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# MEASUREMENT AND MODELLING OF SALT AND NUTRIENT DYNAMICS UNDER SALICORNIA IRRIGATED WITH SALINE GROUNDWATER, DESALINATION REJECT-BRINE, AND AQUABRINE

**A thesis presented in partial fulfilment of the requirements for the degree of**

**Doctor of Philosophy (PhD)**

**in**

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# ABSTRACT

Environment Agency-Abu Dhabi (EAD) has implemented several scientific research projects with Plant and Food Research (PFR) New Zealand and OnlyFromNZ Limited (OFNZ) to determine the irrigation requirements for date palms, arid forestry, and field crops, for Law 5 which states that groundwater in the Emirate is the property of the Government which has the responsibility for management, organization and licensing the activities related to groundwater. The Government entity is EAD-Environment Agency of Abu Dhabi).
can be implemented using sound scientific bases to protect the interests of all. This is a cooperation with external partners, plus both governmental and non-governmental agencies. These projects aimed to determine the irrigation requirements for date palms, forests, and field crops. While these projects have determined irrigation requirements, they have not, to date, addressed the environmental impacts of farming on groundwater quantity and quality.

This Ph.D. research explored the trade-offs between improved technologies for the use of alternative water supplies, such as desalination brines, and the environmental consequences of brine re-use. The results will form part of the future solutions at the nexus among food, energy, and water in Abu Dhabi. This doctoral research builds on nearly a decade of scientific knowledge developed in collaboration with the New Zealand teams. It identifies the opportunities for reject brine from desalination units in aquaculture and halophytic agriculture, as well as the environmental consequences of the fate of this salt and nutrients. Measurements are critical to understand groundwater impacts and the benefits of using saline groundwater and brines from desalination plants to irrigate halophytes in hyper-arid environments. In 2020, a pilot trial was set up using irrigation with highly saline waters. However, two difficulties were encountered, and the pilot trial was a failure.
The first part of the thesis describes how the practical challenges of the measurement technologies used in this saline environment were overcome. Further, experiments were then carried out to quantify the efficiency and impact of salt leaching in removing salt from the rootzone.
Two years of field experimentation were undertaken to determine the economic productivity and environmental impact on groundwater of irrigating the halophyte Salicornia bigelovii with three types of saline waters in the hyper-arid United Arab Emirates. In the first year, the irrigation waters employed were groundwater (GW) at 25 dS $m^{-1}$, reverse-osmosis brine (RO) from a desalination unit at 40 dS $m^{-1}$, and Aquabrine (AQ) effluent from land-based aquaculture in tanks filled with RO brine, also at 40 dS $m^{-1}$. Bubblers (BUB), pressure-compensated drippers (PCD), or subsurface irrigation tape (SUB) were used to apply the three waters Salicornia fresh tip, harvest forage, and seed yields were highest for AQ applied through BUB, reaching 650 g $m^{-2}$. The dry forage yield with AQ through BUB was found to be 2-2.6 kg $m^{-2}$, compared to 1-2.3 kg $m^{-2}$ for the other irrigation waters and emitter devices. The highest water productivity WPI (kg $m^{-3}$) across all three crop outputs resulted from Aquabrine applied by pressure-compensated drippers. Gross economic water productivity ($GEWP_I$, \$ $m^{-3}$) was assessed based solely on gross revenue. The highest $GEWP_I$, at US\$5.8-

6.2, was achieved with AQ applied through PCD and SUB, primarily due to revenue from fresh tips. Notably, the $GEWP_l$ significantly exceeded the cost of desalination at \$1.5 $m^{-3}$. Drainage and leaching were measured using fluxmeters. The greatest salt load into the groundwater, at 135-195 kg $m^{-2}$, was observed with BUB irrigation. For PCD and SUB, the salt load ranged between 14-36 kg $m^{-2}$. Simple mass-balance calculations of these salt loadings were then employed to predict the impact on the saline quality of aquifers. An exemplar loading of 75 kg $m^{-2}$ was used, resulting in a projected annual salinity rise of 2.6 dS $m^{-1}$ $y^{-1}$ for an aquifer with a saturated depth of 100 m. This significant increase in groundwater salinity would represent a continual decline in the resource's utility. This simple mass-balance arithmetic highlighted the need for modelling.

New data from the following year's experiments highlighted the economic value of using nitrogen-rich saline waters, either from groundwater or reject brines from desalination units, to irrigate the halophytic crop *Salicornia bigelovii* for food, fodder, and fuel in a hyper-arid environment. The greatest benefit was, again, achieved using pressure compensated drippers. Field measurements of drainage and leaching under the crop showed that, in sum, all of the salt, as well as the nitrogen drawn up from the groundwater were returned back to the aquifer as leachate. The only loss of water to the system was through crop evapotranspiration $ET_c$.

A simple heuristic model of groundwater quantity and quality was developed to infer the environmental impacts of irrigating crops with saline and high-nitrate groundwater in a hyper-arid environment. The time-rise in solute concentration in groundwater is found to be a hyperbola. The parameters needed for this simple model are the fraction of the land above the aquifer that is irrigated, the initial depth of the saturated thickness of the aquifer, the saturated water content of the aquifer, and the annual rate of crop evapotranspiration. An indicator of the rate-of-rise in solute concentration, akin to a half-life, is the numbers of years to double the solute concentration in groundwater. This can be found as $\Theta h_o /2 ET_C$, where $\Theta$ is the saturated water content, $h_o$ is the original thickness of the saturated layer, and $ET_c$ is the annual rate of crop evapotranspiration. The general model is simple and straightforward to parameterise. It is easily understood and useful for assessing the impacts and trade-offs of policy and regulatory options.

The knowledge gained from these experiments and the predictions resulting from the heuristic modelling have been used to highlight future needs to be addressed for the critical issues at the food-water-energy nexus in hyper-arid regions.

# ACKNOWLEDGEMENTS

The announcement of His Highness the President of the UAE on the extension of the "Year of Sustainability to 2024" reflects the keenness to consolidate sustainable practices in the state's sectors, instil them in society's behaviour, build on the UAE's achievements, and build on the achievements of the UAE and increase its contribution to the protection of the Earth. The Twenty-Seventh National Environment Day in the UAE annually 4th Feb was celebrated under the slogan" “Together for the sustainability” of the local production which builds on the achievements of COP28, emphasising the importance of transforming food systems and aligning them with sustainability standards.

The Government directed the concerned authorities in the government, private sectors, and community groups to join efforts and continue to work to protect the environment, conserve resources, support and encourage the adoption of local products, and note the continued promotion of awareness of sustainability practices and the importance of transforming our food systems to become more sustainable, flexible, and community groups to join efforts and continue to work to protect the environment. It is good that I have completed my PhD during this Year's "Year of Sustainability". The aim was to achieve even a tiny part of the government's strategy of preserving our natural resources and the environment.

First of all, a gift to my father's soul. Who taught me how to hold a pen and write words without regret. At the outset, it was my father's desire, may Allah bless his soul, for me to complete a doctorate. I hope that through this PhD, I have fulfilled his wish. I appreciate my family for supporting me in this doctoral project, especially my mom, my wife, and my children, who were patient while I was away from them and busy studying. My brothers, sisters, family, and friends supported and encouraged me, and I hope they are proud of what I have achieved.

I sincerely thank Her Excellency Dr Shaikha Al Dhaheri, the Secretary General of the Environment Agency - Abu Dhabi (EAD), for supporting me when I began my doctoral studies. Thanks also to the Eng. Sheikha Al Hosani, former executive director, for my support and Eng. Faisal Al Hammadi, current executive director EQS (Environment Quality Sector), Eng. Abdulsalam Al Hashmi, Division Director of Environment Quality Monitoring and Control Environment Quality, and Eng. Kamal Aldeen Alhashmi, Section Head of Groundwater and Soil Quality, continued support for my research and PhD degree.

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This extensive research project required a team approach. So, I would like to thank Dr Steve Green for his energy and enthusiasm for working on salt leaching and for the pre-analysis of the data from the loggers. Also, thanks to my best colleagues, Dr Ahmed Al-Muaini and Eng. Wasel Abdel Wahid from EAD for their field assistance and technical support at ICBA. Thanks also to Dr Osama Sallam and the Water teams in EAD for helping me with advice and technical support. My thanks also to auxiliary workers in the field supervised by engineer Bala from ICBA and to the ICBA laboratories for analysing the research samples; finally, my great thanks to Lesley Kennedy from OnlyFromNZ Ltd for consulting and supervising the research closely.

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were for salt $C_0$ = 18.8 kg $m^{-3}$, and nitrate $N_0$ = 30 mg $L^{-1}$. The origin of the abscissa, $t$ = 0, is time to when the impacts of solute leaching are first felt in groundwater at the depth of the unsaturated vadose zone $d$.

# LIST OF ABBREVIATIONS

| | |
|---|---|
| AD | Abu Dhabi |
| AQ | Aquabrine |
| BTC | Breakthrough Curve |
| BUB | Bubblers |
| CHPM | Compensation Heat Pulse Method |
| DFM | Drainage fluxmeters |
| DST | Decision Support Tool |
| EAD | Environment Agency Of Abu Dhabi |
| EC | Electrical Conductivity (dS $m^{-1}$) |
| *ET*c | Crop Transpiration (mm $d^{-1}$ or L $hr^{-1}$) |
| *ET*o | Reference Evapotranspiration (mm $d^{-1}$ or L $hr^{-1}$) |
| FAO | Food and Agriculture Organization |
| $GEWP_I$ | Gross Economic Water Productivity of Irrigation \$ $m^{-3}$ |
| GW | Groundwater |
| HD | Heat Dissipation |
| HFD | Heat Field Deformation method |
| HPV | Heat pulse velocity (m $s^{-1}$) |
| IAAS | Integrated Agri-Aquaculture System |
| ICBA | International Centre for Biosaline Agriculture |
| *K*c | Crop Factor = *ET*c / *ET*o (-) |
| L | Litre |
| LAI | Leaf Area Index (-) |
| LF | Leaching fraction |
| LI | Light-Interception Fraction (-) |
| LR | Leaching requirement |
| LT | Light-Transmission Fraction (-) |
| NZ | New Zealand |
| PAR | Photosynthetically Active Radiation (µmol $m^{-2}$ $s^{-1}$) |
| PCD | Pressure-compensated drippers |
| PVC | Polyvinyl chloride |
| R | Retardation |
| Rg | Net radiation (W $m^{-2}$) |
| RO | Reverse osmosis |
| SBRC | Sustainable Bioenergy Research Consortium |
| SF | Sap flux (L $h^{-1}$) |
| SFD | Sap flux density (m $s^{-1}$) |
| SUB | Sub-surface irrigation |
| T | Transpiration (mm $d^{-1}$ or L $hr^{-1}$) |
| TDR | Time Domain Reflectometry |
| Tmax | Maximum Air Temperatures (° C) |
| TSE | Treated Sewage Effluent |
| UAE | United Arab Emirates |
| UAEU | United Arab Emirates University |
| VPD | Vapour Pressure Deficit (kPa) |
| W | Windspeed (m $s^{-1}$) |
| $WP_I$ | Irrigation water productivity |

# CHAPTER 1

# 1 INTRODUCTION & LITERATURE REVIEW

Globally, there is a challenging nexus between our need for food security, and our ability to maintain energy supplies, whilst protecting our water resources. This challenge is heightened through a rapidly rising population, reducing water resources, both in terms of quantity and quality, plus the need to maintain energy supplies (Borgomeo, at, el 2018). Zubair (2018) noted that "…addressing water scarcity, both natural and human-induced, in the Arab region is considered one of the major and most critical challenges facing the Arab countries. This challenge is expected to grow with time due to many pressing driving forces, including population growth, food demand, unsettled and politicized shared water resources, climate change, and many others, forcing more countries into more expensive water sources, such as desalination, to augment their limited freshwater supplies".

In the hyper-arid deserts of Abu Dhabi these exigencies at the nexus are even greater. Although there may well be cheap and available energy sources nowadays, this might not be so in the future. Future energy technologies need to be considered and assessed for their impact across the nexus. Groundwater is in short supply for food production, and furthermore it is becoming more saline in the Emirates. Future technologies offer hope, notably small-scale solar-powered desalination units on farm. But inevitably there are environmental impacts and trade-offs. Natural capital stocks need to be maintained for future generations. Food production must ensure food security and supply healthy diets. Figure 1.1 shows a visualisation of the upstream inflows to the nexus, and the downstream consequences.

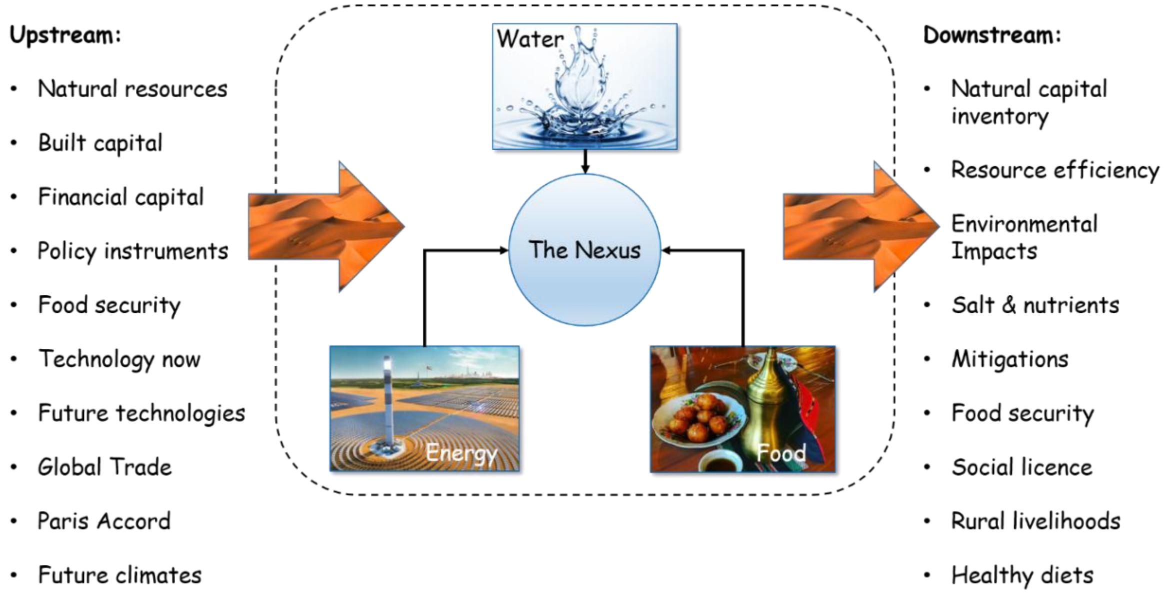


**Figure 1.1 A visualisation of the upstream inflows to the nexus, and the downstream consequences.**

## 1.1 Background of Thesis

The United Arab Emirates (UAE) has a hyper-arid climate with reference evapotranspiration (*ET*o) exceeding 2000 mm (Allen et al. 1998), whilst having an average annual precipitation of around just 50 mm $y^{-1}$. There are very high summer temperatures, often exceeding 40 °C, and there are virtually no surface-water resources. Groundwater is relied upon for irrigation, yet the water-tables are falling rapidly, primarily due to pumping for agriculture, which greatly exceeds the natural recharge rates from the scant rainfall. Wada et al. (2012) reported that in the UAE groundwater abstraction is some 1.55 (± 0.3) $km^3$ $y^{-1}$, and the groundwater resource is being depleted at a rate of 1.18 (± 0.4) $km^3$ $y^{-1}$. They calculated that 64% of the gross irrigation water demand in the UAE is supplied by non-renewable groundwater extraction. The UAE State of the Environment Report in 2015 (MOEW, 2015) reported that groundwater levels had dropped at a rate of 10 m per decade until the mid-nineties, and by a further 70 m since then. The agricultural, forestry, and landscape sectors account for nearly 85% of the annual water demand of 4.2 $km^3$ across all of the UAE. This overall demand is met by desalinated water (42%), treated sewage effluent (11%), or groundwater (44%) (MOEW, 2015). The groundwater across the UAE is generally saline and increasing (Figure 1.2), especially across the farming areas of Abu Dhabi (Figure 1.3).

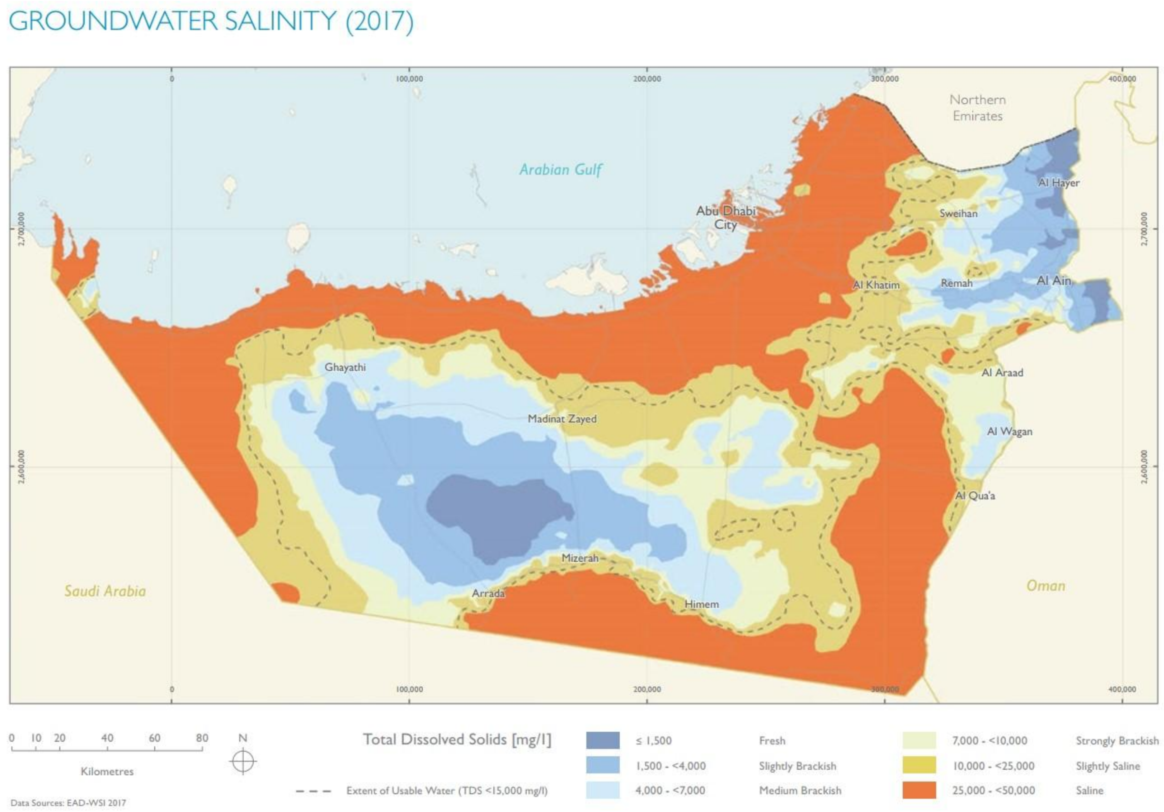


**Figure 1.2. Groundwater Salinity in the Abu Dhabi Emirate in mg $L^{-1}$. The electrical conductivity, EC (dS $m^{-1}$), is Total Dissolved Solids (mg $L^{-1}$). (Groundwater Wells Inventory and Soil Salinity Mapping for Abu Dhabi Emirate, Final Report)**

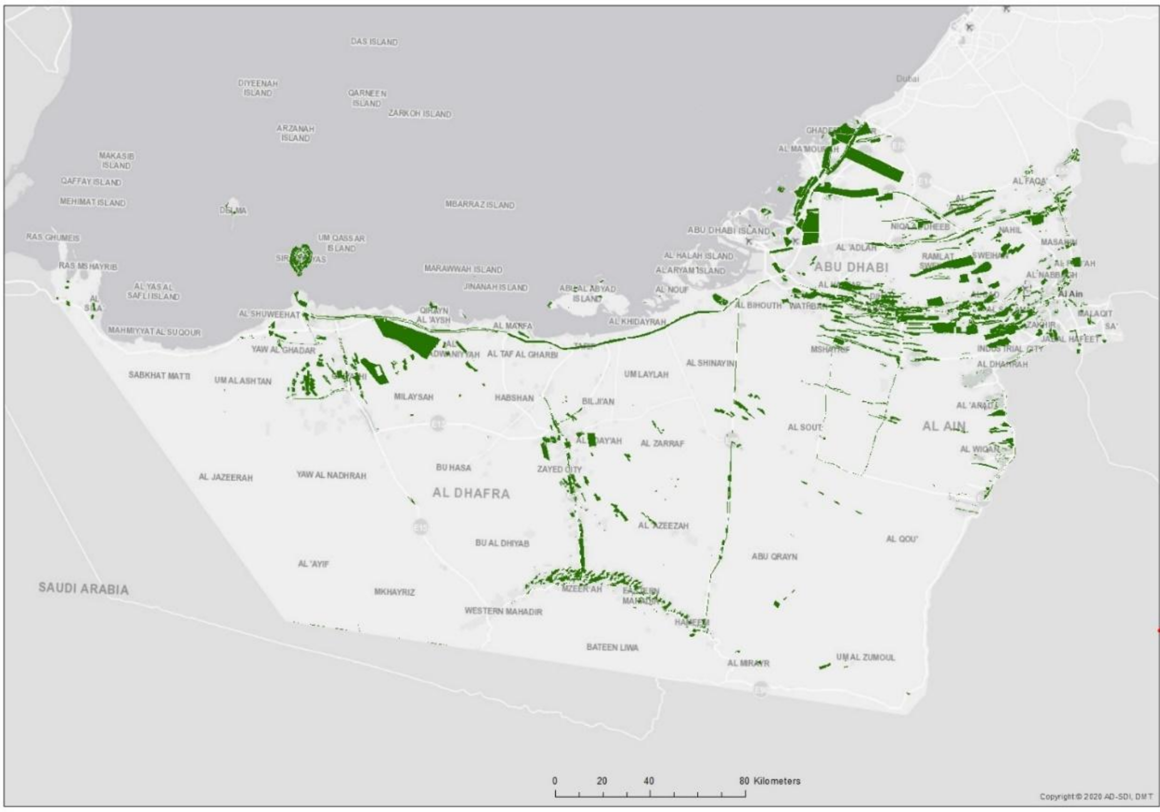


**Figure 1.3. The farmed areas of the Emirates of Abu Dhabi, including the areas of irrigated arid forests. The green areas identified where there are farms.**

There has been a rapid growth in small-scale, on-farm desalination units to 'freshen-up' groundwater for the irrigation of crops (Bales et al. 2019; Dawoud, 2017). Al Muaini et al. (2019) found the benefit cost ratio of using this process to be 1.4:1. There is likely to be further growth due to new low-cost technologies such as solar-powered capacitive deionisation (CDI), which is becoming practical and being adopted (Bales et al. 2019). Private desalination plants are now located on more than 1150 farms in Abu Dhabi 5% of the 25,000 farms in the Emirate (Abu Dhabi Static Center,2019). The farmer's desalination plants are mainly used to irrigate vegetables in greenhouses, or shade houses. However, there is a small and growing number of date farms that have begun to install small self-contained desalination units.

Environment Agency-Abu Dhabi (EAD) has implemented several scientific research projects with Plant and Food Research (PFR) New Zealand and OnlyFromNZ Limited (OFNZ) to determine the irrigation requirements for date palms, arid forestry, and field crops so that Law 5 can be implemented using sound scientific bases to protect the interests of all. These projects aimed to determine the irrigation requirements for date palms, forests and field crops. From those projects a decision support tool, the Crop Calculator (Al Tamimi et al. 2022), was developed for irrigation allocation to be used by EAD in the Emirate of Abu Dhabi, and beyond. This work was led by the PhD candidate from within EAD (Al Tamimi et al. 2022). While these projects have determined irrigation requirements, they have not, to date, addressed the environmental impacts of farming on the groundwater quality. That is the focus of this PhD thesis.

Since 2013, EAD has contracted PFR and OFNZ to carry out research projects that have been doubly beneficial. Firstly, they have provided the evidence basis to enable EAD to implement water policies through Law 5. Secondly, through having the EAD staff of Dr Wafa Al Yamani and Dr Ahmed Al Muaini gain their PhDs though Massey University, this has resulted in the development of Emirati capabilities to support the Government policy of Emiratisation. This policy seeks to build local capacities for Government in general and for EAD in particular through water policies and implementation sustainable practices. This current PhD research continues this pathway of research and policy implementation.

## 1.2 Completed Projects

Before proceeding to describe the PhD salt-leachate project, it is worthwhile to briefly describe the antecedent projects, as the current PhD project built on those findings and techniques previously developed through this cooperation. The PhD candidate was also involved in some of these projects, and they set the scene for the design and implementation of this doctoral research.

### 1.2.1 Protecting Groundwater using Treated Sewage Effluent for Arid-

In the EAD project that led to the PhD programme by Dr Wafa Al Yamani at Massey University, the goal was to protect groundwater quantity by replacing irrigation using groundwater, with irrigation of treated sewage effluent (TSE). The TSE could beneficially be used to irrigate arid forests and amenity vegetation. This work is described in the international peer-reviewed publications of Al Yamani *et al.* (2017, 2018a, 2018b, 2018c, 2019a, 2019b, 2019c, 2019d) and Rahmati et al. (2019).

McDonnell and Fragaszy (2016) found that agriculture and forestry accounted for almost 70% of total water use in the Emirate, and with the addition of water used in amenity irrigation and for roadside planting, almost 85% of all water use in the Emirate is for vegetation. Agriculture, forests, and parks consume 2,414 $Mm^3\ y^{-1}$, of which only 5.7% is sourced from recycled water. Groundwater is not used directly as a source of potable water. All potable water is from desalination of either seawater, or brackish groundwater (EAD 2015-2017).

The 2017 Abu Dhabi State-of-the-Environment Report (Environment Agency - Abu Dhabi (EAD, 2017) considered that irrigation of the arid forests in the Emirate consumed 214 $Mm^3\ y^{-1}$. Therefore, 10% of the Emirates groundwater usage is destined for use in forestry. The EAD (2017) report noted that this rate of water use may exhaust groundwater re-sources within the next few decades, especially in the western region of the Emirate, Al Dhafra, where there is essentially no groundwater recharge.

Using TSE to irrigate the forests leaves groundwater available for food and fodder crops. There is now an increasing use of TSE for food and food crops. The government is planning to replace the use of brackish water in irrigation with tertiary-treated wastewater. There are two mega-projects on the construction of infrastructure to supply of 4200 farms with treated wastewater in April 2022.

### 1.2.2 Maximising the value of irrigation for dates.

Irrigation is essential for dates (*Phoenix dactylifera* L.), which is an important crop both economically and culturally. Groundwater is relied on, yet it is a non-renewable resource at the rate it is being used this EAD programme, in conjunction with PFR and OFNZ, which led to the PhD of Dr Ahmed Al Muaini through Massey University which had five goals. These were:

1. Maximising the Value of Irrigation is undertaking research to develop management strategies and new technologies that through support industry to improve productivity, minimise wasted water, and reduce negative environmental impacts.
2. Spatial information for irrigation equipment selection and operation.
3. Water management to effectively use water and reduce water losses.
4. Development of tools for improving irrigation efficiency.
5. Assisting the decision maker by developing effective policies and procedures to sustain this date production whilst conserving groundwater.

The results from this doctoral research have been published in the international peer-reviewed literature by Al Muaini et al. (2018, 2019a, 2019b, 2019c, 2019d, 2019e).

This research investigated the combined effect of irrigation management and water salinity on the crop yield of dates and their fruit quality. The experiments assessed the impact of two different levels of water salinity (5 dS $m^{-1}$ and 15 dS $m^{-1}$) on palm-tree water use, irrigation needs and date production. They showed how different cultivars of date palm responded to altered irrigation volumes and salinity levels for the three varieties of date palms: Lulu, Khalas & Shahlah. These three varieties were selected from a long-term date experiment at ICBA involving 18 varieties as they represent a range of salt-tolerances.

Superimposed on these two salinity treatments were four irrigation treatments, and these results allowed owners to minimise the use of irrigation water yet maintain a salt-leaching fraction to flush excess salts from the rootzone in order to maintain date production. The irrigation treatments were set in relation to the date palms' evapotranspiration, $ET_c$ ($Ld^{-1}$), and were 2.5 $ET_c$ which is the current practice, plus 2 $ET_c$, 1.75 $ET_c$ and 1.5 $ET_c$.

Heat-pulse sapflow sensors were inserted into the trees to monitor tree water-use. Time domain reflectometer (TDR) probes were installed in the soil surrounding the trees, both within the irrigation bund and beyond, to monitor the changing pattern of soil water content in the rootzone. In addition, electrical conductivity (*EC*) sensors were placed in the soil within the irrigation bund to monitor the changing pattern of soil salinity. Regular monitoring of the trees' canopy area was carried out using a new device which is called the 'light-stick'. The appropriate level of irrigation was found to be at 1.5 ETc, as this allowed a factor-of-safety and a sufficient salt leaching fraction (Al Muaini et al., 2019a).

### 1.2.3 Commercial Dates

In the UAE there are over 40 million date palms from approximates 70, or so, varieties. In the Emirate of Abu Dhabi alone there are 33 million date palms, and these are primarily concentrated in the region surrounding Al Ain in the east, and along the Liwa Oases in the west (Gulf News, 2015). These date palms require irrigation (Tripler et al., 2011; Sperlin et al., 2014). The rainfall in this hyper-arid region is generally less than 100 mm $y^{-1}$, whereas the reference evapotranspiration, ETo, (Allen et al., 1998) exceeds 2500 mm $y^{-1}$. Groundwater is the prime source of this irrigation water, and about one-third of all groundwater extracted in Abu Dhabi is used to irrigate date palms (MOEW, 2015). However, groundwater is being used at over 25 times the rate at which it is being recharged, such that the groundwater table is dropping at between 1 and 5m per year (EAD, 2019a). The salinity of the groundwater is also increasing, such that only 20% of groundwater usable for agriculture is without desalination (Environment Agency – Abu Dhabi, EAD, 2019b). EAD (2019a) estimated that at the current rate of extraction, usable groundwater will be exhausted within the next two generations. (Environment Agency – Abu Dhabi (EAD, 2019b)). It has been stated by General Sheikh Mohammed bin Zayed Al Nahyan, the president of UAE, that water is more important than oil for the UAE. This major issue is being preoccupied with, and ways to meet future demand and preserve natural resources for coming generations must be devised.

Water-use experiments on date palms at the (ICBA) suggested for Law 5 that the sustainable rate of irrigation for date palms should be 1.5 $ET_c$, where $ET_c$ (L $d^{-1}$) is a daily rate of water transpiration by the date palm (Al-Muaini et al., 2019a). This multiplier of 1.5 includes a 25% factor-of safety, plus a 25% salt-leaching fraction. (Al-Muaini et al. (2019a)) showed that this would mean application of 66 kL $y^{-1}$ with irrigation groundwater at 5 dS $m^{-1}$, and 43 kL $y^{-1}$ for water at 15 dS $m^{-1}$. This is 25–50% less than the 275 L $d^{-1}$ that was previously being applied by ICBA every day of the year, except on Friday. (Al-Muaini et al., 2019).

Further work has revealed the blue and grey-water footprints (L $kg^{-1}$) of date production (Al Muaini et al., 2019c). The challenge, however, is to implement these findings on commercial date farms. EAD (2019b) reported that the Abu Dhabi Farmers Service Centre (ADFSC) had set up an Efficient Irrigation Fund. Whereas some date farmers were using 1500 L $d^{-1}$ (470 kL $y^{-1}$), they have now managed to reduce this to 300 L $d^{-1}$, a saving of 80%. But there is clearly still more to be done to reduce further groundwater use for irrigation on commercial date farms.

Al Muaini et al. (2019c) reported that the benefit-cost ratio of using small-scale on-farm desalination units was 1.4:1. So not surprisingly, small scale desalination plants are being used to freshen-up saline groundwater to maximise its value. But two challenges remain:

- What are the options and impacts of salt leaching from desalination plants when used to freshen groundwater?
- How can saline groundwater and reject brines be better used through growing fish in aquaculture tanks, and then through irrigating halophytic crops with brines.

These two imperatives form the bases of this doctoral research.

### 1.2.4 Crop Calculator

Under Law 5, all groundwater extractions will be monitored by the Environment Agency-Abu Dhabi (EAD) and all farmers will need to operate within their allocation limits. To enable this Law to be easily implemented EAD and Plant and Food Research NZ (PFR) developed the Crop Calculator Decision Support Tool (DST) to help define water allocation limits for groundwater takes. The tool uses the standard FAO-56 guidelines approach for calculating crop water requirements (Allen et al, 1998).

The collaborators have been working with the Abu Dhabi Food Control Authority (ADFCA) on field experiments in Year 1 in an open field at Al Salamat, near Al Ain, and Year 2 in tunnel houses and greenhouses at ICBA near Dubai. This research examined a range of vegetable crops (cabbage, capsicum, cucumber, eggplant, and tomato) grown under outdoor conditions, and in tunnel houses and greenhouses. The crop water balance was measured using weighing lysimeters to provide a precise measurement of crop evapotranspiration, irrigation, rainfall, and drainage.

New data were collected to parameterize the Crop Calculator for the vegetable crops (Al Tamimi et al. 2022). Local values for the crop coefficient have been developed, $K_c$, derived from the lysimeter data. In addition, it allowed for a computed value of the so-called water-use efficiency, in terms of kg of crop per $m^3$ of irrigation water. Environment Abu Dhabi Agency sought to demonstrate the water savings that are possible through good irrigation management.

The crop water balance was measured in the outdoor fields using weighing lysimeters that were designed and constructed in NZ (PFR). These devices are the most accurate way to measure crop evapotranspiration (Marek et al 2006). They measured changes in a container of soil under controlled conditions and could accurately quantify moisture loss due to plant uptake, soil evaporation and drainage. Crop water use was measured directly from the change in pot weight (kg $h^{-1}$) with an allowance being made for irrigation volumes, as measured by the flow meters, and drainage volumes as measured by the tipping-spoon devices placed at the outflow of the lysimeters.

In year two of this project, experiments were set up at ICBA to determine water requirements for vegetable crops grown in a protected (indoor) environment. The selected crops were cucumber, capsicum and tomato and these were planted inside, both a greenhouse (Figure 1.4a) and a shade house (Figure. 1.4b).

**Figure 1.4. (a) The greenhouse facility at the (ICBA) near Dubai and shows the lysimeter pots in the greenhouse. (b) The figure on the left shows the shadehouse and lysimeter pots for the three crops.**

The yields in the greenhouse were much higher than those in the shadehouse. However, the amount of water used to cool the greenhouse was over ten times than used for irrigation, on a per plant basis. Therefore, the WUE is much lower in the greenhouse than the shadehouse. One option to reduce the impact of this water use for cooling would be to use treated sewage effluent in the evaporative coolers "A paper on this research has been published (Al Tamimi et al. 2022)" (See Appendix 8.1). The PhD candidate was the EAD lead on this project.

## 1.3 New Challenges

Salinity impacts on the growth and productivity of most food crops by reducing yields, and in some cases leading to high levels of salt accumulation in the soil, which will limit the choice of crops that can be grown in the future. Food security is a priority area for UAE government. Farmers in many coastal and inland areas will increasingly have to rely on the use of brackish, or saline groundwater, for irrigation of their crops, meaning low yields in most areas and no production in other areas. Thus, there is an imperative to look at the benefit-cost ratios of using alternative water sources and quantifying the environmental impacts.

To combat the problem of salinity and lack of groundwater, the UAE government is promoting the use of small-scale desalination plants to produce fresher water to irrigate high-value crops (Dawoud et al. 2017). However, the desalination plants could pose an environmental threat as the rejected brine, which is very high in salinity (Figure 1.5), has to be disposed of. Typically, this brine goes onto land which then increases the salinity problem, both of the soil, and eventually the underlying groundwater. The use of an Integrated Agri-Aquaculture System (IAAS) is seen as a novel way to make use of the saline or brackish groundwater resources, combining fish farming that utilizes saline water, with cropping that utilizes freshwater for irrigation. Nutrient-rich aquaculture effluents, known as Aquabrine, can be used to irrigate halophytic (salt tolerant) crops for both food and fodder production. Such practices could potentially further increase salinity and contamination of the groundwater if large volumes of drainage water are being generated through poor irrigation practices.

**Figure 1.5. Rejected water from a small-scale desalination plant from one of the farms and which affects both the soil and the underlying groundwaters.**

### 1.3.1 Cheap and small-scale desalination plants.

Through the well-survey project carried out by the EAD from 2015 to 2017, which the PhD candidate was a part of, a new challenge was discovered in the Emirate of Abu Dhabi. This is the return water from desalination plants. Desalination units used by farmers in the surveyed area apparently resorted to, in a considerable number of cases, the use of desalination plants to produce good-water quality. In total, more than 1150 desalination plants were found supplying ‘freshened’ groundwater to crops and livestock (Environment Agency-Abu Dhabi (EAD) (2015-2017)). (Figure 1. 6). Table 1.3 shows the distribution and relative percentage of the desalination plants in these surveyed areas.

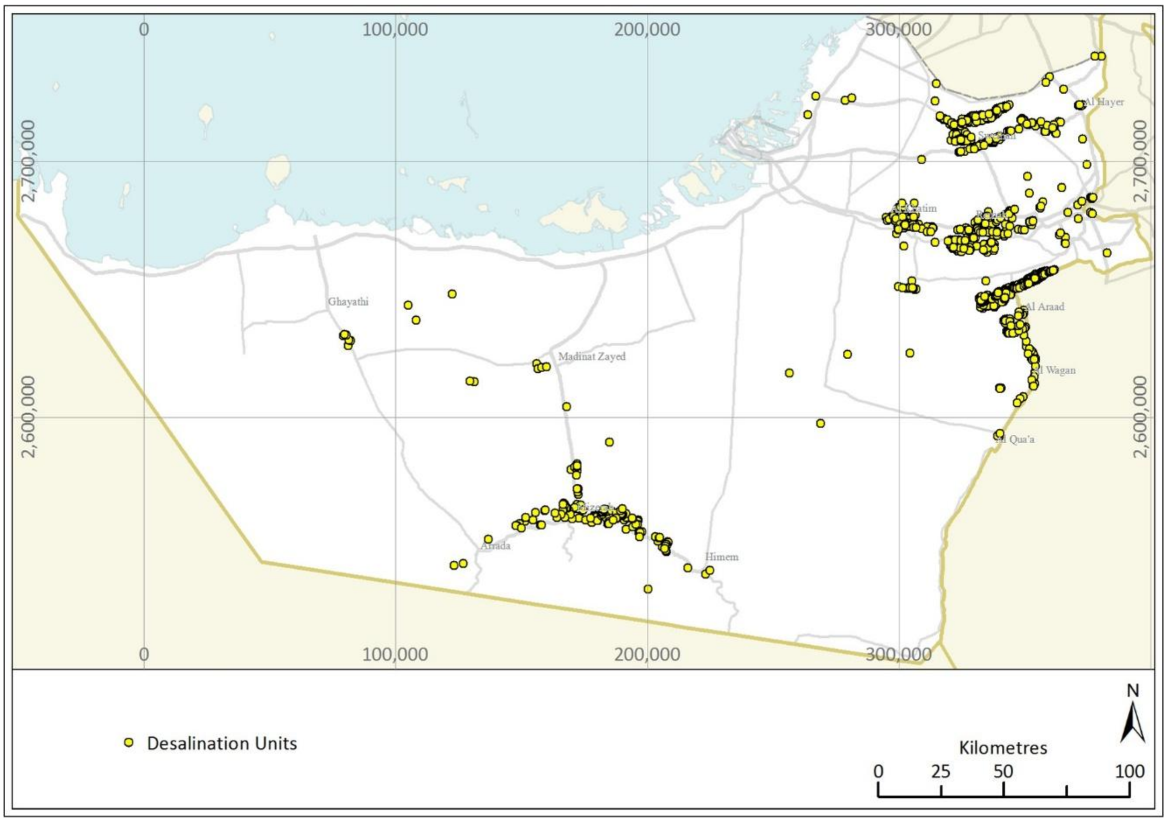


**Figure 1.6. Small-scale on-farm desalination units in the Abu Dhabi Emirate. Al Ain is the area to the east, and Al Dhafra is to the southwest around the crescent of the Liwa oases.**

**Table 1.3: Desalination units in the regions of the Abu Dhabi Emirate.**

| | **Near Abu Dhabi** | | **AL Ain** | | **Al Dhafra** | | **Total In Abu Dhabi** |
|---|---|---|---|---|---|---|---|
| | No. | % | No. | % | No. | % | No. |
| **Desalination Units** | **114** | **10** | **871** | **75%** | **171** | **15** | **1156** |

The EAD project of the Groundwater Well Inventory and Soil Salinity Mapping for the Abu Dhabi Emirate was a major step forward in EAD's efforts to manage effectively and sustainably the groundwater resources of the Emirate. With the number of groundwater wells and the groundwater resources now sufficiently known (Environment Agency-Abu Dhabi (EAD) (2015-2017)), the following steps were considered to ensure proper management in the future:

- Regulation of desalination-unit usage on farms and the related brine disposal.
- Promotion of efficient irrigation practices, via drip irrigation or subsurface systems
- Understanding of the environmental impacts of the use of highly saline water for irrigation of halophytes.

As well, there is a need to link this in with other valuable uses of already saline waters. These knowledge gaps were sought to be filled by the proposed doctoral research.

### 1.3.2 Integrated Agri-Aquaculture Systems

To combat the problem of groundwater salinity and a lack of groundwater, the UAE government is promoting the use small-scale desalination plants to produce freshwater to irrigate high-value crops to aid food security. As already noted, Al Muaini et al. (2019) found there to be a benefit-cost ratio of 1.4 when irrigating dates with desalinated groundwater. Figure 1.7 shows The Integrated Agri-Aquaculture System (IAAS) as set-up at the International Centre for Biosaline Agriculture near Dubai (from Lyra et al. 2014). This enhances food security by producing additional food from the use of the reject brine.

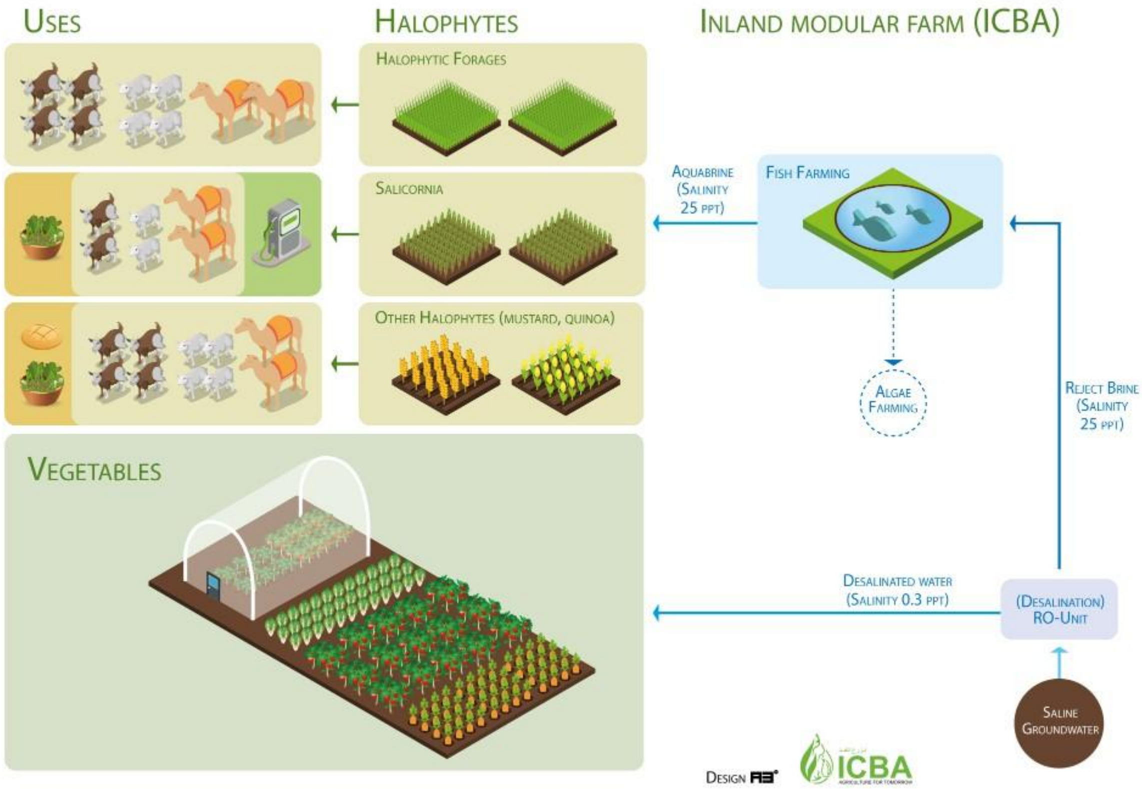


**Figure 1.7. The Integrated Agri-Aquaculture System (IAAS) as set-up at the International Centre for Biosaline Agriculture near Dubai (from Lyra et al. 2014).**

## 1.4 Halophytes in the UAE

Salt-tolerant plants, both cultivated and wild, have had increased importance during recent decades (Al Yamani et al. 2013). Scarcity of freshwater resources suitable for conventional agriculture, salinization of irrigated agricultural lands, intrusion of seawater to inland aquifers due to over-exploitation of groundwater resources, and other natural causes have all led to increased salinity problems in many parts of the world (United Nations Convention to

Combat Desertification, 2022). Arid environments are particularly susceptible to the problems of soil and water salinization. The exploitation of saline water and salt-affected land requires careful selection of appropriate plant species and varieties that have both economic and environmental value (Al Yamani et al, 2013). Although many farmers are reluctant to grow crops in sand with salty water, the disadvantages of these conditions for conventional crops, can indeed become advantages when halophytes and salt-tolerant plants are cultivated (Lyra et al., 2014). Arid countries can benefit significantly from using saline water and soils in agriculture. Salt-tolerant plants can utilize water and land that is unsuitable for salt-sensitive crops. This can lead to the economic production from halophytes of food, fodder, and many, other products. In the UAE, there are at least 125 wild and cultivated plant species, However, one option, Salicornia, is not a native plant in the United Arab Emirates. Rather it is native of the coastal areas of the eastern and southern United States, Belize, and the eastern and western coasts of Mexico (Karam et al (2006).

### 1.4.1 Potential uses of salt-tolerant plants

Salt-tolerant plants and halophytes are typically found along the seashore and in estuaries and saline seeps on the Arabian Peninsula, known as sabkha. These plants can have many potentials uses as food, fodder, fibre, fuel, and other production values. Economic consideration of these plants is now receiving increased attention in the UAE and elsewhere. These potential uses are listed below.

#### *1.4.1.1 Food*

Salt-tolerant genotypes of important cultivated food plants have the potation to offer the same value as traditional food crops. They can grow using saline groundwater for irrigation, and still achieve economic returns (Panta et al. 2014). Numerous salt-tolerant genotypes of several crop plants have already been identified and exploited. Examples are date palm, millets, maize, sorghum, oats, barley and wheat. The Chinese have developed a rice plant they call sea-rice because of its ability to grow under saline conditions (Karam et al.,2006). Many naturally occurring halophytes also have the potential of being utilized as human food (Figure 1.8) (Karam et al.,2006).

**Figure 1.8: Halophytic vegetables eaten in the UAE.**

### *1.4.1.2 Fodder*

Halophytic and salt-tolerant grasses, shrubs and trees are excellent sources of fodder for animals (Panta et al. 2014). Salt-tolerant grasses like *Chloris guayana* (Rhodes grass), *Panicum turgidum*, *Pennisetum* spp., *Lasiurus* spp., and many others, are excellent natural forages. Indeed, many of these have been converted into cultivated crops. Other halophyte grasses like *Sporobolus* spp., *Distichlis* spp., *Paspalum* spp. and *Spartina* spp. have also been successfully used as fodder. Many of these species are currently being evaluated for commercial large-scale production using highly saline waters. Similarly, many trees and shrubs have been used in grazing, although they are generally less palatable than grasses when used for cattle fodder (Figure 1.9) (Karam and Dahkheel., 2006).

**Figure 1.9. Salicornia cultivation in Abu Dhabi, in a pilot project conducted by Masdar Institute's Sustainable Bioenergy Research Consortium (SBRC). This project is bringing private sector firms together to answer the question 'is it possible to create a sustainable jet-powering biofuel?'**

### *1.4.1.3 Fibre, fuel, and Medicinal uses from Halophytes*

Some salt-tolerant plants are suitable for use as fibre, and examples include the hibiscus plant and the common reed (*Phragmite*). This species is frequently used to make fences, roofs, baskets, and firewood, and many salt-tolerant and salt-tolerant trees and shrubs can also be used as fuel for the production of saline environments (Karam and Dahkheel 2006). These include the tree species of *Tamarix* and *Casuarina*. Several plants have been used in the UAE in traditional medicine for a long time. The efficacy of many of these plants in treating specific diseases, such as diabetes, high blood pressure, skin diseases, intestinal diseases, heart diseases, arthritis and urinary tract disorders, is well known in traditional medicine. Others can be used as sedatives and antipyretics. Certain chemical compounds from local plants for medicinal uses are popular in the United Arab Emirates. However, when growing halophytes using very saline irrigation, there is the attendant risk of the leaching of salts, and nutrients, from the rootzone, that could potentially find its way back to the aquifer, thereby rendering the groundwater more saline and of lower quality.

## 1.5 Salt dynamics and leaching under Saline Irrigation

To understand the risks associated with growing halophytes using saline waters, EAD established a new contract with OFNZ and PFR to measure the salt and nutrient leaching under halophytes and to assess the risk of the build-up of salt in the soil, and the risks of further contaminating groundwater through the leaching load of salt and nutrients. This doctoral research is the basis of that programme.

In summary the research aims to be addressed in this PhD programme are:

- Water balance and fluxmeter measurement technologies for assessing the impacts from saline irrigation of the halophyte Salicornia.
- The impact of irrigation of Salicornia on salt and nutrient dynamics in the soil, and salt and nutrient leaching.
- Modelling of saline irrigation on salt dynamics and crop yield, and the development of a heuristic model for salt and nutrient dynamics.
- Analysis of the benefit-costs of the irrigation of Salicornia with various saline irrigation waters and delivery systems, and application of the heuristic model to assess future impacts on groundwater.

### 1.5.1 Pilot Project

#### *1.5.1.1 Background - 2020/2021*

An initial Pilot Project was designed for the first year of 2020/21. The key novelty of this project, which would complement the IAAS studies at ICBA, was to use new measurement devices to measure the impact of irrigation on soil water and soil salt concentrations, as well as the monitoring of leachate. These new devices would be installed in plots of the three halophytic crops of Salicornia, Quinoa, and Blue Panicum. Three types of saline irrigation water would be used: saline groundwater (GW), reverse-osmosis brine (RO-brine) rejected from a desalination plant, and Aquabrine (AQ) from the aquaculture fish tanks.

Drainage fluxmeters (DFMs) have been used to measure leachate moving from the rootzone in crops around the world. A tension DFM has been developed by PFR (Green et al. 2010) wherein a capillary wick 600 mm long sits under a convergence ring atop a reservoir that is buried in the soil (Figure 1.10). This capillary wick mimics the capillary forces that occur natural in the porous medium of the soil. Water can be extracted from the reservoir by a pump to obtain the amount of drainage, and solute concentrations can be measured in the leachate, such that the product is the leachate load in kg $ha^{-1}$. Such devices have never been used for salt leaching studies under halophytes being irrigated with saline groundwaters.

Time domain reflectometry devices were developed for use in saline soils in the two antecedent EAD projects by Al Yamani et al. (2019a) and Al Muaini et al. (2019a). For the saline soil conditions, the rods needed to be sleeved in heat shrink tubing to prevent signal loss as a result of the high EC in the soil. These devices were used in the Pilot Project to monitor soil water and salt dynamics in the rootzone, along with the DFMs to measure salt leaching from the rootzone back to groundwater (Figure 1.11).

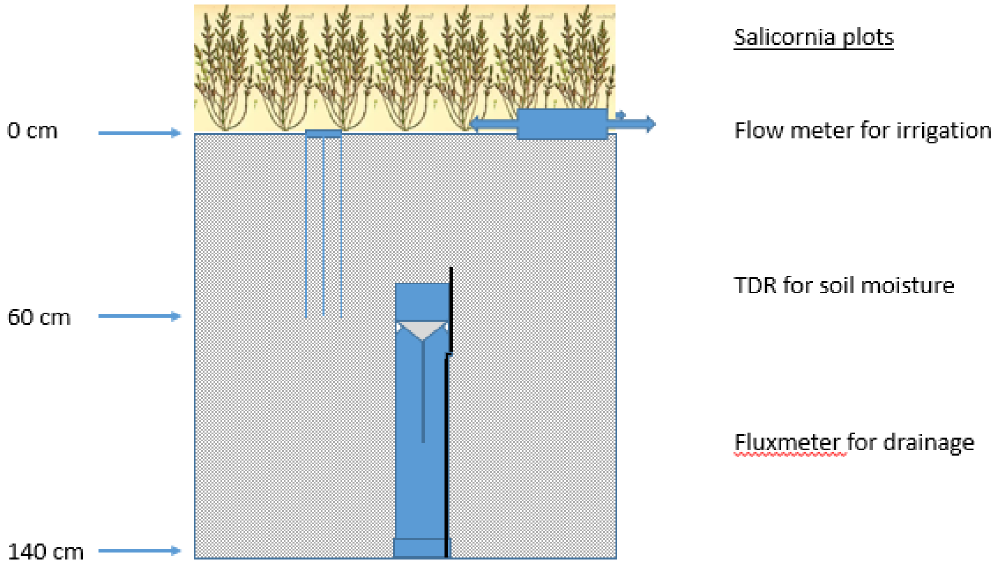


**Figure 1.10. A schematic of the Pilot Project set up of instrumentation to measure the soil water balance and leaching losses of salt and nutrient (nitrate) under a Salicornia crop. Time-domain reflectometer (TDR) waveguides were installed within the rootzone (0-60 cm) to assess changes in soil water content. Drainage flux meters were installed at 60 cm to measure water drainage and salt leaching losses in this Pilot Project.**

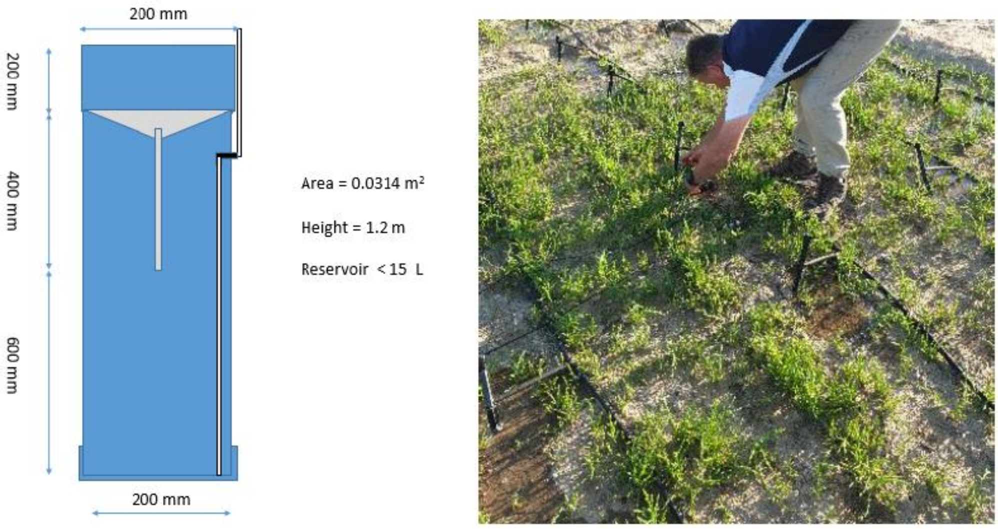


**Figure 1.11. Left panel shows a schematic of the passive-wick drainage flux meters (DFM) that were installed at a soil depth of 60 cm under the three halophytic crops. Volumes of water were extracted from the DFMs, at 10-14 day intervals, using a vacuum pump. Sub-samples of the drainage water were analysed for pH, salt content (total dissolved solids, TDS), electrical conductivity (EC), chloride and nitrate. The right panel shows TDRs being installed in the Pilot Project in a Salicornia plot.**

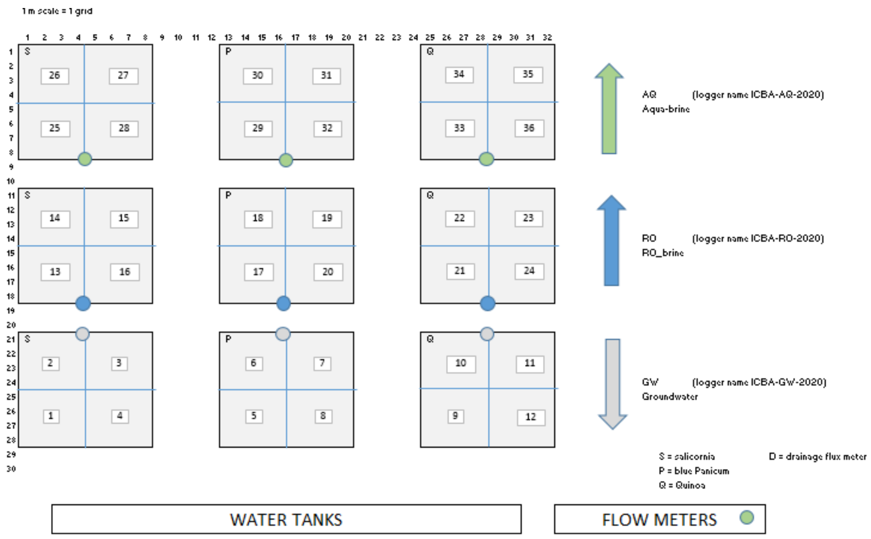


**Figure 1.12. A diagram of the plot layout for Pilot Project of the salt leaching experiments at ICBA beginning in 2020. Irrigation volumes to each plot are monitored using digital flow meters (circles). The numbered squares show locations of drainage fluxmeters. The crop types are labelled as S = Salicornia, P = Blue Panicum and Q = Quinoa. The water sources are labelled as AQ = Aquabrine, RO = RO-brine and GW = Groundwater.**

### *1.5.1.2 Outcome of the Pilot Study*

The Pilot Study was a failure.

The Quinoa and Blue Panicum failed to germinate adequately. The Salicornia was slow in germinating, but eventually produced a moderate crop (Figure 1.13). The yield of Salicornia was greatest under AQ, then RO-brine, followed by GW (Figure 1.14). It was questioned whether the site chosen for this purpose had become contaminated by salts, or other compounds, through its antecedent uses. Additionally, it was identified that the drainage fluxmeters (DFM) were not functioning.

In this soil, at a depth of about 500 mm there is a horizon of gypsum, presumably mobilised from above and precipitated at 500 mm. During the installation of the DFMs this soil is disturbed and repacked above the DFMs. When rewet, it appears that this again re-precipitates, and then at this time it forms an impermeable barrier above the DFMs. Also, the convergence ring atop the DFMs may not have been big enough to draw water in via the capillary forces induced by the wick.

In conjunction with ICBA, EAD, PFR and OFNZ, meetings were held to redesign the trial set-up, experimental location, devices, and crop selection. The new plan that was developed and is discussed in the following section.

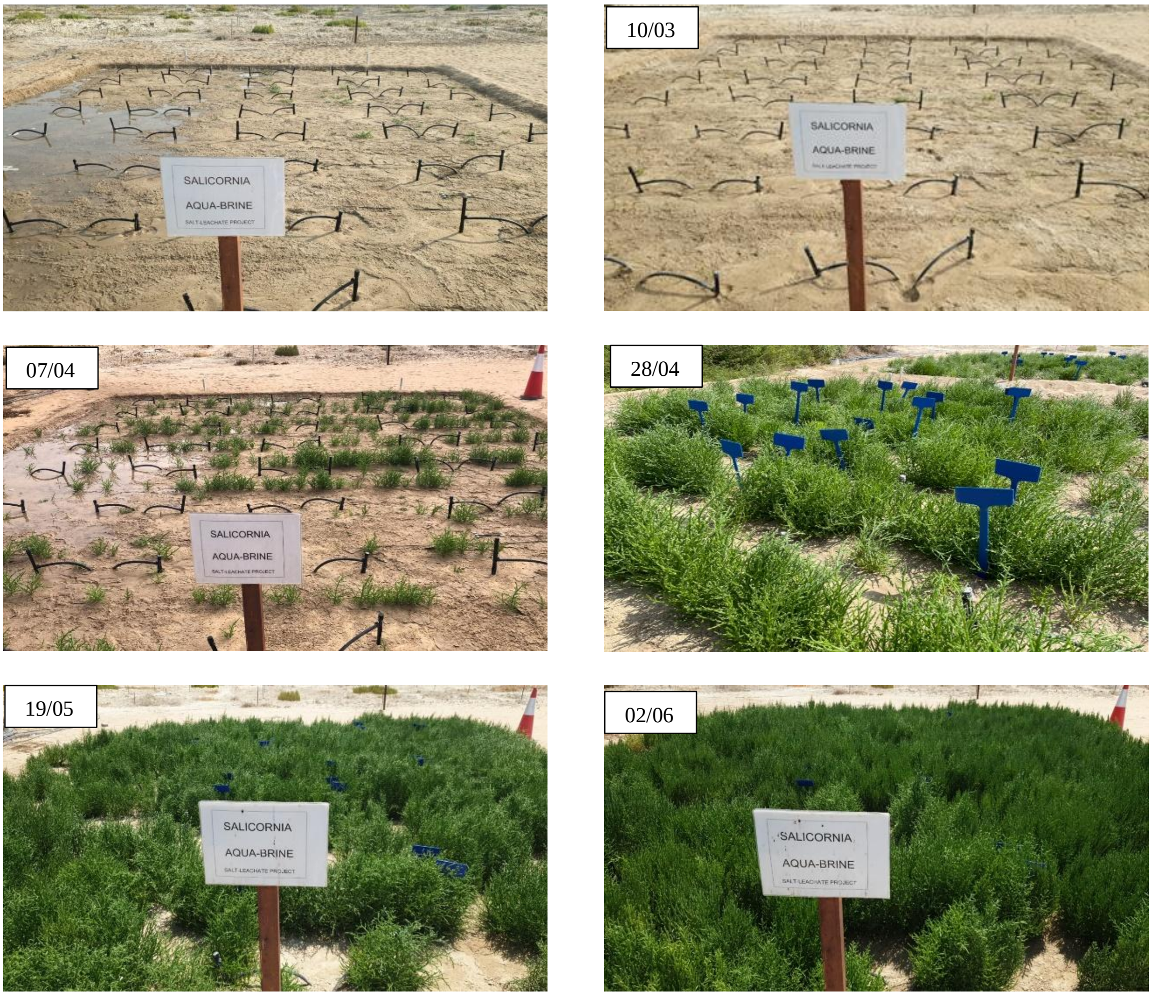

**Figure 1.13. Time sequence of Salicornia growth under Aquabrine (AQ) irrigation. The date of each photo is recorded on the top left-hand corner, in the format dd/mm where dd is day and mm is month. Irrigation is via bubblers arranged on a 1m by 1m grid. The plot is edged with a 10 cm high sand wall.**

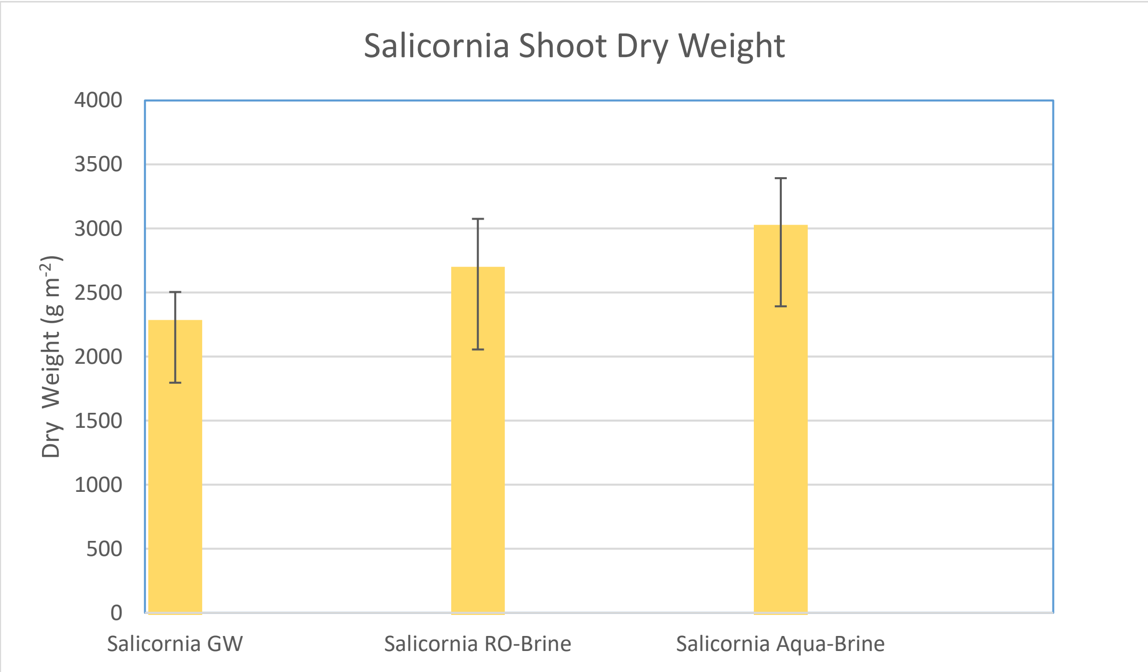


**Figure 1. 14. The dry-weight shoot yield of Salicornia in g m-2 from the Pilot Project for groundwater (GW) irrigation, reverse-osmosis brine (RO-brine) and Aquabrine.**

### 1.5.2 Rethinking the Experiments

Due to the issues experienced with drainage collection and crop growth in the 2020 Pilot Project, several options were developed for 2021 and beyond. These design changes to this doctoral research were:

- To move the entire experiment to a new "previously freshwater site" near the IAAS. The plots in this site had only been irrigated with freshwater for the past 18 months.

- To focus on one crop, Salicornia, only. Salicornia has the best chance of achieving full production during the next two seasons and the fact that it is a halophyte that can tolerate very high soil salinity. Salicornia can also be commercialized and used as food for humans, seeds for oil, and forage for animals. It is a versatile, multi-use halophytic crop.

- Grow Salicornia under the three different water treatments (GW, RO-Brine and AQ-Brine), using three different irrigation methods (bubblers, drippers and subsoil) per treatment.

• Modified fluxmeters, with larger diameter tops and longer (1m) wicks (Figures 1.15 and 1.16). As well, the DFMs were installed closer to the soil surface at about 100 mm to avoid any precipitate layers. As well as conventional suction-cups were be installed in each plot to gather samples of drainage water, as backup in case the modified fluxmeter did not work.

• All plots were equipped with modified TDR instrumentation to monitor soil water contents and EC, and as well digital flow meters were installed to monitor irrigation volumes, as per last year's experiment

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# CHAPTER 2

# 2 OBJECTIVES AND THESIS STRUCTURE

## 2.1 Research Objective and Methodology

This Ph.D. research will explore the trade-offs between improved technologies for the use of alternative water supplies, such as desalination brines, and the environmental consequences of brine re-use, and it will be part of the future solution of the relationship among food, energy and water that will shape Abu Dhabi. This doctoral research builds on nearly a decade of scientific knowledge developed with the New Zealand teams, will identify the opportunities that can be taken advantage with reject brine in aquaculture and halophytic agriculture, as well as the environmental consequences of the fate of this salt and nutrients.

To understand the risks associated with growing halophytes using saline waters, EAD established a new contract with OFNZ and PFR to measure the salt and nutrient leaching under halophytes and to assess the risk of the build-up of salt in the soil, and the risks of further contaminating groundwater through the leaching load of salt and nutrients. This doctoral research is the basis of that programme.

In summary the research aims to be addressed in this PhD programme are:

- Water balance and fluxmeter measurement technologies for assessing the impacts from saline irrigation of the halophyte Salicornia.
- The impact of irrigation of Salicornia on salt and nutrient dynamics in the soil, and salt and nutrient leaching.
- Modelling of saline irrigation on salt dynamics and crop yield, and the development of a heuristic model for salt and nutrient dynamics.
- Analysis of the benefit-costs of the irrigation of Salicornia with various saline irrigation waters and delivery systems, and application of the heuristic model to assess future impacts on groundwater.

## 2.2 Thesis Structure

The thesis consists of seven chapters. The core Chapters 3-5 are published papers, and Chapter 6 is a submitted paper under review. Chapters 1 and 2 set the scene for the research and detail to research aims. Chapter 7 provides the conclusions and outlines recommendations for future research. The Chapter are as follows:

- Chapter One: Introduction & Literature Review
- Chapter Two: Objectives and Thesis Structure
- Chapter Three: Devices to Measure the Impacts on Groundwater Salinity from Irrigating Halophytic Crops with Brackish Waters in a Hyper-Arid Environment

- Chapter Four: Salt Dynamics, Leaching Requirements, and Leaching Fractions during Irrigation of a Halophyte with Different Saline Waters
- Chapter Five: Drainage, Salt-Leaching Impacts, and the Growth of Salicornia bigelovii Irrigated with Different Saline Waters
- Chapter Six: Measurement and Heuristic Modelling of Nitrogen and Salt Dynamics under Salicornia Growing in a Hyper-arid Region and Irrigated with Waters of Differing Nutrient and Salt Loadings
- Chapter Seven: Conclusions & Recommendations for Future Research

# CHAPTER 3

# 3 DEVICES TO MEASURE THE IMPACTS ON GROUNDWATER SALINITY FROM IRRIGATING HALOPHYTIC CROPS WITH BRACKISH WATERS IN A HYPER-ARID ENVIRONMENT

Chapter 3 presents evaluation of the pilot trial in 2020 where two difficulties had been encountered. One related to inability to measure the soil's water content, and the other a failure to monitor leaching using tension drainage fluxmeters (DFM). Three-wire time domain reflectometer (TDR) probes could not measure the water content because the high electrical conductivity. However, it was discovered that Topp's TDR equation applied when all three wires of the probe were shielded with glue-lined heat-shrink. Initially, drainage at a depth of 600 mm was not registered by the passive-tension DFMs.

Yet measurements of the soil hydraulic conductivity showed it to be highly permeable. The failure of the DFMs was due it was considered to the disturbance of the calcic and gypsic materials at the 600 mm depth, such that when the re-packed soil was subsequently re-wet it formed an impermeable layer. The top of the DFMs was installed at just a depth of 200 mm. The diameter of the convergence ring was increased from 150 mm to 250 mm for wider capture, and the length of the wick for the passive tension was increased from 600 mm to 700 mm. The successful use of these modified devices has been presented in this chapter.

The contents of this Chapter have been published in a slightly different form as:

**Al-Tamimi, Mansoor, Steve Green, Wasel Abou Dahr, Ahmed Al-Muaini, Dionysia Lyra, Khalil Ammar, Mohamed Dawoud, Paul Kenyon, Peter Kemp, Lesley Kennedy, and Brent Clothier. 2023 Devices to Measure the Impacts on Groundwater Salinity from Irrigating Halophytic Crops with Brackish Waters in a Hyper-Arid Environment.** ***Journal of Arid Environments*** **220 https://doi.org/10.1016/j.jaridenv.2023.105115**

The DRC 16 Statement of Contribution is provided in Appendix 8.3.

## 3.1 Abstract

There is a need to understand groundwater impacts and the benefits of using saline groundwater and brines from desalination plants to irrigate halophytes in hyper-arid environments. Measurements are critical. In 2020, a pilot trial was set up using irrigation with highly saline waters. However, two difficulties were encountered. One related to the inability to measure the soil's water content, and the other a failure to monitor leaching using tension drainage fluxmeters (DFM). The three-wire time domain reflectometer (TDR) probes could not measure the water content because the high electrical conductivity. Through shielding all three wires of the probe with glue-lined heat-shrink, Topp's TDR equation was found to be applicable. Initially the passive-tension DFMs did not register drainage at a depth of 600 mm. Yet the measurements of the soil hydraulic conductivity showed it to be highly permeable. The failure of the DFMs was thought to be due to the disturbance of the calcic and gypsic materials at the 600 mm depth, such that when the re-packed soil was subsequently re-wet it formed an impermeable layer. The top of the DFMs was installed at a depth of just 200 mm. The diameter of the convergence ring was increased from 150 mm to 250 mm for wider capture, and the length of the wick for the passive tension was extended from 600 mm to 700 mm. Results from the successful use of these modified devices are presented.

## 3.2 Introduction

Globally, there is a challenging nexus between our need for food security, and our ability to maintain energy supplies, whilst protecting our water resources, especially in hyper-arid regions. Niu et al. (2019) noted that in hyper-arid regions *"... agricultural development can occur at the expense of ecosystem conservation and water quality. To balance the conflicting interests, the water-ecosystem-agriculture nexus in such areas needs to be systematically* addressed". Modifications are provided to field devices, enabling measurements to be taken that will provide the understanding necessary for such systematic assessments. The work was carried out in the hyper-arid United Arab Emirates (UAE).

There are no surface water resources in the UAE, and the Ministry of Environment and Water calculates that two-thirds of the gross irrigation-water demand is supplied by non-renewable groundwater extraction. The UAE State of the Environment Report in 2015 noted that groundwater levels had dropped by over 10 m per decade, until the mid-1990s, and by a further 70 m since then (MOEW, 2015). The agricultural, forestry and landscape sectors account for nearly 60% of the annual water demand of 4.2 km$^3$ across all of the Emirates of the UAE. In 2016, the Government of Abu Dhabi passed a regulation (Law 5) to limit groundwater use in the Emirate of Abu Dhabi (EAD, 2016).

Recently, the UAE Government released its national food strategy through to 2051 (UAE, 2019). In 2018, the UAE was ranked 31$^{st}$ out of 113 countries in terms of the global food security index. By 2019 it had improved 10 places, and it has the goal of being number one by 2051. By 2050, the UAE seeks to have some 50% of its energy coming from either clean energy or nuclear power.

A changing aspect at the food-water-energy nexus has been the rise of small, stand-alone desalination units to 'freshen up' groundwater for use to irrigate high-value crops (Dawoud, 2017; Al-Muaini et al., 2019b). A survey by EAD has shown that there are now over 1500 on-farm desalination units.

However, the desalination plants pose an environmental threat to groundwater as the reject brine, which is hyper-saline, requires disposal. Typically, this brine goes onto land which then increases the salinity problem, both for the soil and eventually the underlying groundwater (Mohamed et al., 2005). The use of an Integrated Agri-Aquaculture System (IAAS) is seen as a novel way to make use of the saline or brackish groundwater resources (Lyra et al., 2014). This approach combines fish farming that utilizes saline water, with cropping that utilizes freshwater for irrigation (Sanchez et al., 2015; Somerville et al., 2014). Nutrient-rich aquaculture effluents, known as aquabrine, can then be used to irrigate halophytic (salt-tolerant) crops, for food, fodder and even biofuel production (Lyra et al., 2014; Panta et al., 2014; Robertson et al., 2019).

Therefore, the primary goal of this research was to assess quantitatively the groundwater impacts and production benefits of the use of highly saline water from groundwater and brines from desalination units, for the irrigation of halophytes. However, to manage sustainably the irrigation of *Salicornia* with saline water it is imperative to be able to measure groundwater effects, to assess better the impacts, options, and opportunities at the food-water-energy nexus. The critical nature of measurements was addressed here.

Two technical challenges were encountered initially. One related to measurement of the soil's water content, and the other to monitoring of drainage and leaching.

Vogeler et al. (1997) showed that using time domain reflectometry (TDR) was the best way to measure soil-water content and electrolyte concentration in soil.

TDR devices were therefore employed to measure soil-water content and electrical conductivity in the rootzone soil of halophytes irrigated with saline waters. However, the TDR system initially failed to operate in such a highly saline environment.

Passive-tension drainage fluxmeters (Gee et al., 2009) were then sought to be used for measuring both the drainage and the flux concentration of salt leaching through the soil for despatch to the underlying groundwater. However, these drainage fluxmeters (DFM) also initially malfunctioned in this aeolian desert sand.

Consequently, the following objectives were established:

- To modify three-wire time domain reflectometry probes (Topp et al., 1980) to measure the changing water contents, and soil water and salt dynamics in the rootzone of halophytic crops irrigated with highly saline waters in a hyper-arid region.
- To modify tension drainage-fluxmeters (Gee et al., 2009) to measure water drainage and salt leaching down to underlying aquifers through aridic desert sands with calcic and gypsic horizons. Such Typic Torripsamments are the most extensive soils in the

UAE, covering about 75% of the Emirates, and they occur across much of the Arabian Peninsula (Abdelfattah & Pain, 2012).

The data provided by these modified devices will be used in future analyses and modelling to quantify the groundwater impacts of the use of highly saline waters from groundwater and brines that are used for the irrigation of halophytes.

## 3.3 Materials and Methods

### 3.3.1 Initial Trial - 2020

Initial experiments with *Salicornia bigelovii*, and two other halophytes, blue panicum (*Panicum antidotale*) and quinoa (*Chenopodium quinoa*), were established in November 2020 at ICBA near Dubai in the United Arab Emirates. These pilot experiments had limited success. The blue panicum and quinoa had very poor germination, and so they were dropped from future experimental plans. Only results for Salicornia in 2021 are presented here.

The soil at the site is a Typic Torripsamment. It is a deep sandy soil with a carbonatic mineralogy, and it consists of quartz, mixed sands, volcanic glass, plus calcareous and gypsum concretions at depths beyond about 0.5 m (EAD, 2009). Typic Torripsamments are the predominant soil type across the whole of the Arabian Peninsula.

Two technical difficulties were encountered during this pilot trial. The three-wire time domain reflectometer (TDR) probes, previously developed for use in date-palm orchards (Al-Muaini et al., 2019a), were intended to be used. In that environment, with irrigation waters ranging from 5 to 15 dS $m^{-1}$, the centre-rod required shielding with glue-lined heat-shrink tubing to minimize salinity-induced signal attenuation down the core rod. However, in this pilot trial utilizing highly saline waters exceeding 20 dS $m^{-1}$, complete signal loss was experienced, rendering measurements impossible. Consequently, further modifications to the three-wire design were undertaken to enable TDR measurement of the soil's changing water content.

The tension drainage-fluxmeters (DFM) also failed to capture the percolating drainage water, representing the second difficulty encountered. The fluxmeters were installed with the top of the convergence ring positioned at a depth of approximately 600 mm below the soil surface.

A capillary wick used to create the passive tension was 600 mm long. This design has been used successfully in many other environments (Gee et al., 2009). This failure to measure drainage by the DFM caused a rethink of the fluxmeter design, and the depth below the surface at which the convergence ring should be located.

### 3.3.2 *Salicornia* Trial – 2021

Salicornia seed was sown during the first week in November 2021. The trial design used three types of irrigation emitters: bubblers (BUB), drippers (PCD), and sub-surface tape (SUB). Three types of saline waters were used for irrigation: aquabrine (AQ; ≈ 40 dS $m^{-1}$), reverse-osmosis (RO) reject brine from a desalination plant (≈ 40 dS $m^{-1}$), and groundwater (GW, ≈ 20 dS $m^{-1}$).

### 3.3.3 Time Domain Reflectometry Modifications

Al-Muaini et al. (2019a) found that sleeving the core rod of three-wire TDR probes enabled the use of TDR in the rootzone of date palms growing in a Typic Torripsamment and irrigated with water up to 15 dS $m^{-1}$. The experiments here used irrigation water up to 50 dS $m^{-1}$.

Testing of the three-wire TDR probes, both with bare rods and with all three wires fully sleeved, was conducted in the laboratory using soil wetted with water at 85 dS $m^{-1}$. The TDR traces are shown in Figure 3.1.

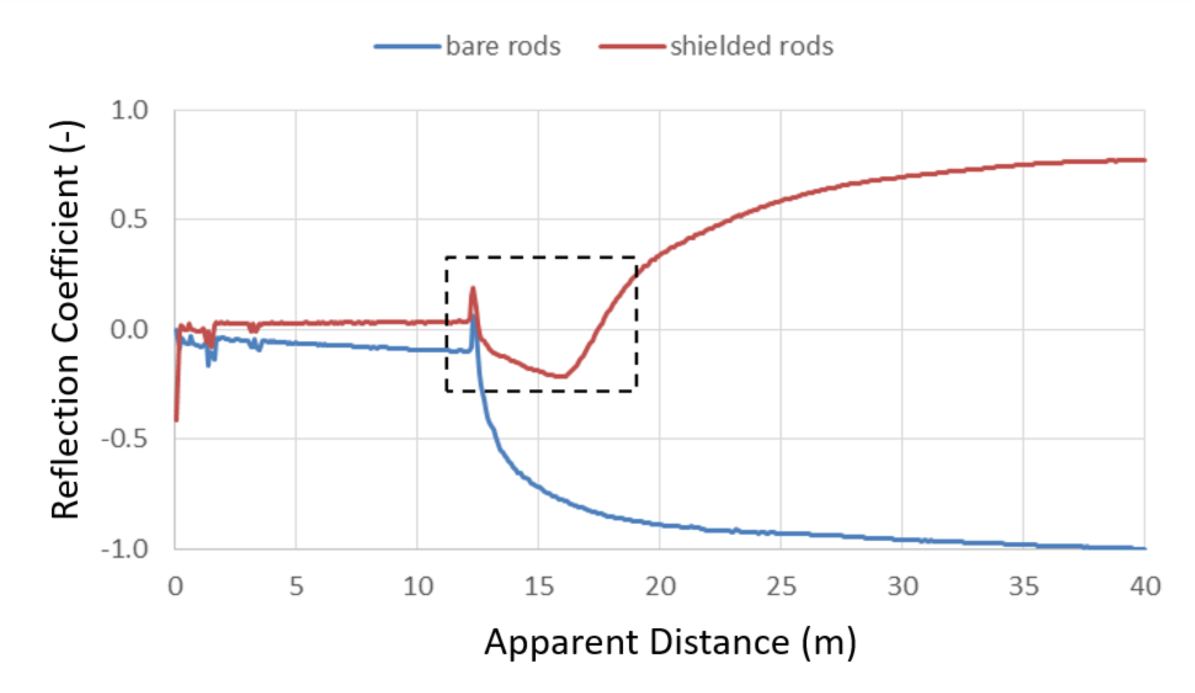


**Figure 3.1. The reflection coefficients of the time domain reflectometer (TDR) waveforms from three-wire TDR probes in soil wet with saline water at 85 dS $m^{-1}$ in the United Arab Emirates. The blue waveform is for probes with all wires unshielded, and the red waveform is for a probe with all three wires insulated by glue-lined, heat-shrink tubing to minimise the effects of signal attenuation down the rods.**

The signal attenuation for the bare rods was so great that the reflection coefficient revealed no echo returned from the ends of the rods. With all three wires sleeved in thin, glue-lined heat-shrink tubing, an echo was detected, and the apparent length of the rods, *L*a, can be found from the distance from the entry of the waveform into the rods to the echo off the end of the wires (Figure 3.4). From the known length of the rods, *L*, the apparent dielectric $K_a$ of the soil can now be found using $(La\ L^{-1})^2$. Topp et al. (1980) established the use of TDR in soil by linking the measured apparent dielectric constant to the soil's volumetric water content (Figure 3.2).

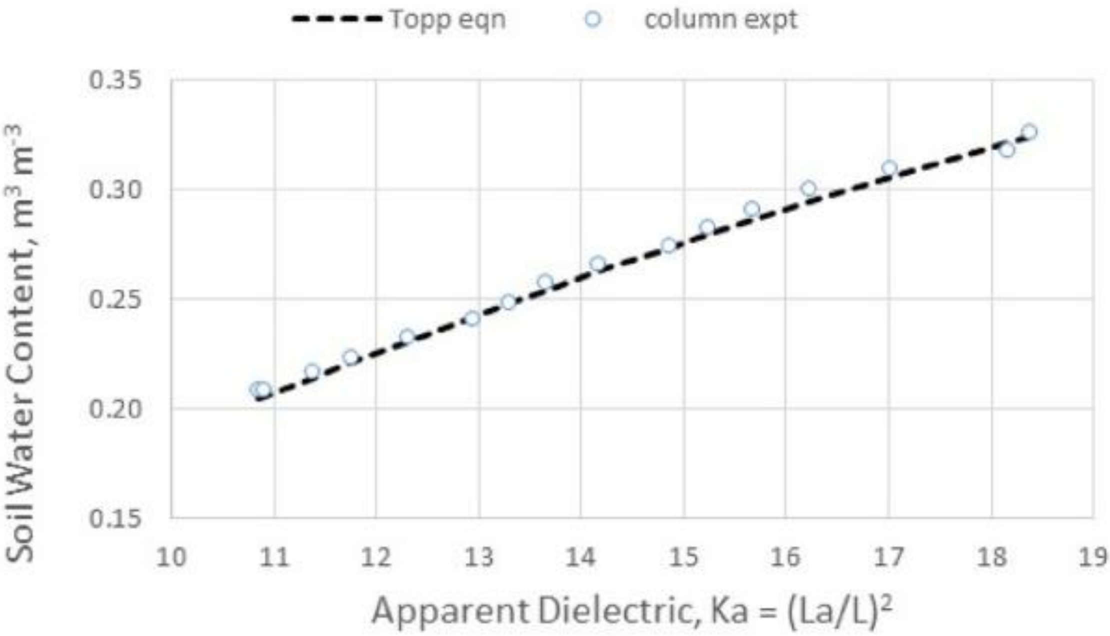


**Figure 3.2. Comparison of the soil-water content measured using the apparent dielectric constant $K_a$ from a three-wire shielded time domain reflectometer (TDR) probe in soil wetted by highly saline water in the United Arab Emirates, and that predicted by the Topp et al. (1980) for non-saline soils.**

A laboratory experiment was set up to verify the soil's water content measured using fully sleeved TDR rods. A cylinder of diameter 200 mm and length 650 mm was filled with dry silica sand to a bulk density of 1.2 g $m^{-3}$. A fully sleeved three-wire TDR probe of length 600 mm was inserted into the sand. Sequential aliquots of 1 L of 85 dS $m^{-1}$ saline water were added to the soil. After each aliquot, TDR measurements were taken until the measured dielectric remained unchanged. Then the next aliquot was added, and the same procedure followed. In total, some 21 aliquots were added to bring the soil up to saturation, at the time water first leaked out from the base. Volumetric arithmetic was used to infer the soil's water content from the amount of water added at each stage.

Figure 3.2 depicts the relationship between the measured soil-water content and the apparent dielectric, which can be observed to align with Topp's equation. This provided confidence in the use of fully sleeved three-wire TDR probes for measuring water content in soil irrigated with highly saline waters.

Measurements obtained from the 600-mm sleeved three-wire probes under the AQ treatment, for BUB, PCD, and SUB emitters, are presented in Figure 3.3. Initially, the plots were irrigated with 10 dS $m^{-1}$ water to facilitate successful germination of the Salicornia.

After 23 February 2022, the water treatments were begun. It can be seen in Figure 3.6 that for the AQ water at about 35–40 dS $m^{-1}$, there was a rise in the water content of the soil as the soil became fully wet over the two months.

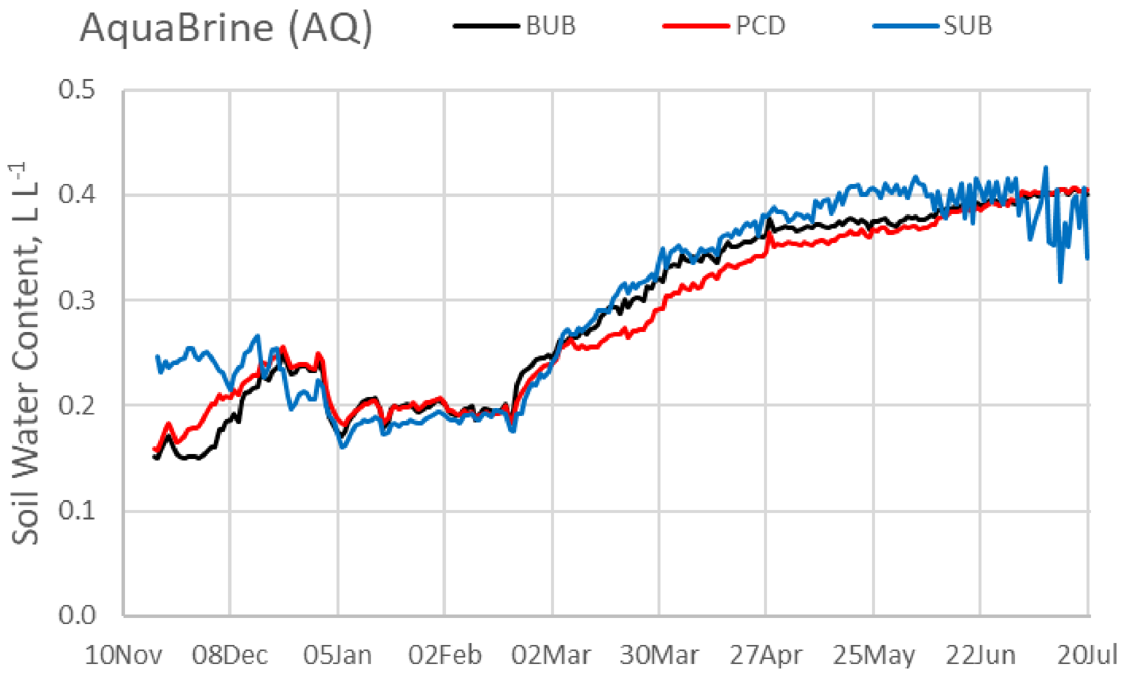


**Figure 3.3. Measurements by shielded three-wire time domain reflectometer (TDR) probes of length 600 mm under a plot of *Salicornia bigelovii* irrigated with aquabrine via either bubblers (BUB), pressure-compensated drippers (PCD) or sub-surface irrigation tape (SUB). The TDR probes were located close to the emitters. The period covered is from November 2020 to July 2022. Irrigation with the aquabrine commenced on 23 February 2022 in the United Arab Emirates.**

Through full sleeving of all three rods, modifications were made to the three-wire TDR probes, enabling measurement of the water content in the rootzone soil irrigated with highly saline water within a sandy desert soil of a hyper-arid region.

### 3.3.4 Tension Drainage Fluxmeter Modifications

The assessment of groundwater impacts from salt leaching under a halophytic crop irrigated with highly saline waters was the intended goal. Passive-tension drainage fluxmeters (DFM) were sought to be employed for direct measurements of drainage and salt leaching.

During the pilot trial, however, the DFMs failed to collect water even with the passive tension set by a wick length of 600 mm.

The surface soil of Typic Torripsamments is known to be highly permeable, being of the order of 8 m $h^{-1}$ (Al-Yamani et al., 2018; Rahmati et al., 2018). Mini-disk infiltrometers were employed here to determine the near-saturated hydraulic conductivity, Ko, at the two pressure heads of −5 mm and −60 mm, utilizing the method outlined by Ankeny et al. (1991). Measurements of Ko were taken at the soil surface and at a depth of 600 mm. A low Ko value at depth could potentially explain the observed failure of the DFMs in 2020, where the convergence ring was positioned. The measurements obtained are presented in Figure 3.4.

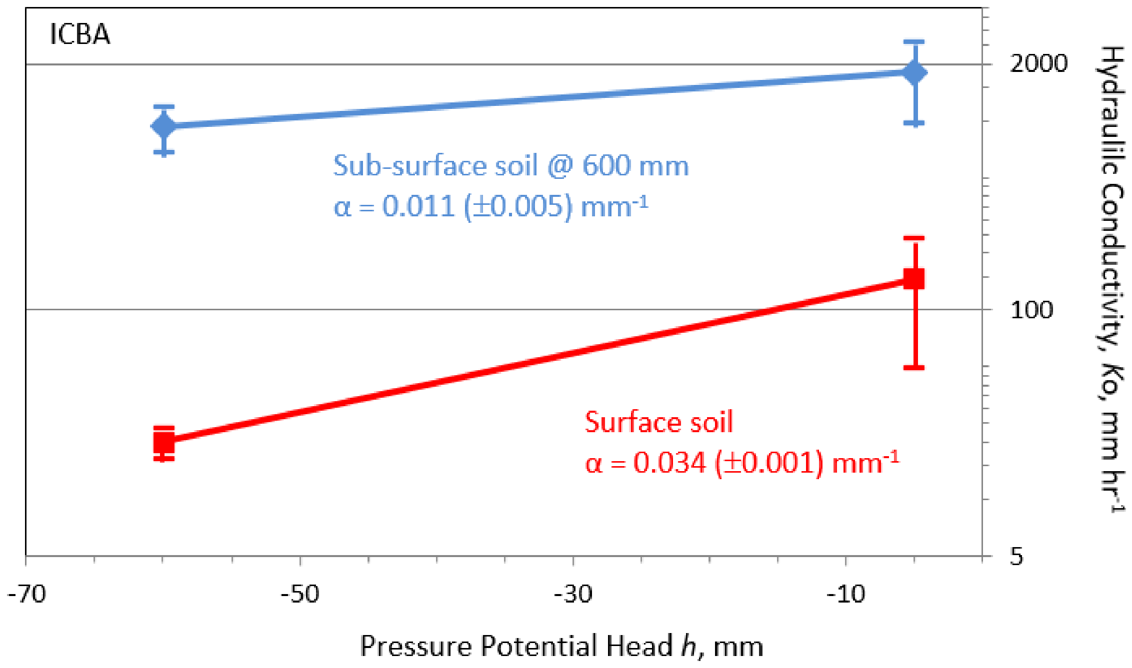


**Figure 3.4. The near-saturated hydraulic conductivity, *Ko*, measured at the two pressure heads, *h*, of −5 and −60 mm using Mini Disk Infiltrometers (Decagon Devices Inc.). Six co-located measurements at both two pressure heads were made both at the surface and at the depth of 600 mm in plots at the International Center for Biosaline Agriculture (ICBA) in the United Arab Emirates. The dual-head method of Ankeny et al. (1991) was used to calculate the hydraulic conductivities, and α is the slope of the exponential.**

The surface soil has, between the heads of −60 and −5 mm, hydraulic conductivities of between 20 and 150 mm $h^{-1}$. This is a highly permeable surface soil. At the 600-mm depth, the soil is even more permeable, being over 100 times more permeable than the surface soil, despite the concretions of calcic and gypsic materials.

The cause of the DFM failures cannot therefore be attributed to a lack of soil permeability. It is hypothesized that the disturbance of the native soil during DFM insertion led to the observed failures. DFM installation involves the creation of a hole through sequential auguring, with the extracted soil being retained in the order it was removed at each depth.

Subsequently, the DFM is placed in the hole, and the extracted soil is meticulously repacked on top of the buried DFM, layer by layer, until the surface is reached. It is believed that the disruption, repacking, and subsequent rewetting of the calcic and gypsic material at depth caused a reprecipitation of these materials, effectively cementing the soil and rendering it impermeable.

To address the failures observed in 2020, two modifications were made to the DFM design, and one change was implemented in the installation protocol. The diameter of the convergence ring was increased from 15 cm to 25 cm to enlarge the capture zone for drainage water (Figure 3.5). Additionally, the length of the capillary wick was extended from 60 cm to 70 cm to enhance the passive tension that draws drainage water into the convergence ring (Figure 3.6). Regarding installation depth, instead of burying the DFM with the top of the convergence zone within the gypsic and calcic horizon at 600 mm depth, the DFMs were positioned at a shallower depth of 200 mm, where the sand remains single-grained and exhibits no apparent concretions.

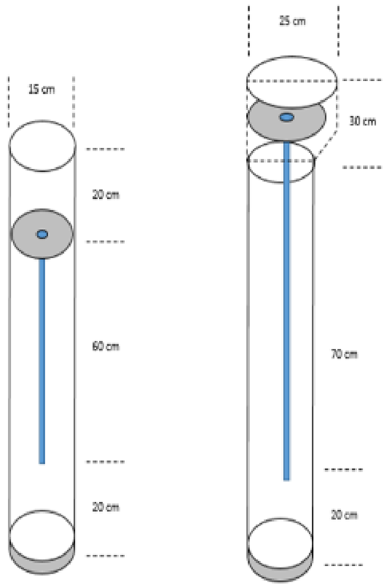


**Figure 3.5. The original design of the tension drainage fluxmeter (left) with a 60-cm tension wick and a 15-cm diameter convergence ring atop the fluxmeter. The successful redesign involved a wider convergence ring of diameter 25 cm, plus a longer tension wick of 70 cm.**

The DFMs performed well during the *Salicornia* experiments of 2021–22. Figure 3.6 shows the flux density of drainage, in mm $d^{-1}$, under the *Salicornia* plots irrigated with Reverse Osmosis (RO) water from the desalination plant by bubblers (BUB), subsurface tape (SUB) and pressure-compensated drippers (PCD). There were four DFMs within each plot. The rate of water applied by bubblers was 30 mm $d^{-1}$, being initially twice that of the other emitter devices.

By implementing these modifications, the DFMs were successfully adapted to function within these desert soils.

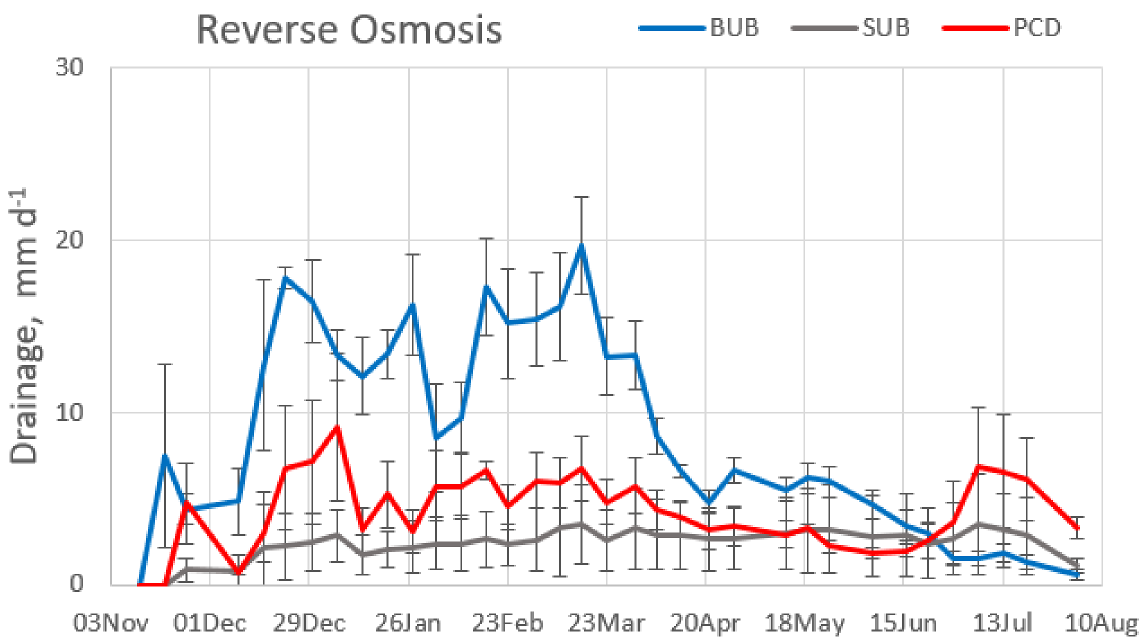


**Figure 3.6. The drainage measured under plots of a *Salicornia bigelovii* crop in the United Arab Emirates by the modified tension drainage fluxmeters (DFM) under irrigation with reverse osmosis water (RO). The switch between low salinity irrigation to RO water was on 23 February 2022. The bars represent the standard errors of the measures from the 4 DFMs for each emitter type.**

## 3.4 Results and Discussion

The electrical conductivities (EC) of the leachates measured in the drainage waters by the DFMs for the RO treatment are shown in Figure 3.7, along with the ECs of the influent irrigation water. Prior to 23 February 2022, all plots were irrigated with 10 dS $m^{-1}$ water to ensure good germination of the *Salicornia*. After that date, the RO water was applied at an $EC_w$ of around 40 dS $m^{-1}$. The change in the EC of the drainage water, $EC_{dw}$ was immediate and within 3 weeks the leachate $EC_{dw}$ exceeded that of the applied $EC_w$. The fluxmeters with the design modifications were working effectively. There were four DFMs in each of the emitter type plots for the RO treatment, and likewise for the other irrigation water types. The variation between DFMs was reasonably small.

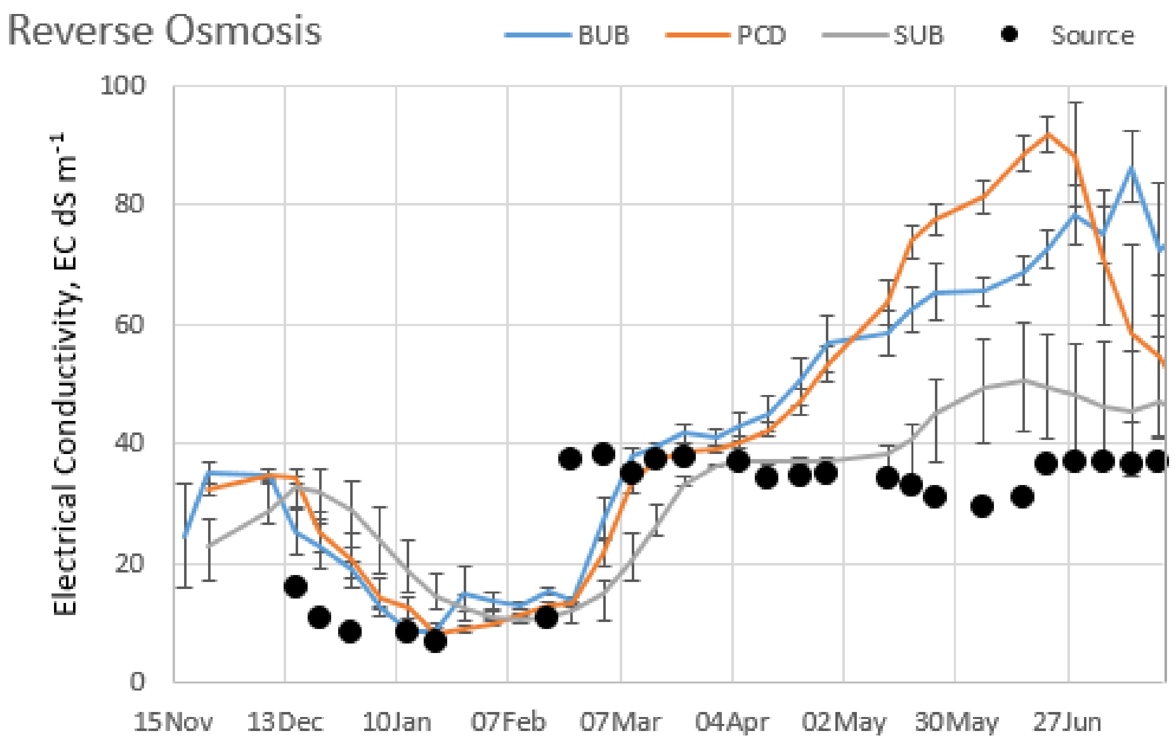


**Figure 3.7. The electrical conductivity (EC) of the leachate measured in drainage under plots of a *Salicornia bigelovii* crop in the United Arab Emirates by the modified tension drainage fluxmeters under irrigation with reverse osmosis water (RO). The switch between low salinity irrigation to RO water was on 23 February 2022. The original irrigation was water at EC at 10 dS m$^{-1}$, and then under RO at about 40 dS m$^{-1}$. The bars represent the standard errors of the measures from the 4 DFMs for each emitter type.**

Initial assessment shows that the salt leachate measurements were consistent with the amounts of water being drained. Ayers & Westcot (1994) noted that when the leaching fraction, *LF*, is defined as

$$LF = \frac{Depth\ of\ water\ leached\ below\ the\ rootzone}{Depth\ of\ irrigation\ water\ applied} \qquad [1]$$

then the EC in leachate, $EC_{dw}$, will be given by

$$EC_{dw} = \frac{EC_w}{LF} \qquad [2]$$

where $EC_w$ is the EC of the applied water. So the lower the *LF*, with less water draining through the profile, the higher the relative EC in the leachate.

A complete analysis of the data regarding applied and drained water depth is yet to be conducted. However, a preliminary evaluation of the results presented in Figures 3.6 and 3.7 indicates consistent performance of the DFMs. Figure 3.6 reveals that drainage from the BUB emitters (≈ 4 mm d$^{-1}$) surpassed that observed under SUB (≈ 3 mm d$^{-1}$) and PCD (≈ 2 mm d$^{-1}$) during May to June 2022. Based on the DFM-measured ECdw/ECw ratios depicted in Figure

3.7, an LF value of 0.4 for PCD, 0.5 for BUB, and 0.7 for SUB can be tentatively suggested using Equation 2. This aligns with the observed general trends in drainage as shown in Figure 3.6.

More detailed analyses and modelling are described in subsequent Chapters using these modified devices.

## 3.5 Conclusions

The ability to measure the environmental impacts on groundwater from irrigating halophytic crops with saline waters was elusive in the 2020 experiments. However, successful modifications were made to three-wire TDR devices, enabling them to measure the soil's water content under these highly saline conditions. Additionally, the design of tension DFMs was altered to facilitate measurement of drainage and salt leaching through a Typic Torripsamment.

Through shielding all three wires of the TDR probe with glue-lined heat-shrink tubing, the length of the TDR rods could be detected, allowing for the calculation of an apparent dielectric constant. This constant was then related to the measured soil water content in sand wetted with 85 dS $m^{-1}$ water. The results were found to align with Topp's equation, which establishes the link between the apparent dielectric constant and the soil's water content. Consequently, shielded TDR probes were readily employed to monitor the changing soil water contents beneath the Salicornia plots irrigated with highly saline waters.

This Typic Torripsamment soil represents the modal soil type of the Arabian Peninsula. Initially, drainage was not registered by the passive-tension DFMs at a depth of 600 mm. However, measurements of the near-saturated hydraulic conductivity of the profile over the top 600 mm revealed that the soil, in its native state, possessed high permeability. It is believed that the initial DFM failure was partly attributable to the disturbance of calcic and gypsic materials within the deeper profile during DFM insertion. This disturbance, followed by re-wetting of the re-packed soil, may have resulted in the formation of an impermeable 'cemented' layer above the DFMs.

Subsequently, a decision was made to install the DFMs at a shallower depth of 200 mm to avoid the calcic and gypsic horizon. Additionally, the diameter of the convergence ring positioned atop the DFM was increased from 150 mm to 250 mm to allow for a wider zone of drainage capture. The length of the wick, which establishes the passive tension, was also extended from 600 mm to 700 mm. These modifications to the design and the changes implemented in the installation protocol enabled successful monitoring of both drainage and salt leaching during irrigation of the Salicornia with saline waters.

These two modifications of key devices for monitoring in the rootzone of crops irrigated with saline waters will enable better monitoring and modelling of the impacts of drainage and salt leaching on aquifer recharge and groundwater quality in the saline environments of hyper-arid regions. This work is described in the subsequent chapters.

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# CHAPTER 4

# 4 SALT DYNAMICS, LEACHING REQUIREMENTS, AND LEACHING FRACTIONS DURING IRRIGATION OF A HALOPHYTE WITH DIFFERENT SALINE WATERS

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Chapter 4 describes the results of field experiments to examine the efficiency and impact of salt leaching. Experiments were conducted on a Typic Torripsamment, the dominant soil across the Arabian Peninsula. Analytical solutions well predicted the salt-breakthrough-curves from repacked soil columns, confirming that all of the soil's water was actively involved in transport and that salt behaved as an inert tracer. Piston displacement was a good assumption, as salt was easily flushed from the columns. Field soil sampling down to 1 m across 36 profiles after the harvest of a halophytic crop irrigated with saline waters found salt storage to be just 1.8 kg $m^{-2}$, even though 80 kg $m^{-2}$ had been applied. One of the most important findings is that salt leaching can maintain uniform salinity in the root zone, but it carries salt back to groundwater at a concentration of 2-3 times the concentration of the applied water. This salt dilemma requires careful management to achieve crop yields and protect the environment.

The content of this Chapter has been published as:

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The DRC Statement of Contribution is provided in Appendix 8.3.

## 4.1 Abstract

More than 830 million hectares of soils are salt affected, representing around 9% of the world's land surface. Groundwaters that are high in salt already cover some 16% of the land area. Saline waters can be used effectively for irrigation by salt leaching to despatch the accumulated salts. But this can pose a risk of salinization of groundwaters. It is important that the efficacy of salt leaching is confirmed, and the impacts of salt loading below the rootzone can be assessed.

The research in this Chapter examines the efficiency and impact of salt leaching in removing salt from the rootzone.The dominant soil across the Arabian Peninsula, a Typic Torripsamment, was used for this investigation. Detailed laboratory experiments were conducted to analyse salt leaching dynamics through salt-breakthrough curves and analytical modelling. Additionally, field monitoring of impacts was undertaken.

Analytical solutions successfully predicted the salt-breakthrough curves obtained from repacked soil columns in the laboratory. This confirmed that all the soil's water was actively involved in the transport process, and salt behaved as an inert tracer. The breakthrough curves were well predicted using a small solute dispersivity, so piston displacement is found to be a good assumption. Salt was easily flushed from the columns. To back this up in the field, soil sampling was carried out down to 1 m across 36 profiles after the harvest of a halophytic crop irrigated with saline waters. Salt storage was found to be just 1.8 kg $m^{-2}$, even though 80 kg $m^{-2}$ had been applied. This is a positive result for managing irrigation. Salt leaching can maintain equable salinity in the rootzone. However, this leaching carried salt back to groundwater at 2–3 times the concentration of the applied water. It is confirmed that the amount of salt leaching back to groundwater can be significant.

This salt dilemma will require careful management to achieve crop yields and protect the environment.

## 4.2 Introduction

The Food and Agriculture Organization of the United Nations has just published a global map of salt-affected soils (FAO, 2021). The FAO (2021) note that salt-affected soils can develop quickly in response to human activities due to inappropriate management, and through saline water leaching to groundwater and then this groundwater being subsequently used for irrigation. These soils undergo a loss of soil health, and lose their abilities for food, fuel and fibre production, natural infiltration, carbon sequestration, and other ecosystem functions.

The FAO has found that more than 830 million hectares of soils are salt affected, representing around 9% of the world's land surface, across all continents with more than two-thirds of these are being in arid and semi-arid zones. Some 10% of the soils of the world's croplands are salt affected, so mitigation measures are needed to ensure global food security and maintain soil ecosystem services, especially where irrigation, mainly drawn from brackish groundwaters, is needed for crop growth (Shahin and Salem, 2015). Leaching of salt from the rootzone can be used with irrigation to minimise the impacts of soil salinization through the flushing of salts out of the soil.

Yet groundwaters that are high in salt already cover 24 million $km^2$, or some 16% of the total land area on earth (van Weert et al. 2009). In the United Arab Emirates, the salinity of groundwater is rising, and the changing geochemistry of the aquifers has been described by EAD (2018).  So, while saline waters can be used effectively for irrigation through using salt leaching, the despatch of salts from the rootzone back to groundwater poses a risk of increasing the salinization of groundwaters (Sherif et al. 2021).

The results from field work on crop growth under irrigation with saline waters and measurements of salt leaching have recently been published (Al Tamimi et al., 2023). This study investigates the salt dynamics within the rootzone soil and quantitatively assesses the effectiveness of the implemented salt leaching procedures in fully removing salts from the rootzone.

An examination of this phenomenon was conducted in both laboratory and field settings to confirm the efficiency of salt leaching in removing salt from the rootzone. Laboratory experiments utilized soil columns to quantify the leaching breakthrough of saline waters through the soil. Additionally, the end-of-season salt residues remaining in the soil were examined after cultivating a halophytic crop of Salicornia irrigated with saline waters using a leaching fraction to maintain optimal crop-growing conditions.

## 4.3 Objectives

The objectives of the work described in Chapter were to use salt-leaching measurements both from soil columns in the laboratory and through field monitoring of salt residues following a season of growing a halophytic crop under saline irrigation to:

- Test whether salt moves through this desert soil as an inert tracer and to assess whether all of soil's pore water is actively involved in salt transport so that salt leaching is fully effective.
- Determine the effectiveness of salt leaching in the field by quantifying the residual salt load left in the soil after a full growth season of irrigating a halophytic crop of Salicornia using three irrigation waters of different salinities and three different irrigation emitters.

## 4.4 Salt Leaching

Sufficient leaching of salt from the soil profile under crops irrigated with saline waters is critical to maintain a viable rootzone for crop growth. The EC of the saturation extract in the rootzone soil that will maintain a tolerable yield depression, usually 10% or less (US Salinity Laboratory Staff, 1954), is deemed the ECse. The leaching criterion that achieves this ECse is called the leaching requirement, *LR* (Rhoades, 1974). Nonetheless, this leaching of salt from the rootzone, realised using a leaching fraction, *LF*, means that high amounts of salt can potentially be despatched to groundwater in the drainage, which can pose a risk to the water quality of the underlying aquifer since the EC of the drainage water, ECdw, will be greater than that of the irrigation water ECiw (Hoffman and van Genuchten, 1983). The leaching requirement, *LR*, and leaching fraction, *LF*, are both defined as the depth of water drained below the root zone divided by the depth of irrigation water applied, as will be discussed below. Rhoades (1974) noted that the *LR* differs from the *LF* in that the *LR* must be used to control the soil-water salinity within the rootzone within tolerable limits. The *LF* is simply the actual fraction of applied water that appears as drainage water, and which carries with it the displaced salts down to the underlying aquifer.

This highlights the conundrum with the irrigation of halophytes using saline waters. There is the requirement to balance the need to flush salts out of the rootzone by leaching, with the imperative to protect groundwater by limiting salt leaching through drainage. Furthermore, all of these leaching analyses are predicated on the assumption that the flux of the invading saline irrigation water completely displaces all of the salty pore water that is antecedently resident in the soil prior to the irrigation. This assumption can be stated in another way, and that is that all the pore water resident in the soil is mobile and can be displaced in its entirety by piston flow with the flux concentration of the infiltrating solution (van Genuchten and Wierenga, 1976).

The hypothesis of piston displacement is tested through the use of both laboratory soil-column experiments and field monitoring.

### 4.4.1 Leaching Requirements

The leaching requirement *LR* is the minimum value of *LF* that would prevent the rootzone salinity becoming too saline for 'good' plant growth (Rhoades, 1974). If *LR* is the minimum value of *LF* when the maximum 'permissible' value of $EC_{dw}$ is $EC_{dw}$*, then:

$$LR = \frac{EC_{iw}}{EC^*_{dw}} \quad . \qquad [4.1]$$

Rhoades (1974) developed a procedure for determining the appropriate values for $EC_{dw}$* and suggested that:

$$EC^*_{dw} = 5EC^*_{se} - EC_{iw} \quad , \qquad [4.2]$$

where $EC_{se}$* is the crop-appropriate value of the saturation extract *EC* of rootzone salinity to realise a tolerable yield depression (Maas, 1990). So,

$$LR = \frac{EC_{iw}}{5EC^*_{se} - EC_{iw}} \quad . \qquad [4.3]$$

Given the cultivation of an obligate halophyte, rather than a facultative crop, in this study, the leaching requirement (*LR*) is of less interest due to the very high $EC_{se}$. Experiments have demonstrated minimal impact of salinity (≈ 10–40 dS m-1) on the yield of Salicornia. Consequently, the focus here shifts to the environmental impacts of the leaching fraction (*LF*) as reflected by $EC_{dw}$ and the potential role of piston displacement, where infiltrating drainage water displaces all resident rootzone salt.

### 4.4.2 Leaching Fractions

Ayers and Westcot (1994) noted that with the leaching fraction, *LF*, defined in general as

$$LF = \frac{Depth\ of\ water\ leached\ below\ the\ rootzone}{Depth\ of\ irrigation\ water\ applied} \quad , \qquad [4.4]$$

then $EC_{dw}$, will be given by

$$EC_{dw} = \frac{EC_{iw}}{LF} \quad . \qquad [4.5]$$

The lower the *LF*, with less water draining through the profile, the higher the relative EC in the leachate. Managing the *LF* to achieve a balance between salt flushing from the rootzone and limit water quality degradation of the underlying aquifer. Equations [4.4] and [4.5] assume that all of the water leaching through the rootzone acts by piston displacement to remove excess salt from the entire wetted pore space. The assumption tested here is that immobile pore water is essentially absent, and all the wetted pore water exhibits full mobility (van Genuchten and Wierenga, 1976).

## 4.5 Materials and Methods

The experiments were carried out at the International Centre for Biosaline Agriculture (ICBA) (25.09° N; 55.39° E; 48 m a.s.l.) near Dubai. The soil there is a Typic Torripsamment. It is a spatially uniform, deep sandy desert soil of aeolian origin (EAD 2009). These soils are the most extensive soils in the UAE, and they are also found across much of the Arabian Peninsula (Abdelfattah and Pain, 2012).

Salt breakthrough experiments were carried out in the laboratory during infiltration into a column of repacked sand using a sequence of saline waters, between which the soil was flushed with fresh water (Section 4.1). These data were interpreted using an analytical solution to the dispersive-convective equation that describes miscible displacement in a soil with fully mobile pore water (Section 4.2). Field data were also obtained from soil monitoring before and after the 2021–22 Salicornia growing season (Section 4.3), as well as from establishing the field profiles of salt left in the soil at the end of the growing season following the harvest in 2022 (Section 4.4).

### 4.5.1 Breakthrough Experiments

To establish three soil columns of length $L$ = 450 mm and diameter 150 mm, sand over the depth range 0–300 mm was taken from the field plots. The sand was air dried (≈1% g $g^{-1}$) and sieved to remove large pieces of organic material. This sand was then carefully packed into the columns in small amounts to ensure that the bulk density was uniformly 1.6 kg $L^{-1}$ (Figure 4.1). The surface of the soil was then ponded with fresh water (FW, ≈ 0.5 dS $m^{-1}$) to leach any initially resident salts from the column. The steady flow through the column, once water was dripping out the free-water base, was ≈ 100 mm $h^{-1}$

The repacking process did not appear to alter the hydraulic characteristics of this single-grained, apedal soil. The observed flow rate corresponded to the hydraulic conductivity previously measured in the undisturbed field using mini-disk tension infiltrometers. This suggests that the repacking of the desert sand did not have a significant impact on the soil's hydraulic properties.

A series of salt leaching pulses were then established in the sequence of groundwater (GW, ≈ 25 dS $m^{-1}$), followed by FW, then reverse-osmosis brine (RO, ≈ 35 dS $m^{-1}$), followed by FW, then the aquabrine sequence (AQ , ≈ 35 dS $m^{-1}$), with another pulse of FW, followed with saline water at 10 dS $m^{-1}$ ($EC_{10}$, , ≈ 10 dS $m^{-1}$) which was eventually flushed again with FW to end the breakthrough experiments. The *EC* of the leachate was measured frequently with a portable conductivity meter (WTW Model 3310). The Time Domain Reflectometry (TDR) probes showed that free water emerged from the base of the column when the soil was at water content $\Theta$ = 0.32 m $m^{-3}$.

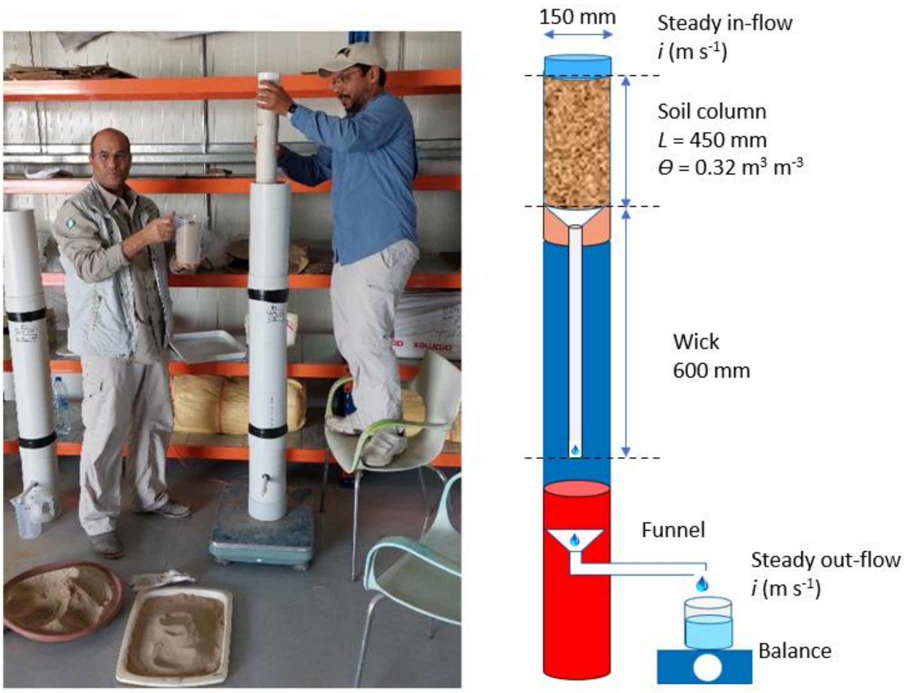



**Figure 4.1. Left Panel. Packing air-dry sand into a soil column in preparation for the collection of salt leaching data to measure the salt break-through curves (BTC) in the leachate. The right panel shows the experimental set-up used to collect the BTC data. This device consists of an upper section of repacked sand within a polyvinyl chloride (PVC) column of 150 mm diameter, length $L$ = 450 mm, and at steady volumetric water content $\theta$ = 0.32 m$^3$ m$^{-3}$. This sand-filled column sits atop a middle section of a PVC pipe of length 650 mm which houses the fibreglass capillary wick of length 600 mm, the top of which is entwined inside a sand-filled funnel which is in contact with the base of the soil column above. A lower basal section of 300 mm contains a funnel to collect the drainage from the wick which feeds into an outflow pipe that drains into a beaker sitting on a balance. The weight change is recorded every 5–10 min to establish that the flow is steady at $i$ (m s$^{-1}$). The leachate is then emptied into another container and the EC of the drainage solution recorded frequently.**

For the sake of brevity, only detailed measurements from a single soil column experiment are presented here. Due to meticulous packing procedures, minimal variation was observed between the columns, as evidenced by the near-identical salt-breakthrough curves.

### 4.5.2 Analyses

The basis for the analysis of the measured breakthrough curves of salt flowing through this vertical soil column of length $L$ (m), is the partial differential equation describing the one-dimensional convective and dispersive flow of a biologically and chemically inert solute, yet one that is potentially adsorbed by the soil (Clothier and Green, 2022).

For simplicity $C$ can be used to be the concentration of salt in the soil solution

The units of $C$ are mg $L^{-1}$, although at the levels of salinity encountered here these can be converted into electrical conductivities, EC (dS $m^{-1}$), by using the conversion 1 dS $m^{-1}$ equals 720 mg $L^{-1}$ (Ayers and Westcott, 1994). The partial differential equation describing this miscible displacement through soil of an inert and potentially adsorbed solute was given by van Genuchten and Alves (1982) as:

$$\frac{\partial c}{\partial x}\left(\theta\, D\, \frac{\partial c}{\partial x} - q\, C\right) \;=\; \frac{\partial}{\partial t}\,(\theta\, C + \,\rho\, S) \qquad , \qquad [4.6]$$

where $\Theta$ is the volumetric soil-water content ($m^3$ $m^{-3}$), $x$ is the soil depth (m), $t$ is time (s), $q$ is the volumetric flux of water flowing through the soil (m $s^{-1}$), $D$ is the solute dispersion-coefficient ($m^2$ $s^{-1}$), ρ is the soil's bulk density (g $m^{-3}$), and $S$ is the adsorbed concentration of salt (mg $m^{-3}$).

In the interest of simplicity, any adsorption of salt onto the soil's surfaces is assumed to be governed by a linear isotherm, as expressed by the following equation:

$$S = K_D\ \mathrm{C} \qquad , \qquad [4.7]$$

where $K_D$ (mg $L^{-1}$) is the distribution coefficient of salt partitioned between the adsorbed and dissolved states. Using this isotherm (Eq. 4.7), and if q the volumetric flow of water through the soil is at a steady rate of $v$ (m $s^{-1}$), then Eq. [4.6] simplifies to:

$$D\,\frac{\partial^2 c}{\partial x^2} = R\ \frac{\partial c}{\partial t} + v\ \frac{\partial c}{\partial x} \qquad , \qquad [4.8]$$

where $R$, the so-called retardation factor, is given by:

$$R\, = 1 + \frac{\rho\, K_D}{\theta} \qquad . \qquad [4.9]$$

If the solute behaves as a simple tracer, with no adsorption, then $K_D$ is zero (Eq. 4.7), and there is no retardation as $R$ = 1 (Eq. 4.9).

The experiments involved pre-leaching of the soil column with fresh water ($C_o \approx 0$, or 0.5 dS $m^{-1}$), and then applying pulses of duration to (s) of staged, influent salt solutions of concentration $C_i$ (mg $L^{-1}$, or dS $m^{-1}$). After $t_o$, the soil was again leached with fresh water, prior to the infiltration of another pulse of $t_o$ with a salt solution of a different $C_i$.

The steady rate of water flow through the soil, $v$, can be observed in breakthrough experiments by observing the steady rate of infiltration, or drainage, through the soil, $i$ (m $s^{-1}$). It follows that:

$$v = \frac{i}{\theta} \qquad . \qquad [4.10]$$

For ease of interpretation, the results are presented here, using the ordinate of the cumulative amount of steady-state infiltration, or drainage, up until time $t$*, namely $I$($t$*) (m). The cumulative infiltration $I$ to time $t$* is simply found from the steady rate of infiltration, $i$, using:

$$I(t^*) = \int_0^{t^*} i\,dt = it^* \qquad [4.11]$$

The initial and upper-boundary conditions that describe each of these infiltration-pulse sequences are:

$$C(x,0) = C_i \qquad 0 < x < L, t = 0 \qquad [4.12]$$

$$C(0,t) = \begin{cases} C_o\,, & 0 < t \leq t_o \\ \approx 0\,, & t > t_o \end{cases} \qquad . \qquad [4.13]$$

The solution for the efflux concentration of salt at the base of the column, $C$($L$,$t$), using Eq. [4.8] subject to Eqs [4.12] and [4.13], was given by Carlsaw and Jaegar (1959), and as Eq. [B5] in van Genuchten and Alves (1982) as:

$$C(L,t) = \begin{cases} C_i + (C_0 - C_i)\,A(L,t) & 0 < t \leq t_o \\ C_i + (C_0 - C_i)\,A(L,t) - C_o\,A(L,t-t_o) & t > t_o \end{cases} \quad , \qquad [4.14]$$

where

$$A(L,t) = \frac{1}{2}\,\mathrm{erfc}\left[\frac{R\,L - v\,t}{2\sqrt{D\,R\,t}}\right] + \frac{1}{2}\,\exp\left(\frac{v\,L}{D}\right)\mathrm{erfc}\left[\frac{R\,L + v\,t}{2\sqrt{D\,R\,t}}\right] \quad , \qquad [4.15]$$

and exp is the exponential function, and erfc is the complementary error function (Carslaw and Jaegar, 1959; loc. cit. Appendix II). A linear relationship between the solute-dispersion coefficient ($D$) and pore water velocity ($v$) is adopted in this study, with dispersivity (α, mm) serving as the proportionality constant. This relationship is expressed by the equation $D = \alpha v$ (Gelhar and Collins, 1971). Eqs [14] and [15] were used to assess, by comparison with the measured breakthrough concentrations of $C$($L$,$t$), the dispersivity, α, of the invading salt solution, and whether, or not, the infiltrating salt behaves as a tracer, without adsorption ($R$ = 1). Furthermore, an investigation was conducted to determine whether the entire volumetric water fraction ($\theta$) of the soil participated actively in solute transport (Eq. 4.5), or whether some of the soil's resident water was immobile and not actively involved in piston displacement of salt (van Genuchten and Wierenga, 1976; Clothier et al., 1992).

### 4.5.3 Field monitoring

The Salicornia bigelovii Torrey was sown during the second week of November 2021 (Al Tamimi et al. 2023). Prior to this on the 25 October 2021, soil samples at 0–300 mm and 300–600 mm depths were taken at three locations across the site.

The crop was sub-sampled for the harvest yield of fresh tips on 14 April 2022, then total dry weight on 6 June 2022, and for seed during mid-September 2022. Irrigation had been stopped in on 31 August 2022 and then the crop had dried off. Following this on 26 October 2022, three soil samples per plot of GW, RO and AQ were taken at 0–300 mm and 300–600 mm for surface soil salinity analysis.

These before-planting and after-harvest surface-soil samples were analysed by a commercial company using the saturated-paste method to determine the electrical conductivity of the extract in dS $m^{-1}$ (US Salinity Laboratory Staff, 1954). From the measured EC and the water content of the paste, then by assuming a bulk density of 1.6 kg $L^{-1}$, these results were converted into a salt concentration in mg $kg^{-1}$.

### 4.5.4 Soil Profiling

In late October 2022, after the Salicornia crop had been harvested, soil profile cores were taken for analysis of the residual salt content in the soil. Cores were taken down to a depth of 1 m, and subsamples of soil were taken in 100-mm increments down the profile. Four core replicate profiles were taken within each of the nine plots which covered the three water types of AQ, GW and RO, and three types of irrigation-emitters of bubblers (BUB), pressure-compensated drippers (D) and subsurface tape (SUB). The 360 sub-samples were dried in an oven at 105°C for 24 h, and the gravimetric water contents (g $g^{-1}$) recorded to establish the soil-water content profiles at the end of the season. From each of the sub-samples, some 30 g of dried soil was placed in a screw-top bottle, and 50 g of water added. The bottles were vigorously shaken and left to rest, then just prior to using an electrical-conductivity electrode the bottles were again shaken, and soon thereafter the *EC* (mg $L^{-1}$) values of the supernatants were measured. Using the measured gravimetric water contents, these data were converted to salt concentrations in mg $kg^{-1}$. The 10 values for each individual profile were summed down to 1 m, and by knowing the bulk density of the soil to be 1.6 g $L^{-1}$, these profile measurements could then be presented in terms of residual salt storage in the top 1 m in kg $m^{-2}$. This resulted in four 0- to 1-m salt-storage values at the end of the season for each of the nine irrigation-water and emitter combinations.

## 4.6 Results and Discussion

Salt breakthrough curves are presented for the sequential leaching of salt solutions through columns of repacked soil. Following this, a discussion is presented on the results obtained from soil sampling conducted in the field. The sampling targeted two timeframes: before and after a season's growth of Salicornia irrigated with saline waters.

### 4.6.1 Breakthrough Curves

The continuous leachate-salinity measurements and the cumulative salt losses per pulse from the repacked columns are shown in Figure 4.2.

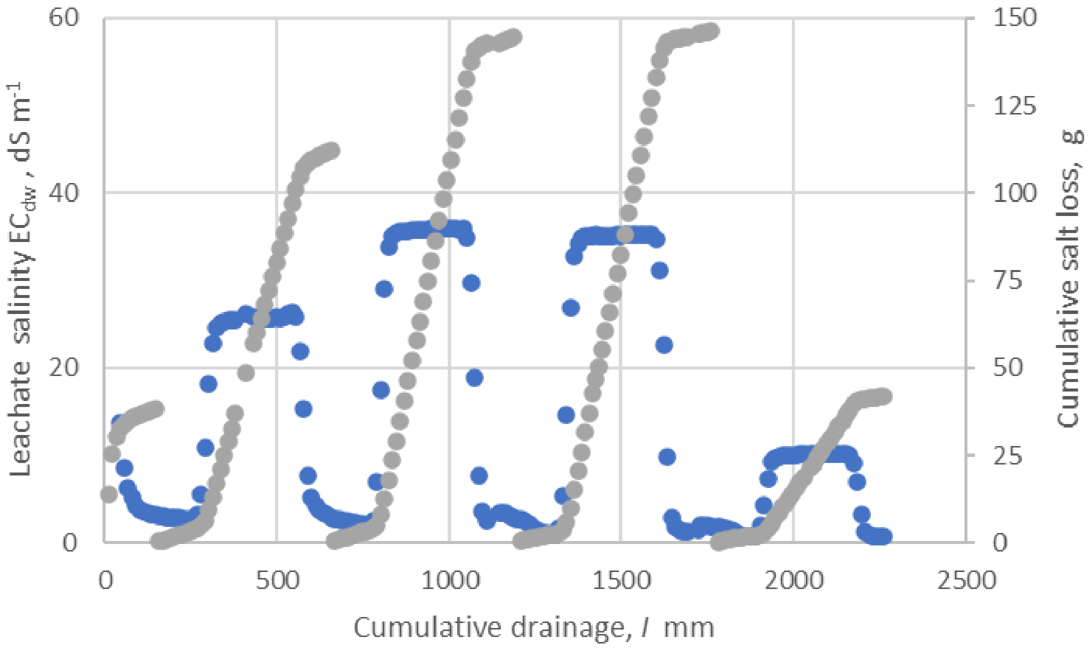
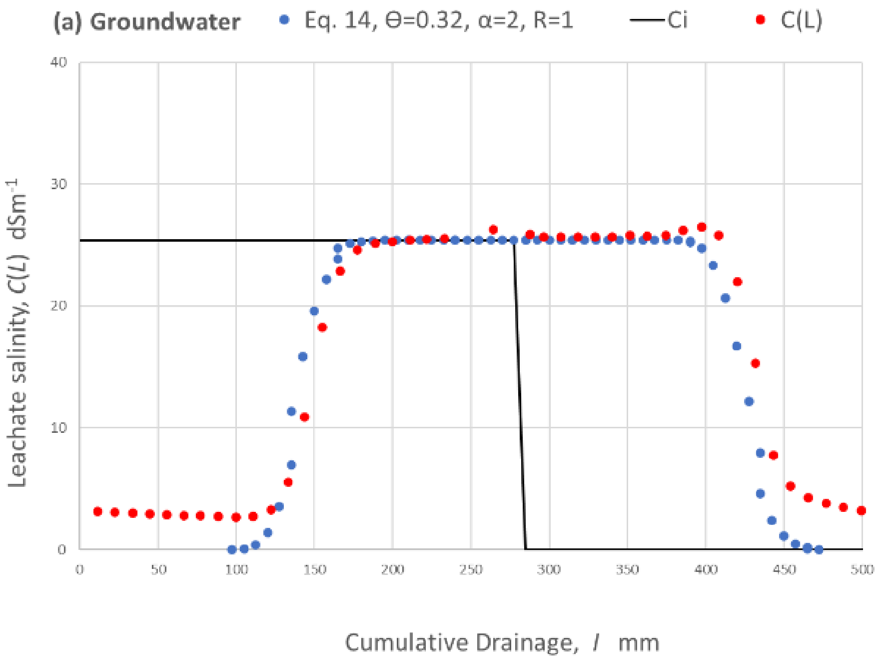
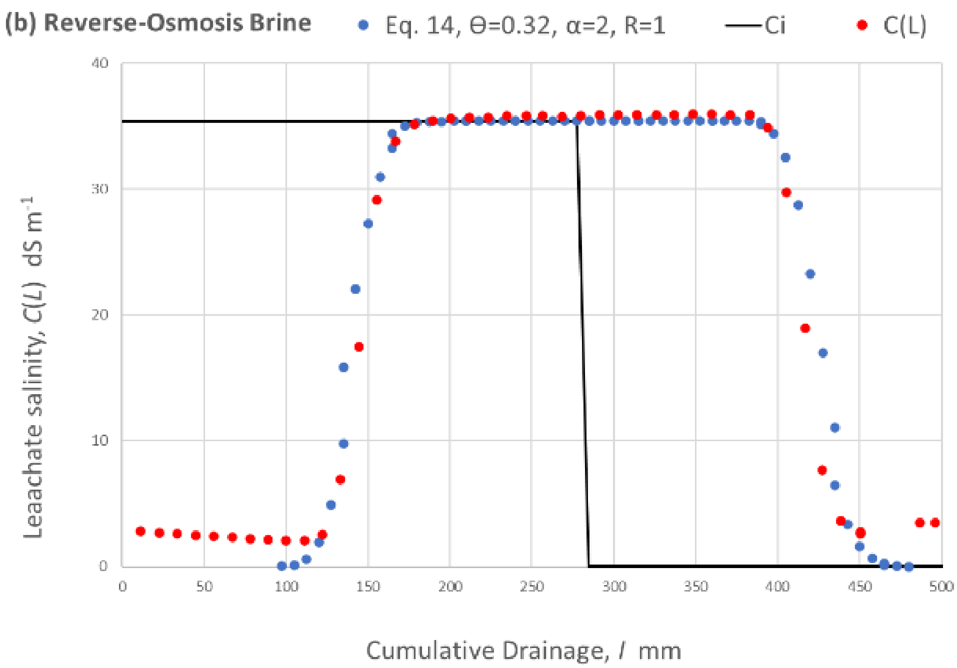


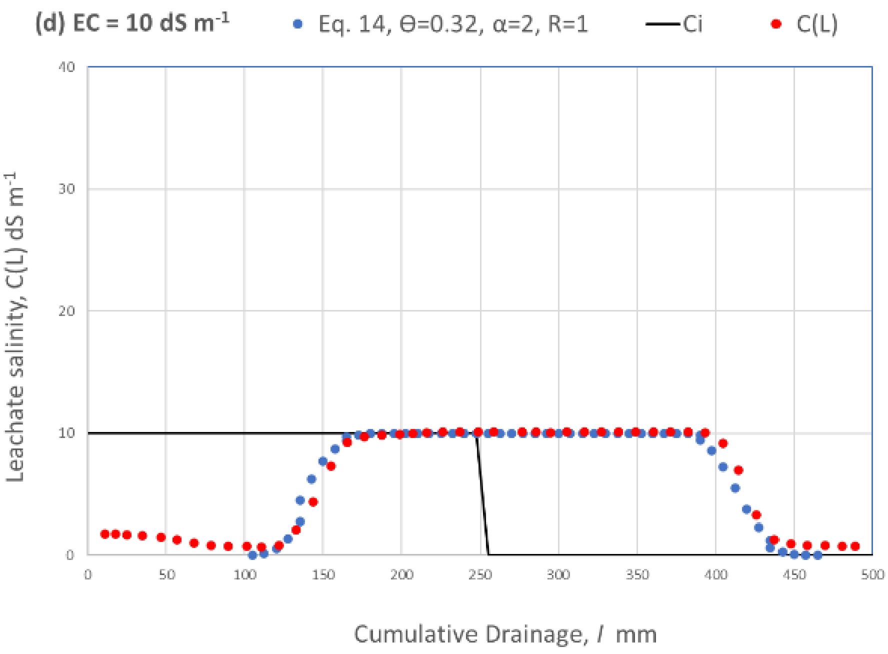

**Figure 4.2. The measured break-through curves (BTC) of salt plotted against the cumulative drainage that followed a sequence of irrigation pulses applied to a 450 mm long vertical column of air-dry repacked sand taken from near the experimental plots where Salicornia was grown. The blue dots show the drainage concentration of salt (EC, dS $m^{-1}$) and the grey dots show the cumulative leaching loss of salt (g). An irrigation pulse of freshwater at influent concentration $C_i \approx 0.5$ dS $m^{-1}$ was used initially to wash out the residual salts. Then pulses of length $t_o$ (s) were sequentially applied in the order of groundwater (GW, $C_i$ = 25 dS $m^{-1}$), reverse-osmosis brine (RO, $C_i$ = 35 dS $m^{-1}$), aquabrine (AQ, $C_i$ = 35 dS $m^{-1}$), and finally saline water at EC=10 dS $m^{-1}$ ($EC_{10}$). Between each set of the saline pulses, the column was flushed out again using freshwater.**

The sequential salinity measurements in the leachates within each salt pulse and subsequent FW flushing are given in Figures 4.3a–4.3d. The influent salt concentrations $C_i$ (dS $m^{-1}$) are given along with the measured effluent concentrations $C(L)$ at length $L$. As well, in Figures 4.3a–4.3d are presented the solutions to Eq. [4.14] for each saline pulse and the subsequent flushing.

An initial water content of $\theta$ = 0.32 $m^3$ $m^{-3}$ was employed in this analysis, based on the assumption that all pore water is mobile. For sands and coarse-textured soils, a dispersivity of $\alpha$ = 2 mm (Clothier et al. 1988) is often used to effectively describe solute dispersion, and this value was adopted here. An inert salt with $K_D$ = 0 was assumed, resulting in a retardation factor ($R$) of 1.


(a) Groundwater
Eq. 14, Θ=0.32, α=2, R=1
Ci
C(L)
Leachate salinity, C(L) dSm-1
Cumulative Drainage, I mm
0
10
20
30
40
0
50
100
150
200
250
300
350
400
450
500


(b) Reverse-Osmosis Brine
Eq. 14, Θ=0.32, α=2, R=1
Ci
C(L)
Leachate salinity, C(L) dS m-1
Cumulative Drainage, I mm
0
10
20
30
40
0
50
100
150
200
250
300
350
400
450
500



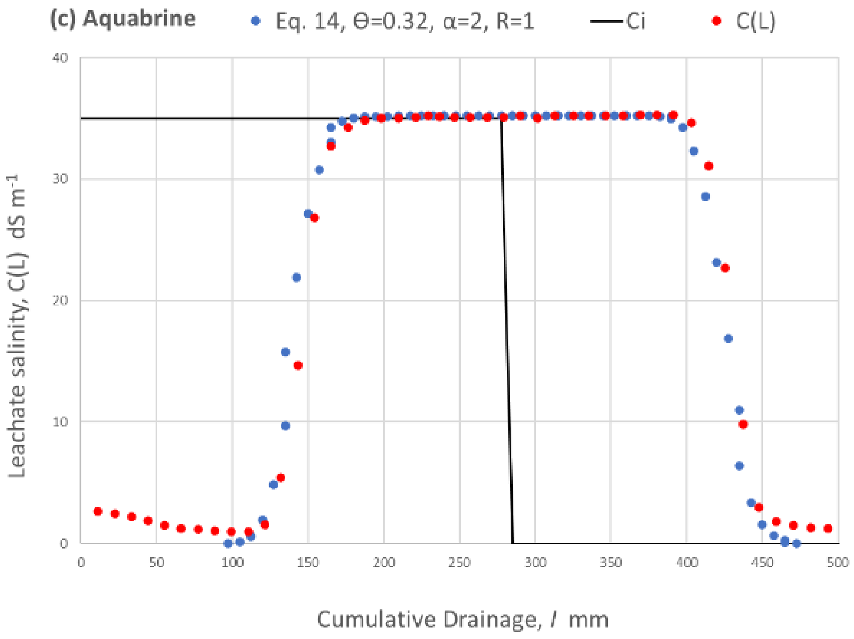




**Figure 4.3. Measured break-through curves (BTC) of salt (●) using an ordinate of cumulative infiltration (*I*, mm) showing a sequence of irrigation 'pulses' applied to an L=450 mm long column of air-dry sand. Irrigation pulses were sequentially applied as (a) groundwater (GW, influent concentration $C_i$ = 25 dS m$^{-1}$), (b) reverse osmosis brine (RO-brine, $C_i$ = 35 dS m$^{-1}$), (c) aquabrine (AQ, $C_i$ = 35 dS m$^{-1}$), and (d) low salinity water ($EC_{10}$, $C_i$ = 10 dS m$^{-1}$). In between each set of saline pulses, the columns were flushed using freshwater at $C_i \approx$ 0.5 dS m$^{-1}$. The measured BTC data (●) are compared**

**with predictions of $C(L)$ (dS m$^{-1}$) using Eq. 4.14 (●) with $\Theta$=0.32 m$^{3}$ m$^{-3}$, a dispersivity $\alpha$ = 2 mm, and a retardation of $R$=1 as would apply for an inert solute.**

The fit of the solutions to Eq. [4.14] with the measured data is in all cases very good. The frontal positions of the salt invasion and flushing are well predicted using the inert-solute assumption for salt of $R$ =1. The transient shapes of the breakthrough curves are also generally well predicted by the assumption that all of soil's pore water is actively involved in transport, with there being no immobile water. Although on closer inspection there can be seen indications of some volumetric fraction of immobile water that is slowly transferring into the main fraction of convecting pore water. Prior to the invasion of the successive salt-fronts, there can be seen salt concentrations higher than the 0.5 dS m$^{-1}$ of the FW used as flushing prior to the salt pulse. Likewise, following the subsequent flushing after the salt pulse, the salt concentrations in the leachate are still above the 0.5 dS m$^{-1}$ of FW being used to push the salt out. This slow 'bleeding' of salt would appear to come via diffusion from salt that is still contained in the smaller pores of less-mobile water. The small cumulative amount of salt involved in this 'late bleeding' of salt after flushing (Figures 4.2 and 4.3) verifies that the volumetric fraction of the soil's pore water that is immobile is very small. Analysis of breakthrough curves generated from laboratory soil column experiments allows confirmation for this desert sand that all the soil's water actively participates in transport, and salt behaves as an inert tracer.

Furthermore, the breakthrough curves were well predicted using a solute dispersivity of $\alpha$=2 mm, such that the invasion and flushing fronts of salt were near-rectangular in shape, indicating that piston displacement of the resident solute is a good assumption. These all lend credence to strategies for effectively managing saline irrigation using the leaching requirement *LR* (Eq. 4.3), and for assessing environmental impacts using the leaching fraction *LF* (Eq. 4.5).

### 4.6.2 Field Profiles

To back this up in the field, depthwise profiles of soil-water content and soil-solution salt contents were obtained from soil sampling down to 1 m from 36 soil profiles. The soil water and soil solution results are shown in Figures 4.4a and 4.4b. These profiles were taken following the harvest of the crop. These 36 profiles comprise four profiles per treatment block. The nine treatment blocks were made up of plots irrigated with the three saline waters of GW, RO and AQ, supplied by the three emitter types of bubblers (_b), drippers (_d), and subsurface (_s).

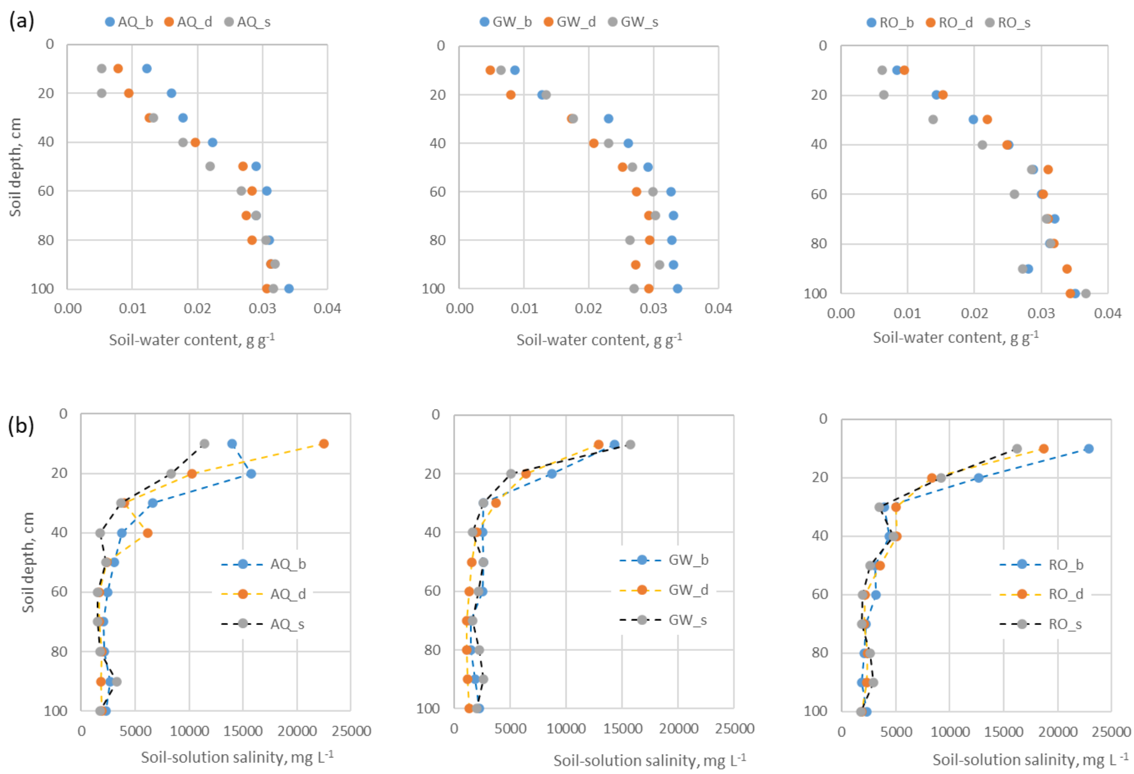



**Figure 4.4. (a) Gravimetric soil-water content (g g$^{-1}$) of the soil profile under the Salicornia plots just prior to planting of the second season, as measured from core samples taken in November 2022. The plots are distinguished by the water source (AQ=aquabrine; GW=groundwater; RO=brine water from the desalination process), and the emitters (b= bubblers; d=drippers; s=subsurface).**

**(b) Soil-solution salt concentration (mg L$^{-1}$) under the Salicornia plots just prior to planting of the second season, as measured from core samples taken in November 2022. The plots are distinguished by the water source (AQ=aquabrine; G=groundwater; RO=brine water from the desalination process), and the emitters (b= bubblers; d=drippers; s=subsurface).**

There were no differences between the profiles either by water type or irrigation emitter, and this applied to both the water contents (Figure 4.4a) and soil-solution salt contents (Figure 4. 4b). The soil had dried out throughout the profile (Figure 4.4a.) by gravity drainage at depth and by root extraction and soil-water evaporation over the top 500 mm. The soil-solution salt content was highest in the top 400 mm, due in part to the concentration of the salt in the diminished soil-water content.

Measurements of salt profiles in the surface soil were also conducted. These measurements were taken before (October 2021) and after (October 2022) a season's growth of Salicornia irrigated with saline waters using various irrigation emitters.

These soil salt-contents were measured 0-600 mm using saturated-paste extracts from samples averaged over the two depths (0-300 and 300-600 mm) across the three profiles before and after crop harvest and these were 3610 (±1510) and 4730 (±1510) mg kg$^{-1}$ respectively. The average salt contents following harvest were slightly higher than those beforehand, although the variation between them was such that this difference was non-significant.  This standard monitoring confirms there to have been no salt accumulation in the upper part of the soil profile following the season's irrigation with brackish waters.

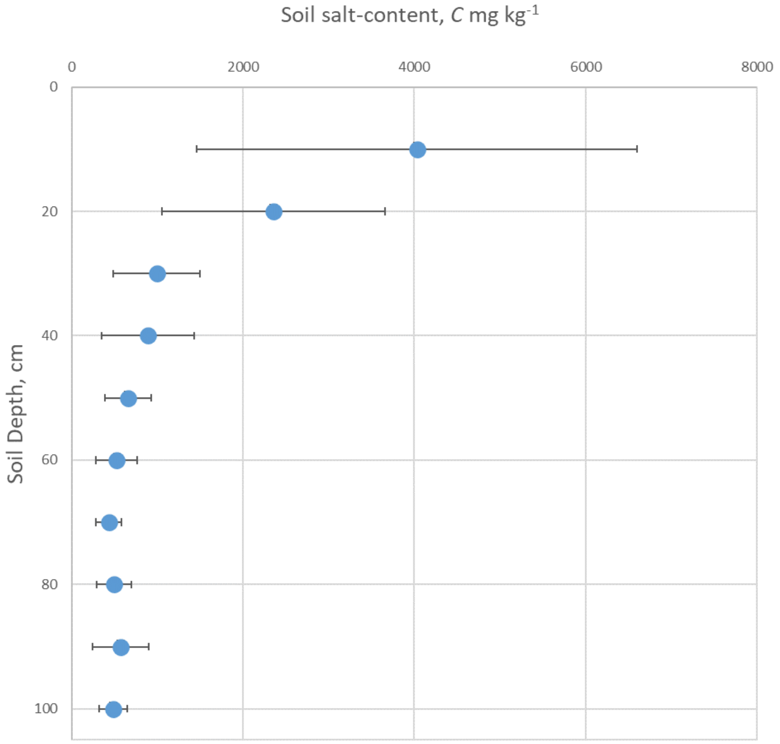



**Figure 4.5. The overall profile of salt concentration (●, mg kg$^{-1}$) measured by soil sampling following crop harvest in early November 2022 and expressed depthwise as the means (n=36) of the 10-cm slabs from the sampling of four profiles within each of the nine plots of the three different saline waters and the three irrigation emitter types.**

An examination of the 36 profiles presented in Figure 4.4 revealed no significant differences. Consequently, the mean profile of soil salt-content in mg kg-1 is presented in Figure 4.5.

That the salt concentrations measured in extracts from the deep-soil profile cores and using the saturated paste method on samples in the surface top 600 mm are in broad agreement is heartening, especially given the disparate measurement methodologies used.

Our 36 profiles show that more salt is stored in the top 200 mm of the profiles, which may be due in some way to the higher organic matter content there resulting from crop and root residues.

**Table 4. 2. Measured salt storage (plus or minus standard deviation) in the top 1 m of soil (kg m-2) in plots irrigated with groundwater (GW), reverse-osmosis brine (RO-brine) and aquabrine (AQ) using either subsurface tape (s), pressure compensated drippers (d), or bubblers (b). Four soil profiles (n=4) were extracted from each of the nine plots and the salt content of each 10-cm slab measured, so that the profile storage of salt could be calculated. The raw data are shown in Figure 4b, and the average depthwise profile of salt storage is shown in Figure 4.5. The soil's bulk density was taken to be 1.6 kg $L^{-1}$.**

| **Treatment** | | **Salt storage 0–1m, kg $m^{-2}$** |
|---|---|---|
| Groundwater – subsurface | (GW_s) | 1.4 (± 0.4) |
| Groundwater – dripper | (GW_d) | 1.3 (± 0.3) |
| Groundwater – bubbler | (GW_b) | 1.6 (± 0.4) |
| Reverse-Osmosis brine – subsurface | (RO_s) | 1.9 (± 0.4) |
| Reverse-Osmosis brine – dripper | (RO_d) | 2.1 (± 0.7) |
| Reverse-Osmosis brine – bubbler | (RO_b) | 2.4 (± 0.6) |
| Aquabrine – subsurface | (AQ_s) | 1.5 (± 0.3) |
| Aquabrine – dripper | (AQ_d) | 2.2 (± 0.4) |
| Aquabrine – bubbler | (AQ_b) | 2.2 (± 0.4) |
| | **Average** | **1.8 (± 0.4)** |

From these profiles of salt concentration data (mg $kg^{-1}$), the total storage of salt in the top 1 m of soil can be calculated (kg $m^{-2}$) (Table 4.1). There were no differences between the nine plots, and the average salt storage in the profile was found to be 1.8 (±0.4) kg $m^{-2}$. The absence of pre-planting soil salinity data hinders a definitive attribution of the observed stored salt. It could be a result of the season's saline water irrigation, or potentially originate from a prior time. Calculations indicate an average seasonal application of approximately 80 kg $m^{-2}$ of salt by the saline irrigation waters. So even if all the salt measured in the profile after harvest had come from the irrigation waters, only 2.25% of the salt had remained in the soil.

A possibility exists that a portion of the 1.8 kg $m^{-2}$ of residual salt is associated with the immobile fraction of the soil's pore water, as observed in the breakthrough curves. In this scenario, this very small amount of 'immobile salt' would indeed resist leaching.

Nonetheless, some 78 kg $m^{-2}$ of salt had been leached through the rootzone by the *LF* and despatched to the groundwater underneath. This reinforces the breakthrough curve analyses that show salt is effectively displaced by piston flow through all of soil's pore water. This highlights the value of simply using the leaching requirement *LR* (Eq. 4.3) to manage the soil-water salinity in the rootzone.

Al Tamimi et al. (2023) have calculated that this leaching fraction *LF* (Eq. 4.5) could have potentially resulted in an annual rise in groundwater salinity of 2.6 dS $m^{-1}$ $y^{-1}$, which could have deleterious consequences for the future quality of the water in the underlying aquifer.

## 4.7 Conclusions

This Chapter investigated the effectiveness of leaching in maintaining rootzone salinity during saline water irrigation. The common practice of employing leaching requirement (*LR*) (Rhoades, 1974) and leaching fraction (*LF*) (Maas, 1990) metrics for managing saline water irrigation implicitly assumes complete flushing of salt from the profile through infiltration. Here, verification was sought to determine if salt leaching could be described by piston displacement with minimal solute dispersivity. Laboratory measurements and field monitoring confirmed that for these dominant desert soils of the Arabian Peninsula, salt can be effectively leached from the profile. The findings indicate that invading irrigation water displaces all the resident salt-laden soil water within the rootzone prior to irrigation, effectively flushing it downwards.

This effectiveness has benefits for maintaining equable salinity conditions in the rootzone through implementation of a leaching requirement, *LR*. However, the effectiveness of the salt leaching fraction *LF* means that the underlying aquifer is receiving drainage water of salinity some 2–3 times higher than that of the irrigation water. This can compromise, in the longer term, the water quality of the groundwater from which irrigation is drawn. This salt dilemma will require careful management to achieve economic crop yields whilst sustaining the environment in semi-arid and arid regions where saline groundwaters are used for irrigation.

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# CHAPTER 5

# 5 DRAINAGE, SALT-LEACHING IMPACTS, AND THE GROWTH OF SALICORNIA BIGELOVII IRRIGATED WITH DIFFERENT SALINE WATERS

Chapter 5 evaluates the impact on groundwater of using three types of saline waters to irrigate the halophyte *Salicornia bigelovii* Torrey in the hyper-arid United Arab Emirates was assessed. These waters were groundwater (GW) at 25 dS $m^{-1}$, reverse-osmosis brine (RO) from a desalination unit at 40 dS $m^{-1}$, and the aquabrine (AQ) effluent from land-based aquaculture in tanks filled with RO brine, also at 40 dS $m^{-1}$. The three waters were applied through bubblers (BUB), pressure-compensated drippers (PCD), or subsurface irrigation tape (SUB). The yields of Salicornia fresh tips, harvest forage, and seed were greatest for AQ applied through BUB, being 650 g $m^{-2}$. It was found that 2-2.6 kg $m^{-2}$ for dry forage yield was achieved with AQ through BUB, compared with 1-2.3 kg $m^{-2}$ for the other waters and emitter devices. The highest water productivities $WP_I$ (kg $m^{-3}$) across all three crop-outputs came from Aquabrine applied by pressure-compensated drippers. The gross economic water productivity ($GEWP_I$, \$ $m^{-3}$) was assessed based solely on gross revenue. It was found that the $GEWP_I$ was highest for AQ applied through PCD and SUB, namely 5.8-6.2 \$ $m^{-3}$. The value was derived primarily from fresh tips. The $GEWP_I$ was well above the cost of desalination at \$1.5 $m^{-3}$. Drainage and leaching were measured using fluxmeters. The greatest salt load to groundwater came from BUB, being 135-195 kg $m^{-2}$. For PCD and SUB it was between 14-36 kg $m^{-2}$. Mass-balance calculations of these salt loadings can be used to predict the impact on the saline quality of aquifers. An exemplar loading of 75 kg $m^{-2}$ was used, and resulted in an annual salinity rise of 2.6 dS $m^{-1}$ $y^{-1}$ for an aquifer of saturated depth of 100 m. This significant rate of rise in the salinity of groundwater would represent a continuing deterioration in the utility of groundwater.

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The DRC Statement of Contribution is provided in Appendix 8.3.

## 5.1 Abstract

An assessment was undertaken to determine the environmental impact on groundwater of irrigating the halophyte *Salicornia bigelovii* Torrey with three types of saline waters in the hyper-arid United Arab Emirates. The irrigation waters employed were groundwater (GW) at 25 dS $m^{-1}$, reverse-osmosis brine (RO) from a desalination unit at 40 dS $m^{-1}$, and aquabrine (AQ) effluent from land-based aquaculture in tanks filled with RO brine, also at 40 dS $m^{-1}$. Bubblers (BUB), pressure-compensated drippers (PCD), or subsurface irrigation tape (SUB) were used to apply the three waters.

Salicornia fresh tip, harvest forage, and seed yields were highest for AQ applied through BUB, reaching 650 g m-2. Dry forage yield with AQ through BUB was found to be 2-2.6 kg $m^{-2}$, compared to 1-2.3 kg $m^{-2}$ for the other irrigation waters and emitter devices. The highest water productivity WPI (kg $m^{-3}$) across all three crop outputs resulted from Aquabrine applied by pressure-compensated drippers. Gross economic water productivity ($GEWP_I$, \$ $m^{-3}$) was assessed based solely on gross revenue. The highest $GEWP_I$, at 5.8-6.2 \$ $m^{-3}$, was achieved with AQ applied through PCD and SUB, primarily due to revenue from fresh tips. Notably, the $GEWP_I$ significantly exceeded the cost of desalination at \$1.5 $m^{-3}$.

Drainage and leaching were measured using fluxmeters. The greatest salt load to groundwater, at 135-195 kg $m^{-2}$, was observed with BUB irrigation. For PCD and SUB, the salt load ranged between 14-36 kg $m^{-2}$. Mass-balance calculations of these salt loadings were employed to predict the impact on the saline quality of aquifers. An exemplar loading of 75kg $m^{-2}$ was used, resulting in a projected annual salinity rise of 2.6 dS $m^{-1}$ $y^{-1}$ for an aquifer with a saturated depth of 100 m. This significant increase in groundwater salinity would represent a continual decline in the resource's utility.

## 5.2 Introduction

The United Arab Emirates (UAE) have a hyper-arid climate with an annual reference evapotranspiration (*ET*o) exceeding 2000 mm (Allen et al. 1998). Rainfall is rare with the annual precipitation averaging around 50 mm $y^{-1}$ (Al-Tamimi et al. 2022). The agricultural, forestry, and landscape sectors account for nearly 60% of the annual water demand across the UAE of 4.2 $km^3$. Groundwater is relied upon for irrigation of plants of all three sectors, yet the water-tables are falling rapidly, primarily owing to pumping for agriculture, which greatly exceeds the natural recharge rates from the scant rainfall. Sherif et al. (2021) calculated that domestic, industrial, and agricultural activities consume 2854 $Mm^3$ $y^{-1}$ of groundwater from surficial aquifers across the UAE. They then calculated that the net water-balance for these surficial aquifers is -1804 $Mm^3$ $y^{-1}$. Groundwater quantity is at risk. Furthermore, because of these practices, groundwaters are becoming increasingly saline. Sherif et al. (2021) found that between 1969 and 2015 the quantity of ‘fresh’ groundwater in the Quaternary aquifers, with electrical conductivities (EC) less than 2 dS $m^{-1}$, declined from 238 $km^3$ to just 10 $km^3$. Over the same period, the volume of ‘brackish’ groundwaters (2 dS $m^{-1}$ < EC < 25 dS $m^{-1}$) rose from 136 $km^3$ to 270 $km^3$. These changes in aquifer salinities indicate declines in the quality and utility of groundwaters.

Environment Agency – Abu Dhabi (EAD) has a mandate to conserve groundwater, protect its quality, and to ensure best use of all available waters in the Emirate of Abu Dhabi.

One option to improve the production benefits of irrigation using saline groundwater is for farmers to use stand-alone desalination units to ‘freshen-up’ groundwater to irrigate high-value crops (Al Muaini et al. 2019a). Al Muaini et al. (2019b) found the financial benefit:cost ratio in operational expenses of using desalinated groundwater to irrigate dates was 1.4. Not surprisingly then there has been a rapid growth in small-scale, on-farm desalination units for irrigating of crops (Dawoud, 2017). Private desalination plants are now located on 1150 farms in Abu Dhabi, being 5% of the 25,000 farms in the Emirate (Al Muaini et al. 2019b).

An Integrated Agri-Aquaculture System (IAAS) has been developed to maximise the value of using brackish groundwater resources coupled with reverse-osmosis desalination technologies (Lyra et al. 2014). Land-based fish-farming uses the reject reverse-osmosis brine (RO brine) from the desalination units, whilst high values crops are irrigated with the ‘freshened’ groundwater (Sanchez et al. 2015; Somerville et al. 2014). Nutrient-rich aquaculture effluents, known as aquabrine, from the fish tanks are then used to irrigate halophytic crops, for either food, fodder, or seed for grain or for biofuel production (Lyra et al. 2014, 2016; Panta et al. 2014; Robertson et al. 2019). Robertson et al. (2019) carried out a financial analysis of IAAS and found positive net returns from irrigating *Salicornia bigelovii* Torrey with RO brine. They reported even greater returns for *Salicornia* grown under aquabrine irrigation.

In this Chapter, the benefit-cost analysis is extended to encompass the environmental considerations of potential salt accumulation within the soil and the subsequent leaching of salts back to underlying groundwater resources (Mohamed et al., 2005).

The research in this Chapter investigated the trade-offs and impacts on groundwater salinity associated with utilizing various saline waters for irrigation of the halophytic crop, *Salicornia bigelovii* Torrey.

The fresh tips of the *Salicornia* plant can be harvested as a fresh food-crop known as 'sea asparagus' or 'sea bean' (Al-Yamani et al. 2013; Lyra et al. 2021). *Salicornia* can also be used as dried fodder for animals (Al-Owaimer et al. 2000), and its seed has a high oil content of more than 25% which can be used to produce a biofuel (Bailis and Yu, 2012). To manage *Salicornia* irrigation sustainably with saline water it is critical to measure the groundwater effects directly to assess better the impacts, options, and opportunities for the use of stand-alone desalination units.

A prior publication (Al Tamimi et al., 2023), and Chapter 3, detailed modifications made to two devices for the purposes of: directly measuring soil water content via time-domain reflectometry (TDR) and monitoring drainage and leaching through the use of modified passive tension drainage fluxmeters (DFM) (Gee et al., 2009).

The top of the convergence ring of the DFMs was set at about 200 mm to avoid the calcareous and gypsic horizon deeper in the soil profile. These modifications made it possible to measure the changing patterns of soil water content and to monitor water drainage and salt leaching in this Typic Torripsamment desert soil during the experimental trial with *Salicornia* in 2021/22.

- Consequently, these measurements were targeted to facilitate the establishment of linkages between land management practices and groundwater quality through the following approaches: Quantifying the impact of irrigation waters of different salinities and nutrient contents on the drainage of water and salt leaching to groundwater under *Salicornia* cultivation.
- Measuring the impact of irrigation waters of different salinities and nutrient contents delivered by different irrigation systems on *Salicornia* yields of fresh tips (food), fresh weight (fodder) and dry weight (conserved fodder) and seed weight (oil).
- Determining the water productivity (kg $m^{-3}$) and economic productivity (\$ $m^{-3}$) of using saline waters to irrigate *Salicornia* and quantify the environmental impacts of the salt leaching (kg $m^{-2}$) in the drainage (L $m^{-2}$) back to groundwater.

## 5.3 Materials and Methods

### 5.3.1 Experimental trials

The field experiments were carried out at the International Centre for Biosaline Agriculture (ICBA) (25.09° N; 55.39° E; 48 m a.s.l.) near Dubai. The experiments reported in this study were for just one year, namely 2021/2022. This approach is considered agronomically valid in this hyper-arid environment.

The weather is virtually always cloud-free, and rainfall is extremely rare and negligible, so the annual trend in the weather is dominated by the seasonal pattern of incident radiation, which is year-wise invariant (Al Yamani et al. 2018). Inter-annual variation is virtually non-existent.

The soil at the site is a Typic Torripsamment. It is a spatially uniform, deep sandy soil of aeolian origin with a carbonatic mineralogy, comprising quartz, mixed sands, volcanic glass, plus calcareous and gypsum concretions at various depths below half a metre (EAD 2009).

### 5.3.2 Crop Agronomy

The *Salicornia* seeds were sown in the second week in November 2021. To enable good germination and establishment, all the plots were irrigated through until 23 February 2022 with low salinity water at 10 dS $m^{-1}$ water. Then three types of saline waters were used for irrigation: aquabrine (AQ; ≈ 40 dS $m^{-1}$), reverse-osmosis (RO) reject brine from the desalination plant (≈ 40 dS $m^{-1}$), and groundwater (GW, ≈ 22.5 dS $m^{-1}$). There were three irrigation systems: bubblers (BUB), pressure-compensated drippers (PCD), and sub-surface tape irrigation (SUB). Irrigation was stopped in mid-August.

Nine separate plots each of 8 m by 8 m were established in a square matrix layout, with 4m borders between plots. The rows of the matrix were the different water-sources of AQ, RO, and GW. The columns of the matrix were the emitter-device types of BUB, PCD, and SUB. Within each plot, four quadrants, each of 2 m by 2 m, were created, and drainage fluxmeters and vertical TDR probes of length 600 mm were installed near the centre of each quadrant.

The complexity of the irrigation plumbing, and the need to group the devices spatially with data-loggers necessitated the nine four-quadrant plots. As a result, there was only one plot per treatment, albeit with four separate sampling sites near to the centre of each quadrant per plot. So strictly this is not replication, but rather a form of pseudo-replication. Accounting for the spatial uniformity of this ancient desert soil, the consistent application within each plot due to uniform irrigation emitters and plumbing, and the absence of significant weather variation across the exposed site, this pseudo-replication is nevertheless considered as true replication for the purposes of statistical analysis. The data were analysed using analysis of variance (ANOVA) using Genstat 22$^{nd}$ edition (VSN International, 2022). In the analysis the sub-samples were treated as replicates and a full 2-way factorial model was fitted.

The crop was harvested for the yield of fresh tips on 14 April 2022, total dry weight on 6 June 2022, and for seed during mid-September after irrigation had been stopped in on 31 August, and the crop had then dried off.  Crop samples were taken from randomly selected locations within each plot, although locations near to measuring devices were avoided.

### 5.3.3 Water Productivity: Irrigation and Economic

Drawing on the clear exposition of water-use nomenclature and irrigation-water productivity definitions provided by Fernández et al. (2020), this study adopts these definitions. Irrigation-water productivity (WPI, kg $m^{-3}$) is considered the primary metric of irrigation water's productive value. It is calculated by dividing crop yield (kg $m^{-2}$) by the amount of irrigation water used (IWU, $m^3$ $m^{-2}$).

As Fernandez et al. (2020) noted this metric can have the limitation in that it does not consider any water supplied by rainfall. But in this hyper-arid region there is essentially no rainfall, so the metric of $WP_I$ is appropriate (Al Tamimi et al. 2022). The referencing of WP to *I*, rather than *ET*, is considered appropriate.  Whereas there is a degree of academic value in examining $WP_{ET}$ to assess the physiological responses of crop growth to transpiration, here the interest was to assess the impact of irrigation usage, *I*, on WP.

A slight variant of the Gross Economic Irrigation-Water Productivity, $GEWP_I$ ($ $m^{-3}$), is taken for the assessment of the economic value of the irrigation waters. For the numerator in this metric, the Gross Margin ($ $ha^{-1}$), being the revenue minus variable costs, was used by Fernandez et al. (2020). Because an actual farm is not dealt with, but rather experimental plots, there is little practical relevance for the costs that were incurred during production. So here, the numerator is simply taken to be the revenue received for the products ($ $ha^{-1}$). The denominator is the amount of irrigation used (IWU $m^3$ $m^{-2}$) to produce the products for which the revenue would be received.

The simple benefit-cost assessment compares the $GEWP_I$ with the direct operational-expenses to produce desalinated water. As given by the company Advisian for small desalination plants, the cost of desalination is considered US$1.5 (±0.25) $m^{-3}$, (https://www.advisian.com/en/global-perspectives/the-cost-of-desalination ).  At the current exchange rate, this translates to AED 5.5 (±0.9) Arab Emirati Dirhams $m^{-3}$.  At this stage it is not considered the economic value that would come from the use of the desalinated water to grow high-value crops such as vegetables and dates, nor were considered the revenues that would come from aquacultural production.  That future analysis will await a full economic analysis of the entire system, which will include an assessment on the other side of the ledger resulting from the costs of environmental degradation as a result of the salt leachate from the *Salicornia* down to the groundwater resource.

### 5.3.4 Statistical Analyses

To equalise the variances across the various irrigation water-sources and emitter devices for statistical treatment by analysis of variance (ANOVA) using Genstat (VSN International, 2022), the original fresh-tip yield data were log-transformed.  For the crop-harvest yields and the seed yield data, there was no need to log-transform the data prior to the ANOVA procedures.

## 5.4 Crop Growth and Yields:

The crop yields are presented in terms of fresh tips for food value, dry weight for the value of fodder (Section 3.2), and seed yield for the potential value as biofuel, or fodder.

### 5.4.1 Fresh-tip yields

The yields of the young, fresh tips harvested for food from the top 200 mm of the canopy are presented in Table 5.1 and Figure 5.1. The back-transformed means are presented in Table 4.1 along with the 95% confidence limits. The fresh-tip yields ranged from 247 g $m^{-2}$ for RO applied through BUB, up to 649 g $m^{-2}$ for AQ and BUB.

**Table 5.3. Back-transformed means (n=5) and 95% confidence intervals for the weight of fresh tips of *Salicornia bigelovii* (g $m^{-2}$) for each water type and irrigation-emitter type. The original data were log-transformed to equalise the variances. RO is reverse osmosis.**

| Water type | Device type | Mean | 95% C.I. |
|---|---|---|---|
| Groundwater | Bubbler | 257 | (173, 380) |
| | Dripper | 323 | (218, 478) |
| | Subsurface | 253 | (171, 375) |
| Aquabrine | Bubbler | 649 | (438, 961) |
| | Dripper | 501 | (338, 741) |
| | Subsurface | 522 | (352, 772) |
| RO Brine | Bubbler | 247 | (167, 366) |
| | Dripper | 448 | (302, 663) |
| | Subsurface | 517 | (349, 766) |

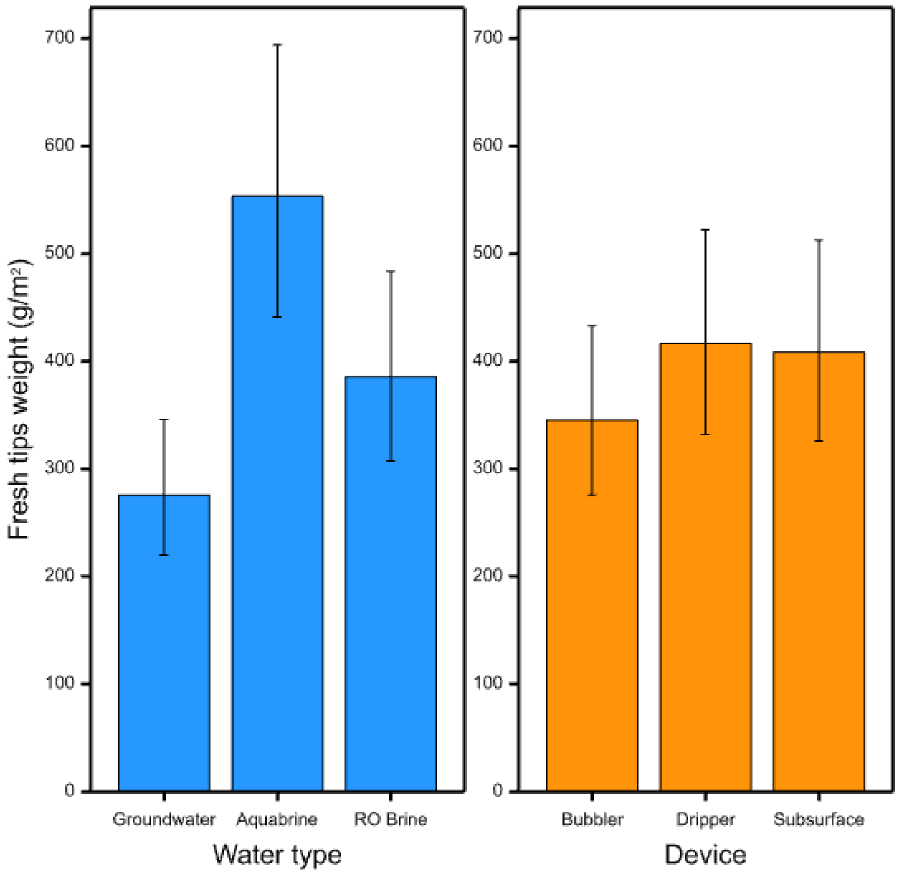


**Figure 5.1. Mean back-transformed weight of *Salicornia bigelovii* fresh tips in g m$^{-2}$ for the three water types of groundwater, aquabrine, and reverse osmosis brine; and three irrigation emitter devices of bubblers, pressure-compensated drippers, and subsurface tape. The errors bars are 95% confidence limits for the mean (*n*=15). The original data were log-transformed to equalise the variance.**

There was a significant effect of water type ($F=9.74$, $df=2,36$, $p<0.001$), but no significant effect ($P>0.05$) of irrigation device type ($F=0.85$, $df=2,36$, $p=0.43$) on the yields of fresh tips. There was no significant interaction ($F=2.12$, $df=4,36$, $p=0.10$) between the effects of water source and device on the fresh-tip yields.

### 5.4.2 Crop harvest yields

The crop harvest yields are presented in both fresh and dry weights to acknowledge the dual potential uses of the harvested Salicornia. It can be fed directly to animals as fresh forage or conserved as dry forage for later feeding.

#### *5.4.2.1 Fresh weight yield*

The means of the fresh weights for each water source and irrigation emitter are given in Table 5.2.

**Table 5.2. Means (n=5) for fresh weight yield of *Salicornia bigelovii* (kg $m^{-2}$) for each irrigation-emitter device and water source. The pooled standard error of the mean (SEM) is 0.807. RO is reverse osmosis.**

| | Water source | | |
|---|---|---|---|
| Device type | Groundwater | Aquabrine | RO Brine |
| Bubbler | 11.07 | 16.62 | 13.33 |
| Dripper | 6.82 | 7.12 | 5.96 |
| Subsurface | 5.18 | 7.67 | 5.04 |

The groupings of the means of the fresh-tip yields by water source and emitter device are given in Figure 5.1.

Figure 5.2 presents these fresh-weight yields grouped by water type and emitter device.

There was a significant effect of water source (F=10.4, df=2,36, p<0.001) and irrigation-emitter type (F=84.0, df=2,36, p<0.001). The yields were the highest for AQ and BUB. There was a significant interaction between the effects of water sources and emitters (F=2.76, df=4,36, p=0.042) on the fresh-weight yields.

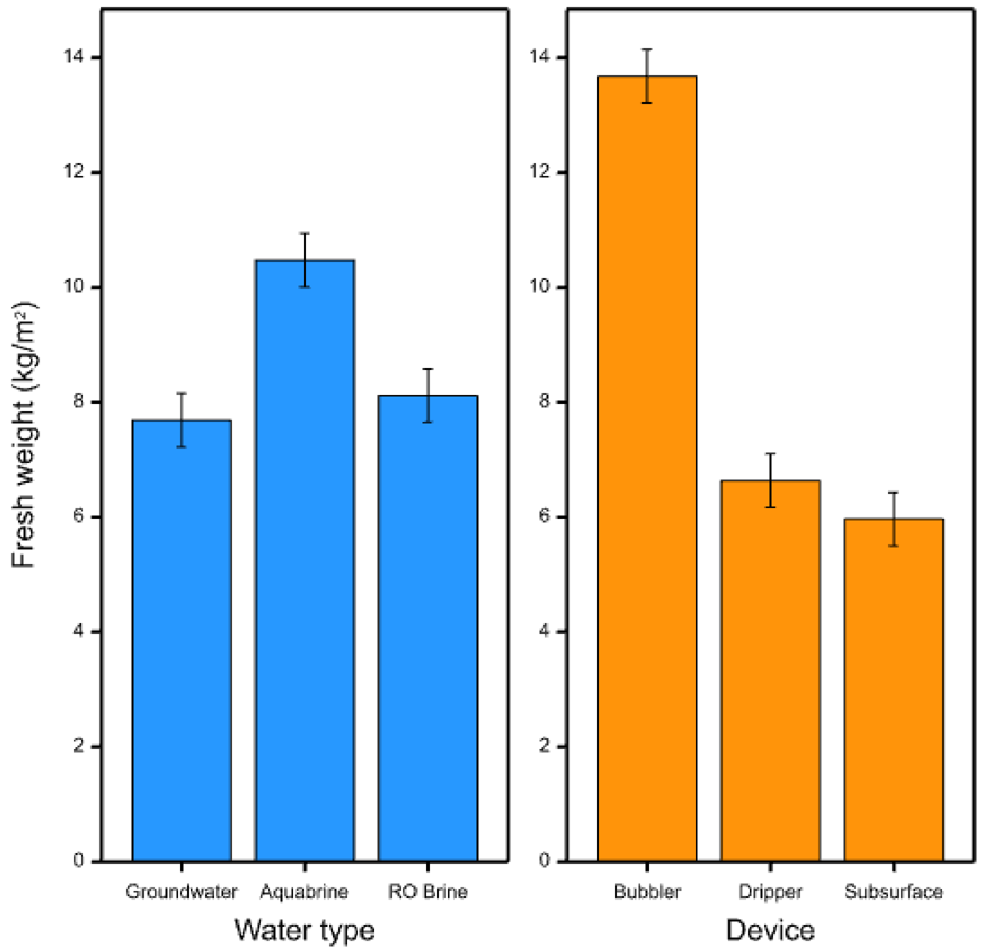


**Figure 5.2. Mean *Salicornia bigelovii* fresh-weight yield in kg m$^{-2}$ for three water types of groundwater, aquabrine, and reverse osmosis brine; and three irrigation emitter devices of bubbler, pressure-compensated drippers, and subsurface tape. The errors bars are pooled standard error of the mean (*n*=15).**

#### *5.4.2.2 Dry weight yield*

The dry-weight yields are presented in Table 5.3 arranged by water source and emitter type.

**Table 5.3. Mean (n=5) for dry-weight forage yield *of Salicornia bigelovii* (kg m$^{-2}$) for each irrigation-emitter device and water source. The pooled standard error of the mean (SEM) is 0.19. RO is reverse osmosis.**

| | Water Source | | |
|---|---|---|---|
| Device type | Groundwater | Aquabrine | RO Brine |
| Bubbler | 1.98 | 2.58 | 2.34 |
| Dripper | 1.49 | 1.55 | 1.36 |
| Subsurface | 1.32 | 1.61 | 1.11 |

These data are presented in Figure 5.3 when grouped by the means of water source and device type.

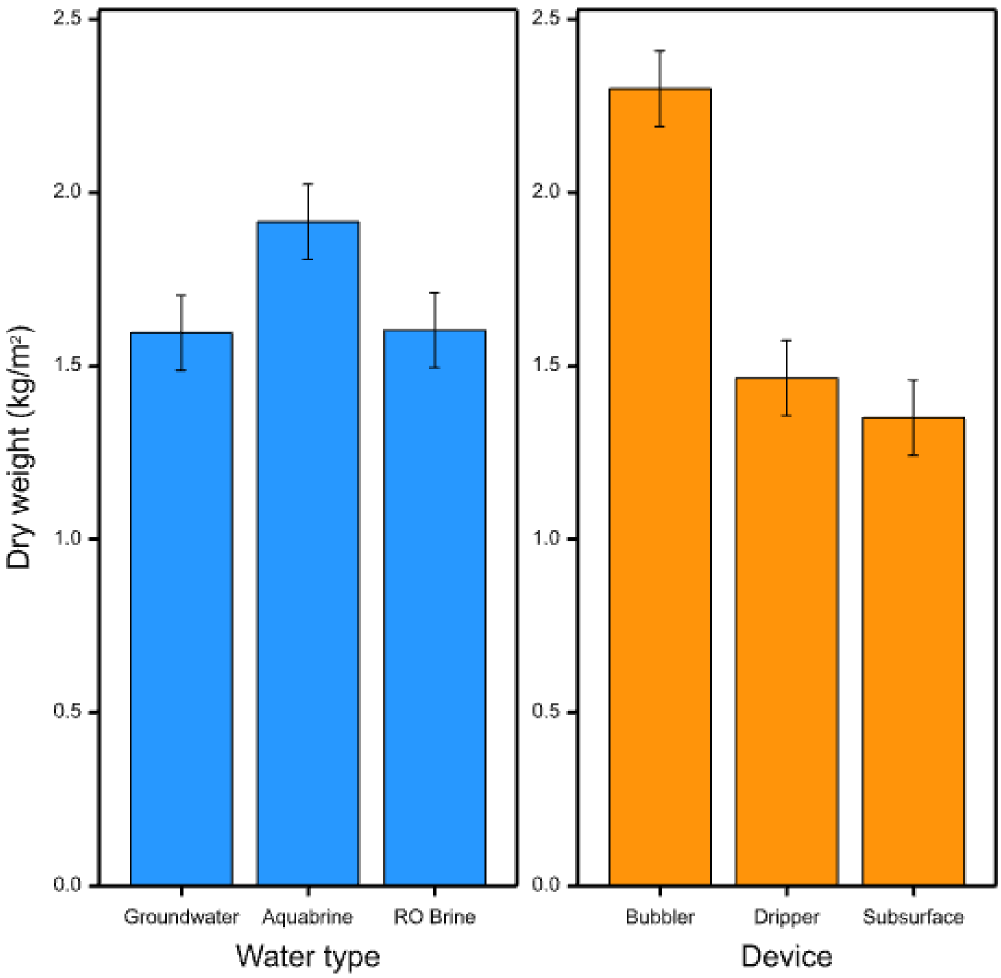


**Figure 5.3. Mean *Salicornia bigelovii* dry-weight yield in kg $m^{-2}$ for three water types of groundwater, aquabrine, and reverse osmosis brine; and three irrigation emitter devices of bubbler, pressure-compensated drippers, and subsurface tape. The errors bars are pooled standard error of the mean (*n*=15).**

For dry-weight yields, unlike fresh-weight yields, there was a tendency for an effect of water type (F=2.84, df=2,36, p=0.072), albeit a significant effect of irrigation device type (F=22.8, df=2,36, p<0.001). Again, the highest yields were realised by AQ and BUB. But here there was no significant interaction (F=0.93, df=4,36, p=0.46) between the effects of water sources and emitters on dry-weight yield.

### 5.4.3 Seed yields

The seed weights in g m$^{-2}$ are presented in Table 5.4 by water source and emitter type.

**Table 5.4. Mean (n=5) for seed weight of *Salicornia bigelovii* (g m$^{-2}$) for each irrigation-emitter device and water source. The pooled standard error of the mean (SEM) is 15.3. RO is reverse osmosis.**

| | Water source | | |
|---|---|---|---|
| Device type | Groundwater | Aquabrine | RO Brine |
| Bubbler | 153.7 | 157.4 | 116.2 |
| Dripper | 131.6 | 162.8 | 122.2 |
| Subsurface | 132.0 | 115.6 | 57.4 |

The seed-yield means are presented in Figure 5.4 grouped by water type and emitter device.

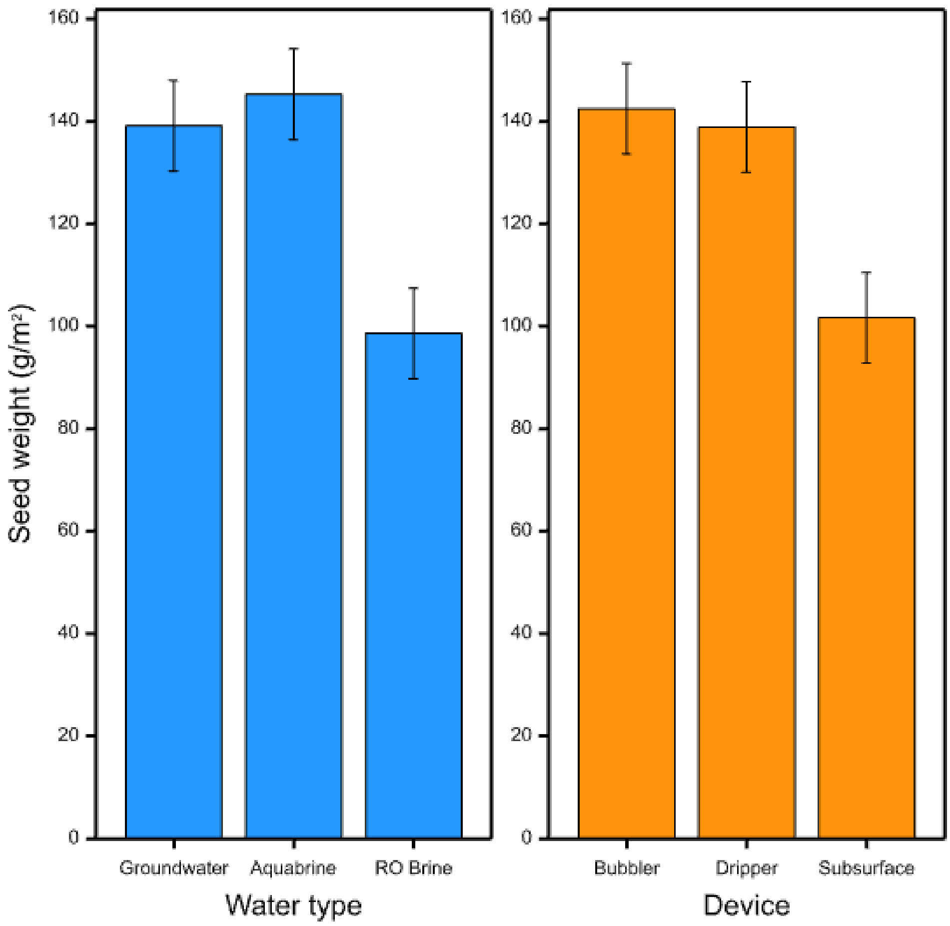


**Figure 5.4. Mean *Salicornia bigelovii* seed-weight yield in g m$^{-2}$ for three water types of groundwater, aquabrine, and reverse osmosis brine; and three irrigation emitter devices of bubbler, pressure-compensated drippers, and subsurface tape. The errors bars are pooled standard error of the mean (*n*=15).**

For the seed yields there was a significant effect of water type ($F=8.22$, $df=2,36$, $p=0.001$) and a significant effect of irrigation device type ($F=6.52$, $df=2,36$, $p=0.004$). The highest yields were achieved using AQ and PCD. However, here there was no significant interactions ($F=1.24$, $df=4,36$, $p=0.31$) between the effects of water sources and emitters on seed weight.

### 5.4.4 Water Productivity Results and Discussion

#### *5.4.4.1 Water Productivity*

These yield results offer valuable data for the determination of irrigation productivity ($WP_I$, kg $m^{-3}$) associated with the various water sources and emitter types.

Table 5.5 presents the irrigation water used (IWU, L $m^{-2}$) for each water source and emitter type employed in the production of fresh tips, dry forage, and seed. It is important to note that the harvesting of Salicornia for direct animal feeding (fresh forage) is not included in this calculation. Thus, the total IWU for forage and seed is the amount of irrigation water used up until the cessation of irrigation on 31 August.

**Table 5.5. The amount of irrigation water added in L $m^{-2}$ to produce the fresh tips of *Salicornia bigelovii* harvested on 14 April 2022, and the irrigation total added in L $m^{-2}$ to produce the final dry yield for forage and seeds harvested in mid-September. Irrigation ceased on 31 August. RO is reverse osmosis.**

| Emitter | Fresh-Tips: Water Added (L $m^{-2}$) - Up to 14 April | | |
|---|---|---|---|
| | Groundwater | Aquabrine | RO Brine |
| Bubbler | 4171 | 4193 | 3889 |
| Dripper | 1251 | 1412 | 1333 |
| Subsurface | 1336 | 1590 | 1420 |
| | Forage & Seed: Water Added (L $m^{-2}$) - To Mid-September | | |
| Bubbler | 8056 | 8243 | 7522 |
| Dripper | 2730 | 2506 | 2669 |
| Subsurface | 2523 | 2791 | 2489 |

In terms of the IWU with the scheduling, the bubblers used two to three times the amount of water than either the drippers or subsurface devices. This total IWU was applied to obtain fresh-tip yields plus those from the forage and seed yields. The amount of water used through to fresh-tip harvest in April was about half of that applied for the whole season. Some 8000 L $m^{-2}$, or 8000 mm, of water was applied in total through the BUB system. The annual reference evapotranspiration, $ET_o$, for this region is just 2000 mm (Al-Tamimi et al., 2022). The schedules for the PCD and SUB were better aligned with $ET_o$.

The experimental designs employed have resulted in the creation of a wide range of salt-leaching fractions. This is advantageous as it enables us to provide a wide assessment of both water productivities and salt-leaching impacts.

The values found for water productivity $WP_I$ (kg $m^{-3}$) are given in Table 5.6 for the three water sources and emitter types for the yields of fresh tips, dry forage, and seed.

While bubbler irrigation (BUB) yielded the highest crop yields, the chosen scheduling strategy for these devices resulted in the lowest irrigation water productivity (WPI) values. These WPI values were approximately 58% and 52% of those achieved with pressure-compensated drippers (PCD) and subsurface irrigation tape (SUB), respectively.

The $WP_I$ for dry forage was between 1.4 - 2.8 kg $m^{-3}$ (Table 6). Not surprisingly this is much lower than the $WP_I$ of 4-7 kg $m^{-3}$ found by Al Tamimi et al. (2022) for outdoor vegetables grown in the UAE using fresher groundwater. The $WP_I$ here for *Salicornia* under saline irrigation is somewhat higher that the 0.5-1.3 kg $m^{-3}$ found by Li et al. (2016) for cereals growing in the hyper-arid Hexi Corridor in Northwest China. The $WP_I$ was also higher than that of 1 kg $m^{-3}$ found by Al Muaini et al. (2019b) for dates growing in the UAE with saline irrigation water using a salt-leaching fraction of 25%.

Our results show the positive value for production of using saline waters to grow *Salicornia* for fresh-tips, forage, and seed. The highest water productivities $WP_I$ across all three crop-output types came from aquabrine applied by pressure-compensated drippers (Table 6).

#### *5.4.4.2 Economic Water Productivity*

An assessment of gross economic water productivity ($GEWP_I$, US\$ $m^{-3}$) is now undertaken, utilizing the established $WP_I$ values (Fernandez et al., 2020). As previously noted, this study's $GEWP_I$ calculation differs slightly from that of Fernandez et al. (2020) by solely considering gross revenue, excluding gross margin.

Robertson et al. (2019) noted that there are very few reports on the market value of *Salicornia* as a fresh-tip vegetable crop. In their analyses they assumed a price of $4.73 kg$^{-1}$. However, a market survey shows that fresh Salicornia sold as either ‘sea asparagus’ or ‘sea bean’, can fetch prices of over $20 kg$^{-1}$. For the purposes of this calculation, a value of $15 kg$^{-1}$ is assigned to the fresh tips.

Robertson et al. (2019) also assessed the value of *Salicornia* as a forage crop on a nutritional comparison with the forage crops of Rhodes grass and alfalfa. Given the lower nutritional value of Salicornia they reckoned the forage value to be $300 t$^{-1}$. A value of $15 kg$^{-1}$ is employed here to represent the gross revenue from *Salicornia* forage. Estimation of the revenue generated from the sale of seed for biofuels is even more challenging. Alassali et al. (2013) estimated the price of *Salicornia* seed for a biorefinery to be up to $0.05 kg$^{-1}$. Fredsgaard et el. (2021) assigned zero value to the Salicornia feedstock, considering it to be a waste product after food production. In this context, a value of $0.3 kg$^{-1}$ is assigned to the seed, mirroring the value assigned to dry forage on a dry weight basis. This is because even if the seed were not used for biofuel, it could still form part of the conserved forage-feed to animals.

The $GEWP_I$ values for the three water types, emitter devices and harvest categories are provided on the right in Table 5.6. The greatest values of around 1 to 5 \$ $m^{-3}$ are for fresh tips, especially under PCD and SUB for AQ and RO. The lowest values for fresh tips are for the production using BUB. The $GEWP_I$ for dry forage is about 15% that of fresh tips, ranging from 0.4 to 0.9 \$ $m^{-3}$. The $GEWP_I$ values for seed production are small because of the low-price set for seed, and the low productivity of seeds. The overall $GEWP_I$ values summed for all the crop outputs are highest for PCD and SUB, with only a small variation between water types, namely 2.5 to 6.2 \$ $m^{-3}$.

The $GEWP_I$ values are dominated by the price received for the fresh tips. This value could be even further enhanced if there were sequential, multiple harvests for fresh tips. Multiple fresh-tips harvests would have additional advantages. Reduced lodging was observed in crop sections that had undergone a fresh-tip harvest.

In those areas not harvested, the crop grew taller and eventually lodged, thereby diminishing the harvest quality of the forage. As well, producing more food for human consumption would support the UAE's goal for increased food security (Shahi and Salem 2015, UAE 2019).

The company Advisian considered the current operating costs of desalination plants to be \$1.5 (±0.25) $m^{-3}$ (https://www.advisian.com/en/global-perspectives/the-cost-of-desalination ). The revenue benefits from *Salicornia* production alone would be greater than these operating costs for the desalinated water-resources from AQ and RO, and for both the emitter types of PCD and SUB (Table 6). The $GEWP_I$ values for all desalinated waters using BUB are below the operating costs of desalination units, despite the BUB yields being higher.

## 5.5 Drainage and Leaching

The groundwater resources of Abu Dhabi are hugely valuable. Baker and van Houtven (2015) carried out an economic quantification of the net present-value of groundwater in Abu Dhabi resulting from its combined utility for agriculture, forestry, amenity and strategic value. They found the net present-value Abu Dhabi's groundwater to be US\$ 272 billion (AED 781 billion at 1 AED = \$0.272) for 3% discount rate, and \$120 billion (AED 443 billion) at an 8% discount rate. Groundwater in this hyper-arid region is a highly valuable natural capital stock well worth protecting, not only interms of quantity, but also in relation to its salinity which could compromise its utility.

### 5.5.1 Drainage

Drainage below the rootzone provides for the recharge of groundwater. The need for a salt-leaching fraction means that there will be drainage through the rootzone of all the *Salicornia* plots. There were four passive-tension drainage fluxmeters (DFM) within each plot. The weekly drainage results, in mm $d^{-1}$, from these 36 DFMs are shown in Figure 5.5 grouped by emitter type and water source.

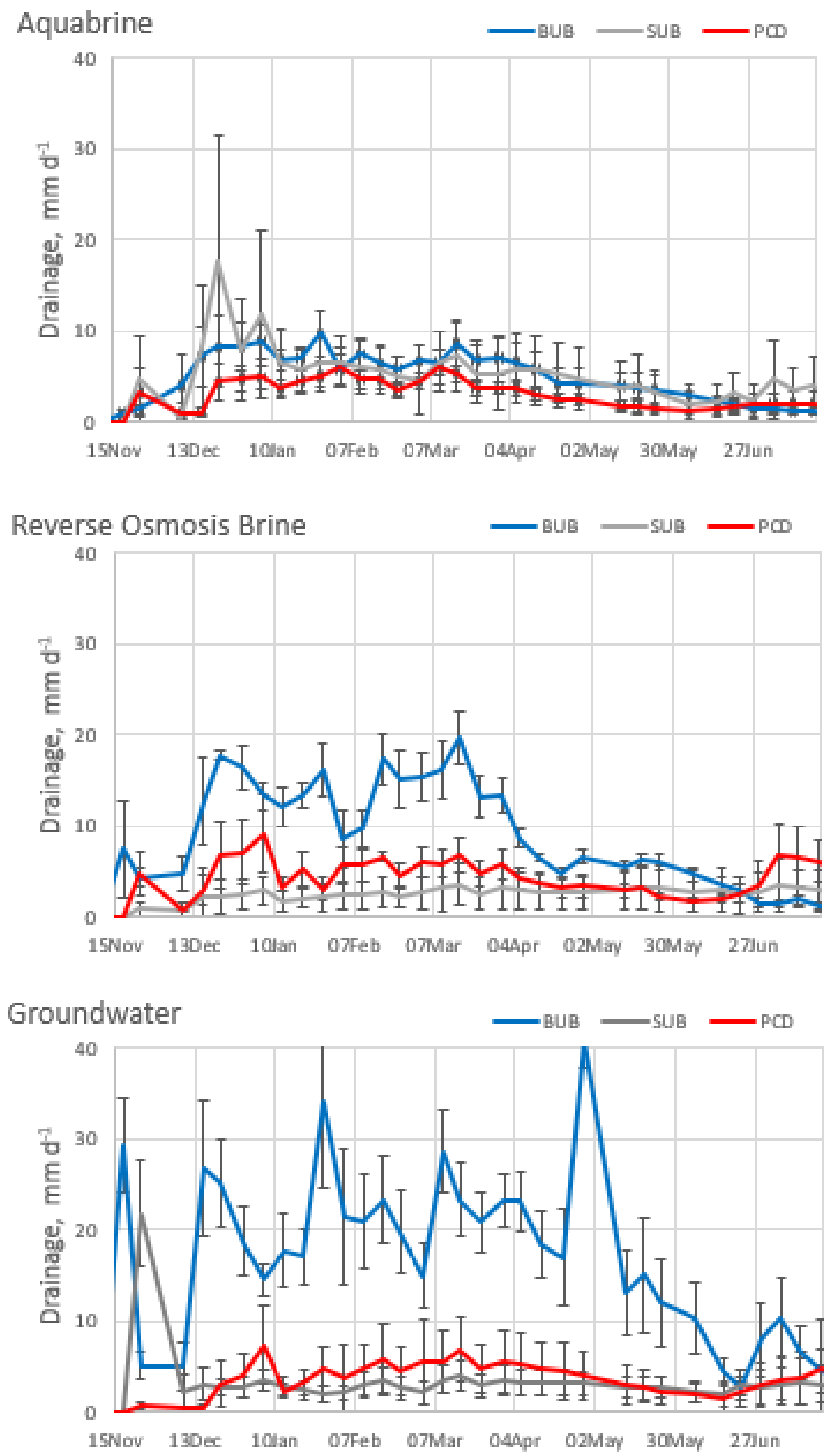


**Figure 5.5. The drainage (mm d$^{-1}$) measured under plots of a *Salicornia bigelovii* crop in the United Arab Emirates by tension drainage fluxmeters under three different irrigation emitter types (BUB, bubbler; SUB, subsurface; PCD, pressure-compensated dripper) with aquabrine (top), reverse osmosis water (middle) and groundwater (bottom). The bars represent the standard errors of the measures from 4 drainage fluxmeters (DFMs) for each emitter type.**

Spatial variability in drainage measurements hindered the establishment of a definitive mass balance between irrigation water inputs and crop evapotranspiration losses. Consequently, to achieve mass balance closure, the drainage component was estimated through mechanistic modelling of the water balance.

The key process in the water-balance model is that of the crop evapotranspiration $ET_C$. Drainage is then calculated as the residual, given that on a daily basis the time-domain

reflectometry measurements showed there was no net daily change in the water content of the rootzone once the irrigation scheduling began. The FAO56 approach to modelling $ET_C$ was adopted in this study, utilizing the crop coefficient (*K*c) methodology outlined in Al-Tamimi et al. (2022). The modelled drainage results (L $m^{-2}$) are presented in Table 5.7 alongside the amount of irrigation (L $m^{-2}$) applied by the various emitter devices for each water type.

**Table 5.6. Left. The irrigation-water productivity (kg $m^{-3}$) for the harvest of fresh tips, fresh forage, and seeds of *Salicornia bigelovii* in relation to water source and emitter type. Right. The gross economic productivity in US$ $m^{-3}$ fresh tips, dry forage, and seed assuming the price for fresh tips to be US$15 $kg^{-1}$ and US$0.3 $kg^{-1}$ for fresh forage and seed. The table on the bottom right is for the combined revenue from all products. Here 1 AED Arab Emirati Dirham is assumed to be US$ 0.27. Here gross economic productivity considers only gross revenue, not gross margin. RO is reverse osmosis.**

| Emitter | Fresh-Tips: Water Added (L $m^{-2}$) - Up to 14 April | | |
|---|---|---|---|
| | Groundwater | Aquabrine | RO Brine |
| Bubbler | 4171 | 4193 | 3889 |
| Dripper | 1251 | 1412 | 1333 |
| Subsurface | 1336 | 1590 | 1420 |
| | Forage & Seed: Water Added (L $m^{-2}$) - To Mid-September | | |
| Bubbler | 8056 | 8243 | 7522 |
| Dripper | 2730 | 2506 | 2669 |
| Subsurface | 2523 | 2791 | 2489 |
| | Forage & Seed: Water Added (L $m^{-2}$) - To Mid-September | | |
| Bubbler | 8056 | 8243 | 7522 |
| Dripper | 2730 | 2506 | 2669 |
| Subsurface | 2523 | 2791 | 2489 |

| Emitter | Fresh Tips Yield (g $m^{-2}$) on 14 April | | |
|---|---|---|---|
| | Groundwater | Aquabrine | RO Brine |
| Bubbler | 257.0 | 649.0 | 247.0 |
| Dripper | 323.0 | 501.0 | 448.0 |
| Subsurface | 253.0 | 522.0 | 517.0 |
| | Dry forage Yield (kg $m^{-2}$) - In Mid-September | | |
| Bubbler | 11.07 | 16.62 | 13.33 |
| Dripper | 6.82 | 7.12 | 5.96 |
| Subsurface | 5.18 | 7.67 | 5.04 |
| | Seed Yield (g $m^{-2}$) - In Mid-September | | |
| Bubbler | 153.7 | 157.4 | 116.4 |
| Dripper | 131.7 | 162.6 | 122.2 |
| Subsurface | 131.8 | 115.3 | 57.3 |

| | $WP_I$, Irrigation-Water Productivity (kg $m^{-3}$) | | |
|---|---|---|---|
| **Fresh tips** | Groundwater | Aquabrine | RO Brine |
| Bubbler | 0.06 | 0.15 | 0.06 |
| Dripper | 0.26 | 0.35 | 0.34 |
| Subsurface | 0.19 | 0.33 | 0.36 |
| **Fresh forage** | | | |
| Bubbler | 1.37 | 2.02 | 1.77 |
| Dripper | 2.50 | 2.84 | 2.23 |
| Subsurface | 2.05 | 2.75 | 2.02 |
| **Seed** | $WP_I$, Irrigation-Water Productivity (g $m^{-3}$) | | |
| Bubbler | 0.02 | 0.02 | 0.02 |
| Dripper | 0.05 | 0.06 | 0.05 |
| Subsurface | 0.05 | 0.04 | 0.02 |

| | $GEWP_I$, Gross Economic Irrigation-Water Productivity ($ $m^{-3}$) | | |
|---|---|---|---|
| **Fresh tips ($15 $kg^{-1}$)** | Groundwater | Aquabrine | RO Brine |
| Bubbler | 0.92 | 2.32 | 0.95 |
| Dripper | 3.87 | 5.32 | 5.04 |
| Subsurface | 2.84 | 4.92 | 5.46 |
| **Fresh forage ($0.3 $kg^{-1}$)** | | | |
| Bubbler | 0.41 | 0.60 | 0.53 |
| Dripper | 0.75 | 0.85 | 0.67 |
| Subsurface | 0.62 | 0.82 | 0.61 |
| **Seed ($0.3 $kg^{-1}$)** | | | |
| Bubbler | 0.0057 | 0.0057 | 0.0046 |
| Dripper | 0.0145 | 0.0195 | 0.0137 |
| Subsurface | 0.0157 | 0.0124 | 0.0069 |

| | $GEWP_I$, Gross Economic Irrigation-Water Productivity ($ m$^{-3}$) | | |
|---|---|---|---|
| **Tips, Forage & Seed** | Groundwater | Aquabrine | RO Brine |
| Bubbler | 1.34 | 2.93 | 1.49 |
| Dripper | 4.64 | 6.19 | 5.72 |
| Subsurface | 3.47 | 5.76 | 6.08 |

**Table 5.7. The modelled drainage (L m$^{-2}$) in relation to the amount of irrigation water applied (L m$^{-2}$), along with the calculation of the leaching fraction *LF* (Eq. 1). The *EC* (dS m$^{-1}$) of the applied waters, $EC_w$, are given for the three water sources, and the predicted EC of the drainage water, $EC_{dw}$, (Eq. 2) is given along with that average measured by the drainage fluxmeters from weekly measurements between May and August for the three waters and three emitter types. RO is reverse osmosis.**

| Water Source | Emitter-Type | Drainage, L m$^{-2}$ | Water Applied, L m$^{-2}$ | Leaching Fraction | $EC_w$, dS m$^{-1}$ | Predicted $EC_{dw}$, dS m$^{-1}$ | Measured* $EC_{dw}$, dS m$^{-1}$ |
|---|---|---|---|---|---|---|---|
| Aquabrine | Bubbler | 6231 | 8366 | 0.74 | 40 | 53.7 | 75.4 |
| | Dripper | 1059 | 2630 | 0.40 | 40 | 99.3 | 88.2 |
| | Sub-surface | 1666 | 2915 | 0.57 | 40 | 70.0 | 52.8 |
| RO Brine | Bubbler | 5498 | 7646 | 0.72 | 40 | 55.6 | 71.5 |
| | Dripper | 817 | 2768 | 0.30 | 40 | 135.5 | 71.6 |
| | Sub-surface | 1146 | 2612 | 0.44 | 40 | 91.2 | 45.6 |
| Groundwater | Bubbler | 6021 | 8179 | 0.74 | 25 | 34.0 | 53.7 |
| | Dripper | 927 | 2854 | 0.32 | 25 | 77.0 | 58.6 |
| | Sub-surface | 1159 | 2647 | 0.44 | 25 | 57.1 | 31.2 |
| * Average of weekly measurements during May-August | | | | | Average | 74.8 | 61.0 |

The amount of drainage was highest under the BUB devices and ranged between about 5500 and 6200 L m$^{-2}$, being about three-quarters of the total irrigation water applied by the bubblers. The drainage under the PCD and SUB emitters was lower, both in terms of amount, being between about 800 and 1600 L m$^{-2}$, and also as a percentage of the irrigation amount applied, which ranged between 30 and 60%.

The irrigation strategies employed here have provided a high degree of groundwater recharge, with recharge being between 30 and 75% of the water drawn originally from groundwater to irrigate the *Salicornia*.

### 5.5.2 Leaching

The electrical conductivities (*EC*, dS m$^{-1}$) in the leachates measured weekly by the DFMs are shown in Figure 5.6. The measurements began with irrigation after the seeds were sown in early November 2021. Up until late February 2022, all the plots were irrigated with low salinity water with an *EC* of 10 dS m$^{-1}$ to ensure good germination and successful early seedling growth of the *Salicornia*. Then the irrigation sources were shifted to AQ and RO at 40 dS m$^{-1}$, plus GW at 25 dS m$^{-1}$. The leachate values responded immediately to these changes in the salinity of the irrigation waters. During this early stage of crop growth, with $ET_C$ being low, the *EC* values of the leachates were essentially those of the applied irrigation waters. However, as the crop grew and $ET_C$ became a more significant component of the water balance, there were rises in the *EC* values of the leachates, and eventually the leachate *EC*s exceeded those of the applied waters.

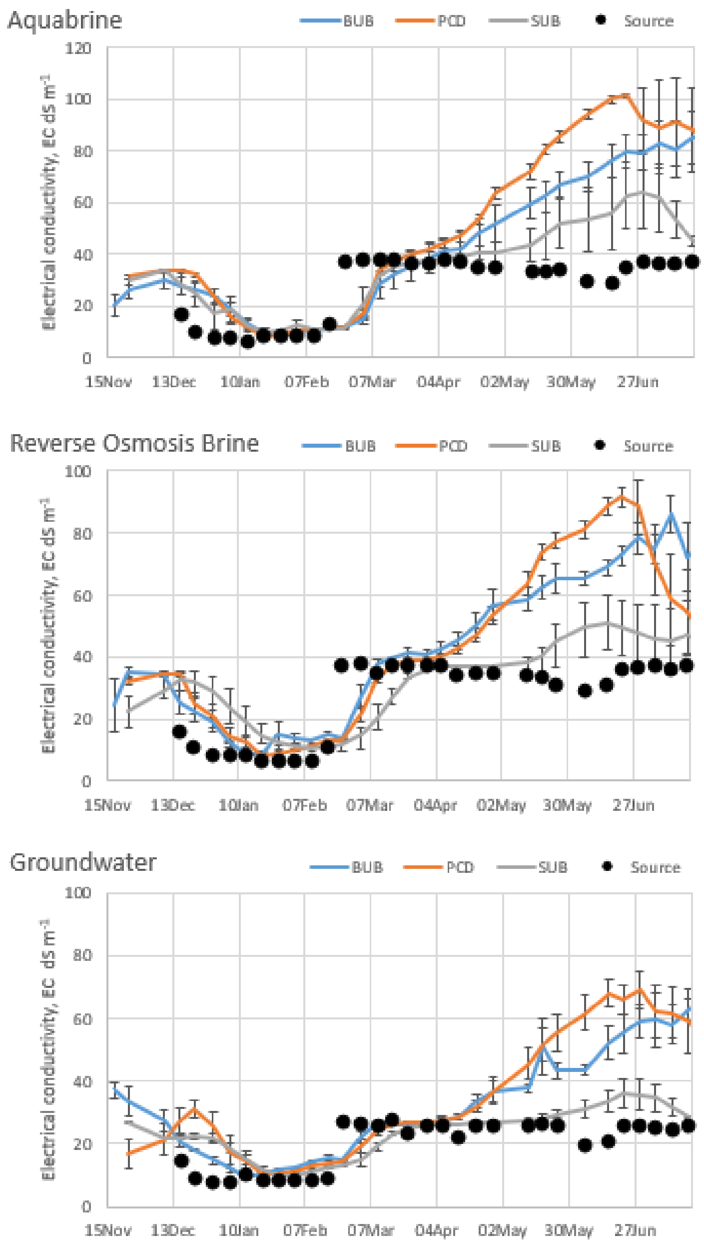


**Figure 5.6. The electrical conductivity (*EC*, dS m$^{-1}$) of the leachate measured in drainage under plots of a *Salicornia bigelovii* crop in the United Arab Emirates by tension drainage fluxmeters under irrigation with aquabrine (top), reverse osmosis (RO) water (middle) and groundwater (bottom). The switch between low salinity irrigation to RO water was on 23 February 2022. The original irrigation was water at EC at 10 dS m$^{-1}$, and then under aquabrine and reverse osmosis brine at about 40 dS m$^{-1}$, and groundwater at 25 dS m$^{-1}$. The bars represent the standard errors of the measures from 4 drainage fluxmeters (DFMs) for each emitter type.**

Ayers & Westcot (1994) noted that for a leaching fraction, *LF*, defined as

$$LF = \frac{Depth\ of\ water\ leached\ below\ the\ rootzone}{Depth\ of\ irrigation\ water\ applied} \quad [5.1],$$

the EC in leachate, $EC_{dw}$, will then be given by

$$EC_{dw} = \frac{EC_w}{LF} \quad [5.2]$$

where $EC_w$ is the *EC* of the applied water. The lower the *LF*, with less water draining through the profile, the higher the relative *EC* in the leachate.

Table 5.7 presents the seasonal leaching fraction (*LF*) values for the various water sources and emitter types. As previously noted, the *LF* values for bubbler irrigation (BUB) were higher (approximately 0.7) compared to those for pressure-compensated drippers (PCD, approximately 0.35) and subsurface irrigation tape (SUB, approximately 0.5). Utilizing these *LF* and electrical conductivity of irrigation water ($EC_w$) values in Eq. 5.2 allows for the prediction of electrical conductivity in the leachates ($EC_{dw}$), which are also presented in Table 5.7.

The predicted $EC_{dw}$ values are in consistent agreement with those measured by the DFMs during the major period of crop growth between May and August (Table 5.7). Across all water sources and emitter types the average predicted $EC_{dw}$ is 74.8 dS $m^{-1}$, and the DFMs measured a somewhat similar value of 61 dS $m^{-1}$.

Irrigating halophytic crops with saline waters requires that there be a salt leaching-fraction *LF* to ensure that salts left in the rootzone after $ET_C$ are flushed out to prevent a build-up of salt in the soil of the rootzone. When a crop uses some portion of the applied water, the *LF* will be less than unity. So when this *LF* is less than one that means that the leachate $EC_{dw}$ in the drainage water will be at a higher concentration than that in the applied water, and this loading of salt could have deleterious impacts, over time, on the quality of the underlying aquifer through this groundwater recharge.

## 5.6 Salt-Leaching Impacts

The mass-balance calculations of the salt added annually across the nine plots of three water sources and three emitter types ranged from 36 to 164 kg $m^{-2}$, and the salt loss measured by the DFMs went from 18 to 195 kg $m^{-2}$ (Table 5.8).

An average of 80 kg $m^{-2}$ of salt was applied across all nine plots. Measurements indicated an average leached amount of 70 kg $m^{-2}$ from the upper portion of the rootzone. An estimated change in salt storage within the soil profile, down to a depth of 120 cm, of approximately 2 to 4 kg $m^{-2}$ is projected to have occurred over the growing season. As this would represent the salt retained after the initial flushing with the 10 dS $m^{-1}$ water that was used to enable good germination and early seedling growth. Within the constraints posed by the spatial variability in the leaching measurements with the DFMs, there is reasonable mass-balance agreement with the applied loads and those measured leaching through the soil profile with the fluxmeters.

**Table 5.8. The salt added in the irrigation water for the three emitter-device types of bubbler (BUB), dripper (PCD) and subsurface tape (SUB) for each of the three waters aquabrine (AQ), reverse osmosis brine (RO) and groundwater (GW), in relation to the leachate losses of salt measured by the tension drainage fluxmeters. The measured losses were calculated using the measured electrical conductivity in the leachate, and the modelled drainage. Modelled drainage (Al Tamimi, et al. 2022) was used because of the high variability in the measured values (Figure 5.5).**

| Water Source | Emitter-Type | Salt Added, kg $m^{-2}$ | Measured Salt Loss, kg $m^{-2}$ |
|---|---|---|---|
| Aquabrine | Bubbler | 164.4 | 195.0 |
| | Dripper | 48.8 | 23.3 |
| | Sub-surface | 53.2 | 36.1 |
| RO Brine | Bubbler | 152.7 | 169.3 |
| | Dripper | 52.6 | 13.6 |
| | Sub-surface | 45.9 | 22.3 |
| Groundwater | Bubbler | 120.1 | 135.0 |
| | Dripper | 42.2 | 21.0 |
| | Sub-surface | 36.4 | 17.8 |
| | Average | 79.6 | 70.4 |

The impact of these leachate salt loadings on the underlying aquifer's water quality was subsequently evaluated. An exemplar annual salt loading ($L$, kg $m^{-2}$) was designated. The underlying aquifer was considered to have a saturated thickness ($d$, m) and a volumetric saturated water content ($\theta$, $m^3$ $m^{-3}$). Consequently, the areal volume of water within the aquifer is represented by $\theta$ d ($m^3$ $m^{-2}$).

The impact of the annual loading of the salt leachate on the underlying aquifer’s water quality has been considered. The descending salt front will be denser than the resident soil solution underneath, and this could create Rayleigh-Taylor instabilities that might lead to fingering and plumes as the heavier salt-solution travels preferentially downwards (Bear, 1972). This plume of the denser leaching front of higher salinity might then descend to the aquifer rapidly with far-reaching consequences that would preferentially impact the area directly under the irrigated plots. This is most likely where the wells used for irrigation are to be located. In such cases there would be a localised short-circuit between well extraction, salt leaching, and the degradation in aquifer water quality. To carry out a detailed risk assessment of the impact of salt leaching would, under such circumstances, be difficult in the absence of information about the dimensions of the fingering plumes. Here a simpler and more conservative approach has been taken.

Complete and rapid equilibration of the leachate from above with the resident water is assumed to occur through a process of gravitational mixing with the denser incoming leachates. Mass balance then determines that the annual rise in the salt concentration of the aquifer, $\Delta C$ (kg $m^{-3}$), will be $L\ (\theta.d)^{-1}$. The relationship between the *EC* of a solution and *C* can be written $EC = \varepsilon.C$ (dS $m^{-1}$), where ε to be 0.72 kg $m^{-3}$/(dS $m^{-1}$). Therefore, the annual rise in the *EC* of the aquifer due to the salt loading from above would be $\Delta EC = L / (\varepsilon.\ \theta.d)$ in dS $m^{-1}$ $y^{-1}$. This can be applied locally, and here is an exemplar calculation. The Groundwater Atlas of the Emirate of Abu Dhabi shows that the saturated thickness of the aquifer in the western Al Dhafra region is of the order of 100 m, whereas close to Al Ain, under the lee of the Omani Mountains, *d* can exceed 400 m (EAD, 2018). the time-domain reflectometry measurements (Al Tamimi et al. 2023) show that $\theta \approx 0.4$. Taking here for heuristic purposes $d = 100$ m, and the average loading *L* of 75 kg $m^{-2}$ (Table 8), means that the annual rise in groundwater salinity would be $\Delta EC \approx 2.6$ dS $m^{-1}$ $y^{-1}$. This is a large impact indicating significant degradation in the water quality of the underlying aquifer through the salt loading as a result of the *LF* being less than unity. This is explored in more detail in Chapter 6.

In 2014, the Emirati Ministry of Environment and Water (MOEW, 2014) presented a map of the rise in the salinity of groundwaters in the UAE. For the crescent oases surrounding Liwa in the Al Dhafra region, and along the western flanks of the Omani Mountains the rise in groundwater salinity between 1996 and 2012 was about 1-2 dS $m^{-1}$. Intensification of land-use using saline groundwater, with the required leaching fraction $LF < 1$, will accelerate the saline degradation of these aquifers. The current work focussed on an economic valuation of the environmental impacts of this salt loading and exploring solutions, in order to facilitate an assessment of the benefit-cost ratios associated with the different methods of utilizing saline waters for the production of food, forage, and fuel.

This has now established the valuable economic water productivity of *Salicornia* production using saline irrigation waters, as measured by gross economic water productivity ($GEWP_I$, \$ $m^{-3}$). Additionally, the biophysical environmental impact on the underlying aquifers, resulting from the increased salinity of leachate loadings, has been determined.

The challenge now is to quantify the change in value of the ecosystem services supplied by groundwater because of these increases in salinity resulting from the productive growth of halophytic crops using saline waters.

## 5.7 Conclusions

Three types of saline waters have been used to irrigate the halophytic crop of *Salicornia* in the hyper-arid United Arab Emirates. The three waters were GW at 25 dS $m^{-1}$, RO from a desalination unit at 40 dS $m^{-1}$ and AQ being the effluent from land-based aquaculture producing fish in tanks filled with RO brine, again at 40 dS $m^{-1}$. These three waters were applied through BUB, PCD, and SUB. The reference *ET*o at the site was of the order of 2000 L $m^{-2}$ (2000 mm). The irrigation schedule for BUB applied around 8000 L $m^{-2}$, and for PCD and SUB about 2600 L $m^{-2}$.

The yields of harvest forage were greatest for BUB being 2.0-2.6 kg $m^{-3}$ compared to 1.1-1.6 kg $m^{-3}$ for the other emitter devices (Table 5.3). However, the water productivities $WP_I$ (kg $m^{-3}$) for forage were greatest for PCD and SUB being 2.0 to 2.8 kg $m^{-3}$ for all waters across, whereas for BUB ranged from 1.4 to 2.0 kg $m^{-3}$ (Table 5.6).

An assessment of gross economic water productivity ($GEWP_I$, US$ $m^{-3}$) was subsequently undertaken, considering only gross revenue. The $GEWP_I$ for the total potential revenue from fresh tips, forage, and seeds was determined to be highest for Aquabrine (AQ) applied through pressure-compensated drippers (PCD) and subsurface irrigation tape (SUB), with values ranging from 5.8 to 6.2 $ $m^{-3}$ (Table 5.6). This is well above the presumed cost of desalination at $1.5 $m^{-3}$ and this does not consider the additional value that would come from the saline groundwater freshened by desalination for irrigation of high value crops, or from the fish grown in the aquaculture tanks. The BUB had the lowest $GEWP_I$ of between 1.3 and 2.9 $ $m^{-3}$. It is concluded that the most economically beneficial approach for halophyte production, considering the balance between water use and yield, involves cultivating fresh tips irrigated with Aquabrine (AQ) delivered through either pressure-compensated drippers (PCD) or subsurface irrigation tape (SUB). This economic benefit has the potential to be further enhanced by employing a multiple fresh-tip harvesting strategy.

The GW had a salinity of 25 dS $m^{-1}$, whereas the RO and AQ were at 40 dS $m^{-1}$. The leaching fractions *LF* were about 0.72-0.74 for BUB, and 0.3-0.6 for PCD and SUB. Given the irrigation scheduling, the greatest salt load to groundwater came from BUB, being 135-195 kg $m^{-2}$. For PCD and SUB it was less, between 14-36 kg $m^{-2}$. Simple mass-balance calculations were then undertaken to assess the biophysical impacts of these salt loadings on the underlying aquifer's salinity. An exemplar loading of 75 kg $m^{-2}$ was employed within this simplified model. This loading was found to result in an annual salinity rise of 2.6 dS $m^{-1}$ $y^{-1}$ for an aquifer with a saturated depth of 100 m. This would be a significant rate of rise in the salinity of groundwater and represents a deterioration in the utility of the subterranean water reserves. This impact on aquifer quantity and quality will be further assessed via heuristic modelling in the next Chapter.

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# CHAPTER 6

# 6 Measurement and Heuristic Modelling of Nitrogen and Salt Dynamics under Salicornia Growing in a Hyper-arid Region and Irrigated with Waters of Differing Nutrient and Salt Loadings

New data presented here highlight the economic value of using nitrogen-rich saline waters, either from groundwater or reject brines from desalination units, to irrigate the halophytic crop Salicornia bigelovii for food, fodder, and fuel in a hyper-arid environment. The greatest benefit was achieved using pressure compensated drippers. Field measurements of drainage and leaching under the crop showed that, in sum, all of the salt and nitrogen drawn up from the groundwater was returned back to the aquifer as leachate.

A simple heuristic model of groundwater quantity and quality was developed to infer the environmental impacts of irrigating crops with saline and high-nitrate groundwater in a hyper-arid environment. The time- rise in solute concentration in groundwater is found to be a hyperbola. The parameters needed for this simple model are the fraction of the land above the aquifer that is irrigated, the initial depth of the saturated thickness of the aquifer, the saturated water content of the aquifer, and the annual rate of crop evapotranspiration. An indicator of the rate-of-rise in solute concentration, akin to a half-life, is the numbers of years to double the solute concentration in groundwater. This can be found as $\Theta\ h\text{o} /2\ ET_C$, where $\Theta$ is the saturated water content, $h_o$ is the original thickness of the saturated layer, and $ET_c$ is the annual rate of crop evapotranspiration. The general model is simple and straightforward to parameterise. It is easily understood and useful for assessing the impacts and trade-offs of policy and regulatory options.

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The DRC Statement of Contribution is provided in Appendix 8.3.

## 6.1 Abstract

New data presented here highlight the economic value of using nitrogen-rich saline waters, either from groundwater or reject brines from desalination units, to irrigate the halophytic crop Salicornia bigelovii for food, fodder, and fuel in a hyper-arid environment. The greatest benefit was achieved using pressure compensated drippers. Field measurements of drainage and leaching under the crop showed that, in sum, all of the salt and nitrogen drawn up from the groundwater was returned back to the aquifer as leachate.

A simple heuristic model of groundwater quantity and quality was developed to infer the environmental impacts of irrigating crops with saline and high-nitrate groundwater in a hyper-arid environment. The time- rise in solute concentration in groundwater is found to be a hyperbola. The parameters needed for this simple model are the fraction of the land above the aquifer that is irrigated, the initial depth of the saturated thickness of the aquifer, the saturated water content of the aquifer, and the annual rate of crop evapotranspiration. An indicator of the rate-of-rise in solute concentration, akin to a half-life, is the numbers of years to double the solute concentration in groundwater. This can be found as $\Theta\ h_o\ /2\ ET_C$, where $\Theta$ is the saturated water content, $h_o$ is the original thickness of the saturated layer, and $ET_c$ is the annual rate of crop evapotranspiration. The general model is simple and straightforward to parameterise. It is easily understood and useful for assessing the impacts and trade-offs of policy and regulatory options.

## 6.2 Introduction

The United Arab Emirates (UAE) is a hyper-arid region with annual precipitation, *P*, being well less than 5% of the reference evapotranspiration, *ET*o. The former sheikhdoms that now comprise the UAE signed a Perpetual Maritime Truce with the British in 1853, such that they subsequently became known as the Trucial States. In the 1950-60s the British sought to find water to expand agriculture across the ‘fertile sands’ of the Trucial States and Oman (Jospeh and Howarth, 2015). Sheikh Zayed, the first President of the UAE who ruled from 1971 to 2004, continued to expand the development of water resources and agriculture (Jospeh and Howarth 2015; Al Yamani et al. 2019).

Today there is a continuing call for the global development of food, fodder, and fuel production in arid regions under saline conditions. Vellinga et al. (2022) outlined the actions needed to increase opportunities and capacities for agriculture under saline soil and water conditions.

Lyra et al. (2021) showed how innovative practices to grow the halophyte Salicornia bigelovii can provide a value chain from desert farm-to-fork. These initiatives rely on the use of saline groundwaters either directly, or indirectly through land-based aquaculture, to irrigate Salicornia under these hyper-arid and saline conditions. The benefits from the food, fodder, and fuel value of halophyte production have been well detailed (Lyra et a., 2014, 2016; Araus et al. 2021; Al Tamimi et al 2023a). However, less is known about the environmental impacts on groundwaters from the use of saline aquifers for irrigation. It is known that across the UAE groundwater levels are dropping and that groundwaters are high in nitrogen, with salinity concentrations rising (EAD, 208; MOEW, 2014, 2015; McDonnell and Fragaszy, 2016). From global evidence it is also known that if appropriate policy actions are implemented, then recovery in aquifers is possible (Jasecho et al. 2024).

The earlier research on irrigation in this hyper-arid region developed a crop-factor, *K*c, parameterisation to predict crop water-use *ET*c (Allen et al. 1998) from *ET*o across a range of crops (Al Tamimi et al. 2022), as well as the development of modified devices to measure soil-water content and leaching in saline desert soil (Chapter 3 and Al Tamimi et al. 2023b), the validation of a piston-displacement model of salt leaching under saline irrigation (Chapter 4 and Al Tamimi et al. 2023c), and the water productivity of Salicornia under saline irrigations (Chapter 5 and Al Tamimi et al. 2023a). This Chapter now presents an evidence base and a heuristic modeling framework. These tools link contemporary halophyte irrigation practices with their potential current and future impacts on the underlying aquifer in this hyper-arid region.

The new research in this Chapter had three objectives:

To build on earlier results of halophyte yield and gross economic water productivity, but now through irrigating Salicornia with lower salinity water at 10 dS $m^{-1}$, and to test the impact of a halving of the leaching fraction under bubblers, and

To measure not only salt leaching (Chapters 3,4 and 5, and Al Tamimi et al. 2023a, b, c), but also the leaching of nitrogen from the rootzone of the halophyte Salicornia when irrigated with nitrogen-rich saline groundwaters and brines, and

To develop a heuristic model to predict the impact on groundwater quantity and quality from irrigation of a halophyte with saline and nitrogen-rich waters in a hyper-arid region.

## 6.3 Materials and Methods

### 6.3.1 Experimental trials

The experiments described here were conducted using the same plots described in Chapters 4 and 5 (Al-Tamimi et al., 2023 a,b). Six of the nine treatments were repeated. The two of the three new treatments were to examine the impact of irrigating with lower salinity water at 10 dS m-1, and the third was to test whether halving the leaching fraction would have any impact. Most of the experimental details can therefore be gleaned from Chapter 5 and Al-Tamimi et al. (2023a). Only a brief summary is provided here.

The experiments were carried out at the International Centre for Biosaline Agriculture (ICBA) (25.09° N; 55.39° E; 48 m a.s.l.) near Dubai. Whereas these new results repeat six of the earlier treatment the three new experiments reported here are for just one year, namely 2022/2023. The continued agronomic validity of this practice within this hyper-arid environment is again supported.

The weather is virtually always cloud-free, and rainfall is extremely rare and negligible. Inter-annual variation is virtually non-existent.

The soil at the site is a Typic Torripsamment

### 6.3.2 Crop Agronomy

The Salicornia seeds were sown on 15 November 2022. To enable good germination and establishment, all the plots were irrigated through until 22 February 2023 with low salinity water at 10 dS $m^{-1}$ water. Then four types of saline waters were used for irrigation: aquabrine (AQ; ≈ 40 dS $m^{-1}$), reverse-osmosis (RO) reject brine from the desalination plant (≈ 40 dS $m^{-1}$), groundwater (GW, ≈ 22.5 dS $m^{-1}$), and lower salinity water ($EC_{10}$, ≈10 dS $m^{-1}$). There were three irrigation systems: bubblers (BUB), pressure-compensated drippers (PCD), and sub-surface tape irrigation (SUB). Irrigation was stopped in the first week of August 2023.

Nine separate plots each of 8 m by 8 m were established in a square matrix layout, with 4m borders between plots. The rows of the matrix were the different water-sources of AQ, RO, GW and $EC_{10}$. The columns of the matrix were the emitter-device types of BUB, PCD, and SUB. The AQ-BUB treatment applied 30 mm $d^{-1}$, whereas the AQ-BUB* applied half that at 15 mm $d^{-1}$ in order to reduce the leaching fraction. Within each plot, four quadrants, each of 2 m by 2 m, were created, and modified drainage fluxmeters (Chapter 3 and Al Tamimi et al. 2023b) and vertical TDR probes of length 600 mm were installed near the centre of each quadrant.

The crop was harvested for the yield of fresh tips on 14 April 2023, total harvest fresh weight on 14 June 2023, and for seed during 15 August 2023 after irrigation had been stopped on 2 August, and the crop had dried off. Crop samples were taken from randomly selected locations within each plot, although locations near to measuring devices were avoided. Only the fresh-weight harvest data are presented here in order to highlight the impact of the three new treatments. The data were analysed using one-way ANOVA. Comparisons among means were made using Fisher's least significant differences at p=0.05 (5% LSD).

## 6.4 Results and Discussion

### 6.4.1 Crop yields

The fresh weights of Salicornia at harvest for each of the treatments are given in Figure 6.1. In agreement with the earlier results from Chapter 5 and Al Tamimi et al. (2023a) the yields with aquabrine (AQ) were the largest. However, there is no difference between AQ-BUB and AQ-BUB* for drippers indicating the reducing the irrigation to lower the leaching fraction had no impact, given that the leaching fraction was still well above unity.

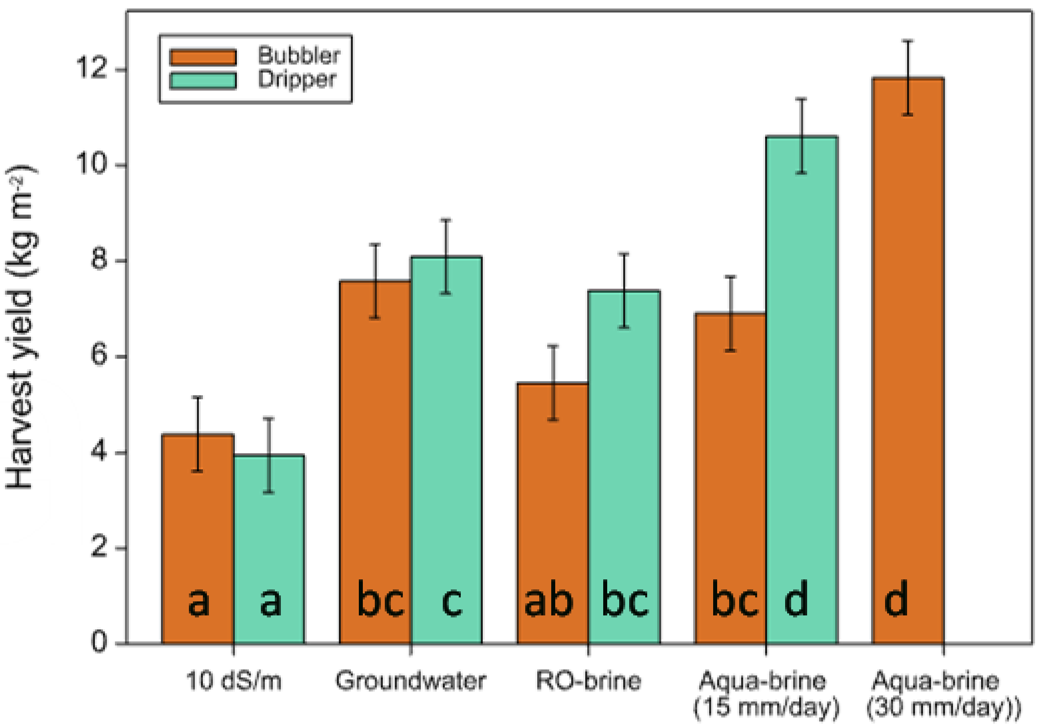



**Figure 6.1. The mean fresh weight of Salicornia at harvest (kg m$^{-2}$) for the nine plots: EC10-BUB, EC10-PCD, GW-BUB, GW-PCD, RO-BUB, RO-PCD, AQ-BUB, AQ-PCD, and AQ-BUB*. The error bars are the 95% standard errors. Means with the same Least Squares Difference (LSD) comparison letter are not significantly different (p>0.05).**

And in all cases, the application of irrigation water via drippers was the same, or better, than that achieved with bubblers.

### 6.4.2 Irrigation and Productivity

Table 6.1 presents the seasonal irrigation amounts ($I$, m$^3$ m$^{-2}$) across the treatments, along with the yield ($Y$, kg m$^{-2}$) information that is presented in Figure 6.1. Using the terminology of Fernández et al al. (2020) Table 6.1 presents the irrigation water productivity WP ($Y$ / $I$, kg m$^{-3}$) and gross economic water productivity (GEWP, US$ m$^{-3}$).

**Table 6.1. The seasonal application of irrigation, $I$ (m$^3$ m$^{-2}$) to the nine treatment plots of aquabrine (AQ), reject brine (RO), groundwater (GW) and low salinity ($EC_{10}$), by two types of emitters of bubblers (BUB) and pressure compensated drippers (PCD). The AQ-BUB treatment applied 15 mm day$^{-1}$, whereas the AQ-BUB* treatment added 30 mm day$^{-1}$. Also shown are the modelled drainage losses (I – ETc) (m$^3$ m$^{-2}$), plus the measured drainage losses over the 2022-2023 season from the four tension-fluxmeters within each of the plot. Crop evapotranspiration over the season, $ET_c$ (m$^3$ m$^{-2}$), was modelled following Al Tamimi et al. (2022). The biomass fresh-weight yields, $Y$ (kg m$^{-2}$) are given along with the water productivity of WP = $Y$ / $I$ (kg m$^{-3}$) and the gross economic water productivity (GEWP, US$ m$^{-3}$) using a mean-weighted price of $1.3 kg$^{-1}$ adapted from Al Tamimi et al. (2023).**

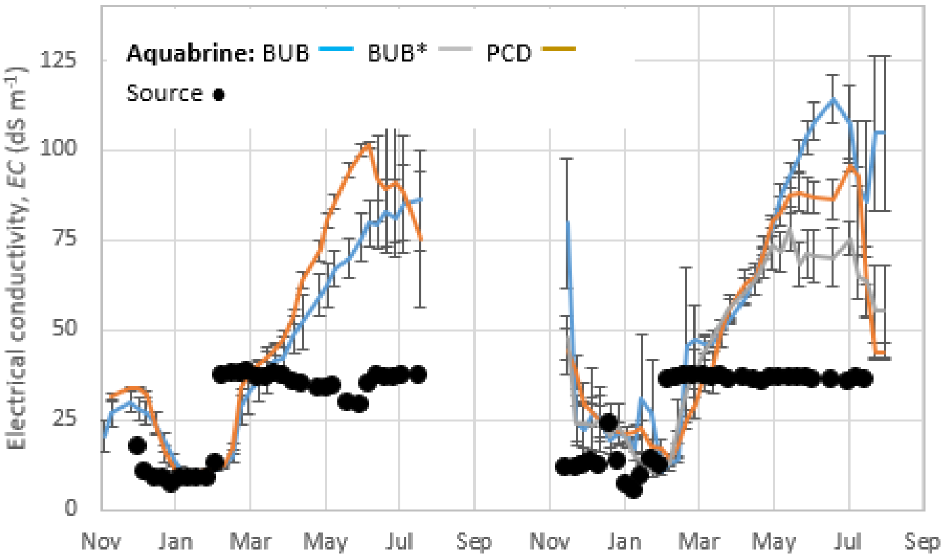
| Treatment | Irrigation *I* ($m^3$ $m^{-2}$) | Modelled Drainage (*I - ETc*) ($m^3$ $m^{-2}$) | Measured Drainage ($m^3$ $m^{-2}$) | Biomass Yield *Y* (kg $m^{-2}$) | Water Productivity *WP* (kg $m^{-3}$) | Gross Economic Water Productivity ($ $m^{-3}$) |
|---|---|---|---|---|---|---|
| AQ-BUB* | 6.37 | 4.69 | 3.42 | 11.83 | 1.86 | 2.40 |
| AQ-BUB | 3.38 | 1.80 | 1.33 | 6.90 | 2.04 | 2.63 |
| AQ-PCD | 2.95 | 1.47 | 0.57 | 10.61 | 3.60 | 4.64 |
| EC10-BUB | 4.15 | 2.50 | 0.84 | 4.38 | 1.06 | 1.36 |
| EC10-PCD | 3.17 | 1.70 | 0.30 | 3.95 | 1.25 | 1.61 |
| GW-BUB | 4.47 | 2.62 | 1.31 | 7.58 | 1.70 | 2.19 |
| GW-PCD | 3.05 | 1.58 | 1.18 | 8.09 | 2.65 | 3.42 |
| RO-BUB | 4.37 | 2.69 | 1.10 | 5.46 | 1.25 | 1.61 |
| RO-PCD | 2.51 | 1.03 | 1.11 | 7.38 | 2.94 | 3.79 |
| **Average Values** | **3.82** | **2.23** | **1.24** | **7.35** | **2.04** | **2.63** |

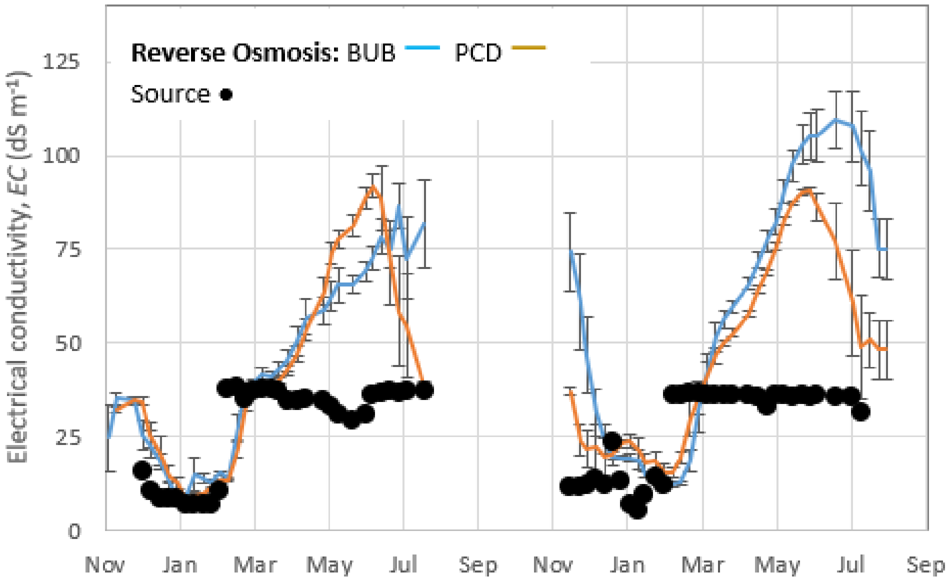
The highest WP values are for the saline irrigation waters applied through drippers, and they exceed 2.5 kg $m^{-3}$. Being an obligate halophyte, the water productivities using the lower salinity $EC_{10}$ waters were less than half of those. Detailed pricing for fresh-tips, forage harvest, and seeds were given in Chapter 5 and Al Tamimi et al. (2023a). Here for illustrative purposes, a weighted-mean price for the fresh harvest of US$1.3 $kg^{-1}$ have been used to calculate the GEWP. For all of the saline waters, the highest economic returns were for the crops irrigated by drippers, being above about $3.50 $m^{-3}$. Since two of these saline water sources are derived from the reject brine of desalination units, it is pertinent to note that the operational cost of desalination is now, thanks to solar-powered units, of the order of just $0.55-0.63 $m^{-3}$ (Dawoud et al. 2024). As well, there is the primary value which is derived from the desalination units through the use 'freshened' brackish groundwater to irrigate high-value crops (Dawoud, 2017).

The use of desalination units to irrigate both high value crops with freshened groundwater, and halophytes with the reject brines, provides economic benefits for agriculture in hyper-arid regions with saline groundwaters.

### 6.4.3 Salt

The modified drainage tension fluxmeters (DFM) have been used (Chapter 3 and Al Tamimi et al. 2023b) the leachate loads of salt leaving the rootzone of the halophyte Salicornia under irrigation regimes that ensure there is a salt leaching fraction to flush excess salts from the rootzone. The results here extend those in Chapter 5 and Al Tamimi et al. (2023a) and include the three new treatments. The electrical conductivities of the leachates measured by the DFMs are shown in Figure 6.2. These results include, where relevant, the concentrations measured during the previous season.


Aquabrine: BUB
BUB*
PCD
Source
Electrical conductivity, EC (dS m-1)
0
25
50
75
100
125
Nov
Jan
Mar
May
Jul
Sep
Nov
Jan
Mar
May
Jul
Sep


Reverse Osmosis: BUB
PCD
Source
Electrical conductivity, EC (dS m-1)
0
25
50
75
100
125
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Mar
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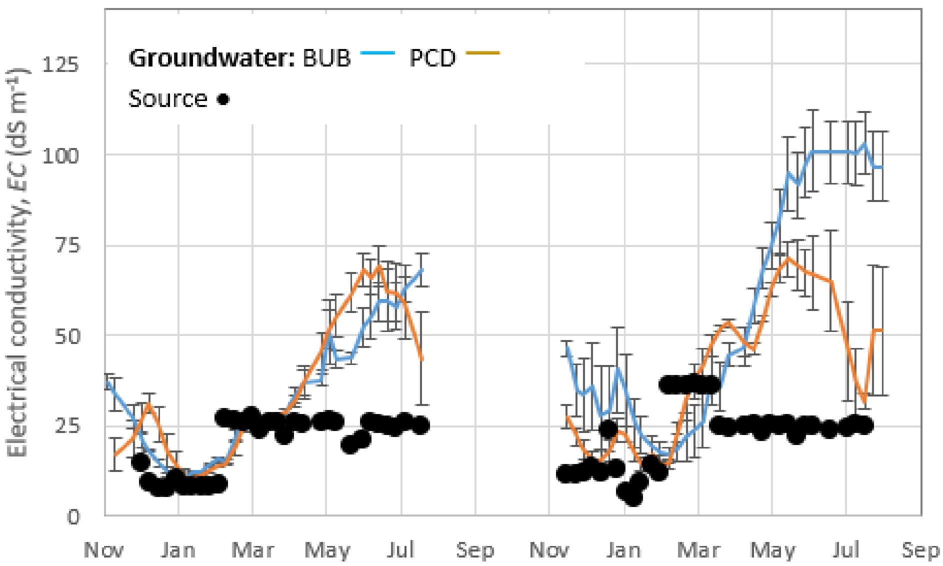
Jul
Sep


Groundwater: BUB
PCD
Source
Electrical conductivity, EC (dS m-1)
0
25
50
75
100
125
Nov
Jan
Mar
May
Jul
Sep
Nov
Jan
Mar
May
Jul
Sep

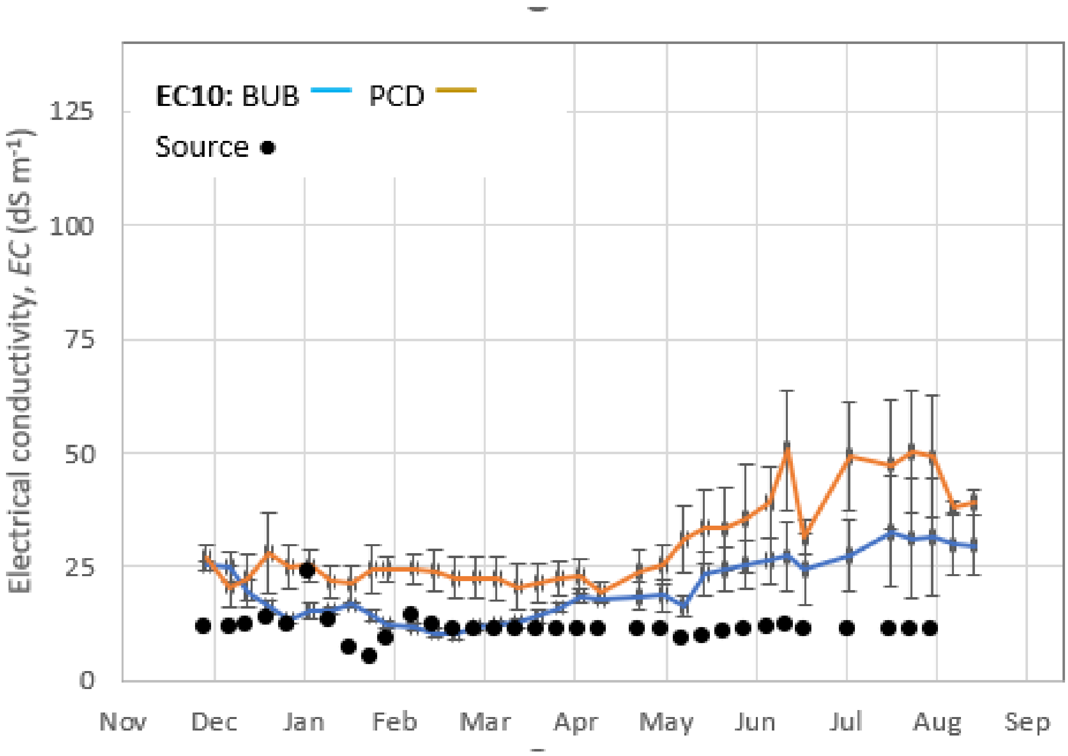



**Figure 6.2. The electrical conductivity (EC, dS m$^{-1}$) of the leachate measured over two years (2022 and 2023) in drainage under plots of a Salicornia bigelovii crop in the United Arab Emirates by tension drainage fluxmeters (DFM) under irrigation with aquabrine (AQ, top), reverse osmosis water (RO, upper middle), groundwater (GW, lower middle), and water at *EC*=10 dS m$^{-1}$ ($EC_{10}$, bottom, for just 2023). Water was applied either through bubblers (BUB) or pressure compensated drippers (PCD). There was in 2023 an extra aquabrine treatment (AQ-BUB*) where water was applied at 30 mm d$^{-1}$, rather than 15 mm d$^{-1}$. The switch between low salinity irrigation to the treatment waters was on 23 February 2022 and 22 February 2023. The original irrigation was water was at EC at 10 dS m$^{-1}$, and then under aquabrine and reverse-osmosis brine at about 40 dS m$^{-1}$, and groundwater at 25 dS m$^{-1}$, and in 2023 low salinity water at EC =10 dS m$^{-1}$. The bars represent the standard errors of the measures from 4 DFMs for each emitter type.**

These data were used in conjunction with the drainage measurements to calculate the mass balances of salt lost from the rootzones over the 2022/2023 season (Table 6.2), along with the salt loading measured in the irrigation water that was applied.

**Table 6.2. The seasonal loadings of salt (kg m$^{-2}$) and nitrogen (kg ha$^{-1}$) from the various irrigation waters applied to the nine treatment plots of aquabrine (AQ), reject brine (RO), groundwater (GW) and low salinity (EC10), by two types of emitters of bubblers (BUB) and pressure compensated drippers (PCD), along with the average leaching losses measured over the 2022-2023 season from the four tension-fluxmeters within each of the plot. The AQ-BUB* treatment applied 15 mm day$^{-1}$, whereas the AQ-BUB treatment added 30 mm day$^{-1}$. The crop evapotranspiration over the season, ETc (m$^3$ m$^{-2}$), was modelled following Al Tamimi et al. (2022).**

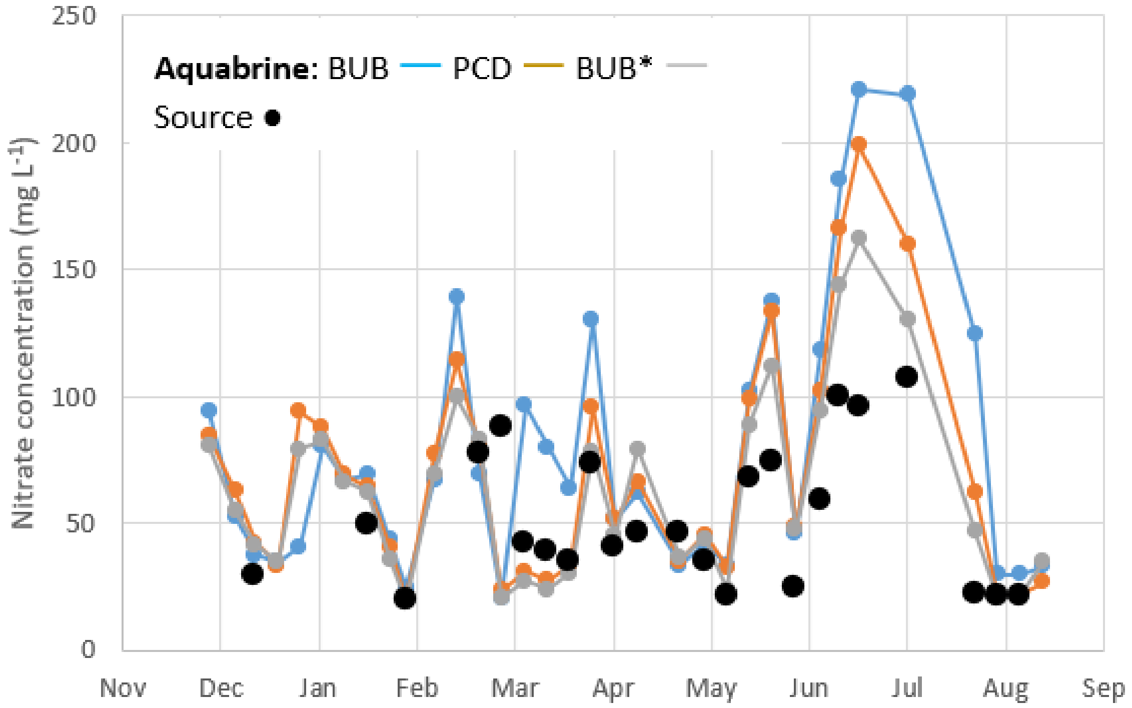
| Treatment | $ET_c$ (m$^3$ m$^{-2}$) | Salt Load (kg m$^{-2}$) | Salt Lost (kg m$^{-2}$) | Nitrogen Load (kg ha$^{-1}$) | Nitrogen Lost (kg ha$^{-1}$) |
|---|---|---|---|---|---|
| AQ-BUB* | 1.72 | 51.6 | 58.4 | 715 | 769 |
| AQ-BUB | 1.61 | 117.0 | 143.5 | 325 | 248 |
| AQ-PCD | 1.47 | 62.3 | 53.2 | 429 | 516 |
| EC10-BUB | 1.69 | 35.0 | 34.1 | 456 | 442 |
| EC10-PCD | 1.46 | 25.5 | 35.3 | 281 | 381 |
| GW-BUB | 1.89 | 37.5 | 89.3 | 312 | 339 |
| GW-PCD | 1.46 | 51.2 | 45.8 | 304 | 181 |
| RO-BUB | 1.72 | 71.5 | 96.1 | 343 | 270 |
| RO-PCD | 1.47 | 51.2 | 28.2 | 197 | 292 |
| **Averages** | **1.61** | **55.9** | **64.9** | **373.6** | **382.0** |

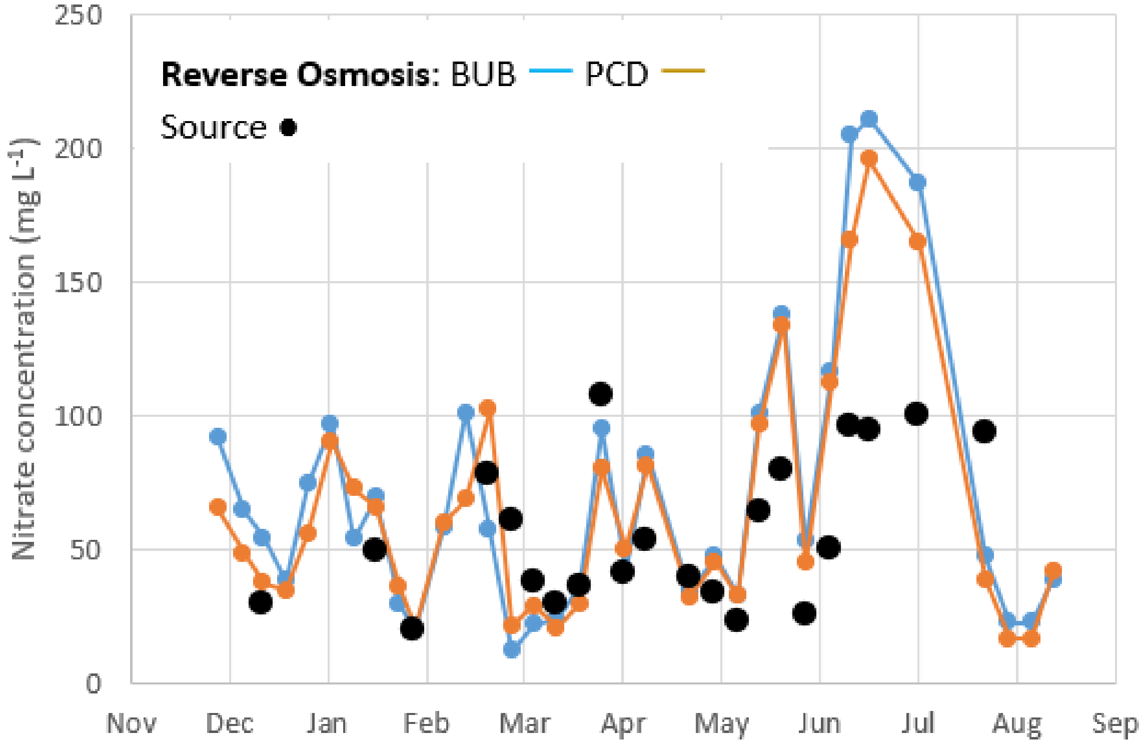
Averaged across all nine plots, the amount of salt added of 55.9 (±26.9) kg m$^{-2}$, was equal, given natural variability, to that lost in the leachate of 64.9 (± 37.9) kg m$^{-2}$. For the previous season, Chapter 5 and Al Tamimi et al. (2023a) found that the salt loading was 79.6 ±48.2 kg m$^{-2}$, and that leaching was 70.4 ±69.6 kg m$^{-2}$. Again, the salt loss balanced with the salt added. The halophyte Salicornia has been found to accumulate salt at between 37-52% of dry weight (DW) (Grattan et al. 2008). Chapter 5 and Al Tamimi et al. (2023a) found that in 2022/2023 the Salicornia yielded about 1.75 kg m$^{-2}$ on a dry weight basis (DW). So even if the salt content were 50% DW, the amount of salt removed in the vegetation would be less than 1 kg m$^{-2}$. So it is reasonable to assume that the total amount salt applied in the water used to irrigate an obligate halophyte is lost in the leachate.

### 6.4.4 Nitrogen

The nitrate concentrations in the leachate were also measured by the DFMs are shown in Figure 6.3, along with the nitrate concentrations in the irrigation water. Equipment to measure nitrate concentrations in the irrigation waters and leachates only became available in the second year of this study.

Unlike salinity, the nitrate levels vary temporally, albeit they are quite high. Groundwaters in the Abu Dhabi Emirate are often naturally high in nitrogen (McDonnell and Fragaszy, 2016). The groundwater concentrations can exceed 50 mg L$^{-1}$ nitrate in many areas around Al Ain and the Liwa Oases. The soil, vadose zone, and groundwaters are all well-aerated, and so denitrification is considered to be negligible, thus nitrogen transformations were ignored. All the results presented here are in terms of nitrate-N.


Aquabrine: BUB — PCD — BUB* —
Source ●
Nitrate concentration (mg L-1)
250
200
150
100
50
0
Nov
Dec
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep


Reverse Osmosis: BUB — PCD —
Source ●
Nitrate concentration (mg L-1)
250
200
150
100
50
0
Nov
Dec
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Mar
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May
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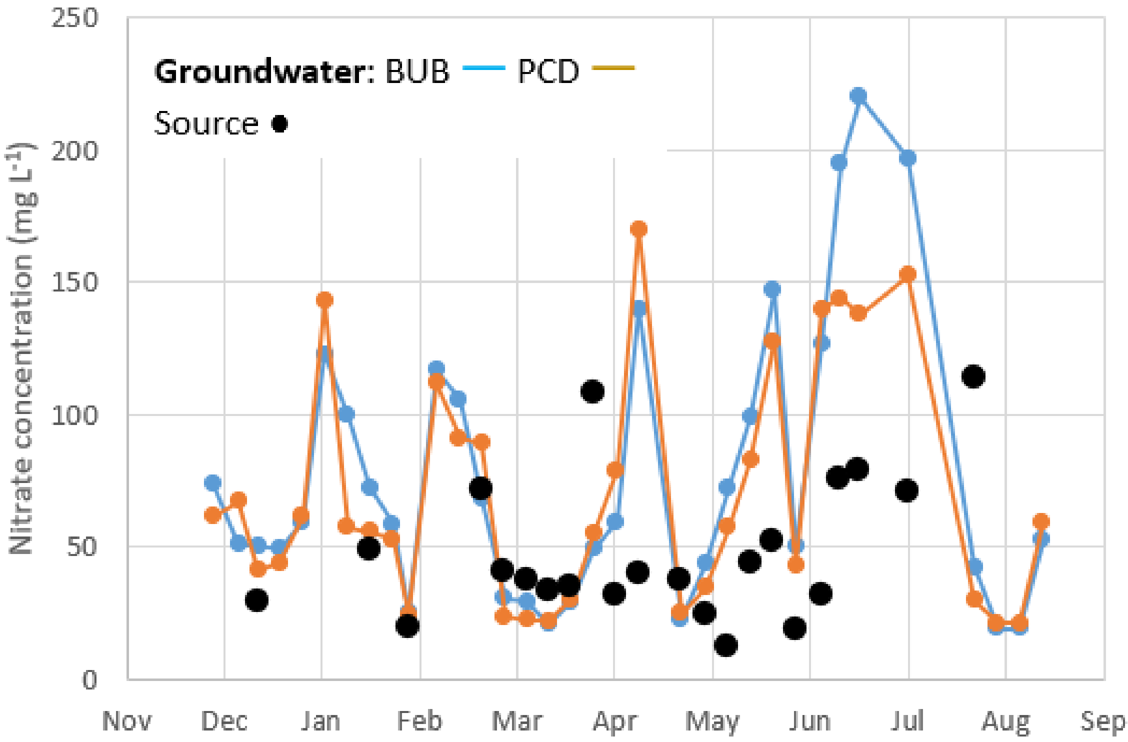
Sep



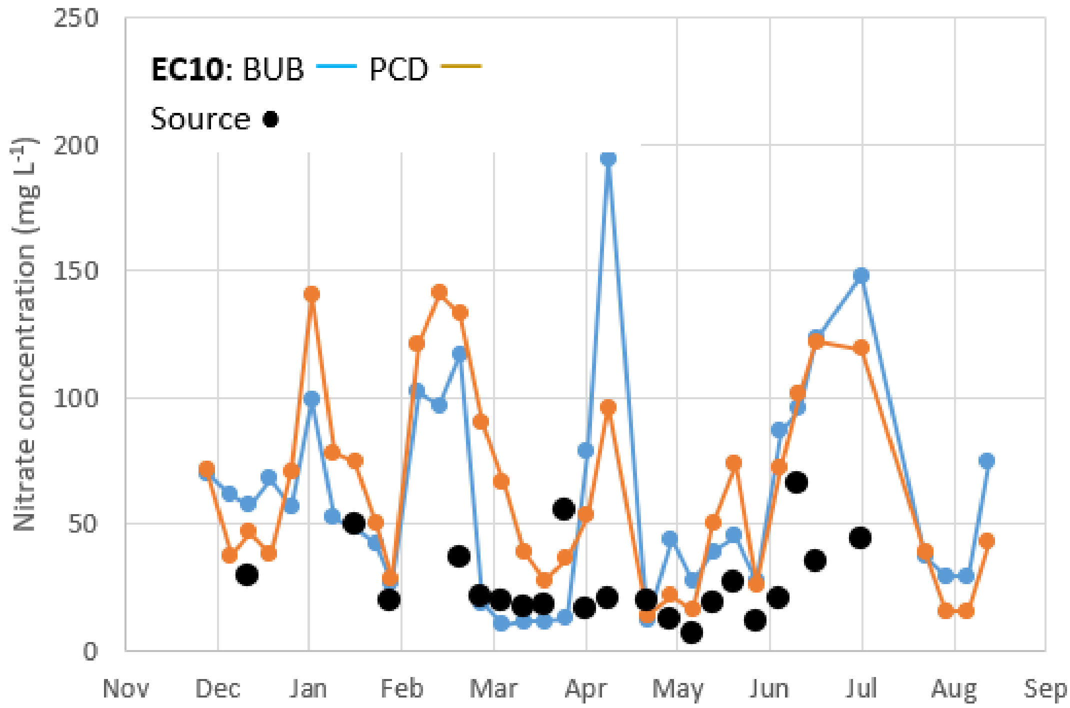




**Figure 6.3. The nitrate concentration (*C*, mg L$^{-1}$) of the leachate measured over 2023 in drainage under plots of a Salicornia bigelovii crop in the United Arab Emirates by tension drainage fluxmeters (DFM) under irrigation with aquabrine (AQ, top), reverse osmosis water (RO, upper middle), groundwater (GW, lower middle), and water at EC 10 dS m$^{-1}$ ($EC_{10}$, bottom, for just 2023). Water was applied either through bubblers (BUB) or pressure compensated drippers (PCD). There was an extra aquabrine treatment (AQ-BUB*) where water was applied at 30 mm d$^{-1}$, rather than 15 mm d$^{-1}$. The switch between low salinity irrigation water to the treatment waters was on 22**

**February 2023. The bars represent the standard errors of the measures from 4 DFMs for each emitter type.**

The average nitrate concentration across all the waters used for irrigation, prior to the establishment of the treatments, was 30.2 mg $L^{-1}$ nitrate (Figure 6.3). The temporal variations in nitrate are quite high. Nonetheless, there is a high degree of coherence in the nitrate concentrations among the various irrigation waters (Figure 6.3). The reasons for this variability are unknown, except it is noted that the groundwater here is shallow, being between 5-10 m. Furthermore, the flow velocities and directions are unknown, but it is noted that the plots here are surrounded by agronomic trials with unknown irrigation and fertiliser practices.

From Table 6.1 can be seen that the average load of nitrogen applied over the 2022/2023 season through the irrigation waters was 374 (±149) kg-N $ha^{-1}$. The average seasonal leaching loss of nitrogen measured by the nine tension-drainage fluxmeters was found to be 382 (±178) kg-N $ha^{-1}$. So, in a mass-balance sense, as much nitrogen that was applied in the irrigation water was lost as leachate back to groundwater (Table 6.2).

However, the nitrogen removed by the Salicornia at harvest was found to be 303 (±130) kg-N $ha^{-1}$. Prior to transplanting, organic fertiliser was applied to the plots at a rate of 539 kg-N $ha^{-1}$. Geissler et al. (2021) showed that depending on the constituent make-up and C:N ratio of organic amendments, some 32-72% of the N in the compost could be mineralised in the first 100 days. Therefore, it would not be surprising if 56% (viz. 303÷539 as a %) of the N in the compost were to be mineralised and taken up by the Salicornia crop. This would support the notion that under current land-management practices using pre-planting compost, the total amount of nitrogen applied in the irrigation water would be leached back to groundwater in the drainage.

### 6.4.5 The Leaching Fraction

Figures 6.2 and 6.3 show the time course of the concentrations of salt and nitrate in the irrigation water applied to the plots, $C_{in}$ (kg $m^{-3}$), relative to that in the leachates leaving the rootzone, $C_{out}$ (kg $m^{-3}$) destined for groundwater below via the unsaturated vadose zone. Ayers & Westcot (1994) noted that for a leaching fraction, *LF*, defined as

$$LF = \frac{Depth\ of\ water\ leached\ below\ the\ rootzone}{Depth\ of\ irrigation\ water\ applied} \quad [6.1],$$

the $C_{out}$ in leachate will then be given by

$$C_{out} = C_{in}\, LF^{-1} \quad . \quad [6.2]$$

The lower the *LF*, with less water draining through the profile, the higher the relative $C_{out}$ in the leachate. Eq. [6.1] for the *LF* can be written as being the drainage, namely ($I - ET$c) divided by irrigation I. Thus using this simple mass-balance approach,

$$\frac{C_{out}}{C_{in}} = LF^{-1} = \frac{I}{I - ET_c} \quad . \quad [6.3]$$

The average measured numerator of irrigation is given in Table 6.1 as 3.82 $m^3\ m^{-2}$. There are two ways to infer the drainage in the denominator: that directly measured which is on seasonal average 1.24 (±0.9) $m^3\ m^{-2}$ (Table 6.1), or that found using the modelled $ET$c (Al Tamimi et al. 2022) of 2.23 (±1.1) $m^3\ m^{-2}$. These are not significantly different (P=0.05). For inferential purposes using daily values of $I$ and $ET_c$ in Eq. [6.3], the modelled $(I - ET_c)$ have been used as it has fewer errors-of-observation. The average daily values of $I / (I - ET_c)$ across all nine treatments are shown in Figure 6.4, along with the 14-day running mean to show the general seasonal trend.

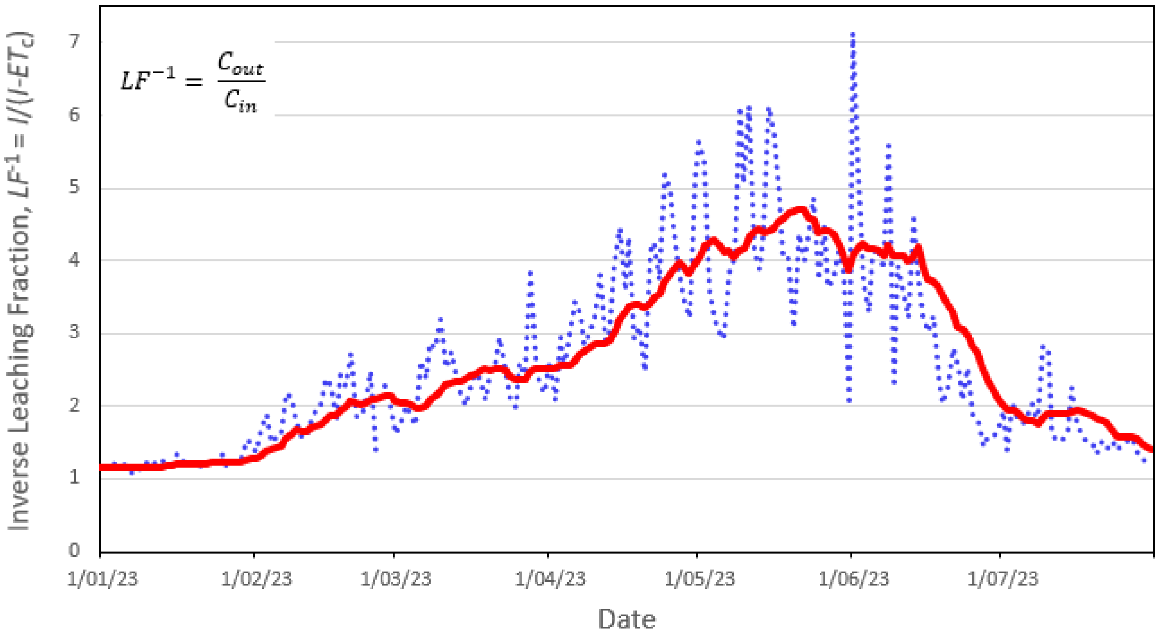



**Figure 6.4. Average daily values (- - -) across the 9 plots of the inverse of the leaching fraction, *LF*, namely $LF^{-1} = I / (I - ET_c)$ where *I* is the daily amount of irrigation applied ($m^3\ m^{-2}$) and $ET_c$ is the crop evapotranspiration ($m^3\ m^{-2}$). This inverse leaching fraction would correspond to the ratio of the solute concentration in the leachate, $C_{out}$ (kg $m^{-3}$), divided by the concentration in the irrigation water, $C_{in}$. Here *I* was measured daily for each of the 9 plots, and $ET_c$ was found using the crop-factor model proposed by Al Tamimi et al. (2022). The line (—) is the 14-day running mean of the daily values.**

The seasonal pattern in Figure 6.4 mimics the salt concentration ratios in Figure 6.2 for salt. It is more difficult to discern this trend in the nitrate concentrations (Figure 6.3) because of the temporal variation in the $C_{in}$. However, it is clear that at the peak of the growing season between May and July, $C_{out}$ well exceeds $C_{in}$ for nitrate. Between 3 May and 5 July 2023, the average $I / (I - ET_c)$ was 3.5 (±1.3). The measured ratios of $C_{out} / C_{in}$ (Eq. 6.3) were 3.0 (±1.4) for salt, and 2.1 (±0.5) for nitrate. These are not significantly different (P=0.05). This demonstrates that irrigation and crop water-use dictate both the concentration of solutes leaching back to groundwater ($C_{out}$, Eq. 6.3), and the total loading of solutes onto groundwater of $C_{out} \,.\, (I - ET_c)$ (kg $m^{-2}$).

These simple mass-balance calculations can be used to develop a heuristic model to link land-management practices to groundwater quantity and quality.

### 6.4.6 Heuristic modelling of impacts on groundwater

#### *6.4.6.1 Heuristic modelling*

A simple heuristic model has been developed to predict the impact of land management on groundwater. A heuristic method is a modelling approach for finding a simple, yet practical, solution to a problem. The wording comes from the ancient Greek word 'eurisko', meaning to 'find', 'search' or 'discover'. One of the founders of heuristics was the Hungarian mathematician György Pólya, who published a book about the subject in 1945 called 'How to Solve It'. This heuristic approach was extended to environmental issues by Harte (1988) in his book "Consider a spherical cow: A course in environmental problem solving". Here, in order to solve heuristically the problem of predicting the impact of irrigation on groundwater quantity and quality, it is guided by a strong evidence-base of field measurements, and the underpinning law of mass conservation. Consider an aquifer and overlying unsaturated vadose zone as a rectangular prism (Figure 6.5).

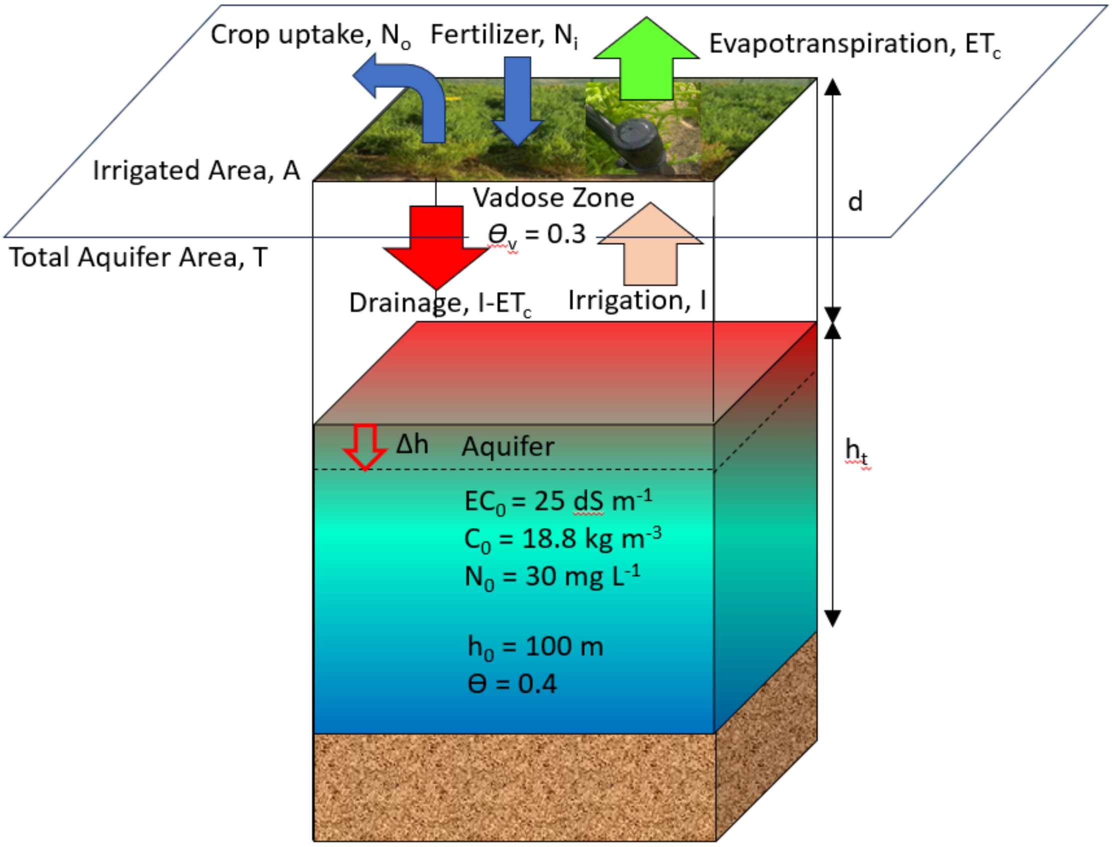



**Figure 6.5. A schematic representation of a closed-system aquifer covering a spatial land area of $T$ ($m^2$), within which an agricultural area of $A$ ($m^2$) is irrigated with $I$ ($m^3$ $m^{-2}$) of groundwater drawn from the aquifer. The evapotranspiration from the crop is $ET_c$. Solutes are leached back to the aquifer through the unsaturated vadose zone in the drainage of ($I - ET_c$). The crop is fertilized with an amount of nitrogen $N_i$ (kg-N $ha^{-1}$), and the amount of nitrogen taken off by the crop is $N_o$ (kg-N $ha^{-1}$). The depth of the unsaturated vadose-zone above the aquifer is $d$ (m) and has a mobile water content of $\theta_v$ ($m^3$ $m^{-3}$). At any time, $t$, the depth of the saturated layer is $h_t$ (m), and every year it**

**changes by $\Delta h$. The volumetric water of the saturated layer of the aquifer is a time-invariant $\Theta$ ($m^3$ $m^{-3}$).**

### *6.4.6.2* Modelling groundwater impacts

It is assumed that only a portion, $A$ hectares (ha), of the total land area ($T$ hectares, ha) overlying a specific closed-system aquifer is actually under irrigation (Figure 6.5). Outside of the total area, $T$, there are no-flow boundaries at the base and surface, as well as along the perimeter walls. The only flows are of water and solutes drawn from, and returned to, the aquifer under the irrigated area. A seasonal equilibrium across the whole aquifer domain is assumed, so that when impacts are predicted for the aquifer directly under area $A$, the wider impact for the whole aquifer can be assessed using a multiplier of $A/T$. The depth of the unsaturated vadose zone above the aquifer is $d$ (m). The depth of the saturated layer at any time $t$ is $h_t$. Over one year, the change in the depth of the saturated layer is $\Delta h$. The mobile water content for flow through the unsaturated vadose zone is $\Theta_v$ ($m^3$ $m^{-3}$). The volumetric water content of the saturated layer is $\Theta$ ($m^3$ $m^{-3}$). In Abu Dhabi, the reference evapotranspiration $ET_o$ greater the 2000 mm $y^{-1}$, whereas there is generally less than 50 mm of rainfall. Rainfall is ignored. This lack of rainfall also means that natural recharge of groundwater by drainage is negligible, and ignored were natural flows of water into the groundwater system.

The annual amount of water drawn from the aquifer to irrigate the crops within $A$ is $I$ ($m^3$ $m^{-2}$). The seasonal evapotranspiration by the crop over the year is $ET_c$ ($m^3$ $m^{-2}$). The drainage of water back to the aquifer, which carries with it solutes, is therefore $I\text{-}ET_c$.

The concentration of solutes of either salt or nitrogen leaving the groundwater in the irrigation water is $C_{out}$ (kg $m^{-3}$), and the concentration of solutes returning to the groundwater in the drainage $I\text{-}ET_c$ is $C_{in}$ (kg $m^{-3}$). Nitrogen fertilizer is applied at the rate of $N_i$ (kg-N $ha^{1}$), and the loss of nitrogen to the system via crop uptake and removal by harvest is $N_o$ (kg-N $ha^{-1}$). As noted above, it is considered that in a mass balance sense $N_o$ is balanced by the mineralised nitrogen-fraction from the organic fertiliser $N_i$, such that the loading of nitrogen brought in by the irrigation water is lost back in total by drainage eventually back to groundwater.

To maintain analytical simplicity for heuristic clarity, it is assumed a quasi-steady-state system. However, in reality there is a temporal dimension to the transmission of leachate impacts down through the unsaturated vadose zone to the saturated depth of groundwater. The initial time $t_0$ in the groundwater-quality predictions is essentially when the leachate first arrives from above, having traversed the vadose zone. The drainage through the vadose zone is $I - ET_c$ such that velocity of transmission is $v = (I - ET_c)/\Theta_v$, where $\Theta_v$ is the mobile water-content of the vadose zone. For the experiments with *Salicornia* the average drainage rate was found to be 2.23 $m^3$ $m^{-2}$ $y^{-1}$ (Table 6.1). For a typical vadose zone with $\Theta_v = 0.3$ (Chapter 3 and Al Tamimi et al. 2023c), $v$ would be about 7.4 m $y^{-1}$. The transit time for the piston displacement of solutes to reach the saturated layer will establish the initial time $t_0 = d / v$ when leached solutes first reach back to the groundwater. This $t_0$ will be the origin of the abscissa ($t$ = 0) in Figure 6.6. Typically the depth of the vadose-zone layer in the UAE is about 50 m, such that $t_o$ = 6.7 y, being the delay for the solutes to first reach groundwater following the initiation of irrigation using saline water from the aquifer.

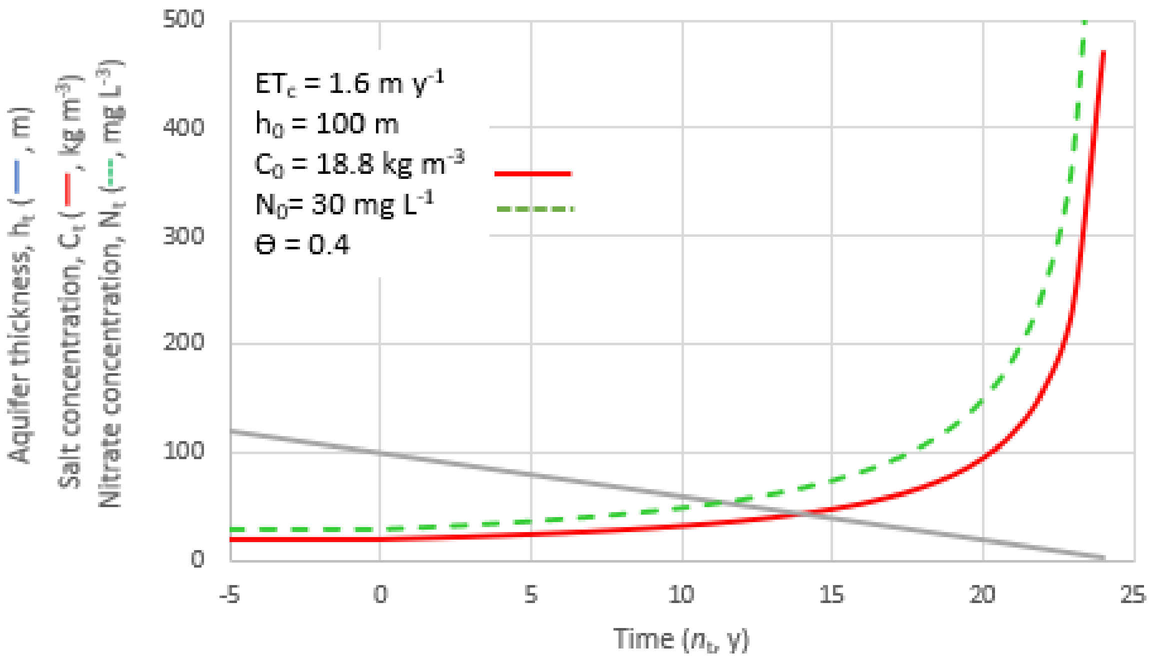



**Figure 6.6. The predicted temporal draw-down in the aquifer depth with the number of years using the prediction of the depth of the saturated layer $h_t$ from Eq. (6.1) (—). The initial aquifer thickness is assumed to be $h_o$ = 100 m, and the annual rate of evapotranspiration from the irrigated crop is 1.61 $m^3\ m^{-2}$. The time course in the concentration of salt and nitrate in groundwater predicted by Eq. [6.3] is given for salt (—) and nitrate (----). The initial values were for salt $C_0$ = 18.8 kg $m^{-3}$, and nitrate $N_0$ = 30 mg $L^{-1}$. The origin of the abscissa, $t$ = 0, is time to when the impacts of solute leaching are first felt in groundwater at the depth of the unsaturated vadose zone $d$.**

### *6.4.6.3 Aquifer Volume*

For the aquifer over the growing season of one year, an amount I ($m^3\ m^{-2}$) of water is drawn to irrigate the crop, and an amount ($I - ET_c$) ($m^3\ m^{-2}$) is returned to groundwater as drainage. Over the year, the net loss of water to the groundwater system is $ET_c$. Volumetrically, this comprises a net-usage volume $ET_c\ .\ A$ ($m^3$), such that this loss results in an annual volumetric removal of water from the aquifer of $A\ .\ \Delta h\ .\ \Theta$ ($m^3$). Combining these means that the annual change in the depth of the saturated layer is $\Delta h = ET_c / \Theta$ (m). It is assumed that the annual usage of irrigation ($I$) and evapotranspiration ($ET_c$) remain unchanged. At time $t > t_o$, after a number of years $n_t$, this can be generalised to

$$h_t = h_0 - \frac{n_t\, ET_c}{\theta} \qquad . \qquad \text{Eq. [6.4]}$$

Here $h_o$ is the initial depth of the saturated layer (m). The total depth-amount of water stored in the aquifer initially is $h_o\ .\ \Theta$ ($m^3\ m^{-2}$), and when consumed at an annual rate of ETc the number of years to exhaust this groundwater stock is $n_f = h_o\ \Theta / ET_c$.

For illustrative purposes, an initial saturated depth of $h_o$ = 100 m at $t_o$, which is representative of the aquifers surrounding Al Ain, and along the Liwa oases (EAD, 2018). The saturated water content of the aquifer is assumed to be $\Theta$ = 0.4 with $ET_c$ = 1.61 $m^3 m^{-2} y^{-1}$ (Table 6.2). The time course of the draw-down of the aquifer is shown in Figure 6.4, with the time-to-exhaustion $n_f$ = 24.8 years. This is an average decline in the groundwater level of 4 m $y^{-1}$, which is comparable to the 2.75 m $y^{-1}$ decline observed around Al Ain at Al Wagan and Remah (EAD, 2018). This, of course, assumes that all of the land-surface is irrigated, namely $A = T$. This will generally not be the case, so the draw-down result (Eq. 4) will need to be multiplied by $A / T < 1$ to account for the fractional irrigation of the land above the aquifer. If only one third of the land area were irrigated, then $n_f$ would be 74.5 years, with rates of water-table decline of around 1.3 m $y^{-1}$ (MOEW 2015).

#### *6.4.6.4 Groundwater quality*

This study focuses on two solutes of concern: salt and nitrate.

The mass of solute in the aquifer at any time $t$ is $M_t$ (kg), and this will be equal to the concentration, $C_t$ (kg $m^{-3}$, or kg $L^{-1}$) times the aquifer volume $V_t$ ($m^3$, or L): $M_t = C_t \cdot V_t$. The initial mass of solute in the groundwater is $M_0 = C_0 \cdot V_0$. As seen in Table 6.2, the mass of salt will be time invariant, as the salt taken out in the irrigation water is returned in the drainage. Likewise, in a mass-balance sense, the nitrate mass in the groundwater volume and vadose zone will under current practices be unchanging with time, as the nitrogen removed by the harvest of the crop is essentially equivalent to that mineralised from the organic fertiliser applied at sowing. Hence the nitrate removed by the irrigation water is eventually returned in sum in the drainage (Table 6.2).

Solutes in drainage through the vadose zone will begin to arrive back in the groundwater some time to after the leaving the rootzone in drainage. It is assumed that the solutes move via piston displacement through the unsaturated soil of the vadose zone (Chapter 3 and Al Tamimi et al. 2023b). After the initiation of irrigation, but prior to $t_o$, the water level will begin to drop straightaway according to Eq. [6.4]. However, the leachate consequent upon this irrigation will not arrive at depth d until time to, such that the concentration of solutes in the aquifer will remain unchanged at $C_o$ for $t < t_o$. After to, because the plants are not taking up the solutes drawn up in the irrigation water, they are returned in sum to the aquifer via the leachate. From simple mass conservation, -it is assuming $M_t \approx M_o \ \forall \ t > t_o$, and the concentration of solute in the groundwater at any time after $t_o$ is now:

$$C_t = C_0 \frac{V_o}{V_t} = C_0 \frac{A\,\theta\,h_0}{A\,\theta\,h_t} = C_0 \frac{h_0}{h_t} \quad , \qquad \text{Eq. [6.5]}$$

where $h_t$ is given above by Eq. [6.4], which upon substitution results in

$$C_t = \frac{C_0}{\left(1 - n_t \left[\frac{ET_C}{\theta\, h_0}\right]\right)} \quad . \qquad \text{Eq. [6.6]}$$

From Eq. [6.6] it is possible to predict the time-course in the concentration of solute in the groundwater as a function of the number of years, $n_t$, since the beginning of irrigation to supply water to a crop that loses water to the atmosphere at an annual rate of $ET_c$.

As can be seen from the form of Eq. [6.6], the time- rise in concentration is a hyperbola for $t > t_o$. The initial rise in concentration is gradual, however as time progresses the concentration rises rapidly and then asymptotes to infinity at the time to groundwater exhaustion. A useful ready-reckoner for the rise in solute concentration, akin to an inverse half-life, would be the numbers of years required when $t > t_o$, to realise the first doubling of the solute concentration in groundwater, $n_2$ (y). From Eq. [6.6] this can be found as

$$n_2 = \frac{\theta\, h_0}{2\, ET_c} \qquad . \qquad \text{Eq. [6.7]}$$

Our simple model predicts a doubling of the salinity in 12.5 years, assuming $A = T$. This rate of salinity rise of 1.5 kg $m^{-3}$ $y^{-1}$ is not dissimilar to the rises of around 2.3 kg $m^{-3}$ $y^{-1}$ shown in regions of the UAE by EAD (2018) and MOEW (2014,2015). The predictions show a further doubling in just the 5 years after the first 12.5 years of leachate returns. This analysis is for an aquifer underneath an area of land that is fully irrigated $A = T$. Clearly this is not the case (EAD, 2018. Especially p77), namely $A < T$, then the concentrations will need to be multiplied by $A / T$.

Well before the time-to-exhaustion ($n_f$, years) of the groundwater resource (Eq. 6.4), the utility value of the aquifer will have become worthless because of the high salinity, such that it would be neither practical to desalinate, nor useful for irrigating halophytes. Changed practices will be needed to ensure the sustainability of land use and the protection of groundwater.

It is likely that the current trend of using inland desalination units for irrigated agriculture will continue. Dawoud et al. (2024) noted, however, that there are three challenges that need to be assessed and evaluated. The first is to discharge the brine into an evaporation bund. The second approach, employed in this study, involves utilizing the water for halophyte irrigation. However, this practice is shown to potentially impact groundwater quality. The third is to develop zero level discharge (ZLD) desalination units. The latter would allow for the desalinated groundwater to be used for high value crops and eliminate the need for discharge of brine onto land. New technologies, even using renewable energy sources. are being developed apace for minimal and zero liquid discharge desalination technologies (Prado de Nicolas et al. 2023). These would help protect groundwater quality by reducing salt leaching. Furthermore, if ZLD were to be used, then only fresh water would be applied to land to irrigate high-value crops. Irrigation would then be able to have the goal of 100% efficiency in terms of the amount applied to supply crop-use, as the need for salt-leaching would be eliminated. The dry salt precipitate could then be safely stored on land and isolated from the hydrological cycle.

To protect groundwater quantity, it is important that policies be developed, and regulations implemented to limit groundwater extraction to levels commensurate with whatever groundwater recharge rates exist. Sadly, the acceleration of groundwater deepening highlights this urgent need for more effective measures to address groundwater depletion (Jasechko et al. 2024). These authors then presented specific cases of where depletion trends have been reversed following policy changes, and this highlights the potential for depleted aquifer systems to recover, given natural recharge.

## 6.5 Conclusions

Data and results highlighting the economic value of irrigating the halophytic crop Salicornia bigelovii with nitrogen-rich saline waters, either from groundwater or reject brines from desalination units, have been produced by the experiments.

The greatest benefit was achieved using pressure compensated drippers to supply the water to the plants. The measurements of drainage and leaching under the crop showed that, in sum, all of the salt and nitrogen drawn from the groundwater to supply the irrigation, was returned back to the aquifer in the drainage water as leachate.

From this comprehensive evidence-base of measurements, a simple heuristic model of groundwater quantity and quality was developed to infer the environmental impacts of irrigating crops with saline and high-nitrate groundwater in a hyper-arid environment. The key parameters needed to parametrise this simple model are the fraction of the land surface above the aquifer that is irrigated, the initial depth of the saturated thickness of the aquifer, the saturated water content of the aquifer, and the annual rate of evapotranspiration from the crop which can be found using the crop-calculator model of Al Tamimi et al. (2022). The model is simple and straightforward to parameterise. It is easily understood and could be useful for assessing the impacts and trade-offs of policy developments and regulation options.

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# CHAPTER 7

# 7 Conclusions & Recommendations for Future Research

## 7.1 Conclusions

The research aims set out in Section 1.5 to be addressed in this PhD programme were:

- Water balance and fluxmeter measurement technologies for assessing the impacts from saline irrigation of the halophyte Salicornia.
- The impact of irrigation of Salicornia on salt and nutrient dynamics in the soil, and salt and nutrient leaching.
- Modelling of saline irrigation on salt dynamics and crop yield, and the development of a heuristic model for salt and nutrient dynamics.
- Analysis of the benefit-costs of the irrigation of Salicornia with various saline irrigation waters and delivery systems, and application of the heuristic model to assess future impacts on groundwater.

These have been realised in full.

### 7.1.1 Measurement technologies

The ability to measure the environmental impacts on groundwater from irrigating halophytic crops with saline waters proved elusive in the 2020 experiments.

In Chapter 3 it was shown that through shielding all three wires of the TDR probe with glue-lined heat-shrink tubing, the length of the TDR rods could be detected, allowing for the calculation of an apparent dielectric constant. Consequently, shielded TDR probes were readily employed to monitor the changing soil water contents beneath the Salicornia plots irrigated with highly saline waters.

The Typic Torripsamment soil of the experimental site represents the modal soil type of the Arabian Peninsula. Initially, drainage was not registered by the passive-tension DFMs at a depth of 600 mm. It is believed that the initial DFM failure was partly attributable to the disturbance of calcic and gypsic materials within the deeper profile during DFM insertion. This disturbance, followed by re-wetting of the re-packed soil, may have resulted in the formation of an impermeable 'cemented' layer above the DFMs.

Subsequently, a decision was made to install the DFMs at a shallower depth of 200 mm to avoid the calcic and gypsic horizon. Additionally, the diameter of the convergence ring positioned atop the DFM was increased from 150 mm to 250 mm to allow for a wider zone of drainage capture. The length of the wick, which establishes the passive tension, was also extended from 600 mm to 700 mm. These modifications to the design and the changes implemented in the installation protocol enabled successful monitoring of both drainage and salt leaching during irrigation of the Salicornia with saline waters.

These two modifications of key devices for monitoring in the rootzone of crops irrigated with saline waters enabled better monitoring and modelling of the impacts of drainage and salt leaching on aquifer recharge and groundwater quality in the saline environments of hyper-arid regions.

## 7.1.2 Salt Leaching Dynamics

In Chapter 4 the effectiveness of leaching in maintaining rootzone salinity during saline water irrigation was investigated. This examined the common practice of employing the metrics of the leaching requirement (*LR*) (Rhoades, 1974) and leaching fraction (*LF*) (Maas, 1990). Managing saline water irrigation implicitly assumes complete flushing of salt from the profile through infiltration. In Chapter 4 it was verified that salt leaching could be described by piston displacement with minimal solute dispersivity. Laboratory measurements and field monitoring confirmed that for these dominant desert soils of the Arabian Peninsula, salt can be effectively leached from the profile. The findings indicated that the invading irrigation water displaces all the resident salt-laden soil water within the rootzone prior to irrigation, effectively flushing it downwards. This effectiveness has benefits for maintaining equable salinity conditions in the rootzone through implementation of a leaching requirement, *LR*. However, the effectiveness of the salt leaching fraction *LF* means that the underlying aquifer is receiving drainage water of salinity some 2–3 times higher than that of the irrigation water. This can compromise, in the longer term, the water quality of the groundwater from which irrigation is drawn. This salt dilemma was then further examined in Chapter 6 using heuristic modelling.

### 7.1.3 Saline irrigation, crop yield and economic water-productivity

Three types of saline waters were used to irrigate the halophytic crop of *Salicornia* in the hyper-arid United Arab Emirates. The three waters were GW at 25 dS $m^{-1}$, RO from a desalination unit at 40 dS $m^{-1}$ and AQ being the effluent from land-based aquaculture producing fish in tanks filled with RO brine, again at 40 dS $m^{-1}$. These three waters were applied through BUB, PCD, and SUB devices. The reference ETo was of the order of 2000 L $m^{-2}$ (2000 mm). The irrigation schedule for BUB applied around 8000 L $m^{-2}$, and for PCD and SUB about 2600 L $m^{-2}$. These experiments were described in Chapter 5.

The yields of harvest forage were found to be greatest for BUB being 2.0-2.6 kg $m^{-3}$ compared to 1.1-1.6 kg $m^{-3}$ for the other emitter devices. However, the water productivities WPI (kg $m^{-3}$) for forage were greatest for PCD and SUB being 2.0 to 2.8 kg $m^{-3}$ for all the waters, whereas for BUB it ranged from 1.4 to 2.0 kg $m^{-3}$. An assessment of gross economic water productivity (GEWPI, \$ $m^{-3}$) was subsequently undertaken, considering only gross revenue. The GEWPI for the total potential revenue from fresh tips, forage, and seeds was determined to be highest for Aquabrine (AQ) applied through pressure-compensated drippers (PCD) and subsurface irrigation tape (SUB), with values ranging from 5.8 to 6.2 \$ $m^{-3}$.

The value of this gross revenue is well above the presumed cost of desalination at \$1.5 $m^{-3}$ and it does not even consider the additional value that would come from the saline groundwater freshened by desalination for irrigation of high value crops, or from the fish grown in the aquaculture tanks. The BUB had the lowest $GEWP_I$ of between 1.3 and 2.9 \$ $m^{-3}$. It is concluded that the most economically beneficial approach for halophyte production, considering the balance between water use and yield, involves cultivating fresh tips irrigated with Aquabrine (AQ) delivered through either pressure-compensated drippers (PCD) or subsurface irrigation tape (SUB). This economic benefit has the potential to be further enhanced by employing a multiple fresh-tip harvesting strategy.

The GW had a salinity of 25 dS $m^{-1}$, whereas the RO and AQ were at 40 dS $m^{-1}$. The leaching fractions LF were about 0.72-0.74 for BUB, and 0.3-0.6 for PCD and SUB. Given the irrigation scheduling, the greatest salt load to groundwater came from BUB, being 135-195 kg $m^{-2}$. For PCD and SUB it was less, between 14-36 kg $m^{-2}$. In Chapter 5, simple mass-balance calculations were then undertaken to assess the biophysical impacts of these salt loadings on the underlying aquifer's salinity. An exemplar loading of 75 kg $m^{-2}$ was employed within this simplified model. In Chapter 5, some simple arithmetic was used to show that this salt loading could result in an annual salinity rise of 2.6 dS m-1 $y^{-1}$ for an aquifer with a saturated depth of 100 m. Better modelling was needed to assess the environmental impacts.

### 7.1.4 Heuristic modelling of impacts

The data, results and simple analyses in Chapter 5 highlighted the economic value of irrigating the halophytic crop Salicornia *bigelovii* with nitrogen-rich saline waters, either from groundwater or reject brines from desalination units, have been produced through the experiments. However, simple arithmetic in Chapter 5 suggested that this would result in a significant rate of rise in the salinity of groundwater and would represent a deterioration in the utility of the subterranean water reserves. Modelling would be needed to extrapolate these findings.

From the comprehensive evidence-bases of measurements described in Chapters 3, 4 and 5, a simple heuristic model of groundwater quantity and quality was developed to infer the environmental impacts of irrigating crops with saline and high-nitrate groundwater in a hyper-arid environment. This model was presented in Chapter 6. The key parameters needed to parametrise this simple model are the fraction of the land surface above the aquifer that is irrigated, the initial depth of the saturated thickness of the aquifer, the saturated water content of the aquifer, and the annual rate of evapotranspiration from the crop which can be found using the crop-calculator model of Al Tamimi et al. (2022). The model is simple and straightforward to parameterise. It is easily understood and could be useful for assessing the impacts and trade-offs of policy developments and regulation options. Some simple prognostics using this model suggests that urgent action is needed to sustain both the quantity and quality of some of the groundwaters resources in the Emirates.

## 7.2 Recommendations and Future Needs

This need for action is not limited to the United Arab Emirates, as there are critical challenges at the food-water-energy nexus in the many and widespread arid and semi-arid regions of the world. Arid and semi-arid regions cover some 41% of the world's land area and are home to over 2.5 billion people. Yet about 44% of the world's food is produced from these water-short arid and semi-arid lands. Around 16% of the world's groundwaters are saline, and the area of aquifers affected by salinity is increasing by 10% each year. The global cost of salt-induced land degradation in irrigated areas is estimated at €21.3 billion annually. It is estimated that 50% of all arable land will be impacted by salinity by 2050. These data, and more, can be found at Salinity Magazine (netherlandswaterpartnership.com) .

These issues require solutions to provoke policy development and practical actions. The work described in this thesis using saline groundwaters from a range of sources to irrigate halophytes is a positive step towards providing food security and water security in an arid region with a reasonably plentiful supply of energy, albeit with a rapidly changing mix of energy carriers. In future it will be critical to address the needs described below:

- Whereas this work has outlined the economic productivity of irrigation water, there needs to be a countervailing economic assessment of the environmental impacts of the declining quantity of groundwater, and its continuing degradation in water quality.

- The experiments here have been carried out with one halophyte in one location. It would be worth considering how the results obtained here might apply to other hyper-arid regions around the world where there are similar issues at the food-water-energy nexus.

- The simple heuristic one-dimensional modelling outlined here in Chapter 6 considers two assumptions that should be further investigated. The irrigated area A above the total area of the aquifer T is simply considered to be a multiplier that could be used to extrapolate the results. More detailed 2-D and 3-D mechanistic modelling would be merited. As well, the heuristic modelling does not account for lateral recharge and discharge of the aquifer, and the impact of this assumption would be worth considering.

- A consequence of the investigations outlined in the bullet-point above would be to assess how a reduction in A, through policy change and the stopping of well permits in the so-called ‘red zones’ to withdraw water for irrigation, would prolong the quantity and quality of the underlying aquifers. Important questions to ask are - what would be the impacts and trade-offs.

- To protect the soils and waters of the lands upon which reject brines from desalination are applied, it would be valuable to assess the alternative uses of zero liquid discharge (ZLD) desalination technologies as a means to supply economically the freshened water for use in agriculture that comes from desalination units.

- It has been found that many of the groundwaters in the Emirates are high in nitrate, as is the effluent from aquaculture. It would be worthwhile to examine the impacts and trade-offs of balancing the nutritional needs of crops irrigated with these waters to determine how much organic and inorganic fertilizer is needed to maintain crop yields.

- Because irrigated crops often require pesticides and insecticides, what is the transmission and fate of these agrichemicals as they move back to the aquifer. Is there a contamination risk to groundwater from these chemicals.

- As found in earlier work by Dr Wafa Al-Yamani, treated sewage effluent (TSE) from municipal areas is a valuable alternative water source. The cultural or societal acceptance and economic viability of using TSE demands further investigation. What would the value and benefits be of injecting TSE into the aquifers to enhance groundwater recharge?

- To assess comparatively the benefits and trade-offs at the food-water-energy nexus, new economic models for the valuation of environmental impacts are needed, because presently the discourse is strongly weighted to the value of food production and the economic returns from agriculture.

## 7.3 Conclusions

The research presented in this thesis has provided strong empirical evidence of the value of growing a halophytic crop using saline waters derived from aquifers, desalination units, and through recycling through an aquacultural system. The value has been assessed in terms of both food, fodder and fuel value of the production, as well as the gross economic water productivity of the saline irrigation waters. As well, empirical evidence and heuristic modelling have identified the future risks to groundwater quantity and quality in this hyper-arid region. This dual measurement-modelling research has clearly identified future opportunities and challenges.

# APPENDIX A

# 8 Appendix A: Record of Achievement

## 8.1 Prior Publication

From 2017 through until 2020, the candidate was the EAD-lead in the Crop Calculator Project between EAD, Plant & Food Research and (then) Maven International. The Crop Calculator is a decision support tool (DST) for irrigation allocation based on a daily water balance model for tree and vegetable crops growing in Abu Dhabi. This work led to the following publication, which was then used in parts of the subsequent work described in this thesis.

- Al Tamimi, M., S. Green, Z. Hammami, K. Ammar, M. Al Ketbi, A.M. Al-Shrouf, M. Dawoud, L. Kennedy, and B. Clothier. 2022. Evapotranspiration and crop coefficients using lysimeter measurements for food crops in the hyper-arid United Arab Emirates. *Agricultural Water Management* https://doi.org/10.1016/j.agwat.2022.107826

## 8.2 Thesis Publications

The work described in this thesis has been published as four papers. These papers are listed below, and they form the core of the four main Chapters of the thesis. The DRC 16 forms of Statements of Contribution are provided in the next Section.

Al-Tamimi, Mansoor, Steve Green, Wasel Abou Dahr, Ahmed Al-Muaini, Dionysia Lyra, Khalil Ammar, Mohamed Dawoud, Paul Kenyon, Peter Kemp, Lesley Kennedy, and Brent Clothier. 2023 Devices to Measure the Impacts on Groundwater Salinity from Irrigating Halophytic Crops with Brackish Waters in a Hyper-Arid Environment. *Journal of Arid Environments* 220 https://doi.org/10.1016/j.jaridenv.2023.105115 .

Al-Tamimi, Mansoor, Steve Green, Wasel Abou Dahr, Ahmed Al-Muaini, Dionysia Lyra, Khalil Ammar, Mohamed Dawoud, Paul Kenyon, Peter Kemp, Lesley Kennedy, and Brent Clothier. 2023 Salt dynamics, leaching requirements, and leaching fractions during irrigation of a halophyte with different saline waters. *Soil Research* 62 SR23173. https://doi:10.1071/SR23173 .

Al-Tamimi, Mansoor, Steve Green, Wasel Abou Dahr, Ahmed Al-Muaini, Dionysia Lyra, Khalil Ammar, Mohamed Dawoud, Paul Kenyon, Peter Kemp, Lesley Kennedy, Andrew

McLachlan, and Brent Clothier. 2023. Drainage, Salt-Leaching Impacts, and the Growth of Salicornia bigelovii Irrigated with Different Saline Waters. *Agricultural Water Management* https://doi.org/10.1016/j.agwat.2023.108512

Al-Tamimi, Mansoor, Steve Green, Wasel Abou Dahr, Ahmed Al-Muaini, Dionysia Lyra, Khalil Ammar, Mohamed Dawoud, Paul Kenyon, Peter Kemp, Lesley Kennedy, Andrew McLachlan, and Brent Clothier. 2024. Measurement and Heuristic Modelling of Nitrogen and Salt Dynamics under Salicornia Growing in a Hyper-arid Region and Irrigated with Groundwaters of Differing Nutrient and Salt Loadings. *Irrigation Science* [under review].

## 8.3 DRC 16 Statements of Contribution

MASSEY UNIVERSITY
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UNIVERSITY OF NEW ZEALAND

GRADUATE RESEARCH SCHOOL

### STATEMENT OF CONTRIBUTION
### DOCTORATE WITH PUBLICATIONS/MANUSCRIPTS

We, the student and the student's main supervisor, certify that all co-authors have consented to their work being included in the thesis and they have accepted the student's contribution as indicated below in the Statement of Originality.

| | |
|---|---|
| Student name: | Mansoor Al-Tamimi |
| Name and title of main supervisor: | Prof Paul Kenyon |
| In which chapter is the manuscript/published work? | 3 |
| What percentage of the manuscript/published work was contributed by the student? | 80% |

Describe the contribution that the student has made to the manuscript/published work:

Identification of the problems.
Attempted remedial actions
Discussions of solutions
Implementation and testing of the prototypes
Analyses and writing

Please select one of the following three options:

(●) The manuscript/published work is published or in press

Please provide the full reference of the research output:

Al Tamimi et el. (2023) Devices to Measure the Impacts on Groundwater Salinity from Irrigating Halophytic Crops with Brackish Waters in a Hyper-Arid Environment. Journal of Arid Environments 220
https://doi.org/10.1016/j.jaridenv.2023.105115

( ) The manuscript is currently under review for publication

Please provide the name of the journal:

( ) It is intended that the manuscript will be published, but it has not yet been submitted to a journal

| | | | |
|---|---|---|---|
| Student's signature: |  | Main supervisor's signature: | P R Kenyon Digitally signed by P R Kenyon DN: cn=P R Kenyon, c=NZ, o=Massey University, ou=School of Agriculture and Environment, [illegible] |

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We, the student and the student's main supervisor, certify that all co-authors have consented to their work being included in the thesis and they have accepted the student's contribution as indicated below in the Statement of Originality.

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| Student name: | Mansoor Al-Tamimi |
| Name and title of main supervisor: | Prof Paul Kenyon |
| In which chapter is the manuscript/published work? | 4 |
| What percentage of the manuscript/published work was contributed by the student? | 75% |

Describe the contribution that the student has made to the manuscript/published work:

Rationale for the study
Design of the experiments
Running of the experiments
Analyses and writing

Please select one of the following three options:

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Please provide the full reference of the research output:

Al Tamimi et al. (2023) Salt dynamics, leaching requirements, and leaching fractions during irrigation of a halophyte with different saline waters. Soil Research 62 SR23173. https://doi:10.1071/SR23173

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| Student name: | Mansoor Al-Tamimi |
| Name and title of main supervisor: | Prof Paul Kenyon |
| In which chapter is the manuscript/published work? | 5 |
| What percentage of the manuscript/published work was contributed by the student? | 80% |

Describe the contribution that the student has made to the manuscript/published work:

Overall design of experiment and liaison with ICBA
Implementation & running of the experiment
Discussion of results with ICBA
Working with biometrician
Analyses and writing

Please select one of the following three options:

(●) The manuscript/published work is published or in press

Please provide the full reference of the research output:

Al Tamimi et al. (2023) Drainage, Salt-Leaching Impacts, and the Growth of Salicornia bigelovii Irrigated with Different Saline Waters. Agricultural Water Management https://doi.org/10.1016/j.agwat.2023.108512

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|---|---|---|---|
| Student's signature: | [signature] | Main supervisor's signature: | P R Kenyon (digitally signed) |

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|---|---|
| Student name: | Mansoor Al Tamimi |
| Name and title of main supervisor: | Prof Paul Kenyon |
| In which chapter is the manuscript/published work? | 6 |
| What percentage of the manuscript/published work was contributed by the student? | 75% |

Describe the contribution that the student has made to the manuscript/published work:

Design of experiment and discussions on heuristic modelling protocols
Implementation & running of experiments
Discussions with biometrician
Analyses and modelling assessments
Writing

Please select one of the following three options:

( ) The manuscript/published work is published or in press

Please provide the full reference of the research output:

(•) The manuscript is currently under review for publication

Please provide the name of the journal:

Al Tamimi et al. (2024) Measurement and Heuristic Modelling of Nitrogen and Salt Dynamics under Salicornia Growing in a Hyper-arid Region and Irrigated with Groundwaters of Differing Nutrient and Salt Loadings. Journal of Arid Environments [under review].

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