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Soil Salinisation in Irrigated Drylands of the Middle East and North Africa: Drivers, Extent, Crop Impacts and Reclamation Strategies

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Abstract

Salt-affected soils cover an estimated 8–12 million km² worldwide, and secondary salinisation caused by irrigation threatens a large share of the irrigated land on which food security in the Middle East and North Africa (MENA) depends. This review synthesises evidence on the processes, extent, agronomic impacts, economic costs and management of soil salinity, with emphasis on Egypt and the wider MENA region. The main drivers are high evaporative demand, shallow saline water tables resulting from inadequate drainage, the use of saline or reused drainage water for irrigation, seawater intrusion in coastal deltas and, increasingly, climate change. Salt reduces crop yields once soil salinity exceeds crop-specific thresholds, ranging from about 1 dS/m for beans to about 8 dS/m for barley, with globally estimated losses of the order of tens of billions of US dollars per year. Remote sensing and machine-learning approaches now allow salinity to be mapped and projected at continental scale, and suggest that salinity in many drylands will increase under climate change. Effective responses combine drainage, leaching with good-quality water, gypsum for sodic soils, precision irrigation, salt-tolerant crops and halophytes, and policies that link the reuse of drainage water to soil monitoring. The review argues that salinity management must be integrated with water-reuse and coastal-adaptation strategies, which in Egypt are expanding rapidly.

Keywords: *soil salinity; sodicity; irrigation; drainage; salt tolerance; Nile Delta; Mesopotamia; remote sensing; reclamation; halophytes*

1. Introduction

Irrigation made the civilisations of Mesopotamia and the Nile possible, and salinity is one of the oldest documented threats to it. Clay tablets from southern Mesopotamia record a shift from wheat to the more salt-tolerant barley and declining yields as fields became salty over centuries of irrigation. Today, the MENA region is the most water-scarce in the world, relies heavily on irrigated agriculture, increasingly reuses drainage and treated wastewater, and faces rising temperatures and sea levels. These conditions make salinisation one of the most significant, but least visible, forms of land degradation in the region.

Salt-affected soils lie across all climate zones and continents, with estimates of their global area ranging from about 8.3 to 11.7 million km² depending on the method used (Hassani et al., 2021). Of particular concern is secondary (human-induced) salinisation of irrigated land. Qadir et al. (2014) estimated that about 62 million hectares of irrigated land, roughly 20% of the world's irrigated area, are affected by salt-induced degradation, with annual economic losses of the order of US$27 billion.

This review covers (i) the processes of salinisation and sodification, (ii) the extent of the problem in MENA, with emphasis on Egypt, (iii) effects on crops and the economy, (iv) approaches to monitoring and prediction, and (v) management and reclamation options.

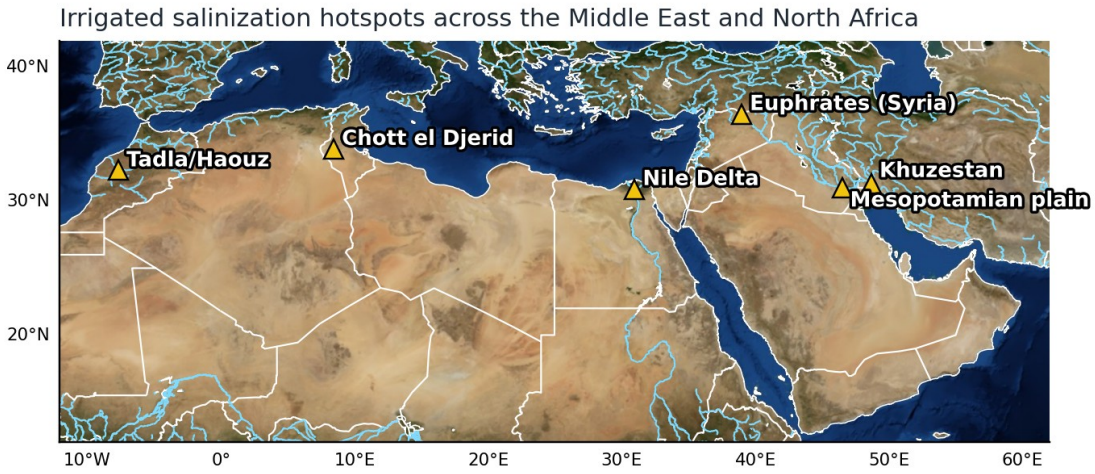


Figure 1. Irrigated salinisation hotspots in the MENA region discussed in this review, on a NASA Blue Marble satellite composite: the northern Nile Delta, the Mesopotamian plain of Iraq, Khuzestan in Iran, the Euphrates valley in Syria, the chott region of southern Tunisia and Morocco's Tadla and Haouz plains.

2. Processes of salinisation and sodification

Primary salinisation results from natural processes such as weathering of parent materials, deposition of marine aerosols, and accumulation of salts in closed basins and coastal lowlands. Secondary salinisation is caused by human activity, mainly irrigation. All irrigation water contains dissolved salts; under the high evaporative demand of drylands, water is removed by evapotranspiration while salts remain in the root zone. Unless enough water

percolates below the root zone to carry salts away (the leaching fraction), and unless drainage removes that water, salt accumulates.

The critical factor in many irrigated plains is a rising water table. Over-irrigation and canal seepage without adequate drainage raise the groundwater level; once a saline water table lies within one to two metres of the surface, capillary rise brings salts into the root zone, a process greatly accelerated by high temperatures. Waterlogging and salinisation therefore usually occur together.

Sodification is the accumulation of exchangeable sodium relative to calcium and magnesium. Sodic soils have poor structure: clays disperse, pores collapse, infiltration and aeration fall, and the surface crusts. Sodicity is commonly associated with irrigation using water with a high sodium adsorption ratio, including some drainage and treated wastewater. Its reclamation requires a source of calcium, typically gypsum, in addition to leaching.

Salinity is measured as the electrical conductivity of a saturated paste extract (ECe), expressed in decisiemens per metre (dS/m). Soils with ECe above 4 dS/m are conventionally classed as saline, and soils with an exchangeable sodium percentage above 15 as sodic.

3. Extent and drivers in the MENA region

3.1 Egypt

Egypt irrigates about 3.5–4 million hectares, almost entirely with Nile water. Before the High Aswan Dam, the annual flood leached salts from the valley and delta soils. Perennial irrigation, introduced progressively from the nineteenth century and made universal after the High Dam, removed that natural flushing and raised water tables. Egypt responded with one of the world's largest subsurface drainage programmes, covering several million feddans, which substantially improved soil conditions in much of the old lands.

Nonetheless, salinity remains a major constraint in the northern delta, where four processes coincide: low elevation and poor natural drainage; seawater intrusion into the Quaternary aquifer, aggravated by land subsidence and sea-level rise (see the companion review on the Nile Delta in this issue); the use of drainage water, often mixed with fresh water in "mixing stations", to irrigate tail-end lands; and the cultivation of rice, which is sometimes encouraged precisely to leach salts but consumes large volumes of water. In the newly reclaimed desert lands, salinity arises from saline groundwater, inadequate drainage in closed depressions and, in some areas, rising water tables caused by inefficient irrigation, as in the Siwa Oasis.

As Egypt expands the reuse of agricultural drainage water through large treatment plants such as Bahr El-Baqar and El-Hammam (see the review on wastewater reuse in this issue), the salt load applied to soils will increase, making routine soil-salinity monitoring essential.

3.2 Mesopotamia and the Levant

Iraq's Mesopotamian plain is one of the most severely salt-affected irrigated regions in the world. Poor drainage, flat topography, upstream dams on the Tigris and Euphrates that have reduced flows and raised river salinity, and the collapse of drainage infrastructure during decades of conflict have left large areas of formerly productive land abandoned or degraded. Salinity in the lower Euphrates and in the Shatt al-Arab has risen sharply during low-flow

years, with seawater intrusion reaching far upstream. In Syria, irrigation development in the Euphrates valley has also led to secondary salinisation where drainage was not provided.

3.3 Iran and the Maghreb

In Iran, salinisation affects irrigated plains of Khuzestan and the central plateau, aggravated by groundwater depletion and declining water quality. In the Maghreb, salinity is a constraint in the irrigated perimeters of Morocco's Tadla and Haouz plains, in southern Tunisian oases near the chotts, and in Algeria's high plateaux, often linked to the use of increasingly saline groundwater as aquifers are depleted.

3.4 Climate change

Higher temperatures increase evaporative demand and the salt concentration of soil water; lower and more variable rainfall reduces natural leaching; and sea-level rise drives seawater intrusion into coastal aquifers and deltas. Using machine-learning models trained on global soil-salinity observations, Hassani et al. (2021) projected changes in primary soil salinity across the world's drylands up to 2100 and identified a number of dryland regions as salinisation hotspots under climate change, while projecting decreases in others. Combined with the trends in irrigation and water reuse, the overall outlook for MENA is one of increasing pressure.

4. Effects on crops and the economy

Salt affects plants through osmotic stress, which reduces water uptake immediately, and through ion toxicity, primarily of sodium and chloride, which accumulates over time and damages leaves (Munns & Tester, 2008). For practical purposes, crop responses are well described by the threshold–slope model of Maas and Hoffman (1977): relative yield remains at 100% up to a threshold soil salinity and then declines linearly with a crop-specific slope. Figure 2 illustrates this relationship for crops important in MENA.

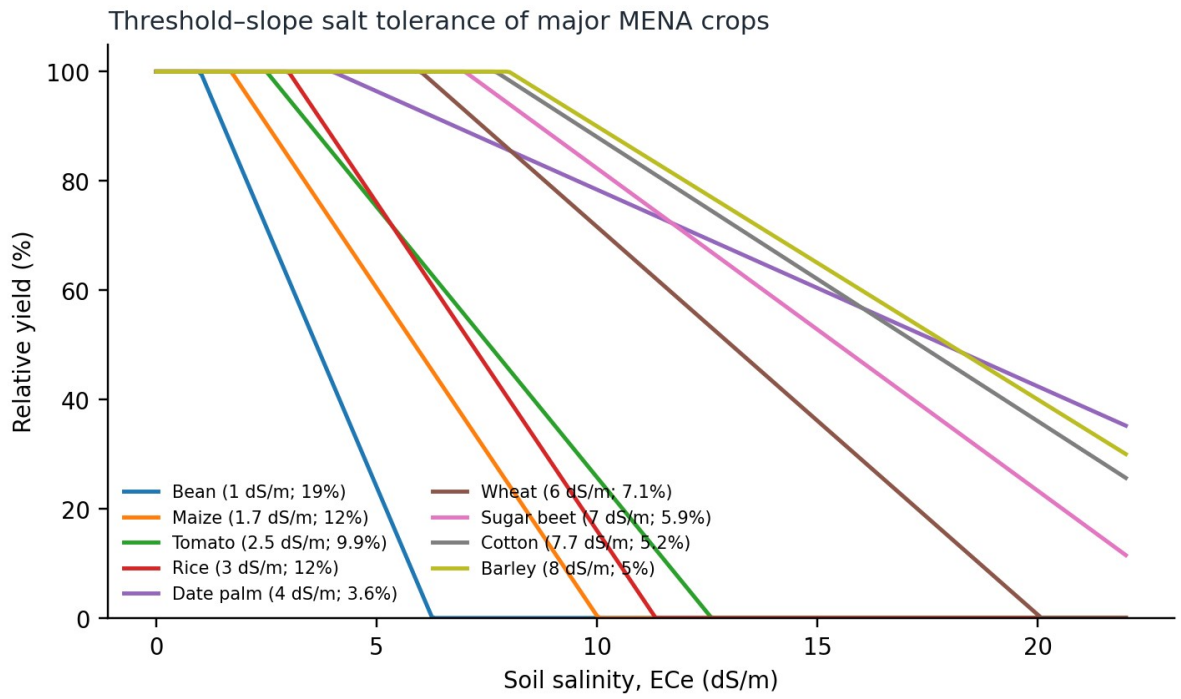


Figure 2. Threshold–slope salt tolerance of major MENA crops, after Maas and Hoffman (1977) and Maas (1990). The legend shows the threshold ECe and the percentage yield decline per dS/m above the threshold. Beans and maize are sensitive; wheat, sugar beet, cotton and barley are relatively tolerant. Date palm has a moderate threshold but a shallow slope, which makes it suited to marginal saline lands.

The figure shows why salinity forces changes in cropping patterns. A field with ECe of 6 dS/m loses roughly half of a bean crop and about a quarter of a maize crop, but no wheat or barley yield. Farmers on salinising land therefore shift to tolerant crops, as Mesopotamian farmers did four millennia ago. In Egypt's northern delta, cotton, sugar beet and barley are often favoured on saline soils, while sensitive vegetables and fruit trees retreat to better land.

The economic consequences are large but under-reported because yield losses accumulate gradually. The global estimate of US$27.3 billion per year in lost crop value from salt-induced land degradation (Qadir et al., 2014) does not include the costs of abandoned land, reduced land values, health effects of saline drinking water or damage to infrastructure from saline groundwater.

5. Monitoring and prediction

Traditional salinity surveys based on soil sampling and laboratory measurement are accurate but expensive and sparse. Electromagnetic induction sensors now allow rapid field mapping of apparent conductivity. At larger scales, remote sensing exploits the spectral signature of salt crusts, vegetation stress and thermal anomalies in Landsat, Sentinel-2 and MODIS data. Ivushkin et al. (2019) combined thermal infrared imagery with soil observations to map changes in global soil salinity between 1986 and 2016, estimating the total salt-affected area at about one billion hectares with a clear increasing trend over that period. Machine-learning models that integrate climate, terrain, groundwater and remote-sensing predictors (Hassani et al., 2021) are improving the ability to project future salinity.

For national programmes such as Egypt's, a practical monitoring system would combine a permanent network of soil and groundwater salinity stations in the drainage districts, regular electromagnetic surveys of high-risk areas, Sentinel-2-based vegetation indices to flag stress, and public reporting through the soil-information systems of the agricultural research institutes.

6. Management and reclamation

Table 1 summarises the main management options, which are complementary rather than alternatives.

Table 1. Management and reclamation options for salt-affected irrigated soils

Option	How it works	Best suited to	Key limitations
Subsurface drainage	Lowers water table; removes leached salts	Waterlogged, saline plains	Capital cost; disposal of saline effluent
Leaching with good-quality water	Moves salts below the root zone	Saline (non-sodic) soils with drainage	Requires extra water; ineffective without drainage
Gypsum and other calcium amendments	Replace exchangeable sodium	Sodic and saline-sodic soils	Cost; must be combined with leaching
Precision irrigation (drip, scheduling)	Maintains moisture, reduces deep percolation and water-table rise	High-value crops; new lands	Salt accumulates at wetting front; needs periodic leaching
Salt-tolerant crops and varieties	Maintain yields at higher salinity	Moderately saline land	Market and price constraints
Halophytes and biosaline agriculture	Productive use of highly saline land and water	Coastal and abandoned land	Limited markets; research stage for many species
Blending and cyclic use of drainage water	Uses saline water while managing salt balance	Regions with fresh and drainage water	Requires monitoring; long-term salt build-up
Soil organic matter and mulching	Improves structure; reduces evaporation	All soils	Slow effect

Three principles emerge from the literature. First, there is no reclamation without drainage: leaching only moves salt if the water carrying it can leave the root zone and the field. Second, the salt balance must be managed at the scale of the irrigation system and basin, not only the field; drainage water carries salts downstream, so reuse schemes must track salt loads. Third, biological and agronomic measures, such as tolerant varieties, halophytes and organic amendments, extend the productive life of saline land but do not remove salt.

Biotechnology offers new tools: marker-assisted breeding and genome editing for traits such as sodium exclusion and tissue tolerance have produced salt-tolerant wheat and rice lines (Munns & Tester, 2008), and plant growth-promoting microorganisms can improve plant performance under salinity in field trials. These approaches are promising but should complement, not replace, good water and drainage management.

7. Policy recommendations for Egypt and MENA

1. Link every drainage-water and treated-wastewater reuse scheme to a soil- and groundwater-salinity monitoring plan with published data.

2. Maintain and expand subsurface drainage in the northern delta and the reclaimed lands, financed in part by water-user associations.
3. Use crop-zoning that matches crop salt tolerance to soil and water salinity, supported by extension services and seed systems for tolerant varieties.
4. Develop biosaline value chains for halophytes, fodder shrubs and salt-tolerant aquaculture on abandoned coastal land.
5. Integrate salinity into coastal adaptation planning, since seawater intrusion in the delta will intensify with sea-level rise and subsidence.
6. Invest in national salinity mapping using remote sensing and machine learning, validated against field data.

8. Conclusions

Soil salinisation is a slow-onset but pervasive threat to irrigated agriculture in MENA, driven by inadequate drainage, saline water use, seawater intrusion and a hotter climate. Its costs are already large and are likely to increase as the region reuses more drainage and wastewater and as sea levels rise. The tools to manage salinity are well known; the main gaps are in monitoring, drainage maintenance, crop-system adaptation and the integration of salinity into water-reuse and coastal policies. Treating soil salinity as a core component of water security, rather than as a local agronomic problem, is essential for sustaining food production in the region.

Declarations

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