SWUP-MED Project

Sustainable Water Use Securing Food Production in Dry Areas of the Mediterranean Region

***Work Package* 4:** **Environmental Impact Assessment**

***Deliverable* 7.4:** **Guidelines on irrigation strategies using marginal-quality water (saline water and treated wastewater) avoiding the negative impact on soil characteristics, particularly on soil salinity, groundwater pollution, and health risks (Report)**

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Executive Summary

Water scarcity and deteriorating water quality have major impacts on agricultural productivity in dry areas of the Mediterranean region. There is already an increasing competition for high-quality water among different water-use sectors. Amid water scarcity, there is a need to use the available freshwater resources in agriculture more efficiently as well as increasingly rely on alternative water resources such as marginal-quality water to narrow the gap between water demand and supply for agriculture. Marginal-quality waters contain one or more impurities at levels higher than in freshwater, including salts, metals, metalloids, residual drugs, organic compounds, endocrine-disrupting compounds, and the active residues of personal care products and/or pathogens. This report explicitly addresses guidelines on irrigation management strategies using marginal-quality water (saline water and wastewater) to avoid the negative impact on soil characteristics, particularly on soil salinity, groundwater pollution, and health risks.

Wastewater: In case of wastewater, a range of options have to be considered for safe and productive use of wastewater: (1) crop selection and diversification to reduce possible health risks, accounting for market value and tolerance against ambient stresses; (2) irrigation water management covering water access, on-farm treatment, type of irrigation, application rates and scheduling, (3) soil related considerations such as soil characteristics, soil preparation practices, and application of fertilizers and amendments, and (4) health risk mitigation. The awareness of farmers about the best management practices is essential for safe and sustainable wastewater irrigation. The benefits of treating wastewater must also be considered against the human health and environmental costs of not doing it. For example, treating wastewater would reduce the discharge of untreated wastewater into the environment (so reducing water pollution and the contamination of drinking water supplies), and would improve the socioeconomic situation of farmers, and thus their health and that of their families.

Saline water: Long-term irrigation with saline water needs specific preventive measures and management strategies, which may include: (1) appropriate selection of crops or crop varieties capable of producing profitable yield with saline water; (2) selection of irrigation methods reducing crop exposure to salts; (3) application of saline water in excess of crop water requirement (evapotranspiration) to leach excess salts from the root zone; (4) saline water irrigation in conjunction with freshwater, if available, through cyclic applications or blending interventions; (5) use of agronomic interventions such as sowing on relatively less saline parts of ridges, raising seedlings with freshwater and their subsequent transplanting and irrigation with saline water, mulching of furrows to minimize salinity buildup and maintain soil moisture for longer period, and increasing plant density to compensate for possible decrease in growth; and (6) application of calcium supplying amendments, such as gypsum, to the soils in case of irrigation with highly sodic or saline-sodic water to mitigate the negative effects of sodium on soils and crops.

Based on different water quality parameters stemming from wastewater or saline water or both, guidelines are available for safe and productive use of wastewater and saline water use in agriculture. However, in many countries of the Mediterranean region these guidelines are not followed and most farmers use wastewater and saline water in an unplanned manner to irrigate a variety of crops. There are environmental and health risks associated with such practices. In case of wastewater, there are certain situations where complete treatment of sewage may not always be affordable in certain cases. In conclusion, a minimum treatment, together with an efficient wastewater management, based on the WHO guidelines, adapted to the overall health risk to the specific country, could minimize public and environmental risks while minimizing outbreaks and maximizing benefits. In case of saline water resources, their use in conjunction with the adoption of appropriate soil, crop, and irrigation management strategies can boost agricultural productivity far more efficiently than was previously thought. The future use of cyclic, blended, and sequential strategies for using these waters is expected to increase. Therefore, the challenge for achieving sustainable agriculture production systems and livelihoods based on saline water irrigation lies with following the specific guidelines and practices to transform saline water into an economic resource.

1 Introduction

With almost 7% of the world population, the Mediterranean region has less than 3% of the world's freshwater resources. The freshwater resources in the region are also unevenly distributed; 72% in the northern countries, 20% in the eastern countries and the remaining 8% in the southern countries. These southern countries however account for over 35% of the Mediterranean population (FAO-AQUASTAT, 2013). The already limited freshwater resources are becoming scarcer and polluted, as population increases and agglomerates in cities. Furthermore, there is the uncertain umbrella of global climate variability. Climate predictions anticipate not only increase in temperatures, but a pronounce decrease in precipitation in most of the Mediterranean region (Giorgi and Lionello, 2008; IPCC, 2007).

There is already an increasing competition for high-quality water among different water-use sectors in the Mediterranean region (Guardiola-Claramonte et al., 2012). Although agriculture is the dominant user of freshwater in most countries of the region, it has been yielding its share gradually to non-agricultural uses, i.e. household, municipal, and industrial activities. Therefore, it is projected that these countries will have to increasingly rely on alternative water resources such as marginal-quality water — wastewater and saline water — to narrow the gap between water demand and supply for agriculture. Marginal-quality waters contain one or more impurities at levels higher than in freshwater, including salts, metals, metalloids, residual drugs, organic compounds, endocrine-disrupting compounds, and the active residues of personal care products and pathogens. These constituents have undesirable effects on soils, crops, water bodies, and human and animal health.

Although the use of marginal-quality water for agriculture relaxes the current stress on freshwater resources, their use an irrigation source may end up in environmental and health implications if appropriate management practices are not followed (Lazarova and Bahri, 2005; Grangier et al., 2012). In the case of wastewater, its use in untreated, partly treated or diluted forms can expose the public to health risk when not managed properly. Similarly irrigation with saline water can result in environmental degradation through soil and water quality deterioration if appropriate management practices are not followed. This situation warrants rethinking of the ways through which marginal-quality water resources are handled and used for crop production systems in most parts of the region.

2 Guidelines and management options for marginal-quality water resources

Work package 7 of the SWUP-MED project has the following specific objectives: (1) To produce guidelines and recommendations for farmers and extension services on best management of water, crops, soil and field under multiple abiotic stresses; and (2) to maximise the exploitation of results produced, to ensure on-site demonstration of proposed measures, the circulation of papers, reports, methodology and guidelines, and to reach stakeholders and policy makers for creation of a general awareness on problems and solutions dealing with abiotic stresses in Mediterranean agriculture.

This report explicitly addresses guidelines on irrigation management strategies using marginal-quality water (saline water and wastewater) to avoid the negative impact on soil characteristics, particularly on soil salinity, groundwater pollution, and health risks.

2.1 Wastewater

Irrigation with wastewater is a reality to support agricultural production and livelihoods of smallholders in many parts of the Mediterranean region. The rate at which population in the region is increasing means that wastewater treatment and its sustainable use is an issue that requires more attention and investment. Many countries in the Mediterranean region have not been able to build wastewater treatment plants on a large enough scale and, in many cases, they were unable to develop sewer systems fast enough to meet the needs of their growing urban populations (Guardiola-Claramonte et al., 2012).

Owing to the gradual addition of contaminants into freshwater bodies, and the awareness of their possible impacts, wastewater treatment is now receiving greater attention. There is now more scope in the water and environment sectors to develop and implement wastewater treatment technologies that (1) need low capital investment for construction, operation and maintenance; (2) maximize the separation and recovery of by-products (such as nutrients) from polluted substances; (3) are compatible with the intended reuse option in that they yield a product of required quality in adequate quantities; (4) can be applied at different scales; and (5) are accepted by farming communities and the local population.

The benefits of treating wastewater must also be considered against the human health and environmental costs of not doing it (Qadir et al., 2007). For example, treating wastewater would reduce the discharge of untreated wastewater into the environment (so reducing water pollution and the contamination of drinking water supplies), and would improve the socioeconomic situation of farmers, and thus their health and that of their families.

Based on different parameters, various guidelines (Ayers and Westcot, 1985; Blumenthal et al., 2000; Carr et al., 2004; WHO, 2006) are available for wastewater use in agriculture. However, in many countries of the Mediterranean region these guidelines are not followed and most farmers use untreated wastewater in an unplanned manner to irrigate a variety of crops. Most cities in these countries have networks of open and covered interconnected channels located within and around urban premises. In general, these channels carry a mixture of wastewater generated by domestic, municipal, and industrial activities. The farmers divert untreated wastewater from these channels to provide irrigation water as and when it is needed. Although farmers irrigate a range of crops with wastewater, they often prefer to grow high-value crops as a market-ready product to generate a higher income.

Despite official restrictions and potential health implications, farmers in many developing countries of the Mediterranean region irrigate with diluted, untreated or partly treated wastewater because: (1) wastewater is a reliable or often the only water source available for irrigation throughout the year, (2) wastewater irrigation often reduces the need for fertilizer application as it is a source of nutrients, (3) wastewater use involves less energy cost even when pumping, if the alternative clean water source is from deep groundwater, and (4) wastewater generates additional benefits such as greater income generation from cultivation of high-value crops such as vegetables, which create year round employment opportunities.

Based on the above reasons, farmers take health risks and use untreated wastewater when the opportunity presents itself. Owing to the low literacy rate found amongst farmers in many countries, limited and inappropriate information gathering and reporting, insufficient public pressure, most farmers using polluted water in low-income countries remain uninformed about the health and environmental consequences. Moreover, farmers and authorities have insufficient knowledge about the technical and management options available for reducing the environmental and health risks associated with wastewater use. Depending upon the levels of contaminants present, the continued and uncontrolled use of untreated wastewater as an irrigation source could have a variety of implications.

2.1.1 Guidelines and management options while irrigating with wastewater

Under conditions of increasing water scarcity and water quality deterioration, farmers have often little alternative to the use of raw or diluted wastewater to irrigate a range of crops. Aside from the benefits of resource recovery, the practice carries risks for farmers, public health and the environment. A range of options have to be considered for safe and productive use of wastewater: (1) crop selection and diversification to reduce possible health risks, accounting for market value and tolerance against ambient stresses; (2) irrigation water management covering water access, on-farm treatment, type of irrigation, application rates and scheduling, (3) soil related considerations such as soil characteristics, soil preparation practices, and application of fertilizers and amendments, and (4) health risk mitigation. The awareness of farmers about the best management practices is essential for safe and sustainable wastewater irrigation.

2.1.1.1 Crop selection and diversification

Where wastewater is used for irrigation, crop selection is determined by more factors than usual freshwater irrigation conditions. While the market potential of the crop is always an important criterion, the suitability of the crop to its biophysical environment requires more attention than is usually given. Even more important is the potential risk to consumers, which becomes a decisive factor influencing enforcement of regulations and crop restrictions. Especially if irrigated crops are eaten raw, as with salad greens; microbial contamination can be high, hence different crops should be chosen. In guidelines addressing safe use of wastewater, it is advised to avoid cultivating crops eaten uncooked and prefer cereal and fodder crops, and trees (WHO, 2006).

A particular challenge for farmers is the salinity of the wastewater as considerable variation exists among crops in their ability to tolerate saline conditions. An appropriate selection of plant species capable of producing adequate biomass is vital while using saline wastewater for irrigation (Qadir and Drechsel, 2010). Such selection is generally based on the ability of the species to withstand elevated levels of salinity in irrigation water and soil while also providing a saleable product or one that can be used on-farm. There are several field crops, forage grasses and shrubs, bio-fuel crops, and fruit-tree and agroforestry systems, which can suit a variety of salt-affected environments. Such systems linked to secure markets, should support farmers in finding the most suitable and sustainable crop diversifying systems to mitigate any perceived production risks, while ideally also enhancing the productivity per unit of saline wastewater and protecting the environment.

Aside excess salts in the water, there is an increasing possibility of heavy metal contamination where industrial effluent contributes to the water farmers use. In terms of potential toxicity of the metals and metalloids, Hamilton et al. (2007) classified them into four groups based on their retention in soil, translocation in plants, phytotoxicity, and potential risk to the food chain. They categorized cadmium, cobalt, selenium, and molybdenum as posing the greatest risk to human and animal health because they may appear in wastewater-irrigated crops at concentrations that are not generally phytotoxic, i.e. farmers cannot rely on their plants dying before concentrations reach levels not recommended for humans. Guidelines for maximum allowable levels of metals and metalloids in irrigation water are summarized in Table 1.

Table 1 Recommended maximum concentrations (RMC) of selected metals and metalloids (mg L^{-1}) in irrigation water (Modified from Ayers and Westcot, 1985)

Element	RMC[a]	Remarks
Aluminum	5.00	Can cause non-productivity in acid soils (pH < 5.5), but more alkaline soils at pH > 7.0 will precipitate the ion and eliminate any toxicity
Arsenic	0.10	Toxicity to plants varies widely, ranging from 12 mg L^{-1} for Sudan grass to less than 0.05 mg L^{-1} for rice
Beryllium	0.10	Toxicity to plants varies widely, ranging from 5 mg L^{-1} for kale to 0.5 mg L^{-1} for bush beans
Cadmium	0.01	Toxic at concentrations as low as 0.1 mg L^{-1} in nutrient solution for beans, beets and turnips. Conservative limits recommended
Chromium	0.10	Not generally recognized as an essential plant growth element. Conservative limits recommended
Cobalt	0.05	Toxic to tomato plants at 0.1 mg L^{-1} in nutrient solution. It tends to be inactivated by neutral and alkaline soils

Copper [b]	0.20	Toxic to a number of plants at 0.1 to 1.0 mg L^{-1} in nutrient solution
Iron [b]	5.00	Non-toxic to plants in aerated soils, but can contribute to soil acidification and loss of availability of phosphorus and molybdenum
Lithium	2.50	Tolerated by most crops up to 5 mg L^{-1}. Mobile in soil. Toxic to citrus at low concentrations with recommended limit of < 0.075 mg L^{-1}
Manganese [b]	0.20	Toxic to a number of crops at a few-tenths to a few mg L^{-1} in acidic soils
Molybdenum	0.01	Non-toxic to plants at normal concentrations in soil and water. Can be toxic to livestock if forage is grown in soils with high concentrations of available molybdenum
Nickel	0.20	Toxic to a number of plants at 0.5 to 1.0 mg L^{-1}; reduced toxicity at neutral or alkaline pH
Lead	5.00	Can inhibit plant cell growth at very high concentrations
Selenium	0.02	Toxic to plants at low concentrations and toxic to livestock if forage is grown in soils with relatively high levels of selenium
Zinc [b]	2.00	Toxic to many plants at widely varying concentrations; reduced toxicity at pH ≥ 6.0 and in fine textured or organic soils

[a] The maximum concentration is based on a water application rate which is consistent with good irrigation practices (10000 m^3 ha^{-1} yr^{-1}). If the water application rate greatly exceeds this, the maximum concentrations should be adjusted downward accordingly. No adjustment should be made for application rates less than 10000 m^3 ha^{-1} yr^{-1}. The values given are for water used on a long-term basis at one site

[b] Synergetic action of copper and zinc and antagonistic action of iron and manganese have been reported in certain plant species' absorption and tolerance of metals after wastewater irrigation. If irrigation water contains high concentrations of copper and zinc, copper concentrations in the tissue may increase greatly. In plants irrigated with water containing a high concentration of manganese, manganese uptake in plants may increase, and consequently, the concentration of iron in the plant tissue may be reduced considerably. Generally, metal ion concentrations in plant tissue increase with concentrations in irrigation water. Metal ion concentrations in roots are higher than in leaves and metal ion concentrations such as cadmium concentrations are greater in leafy vegetables than non-leafy species.

2.1.1.2 Irrigation management

In addition to the choice of the most appropriate crop(s), irrigation water management (ranging from water access to the type of irrigation, application rates and scheduling) offers a variety of important management practices to address the particularities of wastewater irrigation (Simmons et al., 2010; Keraita et al., 20101).

There are different ways in which crops are irrigated with wastewater, such as surface or flood irrigation, manual irrigation with watering cans, furrow irrigation, sprinkler irrigation, and micro-irrigation such as drip or trickle irrigation. There are also different ways of water access from manual water fetching, to pumping and gravity flow. Each method has a different level of risk for farmers (through farmers' contact with the irrigation water) and consumers (through the contact of the harvested (and eventually consumed) crop part and the water). Several parameters for the evaluation of commonly used irrigation methods in relation to risk reduction are given in Table 2 (Pescod, 1992). Key criteria are health risks, costs and water use efficiency.

Table 3 Parameters for evaluation of selected irrigation methods in relation to risk reduction for crops and humans (Modified from Pescod, 1992)

Evaluation parameter	**Irrigation method**			
	Furrow irrigation	Flood irrigation	Sprinkler irrigation	Drip irrigation
Farmer exposure to *pathogens*	Low to medium	Medium to high	Low when sprinkler is off	Very low
Crop exposure to *pathogens*	Low if planted on ridge	High only for low-growing crops	High	Very low
Possibility of *leaf damage* from salts resulting in poor yield	No foliar injury as the crop is planted on the ridge	Some bottom leaves may be affected but the damage is not so serious as to reduce yield	Severe leaf damage can occur resulting in significant yield loss	No foliar injury likely
Root zone *salt accumulation* with repeated applications	Salts tend to accumulate in the ridge which could harm the crop	Depending on soil texture, salts might move vertically downwards or can accumulate in the root zone	Salt drainage is limited as water amounts are low. Surface crusting possible.	Salt movement is radial along the direction of water movement. A salt wedge is formed between drip points; clogging of pipes can occur.
Ability to maintain high *soil water potential* (Risk of soil moisture stress)	Plants may be subject to stress between irrigations	Plants may be subject to water stress between irrigations	Not possible to maintain high soil water potential throughout the growing season	Possible to maintain a high and well-targeted soil moisture content throughout the growing season
Suitability to handle *brackish wastewater* without significant yield loss	Fair to medium. With good management and drainage acceptable yields are possible	Fair to medium. Good irrigation and drainage practices and conditions can produce acceptable levels of yield	Poor to fair. Crops might suffer from leaf damage resulting in low yields	Excellent to good. Almost all crops can be grown with very little reduction in yield, unless the pipes clog

Flood irrigation is usually a low cost method with however also low water use efficiency. Health protection for the farmers is limited and – if the crops are low growing - also for consumers. With medium level of health protection, furrow irrigation needs more soil preparation and is suitable when there is a greater leaching need to remove high levels of salts. Irrigation with sprinklers is medium to high cost, does not require soil preparation, but has medium-level water use efficiency. Sprinkler irrigation systems have the advantage of reducing the amounts of water and salts applied to soil and crop (Lazarova and Bahri, 2005). The disadvantage compared to flood and furrow irrigation is that sprinklers distribute any water contaminants straight on the top of the plants. The same applies to the use of watering cans unless they are directed towards the roots. Overhead irrigation may also cause leaf burn under direct sunlight, from salts absorbed directly through wetted leaf surfaces (Ayers and Westcot, 1985), which can be avoided by irrigating at night.

Drip irrigation systems are costly, but highly efficient in water use along with the highest levels of health protection for farmers and consumers. The clogging of drippers on the other hand may limit the use of drip irrigation systems for many types of wastewater. Therefore, prior filtration is needed to prevent clogging of emitters (Minhas and Samra, 2004). Irrigation frequency is an ambivalent issue in wastewater irrigation. Because soluble salts reduce the availability of water in almost direct proportion to their concentration, irrigation frequency should generally be high. This helps in maintaining moisture content and salinity of irrigated soils at acceptable levels, which is important especially during seedling establishment. On the other hand, a low frequency of irrigation, if possible even the cessation of irrigation for several days before harvest, supports natural die-off of pathogens and is an important low-cost measure for health risk reduction (WHO, 2006). Other options for on-farm interventions addressing risks from pathogens are given in Table 3.

Table 3 On-farm options for pathogen reductions (Modified from Keraita et al, 2010)

Control measure	Pathogen reduction (log units)	Notes
Alternative safe water source	> 6	Depends on availability of safe groundwater and/or alternative farm land
Crop restrictions	> 6	Acceptance depending on controls and profit margin of the alternative crop
Drip irrigation	2−4	2-log unit reduction for low-growing crops, and 4-log unit reduction for high-growing crops
Pathogen die-off	0.5−2 per day	Die-off after last irrigation before harvest (Rate depends on climate, crop type, etc.)
Slow sand filter	1−3	Depends on appropriate particle size
Furrow irrigation	1−2	Might reduce cropping density and yield
Reduced splashing	1−2	Splashing adds contaminated soil particles onto the crop which can be avoided
Allow sedimentation in ponds and dugouts	1−2	During dry season via natural die-off. Reduction of helminths to less than 1 egg over 2-3 days possible

2.1.1.3 Soil-based practices

Good management practices play a crucial role in the preservation of key soil properties while irrigating with wastewater. Soil-based interventions are important, particularly in case of inorganic contaminants, which usually accumulate in the upper part of the soil because of strong adsorption and precipitation phenomena. For moderate levels of metals and metalloids in wastewater, there is no particular management needed if the soils are calcareous, i.e. contain appreciable levels of calcite which renders most metals immobile (Ayers and Westcot, 1985). In case of irrigation with wastewater containing elevated levels of sodium, care should be taken to avoid soil structure deterioration. Application of a source of calcium such as gypsum is desirable. Procedures are available to determine the rate of gypsum application to mitigate the effects of sodium resulting from sodic wastewater irrigation.

The quality and depth of groundwater prior to wastewater irrigation determine the detrimental effects of salts, nitrates, and metals reaching groundwater. The deeper the groundwater, the longer it will take to have such effects. In case of shallow groundwater or coarse-textured soils i.e. sandy soils which are highly permeable care must be taken to prevent groundwater pollution.

Although the fertilizer value of undiluted wastewater, in particular, is of great importance as nutrients in wastewater contribute to crop requirements, periodic monitoring is required to estimate the nutrient loads in wastewater and adjust fertilizer applications accordingly (Lazarova and Bahri, 2005). Excessive nutrients can cause nutrient imbalances, undesirable vegetative growth, delayed or uneven maturity, and can also reduce crop quality while polluting groundwater and surface water. The amount of nutrients applied via wastewater irrigation can vary considerably if it is raw, treated or diluted with stream water. The contribution in terms of nutrient addition to the soil from irrigation with recycled wastewater is given in Table 5.

Table 5 Contribution of irrigation with recycled wastewater in terms of nutrient addition to the soil. Derived from the data on nutrient concentrations in recycled wastewater and volume of applied irrigation (Modified from Lazarova and Bahri, 2005)

Nutrient	Concentration (mg L^{-1})	Fertilizer contribution (kg ha^{-1})	
		Irrigation at 3000 m^3 ha^{-1}	Irrigation at 5000 m^3 ha^{-1}
Nitrogen	16-62	48-186	80-310
Phosphorus	4-24	12-72	20-120
Potassium	2-69	6-207	10-345
Calcium	18-208	54-624	90-1040
Magnesium	9-110	27-330	45-550

It becomes obvious that irrigation with wastewater has a variety of implications steering farmers' decision making process in view of crop selection as well as soil and water management. Most of them are limiting the choice of options. However, while a wrong choice for example in view of salinity management or any other phytotoxic hazard usually results in a quick learning process for the farmer, hazards affecting farmers' and especially consumers' health might remain less obvious and hidden among various confounding factors, such as poor sanitation at home . With economic interests being in most cases of paramount importance, it is not surprising that farmers might opt for those options which yield highest returns while keeping investments as low as possible. The result is the common picture of high value exotic vegetables irrigated with low cost watering cans or via flood irrigation, both imposing high risks for human health. Increasing awareness about these risks, and providing incentives and regulations to encourage alternative crop choices in spite of possible disadvantages will create the conditions that would favor the utilization of farm-based interventions for the safe and productive use of wastewater in irrigated agriculture.

2.1.1.4 Health risk mitigation

For health risk mitigation, WHO guidelines (WHO, 2006) propose the use of a number of barriers (multiple-barrier approach) along the sanitation and food chains – from wastewater generation to consumption – instead of focusing only on the quality of wastewater at its point of use (Figure 1).

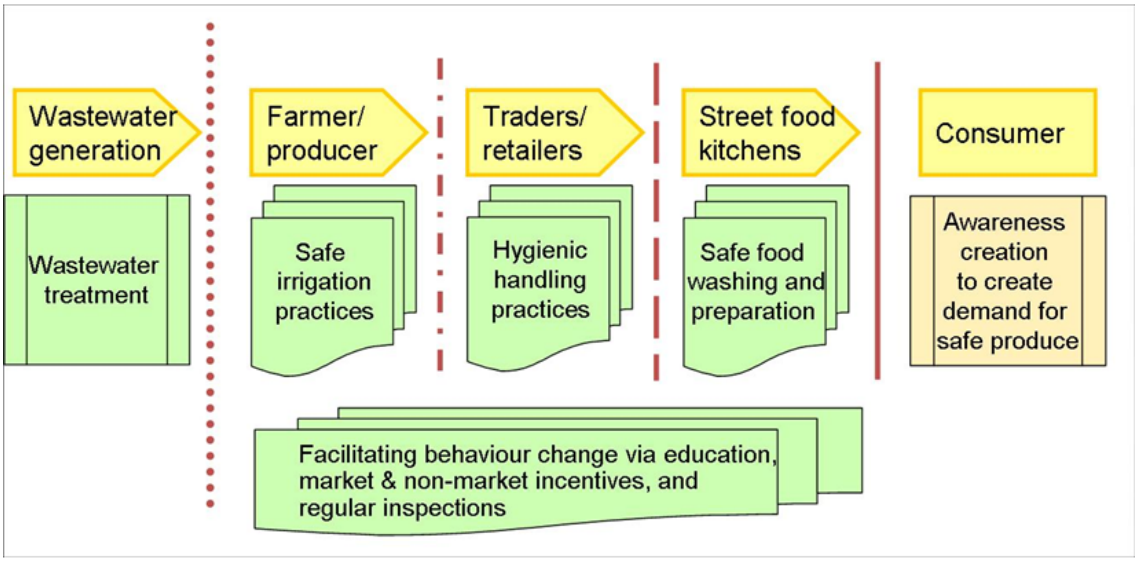

Figure 1 The multiple-barrier approach as applied in wastewater irrigation systems (WHO, 2006)

In case of applying multiple-barrier approach, for example, barriers can be placed at wastewater generation points (e.g. low-cost wastewater treatment), on farms (e.g. on-farm sedimentation ponds, crop restriction or safer irrigation techniques), at markets (e.g. washing crops with clean water), and even at consumer level (e.g. disinfection, cooking or pealing). This needs to go together with control of human exposure (e.g. gloves and boots for farmers) and may require engaging a wide range of actors beyond the wastewater treatment facility. This approach is more applicable in areas where comprehensive wastewater treatment and disinfection is failing due to the high capital and recurrent costs involved in operation and maintenance and the technical and managerial capacities required. It allows a regulatory and monitoring system in line with the socio-economic realities of the country or locality.

2.1.2 Guidelines and management options while irrigating with saline water

Long-term irrigation with saline water needs specific preventive measures and management strategies, which may include: (1) appropriate selection of crops or crop varieties capable of producing profitable yield with saline water; (2) selection of irrigation methods reducing crop exposure to salts; (3) application of saline water in excess of crop water requirement (evapotranspiration) to leach excess salts from the root zone; (4) saline water irrigation in conjunction with freshwater, if available, through cyclic applications and/or blending interventions; (5) use of agronomic interventions such as sowing on relatively less saline parts of ridges, raising seedlings with freshwater and their subsequent transplanting and irrigation with saline water, mulching of furrows to minimize salinity buildup and maintain soil moisture for longer period, and increasing plant density to compensate for possible decrease in growth; and (6) application of calcium (Ca^{2+}) supplying amendments, such as gypsum, to the soils in case of irrigation with highly sodic or saline-sodic water to mitigate the negative effects of sodium (Na^{+}) on soils and crops.

2.1.2.1 Crop selection and diversification based on salt tolerance

Considerable variation exists among crops in their ability to tolerate saline conditions (Maas and Grattan, 1999). An appropriate selection of plant species capable of producing adequate biomass is vital while using saline water for irrigation. Such selection is generally based on the ability of the species to withstand elevated levels of salinity in irrigation water and soil while also providing a saleable product or one that can be used on-farm (Qadir and Oster, 2004). The salt tolerance of a crop is not an exact value because it depends on several soil, crop and climatic factors. This diversity can be exploited to identify local crops that are better adapted to saline and/or sodic soil conditions.

Based on the linear response equation proposed by Maas and Hoffman (1977), crops can be characterized for their salt tolerances. Two parameters obtained from the Maas-Hoffman equation are: (i) the maximum allowable soil salinity for a crop without yield reduction (the threshold soil salinity), and (ii) the percent decrease in crop yield per unit increase in salinity beyond the threshold salinity level for the crop (the slope). Both values can be used to calculate relative yield (Y_r) for any given soil salinity exceeding the threshold level by using Equation 1.

$$Y_r = 100 - b\,(EC_e - EC_{th}) \qquad [1]$$

EC_{th} refers to threshold saturated paste extract salinity level expressed in dS m^{-1}; *b* is the slope expressed in % per dS m^{-1}; and EC_e is the average electrical conductivity of the saturated soil paste extract of the root zone expressed in dS m^{-1}. Based on these values, the yield potential of crops can be estimated at specified salinity levels (Table 6). The capacity of crops to withstand salinity is described in relative terms and generally divided into four classes, i.e. sensitive, moderately sensitive, moderately tolerant, and tolerant.

Crop diversification systems based on salt-tolerant plant species or varieties are likely to be the key to future agricultural and economic growth in regions where saline water is used for irrigation (Qadir et al., 2008). Such systems linked to secure markets, should support farmers in finding the most suitable and sustainable crop diversifying systems to mitigate any perceived production risks, while ideally also enhancing the productivity per unit of saline water and protecting the environment.

Table 6 Yield potentials of some crops as a function of average root zone salinity (Based on the salt tolerance data of different crops as reported by Maas and Grattan (1999) and based on experimental data from SWUP-MED project for three food legume crops (Faba bean, chickpea, and lentil)

Common name	Salt tolerance based on	Yield potential (%) at specified salinity (dS m^{-1})			
		25%	50%	75%	100%
Durum wheat	Grain yield	25.6	19.1	12.5	5.9
Cotton	Seed cotton yield	22.1	17.3	12.5	7.7
Sugar beet	Storage root	19.7	15.5	11.2	7.0
Barley	Forage yield	16.6	13.0	9.5	6.0
Wheat	Grain yield	16.6	13.0	9.5	6.0
Sorghum	Grain yield	11.5	9.9	8.4	6.8
Alfalfa	Shoot dry weight	12.3	8.8	5.4	2.0
Spinach	Top fresh weight	11.9	8.6	5.3	2.0
Broccoli	Shoot fresh weight	11.0	8.2	5.5	2.8
Egg plant	Fruit yield	12.0	8.3	4.7	1.1
Rice, paddy	Grain yield	9.3	7.2	5.1	3.0
Potato	Tuber yield	8.0	5.9	3.8	1.7
Maize	Ear fresh weight	8.0	5.9	3.8	1.7
Faba bean	Grain yield	9.7	5.2	3.2	0.8
Lentil	Grain yield	7.7	4.4	2.7	0.7
Chickpea	Grain yield	7.2	4.2	2.6	0.7

These data serve only as a guideline to relative tolerances among crops. Absolute tolerances can vary between varieties also depending on climate, soil conditions, and cultural practices.

2.1.2.2 Selection of irrigation methods and irrigation scheduling

There are different ways to irrigate crops, such as surface or flood irrigation, furrow irrigation, sprinkler irrigation, and micro-irrigation such as drip or trickle irrigation. Some methods are more suitable for saline water or other types of marginal- or low-quality water than others. Sprinkler and especially drip irrigation systems, for example, have the advantage of reducing the amounts of water and salts applied to soil and crop. As sprinkler irrigation may cause leaf burn from salts absorbed directly through wetted leaf surfaces where climatic conditions favor fast evaporation (Ayers and Westcot, 1985), irrigation at night can help avoiding this. Alfalfa leaves, for example, are known for margin leaf-burn when sprinkled with saline water of 3-5 dS m^{-1}. Sprinkler irrigation of cotton when practiced during daytime with saline water of 4 dS m^{-1} may cause about 15% reduction in lint yield. Severe leaf burns and extremely low yields have been reported from the daytime sprinkling with saline water of $\geq$ 5 dS m^{-1}. In both cases, no significant yield reduction was observed when such waters were applied at night (Rhoades, 1999). Several other factors affect salt deposition on leaf surfaces when sprinkler irrigation is practiced, including leaf age, shape, angle, and position on plant; type and concentration of salt; ambient temperature; air velocity; irrigation frequency; and length of time the leaf remains wet (Maas and Grattan, 1999). Since the problem is also related more to the number than the duration of sprinkler irrigation, infrequent and heavy irrigations should be preferred over frequent and light sprinkler irrigations (Qadir and Minhas, 2008).

Because soluble salts reduce the availability of water in almost direct proportion to their salt concentration in soil solution, irrigation frequency except for sprinkler irrigation should be increased. This will help in maintaining the moisture content and salinity of irrigated soils as high and low respectively, as is practicable, especially during seedling establishment i.e. the sensitive early stages of vegetative growth (Rhoades, 1999).

2.1.2.3 Root zone salinity management

While using saline water, the volume of irrigation water applied should ideally be in excess of crop water requirement (evapotranspiration) unless the predictable rainfall can be taken into consideration to leach excess salts from the root zone. Salinity control by effective leaching of the root zone becomes therefore an important management option for farmers who are not limited in terms of water allocations. In order to calculate leaching requirement, farmers need assistance to analyze the electrical conductivity of soil and irrigation water to use the following relationship between irrigation water and soil salinity (Equation 2).

$$LR = EC_w / [5(EC_e) - (EC_w)] \qquad [2]$$

Where LR refers to leaching requirement (additional water fraction of the irrigation water) needed to control salts in the root zone within the salt tolerance level of a specific crop with routine surface irrigation method, i.e. the fraction of infiltrated water that must pass through

the root zone to keep soil salinity within a specific level. EC_w is EC of applied irrigation water expressed in terms of dS m^{-1}. EC_e refers to the average soil salinity (expressed as dS m^{-1}) in the root zone that can be tolerated by the crop under consideration (see values in Table 6).
Leaching requirement is needed to calculate the total water requirement (AW) of the crop. This can be estimated from Equation 3 (Ayers and Westcot, 1985):

$$AW = ET / (1 - LR) \quad [3]$$

Where AW refers to the depth of applied water per unit area on yearly or seasonal basis (mm yr^{-1}), ET is the annual or seasonal crop water consumption expressed as evapotranspiration (mm yr^{-1}), and LR is the leaching requirement expressed as fraction of 1. Both AW and ET can also be expressed in terms of m^3 of water (1 mm = 10 m^3 ha^{-1}).

The leaching required to maintain salt balance in the root zone may be achieved either by applying sufficient water at each irrigation to meet the LR or by applying, less frequently, a larger leaching amount sufficient to remove the salts accumulated from previous irrigations. The leaching frequency depends on the salinity status in water or soil, salt tolerance of the crop, rainfall and other climatic conditions.

Adequate soil drainage is considered as an essential prerequisite to achieve leaching requirement vis-à-vis salinity control in the root zone (Ayars and Tanji, 1999). Natural internal drainage alone may be adequate if there is sufficient storage capacity in the soil profile or a permeable subsurface layer occurs that drains to a suitable outlet. An artificial system must be provided if such natural drainage is not present. Otherwise the resultant root zone salinity control will not be sustainable. Besides adequate soil drainage, land leveling and adequate depth of groundwater are also basic components to maintain salinity in the root zone at a specific level.

2.1.2.4 Saline water irrigation in conjunction with freshwater

Saline water can be used for irrigation in conjunction with freshwater, if available, through cyclic (temporal alternating) and in-situ blending approaches. Both options are possible: stretching of freshwater by adding saline water, as well as blending saline water with freshwater. Blending saline waters with good-quality irrigation waters has been a common practice in several water-short regions. Several studies have evaluated different aspects of this approach on a field scale (Oster, 1994; Sharma and Rao, 1998; Qadir and Oster, 2004). They found that the practice allows a good degree of flexibility to fit into different situations. Guidelines pertaining to water quality for irrigation in terms of salinity and sodicity related parameters are available elsewhere (Ayers and Westcot, 1985; Tanji and Kielen, 2002). The most commonly used guidelines are presented in Table 7.

The cyclic strategy involves the use of saline wastewater and non-saline irrigation water in crop rotations that include both moderately salt-sensitive and salt-tolerant crops. Typically, the non-saline water is also used before planting and during initial growth stages of the salt-tolerant crop while saline water is usually used after seedling establishment (Oster, 1994). The cyclic strategy requires a crop rotation plan that can make best use of the available good-quality water and saline wastewater, and takes into account the different salt sensitivities among the crops grown in the region, including the changes in salt sensitivities of crops at different stages of growth. The advantages of cyclic strategy include: (1) soil salinity is kept lower over time, especially in the topsoil during seedling establishment; (2) a broad range of crops, including those with high economic-value and moderate salt sensitivity, can be grown in rotation with salt-tolerant crops; and (3) conventional irrigation systems can be used. Studies addressing the cyclic use of saline waters (Rhoades, 1989; Oster, 1994; Tyagi, 2003) have shown that this strategy is sustainable for cotton, rice, wheat, safflower, sugar beet, tomato, cantaloupe, and pistachio provided the problems of crusting or poor aeration are dealt with through optimum management.

Table 7 Guidelines for interpretation of EC of irrigation water affecting crop water availability, and combined effects of SAR and EC of irrigation water on soil physical properties, particularly infiltration rate (Adapted from Ayers and Westcot, 1985)

Potential problem	Parameter	Degree of restriction on use		
		Severe problem	Slight to moderate	No problem
Crop water availability[1]	EC (dS m^{-1})	> 3.0	0.7–3.0	< 0.7
Soil infiltration rate[2]	SAR	EC (dS m^{-1})		
	0–3	< 0.2	0.2–0.7	> 0.7
	3–6	< 0.3	0.3–1.2	> 1.2
	6–12	< 0.5	0.5–1.9	> 1.9
	12–20	< 1.3	1.3–2.9	> 2.9
	20–40	< 2.9	2.9–5.0	> 5.0

[1]Salinity (EC) of irrigation water affecting crop water availability
[2]Combined effects of salinity (EC) and sodicity (SAR) affecting soil infiltration rate

Blending consists of mixing good- and poor-quality water supplies before or during irrigation. Saline wastewater can be pumped directly into the nearest irrigation canal or water channel. The amount of saline wastewater pumped into the canal can be regulated so that target salinities in the blended water can be achieved (Rhoades, 1989; Oster, 1994). Different water qualities are altered, according to the availability of different irrigation water qualities and quantities, between or within an irrigation event.

Studies have been carried out to estimate the percentage of saline water that can be blended with freshwater to achieve different yield potentials. Assuming a leaching fraction of 25%, the percentage of saline water depends on crop salt tolerance, salinity of the drainage water, and desired yield potential (Table 8). For a moderately sensitive crop, like lettuce, additions of saline waters (4 to 6 dS m^{-1}) have little usefulness unless a potential yield of 80% is acceptable. Even then, the percentage of saline water ranges from 23 to 37%. For a salt-tolerant crops such as cotton, 35% of the water applied can have a salinity of 10 dS m^{-1} at a 100% yield potential; at a yield potential of 80%, all the applied water can have a salinity of 10 dS m^{-1}, except for the seedling establishment that requires soil salinity less than 2 dS m^{-1} in the seed zone (Oster and Grattan, 2002).

Table 8 The maximum percentage of saline water (EC = 4-10 dS m^{-1}) that can be mixed with non-saline irrigation water (EC = 0.8 dS m^{-1}) to achieve a yield potential of 100 and 80% of selected crops varying in salt tolerance (Adapted from Oster and Grattan, 2002)[1]

Crop	Salt tolerance[2]	Threshold salinity[3]	Slope[4]	EC of saline water (dS m^{-1})			
				4	6	8	10
				100% yield			
Lettuce	MS	1.3	13.0	2	2	1	1
Alfalfa	MS	2.0	7.3	14	9	6	5
Tomato	MS	2.5	9.9	25	15	11	9
Zucchini	MT	4.7	9.4	62	38	28	22
Cotton	T	7.7	5.2	100	62	44	35
				80% yield			
Lettuce	MS	1.3	13.0	37	23	17	13
Alfalfa	MS	2.0	7.3	80	52	39	31
Tomato	MS	2.5	9.9	78	48	35	27
Zucchini	MT	4.7	9.4	100	84	68	58
Cotton	T	7.7	5.2	100	100	100	100

[1]Estimates are based on the assumption of 25% leaching fraction

[2]Salt tolerance ratings abbreviated as moderately sensitive (MS), moderately tolerant (MT), and tolerant (T)

[3]Threshold salinity (electrical conductivity, EC, expressed as dS m^{-1}) refers to the maximum allowable ambient salinity in the root zone for a crop without yield reduction

[4]Slope expressed in terms of percent decrease in yield per unit increase in salinity expressed as dS m^{-1}

2.1.2.5 Seedbed preparation and agronomic interventions

Since most crops are salt sensitive in particular at the germination stage, it is important to avoid the use of saline wastewater during this critical growth stage. Under field conditions, it is possible by modifications of planting practices to minimize salt accumulation around the seed and to improve the stand of crops. For examples, double row planting on flat beds can be practiced with lettuce, onion, and in certain cases other field crops. Seeds are planted on the edges of the beds where salt accumulation is minimal (Rhoades, 1999). For larger seeded crops, the seeds can be planted in furrows. The seed is placed in a wet and less saline zone, as during the preparation of ridges more saline surface soil goes to the ridges and a pre-sowing irrigation helps in leaching the salts from furrow soil more efficiently than those of the ridge soil. The beneficial effects of furrow planting in mustard and sorghum over flood irrigation with saline water have been reported. The practice of furrow planting has also been utilized for creating favorable environment for the establishment of tree plantations when saline water was the source of irrigation.

Other interventions in addition to planting techniques include pre-sowing irrigation to leach the salts from seeding zone, raising seedlings with freshwater and their transplanting and subsequent irrigations with saline water, use of mulches to maintain soil moisture for longer period, and increase in seed or seedling rate per unit area (plant density) to compensate for possible decrease in growth (Tanji and Kielen, 2002). For examples, studies have shown 10-15% improvement in grain yield by using 25% extra seed rate (Minhas, 1998).

2.1.2.6 Soil and water treatment while using saline-sodic or sodic water

Irrigation with saline-sodic or sodic water needs provision of a source of Ca^{2+} to mitigate Na^{+} effects on soils and crops. Gypsum ($CaSO_4{\cdot}2H_2O$) is the most commonly used source of Ca^{2+}; its requirement for sodic water depends on the Na^{+} concentration and can be estimated through simple analytical tests. Gypsum can be added to the soil or applied with irrigation water. Gypsum application techniques have been refined in the form of ‘gypsum beds’, the use of which improves gypsum’s solubility and application efficiency and reduces the costs of its application. This method provides considerable savings and produces higher crop yields (Sharma and Minhas, 2005). Applying gypsum by mixing it with sodic irrigation water has been a common practice in several countries. Such application of gypsum has the potential to improve the soil’s infiltration rate. The use of chemical amendments such as gypsum is particularly recommended when RSC values in irrigation water exceed 5 $mmol_c\ L^{-1}$, soils are medium-textured, and annual rainfall is below 500 mm (Minhas et al., 2004).

In the case of calcareous soils, containing precipitated or native calcite ($CaCO_3$), the dissolution of low-solubility calcite can be enhanced through plant root action to increase Ca^{2+} levels in the root zone. The increased partial pressure of carbon dioxide within the root zone triggers calcite dissolution (Qadir et al., 2005). In case of good crop growth and root proliferation facilitating increased calcite dissolution, there may not be a need to add gypsum to calcareous soils. In other cases, a lower rate of gypsum application may work well on such soils. Organic materials can be useful in ameliorating the effects of soil and/or irrigation water sodicity. Plant residues and other organic matter left in or added to the field can improve chemical and physical conditions of the soils irrigated with sodic water by supporting the dissolution of calcite.

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