Journal of Agricultural Science; Vol. 7, No. 8; 2015
ISSN 1916-9752 E-ISSN 1916-9760
Published by Canadian Center of Science and Education

Impact of Climate Change on Salinity and Drainage of Irrigated Lands in Mexico

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Received: April 28, 2015 Accepted: June 2, 2015 Online Published: July 15, 2015

doi:10.5539/jas.v7n8p197 URL: http://dx.doi.org/10.5539/jas.v7n8p197

Abstract

About 10-40% of all irrigated lands in Mexico are affected by soil salinity at a high to moderate level, with 6 to 9% of irrigated lands having field drainage to control salinity. According to the existing climate change scenarios, a reduction of mean annual precipitation by 10 to 30% and a rise of mean annual air temperature by 2.3±1.0 °C are expected by the middle of the 21st century in the main irrigation regions in the center and northern parts of the country. These changes will reduce the availability of irrigation water by 30% compared to present levels. The objective of our study was to assess how the expected reduction in the availability of irrigation water could influence the salinity of irrigated lands and necessity for field drainage installation. Analysis of national data on the change of irrigated area affected by soil salinity during last years in Mexico and the experience of Aral Sea basin in the Central Asia with similar natural conditions and sufficiently detailed monitoring of the salinity of irrigated lands permitted to conclude that in case of less availability of irrigation water in Mexico the area affected by soil salinity will reach about 20 to 25% of irrigated lands, which means necessity not only to save irrigation water, but also further field drainage installation in large area.

Keywords: availability, irrigation water, area affected by salinity, Aral Sea basin experience, field drainage

1. Introduction

According to Cavazos et al. (2013) and Martinez-Austria and Patino-Gomez (2010), by the middle of the 21st century in the principle irrigated regions of Mexico, located in the central and northern arid parts of the country with arid and semiarid climate, the average annual air temperature is expected to increase by 2.3±1.0 °C, the annual potential evapotranspiration from the most irrigated agricultural lands is expected to increase by 10% and the annual precipitation to decline by 10 to 30% depending on location and scenario for increasing CO_2 concentration in the atmosphere. Thus, the availability of water will be reduced, leading to declines in agricultural productivity on irrigated lands. One of the problems related with the reduction of water availability is the increase in irrigated area affected by soil salinity and, as a result, the necessity for more agricultural drainage installation.

At present, the total irrigated area in Mexico is about 6.5×10^6 ha (growing from 4×10^6 ha since 1960 to 6.3×10^6 ha in 1998, and to 6.46×10^6 ha currently), of which 3.5×10^6 ha are contained in 85 irrigation districts, and 3×10^6 ha are contained within 39,492 relatively small irrigation units (CONAGUA, 2013). Mean annual values of air temperature in the principle irrigated regions vary between 16 and 28 °C, with annual precipitation between 10 to 70 cm, and annual potential evapotranspiration between 100 to 190 cm (CONAGUA, 2009). Corn and wheat are the primary food crops occupying roughly 20% of the total irrigated area of the country. The average annual gross irrigation depth (the quantity of water removed from nature) has not really changed over the past 20 years (115 cm), varying between 95 to 118 cm (CONAGUA, 2013). The principle source of irrigation is surface water from reservoirs located mostly in mountainous areas. More than 85% of the total irrigated areas use surface water. Around 90% of the total irrigated area is irrigated by furrows and border strips. The efficiency of irrigation water conduction in the networks of irrigation canals (i.e. the quantity of water coming to the irrigation plots as a fraction of water taken from reservoirs) has not changed notably over the last 25 years (0.62 to 0.64), with higher water loss from small canals. The efficiency of the networks of small canals is approximately 0.74, while in the networks of large canals it approaches 0.85. No significant improvement of this efficiency is expected in the coming years (CONAGUA, 2009; Chavez-Guillen, 2011).

The quality of surface waters in most cases is good for irrigation. The typical cation and anion content (cmol/L), electrical conductivity (*EC*, dS/m) and relative sodium content [*SAR*, $(cmol/L)^{1/2}$] are presented in Table 1.

Table 1. Cation and anion content of surface waters for irrigation (CONAGUA, 2009; De la Pena-De la Torre & Llerena-Villalpando, 2011)

Cation/Anion	**Content**	**Units**
Ca^{2+}	0.1-1	cmol/L
Na^{+}	0.1-0.5	cmol/L
Mg^{2+}	0.02-0.2	cmol/L
K^{+}	0.02-0.05	cmol/L
Cl^{-}	0.1-0.4	cmol/L
SO_4^{2-}	0.1-0.2	cmol/L
HCO_3^{-}	0.1-0.2	cmol/L
CO_3^{2-}	0-0.005	cmol/L
pH	6-8	
EC	0.002-0.004	dS/m
SAR	0.2-0.3	$(cmol/L)^{1/2}$

The soils are mainly Xerosols (or Calcisols: FAO, 2006), Rendzinas (Leptosols) and Kastanozems (INEGI, 2004; Krasilnikov et al., 2011). Soil depth usually exceeds 1.5 m, and all soils have good agricultural potential, high saturation by exchangeable bases and the presence of stable aggregates.

According to De la Pena (1996), 10-40% of all irrigated lands in Mexico have some degree of salinity or sodicity, including 20% in the Northwest region, 17% in the North Central region, 12% in the Northeast and Lerma-Balsas regions (Figure 1).

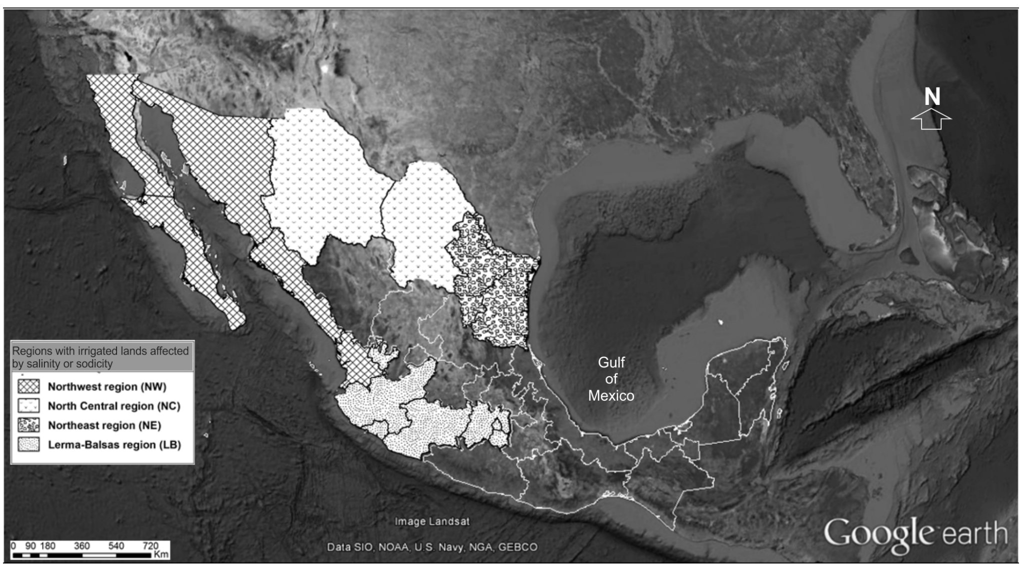

Figure 1. Main regions affected by salinity or sodicity at the beginning of the 21st century. NW is the Northwest region with 20%; NC is the North Central region with 17%; NE is the Northeast region with 12%; and LB is the Lerma-Balsas region with 12% (De la Pena, 1996)

Over the last 30 years, the area affected by soil salinity has increased by 5 to 10%, mainly in large irrigation districts, reaching 15 to 20% of all irrigated area and yielding salinity levels from high to moderate (Pulido-Madrigal et al., 2010; De la Pena-De la Torre & Llerena-Villalpando, 2011; Llerena-Villalpando, 2011).

Increased soil salinity is due to the gradual rise of the upper surface of saline ground waters to depths less than 1 to 1.5 m from a soil surface mainly due to infiltration from networks of irrigation canals (0.36 to 0.38 of the amount of water taken from reservoirs), deep water percolation through the soil profile in irrigated plots (about 0.1 to 0.3 of irrigation depth in the plots) and deficiency of groundwater removal from agricultural lands. Drainage, as open main drains, with spacing of about 500 to 1000 m and a depth of 2 to 3 m, as installed during the 1960-1970s in most irrigation districts, is not sufficient to remove ground water at present (Nikolskii et al.., 2011). The typical cation and anion content (cmol/L), electrical conductivity (*EC*, dS/m) and relative sodium content [*SAR*, $(\text{cmol/L})^{1/2}$] of groundwater in irrigated lands with salinity or sodicity problems are shown in Table 2.

Table 2. Cation and anion content of ground water in irrigation lands with salinity or sodicity problems (Llerena-Villalpando, 2011; Perez et al., 2013)

Cation/Anion	**Content**	**Units**
Ca^{2+}	0.1-1	cmol/L
Na^{+}	5-20	cmol/L
Mg^{2+}	0.02-0.5	cmol/L
K^{+}	0.2-2.5	cmol/L
Cl^{-}	1-10	cmol/L
SO_4^{2-}	1-7	cmol/L
HCO_3^{-}	1-10	cmol/L
CO_3^{2-}	1-10	cmol/L
pH	7.5-9.5	
EC	2-12	dS/m
SAR	10-30	$(\text{cmol/L})^{1/2}$

In order to accelerate the removal of groundwater and maintain a water table depth not less than 1.5 m, field subsurface pipe drainage with a depth to 1.7 m and spacing between 20 and 50 m have been installed over last 20 years in approximately 6×10^3 ha, which is only 6% to 9% of irrigated lands with high to moderate soil salinity (Palacios, 2013).

The objective of this study was to assess the potential impact of global climate change in the 21st century on the problem of salinity of irrigated lands and the necessity for installing field drainage.

2. Materials and Methods

Reduction of irrigation water availability leads to reduced irrigated area or reduced gross irrigation depth, which corresponds to the amount of water annually taken from reservoirs and related to a unit of irrigated area.

The mean annual quantity of water coming to reservoirs (in mm/year or cm/year) and available for irrigation (*AW*) can be estimated as total surface and subsurface runoff (*S*):

$$AW = S = Pr - ET \tag{1}$$

Where *Pr* and *ET* are precipitation and evapotranspiration (in water depth per year) in the watershed supplying a reservoir with water.

Equation (1) can be used to assess the relationship $\frac{AW_2}{AW_1}$ or $\frac{S_2}{S_1}$ corresponding to the change in mean annual availability of irrigation water in a reservoir at the middle of 21st century ($AW_2 = S_2$) in comparison with its beginning ($AW_1 = S_1$):

$$\frac{AW_2}{AW_1} = \frac{S_2}{S_1} = \frac{\Pr_2}{\Pr_1} \frac{\left(1 - \frac{ET_2}{\Pr_2}\right)}{\left(1 - \frac{ET_1}{\Pr_1}\right)} = \frac{\Pr_2}{\Pr_1} \frac{K_{S2}}{K_{S1}} \quad (2)$$

Where subindices 2 and 1 correspond to the middle and the beginning of 21st century, respectively; with $K_S = \frac{S}{\Pr} = 1 - \frac{ET}{\Pr}$.

In the main irrigation zones of Mexico, it is expected that during the middle of the 21st century $\frac{\Pr_2}{\Pr_1} = 0.7 - 0.9 \cong 0.8$ and $\frac{K_{S_2}}{K_{S_1}} = 0.82 - 0.92 \cong 0.87$ (Cavazos et al., 2013; Martinez-Austria & Patino-Gomez, 2010), depending on site and scenario for increasing CO_2 concentration in the atmosphere. Thus, water available for irrigation in 2050 (AW_2) as a fraction of availability at present (AW_1) will be equal to $\frac{AW_2}{AW_1} = 0.8 \times 0.87 = 0.7$. This corresponds to estimations made by Martinez-Austria and Patino-Gomez (2010) for arid and semiarid climatic zones of Mexico.

Taking into account a lack of information about water conduction efficiency in irrigation canals, soil salinity, hydrogeological conditions, chemical composition of irrigation and groundwater and water table depth in each irrigation district, it is practically impossible to model and predict future problems regarding salinity and drainage in Mexico depending on climate change. However, it is possible to explore the issue using the following two approaches:

1. Evaluate future change in the irrigated area affected by soil salinity, which needs field drainage, depending on assessed future change in recharge of groundwater over all irrigation districts in Mexico.

2. Use the experience of other countries with similar natural conditions and the presence of sufficiently detailed monitoring of the salinity of irrigated lands in case of declining availability of irrigation water.

The assessment of future change in recharge of groundwater, in general, can be made as follows:

$$\frac{g_2}{g_1} = \frac{F_2 + q_2}{F_1 + q_1} \cong \frac{F_1 + q_1 \frac{AW_2}{AW_1}}{F_1 + q_1} \quad (3)$$

where g is the recharge of groundwater in irrigated lands affected by salinity; F is the water loss by infiltration in networks of irrigation canals (as a fraction of water taken from reservoirs); q is deep water percolation through the soil profile in irrigated plots in general (as a fraction of depth of irrigation water applied in agricultural plots) and subindices 1 and 2 correspond to the present and future time (in 2050), respectively. As mentioned above, it is expected that $F_2 \cong F_1$. The value of q_2 can be estimated proportionally to provide the change in water availability, i.e.: $q_2 \cong q_1 \frac{AW_2}{AW_1}$ (CONAGUA, 2009; Chavez-Guillen, 2011).

As an example from another country, it might be possible to use irrigation development data from the Aral Sea Basin of Central Asia. This basin has climatic conditions similar to Mexico and similar water use efficiency in irrigation districts. As well, in this basin (Nikolski, 1996; Pankova et al., 1996; Dujovny, 2004; Aidarov, 2006; Tabiat, 2011):

- Due to the gradual increase in irrigated area since the 1950s, the water obtained from the two main rivers, the Amu-Darya and Syr-Darya, was exhausted by the end of the 1980s and the availability of water per hectare was reduced by 30%.
- Soil salinity issues began because of seepage from irrigation canals and deep water percolation through soil profiles in the irrigated plots. As a result, the water table, initially located deeper than 30-50m, rose close to the soil surface. During the 1950s about 50% of irrigated lands were affected by salinity.
- Due to agricultural field drainage installation, the irrigated area affected by salinity was reduced to 20% by the end of the 1980s.
- Since the beginning of the 1990s, with the cessation of irrigation and agricultural drainage system installation, the area affected by salinity increased.

By using data analyses of how irrigated area affected by soil salinity in the Aral Sea Basin had been changed over the last 30 years, when the availability of water was reduced by 30% and agricultural drainage had not been constructed, we can begin to understand what could happen in Mexico with salinity of irrigated lands, due to the reduced availability of irrigation water during the first half of the 21st century.

3. Results and Discussion

Using Equation (3), where F_1 and q_1 are dimensionless values and $F_1 = 0.37$, $q_1 = (0.1\text{-}0.3)0.63 \cong 0.13$ on average, and $\frac{AW_2}{AW_1} = 0.7$, we obtain $\frac{g_2}{g_1} = 0.92$. The value of 0.63 is the mean efficiency of irrigation water conduction in the networks of irrigation canals (0.62-0.64). The fraction $F_1 = 1 - 0.63 = 0.37$ is the water loss by infiltration in networks of irrigation canals.

This means that the recharge of groundwater in irrigation districts of Mexico will not change significantly and that the irrigated area affected by salinity will increase up to the middle of the 21st century (or in 35 years) by approximately 5 to10%, as observed during the last 30 years, which is at present reaching a value that varies between 15 to 20%. This will result in an affectation of 25% approximately of all irrigated area. This means that about 25% of the irrigated lands in 2050 will be in need of ameliorating soil salinity by using agricultural drainage installation and agrochemical and organic soil improvers.

In order to verify this conclusion, at least qualitatively, the experience of irrigation development and agricultural drainage application in the Aral Sea Basin over the last 60 years should be analyzed.

This basin has an arid to semiarid climate with a mean annual air temperature of 14 to 16 °C, a mean annual temperature during the vegetation growth season between 20 and 35 °C, a mean annual precipitation of 10 to 40 cm, and an annual potential evapotranspiration of 120 to140 cm (Balbakova, 2006). These conditions are similar to those from irrigation regions in Mexico. The irrigated area is 7×10^6 ha, which is slightly more than in Mexico. Almost all irrigated lands (96%) use surface water from large rivers, the Amu-Darya and Syr-Darya, with a total annual runoff of 100 km^3 approximating. Until 1950s, these rivers had delivered annually to the Aral Sea (a large inland lake, more exactly) almost 60 km^3 of freshwater.

From the 1920s to the 1950s, the irrigated area in this basin increased from 2.5 to 4.6×10^6 ha. Large irrigation systems covering hundreds of thousands of hectares were constructed mainly in the steppe and desert parts of the basin where the groundwater initially was deep (deeper than 30 to 50 m from the soil surface). Due to the construction of large irrigation systems and as a result insignificant lateral outflow of subsurface waters, seepage from irrigation canals and deep water percolation through the soil profile in the irrigated plots. The water table has been rising to the soil surface and the problem of soil salinity has appeared. During the 1950s, almost 50% of irrigated lands had been affected by salinity (Nikolski, 1996; Pankova & Aydarov, 1996, 2010, 2011, 2012; Aidarov, 2006; Tabiat, 2011; CAWATER, 2012).

From the 1950s to the end of the 1980s, the irrigated area in the Aral Sea Basin rose to 7×10^6 ha. More than 95% of agricultural lands are presently irrigated by furrows and border strips, as in Mexico. The quality of surface waters in general is good for irrigation. The typical cation and anion content (cmol/L), electrical conductivity (*EC*, dS/m) and relative sodium content [*SAR*, $(cmol/L)^{1/2}$] are: Ca^{2+} = 0.2-1.5; Na^+ = 0.5-2; Mg^{2+} = 0.05-0.4; K^+ = 0.04-0.2; Cl^- = 0.1-1; SO_4^{2-} = 0.1-1.5; HCO_3^- = 0.2-0.8; CO_3^{2-} = 0-0.01; pH = 7-8.5; EC = 0.1-8; SAR = 1-5 (Gapparov et al., 2011). The principle soils of irrigated lands are Haplic and Calcic Xerosols, Kastanozems and alluvial soils.

From the 1950s to 1980s, water conduction efficiency through irrigation canals rose from 0.38 to 0.60 for entire irrigation systems, from 0.60 to 0.84 for main canals and from 0.66 to 0.70 for small canals (Figure 2). Cotton was a primary crop occupying almost 70% of the total irrigated area. The average annual gross irrigation depth did not change during this period and was approximately 145 cm, which is 26% more than in Mexico.

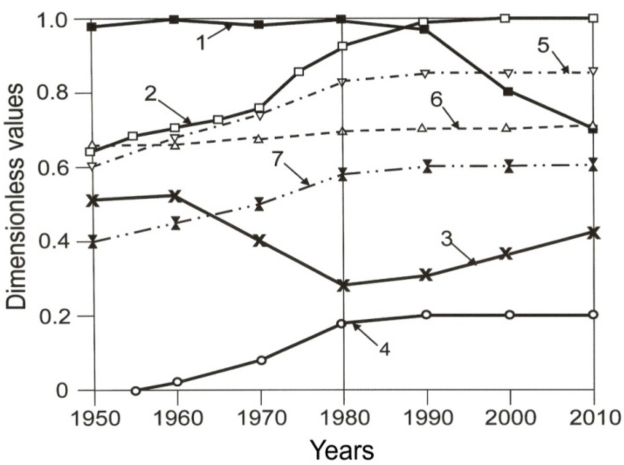

Figure 2. Change in the characteristics of irrigation and the area affected by soil salinity in the Aral Sea Basin during the 20th century and beginning of the 21st century

Note. 1 is the mean annual gross irrigation depth; 2 is the total irrigated area; 3 corresponds to the area affected by soil salinity; 4is the area with field drainage; 5, 6 and 7 are the water conduction efficiency in main canals, small canals and in the entire irrigation systems, respectively; 1 is expressed as a fraction of the maximal value that is equal to 145 cm/year; 2, 3 and 4 are expressed as fractions of the irrigated area.

Since the beginning of the 1950s to the end of the 1980s (Nikolski, 1996; Aidarov, 2006; Pankova & Aidarov, 2010, 2011, 2012):

1) Field drainage has been intensively constructed for soil salinity control, thus reducing the area with soil salinity from 50 to 28%.

2) Due to irrigated area expansion and large gross irrigation depths, entire river runoff was used during the 1980s, ceasing river discharge into the Aral Sea, causing sea level to fall about 1 m/year. Since the beginning of 2000, the Aral Sea has disappeared, turning its bottom into a salty desert.

Thus, since the 1990s, the irrigated area has not increased, cereal grains (mainly corn and wheat) using less water were introduced instead of cotton in 50% of the irrigated areas and the mean annual gross irrigation depth gradually declined about 30% during the 1980s to 2010, from 145 cm/year to 100 to 110 cm/year (Figure 2), closer to the mean annual gross irrigation depth in Mexico. The water conduction efficiency in the networks of irrigation canals from 1990 to 2010 rose up to 0.60 to 0.62 in the entire systems; 0.8 to 0.82 in main canals and 0.70 to 0.72 in small canals, similar to Mexican conditions (Nikolski, 1996; Dujovny, 2004; Aidarov, 2006; Tabiat, 2011).

Due to the deteriorating economic situation since the 1980s, the measures for improving water conduction efficiency in irrigation canals were not applied so widely as before; field drainage construction nearly stopped and, as a consequence, the area of salinity increased by 14%, from 26% in 1980 to 40% in 2010 (Nikolski, 1996; Dujovny, 2004; Aidarov, 2006; Tabiat, 2011; Pankova & Aidarov, 2012) (Figure 2). This happened because of the remaining intensity of groundwater recharge and continuous rise of water tables in lands without field drainage or with insufficient field drainage. The term *insufficient field drainage* corresponds to lands having only primary and partial (incomplete) field drainage, where the field drains had been installed only in some parts of irrigated areas affected by salinity or field drains themselves (with depths of 2 to 2.5 m) and spacing very wide (up to 150 to 250 m) (Nikolski, 1996; Dujovny, 2004). The intensity of groundwater recharge continued due to low efficiency of the canal network (0.60 to 0.62 in the entire system) and large deep water percolation in the irrigation plots (about 20 to 30% of net irrigation depth applied over the agricultural plots) as previously mentioned. Reduction in water availability has also led to a reduction in soil leaching, which also contributed to the expansion of the area affected by soil salinity (Aidarov, 2006; CAWATER, 2012; Pankova & Aidarov, 2012).

From these observations the irrigated area in Mexico affected by soil salinity would be expected to increase in the future due to the gradual rise of the water table, assuming there is less irrigation water available. Thus, Mexico will need to apply measures to save water and combat soil salinity by constructing field drainage in 20 to 25% of irrigated lands by 2050.

4. Conclusion

Based on the existing climate change scenarios, it is expected that the availability of irrigation water during the middle of the 21st century will be reduced by 30% compared to present times in the main irrigation regions of Mexico. This will increase the area affected by soil salinity by up to 20 to 25% of the total irrigated area, which demands not only the saving of irrigation water, but also initiating field drainage installation over large territories.

Acknowledgements

To Colegio de Postgraduados, Campus Montecillo and Campus Veracruz (LPI-8 Impacto y Mitigación del Cambio Climático and LPI-2 Agroecosistemas Sustentables) for financial support.

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