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Chapter 25

Water reuse for irrigated agriculture in Jordan: soil sustainability, perceptions and management

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Abstract: Treated domestic wastewater offers a valuable contribution to Jordan's water balance. Water reuse is particularly well-suited to irrigated agriculture, for which water is in constant demand. The Jordanian reclaimed water generally has a high concentration of both plant beneficial ions (nutrients) and potentially plant toxic ions. Suitable soil management strategies such as periodic leaching and nutrient management are therefore required to maintain productivity. In this research the effect of water reuse on soil sustainability has been investigated by means of soil analysis combined with interviews with farmers and organisations working with reclaimed water. The soil analysis results suggest that irrigation does lead to the accumulation of plant toxic solutes, however, soil analysis from farms which have been irrigated with reclaimed water for several decades reveal that solute accumulations have been avoided through water management strategies on the farm. Interviews with farmers have shown that on-farm water management is influenced by a range of factors, which include the decisions taken by organisations with regards to water allocation and management. Interviews with organisations have shown that the priorities of decision-makers are often different to those of farmers and that they have a limited awareness of the challenges faced by farmers. Maintaining soil sustainability is imperative and can be achieved through water management both on and off the farm.

25.1 Introduction

25.1.1 Background to water reuse in Jordan

Water scarcity is a growing problem across the world as greater pressure is placed on the available water resources. The rising global population requires more freshwater for drinking, domestic usage and particularly for food production (Postel, 1992). Irrigated agriculture is essential to sustain the increasing populations and in arid and semi-arid lands it commonly absorbs the majority of freshwater resources (Allan, 2001; Molle and Berkoff, 2006). The countries of the Middle East are facing some of the greatest water shortage problems in the world, with their available resources being significantly lower than the potential demands arising from industry, agriculture, tourism and domestic needs (MWI, 2004). Jordan, at the centre of the Middle East, is one of the most water scarce countries of the world. With only 160 cubic metres per person per year (MWI, 2004) Jordan is classified as experiencing *absolute scarcity* according to the Falkenmark indicator of water stress (Falkenmark *et al.,* 1989).

There are three principal ways by which water scarcity can be alleviated. Firstly, through developing new resources via the construction of dams, desalination of sea water or exploiting groundwater resources. Such schemes typically involve hard engineering and technological developments and tend to be expensive and often have negative social and environmental consequences (Gleich, 2003; Molle *et al.*, 2009). Secondly, water scarcity can be confronted through water demand management which aims to lower the demand for water by encouraging water saving devices and reducing water use in the home, in industry and in agriculture. The third approach is by reusing urban domestic wastewater after it has been treated.

Treated wastewater (reclaimed water) is particularly well suited for agriculture as it often contains significant quantities of plant essential nutrients like nitrogen, phosphorus and potassium and can have high amounts of suspended and dissolved organic matter. The release of such nutrient rich water to natural water bodies can have detrimental ecological effects while its reuse for irrigation offers a means of waste disposal that potentially avoids the pollution of the natural environment (Feign *et al*., 1991; Shelef and Azov, 1996). Crop growing experiments in Saudi Arabia found that the use of reclaimed water reduced the need for fifty per cent of the inorganic nitrogen usually required for maximum crop productivity (Hussain and Al-Saati, 1999). A survey of farmers in Jordan by Abu-Madi (2004) found that farmers could reduce their fertiliser expenditure by sixty-five per cent when irrigating fruit trees with reclaimed water compared to groundwater.

Despite the benefits, there are disadvantages associated with the use of reclaimed water. Public health concerns have arisen because the water has the potential to carry human pathogens such as *Escherichia coli* and intestinal worm eggs (WHO, 2006). These present a degree of risk to the farmer in contact with the water as well as the consumer who may ingest contaminants present on the surface of the irrigated produce. However, the risk is very low provided that the water is adequately treated and careful management is undertaken on the farm to prevent contact between the produce and the water (Raschid-Sally *et al.*, 2005; Oron *et al.*, 1999; Jimenez, 2008; WHO, 2006).

Another area for concern is the risk that the water presents to the sustainability of the soil. While the water contains nutrients it also contains solutes of sodium chloride and boron which are potentially toxic to plants if they accumulate in the soil to levels beyond the tolerance threshold of the crop (Shainberg and Oster, 1978). Sodium also has the potential to damage the soil structure under certain conditions. These solutes enter domestic wastewater from household cleaning products such as dishwasher and laundry detergents. Sodium chloride is added to these as a manufacturing agent and water softener (Patterson, 2001) and sodium perborate is added as a bleaching agent (Barth, 1998).

Arid region, irrigated soils are particularly sensitive to the potentially detrimental effects of slightly saline, reclaimed water (Feign *et al.,* 1991; Carr *et al.,* 2008). The low input of freshwater due to limited precipitation means that accumulated ions are rarely removed naturally from the soil profile by flushing or leaching. Significant long-term problems for soil productivity can occur if irrigation with slightly saline water continues without additional water being applied to leach the solutes. The problems of solute accumulation include salinity (high salt content), sodicity (high sodium content), anion toxicity (high concentrations of chloride, carbonate or bicarbonate) or specific toxicity which may arise from the presence of minor elements such as boron.

Consideration must also be given to the nutrient additions from the irrigation water. While these are generally beneficial, the application of some nutrients in quantities beyond the requirement of the crop at certain times in the growing season can be detrimental to productivity. A high concentration of solutes in the soil solution, including beneficial solutes, can reduce water availability to the plant if the osmotic pressure in the soil solution exceeds that in the root. High availability of nitrogen during certain plant growth stages can result in reduced fruiting, while excesses of some nutrients can lead to deficiency in others nutrients, for example, magnesium can replace calcium, leading to calcium deficiency in the plant. Careful management of mineral fertiliser inputs are therefore needed and this can only be obtained through awareness of the nutrient content of the irrigation water and adjusting the fertiliser schedule accordingly to prevent crop damage from excess nutrients. Farmers can attempt to manage these risks by reducing chemical fertilisers and applying only the required quantity of irrigation water to meet the crop requirements when the crop is sensitive to excess nutrients.

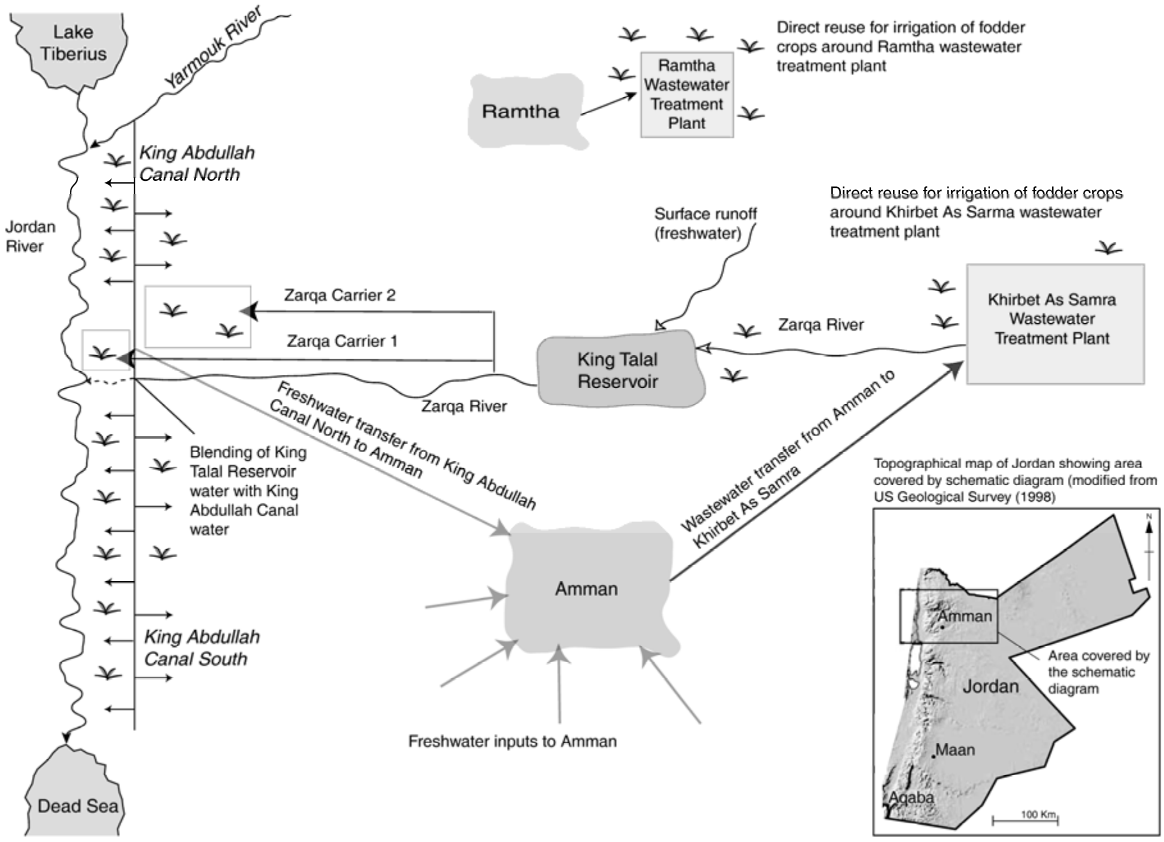
Despite the potential hazards from irrigation with reclaimed water the benefits for arid region soils are substantial. Irrigation raises productivity, the soil organic matter should increase with commensurate improvements in the soil structure and aggregate stability (Vogeler, 2009) and plant beneficial ions in the water help to meet the nutrient demands of the crop and reduce the quantities of non-renewable mineral fertilisers that are needed (Lazarova *et al.*, 2005).

In Jordan, water reuse is already taking place on a substantial scale. Sixty-two per cent of households are connected to a central sewage system (MWI, 2009) which means that about 80 million cubic metres (MCM) of wastewater are produced annually (Vallentin, 2006). This constitutes just under ten per cent of Jordan's 867 MCM of renewable water annually (MWI, 2009). The majority of the reclaimed water is produced at the Khirbet As Samra wastewater treatment plant located thirty kilometres east of Amman (the capital of Jordan).

Figure 25.1 is a schematic diagram showing the movement of domestic and reclaimed water in north-west Jordan. Domestic water enters Amman from a variety of sources, the sewage water is subsequently transferred to Khirbet As Samra where it is treated before being released into the Zarqa River. Some water is abstracted directly from the Zarqa River for irrigation by riparian farmers but the majority of the water flows, along with natural runoff, down to the King Talal Reservoir. From the reservoir, the water is released as required to be used for irrigation in the Jordan Valley (a major agricultural area). The use of reclaimed water is therefore split between that consumed directly around the treatment plant and that used indirectly (after significant transportation and the seasonal addition of natural surface runoff) in the Jordan Valley.

Two different types of agriculture take place at the direct reuse and the indirect reuse sites in Jordan. Directly around the treatment plants the water is used for the supplementary irrigation of fodder crops such as alfalfa and barley. Flood irrigation is used and the farmers have low outlay costs in cultivating these cash crops. In the Jordan Valley, the blended mixture of reclaimed water and fresh surface water is used for the irrigation of high value fruits and vegetables. The farmers have high outlay costs and must invest in drip irrigation to maximise productivity with the available water resources. Plastic mulch (plastic soil covering) is commonly used to reduce evaporative losses; high cost fertilisers and pesticides are typically needed due to the intensity of cropping.

Figure 25.1 Schematic diagram and corresponding map of the pathway of water reuse in north-west Jordan



25.1.2 Aims of the research

Water reuse is a complex and fragmented process. It impacts upon the environment and includes a variety of stakeholders such as farmers and various decision-making institutions. As such, the aims of this work were threefold, with the overall objective of investigating how and why water reuse can be managed sustainability. Firstly, to explore how soil sustainability is affected by irrigation with reclaimed water; secondly, to identify how farmers are managing reclaimed water on their farms to enhance productivity and soil sustainability; and thirdly, to describe how organisations are affecting soil sustainability under irrigation with reclaimed water through their actions, decisions and strategies.

The research is therefore highly interdisciplinary, combining both the natural and the social sciences. Such an approach has been chosen purposefully because of the insights required to fully understand the processes and challenges of water reuse in a water limited country. Water management is increasingly emphasising the importance of an holistic and interdisciplinary approach to overcome the water challenges of the 21st century in a sustainable manner (Braimoh and Craswell, 2008). The need to incorporate social factors alongside technical planning is frequently discussed, yet in reality social considerations are often limited. This research aims to emphasise that combining approaches from the social and physical sciences is highly rewarding when investigating water management issues.

25.2 Research Methods

To reflect the interdisciplinary nature of the work, three different research methods were utilised:

1) Soil sampling and laboratory analysis to explore how reclaimed water alters the soil chemistry;

2) Mathematical modelling to further understand the processes occurring in the soil; and

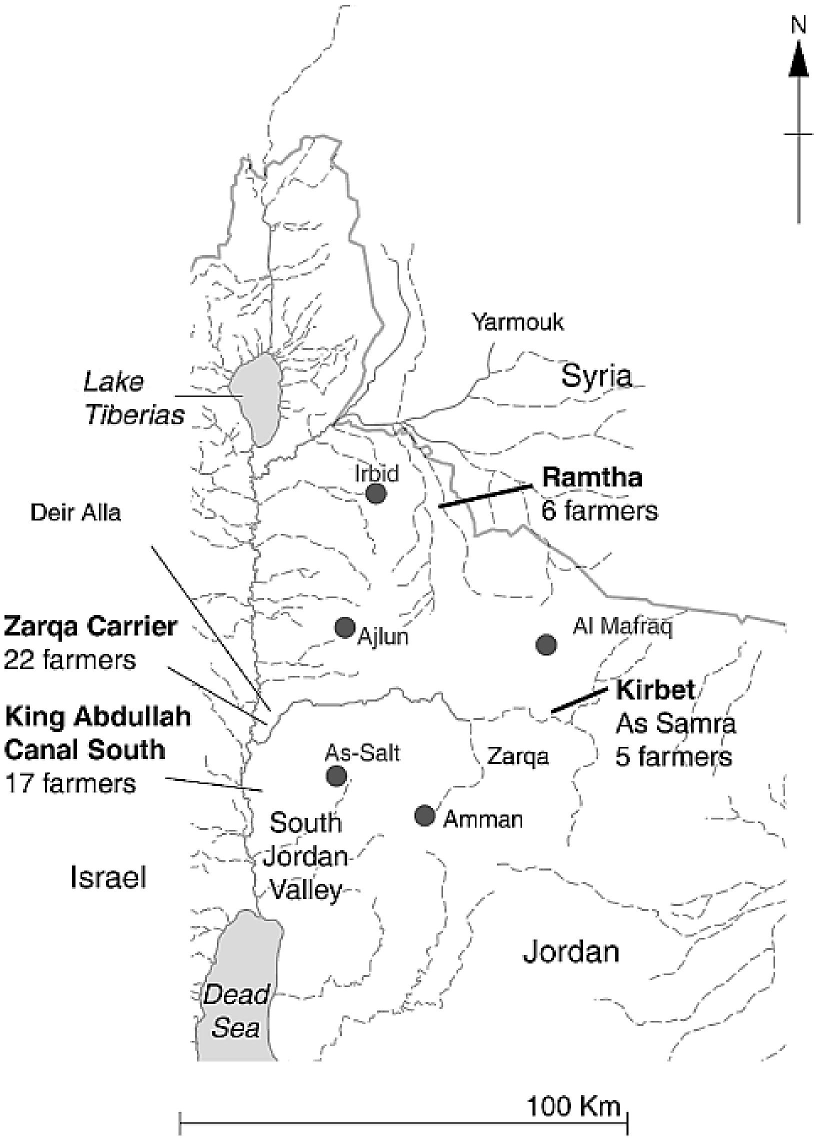
3) Semi-structured interviews with farmers and organisations (including governmental, non-governmental, research and private sector organisations) involved with water reuse to investigate the management strategies, priorities and concerns of these stakeholder groups.

25.2.1 Soil and water sampling and analysis

Soil and water samples were taken from three research sites, Khirbet As Samra, Ramtha and Deir Alla, the locations of which are shown on Figure 25.2. At each site experimental barley (*Hordeum vulgaris*) was being grown with reclaimed water under carefully regulated water supply conditions. Data were therefore available on the exact quantities of irrigation water applied to the crop which had been calculated according to the crop water demand (Allen *et al.*, 1998). At each locality soils were available which had been irrigated to meet 100 per cent and 120 per cent of the crops water demand. This meant that the soils irrigated to 120 per cent had received 20 per cent more water than required by the plant, resulting in percolation of excess water through the soil profile and potential leaching of soil solutes. This made it possible to compare how water reuse affected soils which had been leached to those which had not been leached. Soil samples were taken with an auger to extract material from a number of set depths in the profile and were collected at the end of the cropping season (May) over two consecutive years (2006 and 2007). Composite samples were formed by mixing soil taken from four places in the irrigated area in order to reduce the effect of localised variation in the soil.

As well as sampling from the research sites it was also possible to take soil samples from farms which had been irrigated with reclaimed water for extensive periods of time. At one site in the Jordan Valley land had been irrigated for twenty-eight years with water from the King Talal Reservoir. The farmer of this land was able to give information on the management methods used, that had included covering the soil with plastic mulch during the growing season and excess reclaimed water had been applied periodically to leach the soil and maintain low salinity. At Khirbet As Samra it was possible to sample soil from an olive plantation which had been irrigated with effluent from the wastewater treatment plant for eighteen years.

Figure 25.2 Map of north-west Jordan showing the locations of soil sampling and farmer interviews



Soil analysis was conducted to determine the soil salinity through the measurement of the electrical conductivity of the soil saturation extract (ECe) measured in deci-siemen per metre (dS m^{-1}). This was performed using the method of Rowell (1994) whereby a sample of soil was moistened with ultra-pure water until it reached saturation. After allowing the mixture to equilibrate for sixteen hours the solution was removed from the soil using a vacuum pump. The solution was then analysed to determine the pH of the extract (pHe), the ECe and the concentration of soluble cations (sodium, calcium, magnesium, potassium and boron) and anions (chloride, sulphate and phosphate) using inductively coupled plasma optical spectroscopy (ICP-OES) (Optima 3000) and ion chromatography (Dionex) respectively. The water samples taken in the field were analysed in a similar manner. The water data were then integrated with historic data collected from published and grey literature from Jordan (GTZ, 2005; Al-Zu'bi, 2007; Ammary, 2007; Bashabsheh, 2007) in order that a more complete picture of the water quality could be obtained.

25.2.2 Mathematical modelling

A pre-developed mathematical model of solute movement through a variably saturated medium (HYDRUS-1D, Šimůnek *et al*., 2005) was used to further understand solute movement through the soil and to attempt to develop scenarios of appropriate management methods to maintain soil sustainability under irrigation with reclaimed water. For simplicity, only chloride (Cl) was modelled using HYDRUS. This ion was chosen because it is negatively charged which means it is not retained by the negatively charged soil particles and so it travels easily through the soil in solution with the water. Chloride is also closely correlated to total salinity (Hajrasulih *et al*., 1991) and therefore knowledge of the Cl concentration is a valuable indicator of soil salinity.

The HYDRUS model was calibrated so that the modelled soil solution Cl concentration at the end of the growing season in 2006 and 2007 would fit as closely as possible to the measured soil solution Cl concentration which had been determined in the soil samples. The calibration was done through careful adjustment of the soil and solute numerical parameters required by the model. This allowed a reasonably good fit to be achieved between modelled and measured data from Deir Alla. Using the determined soil parameters and the available data on irrigation, rainfall, evaporation and transpiration from this location, the model was run for a variety of scenarios whereby the amounts and timings of leaching water were changed while all other parameters remained the same. This allowed the identification of how changes in the irrigation schedule would affect the concentration of Cl at different depths in the soil profile and at different times in the season.

25.2.3 Interviews with farmers irrigating with reclaimed water

Extensive semi-structured interviews were conducted with thirty-nine farmers irrigating with reclaimed water. The aims of these interviews were to gauge the opinions of farmer to the water, to identify perceived and real problems and benefits and to document local knowledge as to how reclaimed water is managed to minimise adverse effects on crops and soil. Through interviewing farmers who were using reclaimed water directly around the wastewater treatment plants at Ramtha and Khirbet As Samra and those using reclaimed water in the Jordan Valley it was possible to compare the perceptions and management strategies adopted by direct reusers to those of indirect reusers. The location and number of farmers interviewed are shown in Figure 25.2.

To ensure that an economically diverse selection of farmers were interviewed the size of the farm was used as an economic indicator. A sampling frame was devised which gave quotas of small, medium and large scale farmers to be interviewed. These quotas were not rigidly enforced to the extent that they limited spontaneous interviews, but they were used to shape the sampling. The interviews were conducted in the field via a translator with advanced knowledge of Jordanian agricultural systems. Notes were taken and often a tour of the farm was provided to clarify and explain management methods and issues. Interview notes were typed up and expanded according to memory immediately after the interviews. Each data bit (piece of information) within the interview transcript was then coded and grouped according to its code. For example, all comments related to fertiliser application were grouped together. This method meant that similarities and discrepancies between the farmers' views became clear and factors that were frequently mentioned or ignored were highlighted (Kitchin and Tate, 2000).

25.2.4 Interviews with organisations working with reclaimed water

Semi-structured interviews were held with representatives from organisations identified (through desk based review and networking) as being involved in some form with water reuse in Jordan. These came from the private sector (such as consultancy and agri-business), international agencies (such as bilateral donors), the governmental sector (such as the Ministry of Water and Irrigation and its associated departments), the non-governmental sector and research institutions (such as private and public universities).

The interviews focussed on the perception of the organisation towards water reuse, but also covered wider management and implementation challenges, priorities for the future and attempted to explore how the organisation regarded the farmers and accommodated their involvement in the management of water reuse. These interviews were conducted in English and were either recorded or notes were taken during the interview. They were transcribed immediately after the interview with additional observations and comments. For analysis, they were coded according to various themes and the coded data were analysed to identify similarities and differences between the individuals and the organisational groups. Quotes were identified for each theme and compiled together in order that narratives could be developed on water reuse from the perspective of the organisations.

25.3 Research Findings and Discussion

25.3.1 Water quality

Table 25.1 shows the solute content of irrigation water at Khirbet As Samra, Ramtha and Deir Alla (Jordan Valley), as determined by the water samples collected and the long-term averages identified in the available literature. The data in Table 25.1 show that both potentially plant beneficial and potentially plant toxic ions are present in the irrigation water.

Potentially plant toxic solutes in the irrigation water can be coarsely estimated by the EC of the water. The reclaimed water at all sites has an EC of around 2 dS m^{-1} which classifies it as having a slight to moderate restriction to use according to FAO guidelines (Ayers and Westcott, 1985). Of greater concern is the Cl concentration which can reach almost 400 mg L^{-1} and the boron concentration which can reach almost 1 mg L^{-1}. These concentrations can cause a specific toxicity hazard for some crops (Ayers and Westcott, 1985). There is some difference between the water qualities at each of the research sites. The water of Deir Alla has a lower solute concentration than the water of Khirbet As Samra and Ramtha, due to the addition of fresh, surface water to the Zarqa River, the source of the irrigation water at Deir Alla.

Careful management of the soil is therefore required to ensure that potentially toxic ions do not accumulate to levels that serve to reduce plant productivity and that the addition of mineral fertilisers does not lead to excessive nutrient availability which has the potential to reduce productivity.

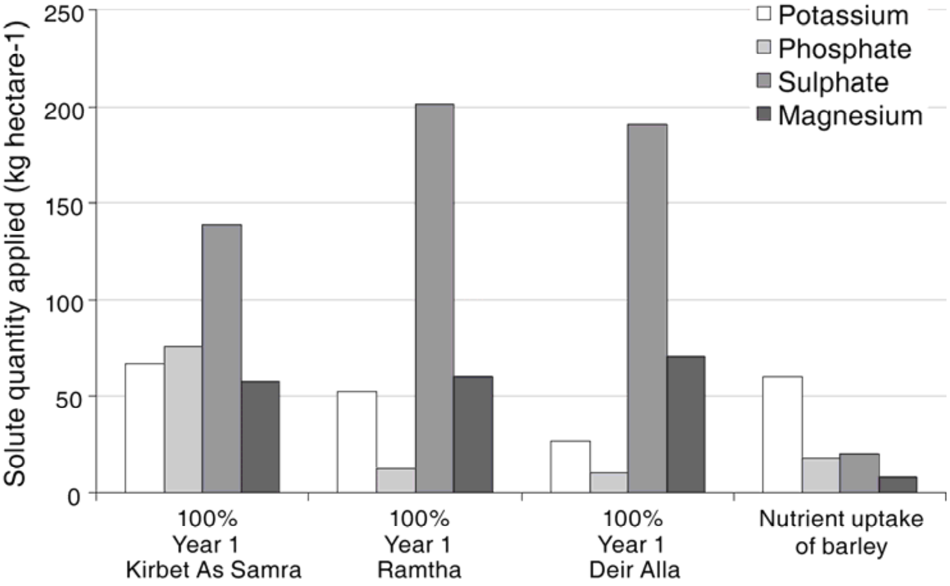
Table 25.1 Water quality parameters at Khirbet As Samra, Ramtha and Deir Alla based on data determined through water sampling and published data (GTZ, 2005; Al-Zu'bi, 2007; Ammary, 2007; Bashabsheh, 2007)

Location	Potentially plant beneficial ions in the irrigation water (mg L^{-1})				Potentially plant toxic ions in the irrigation water (mg L^{-1})			Additional parameters		
Average determined from all available data	K	P	S	Mg	Cl	Na	B	EC (dSm^{-1})	pH	SAR
Khirbet As Samra	31.32	35.63	65.01	27.22	364.61	261.14	0.91	2.14	7.86	7.67
Ramtha	32.97	6.80	104.66	34.19	398.76	232.46	0.73	1.71	8.21	6.30
Deir Alla (water from the King Talal Reservoir)	15.74	21.74	90.78	31.39	276.66	125.67	0.54	1.91	7.85	1.92

25.3.2 Crop nutrients and farmer awareness to "free" fertilisers

The nutrient content of the water has been extrapolated to show the quantities of nutrients added to the soil through the irrigation water when sufficient water is applied to meet 100 per cent of the water requirement of a typical barley crop (Figure 25.3). The data suggest that the irrigation water meets the nutrient requirements of the crop with regards to potassium, phosphorous, sulphur and magnesium at Khirbet As Samra. At Ramtha all the nutrient requirements are met by the water except for phosphorous and at Deir Alla the requirements of phosphorous and potassium are not met by the water. The exact crop nutrient requirements will vary depending on the type of crop and its yield but the available data give an indication of the high nutrient capacity of the water, particularly at Khirbet As Samra.

Figure 25.3 Nutrient inputs and nutrient requirements of barley at the research sites (nutrient uptake of barley is based on data from Cooke, 1982)



The interviews with farmers explored their awareness of the nutrients provided by the reclaimed water. The interviews revealed that seventy-four per cent of the indirect reuse farmers in the Jordan Valley were aware that the water contained nutrients and subsequently reduced their use of chemical fertilisers. However, one farmer explained:

> “I know that I over fertiliser. When the price of cucumbers is high I’ll add more fertilisers. I'll try and use less fertiliser. But when the price of cucumbers is high it’s a psychological thing to add fertiliser as I wish for the best productivity.”

Another farmer explained how:

> “I went to a training course about how the water has fertilisers in it just a few days ago. But then the fertiliser company sales representatives came here and persuaded me to buy fertilisers!”

To indirect reuse farmers the nutrient content of the water appears to be considered but many factors influence whether mineral fertilisers are also applied. Information to farmers on the exact nutrient content of the water would be of value in facilitating farmers to plan their fertilisation schedules, however, the psychological factors and persuasiveness of sales agents also need to be considered when providing information to farmers in order that awareness to these issues is acknowledged.

Several of the farmers commented that while they can save money on nutrients they felt that these savings are offset by greater spending on buying, installing and operating water filters to reduce the suspended load of the irrigation water. The organic and mineral constituents of the irrigation water leads to the clogging of irrigation pipes and drip emitters through mineral precipitation and algal growth (Duran-Ros *et al.,* 2009). To overcome this challenge the farmers use water filters and replace components of the drip irrigation systems every few years. One third of all the indirect reuse farmers interviewed spoke of having additional irrigation costs due to filters and irrigation pipe/emitter replacement as a direct result of the quality of the irrigation water.

The farmers' directly reusing water around the wastewater treatment plants also had an enhanced awareness of the nutrients in the irrigation water. In contrast to the indirect reuse farmers, they tended to recognise the financial benefits. This was particularly apparent at Ramtha where the treatment plant had been upgraded in 2004, resulting in a greater quantity of the nutrients being removed from the irrigation water. Here the farmers commented how this had resulted in them needing to buy mineral fertilisers:

> "Since the upgrade of the wastewater treatment plant from primary to secondary the natural fertiliser in the water has decreased. This means there is now an additional expense of adding fertiliser."
>
> "The wastewater treatment plant was upgraded two years ago to include anaerobic digestion and chlorination. This results in less nitrogen being available in the water and now I need to apply mineral fertiliser."
>
> "Before the upgrade of the plant we didn't add manure to the soil. Now we have to add manure as there is less fertiliser in the water."
>
> "The water is good. But now we need to use much more fertiliser since the water treatment plant was upgraded two years ago."
>
> "Before, when I was irrigating alfalfa the plants survived for five years. Now I have to plant a new crop every two years because the water is better treated now and so the plant productivity is lower."

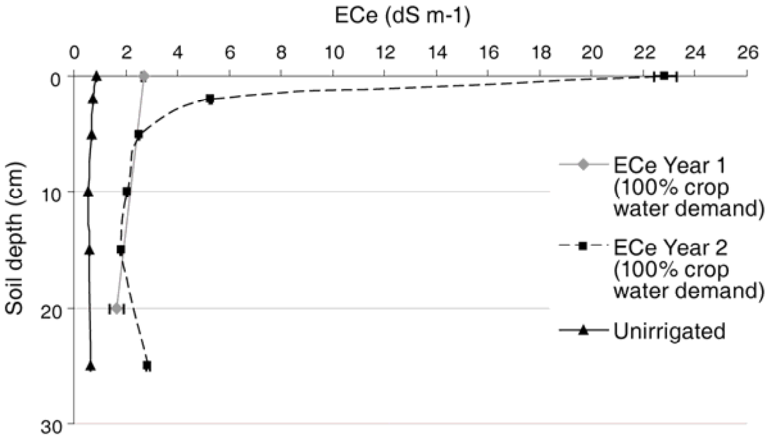
These findings emphasise the importance of the water chain concept developed by Huibers and Van Lier (2005), which emphasises consideration for the end use and user of reclaimed water when planning wastewater collection and treatment. For direct reuse around Ramtha it could be argued that the employment of treatment methods which remove nitrogen and phosphorous is unnecessary. Around Khirbet As Samra, where the water is released to the environment, the case for advanced treatment is much stronger in order to protect the natural surface water.

The direct reuse farmers appeared to have a higher regard for the beneficial nutrients than the indirect reuse farmers. This is likely to be a result of the type of agriculture and the investment requirements at each site. The negative effects of reclaimed water on drip irrigation systems through clogging leads to additional expense which is outside the control of the farmer. It would seem that in areas of intensive, high value agriculture, the farmers inability to control the negative effects of the water outweigh the recognised benefits of free nutrients.

25.3.3 Solute accumulation from irrigation with reclaimed water

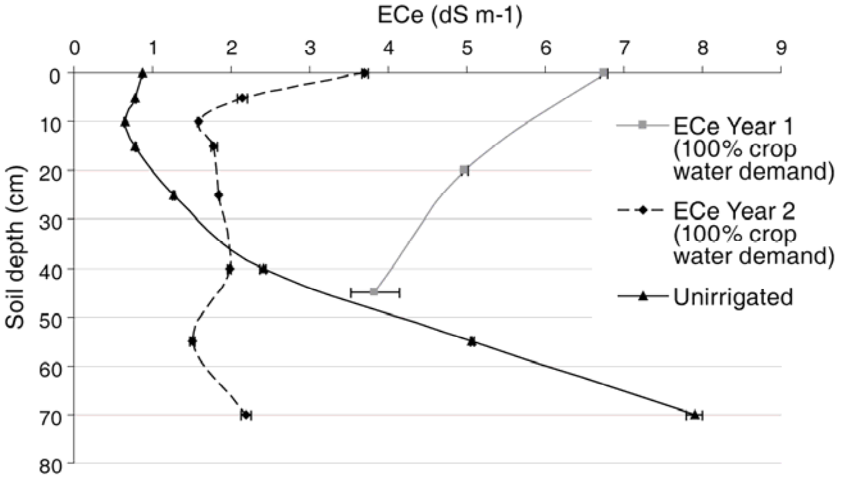
It was hypothesised that irrigation with reclaimed water to meet 100 per cent of the crop water requirement would lead to an increase in the solute concentration in the soil solution as the number of years of irrigation with reclaimed water increased. Figure 25.4 shows the soil salinity through the soil profile at Ramtha following one and two years of irrigation compared to an unirrigated control. The data show that the soil salinity at the surface is much higher following two years of irrigation than after one year of irrigation which supports the hypothesis that soil salinity increases with the length of the irrigation period. Though there is no difference between the salinity after one and two years of irrigation below 5 cm depth.

Figure 25.4 Salinity of the saturation extract (ECe) from Ramtha after one and two years of irrigation with reclaimed water (error bars give standard error from the mean)



The data from Khirbet As Samra show that the relationship between irrigation period and soil salinity is less straight forward (Figure 25.5). The data show that soil irrigated for two years has lower salinity than soil irrigated for one year. This is likely to be due to the mobilisation and upward transfer of solute during the first year of irrigation from deeper in the soil profile driven by evaporation from the soil surface. The unirrigated soil shows a high solute concentration at depth which is likely to be present due to the movement of saline groundwater. During the second year of irrigation it appears that the solute is transferred back down through the soil profile. The reasons for this are unclear, possibly being connected to the timing and magnitude of rainfall events in conjunction with irrigation.

Figure 25.5 Salinity of the saturation extract (ECe) from Khirbet As Samra after one and two years of irrigation with reclaimed water (error bars give standard error from the mean)

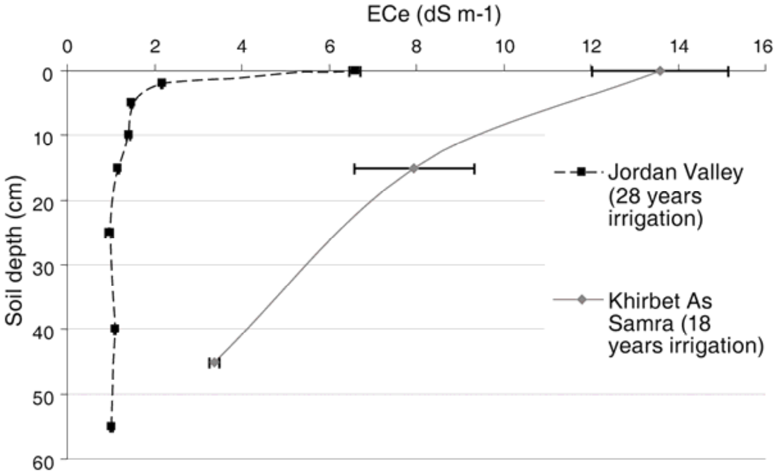


Soil samples were also taken from two sites which had been irrigated with reclaimed water for 18 years (where flood irrigation had been used for olive cultivation) and 28 years (where drip irrigation had been used for vegetable production). The site irrigated for 28 years had received water from the King Talal Dam (blended freshwater and reclaimed water) with a lower solute concentration than that applied to the site irrigated for 18 years with water directly from the Khibet As Samra wastewater treatment plant (Table 25.1). Both sites were equally well drained but the irrigation quantities applied and the soil management differed to reflect the different crop types grown. The 28 year site had received no rainfall inputs but it had been leached annually with reclaimed water, manure had been applied regularly and plastic mulch had been used to prevent evaporative losses. It is estimated that approximately 900 mm of irrigation water were applied annually to meet the water requirements of tomatoes (Harmanto *et al.*, 2005). The 18 year site had received supplementary irrigation to meet the requirements of olives (estimated at 600 mm per year (Testi, 2006)), but due to the deeper rooting depth of the olives, leaching of the surface soil had not intentionally taken place. The two sites therefore offered an opportunity to compare a soil that had been managed through leaching and one which had not.

Figure 25.6 gives the ECe through the soil profile from the sites irrigated for 18 and 28 years. The data show that while salinity can be slightly high at the soil surface of the site irrigated for 28 years a very suitable salinity is maintained in the root zone due to leaching. In comparison the site irrigated for 18 years has a much higher salinity throughout the soil profile.

These soil samples highlight that irrigation with reclaimed water does not have to lead to a rise in soil salinity. While salinity may rise from the long-term application of reclaimed water the addition of a leaching fraction coupled with adequate drainage means the irrigation water can be managed for sustainable crop cultivation over the long-term.

Figure 25.6 Salinity of the saturation extract (ECe) from sites irrigated with reclaimed water for extensive periods of time (error bars give standard error from the mean)



The role of leaching in maintaining low soil salinity has been investigated at the research sites by comparing the salinity of the soils irrigated with 100 per cent and 120 per cent of the crop water requirement. It was expected that the soils irrigated with 120 per cent of the water demand would have lower soil salinity than the soil irrigated to 100 per cent.

Table 25.2 shows the average salinity of the soil saturation extract of the root zone of the soil irrigated to 100 per cent and 120 per cent of the crop water requirement following two years of irrigation at each locality. These data show that the application of a 20 per cent leaching fraction reduces the average root zone salinity at Ramtha by just over 20 per cent. However, leaching does not appear to reduce the salinity at Khirbet As Samra and only slightly reduces it at Deir Alla. These observations are interesting as it suggests that at Ramtha leaching is effective in transferring solute through the soil profile, but at the other sites additional factors are preventing the transfer of solute through the soil.

At Khirbet As Samra it is possible that the application of excessive quantities of irrigation water is leading to greater upward mobility of solute from deeper in the soil profile resulting in a higher soil solute concentration in the leached soil. The crop water uptake may also exceed that calculated resulting in reduced downward percolation of water. Further data on soil moisture through the profile would be needed to determine the extent to which these factors are responsible for the lack of leaching at Khirbet As Samra. At Deir Alla the solute concentration of the irrigation water is generally fairly low, which is reflected in the low soil salinity in both the leached and unleached soils which masks the effects of leaching.

Table 25.2 Comparison between the average ECe in the root zone (10-40 cm depth) of soil irrigated to 100% and 120% of the crop water demand for two years (the standard error from the mean is given in brackets)

Location	Unleached soil (irrigation to 100% of the crop water demand) Average ECe of the root zone (10-40 cm) (dS m-1)	Leached soil (irrigation to 120% of the crop water demand Average ECe of the root zone (10-40 cm) (dS m-1)	ECe reduction in the root zone as result of leaching as a percentage
Khirbet As Samra	1.74 (0.06)	1.78 (0.10)	-2.69
Ramtha	2.24 (0.20)	1.76 (0.05)	21.47
Deir Alla	1.28 (0.04)	1.24 (0.05)	2.63

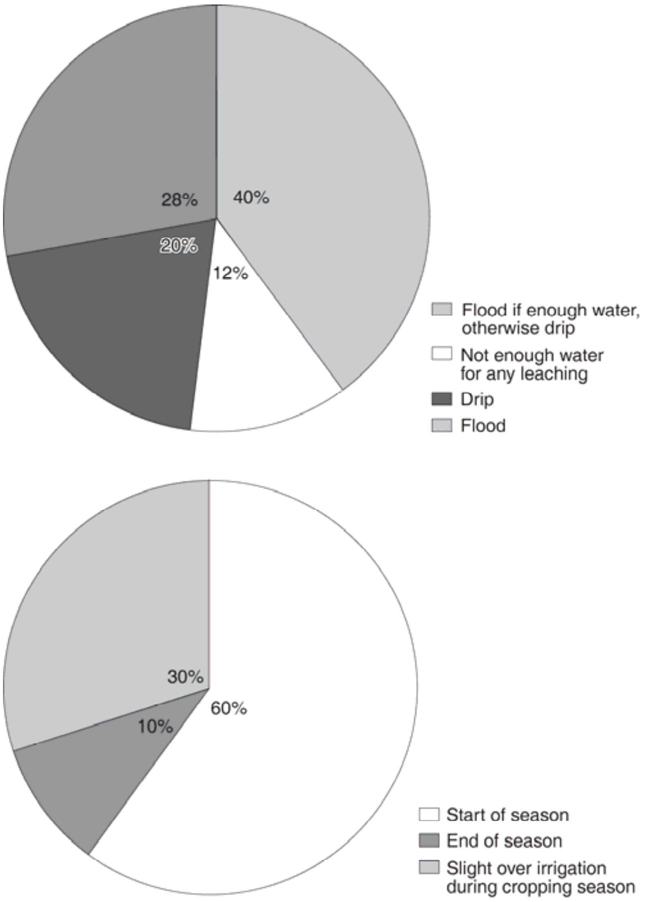
25.3.4 On-farm management methods to prevent soil salinisation

During the interviews, the farmers were asked about their leaching schedules and methods in order to identify if they experienced any salinity problems and to record how they attempted to overcome these problems. A clear difference in perception and management of the water was seen between the direct and indirect water users. Those directly using reclaimed water did not describe any negative observations with regards to the water and its effect on soil. No direct reuse farmers spoke of soil salinity problems and this is probably because flood irrigation is used around the treatment plants which results in excessive quantities of water being applied on a regular basis leading to leaching and preventing the accumulation of salt in the soil.

In contrast, soil salinity was mentioned by fifty-one per cent of the indirect reuse farmers. Awareness to salinity clearly exists in the Jordan Valley where, even before treated wastewater became part of the water resource, salinity awareness and management were required due to inherent soil salinity and the use of water from saline springs. As a result, all of the Jordan Valley farmers explained how they aim to leach the soil regularly to prevent salt accumulation.

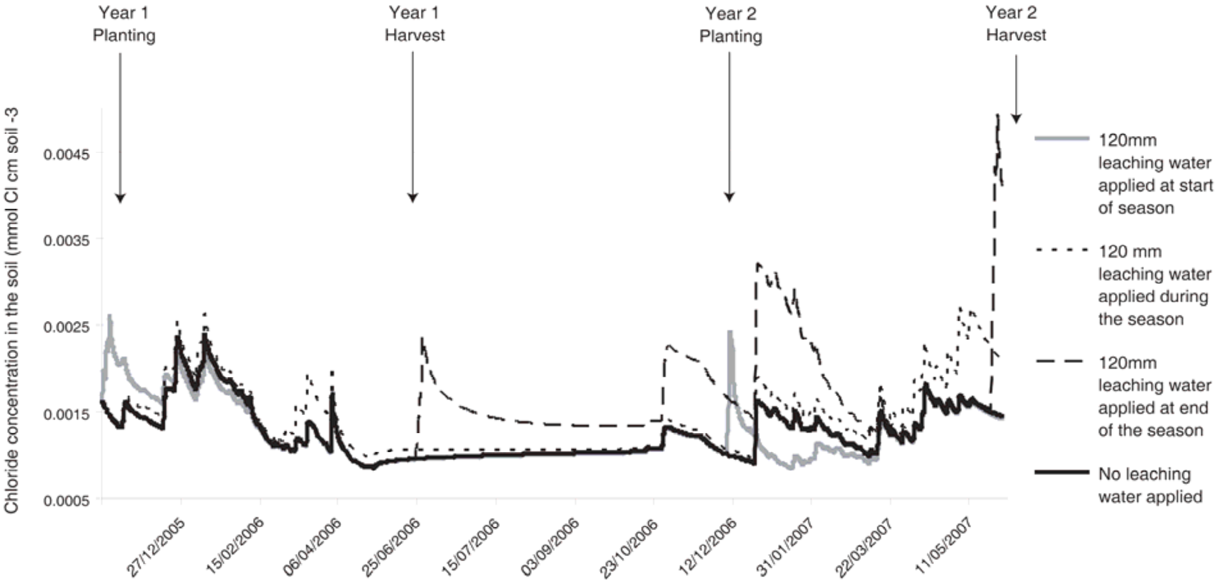
Leaching methods and timings for the Jordan Valley farmers are given in Figure 25.7, which shows that forty per cent of farmers prefer to use flood irrigation for leaching if there is sufficient water but substitute this method for drip irrigation due to water scarcity. Sixty per cent of farmers described that leaching is performed with drip irrigation at the start of the season (September) though two farmers mentioned that they were planning on changing their schedule to leach at the end of the season when they can make use of the residual moisture in the soil. Six farmers (10 per cent of the sample) said they irrigate through applying excessive quantities of water through the cropping season, as more water is available at this time.

Figure 25.7 Leaching methods and timings of leaching described by farmers irrigating with reclaimed water in the Jordan Valley



The HYDRUS model has been used to explore how the timing of leaching effects the soil solute concentration during the growing season. Figure 25.8 shows how alterations in the timing of the irrigation water change the soil solute concentration in the root zone (25 cm depth) over a period of two years. The modelled outputs suggest that leaching at the start of the season reduces the Cl concentration in the root zone by a greater amount through the growing season than leaching during or at the end of the season. Further work into leaching timings based on the experiences of farmers would be of immense value for verifying the modelled solute concentrations.

Figure 25.8 Modelled scenario of leaching timings on the Cl concentration in the soil solution at 25 cm depth at Deir Alla



Although leaching was recognised as important by the indirect reuse farmers, thirty-five per cent of these farmers said that their leaching schedules were limited by water shortage. The Jordan Valley Authority (JVA) is the government department responsible for water allocations in the Jordan Valley. This institution has an important role in ensuring adequate water is provided to farmers for leaching management but this is not an easy task due to Jordan's delicate water supply situation. If too much water is sent to farmers for leaching during the non-cropping period there is a risk that the available resources may be insufficient to meet the demands of the cropping period, a particular hazard if rainfall is low or comes late. The ability of the farmer to manage the water on the farm in a manner that allows the sustainability of the soil to be maintained is therefore heavily connected to the management of water off the farm.

25.3.5 Water reuse management: Organisations and farmer interactions

During the interviews, an attempt was made to explore the factors which the farmers associated with the water management challenges they faced and to identify means by which they would be empowered to improve their soil management. Some key observations were made which highlighted the effect of decision-making at the institutional level on soil-water management at the farm level.

While the majority of farmers were aware of the nutrients in the water, those who were not spoke of not having been given information on the nutrient content of the water or that even though they suspected the water had nutrients they continued to apply mineral fertilisers to ensure maximum productivity. The provision of information and training to farmers on the nutrient content of the irrigation water has been recognised by some organisations as being essential to enable farmers to manage their fertilisation schedules and maximise profits. During the interviews with representatives of organisations it became clear that data access and management was one of the challenges which restricted organisations from passing on data on water quality to farmers:

> "There is a lot [of data] available which is measured by universities and research institutes, some even have a contract with the JVA to monitor the [water] quality. For example, reports are written and given to JVA and as far as I know nothing happens afterwards. All this information would be interesting for farmers. … Every organisation is collecting [data] for themselves so I think there's a lot of duplication. And the information is not passed onto the next organisation who might have a use for it and they have to collect the data again and so there's inefficiency. But there is also a problem because the JVA don't want to publish this data. The quality of water in the King Talal [Reservoir] is a very sensitive issue."

An International organisation representative

The sensitivity of water reuse as an issue in Jordan must be fully appreciated as this adds a further challenge to the sustainable management of water reuse in Jordan. As one Jordan Valley farmer explained when asked if he had any problems selling his produce:

> "I don't have problems selling my produce, but in 1994 a foolish journalist wrote that the vegetables from the Jordan Valley are irrigated with water from Kirbet As Samra wastewater treatment plant. Since then Saudi Arabia has banned all Jordanian products. We are still suffering from this article. Though now it is slowly getting better."

In the early 1990s Saudi Arabia placed a ban on the import of Jordan Valley vegetables due to concerns about the use of reclaimed water for irrigation (Haddadin, 2006). As a result, both farmers and the government are extremely cautious in discussing water reuse for irrigation in the Jordan Valley. Comments from government representatives demonstrate this caution:

> "No vegetables are irrigated with treated wastewater, by our standards we can irrigate with this water but we do not use it in Jordan."

A government representative

> "So in Jordan treated wastewater is only for the restricted agriculture, it's not for unrestricted crops. So we irrigate trees, industrial trees, we irrigate wood plants, we irrigate forages. But we do not allow under the Jordanian Standard [for water reuse] to irrigate vegetables or edible crops or plants."

A government representative

> "For water reuse you have to be sure of a very high quality of treated water to be sure that no problems will be encountered. If pure wastewater would be used then exports would be limited, this makes water reuse a very sensitive topic."

A representative from a non-governmental organisation

These comments show that before farmers can be provided with open and reliable data on the nutrient content of the irrigation water the sensitivity to water reuse needs to be overcome. Communication from the research and scientific community to society on the risks and benefits of reclaimed water based on empirical data is essential to help overcome these challenges.

The interviews with farmers in the Jordan Valley highlighted concerns about water quality due to its salinity and effect of clogging irrigation pipes. The interviews further suggested that farmers in the Jordan Valley place the responsibility for water quality on the government who have the power to make and enforce regulations to prevent industrial waste and poorly treated sewage entering the irrigation water supply. As one farmer commented:

> "The water would be 100 per cent better if there were controls to stop industry dumping waste into the water."

Through interviews with governmental representatives it became clear that while legislation is in existence to prevent industrial waste from entering the domestic sewage network, illegal dumping by industries is considered to be a problem to which action is required:

> "Industrial wastewater is legally disposed of to the sewage system from only four or five factories but there is a big problem of illegal disposal by many factories."

A government representative

> "Some areas, like Kirbet As Samra wastewater treatment plant, have huge industries linked to their sewage systems. I don't know if I have to say this, but everywhere you can have illegal uses [of the sewage system]. Sometimes [the industries] just open the manholes and drain in their waste. So you cannot control waste like heavy metals. Now the Ministry of Environment has a law for the environment. They restrict for all industries [from putting waste into the sewage system]. Industries have to use their own treatment plants inside the industry and the output of their own treatment plants should conform to the Jordanian standard specifications [on effluent quality]. Otherwise, as it happens in Jordan, the industries will be closed and we already closed around fifty industries. So this issue is really important."

A government representative

The problem of highly saline brine from desalination plants being added to the sewage network or released directly to the wadis was also mentioned by a number of organisations:

> "The salinity problem is not only from the domestic wastewater but they also have to find solutions for the brine of the desalination plants which they have in industries and until now, as far as we know, this waste is just drained into the sewer system or released to wadis. This is a management issue and very difficult to solve."

An international organisation representative

Clearly greater enforcement of existing legislation is required with consideration for both the illegal dumping of waste to the sewage system and for waste which is released untreated to the wadis. Control over the waste released by industries is needed in order that the water chain approach is applied which considers the water quality needs of the farmers and provides them with suitable water.

Farmers identified issues of water scarcity with the limited availability of water for leaching. However, the interviews showed that the farmers of the Jordan Valley believed that water shortage was not just a result of environmental conditions. While thirty-eight per cent of indirect reuse farmers did relate water shortage to environmental scarcity, forty per cent of these farmers then went on to say how the management of the available water exaggerated the water shortage problems.

Water management issues identified by farmers could be divided into three groups. The allocation of water, which includes the geographical and temporal distribution of water to farmers; the infrastructure for water provision and the competition for water resources from other water use sectors such as tourism and domestic supply.

Many farmers claimed that the distribution of water was unfair; as one farmer said:

> “The JVA is biased. They cut 30 per cent of my water and pump it to another person of their favour.”

Other farmers said how the JVA gave water to those who it favoured and turned a blind eye to some farmers who stole water (by illegally opening the pipes) while others received fines. However, several farmers maintained that they did not experience problems with the water allocation and this may support claims that water distribution is inequitable. As another farmer explained:

> “There isn't mismanagement, but the resource is limited. So what can the JVA do? The JVA tries to fulfil the needs of all the farmers. The problem is in the limitation of water resources.”

A second aspect of water distribution involves the seasonal allocation of water by the JVA. As one farmer explained:

> "There is water shortage and low water availability - but there is mismanagement. For example, lots of water is provided in winter when it is not needed but less water is given in March when the plant needs it. Why are they sending water when it is not needed - they can keep it in the dam? It is a simple problem of arranging the water balance - like financial accounts."

Water in the Jordan Valley is allocated by the JVA according to land area, crop type and season (Molle *et al.,* 2008) and none of the interviews with organisations raised any issues regarding water distribution. In fact, no institutional agency recognised the importance of the timing of water supply in enabling farmers who irrigate with reclaimed water to leach their land.

Scarcity of water was mentioned by fifty-five per cent of the organisations interviewed and solving the water shortage problems of Jordan is high on the political agenda. Several of the farmers felt it was the responsibility of the government to install and maintain appropriate infrastructure to meet the agricultural water demands:

> “There are three items the government are responsible for: 1) The military, and you will see that they pay military salaries for 50 years. 2) To protect the basic

> supply of bread for the people through strategic sources. 3) Water, the government is responsible for this. If they can fund the military they can fund the water."

Jordan Valley farmer

Despite the high awareness of water scarcity, very few organisations noted that infrastructure developments offered a means by which greater quantities of wastewater could be collected and transferred to irrigation. This suggests that infrastructure developments are not closely associated with the expansion of water reuse.

Within Jordan there is competition for the available water resources and an increasing amount of the Yarmouk River water is being transferred from the Jordan Valley to Amman to meet domestic demands. This results in increased scarcity for irrigation water in the Jordan Valley. Some farmers expressed bitterness over this transfer, feeling that the water is put to better use in the Valley:

> "The Yarmouk water which is sent to Amman is not acceptable for drinking. They pump it just to be used for car washing and irrigating the gardens!"

The transfer of water for tourism was the subject of even more resentment with comments emphasising the farmers' feelings that agriculture is the sector to which the country should be aligned, not tourism. As one farmer said:

> "The government is interested in tourism, and I don't know why, we're not even adapted for this sector."

The organisations were encouraged to speak about the distribution of reclaimed water between the different water use sectors within Jordan to identify if there were likely to be any competing demands for reclaimed water. Three institutions emphasised that there was no conflict for reclaimed water between agriculture and industry and during one interview it was clearly shown that the farmers would always be given priority to the reclaimed water:

> "Some industries are using reclaimed water and if the industry does want it then they will be given it. If there is any competition between the farmers and the industry then the farmers are given the priority. They are poor, have nothing and are suffering from the treatment plants and so it is important to try to solve their social problems."

A government representative

However, during one organisational interview a situation of conflict for reclaimed water was described:

> "That's happening in Aqaba now, there is a conflict now. All of the people want the water. The industry, they are asking for the water, the agriculture, they are asking for the water, the local authority, they are asking for the water for the landscape irrigation."

A representative from the private sector

Of greater potential concern is the allocation of reclaimed water within agriculture. One institutional representative explained:

> "But then there's another challenge coming up. Because the [reclaimed] water quality is better the farmers upstream are more interested in it and so it could happen that the water doesn't even reach the Valley. … It's a bad thing for the livelihoods of the [Jordan Valley] farmers, and also the question is why invest in upland farming when there's no farming there at the moment, threaten groundwater resources [due to possible nutrient leaching to groundwater – author's addition] and loose the market advantage of the Jordan Valley in the wintertime. Because upland farming is summer farming. They don't get as much money as the farmers in the Valley as there's a market gap there. It's always an economic decision what or where the water is used. And if they come up with these ideas of growing economic crops, it would be a disaster."

An international organisation representative

> "The sustainability of agriculture in the Jordan Valley is more or less connected to water reuse. You cannot imagine how the situation would be if the government decided not to [allow water reuse]. To stop, for example, [because of] health aspects. The water that comes from Khirbet As Samra means that agriculture can continue in the Middle Jordan Valley. And if this stops the situation will be very bad, I cannot imagine, because there is no water for agriculture. And from a social and economical point of view [reclaimed water] is the only guarantee for the sustainability of agriculture."

An international organisation representative

Farmers were asked about whether they felt supported and to whom they go when they need help in order to determine the extent to which the institutions went beyond just issuing water and followed through with an aftercare programme that encouraged, trained and supported farmers working with reclaimed water. Of all the issues discussed these questions prompted the most passionate responses which ranged from bitter disappointment in the lack of support to convinced enthusiasm that there was plenty of support.

The majority of indirect reuse farmers spoke negatively of institutional support (64 per cent). However, forty-four per cent also spoke positively about the support they had received (the total is greater than one hundred as some farmers spoke both positively and negatively). The issue of support required further questioning and analysis to determine from whom farmers were and were not receiving support. Most negative comments were directed at state run institutions such as the JVA and Ministry of Agriculture, with forty-one per cent of indirect users speaking about a lack of support supplied by these institutions, compared to thirty-six per cent of direct water users. The support of projects was viewed positively by twenty-three per cent of indirect water users and negatively by eight per cent, while no direct reuse farmers spoke of project support.

During one interview the frustrations of the Jordan Valley Authority were described:

> "It's difficult because by law the responsibility of the JVA ends at the entrance to the farm. Any advice that they give to farmers is more than they need to do. But

> actually they are interested in giving information to the farmers and at the moment they have an information sheet. But it is not fully promoted or given to the farmers because they don't have the staff to do it. Or the skills. They don't have extension workers. They are the water distributors."
>
> An international organisation representative

The importance of communication between the wastewater treatment plant and the end user of the water (farmer) was demonstrated at Ramtha. Here, several farmers explained how they had a good relationship with the manager of the treatment plant. They gave an example of when the added chlorine (to sterilise the treated effluent) was too high and causing crop damage and so the manager agreed to reduce the quantity of chlorine being added to the water. This involvement in the treatment process is very valuable and undoubtedly leads to an improved perception of the water and greater ability to manage the potential problems at the farm level.

25.4 Conclusions

This research has demonstrated the complex and multi-faceted aspects of water reuse and shown that a key approach to improved understanding is that of multidisciplinarity, which incorporates both the natural and social sciences. The available data on water quality have shown that careful nutrient management and leaching to prevent the accumulation of potentially plant toxic ions are essential to ensure maximum productivity is obtained when using reclaimed water. The interviews with farmers have shown that awareness to nutrients in the irrigation water is generally high but consideration for the nature of agriculture is required to understand how the farmer responds to this knowledge. The direct reuse farmers, irrigating fodder crops with low outlay costs appear to appreciate the "free" nutrients more than the indirect reuse farmers who irrigate high added value fruit and vegetable crops with high outlay costs. These farmers seem to place greater emphasise on the negative elements of reclaimed water which they cannot control (such as salinity and high suspended load) than the positive elements (nutrients) which they are able to control on the farm through mineral fertiliser additions.

The soil sampling and analysis from sites irrigated with reclaimed water has shown that solute accumulation does appear to occur in soils irrigated with reclaimed water but the application of an adequate leaching fraction reduces the soil salinity. A mathematical model (HYDRUS) has been of value for comparing the timings of leaching and suggests that leaching at the start of the growing season is more effective at maintaining low salinity in the soil root zone than leaching during or after the season. More data would be needed to confirm this result and explore how knowledge of the optimum timing of leaching can be applied to soil management on the farm.

Water quality control and water resource management at the institutional level has been shown to affect the ability of farmers to manage their soil resources successfully. The interviews with both farmers and organisations suggest that greater institutional awareness to the needs of the farmer would be beneficial in overcoming the challenges of water reuse. Consideration for the water quality and quantity requirements of the farmer would help shape an appropriate water reuse management strategy. However, the political sensitivity surrounding water reuse in Jordan raises an additional challenge. Awareness to the needs of the farmer (as the end user of reclaimed water) is made more difficult when the farmer is not recognised as a user of reclaimed water, as in the Jordan Valley.

Water reuse for irrigation will increase in the future, as urban populations rise, per capita water consumption goes up and sewerage networks are extended to connect more households with the wastewater treatment plants. The formation of an effective strategy which permits the long-term use of reclaimed water without detrimental effects on natural soil resources is essential. It is also achievable through recognising and building on the knowledge of all stakeholders.

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