, 2004). The solubilised Ca during above processes thereby replaces a part of exchangeable-Na. The long-term effects of additions of organic/green manures on lowering of sodicity in soils have been well recognised. Nevertheless, these may rather lead to enhanced dispersion of sodic soils on a short-term basis and therefore caution is placed on their application to soils undergoing sodication. In an already deteriorated soil with the use of alkali water (EC 4 dS m^{-1}, SAR 26, RSC 15 meq L^{-1}), wheat yield and soil permeability further declined when FYM was applied alone, but the performance of pearl millet and sorghum improved markedly with combined use of FYM and gypsum (Sharma and Manchanda, 1989). Dhankar et al. (1990) later reported that longer-term additions of FYM improved pH, infiltration rate and wheat yield to 9.7, 8.1 mm h^{-1} and 3.14 Mg ha^{-1} respectively, while the corresponding values were 10.3, 5.3, mm h^{-1} and 2.7 Mg ha^{-1} under alkali water irrigation (RSC 2.4–16 meq L^{-1}) alone. The response to FYM, however, declined at higher RSC (16 meq L^{-1}). Therefore, to overcome short term enhancement in dispersion with FYM, the upland *Kharif* crops should be preceded with gypsum whilst the rice crop, which requires submergence, may benefit from reduced infiltration rates. Minhas et al. (1995) reported rice and wheat yields to improve by 8–10% by additions of FYM in alkali water (EC 3.2 dS m^{-1}, RSC 5.6 meq L^{-1}, SAR 11.3) irrigated soils through improved soil pH, sodicity and fertility. Synergetic effects of adding FYM and gypsum for improving sugar yield were later observed by Choudhary et al. (2004). The productivity (8.6–12.3 Mg ha^{-1}) was higher with alkali water–-irrigation as compared with saline–sodic water (7.4–10.7 Mg ha^{-1}). In the case of saline–sodic water, sugar yield (10.8 Mg ha^{-1}) with FYM additions was higher as compared with gypsum (9.1 Mg ha^{-1}) and was at par with combined use of gypsum plus FYM. Murtaza et al. (2013) also recorded marked improvements in yields of rice and wheat when these received FYM and gypsum and were irrigated alternatively with fresh and sodic water. Sekhon and Bajwa (1993) reported the potential of the organic materials to decrease the precipitation of Ca and HCO_3, cause removal of Na, decrease soil pH and ESP under rice–wheat–maize system irrigated with alkali waters (RSC 6.0 and 10.6 meq L^{-1}). The improvement in crop yields was the maximum with rice straw followed by green manuring and FYM. Choudhary et al. (2011b) after monitoring the long term (15–year) impacts of FYM and green manuring (GM), concluded that improvements in soil pH and ESP were on par while the performance of both rice and wheat was better with FYM. The yields of rice and wheat were increased by 38% and 26% with FYM, respectively over those obtained with sodic water without amendment application (RSC 10–12.5 meq L^{-1}). The corresponding increase with gypsum applied @50% GR was 18% and 19%. Similarly, the GM and wheat straw (WS) resulted in 22% and 17% higher yields of rice while the impacts on wheat were similar (20%). Even in a long-term experiment with vegetables (RSC 11.6 meq L^{-1}), the addition of gypsum (50% and 100% neutralisation of RSC) along with organic amendments (FYM 10–20 Mg ha^{-1}) triggered the process of amelioration of these waters and consequently enhanced the yields of crops (Phogat et al., 2010). Other reports (Yaduvanshi and Swarup, 2005; Murtaza et al., 2009; Buttar et al., 2017) further support the above results whereby synergetic effects of organic and inorganic amendments were reported for improvements in crop productivity. The trade-off of organic materials is that it can help in reducing the gypsum demands required to off-set the impacts of alkali waters and thus their use should be promoted for better crop productivity.

3.2. Conjunctive use of water

Under many situations, supplies of good quality canal waters may be available to a limited extent and farmers may need to use these waters along with poor-quality ground waters for meeting the crop demands. The strategies usually adopted for the combined use of the two sources are either to apply these in cyclic mode where canal water irrigation coincides with sensitive growth stages or after mixing the two waters to attain water of acceptable quality by dilution. Most efforts thus far have been directed towards combining canal water with saline water for irrigation. Since soluble salts are mobile and relatively easier to displace, the strategies include either the use of non-saline/canal water for pre-plant irrigation and early crop growth to control salinity of the seed zone and prospective root zone during initial stages or for salt sensitive crops and switching over to saline water irrigation at tolerant growth stages/crops (Minhas and Gupta, 1992; Rhoades et al., 1992; Minhas, 1996). Nevertheless, the strategy that minimises the sodification, either reducing Ca precipitation as calcite or increasing its release through calcite dissolution should be better (Minhas and Bajwa, 2001).

Groundwaters in aquifers are in equilibrium with soil minerals like calcite, dolomite, etc at a higher pCO_2 while surface canal waters with low Ca are in a state of unsaturation with respect to calcite. Therefore, irrigation with the latter and their blends should have a tendency to solubilise inherent Ca, which would decline with proportions of alkali groundwater in the blend. The effect of the cyclic uses either inter/intra-seasonally or blending the two water supplies has been evaluated on longer-term basis (Bajwa and Josan, 1989c; Minhas et al., 2007a; Chauhan et al., 2007; Choudhary et al., 2011b). The crop productivity data under different modes of application of good quality (GW) and alkali (AW) waters for various cropping rotations have been included in Table 3. It is evident that even when using waters with residual alkalinity, the better intra-seasonal cyclic use option is to start with good quality water (GW) and if opting for inter-seasonal cyclic use, using alkali water (AW) during monsoon rains would help sustain higher crop yields. Crops irrigated under a cyclic regime also tended to out-perform those that are irrigated with blended waters.

While revisiting data, it emerged that because of the number of irrigations required to raise crops in the different sequences, the fractions of alkali waters (AW) were lower when good quality water (GW) was used to start with as compared to those in blended waters and sometimes also when alkali waters were applied initially. Therefore, based upon the relations between relative crop yields (RY) and the fractions of alkali water (AW) applied under blending, the RY's were estimated for same fractions of AW used under different cyclic use modes and are plotted in Fig. 5. The cyclic use still showed a marginal advantage when GW was used initially over blending. The yields matched each other when AW was used for the initial one or two irrigations, while these were less when the initial four irrigations were with AW. Similar advantages were earlier reported for equal salt input when saline and non-saline waters were applied in cyclic or mixing mode (Minhas and Gupta, 1992, 1993). Rhoades (1999) also proposed that more crop consumable water is lost under blending and therefore for similar supplies of water, the sequential use of non-saline and saline water performs better. The alterations in precipitation with alkali water irrigation and dissolution of freshly precipitated calcite with good quality/canal water under cyclic uses seem to retain more Ca in solution phase as compared with continued precipitation vis-à-vis sodication phase under blending, though it occurs at a slower pace than original alkali water. This was substantiated from pH, SARe and ESP build-up in soils monitored after 6-years of combined use either cyclic or blends with same proportions of GW (EC 0.5 dS m^{-1}, RSC nil) and AW (EC 2.3 dS m^{-1}, RSC 11.3 meq L^{-1}, SAR 15) in rice-wheat system (Minhas et al., 2007a). On the whole, the cyclic use of surface/canal and alkali water - a strategy that shows higher yield potential and also more flexibility in its implementation, can be considered as practical way to alleviate sodicity problems.

3.3. Choice of crops and varieties

Crops vary a lot in their tolerance of sodicity in soils. In addition, the ability of crops to perform under sodic irrigation is also defined by their tolerance to excessive soil moisture in rhizosphere or surface water-logging. Permissible limits of ESP (surface 0.15 m soil) tolerance of crops have been established from alkali sites undergoing reclamation with additions of gypsum, and were compiled by Gupta and Abrol (1990). Under these conditions, rice, with ESP limit of 60–70, was the most tolerant, followed by beets, barley, and sesbania (ESP 50–60), oats, mustard, cotton, wheat, and tomatoes (ESP 30–50), clover, groundnut, cowpea, onion, pearl millet, linseed, garlic, and cluster bean (ESP 20–30) and chickpea, soybean, black gram, peas, lentil, and pigeon pea (ESP 10–20). However, the tolerance to sodicity (ESPt) in soils undergoing sodication with water having residual alkalinity is comparatively lower than the sodic soil under reclamation with gypsum (Minhas and Sharma, 2006). The obvious reasons seem to be the differential availability of Ca in soil solution. Ca precipitates out as calcite in soils irrigated with alkali waters whereas dissolution of applied gypsum improves Ca in the soil solution of alkali soils under reclamation. Moreover, the concentration of soil solutions after the cessation of monsoon rains when the most *Kharif* crops are at critical flowering and grain filling stages, affects crop performance e.g. rice with threshold salinity level as 1.4 dS m^{-1}. In addition to their sodicity/salinity tolerance, the choice of crops is governed by their water demands and the agro-climatic conditions. Rice, being a high water requiring crop, also results in the maximum sodification of soils as compared to other upland crops and is also more sensitive under sodic irrigation. The permissible limits for sustaining yields in the cropping sequences prevalent in north-west India have been established (Table 4) in terms of adj.RNa of alkali waters for different rainfall zones (Minhas and Sharma, 2006). Rice-wheat, with permissible limits of adj.RNa being almost half compared with millet–wheat rotations, is the most unsustainable cropping sequence. Therefore, a general recommendation is to avoid rice with sodic waters. The importance of rainfall is also evident e.g. in areas with annual rainfall more than 600 mm, the permissible limit of adj.SAR is almost two-fold (1.8 times) as compared to sites where annual rainfall less than 400 mm.

The crop cultivars also show variability in their tolerance to sodicity. Maintenance of low Na:K ratio in shoot either through avoidance of Na uptake or its exclusion (Sharma et al., 2015) and the profuse rooting (Choudhary et al., 2012) are the preferred characters for their better sodicity tolerance. The cultivars with high yield potential were earlier preferred even for higher sodicity conditions but with later breeding efforts, crop varieties e.g. CSR-30 in rice and KRL-219 in wheat, which are both high yielding and tolerant to sodicity are now available. These varieties are becoming an attractive option for the poor

Table 3
Effect of irrigation with alkali and good quality water in cyclic modes or blending on yield (Mg ha^{-1}) performance of crops cultivated in different sequences. Source: and Bajwa and Josan (1989a,b,c), Choudhary et al. (2006), Choudhary and Ghuman (2008), Chauhan et al. (2007), Minhas et al. (2007a)

Water Quality	Rice*	Wheat*	Potato	Sunflower	Rice	Wheat	Cotton	Wheat	Sunflower
Good water, GW	1.26	0.92	35.0	1.54	6.8	5.4	2.02	5.21	3.28
Alkali water, AW	0.81	0.75	11.9	0.49	4.2	3.1	1.31	4.07	2.55
Mixing Mode									
2 GW : 1 AW	1.00	0.86	28.9	1.24	6.7	5.2	–	–	–
1 GW : 1 AW	0.99	0.82			6.2	5.7	–	–	–
1 GW : 2 AW	0.95	0.79	23.0	1.09	5.7	4.9	–	–	–
Cyclic Mode (Intra-seasonal)									
2 GW : 1 AW	1.05	0.89	–	–	–	–	1.93	5.01	2.99
1 GW : 1 AW	1.02	0.86	29.8	1.44	–	–	1.85	4.88	2.88
1 GW : 2 AW	0.99	0.81	–	–	–	–	1.64	4.61	2.67
2 GW : 2AW	–	–	28.4	1.28	–	–	–	–	–
1 AW : 2 GW	–	–	–	–	–	–	1.82	4.88	3.01
1 AW : 1 GW	–	–	–	–	–	–	1.59	4.63	2.8
2 AW: 1 GW	–	–	–	–	–	–	1.52	4.31	2.69
2 AW : 2 GW	–	–	22.7	1.01	–	–	–	–	–
4 AW : 2 GW	–	–	14.0	0.68	–	–	–	–	–
Cyclic Mode (Inter-seasonal)									
AWrp : GWws	0.86	0.81	–	–	–	–	–	–	–
GWrp : AWws	1.03	0.81	28.0	0.94	–	–	–	–	–
LSD (p = 0.05)	0.23	0.12	2.4	0.19	0.5	0.4	–	–	–
GW(EC,SAR,RSC)	(0.5, 0.6, nil)		(1.1, 1.8, nil)		(0.5.0.3.04)		(0.2, 0.4, nil)		
AW(EC,SAR,RSC)	(2.3, 15,112)		(3.5, 15.8,12.4)		(1.4, 13.5, 10.1)		(1.4, 14.9, 10.1)		

Subscript 'rp' and 'ws' refer to rice/potato and wheat/sunflower; *yield in kg per m^2.

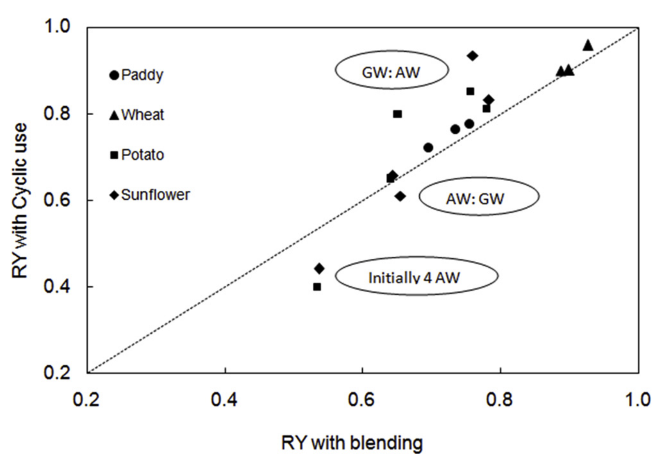

Fig. 5. Relative yields (RY) for various cyclic uses and blending with good water (GW) for the similar proportion of alkali water (AW) usage.

Table 4
Permissible limits of adj.RNa for sustainable irrigation in different cropping sequences.
Source: Minhas and Sharma (2006).

Cropping Sequence	Permissible adj.RNa for Rainfall Zone (mm)		
	250–400	400–600	600–750
Fallow–wheat	16	21	27
Maize/millet–wheat	14	17	23
Rice–wheat	6	9	14
Cotton–wheat	14	20	26

farmers lacking resources for affording costly amendments. Marker-assisted and genomics based approaches are further being employed to accelerate the pace of genetic improvement for developing high yielding and multiple stress (e.g., salt, sodicity, drought and water-logging) tolerant cultivars.

3.4. Fertiliser use practices

In most situations, the alkali/sodic water irrigation is usually initiated on soils which are already under cultivation. Sodification affects the availability of nutrients by changing their form in which these are present is soils (e.g. phosphorus) and their losses (e.g. aggravation of nitrogen losses through NH_3 volatilization and their interactions with modified ionic constituents in soil solution). To compensate for N-losses, the recommended doses of fertiliser-N are about 25% more for sodified soils than those for normal soils. Practices to increase N-use efficiency include its splitting as per crop demand, deeper placement, shift to slow-release fertilizer and additions of organic N sources. Splitting of N in three equal doses, at planting (basal), three and six weeks after planting resulted in highest productivity of both rice and wheat (Yaduvanshi and Swarup, 2005). Deeper placement of fertilizers in soils has the requirements for relevant machines. However, a simple method to redistribute the fertilizer in soils is to apply before the pre-plant irrigations. This practice especially when combined with deep tillage (chiseling) on alkali water irrigated soil saved upon 30–40 kg N ha^{-1} (Minhas and Bajwa, 2001). Organic materials temporarily immobilize the NH4-N subsequently release it slowly with decomposition during crop season. Therefore, combining the inorganic fertiliser-N with additions the organic/green manures reduced N doses by 50% in *Rabi* (winter season) and by 25% in *Kharif* crops (Minhas et al., 2004). Yaduvanshi and Swarup (2005) also concluded that fertilizer use efficiency improved considerably in rice and wheat crops when gypsum was combined with FYM or SPM (sugarcane press mud) in a soil irrigated with alkali water (RSC 8.5 meq L^{-1}, SAR 8.8). Therefore, for judicious use of fertilizers in sodic water irrigated soils, extraneous application of organic amendments seems a helpful strategy.

3.5. Irrigation scheduling

Steady state conditions have been traditionally assumed to exist in the long run when irrigating with brackish water and therefore a concept of leaching requirement (LR) was put forward to control salt balances in the root zone (USSL, 1954; Rhoades et al., 1992). Since the alterations of cycles of salt/sodicity build-up with irrigation to winter season crops and their dilution/leaching with monsoon rains do not allow for steady state conditions, the LR's do not work under the monsoonal climate. Any effort to attain LR's during winter crops rather results in higher input of salts to mix-with or push the carried over rainwater in soils and thereby reducing its availability to crops (Minhas, 1996). Similarly, various indices like adj.SAR also predict reduced sodification if higher levels of leaching fraction (LF) are attained. Nevertheless, as presented earlier, the ESP build-up is the maximum (2.4 x adj.RNa) under rice-wheat cropping system with LF of almost 0.6–0.8 where as it is about 1.1 times in maize/millet-wheat system (Minhas and Sharma, 2006). Moreover, attempts to achieve leaching requirement (LF 0.5) with additional amount of saline-sodic water (EC 3.2 $dS\,m^{-1}$, SAR 21, RSC 4 meq L^{-1}) rather resulted in 1.3-1.5-fold higher salinity to reduce crop yields in both rice-wheat and maize/pearl millet-wheat sequence (Bajwa et al., 1983).

Light and frequent irrigations have also been tried to overcome the effects of lower water transmission with build-up of sodicity (Bajwa et al., 1993). Salinity and ESP remained at par with different irrigation frequencies created by variable quantities for each irrigation event (4, 6, 7, 10 cm) while the total applied alkali water (EC 1.2 and 2.9 $dS\,m^{-1}$; SAR 12.2 and 29.4; RSC 9.5) was kept the same. The fodder maize and wheat grown during monsoon and winter season also did not respond to smaller intervals of irrigation while its effects were monitored in terms of bringing down the supra-optimal soil temperature that improved the yields of summer maize. Similar treatments were also tried for 7 years with alkali water (RSC 12 meq L^{-1}) on wheat where application of 6 cm water at each irrigation with sprinklers improved its grain yield by 12.8% and 4.2% over the treatment when irrigation amount was kept as 4 and 5 cm, respectively. This was in spite of higher pH being observed in the former (Yadav et al., 2013). Since the Na:K increased remarkably in leaves of wheat, its toxicity did not allow for attainment of potential yields even with increased quantities of sprinkled alkali water (Singh et al., 2009).

3.6. Tillage practices

The progressive infilling with the dispersed and displaced surface clays increases the possibilities of development of dense subsoil/plow sole in sodified soils. This induces perched water-table and restricts salt displacement to sub-soil layers. Moreover, the sodified surface soils are prone to crusting and becoming very hard and dense (hard setting soils) on drying. All these factors impede root proliferation and thus impact crop growth. To overcome these constraints, deep ploughing/chiselling offers a short-term measure e.g. deep chiselling before planting of wheat resulted in about 10% improvement in wheat yield over conventional tillage (Minhas and Bajwa, 2001). Singh et al. (2013) reported that deep tillage during alternate years in combination with gypsum (50% GR) could sustain the yields of cluster bean–wheat in alkali water (RSC 8.5 meq L^{-1}, SAR 14.7). The other alternative to improve surface soil drainage is to adapt furrow irrigation and raised bed planting (FIRB) system (AICRP-SSW, 1972–2016). Its comparison with conventional planting for 3 years showed an overall improvement in yields of pearl-millet and wheat by 16% and 22%, respectively. In addition to few water-logging effects during monsoon, the advantage of such a system was low irrigation water requirements during *Rabi* season. Nevertheless, during the deficit rainfall years, more salt accumulated toward the centre of the beds, thus affecting the growth of the central row. Conservation tillage systems, which are now becoming popular with rice-wheat, have also been tried in alkali water irrigated soils (Malik et al., 2000). The practice of zero tillage in a soil irrigated with alkali water (EC 2.8 $dS\,m^{-1}$; RSC 8.5 meq L^{-1}; SAR 8.8) either with or without application of gypsum or FYM before rice decreased soil pH, SARe, sustained higher yields of wheat and saved irrigation water (Yaduvanshi and Sharma, 2008). As an alternative, a practice popular with the farmers of the alkali water irrigated areas is to spread the wheat seed at the time of last irrigation to rice which is later harvested by combines that leave stubble at the soil surface. Such a practice not only helps in timely seeding of wheat, the straw mulch improves thermal regimes and checks evaporation losses such that the crop matures with only two-three post-plant irrigations as compared with normal recommendation of four-five irrigations (Singh et al., 2010).

4. Conclusions and future directions

Ground waters which induce sodicity build-up in soils and thereby, diminish the benefits of irrigation exist in many parts of arid and semiarid regions. Sustained irrigations with these waters will possibly off-set impacts of future scarcity of water resources and thus help in maintaining food security of especially the developing nations. With concerted efforts at various research centers, state-of-the art technologies are now available for controlling the sodification impacts on crop productivity and fragility of environment. The recommended practices target the maintenance of soil structure vis-à-vis infiltration rates through chemical/bio-remediation means, conjunctive use/improved irrigation techniques, enhanced organic carbon/nutrient use efficiencies and other agronomic practices like proper crop selection, deep tillage etc. The integrated use of these component technologies is recommended for their economic viability under site-specific conditions. Issues that require further attention include the utility of resource conservation technologies, simulation models to perceive their long-term impacts based upon ion chemistry of irrigation waters for typical agro-ecosystems, role of deficit irrigation/micro-irrigation techniques, feasibilities for non-food but economically viable crops, etc.

Some of the selected technologies can now be transferred to stakeholders i.e. farmers developmental agencies and policy planners for their implementation. Taking clues from success stories on reclamation of naturally occurring sodic lands (Cook, 2014), similar impetus is desired for sustenance of agricultural productivity on soils irrigated with sodic/alkali waters. For achieving desired success and economic returns based on specific conditions and resource mobilization, future investments should be on comprehensive programs at the river basin or national level by taking into consideration a range of factors, such as water availability and quality, land-use options and strategy, and national strategies for climate change management and national water and food security priorities. Community mobilization and preparatory activities are essential for successful implementation of large-scale projects based on sound economic analysis. Initially, some pilot studies should provide insights into subsequent implementation of large-scale projects. In addition, consistent and independent monitoring and evaluation of large-scale projects is important to identify and address challenges in a timely and efficient manner. In addition to socio-economic benefits in terms of food security, the environmental benefits from these waters would help mitigate climate change impacts by enhancing soil carbon sequestration. This would contribute to the 2030 Sustainable Development Agenda by addressing SDG 13 on combating climate change and SDG 15 on reversing land degradation. Eradicating extreme poverty and meeting the SDGs without adequately addressing underperforming land and water resources is highly unlikely.

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