ENVIRONMENTAL SCIENCE

Rethinking Desalinated Water Quality and Agriculture

Damage to crops after irrigation with extremely pure water from the world's largest reverse-osmosis desalination plant reveals a need for revised treatment standards.

U. Yermiyahu,[1] A. Tal,[2*] A. Ben-Gal,[1] A. Bar-Tal,[3] J. Tarchitzky,[4] O. Lahav[5]

With almost half of humanity suffering insufficient access to potable water (*1*) and water scarcity for agriculture considered to be a global crisis (*2*), seawater desalination has emerged as a feasible solution. Between 1994 and 2004, world desalination capacity increased from 17.3 to 35.6 million m^3/day (*3*). At present, seawater desalination provides 1% of the world's drinking water (*4*).

Desalinized water is increasingly considered a source of water for agriculture as well. With 69% of the global water supply going to irrigation (*5*), present freshwater resources may soon be insufficient to meet the growing demand for food. A recent report (*6*) concludes that, although the costs of desalination remain prohibitively expensive for full use by irrigated agriculture, for high-value cash crops like greenhouse vegetables and flowers, its use may be economically feasible.

In a few countries, desalinized brackish water (whose price is typically a third of desalinated seawater) is already widely used by farmers. For instance, ~22% of water desalinated in Spain goes to agricultural irrigation (*6*). An Australian survey found that 53% of the population envisioned desalinated water usage for irrigation of vegetables as highly likely (*7*). In Israel, the promise of new, profitable crop options has inspired farmers to request allocations of relatively higher priced desalinized waters.

In December 2005, a new seawater desalination plant was opened in Ashkelon, on Israel's southern Mediterranean coast. Its 100,000,000 m^3/year production makes it the largest reverse-osmosis (RO) desalination facility presently in operation worldwide (*8*). It is also the world's first desalination facility to produce potable water from seawater at a price below \$0.55/m^3 (*9*). Although the Ashkelon facility was designed to provide water for human consumption, because of relatively modest population densities in southern Israel, a substantial percentage of the desalinated seawater was delivered to farmers. Recent evaluation of the effect of the plant's desalinized water on agriculture, however, produced some surprising, negative results. Changing these outcomes will require modifying future water management orientation and revision of desalination standards.

WATER-QUALITY PARAMETERS AFTER DESALINATION

Parameter	Water from Ashkelon desalination plant	Recommendation for domestic and agricultural usage
EC (dS/m)	0.2–0.3	<0.3
[Cl^-] (mg/liter)	15–20	<20
[Na^+] (mg/liter)	9–10	<20
[Ca^{2+}] (mg/liter)	40–46	32–48*
[Mg^{2+}] (mg/liter)	0	12–18
[SO_4^{2-}-S] (mg/liter)	20–25	>30
[B] (mg/liter)	0.2–0.3	0.2–0.3
Alkalinity (mg/liter as $CaCO_3$)	48–52	>80*
CCPP (mg/liter as $CaCO_3$)	0.7–1.0	3–10*
pH	8.0–8.2	<8.5*

**Value based on the new Israeli recommendations for desalinated water.*

Effects of Desalinization

When farmers receive desalinized water, the lowered salinity is perceived as a bonus, because the salts (especially Na^+ and Cl^-) damage soils, stunt plant growth, and harm the environment. Salinity in water is measured by its electrical conductivity (EC). The EC of water produced at the Ashkelon desalination plant is 0.2 to 0.3 dS/m, replacing water from a national distribution system with an EC higher by a factor of three to five.

Boron (B) concentration in seawater averages 4.5 mg/liter and is slightly higher in the Mediterranean Sea. At these concentrations, B does not constitute a threat to human health (*10*) but is highly toxic to many crops (*11*). Boron in neutral and acidic environments readily passes through the RO membranes. Without additional treatment, B in Mediterranean seawater after RO will reach 2 mg/liter, which is toxic for all but the most tolerant crops (*11*). Toxicity symptoms in orchards were observed after irrigation with effluent originating from desalinated municipal water in Eilat with ~1.2 mg/liter B produced. Concentrations of 2 mg/liter B in irrigation water also caused reductions in yields in peanuts and tomatoes in the Negev region (*12*, *13*).

Desalination not only separates the undesirable salts from the water, but also removes ions that are essential to plant growth. Desalinized water typically replaces irrigation water that previously provided basic nutrients like calcium (Ca^{2+}), magnesium (Mg^{2+}), and sulfate (SO_4^{2-}) at levels sufficient to preclude additional fertilization of these elements.

Although water from Israel's national water carrier typically contains dissolved Mg^{2+} levels of 20 to 25 mg/liter, water from the Ashkelon plant has no Mg^{2+}. After farmers used this water, Mg^{2+} deficiency symptoms appeared in crops, including tomatoes, basil, and flowers, and had to be remedied by fertilization. Current Israeli drinking water standards set a minimum Ca^{2+} level of 20 mg/liter. The postdesalination treatment in the Ashkelon plant uses sulfuric acid to dissolve calcite (limestone), resulting in Ca^{2+} concentration of 40 to 46 mg/liter. This is still lower

[1]Agricultural Research Organization, Gilat Research Center, Mobile Post Negev 2, 85280 Israel. [2]Mitrani Department of Desert Ecology, Blaustein Institutes of Desert Research, Ben-Gurion University of the Negev, Sede Boqer Campus, 84990 Israel. [3]Institute of Soil, Water, and Environmental Sciences, Agricultural Research Organization, The Volcani Center, Post Office Box 6, Bet Dagan, 50250 Israel. [4]Extension Service, Ministry of Agriculture, Post Office Box 25, Bet Dagan, 50250, Israel. [5]Faculty of Civil and Environmental Engineering, Technion, Haifa, 32000 Israel.

*Author for correspondence: E-mail alontal@bgu.ac.il

than the 45 to 60 mg/liter found in typical Israeli freshwaters. Other posttreatment processes, such as dissolving $CaCO_3$ with gaseous CO_2, planned in future local desalination plants, will produce a Ca^{2+} concentration of 32 mg/liter. Calcium is not just a nutrient required by plants; its interactions with other nutrients and with growth-limiting factors, including plant disease agents, makes changes in its content and relative concentration particularly problematic (*14*, *15*).

During the desalination process, SO_4^{2-} is removed completely. In the Ashkelon plant, sulfur is added coincidental to the use of sulfuric acid for dissolving calcite in the posttreatment stage. Ultimately, SO_4^{2-} concentrations settle at 20 to 25 mg S/liter, similar to freshwater levels. However, sulfur deficiency could emerge as a problem in other systems where alternative methods for Ca^{2+} enrichment are practiced. In intensive horticulture, the average recommended SO_4^{2-} concentration in irrigation water is 58 mg S/liter, whereas the minimum concentration recommended for tomatoes is much higher: 141 mg S/liter (*16*).

Desalinated irrigation water in Israel is often blended with other water sources. As a result, the quality of the final water actually delivered to farmers is unreliable. RO water is low in dissolved substances, with little buffering capacity relative to that of freshwater. Low buffering capacity increases risks of corrosion to metal distribution pipes. It also can have a profound impact on pH (and agricultural productivity) when the water is mixed with other sources.

Economic Factors

The cost of desalinating 1 m^3 of seawater at the Ashkelon plant was \$0.55 in 2006; in smaller facilities, the cost using the same technology could reach \$1/m^3. This cost includes B removal and addition of SO_4^{2-}, Ca^{2+}, and alkalinity by means of a calcite-dissolution posttreatment process. Additional enrichment of the desalinated water with Mg^{2+} would raise the price further.

According to new recommendations for desalinated water in Israel (*17*), dissolved Ca^{2+} concentrations should not be increased beyond 48 mg/liter. This Ca^{2+} ceiling is based on economic considerations, to minimize problems related to excess hardness for users in the industrial and municipal sectors. Although magnesium is not included in local water-quality criteria, it is welcome in desalinated water not only for agricultural but also human health objectives: The World Health Organization (WHO) recommends maintaining levels of about 20 to 30 mg/liter Ca^{2+} and 10 mg/liter Mg^{2+} in drinking water (*18*).

To meet agricultural needs, missing nutrients might be added to desalinized water in the form of fertilizers. Supplying Ca^{2+} and Mg^{2+} at 24 and 12 mg/liter, respectively, costs ~\$0.09/m^3. Direct chemical dosage at the desalination plant to increase Mg^{2+} is also a relatively expensive alternative (adding ~\$0.045/m^3 to the overall posttreatment cost when 10 mg/liter Mg^{2+} is supplied as $MgCl_2$). It also results in addition of unwanted counter anions. Dissolving dolomite rock [$CaMg(CO_3)_2$] to meet Ca^{2+}, Mg^{2+}, and alkalinity criteria would only cost between \$0.01 and \$0.02/m^3 above the cost of existing calcite dissolution (*17*). Yet there are several potential problems associated with dissolved dolomite rock, most notably the relatively slow dissolution kinetics. An alternative process, where excess Ca^{2+} ions (generated in the common H_2SO_4-based calcite dissolution posttreatment process) are replaced with Mg^{2+} ions originating from seawater (extracted using specific ion-exchange resins) has been suggested. This alternative will balance SO_4^{2-}, Ca^{2+}, Mg^{2+}, alkalinity, and pH composition in desalinated water at a cost-effective price (*19*).

If the minerals required for agriculture are not added at the desalination plant, farmers will need sophisticated, independent control systems in order to cope with the variable water quality. Such systems can involve farm-scale water storage facilities, water-quality monitoring equipment, and fertilizer-pumping facilities capable of reacting to input water quality. The on-farm capital costs of such equipment are likely to reach \$10,000 per agricultural unit, and associated operational costs will add additional expenses to the equation.

Conclusions

If desalinized water was destined for agricultural use alone, simple blending strategies would be the most probable economical strategy, providing stable and high water quality. Yet, in more typical cases, where water supplies both municipal and agricultural uses, economic efficiency requires a balancing of treatment costs, drinking-water quality, and agricultural benefits. On the basis of recent Israeli experience, we recommend expanding water-quality parameters in desalination facilities that may supply water to farmers (see table, p. 920). The proposed standards are based on lessons learned during the initial operation of the Ashkelon plant and water quality guidelines that were subsequently recommended (*20*), as well as the actual agronomic consequences for local farmers discussed above (*14*, *15*). The standards are relevant for dry land regions but will probably not be cost-effective for areas where agriculture does not rely heavily on irrigation.

These expanded criteria neither contradict nor compromise the quality of the water for human consumption as defined by WHO standards (*21*). On the contrary, increased buffering capacity and higher Ca^{2+} and Mg^{2+} concentrations make the water more chemically and biologically stable and provide a higher amount of essential elements, which contribute to public health. Desalination facilities built today will be in place for decades, making planning now essential for long-term increased economic prosperity and agricultural productivity.

References and Notes

1. P. H. Gleick, *The World's Water 2002–2003: The Biennial Report on Freshwater Resources* (Island Press, Washington, DC, 2002).
2. S. Postel, *Pillar of Sand: Can the Irrigation Miracle Last?* (World Watch, Washington, DC, 1999).
3. International Desalination Association (IDA), Worldwide Desalting Inventory (IDA Report no. 18, Wangnick Consulting, Gnarrenburg, Germany, 2004); www.wangnick.com.
4. European Commission, Environmental Technologies Action Plan, "Water desalination market acceleration" (EC, Brussels, 2006); http://ec.europa.eu/environment/etap/pdfs/watedesalination.pdf.
5. G. Meerganz von Medeazza, *Desalination* **169**, 287 (2004).
6. J. Martinez Beltran, S. Koo-Oshima, Eds., *Water Desalination for Agricultural Applications* (FAO, Rome, 2006).
7. S. Dolnicar, A. I. Schafer, presentation at the Proceedings of the AWWA (American Waste Water Association) Desalination Symposium, Honolulu, 7 to 9 May 2006; available at http://ro.uow.edu.au/commpapers/138 (2006).
8. A. Tal, *Science* **313**, 1081 (2006).
9. R. F. Service, *Science* **313**, 1088 (2006).
10. F. J. Murray, *Regul. Toxicol. Pharmacol.* **22**, 221 (1995).
11. R. O. Nable, G. S. Bañuelos, J. G. Paull, *Plant Soil* **193**, 181 (1997).
12. A. Ben-Gal, U. Shani, *Plant Soil* **247**, 211 (2002).
13. U. Yermiyahu, J. Zilberman, A. Ben-Gal, R. Keren, paper presented at the World Congress of Soil Science, Philadelphia, PA, 10 to 15 July 2006.
14. U. Yermiyahu *et al.*, "Irrigation of crops with desalinated water" [in Hebrew] (Report submitted to Chief Scientist, Israel Ministry of Agriculture and Rural Development, Tel-Aviv, Israel, 2007), 15 pp.
15. U. Yermiyahu, I. Shamai, R. Peleg, N. Dudai, D. Shtienberg, *Plant Pathol.* **55**, 544 (2006).
16. C. de Kreij, C. Sonneveld, M. G. Warmenhovn, N. Straver, *Guide Values for Nutrient Element Contents of Vegetables and Flowers Under Glass* (Naaldwijk, Aalsmeer, 3rd ed., Netherlands, 1992).
17. Joint Committee appointed by Israel Ministry of Agriculture and Rural Development and Israel Water Authority, "Quality of Desalinated Water for Agriculture" [Final report, in Hebrew] (Israel Government, Tel-Aviv, Israel, October 2007).
18. WHO, *Nutrients in Drinking Water* (Water Sanitation and Health Protection and the Human Environment, WHO, Geneva, 2005).
19. L. Birnhack, O. Lahav, *Water Res.* **41**, 3989 (2007).
20. O. Lahav, L. Birnhack, *Desalination* **207**, 286 (2007).
21. WHO, *Guidelines for Drinking-Water Quality* (WHO, Geneva, 3rd ed., 2004), chap. 12, annex 4.

10.1126/science.1146339