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Review

Rethinking the sustainability of Israel's irrigation practices in the Drylands[☆]

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ABSTRACT

Broad utilization of drip irrigation technologies in Israel has contributed to the 1600 percent increase in the value of produce grown by local farmers over the past sixty-five years. The recycling of 86% of Israeli sewage now provides 50% of the country's irrigation water and is the second, idiosyncratic component in Israel's strategy to overcome water scarcity and maintain agriculture in a dryland region. The sustainability of these two practices is evaluated in light of decades of experience and ongoing research by the local scientific community. The review confirms the dramatic advantages of drip irrigation over time, relative to flood, furrow and sprinkler irrigation and its significance as a central component in agricultural production, especially under arid conditions. In contrast, empirical findings increasingly report damage to soil and to crops from salinization caused by irrigation with effluents. To be environmentally and agriculturally sustainable over time, wastewater reuse programs must ensure extremely high quality treated effluents and ultimately seek the desalinization of recycled sewage.

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1. Introduction

Israel's efforts to combat desertification are often considered a unique, but largely successful story (Tal, 2006). The country is comprised almost entirely (93%) of drylands — meaning that most lands have an annual aridity index or precipitation to potential evapotranspiration ratio (P/PET) ranging between 0.05 and 0.65 (United Nations Environmental Management Group, 2011). According to conventional UN and international standards (Falkenmark, 1989, Falkenmark and Widstrand, 1992), the country suffers from acute water scarcity. Nonetheless, over the past sixty years it has seen a 1600 percent increase in the value of the produce grown by local farmers (Kislev and Tsaban, 2013). The astonishing surge in agricultural productivity has been part and parcel of the country's land management policies and its ambitious and innovative new irrigation strategies. The two central components of this strategy are: wide utilization of drip irrigation technologies and a complete commitment to "marginal" irrigation water sources, in particular recycled wastewater. Initial results have been hailed as extraordinarily impressive. Traditionally local water managers and scientists joined international experts from Australia (Derry, 2011), Brazil, (Marques et al., 2011) Europe (Raso, 2013) and the U.S (U.S. National Research Council, 2012) in endorsing wastewater reuse. Yet, a growing Israeli scientific consensus suggests that this "grand

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experiment" may be fundamentally unsustainable. In this review, Israel's experience in irrigation, especially in the country's agriculturally revived drylands is considered along with lessons learned and the long-term environmental and agronomic implications.

Irrigation in sundry forms has been utilized for 4000 years. For much of human history it was linked to the development of agricultural surpluses that allowed urban civilizations to emerge (Hillel, 1992). It did not take long for the vast majority of water utilized by humans on the planet to be directed to irrigation (McNeil, 2001) – today 69 percent of the estimated 3240 cubic kilometers (Gleick, 2000, UN, 2014). This is especially the case in the arid regions that cover 42% of the planet's surface. It is true that the United Nations reports that only 20% of cultivated agricultural lands on the planet utilize irrigation (UN -IFAD, 2015). But these technologies are increasingly synonymous with agronomic efficiency: irrigated fields and orchards already produce 40% of the world's crops (UN, 2014). According to one estimate, moving from rain-fed to irrigated agriculture, especially in water scarce regions, boosts crop yields by 300% (Howell, 2001). Any compelling vision of future international food security involves dramatic increases in irrigation globally.

This may be more difficult than many people imagine. According to UNESCO, water extraction on the planet has tripled over the past 50 years (UNESCO, 2012). As the scope of irrigated lands doubled between 1961 and 2000 (Ansfeld, 2010) physical limitations began to emerge. In many areas of the world, especially in dryland regions, irrigation relies primarily on groundwater sources (Siebert et al., 2010). Famiglietti (2014) estimates that over 50 percent of the water used to irrigate the world's crops is supplied from underground sources, with over two billion people directly dependent on groundwater as their primary water source, The estimated 8–10 million cubic kilometers of groundwater on the earth ostensibly constitute an inexhaustible resource, two thousand times the current annual withdrawal of surface water and groundwater combined (Van der Gun, 2012). But a closer look suggests otherwise.

Using geochemical, geologic, hydrological and geospatial data sets, Gleeson et al. (2015) recently estimated the total global supply of groundwater — with a focus on "modern" groundwater. Groundwater that is less than 50 years old accounts for less than 6 percent of all groundwater in earth's uppermost layers. Moreover, unfortunately, a high percentage of the world's aquifers are too salty to utilize, inaccessible, too costly to pump – or simply in the wrong place. Throughout the drylands, where groundwater is essential for irrigated agriculture, from northern China to the Middle East; from North Africa to the American Southwest, water tables are dropping, with most of the major aquifers in the world's arid and semi-arid regions exhibiting "rapid rates of depletion" (Famiglietti 2014). After many years of projections warning about hydrological doom and gloom, many wells really are starting to dry up (Brambila, 2014; Erdbrink, 2015).

With irrigated lands continuing to grow globally at a rate of 0.6%/year, water shortages in many parts of the world are becoming more acute and increasingly constitute the limiting factor for expanding agricultural production or diversifying to water intensive crops (AQUASTAT, 2010). In short, growing water scarcity poses a grave danger for future food security. And if there is any single compelling lesson from irrigated agriculture in days gone by, it is that inappropriate irrigation practices that systematically deliver salt to soils will eventually be disastrous for the environment (Hillel, 1992). One estimate suggests that at least 20% of irrigated lands on the planet suffer from significant soil salinization. In 1995 the estimated economic price of associated lost land productivity was 12 billion dollars/year (Ghassemi et al., 1995). By 2014 the figure had jumped to 27 billion (Qadir et al., 2014). Climate change in many regions threatens to exacerbate salinization phenomena (Várallyay, 2010; Ashour and Al-Najar, 2012).

It was this general context which led to the emergence of drip irrigation some fifty years ago in Israel, a technology that was soon hailed as a breakthrough in agricultural efficiency (Siegel, 2015). In the country's early years, furrow and gravity based flooding systems were normative. But to accommodate a burgeoning population in the arid and semi-arid conditions prevailing throughout most of the country, it was critical to increase agricultural production *without* increasing water demand. Supported by an intensive extension service, farmers in thousands of new agricultural operations soon switched to pressure based sprinklers and with time to micro-irrigation systems based on drippers, micro-sprinklers and point based emitters (Postal, 1997).

Drip systems delivered tiny amounts of water and fertilizer directly to the root zone of plants and trees in a steady flow. Drip irrigation immediately produced significantly "more crop for the drop" and offered farmers myriad operational and environmental benefits (Camp, 1998; Rawlins and Raats, 1975). Drip irrigation can prevent disease by reducing water contact with stems, leaves and fruits; it reduces weed growth by keeping field rows dry; labor required to run irrigation systems dramatically decreases due to computerized operations; and finally, drip irrigation can eliminate nonpoint source runoff pollution, especially in hilly terrain while dramatically reducing the discharge of nutrients and chemicals below the root zone of plants.

While Israeli agriculture was embracing drip irrigation, a parallel process took place: treated sewage effluents became the predominant source of water for the Israeli agriculture sector. Faced by chronic water shortages, during the 1950s, an increasing number of Israeli farmers began to reuse sewage in order to expand their lands under cultivation. Rather than try to discourage the phenomenon, officials at the Ministry of Health, preferred to regulate it. The Ministry set standards for reuse of effluents and along with the Ministry of Agriculture supported a 1956 national masterplan that envisioned utilization of 150 million cubic meters of treated wastewater by Israel's agricultural sector (Tal, 2002). Today, three times that amount is recycled.

While there was initial resistance among some farmers due to aesthetic and health concerns, soon effluent recycling became commonplace and the new norm for irrigation. A range of pathogenic microorganisms' ability to survive extended periods of time in soils is well documented and several studies confirm pathogens ability to penetrate internal plant tissues via the root (Gagliardi and Karns, 2002; Natvig et al., 2002) as well as translocate and survive in edible, aerial plant tissues (Guo et al., 2002; Bernstein et al., 2007). Nonetheless, when the first epidemiological study among Israeli farmers using recycling effluents was conducted in the 1970s, no associated health effects were identified (Fattal and Shuval, 1981). Subsequent research in Israel suggests that if sewage undergoes conventional secondary treatment and water quality parameters are met, even following prolonged periods of irrigation, concentrations of coliforms and fecal pollution in leachate from growing beds remain low and comparable to those in conventional irrigation sources. (Bernstein, 2011).

Slowly and steadily, Israel pursued a policy of maximum effluent utilization. By 2015 the country recycles 86% (400 million m^3) of the sewage which arrives at the country's treatment plants (Kireshner, 2015). This is a *far* greater commitment than other countries. For instance, Spain, the European leader in the field, reportedly recycles 17% of its sewage (Kershner, 2015); Australia fell short of a 30% 2015 target, with wastewater recycling rates between 18% and 20% (Whiteoak et al., 2012). But around the world, there is a growing inclination to see sewage as a critical irrigation source for agriculture and horticulture (Scott et al., 2004). For instance, in California substantial efforts are underway to identify appropriate floriculture and nursery crops, given the quality parameters available in recycled effluents (Grieve, 2011).

In practice, the Israel Water Authority reports that over half the irrigation water used by farmers in Israel today is recycled effluents, allowing for the cultivation of 130,000 ha of agricultural lands (Israel Water Authority, 2015). This is double the area that utilized effluents for irrigation a decade ago. Roughly half of Israel's wastewater is treated at a secondary level, typically utilizing activated sludge technology, while the other half undergoes tertiary treatment. The 15% of effluents which is not utilized by agriculture is released into streams, making many naturally intermittent streams flow perennially. In addition, farmers in the drylands frequently utilize “brackish” waters with high salinity levels.

2. Drip irrigation: sustainability concerns

With strong support from Israel's scientific community (Goldberg et al., 1971, Ben-Gal et al., 2004, Lazarovitch et al., 2007) drip irrigation technology evolved quickly after its initial introduction in the 1960s. Newer systems became more robust and durable, with emitters able to processes lower quality waters without clogging. Computer controls became more sophisticated: Fertilizers were introduced into the irrigation waters, saving labor and allowing for far greater precision in applications. Experience soon taught that it was preferable to rely on multiple, short, daily irrigation events or very low flow rate applications throughout the day, than single intensive pulses. (Pulse irrigation can drastically increase salt accumulation at the soil surface. A low flow rate enables longer irrigations and parallel operations of many plots so it is typically used in light soils with low water holding capacity.)

As the systems' sophistication increased, prices began to drop: Today, some 75 percent of Israeli irrigation involves drip systems. At the same time, low volume, “Family Drip Systems” for rural regions in developing countries were designed for as little as 500 dollars per unit. These can be run by gravity alone, without the need of pumps or electricity.

Some fifty years after Israel first started producing drip irrigation systems it is well to consider whether or not they truly offer extraordinary agronomic solutions and whether they indeed ameliorate the environmental impact of cultivation in dryland regions. The first question that should be asked is “whether drip systems are effective in irrigating the broad range of crops required for human nutrition?” The answer appears to be “yes”. Initial drip irrigation systems were focused on higher priced commodities: grape vineyards, greenhouse vegetables, almonds, etc. But more recently, drip systems have proven commercially viable with basic commodity crops from sugar cane and corn to potatoes and even rice (Panigrahi et al., 2015). Future strategies to ensure global food security will surely require more optimal utilization of farmlands around the world with more attention given to the import/export of produce and the role of virtual water in national water footprints (Orlowsky et al., 2014, Mekonnen and Hoekstra, 2014). But given the anticipated growth in global population, any scenario able to provide sufficient food worldwide for anticipated demand will require massive increases in basic crops in water scarce regions. Drip irrigation systems promise to play an even greater role.

Rice, a crop that was always associated with paddies and copious water supply, may actually be more effectively raised in the drylands with drip irrigation (Behera et al., 2014, Reddy et al., 2013). By moving to drip irrigation, farmers can rotate several crops, increasing their year round income. Drip irrigation reduces flooding, water use and nutrient runoff from submerged fields. It cuts labor costs. And drip irrigation also offers dramatic benefits in terms of climate change mitigation (Adekoya et al., 2014). Conventional production of rice produces roughly four times the greenhouse emissions of maize or wheat, making rice cultivation responsible for over 1% of global greenhouse gas emissions. Field trials at Netafim suggest that drip irrigation can cut methane and other greenhouse gas emissions from rice production by more than half (Udassin, 2014; Barak, 2015).

The durability of drip irrigation systems is another key parameter of sustainability. When Netafim began to develop drip irrigation, the lines and drippers in most of the systems lay on the soil surface. This enabled Israeli scientists to focus on solving many of the threshold engineering challenges: developing filtration systems to prevent the clogging of drippers, averting backwash and ensuring consistent discharges in the emitters across an entire irrigation line. There were also environmental problems that needed to be addressed. When irrigation waters were high in sodium or when conventionally treated effluents were used, soil infiltration became compromised and salinity buildup began (Dudley et al., 2008).

In areas where there is constant and reasonable precipitation, this is less of a problem. But in the drylands, where natural leaching does not take place, crop yields can soon suffer. In arid regions, farmers often rely on saline brackish waters, exacerbating the problem. This is especially true because the drip systems are intentionally designed to be precise and highly efficient, without the need to flush the entire soil volume. Indeed, Netafim, still the world's largest producer of drip irrigation systems, proudly claims that as much of 95% of the irrigation water is delivered to an area in the soil where it can be utilized by plants (Barak, 2015). That is important for water conservation. But it also means that salts accruing in a wetting pattern area around the plants or in the root zone itself do not get flushed out.

Subsurface irrigation systems were eventually developed to solve many of these environmental problems, especially for systems utilizing treated effluents. In these systems, soil can serve as a complementary biofilter to reduce contamination (Asgari and Corneli, 2015; Oron et al., 1999). Keeping wastewater underground adds an additional level of safety with effluents, preventing the likelihood of contact with produce or exposure among workers (Ben-Gal, 2015). At the theoretical level, subsurface irrigation certainly makes sense. Rather than releasing water (and salts) above ground, drippers release water precisely where it is needed, in the root zones, 20 cm underground. Subsurface systems dramatically reduce evaporation (Bidondo et al., 2012), weeds and help minimize soil salinization (Wichelns and Qadir, 2015) while frequently improving yields. (Badr et al., 2010, Hebbar et al., 2004).

For those who care about aesthetics, there is the added benefit of eliminating the unsightly pipes, lines and tubes which are fully “out of sight”. Installing sub-surface irrigation systems in existing orchards poses some challenges, but increasingly, fields and orchards in Israel are designed to include these systems. It is estimated that roughly half of the Israeli drip irrigation systems in use are sub-surface and they seem to be operational after more than a decade below the ground. That doesn't mean that farmers don't have apprehensions. In areas where there are burrowing rodents, sub-surface systems can be compromised. Extension agents express a common concern of farmers who are nervous when they cannot actually see the drippers and the water they are providing, warning: “by the time you find out that a subsurface emitter is clogged – the tree is already dead” (Shemer, 2015). But presumably, proper maintenance along with monitoring of pressures and flowrates can identify most of the problems.

Given the proven increase in yields and precipitous drop in water consumption there are compelling reasons to strongly promote adoption of drip systems in dryland regions which are not yet fully used for agricultural production. Because so many developing countries contain extensive dryland regions, the salient challenge for many farmers is the ability to cobble together the associated start-up costs. These costs are particularly high if state-of-the-art subsurface irrigation systems are to be utilized. Because roots of some trees are only deep enough for subsurface systems after two to three years, there are cases where farmers need to install two systems: a sub-surface system, 30 cm deep, is laid down after which a surface irrigation system is used for the initial years which can be removed when the root zones are sufficiently developed below. Most crops with root systems are able to utilize subsurface system almost from the time they are planted.

This does not mean that drip irrigation is a panacea. Its application requires thoughtfulness and precaution. Not only do the laterals of drip systems deliver water, but also fertilizers and other chemicals. This improved efficiency has proven to be one of the greatest potential benefits of drip irrigation. In most countries, these inputs are hardly regulated and when used excessively can cause contamination. Inappropriate adoption can also be wasteful. In the past, overzealous sales agents or extension agents would urge famers to place as many as five emitters along a one meter line. Depending on the discharge rates of the dripper, today optimal emitter spacing can be a fifth of that, depending on crop, soil type and water requirements (Lazarovitch et al., 2009; Hinnell et al., 2010).

There has been significant progress in determining overall irrigation water requirements based on potential crop evapotranspiration, effective precipitation and the projected change in soil moisture (FAO, 2015 Frenken and Gillet, 2012). Nonetheless, despite the marked improvement in yields and water delivery efficiency there are still potentially copious amounts of water released by drip irrigation systems that are not utilized by crops. Even the most sophisticated, computer regulated, sub-surface drip irrigation systems typically suffer from inefficiency, with significant amounts of water not utilized by plants. These losses are a result of two fundamental gaps in knowledge:

1) The precise amount of water required by crops to maximize yields, particularly given the spatial variability of conditions in a field; and
2) The optimal timing of water release, given the variability in diurnal and seasonal climatic conditions.

In other words, today's drip systems do a superb job of delivering an extraordinarily high percentage of water to the root zones of plants. But they cannot tell farmers how much water the plant actually needs. In a field with undulated topography, by definition water release should not be uniform. To overcome these uncertainties, farmers commonly rely on a conservative, excess-irrigation strategy. In other words, they overcompensate. While this may ensure that all the crop needs are met, fertilizers and agrochemicals are wasted, released on the surface or left percolating into groundwater. Over time, this will exacerbate water quality trends and further compromise available water resources. Reducing this excess supply of water, therefore, constitutes a critical challenge.

This fundamental problem led to development of a new concept called: “Irrigation on the Demand”, an innovation led by Israeli scientist Uri Shani. Sensors are literally built into the dripper: the emitter is covered by a cloth (geotextile) and roots are encouraged to grow inside a soil moisture sensor (tensiometer) itself, making it possible to ascertain the precise conditions between the soil and the root zones and the actual needs of individual plants, with water allocated accordingly (Dabach et al., 2015). When data are collected, water can be allocated optimally throughout a field. It then becomes possible to trigger irrigation events according to the precise conditions at the soil root interface and in so doing provide only the actual needs of crops. This removes the uncertainty in deciding how much to irrigate, assuming that the irrigation unit is uniform or allowing for a reasonable average of actual conditions (Ben-Gal, 2015).

Such systems are no longer “science fiction” and pilot systems have been shown to work. But the more sophisticated equipment raises startup costs even more. Whether “Irrigation on Demand” sensors can be produced at cost-effective levels remains to be seen. As water prices increase and the new technology's production costs drop, it may soon become the new “state-of-the-art”.

It has been claimed that there may be situations where adoption of efficient irrigation technologies reduces valuable return flows and limits aquifer recharge. Accordingly, drip irrigation's widespread utilization might actually increase water depletion (Warda and Pulido-Velazquez, 2008). This argument, however, is based on site-specific conditions such as those in the American southwest which are not relevant for most dryland settings like the hydrological dynamics prevailing in Israel. Here irrigation water comes from recycled wastewater or deep “fossil-water” aquifers which typically are not immediately affected by rainfall and leaching. Such concerns also do not take into account the rapid expansion of desalinated water supplies which dramatically changes wastewater reuse dynamics (Lahav et al., 2010). Empirically, since introducing drip irrigation, Israeli agriculture has reduced the amount of freshwater that it uses by 60% (Siegel, 2015). In short, while drip irrigation systems' efficiency can still be improved, in a world increasingly characterized by water scarcity, they constitute a critical component in a sustainable strategy for global food security.

3. Wastewater reuse: sustainability concerns

The second component of Israel's strategy for overcoming chronic water shortages involves effluent recycling. Reuse of treated sewage can substantially expand water resources but is not without environmental ramifications. Sewage contains plant-damaging substances such as Na, Cl, bicarbonate and heavy metals as well as human pathogenic bacteria which pose ongoing public health and agronomic challenges (Bernstein, 2011). This became apparent immediately in the 1980s. For instance, Boron is a critical element for plants. Indeed, boron deficiency is not uncommon and is associated with inhibition of cell expansion and fertility, causing reduction in yields worldwide. At the same time, when plants are exposed to excessively high levels of boron (either in water or in soil) it can be toxic, causing necrotic lesions and damaging leaf development. It became clear that Israeli farmers utilizing recycled wastewater were paying a price for the high concentrations of boron in the treated effluents, as conventional sewage treatment processes could not effectively remove it. The good news is that source reduction proved to be relatively trivial. Boron is a common component in detergents. By the late 1990s Israeli regulations were enacted, proscribing the inclusion of boron in detergents. The results were immediate, essentially eliminating its presence in effluents entirely (Inbar, 2007).

Initial concerns associated with recycling sewage involved micro-organisms. Beyond affecting farmers through direct contact, pathogens can leave consumers exposed to produce with a range of harmful bacteria (Rai and Tripathi, 2007, Tiimub et al., 2012). Over the years, upgraded Israeli wastewater treatment levels largely eliminated this hazard. Moreover, there was improved compliance with the Ministry of Health's effluent irrigation standards, which steadily stipulated increasingly stringent water quality standards for irrigating different crop types. Other “micro-contaminants” such as pharmaceutical residues, however, are less easily removed and have become the focus of increasing concern. Hebrew University's Benny Chefetz's laboratory has identified concentrations of pharmaceutical compounds such as lamotrigine (an anticonvulsant drug) in crops irrigated with secondary treated wastewater that cross the *threshold of toxicological concern* level for a child (25 kg) that consumes half a carrot a day (60 g carrot/day) (Malchi et al., 2014). Consumption of sweet potato leaves and carrot leaves by a child (25 kg) would also surpass the TTC level for epoxy-carbamazepine (an epilepsy drug) at 90 g leaves/day and 25 g leaves/day, respectively. Other studies have identified considerable concentrations of antibiotics (e.g., sulfamethoxazole – SMX) in a water table region, where monitoring wells were placed to assess the long-term impact of waste-water irrigation (Avisar, Lester et al., 2009). Scientists have also raised concerns about the public health implications of systematic distribution of endocrine disrupting chemicals and other biologically active micro-contaminants (Graber and Gerstl, 2011). Yet, given their di-minimis presence in water relative to other routes of human exposures, these “contaminants of emerging concern” are probably of less concern than the oldest water pollutant of them all: salinity.

Salts, almost without exception are not removed during sewage treatment from wastewater streams. Wastewater by definition has higher salinity relative to its contributing background sources (Lahav et al., 2010). Historically, additional sodium concentrations following wastewater treatment ranged between 40 and 70 mg/l (Pettygrove and Asano, 1985; Tchobanoglous et al., 2003) although there have been reports that the increase is as high as 200–250 mg/l (Friedman et al., 2007).

At the same time, treated effluents may have lower salinity than alternative fresh water sources. For example: wastewater in Israel that is derived today from desalinated sea water can have far lower salt levels than fresh water removed from Lake Kinneret (the Sea of Galilee), the country's national reservoir, that typically contains 250 mg Cl concentrations (Cohen et al., 2014; Kfir et al., 2012). Nonetheless, the salt composition (as opposed to the extent of salinity) can be more problematic in recycled water as it is heavy in sodium and chloride while much of the brackish groundwater is comprised of less problematic ions (Ben-Gal, 2015).

The “Shafdan” sewage treatment plant, Israel's largest and most renowned, achieves consistently impressive performance by injecting tertiary-treated effluents into a sandy aquifer, facilitating their dilution. But it ultimately has no real process for reducing effluent salinity. Accordingly, as recycled wastewater increasingly became integrated into irrigation strategies, the environmental impacts associated with wastewater recycling became impossible to ignore. Even when pathogens are removed by upgrading sewage treatment, given the seasonal demand in Israel's Mediterranean climate, in many locations in Israel wastewater storage contributed to evaporation of water and higher salinity levels (Ben-Hur, 2006).

Over ten years ago, agricultural engineering professor and past national Water Commissioner, Dan Zaslavsky began to challenge the wisdom of recycling effluents given the steady deterioration he observed in the cultivated soils. Zaslavsky argued that over time, using wastewater for irrigation would lead to the accumulation of sodium compounds in soils. This serves to catalyze ion exchange among clay fractions in the soil, reducing fertility irreversibly (Zaslavsky et al., 2004).

A review by Israeli government researcher, Levy (2011) characterized the likely risks to the structure and stability of soils and their hydraulic properties associated with wastewater reuse: Higher levels of dissolved organic matter, suspended solids, sodium adsorption ratio (SAR), and salinity in the treated sewage can cause irreversible damage to soils. In his laboratory studies, specimen clays exhibited enhanced clay swelling and dispersion. This poses a risk of increased clay depletion from the upper soil layer, contributing to deterioration in aggregate soil stability. The result is decreased hydraulic conductivity and increased susceptibility to seal formation, runoff, and soil erosion.

Moreover, the plants themselves suffer from the effluents. In that sense, the risks posed by wastewater recycling are not entirely different than those posed by extended use of brackish groundwater which contains high salt concentrations. It is true that when many crops face the “stress” associated with high salinity levels, the result is production of sugars, creating exceptionally sweet cherry tomatoes or high quality olive oil. But other crops perform poorly when irrigated with waters containing highly salinity levels due to the resulting decrease in osmotic pressure (Ben-Gal et al., 2009a,b). This reduces the ability of the roots to extract water which in turn harms photosynthesis and transpiration in plants.

While chloride is required in very small quantities for photosynthesis and enzymatic reactions, sodium, the other component of salt, makes little if any contribution to plant health or yields. Even modest quantities can be toxic to plants and cause damage to soil structure, making it unproductive for agriculture. Indeed, conventional fresh water used in irrigation can contain sodium at levels two orders of magnitude higher than plants need to develop.

Signs of salinity damage from long-term effluent usage in Israel are everywhere. A study in Israel compared yields in orchards that had been utilizing effluents via drip irrigation for ten years: avocado and citrus yields were 20–30 percent lower than trees in the same orchards that had been using freshwater. Soil damage from wastewater tends to be concentrated in the upper soil layers (Assouline et al., 2015). But again, the plants themselves are affected. Another recent analysis shows that as wastewater reuse in Israel has increased over the last 20 years, so has sodium concentrations in soil and crops (Raveh and Ben-Gal, 2015).

Writing in 2011, Hebrew University irrigation scientist Uzi Kafkafi was already skeptical about the long-term sustainability of waste water reuse: *“High concentrations of chloride in the irrigation water or the soil are toxic to plants and may affect plant function and reduce productivity. Despite the voluminous literature on saline soils, it is difficult to answer the question: how long can water containing high chloride levels safely be used for agricultural purposes under given conditions before damage to soil and plants is observed. The answer to this question must take into consideration soil clay content and clay type, irrigation methods, evaporation conditions, and plant type and composition. The chloride anion is very stable and will not leave the soil system unless it is leached by an excess of good quality irrigation water, or removed from the soil by exported vegetative plant parts. Continuous long-term utilization of recycled water for irrigation may therefore increase the chloride content of the soil, and without proper leaching it will deteriorate.”* (Kafkafi, 2011, 139).

Traditionally, Israeli farmers have indeed overcome salinity problems by applying high irrigation rates to crops, leaching excess salts out of the root zone to protect plant health. In an arid region, farmers may use an additional 30 to 40 percent more water simply to manage salt levels in cultivated soils. But this can contaminate underlying aquifers. Recent experience in large olive tree plantations planted in Israel's Negev desert constitutes a cautionary tale.

The olive trees relied on water from relatively saline, underlying aquifers. The salts were managed by applying water for leaching. With the steady application of high salinity irrigation water and evaporation, salts began to accumulate. During the rare winter storm of 30 mm or more, salts accumulating on the surface could dissolve and be delivered directly into the most active areas of the roots in the soil. This somewhat idiosyncratic phenomenon is a function of hot dry summers when a high demand for irrigation is combined with low quality irrigation water and 20–30 mm rain event's effect on an evergreen perennial crop. Facing chronically high evapotranspiration levels, the trees took in large quantities of the salty water and immediately showed signs of distress (Shemer, 2015). Similar effects in citrus irrigated by effluents have been observed in arid regions within Israel as well (Ben-Gal, 2015). Recently, when olive oil prices dropped, the cost of such massive leaching became prohibitive and the farmers reduced the magnitude of irrigation dramatically. It did not take long before tree production began to suffer due to exposure to the salts.

This has led Alon Ben-Gal, a leading expert in dryland irrigation from Israel's Agricultural Research Organization to make some very clear conclusions: If a farmer lives in a climate where there is sufficient rainfall to naturally drain salts, then one can use marginal water resources to supplement fresh water and still operate with success. But there are frequently cases, especially in arid regions when farmers select a strategy of “deficit irrigation” when less than optimal levels of water are provided (Fereres and Soriano, 2007). This may be due to economic considerations when the cost of additional water is greater than the benefit of expected additional yields. In other cases, stress can improve the quality of agricultural products so that deficit irrigation in the short-run leads to optimized returns when considering yield quality and quantity together. And there are times when irrigation is reduced because water is simply unavailable. Experience in Israel and internationally, however, suggests that in arid and semi-arid regions where there is *not* sufficient precipitation to flush the salts out, deficit irrigation ultimately will not work: low quality (high salt) water must be accompanied by excess applications (Ben-Gal, 2015). This makes leaching imperative but economically and environmentally problematic.

In a recent article in *Agricultural Water Management* he writes along with his colleague Raveh and Ben-Gal (2015): *“Israel's policy of lower prices for salty water and absolute utilization of wastewater for irrigation without addressing salinity may have been reckless. Leaching, necessary in agricultural water management when using water containing salts, is of itself unsustainable, as the water leaving the root zone contains not only the salts that must be leached, but also various other contaminants, contained in the water, added in agricultural processes (fertilizers, pesticides and herbicides), or mobilized from soil and subsoil.”*

Other leading Israeli researchers are also speaking up about the issue. In a recent article in *Water Resources Research* Agricultural Research Organization scientist Shmuel Assouline and three colleagues went public with what most irrigation experts in Israel had been saying discreetly for some time: *“Mounting evidence suggests that long-term use of treated effluent may affect various aspects of soil hydrology, due to increased load of salts, organic matter, surfactants, nutrients, and subsequent interactions with the soil minerals … the potential ramifications on soil function and productivity, and on public health, necessitate significant investment in research and monitoring of such irrigated systems to ensure their long-term sustainability.”* (Assouline et al., 2015). Based on their research, Assouline's team agrees with Raveh and Ben-Gal, recommending that desalinated water be considered as a viable water source for irrigation even as it is “strongly linked with local conditions, technological improvements, and the energy nexus.”

4. Lessons for the drylands from Israel's irrigation experience

Public policies continue to try to address the problems presented by wastewater reuse, with sundry regulatory efforts directed at improving the quality of Israel's effluents. Part of the solution involves reduction of salinity “at the source”. For instance, Israel's Ministry of Environment promulgated regulations in 1994 which established new design standards for slaughter houses. According to Jewish tradition, the kosher slaughtering of animals requires intensive utilization of salts. Local Israeli slaughterhouses historically release effluents with extremely high salt concentrations. Environmental regulations now require discharge of these high salinity wastes into a separate piping system (for ultimate disposal in the sea) as well as limits on ion exchanges. This eliminates a major source of salinity in recycled wastewater.

During the past decade, general salinity levels in Israeli municipal water supply have dropped considerably as they are increasingly based on the 600 million cubic meters (600 billion liters) of high quality water that new sea desalination plants contribute to the national water system. Compared to the salt levels in the brackish waters which have been a traditional source of irrigation for many dryland areas, treated wastewater that complies with Israel's increasingly stringent “tertiary” standards is considered “almost as good as freshwater”. One recent survey indicates that water in reservoirs storing effluents contains low to moderate levels of sodium in over 50% of samples – with overall salinity in effluents dropping by 9% during the two years of the study (Kfir et al., 2012). Nonetheless, due to evaporative processes, by definition, effluents will continue to contain higher levels of salts than fresh water, as salinity steadily increases during the different stages of wastewater treatment, storage and reuse.

Consequently, the amount of water required for leaching out residual salts will remain high. For instance, water quantity–salinity interaction was assessed in bell peppers grown with different saline irrigation schemes in green houses in Israel's hyper-arid southern Arava. The research team found that in order to leach out the soils sufficiently to maintain high pepper yields, irrigation rates needed to increase by more than 50% (Ben-Gal et al., 2009b). A parallel research team concluded that: “The amount of leaching required when irrigating with saline water may make such a practices highly unsustainable” (Ben-Gal et al., 2008).

The trouble is that as salinity increases, the effective soil volume (the soil volume providing 90% of the water uptake by plant roots) diminishes. Even drip irrigation systems utilizing *freshwater* with modest levels of salinity may still have reduced efficiency and will not maximize yields. Research supports this position: For instance, Avner Silber and his colleagues at the Agricultural Research Organization's *Institute of Soil Water and Environmental Sciences* compared conventional irrigation water with desalinated water. The results clearly demonstrated that removal of the salts via desalination in irrigation water prior to delivery to banana crops is a preferable strategy. The treated water obviates salt leaching and the associated waste, reduces salinization of underlying water resources while at the same time significantly improves yields and fruit quality (Silber et al., 2015).

As a result of a litany of such studies, a growing number of Israelis researchers have begun to advocate desalination of wastewater prior to irrigation, as a more sustainable strategy than the conventional “leaching” of salts from root zones which remains prevalent today (Raveh and Ben-Gal, 2015; Assouline et al., 2015). A systematic, full life cycle, economic analysis of the issue should of course consider the long-term costs associated with loss of soil fertility and additional drainage expenses. Also, germane are the subsidies associated with transporting higher quality water to fields in dryland regions.

The immediate question, however, is: “Can farmers afford to pay for such high quality water?” Tsion Shemer, director of the regional extension R&D Center in the Negev Highlands argues that it is patently absurd to expect farmers to grow conventional crops and pay the desalination shadow price of 65 cents/cubic meter to grow onions, carrots, or potatoes. Tomatoes and peppers might be possible, but even their economic calculous is tenuous. Irrigated orchards in the drylands will not be able to compete with groves that enjoy rain-fed conditions. Most crops are no different. Israel used to be a major exporter of tomatoes, onions, peppers and flowers. The high cost of irrigation waters along with transport and relatively high labor expenses has made it increasingly difficult for Israeli farmers to compete on world markets. Today, these crops are almost exclusively raised for local consumption (Shemer, 2015).

5. Conclusions

The final results of the experiment are surely not in yet, but based on Israel's experience, certain implications for other water scarce countries are already clear: drip irrigation should be a central component in any agricultural production strategy. It is simply irresponsible to continue to use flood, furrow and sprinkler irrigation when drip irrigation systems offer such clear agronomic and environmental advantages. At the same time, if a country with croplands in arid or semi-arid regions wishes to sustain irrigated agriculture over the long-term, it must ensure extremely high quality treated wastewater and ultimately seek to utilize desalinated effluents. Otherwise, sooner or later, massive utilization of effluents will lead to salinization and eventually force such a transition.

Farmers using desalinated water frequently will not be able to compete on world markets for most crops. Countries will need to consider subsidizing water produced by such an energy-intensive process (UNESCO, 2014).

In summary, the Israeli experience suggests that drip irrigation significantly contributes to high yield/high water efficiency agriculture, especially under dryland conditions. Yet, the sustainability of irrigated agriculture, especially in arid regions ultimately depends on the quality of irrigation water. Recycling sewage intuitively is a highly compelling notion. But empirical results consistently confirm that it is much more problematic than its advocates may have realized. Extensive wastewater reuse should be seen as a temporary exigency and a transition stage in a country's agricultural evolution. The well-documented, deleterious environmental and agricultural impacts are sufficiently negative to send a clear message that effluent recycling in the drylands is fundamentally unsustainable.

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