MAINTAINING THE HYPER-ARID FORESTS OF ABU DHABI BY SUSTAINABLE IRRIGATION USING TREATED SEWAGE EFFLUENT IN CONJUNCTION WITH GROUNDWATER

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ABSTRACT

The late H.H Sheikh Zayed bin Sultan Al Nahyan, the founding President of the United Arab Emirates sought to 'green the desert' through planting of trees. These forests in the hyper-arid desert of Abu Dhabi depend on irrigation with groundwater (GW). A wide range of valuable ecosystem services are delivered by the forests. In the 2017 State of the Environment Report, Environment Agency – Abu Dhabi (EAD) noted that "… considerable water resources are required to maintain these forests". Over-consumption of GW, and the increasing salinity of the aquifers means that the GW of Abu Dhabi is under threat. To manage sustainably the GW resources, in 2016 the government of Abu Dhabi passed Law 5 on GW management and identified the requirement for limits to be placed on GW allocation for vegetation. The means to realise reductions in GW use are: minimised irrigation schedules for GW; and the replacement of GW with treated sewage effluent (TSE). To achieve this, a Government-to-Government partnership was established between EAD and the New Zealand Government. The NZ partners are Maven International and Plant & Food Research. This doctoral research was carried out under this larger partnership. The actual water uses, *ET*c, of the 3 major forest species of Al Ghaf, Al Sidr and Al Samr were measured by heat-pulse sap-flow methods in trees irrigated with either GW or TSE. The impacts on *ET*c and tree health of the lower salinity TSE are detailed. The complex links between tree water-use, the reference *ET*o, and trees' phenology are described. Relationships between the crop factor, *K*c (=*ET*c/*ET*o), and tree canopy characteristics were inferred using a light-stick to measure the percentage light intercepted by the trees' canopy. From this research, guidelines have been proposed for Law 5 for the water-allocation limits for these 3 species. These guideline values for GW are based on 1.5 *ET*c to account for a 25% factor-of-safety, and a 25% salt-leaching fraction. For TSE, there is no need for salt leaching. These recommendations will lead to GW savings of 35-70% compared to current practice. Eventually TSE should replace GW to sustain the forests.

ACKNOWLEDGEMENTS

This year, 2018, is the year of Zayed. I dedicate my PhD to him - His Highness Sheikh Zayed Al Nahyan, may Allah bless his soul. I hope that my research in his forests will support sustaining his vision of greening the desert, while considering the current challenges with groundwater. I would like to thank him for giving me an opportunity to witness and to enjoy working in a wonderful forest established by him, in a middle of the Abu Dhabi desert as a proof that a dream can come true.

I am honoured to be given this golden opportunity and I would like to sincerely thank Her Excellency Razan Khalifa Al Mubarak, the secretary general of the Environment Agency Abu Dhabi for her trust and belief in me to fulfil EAD requirements from this research, as well as her full support for my PhD degree. My thanks also extend to Dr. Frederic Launay, who worked as Senior Advisor to Secretary General, for his honest advice and strong support at the beginning of my PhD journey.

I respect and have a deep gratitude to Dr Brent Clothier, my advisor who was definitely more than that. He is a unique example of a true scientist that I am so lucky to have had a chance of working closely with him. I would like to thank him for his kindness - simply in everything. He saved no efforts, or time, in continuously teaching, guiding, supporting and encouraging me along my journey. As well as taking care of me while I was in New Zealand. The thanks extend to his adorable wife and nice family for their hospitality.

Beside my advisor, I would like to thank the rest of my PhD research committee: Prof. Peter Kemp from Massey University, and Dr Shabbir Shahid from the International Center for Biosaline Agriculture in Dubai, for their academic support and valuable inputs and feedback to my research progress.

The success and final outcome of this research required massive inputs and processing of data continuously. For that, I would like to thank Dr Steve Green for his passion and intelligence in adjusting the usage of his gears to our desert and the analysis the data accordingly, and of course for coming to love our trees and forestry. Also, many thanks to my best colleague, Rommel Pangilinan from EAD for his field and technical support, as well as for filming our journey in the forest with lovely videos that I can keep as nice mementos.

My sincere thanks to EAD Forestry team for providing me with all required data and widening my thoughts through great and related discussions. Also, thanks to Barari for their technical support in the field, to Maven Consultants for consulting and supervising the research closely, and to UAE University and Exova laboratories for analysing the research samples.

I appreciate the strong role of my family in supporting me spiritually, especially my father and I hope that he is proud of me. I will never forget my mother's desire, may Allah bless her soul, for me to complete my higher education and never to quit learning. I hope that through my PhD I could make them proud and pleased with my success.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATIONS

AAI	Appropriate Agriculture International Company
AD	Abu Dhabi
CHPM	Compensation Heat Pulse Method
CHPV	Compensation Heat Pulse Velocity (mm hr^{-1})
DST	Decision Support Tool
EAD	Environment Agency Of Abu Dhabi
EC	Electrical Conductivity (dS m^{-1})
ET_C	Crop Transpiration-Tree Water Use (mm d^{-1} or L hr^{-1})
ET_o	Reference Evapotranspiration (mm d^{-1} or L hr^{-1})
FAO	Food and Agriculture Organization
GW	Groundwater
HD	Heat Dissipation
HFD	Heat Field Deformation method
HH	His Highness
IWS	International Water Summit in Abu Dhabi
K	Hydraulic conductivity of soil (mm hr^{-1})
K_c	Crop Factor = ET_c / ET_o (-)
L	Litre
LI	Light-Interception Fraction (-)
NES	National Environmental Strategy
NZ	New Zealand
PAR	Photosynthetically Active Radiation (μmol m^{-2} s^{-1})
PET	Potential Evapotranspiration (mm d^{-1})
PSA	Projected Shadow Area (m^2)
SAR	Sodium Adsorption Ratio (-)
SFD	Sap Flux Density (mm hr^{-1})
SHB	Stem Heat Balance
T	Transpiration (mm d^{-1} or L hr^{-1})
TDR	Time Domain Reflectometry
THB	Trunk Segment Heat Balance
Tmax	Maximum Air Temperatures (° C)
TSE	Treated Sewage Effluent
UAE	United Arab Emirates
UAEU	United Arab Emirates University
UNCCD	United Nations Convention To Combat Desertification
UNESCO	United Nations Educational, Scientific and Cultural Organization
VPD	Vapour Pressure Deficit (kPa)
WTP	Willingness to Pay

CHAPTER 1

1 Introduction

1.1 Background

The vision of the late Sheikh Zayed bin Sultan Al Nahyan, the founding President of the United Arab Emirates was to 'green the desert' through planting of trees. These forests in the hyper-arid desert of Abu Dhabi depend on irrigation, and groundwater is the predominant source of this water. These forests deliver a wide range of valuable ecosystem services. But as noted in the 2017 Abu Dhabi State of the Environment Report recently published by Environment Agency – Abu Dhabi (EAD, 2017) '… considerable financial, energy and water resources are required to maintain' these forests. Currently, some 188 $Mm^3\ y^{-1}$ is used to sustain 20 million trees in Abu Dhabi's forests. Over-consumption of groundwater, and the increasing salinity of the aquifers means that the groundwater resource of Abu Dhabi is under threat. To manage sustainably the groundwater resources of the Emirate, in 2016 the government of Abu Dhabi passed Law 5 which requires a resource consent for irrigation, and in which is specified the sustainable limit of the amount of groundwater that can used in relation to the type of vegetation being irrigated.

Environment Agency-Abu Dhabi has indicated that it wishes groundwater consumption for the irrigation of forests be reduced by 80% by the end of 2020. In order to understand the options and how to achieve these savings, EAD embarked on a 5-year research programme, beginning in 2014, on sustainable groundwater management and assessment of the impact and value of replacing groundwater irrigation of arid forests with treated sewage effluent.

1.2 The EAD Project

This project of cooperation on environmental management development is being conducted under a Government-to-Government partnership between EAD and the New Zealand Ministry of Foreign Affairs and Trade. The New Zealand partners in this project are Maven International Ltd and Plant & Food Research Ltd. The Statement of Work (SoW) used in the contract for this project had four major intended outcomes:

- Assessing the impact of treated wastewater on forest plant growth and health across five species of forest trees using two salinity concentrations.

- Determining the irrigation needs of the top five (by planted area) forestry species at different salinity levels.

- Developing a model for forestry irrigation management that incorporates both the data gathered from the above field experiments and the existing data EAD and Barari hold on their forest plantations.

- Developing capability within EAD for the measurement and modelling of irrigation impacts on sustainable forestry including Wafa Faisal Al Yamani completing her research for a PhD.

The doctoral research presented in this thesis relates to the first two, and the last bullet-points. The third bullet point in relation to the decision support tool (DST) is still being carried out by Maven International and Plant & Food Research using the research results developed through my work, and presented here in this thesis. I carried out this research as a full-time employee of EAD on study leave.

Whereas the contract, as signed, covered 5 species, this was subsequently re-negotiated to 4, namely Al Arak (*Salvadora persica*), Al Ghaf (*Prosopis cineraria*), Al Sidr (*Ziziphus spina-christi*), and Al Samr (*Acacia tortilis*). The water use of the four species of Ghaf, Sidr and Samr was measured using the compensation heat-pulse method (CHPM) (Green & Clothier, 1988) of sapflow monitoring, and time-domain reflectometer measurements of the changing soil water content and salinity in the rootzone. These species were amenable to CHPM because they are either single-stemmed (Ghaf), or have only a few branched stems (Sidr and Samr). The experiments with these three species were carried out in the Khub al Dahs Forest near Madinat Zayed which is under EAD management.

The Arak tree possesses a tortuous pattern of many small stems which would make application of the CHPM impossible. Therefore, it was decided to quantify the water use of Al Arak using small weighing lysimeters. These experiments were carried out at the nursery of Barari at Al Salamat, near Al Ain. Technical issues with the lysimeter set-up, and the challenge of maintaining good tree growth in the small 70 L lysimeter pots have meant analysis of the Arak experiments has been compromised. Plant & Food Research will continue with those analyses during 2019 so that Al Arak can be included in the DST. No results for Al Arak are presented in this thesis. Although for completeness, I review the characteristics of the Arak tree, along with the Ghaf, Sidr and Samr in Chapter 3.

1.3 Project Goals and Thesis Structure

The goals of the EAD-contracted work that underpins this thesis are to:

- To minimize the amount of groundwater (GW) used to irrigate the arid-forests in the deserts of Abu Dhabi, and to assess the impact and value of using treated sewage effluent (TSE) to replace groundwater as the source of water for irrigation.

- To provide Environment Agency-Abu Dhabi with water-allocation guidelines for use in their Government's Law 5 which requires to regulate irrigation use according to the nature of the crop, or tree species.

To assist in the realization of these goals, the objectives of my thesis are to:

- Directly measure the water use of the 4 major arid-forest species irrigated with either saline GW or TSE. The details of the compensation heat-pulse method used to do this are given in Chapter 4 for Al Ghaf trees and this has been accepted for publication in *Acta Horticulturae* (Al Yamani, 2018a).
- Understand the complex relationships between tree water use, the prevailing weather, and the phenological characteristics of the trees. To describe this link, a crop-factor, *K*c, approach is used. These results are presented in Chapter 5 for Al Ghaf and Al Sidr for GW and these have been published in *Agricultural Water Management* (Al Yamani et al. 2018b). In Chapter 6 a comparison of the impact of TSE on tree-water use and tree productivity is presented and this has been accepted for publication (pending revision) in *Agricultural Water Management* (Al Yamani et al. 2019a). Chapter 7 describes the water use of Al Samr trees under irrigation with GW and TSE, and a manuscript based on this chapter is under review with *Agricultural Water Management* (Al Yamani et al. 2019b).
- Develop a relationship between the crop factor, *K*c, and the canopy characteristics of the tree species as inferred using a light-stick to measure the percentage light interception by the trees' canopy. These relationships are detailed in Chapter 5 for Al Ghaf and Al Sidr irrigated by GW, and in Chapter 6 for those species irrigated by TSE. The results for Al Samr are given in Chapter 7. These results will be critical for practical implementation of the DST.

- The guidelines that have been proposed for Law 5 for the water-allocation limits are also given for three of these species for GW and TSE in Chapters 5, 6, and 7.

The thesis continues next in Chapter 2 with an assessment of the historical basis and future options for native plant-species in the hyper-arid forests of Abu Dhabi based on a paper that is ready for submission (Al Yamani et al. 2019c).

A review of the characteristics and physiology of the 4 major tree species are given in Chapter 3, along with the current management practices for tree management and irrigation.

In Appendix A, I have provided a list of my record-of-achievement in terms of presentations and publications. In Appendix B, there is a declaration of my role and my percentage contribution within this larger EAD, Maven International, and Plant & Food Research project.

1.4 References

Al Yamani, Wafa, Steve Green, Rommel Pangilinan, Steve Dixon, Peter Kemp, and Brent Clothier. 2018a. Sap flow in Al Ghaf trees growing in the Hyper-Arid Desert of Abu Dhabi. *Acta Horticulturae* [in press], 10th ISHS Sap Flow Symposium, Fullerton, California, 22-26 May 2017.

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CHAPTER 2

2 The historical basis and future options for native plant-species in the hyper-arid forests of Abu Dhabi

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This current Chapter 2 provides a historical perspective on the history of the development of arid forests in Abu Dhabi, and assesses the current drivers for retaining forests, plus outlining the pressures on them, and discusses their present state, and details the impacts they are having. This historical assessment, and consideration of present conditions, leads to a consideration of the future options for managing these arid forests.

This Chapter is primarily written in the form of a paper that has been submitted to the *Land Use Policy*.

The content of this Chapter has been accepted (pending revision) as:

Al Yamani, Wafa, Lesley Kennedy, Steve Green, and Brent Clothier. 2019. The historical basis and future options for native plant-species in the hyper-arid forests of Abu Dhabi. *Land Use Policy* [accepted pending revision].

2.1 Abstract

His Highness Sheikh Zayed bin Sultan Al Nahyan is known as the founding father of the UAE nation. He ruled for 33 years. Sheikh Zayed had a vision to 'Green the Desert' using arid-forest species. These forests deliver valuable ecosystem services. Irrigation from groundwater was the key for this 'greening of the desert'. We detail the historical developments of forests in Abu Dhabi. Abu Dhabi Emirate now has 242,000 hectares of arid forests, comprising 3.5% of Abu Dhabi land area. Some 10% of the Emirates groundwater usage is destined for use in forestry. Groundwater in Abu Dhabi has very low recharge rates, and with irrigation "business as usual" it is estimated that usable groundwater reserves will be depleted within 55 years. Groundwater use in forests is 188 Mm^3 y^{-1} and the short-term target is to reduce that usage to 37 Mm^3 y^{-1} by end of 2020. A recent option has been for the cancellation of irrigation in some low-quality forests, and leaving the trees to die through drought. But, through improved irrigation scheduling we consider that savings of up 50% are possible, so that groundwater usage could be reduced to 94 Mm^3 y^{-1}. Then fulfilment of the remaining gap of 57 Mm^3 could be met through the application of treated sewage effluent

(TSE). It is understood that this amount of TSE is available in Abu Dhabi, although reticulation systems to the forests will need to be put in place. Furthermore, there is competition for this valuable treated-waste resource. Nonetheless, it should be possible to sustain the remaining arid-forests in Abu Dhabi through sustainable irrigation, and the application of TSE.

2.2 Introduction

2.2.1 History

His Highness Sheikh Zayed bin Sultan Al Nahyan became the ruler of the Emirate of Abu Dhabi in 1966. He then became the first President of the United Arab Emirates when they were formed in 1971 by union with six other neighbouring Emirates who were each part of the former Trucial States. In 1972, the Emirate of Ras al Khaimah joined the UAE bringing to seven the number of Emirates in the UAE. Thus Sheikh Zayed is known as the founding father of the UAE nation. He ruled for 33 years. Also, Sheikh Zayed had a vision to 'Green the Desert'.

By promoting agriculture and forestry, plus wildlife conservation, Sheikh Zayed sought to push back the desert, enhance the Emirati lifestyle, and promote an environmental conscience amongst Emiratis. Nonetheless, he had many doubters who did not consider it possible to grow vegetation in such a harsh, hyper-arid environment, where reference evapotranspiration annually exceeds 2000 mm, and annual rainfall is often is often less than 100 mm. Irrigation was therefore the key. Figure 2.1 is a photograph of Sheikh Zayed manually irrigating what looks to be a young Al Sidr tree in the Al Dhafra Region of Abu Dhabi in 1969.

Figure 2.1 His Highness Sheikh Zayed bin Sultan Al Nahyan, the Founding President of the United Arab Emirates, 'greening' the desert by watering a young forest tree in Al Dhafra Region of Abu Dhabi in 1969. [Source: Abu Dhabi Farmers Service Center https://www.adfsc.ae/en/Pages/ADAgriculture.aspx]

In this paper, we detail the historical basis of forest development in Abu Dhabi. From this look backwards, and via an assessment of the current state and pressures, future options for managing the arid forests in the hyper-arid deserts of Abu Dhabi are outlined, and forest management responses are proposed.

Looking back to assess policy for future management options of the arid forests, this follows the dictum of Sheikh Zayed, who said "… he who does not know his past cannot make the best of his present and future, for it is from the past that we learn".

Sheikh Zayed knew that water was the key for his 'greening of the desert'.

2.2.2 Irrigation and Water Resources

Total water consumption in Abu Dhabi in 2012 was estimated to be 3,415 $Mm^3\ y^{-1}$ by McDonnell and Fragaszy (2016). Of this, they found groundwater supplied 2,217 $Mm^3\ y^{-1}$, whereas the remainder was split between desalinated water (1,059 $Mm^3\ y^{-1}$), and recycled water (139 $Mm^3\ y^{-1}$). 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 the irrigation amenity and roadside plantings, 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.

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

Wada et al. (2012) carried out a global assessment of what fraction of irrigation usage is sourced from non-sustainable groundwater extraction. They classified the water sources for irrigated crops as being local precipitation available for root uptake (green water), plus water drawn from surface water bodies or renewable groundwater (blue water), as well as diverted water from non-local sources, and in particular the overdraft of nonrenewable or non-sustainable groundwater. Their assessment for the whole of the UAE was that groundwater extraction from all subterranean reserves used for irrigation was 1.55 (±0.3) $km^3\ y^{-1}$. They separately assessed that groundwater reserves in the UAE are being depleted at a rate of 1.18 (±0.4) $km^3\ y^{-1}$. So groundwater depletion is 76% of extraction. As well, they assessed groundwater recharge. From these extraction and recharge values they concluded that 64% of the water used in the UAE is drawn from groundwater that is not recharged, and is therefore non-sustainable.

According to Wood and Imes (1995), the groundwater resources of Abu Dhabi are essentially a large reservoir of ancient water formed during previously wetter periods. For all intents and purposes the groundwater reserves are ‘fossil water bodies’. There is an absence of significant recharge presently, albeit with some episodic recharge through wadis close to the Oman Mountains near to Al Ain in the east. Pitman et al. (2009) estimated the annual abstraction of groundwater to be 2,174 Mm^3, whereas the maximum recharge rate is just 140 Mm^3. They concluded that with “business as usual” that the estimated usable groundwater reserves would be depleted with 55 years.

So "business as usual" is clearly not an option for keeping the deserts 'green'. The challenge is to propose options to sustain forestry, in some form, whilst sustaining groundwater quantity.

2.2.3 Groundwater Regulation

In response to these pressures on the state of groundwater reserves, in 2016 the government of Abu Dhabi passed Law 5 with the objective of the sustainable management of groundwater in the Emirate. Within that regulation it was specified that groundwater extraction limits will be set, and usage allowances will be defined for the range of irrigated crops, as well as for the species that comprise the arid forests of the desert.

The challenge for forestry irrigation is therefore to determine what the minimum water requirements for the forests should be, so as to ensure adequate tree health and function, whilst ensuring the leaching of salts from the rootzone, since the groundwater used for irrigation is saline.

2.3 The historical development of forestry and today's forestscape

2.3.1 Historical Developments

Following the start of oil exports from Abu Dhabi in 1962, Sheikh Zayed Al Nahyan asserted that to support his vision of 'greening the desert' the "… profit gained by petroleum from the ground has to be returned to the soil" (Figure 2.2). This was realized financially by a part of the profit gained by selling petroleum being allocated to expand the area of afforestation. Sheikh Zayed spared no effort to work on 'greening the desert', challenging those who had no faith or acceptance in growing trees in arid-desert environment such as Abu Dhabi. Next, Sheikh Zayed's efforts in combating desertification were recognized internationally. The UAE became a member at the United Nations Convention to Combat Desertification (UNCCD) in 1999. And, to confirm its commitment towards these international agreements, the UAE established a National Environmental Strategy (NES) to combat desertification.

Figure 2.2 An early photograph, undated but probably in the early 1970s, of Sheikh Tahnoon (middle), a member of the Al Nahyan Royal family, with Japanese researchers near Al Ain inspecting the desert soil to assess its suitability for planting arid-forest trees [Source: Appropriate Agriculture International Company, *pers. comm*. 2018].

Historical reports by the Japanese enterprise called the Appropriate Agriculture International Company (AAI) (http://www.koushu.co.jp/AAI_E/index_E.html) provide useful historical information about early afforestation projects carried out in Abi Dhabi. In their undated on-line report, AAI noted that afforestation in Abu Dhabi was initiated by a French consultancy company in 1969, and that initial plantings covered just 245 ha along Al Ain – Abu Dhabi road (AAI, undated). The afforestation activities continued in the eastern region of Abu Dhabi and rapidly reached 29,200 ha of planted trees by 1992. Afforestation in the western region of the Emirate, now named as Al Dhafra, started in 1976 and rose up to 26,500 ha by 1992 (Figure 2.3). These plantings were around the Liwa Oases and along the main roads (Figure 2.4).

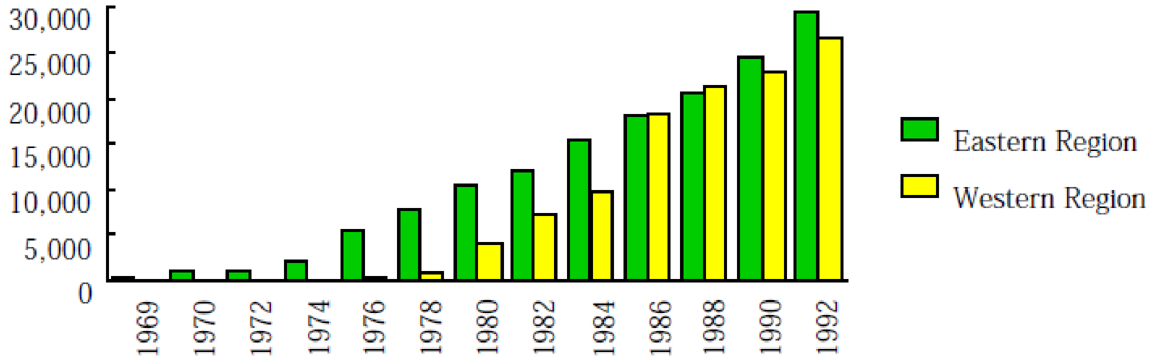

Figure 2.3 The growth in the area of forestry in the Eastern Region of Abu Dhabi (Al Ain) and the Western Region (Al Dhafra) between 1969 and 1992 [Source http://www.koushu.co.jp/AAI_E/NewsE/STreePlantingUAE.pdf].

Figure 2.4 An old photo, probably from the early 1970s, of afforestation in the Liwa region of Al Dhafra in the west of Abu Dhabi. The large sand hills in the background are typical of the landscape between the many Liwa Oases. Unlike today, there was no planting of vegetation in the so-called belt-road, the area alongside and between the divided highway road surfaces [Source: Appropriate Agriculture International Company, *pers. comm*. 2018]

Between September 1985 and March 1989, there was a joint project between United Arab Emirates University (UAEU) and Shizuoka University under the Japan International Cooperation Agency (JICA's). This project focused on improvement of arid-land agriculture and forestry in the UAE. One of the motivations was on fixing the sand dunes using vegetation and physical barriers. The sub-themes of this study were on observation of natural sand-dune movement, experiments with sand-dune fixation, the effects of date-frond mat fences on sand control, and the effects of mulching and other water-holding materials on tree growth (The Japan International Cooperation Agency, 1989).

2.3.2 Plant species used for afforestation

During the 1970's, foreign tree species were mostly introduced for large scale afforestation in the Emirate, and these included Eucalyptus, Casuarina, Prosopis, and others. In 1973 there was a report on the "Australian Forest in Arabian Desert" (Commonwealth Forestry Review, 1973). This report was a short summary of forestry activities in Abu Dhabi and noted that "… a forest of million Australian trees is being established in a harsh desert of Arabia by Sheik Zaid bin Sultan al Nahayan [sic], ruler of Abu Dhabi, one of the seven Trucial States. The first need was for trees which would grow in a land of low rainfall, stand up to sun temperatures of up to 55^o C (140^o F) and survive on water of an extremely high salt ratings. The French consultants, Sogreah, called on Lindsay Prior, Professor of Botany, at Australian National University, Canberra, for advice on the selection of trees. He chose the Australian eucalyptus and some other hardy varieties of Australian trees and shrubs. A system of irrigation was devised whereby water is piped from wells and recirculated through plastic piping to drip outlets around the trees [Figure 2.5]. Early reports claim that work done to date has already checked the shifting sand."

Figure 2.5 Newly planted Australian species in the desert of Abu Dhabi near Al Ain showing driplines and seedlings protected by palm fronds [from Wood et. Al. 1973]. The tree spacings of 7x7 m are still used today.

Wood et al. (1973) in their article on this irrigated plantation project by Australians in Abu Dhabi concluded that "… irrigation will be required throughout the life of the plantations

[and] a high and continuing cost must be expected". And that "... the plantations being created, however, have very much greater importance for amenity and their value in a severe desert environment, in a country with substantial oil reserves, is extremely high. Such plantations should not therefore be evaluated using criteria which have been designed for countries with totally different natural resources and forestry needs".

Nonetheless, the Emiratis quickly became less keen on planting exotic species in their deserts, than in seeking ways to use native species in the greening of the Abu Dhabian desert. It quickly became apparent that the exotic species which had been used in afforestation in Abu Dhabi were causing major problems to the natural ecosystems and it was highly recommended to depend solely on native species in afforestation so as to increase the ecosystem value of these forests and minimize the threats on native species (El-Keblawy and Kisksi, 2005).

So in the mid-1970s, six native species were mainly planted; these were adapted to local conditions and furthermore they required less water to survive and grow. Also, they were well adapted to the saline conditions of the local desert. These species were *Prosopis cineraria* (Al Ghaf), *Acacia tortilis* (Al Samr), *Zizyphus spina-christi* (Al Sidr), *Salvadora persica* (Al Arak), *Leptadenia pyrotechnica* (Al Murkh), and *Acacia ehrenbergiana* (Al Salam). Nowadays, native species comprise 88% of the tree species in the forests of Abu Dhabi (EAD, 2016)

2.3.3 Today's Forestscape

The area of Abu Dhabi forests increased rapidly following establishment by the Abu Dhabi Municipality in the late 1960's (Figure 2.3). The Abu Dhabi Municipality took the lead in developing and managing these forest for many decades. During the late 1990s and early 2000s, the rate of forest development slowed, with few new plantation forests being established.

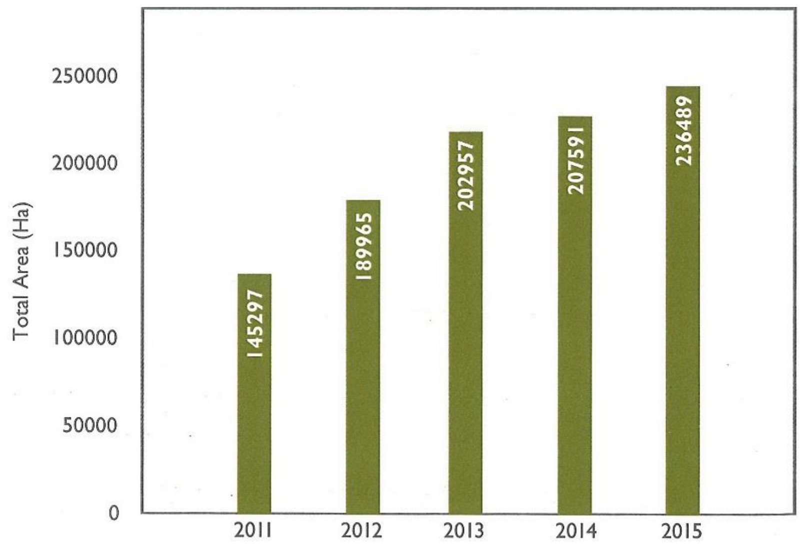

Figure 2.6 The rise in the area of forest being transferred to management by Environment Agency – Abu Dhabi (EAD) as they assumed increasing responsibilities for managing the forests previously carried out by the Abu Dhabi Municipality.

Beginning in 2007, the forests were then progressively transferred from the Municipality to EAD for management. Figure 2.6 shows the rise in the transferred area of forests being progressively managed by EAD as they increasingly assumed more responsibilities for the forests in Abu Dhabi.

The most recent data with EAD (EAD, 2017) show that Abu Dhabi Emirate has 242,000 hectares of arid forests, comprising 3.5% of Abu Dhabi land area. There are now 540 forested areas, comprising 322 named forests, 55 road belts, 73 farms and 44 asset plantations. There are approximately 20 million trees in these forests.

The management of the forests has now been handed back to the Department of Municipal Affairs and Transport (Al Mubarak, 2017)

As noted, the majority of the trees are now native species (EAD, 2017) with the respective tree numbers given in Table 2.1. Some trees are not accounted for in this EAD inventory as presented in Table 2.1.

Table 2.1 The species composition of the arid forests in the Abu Dhabi Emirate as recorded by Environment Agency – Abu Dhabi (EAD, 2017)

Common name	Species name	Number of trees
Al Arak	*Salvadora persica*	6,749,822
Al Ghaf	*Prosopis cineraria*	5,736,645
Al Sidr	*Ziziphus spina- christi*	1,430,486
Al Samr	*Acacia tortilis*	718,941
Date palms	*Phoenix dactyli*	361,584

Figure 2.7 A contemporary forest of Al Sidr trees (*Ziziphus spina- christi*). A herd of native desert gazelles can be seen in the foreground.

Figure 2.8 The forestscape of Abu Dhabi today. Left. Al Sidr trees are in the foreground, and Al Samr (*Acacia tortilis subsp. Raddiana*) are in the background on the ridgeline. The regular spacing of the trees enables drip irrigation lines to be laid out in a regular pattern. Right. A forest of managed Al Ghaf trees.

These tree plantings provide valuable ecosystem services. These services are however critically dependent upon the use of groundwater for irrigation, which consume 10% the Emirate's water consumption.

2.3.4 Irrigation methods

A suitable irrigation system was required before afforestation could commence (Figure 2.5). Information from the early 1970's (Wood, 1975) and 1990's (Municipality of Abu Dhabi, 1990) as well as most recent data (Barari, 2014), reveal that drip irrigation was the preferred technique in the forests of Abu Dhabi. Using drippers helped in maximizing the utilization of irrigated water by reducing its loss from surface evaporation and managing salinity (Al Yamani et al. 2018). An average application of around 40 liters per tree per day was used in 1990's, and groundwater was used exclusively for irrigation at that time (Municipality of Abu Dhabi, 1990).

Today, groundwater is still the main source of irrigation water for forestry. However, given the pressures to protect remaining groundwater reserves, two other sources of irrigation water have been recently introduced. Recycled water, or Treated Sewage Effluent (TSE), was introduced into forestry in 2010. Currently 56 forests have now been supplied with TSE. Desalinated water was introduced in 2013 (Barari, 2014). Both are still being used in forestry, with plans for a rapid increase in the usage of TSE in the future. The irrigation quantity is around 40-60 liters per tree per day, except on a Friday which is an official holiday.

Environment Agency – Abu Dhabi has already been able to implement changes that have reduced groundwater water use in forests by 28% since 2015 (Al Mubarak, 2017). The Agency is committed to work closely with the Department of Municipal Affairs and Transport to ensure that forest management plans lead to further water savings (Al Mubarak, 2017).

The collective goal is to manage better the forest resources to ensure their long-term viability, whilst ensuring that groundwater reserves are protected. The main findings are listed later in this paper

An assessment of the ecosystem services provided by forests is central to managing better the forest resources.

2.4 Ecosystem Services and Forest Classification

In 2001, the United Nations sponsored a major initiative called the Millennium Ecosystem Assessment to determine the state of the world's ecosystem services and to consider the consequences of the diminution of ecosystem services as a result in the degradation of the world's ecological infrastructure. Their findings (Millennium Ecosystem Assessment 2005) classified ecosystem services into four broad, and often overlapping, types:

- *Supporting services*: Those necessary for production of the other services, such as soil formation and nutrient cycling.
- *Provisioning services*: Production of food, fuel, and fiber.
- *Regulating services*: The buffering, filtering and stabilisation of water, sand, carbon, gases, and chemicals.
- *Cultural services*: Heritage, recreation, aesthetics, and spiritual well-being.

It would be possible to carry out a detailed valuation of the ecosystem services provided by the arid forest plantations, road belts, asset forests and farm forests. However, given the urgency to reduce groundwater usage, EAD have through an internal process quickly classified the forests into 7 categories to reflect the overall value of the various forest sites.

These are:

- **Importance to wildlife**. Forest serve as a habitat for wild animals, and managed stock. There are 34 forests which have natural wildlife, and 30 of these are in the Al Dhafra region. In Abu Dhabi there are 55,000 animals from 12 species of antelopes and ungulates whose habitat is in these forests (EAD, 2017). The most common species are sand gazelle (>70%). Local species form about 92% of the total animals in the forest and they are under a protection program by EAD (EAD, 2016).

- **Importance to the environment**. In the desert environment of Abu Dhabi, arid forests play a significant role in combating desertification and reducing sand encroachment into residential areas. They also improve the soil fertility by increasing its organic matter content and they enhance the air quality by reducing fine dust content and by lowering the ambient temperature, as well as by capturing and sequestering carbon.

- **Importance to the economy**. Some 79% of the Abu Dhabi's forests is classified as being in good condition. Most of these forests are suitable for the development of future environmental tourism projects. As well, honey production from native trees such as Al Samr and Al Sidr is carried out in some forests. Production of fodder and medicinal products could be also considered.

- **Importance to infrastructure**. Many forests were planted intentionally to protect important infrastructures. The forests serve as windbreaks to protect main roads, airports, cities and residential facilities such as telecommunications facilities, gas lines, water sources and pipes, plus electricity reticulation.

- **Importance to culture and heritage**. The "Greening of the Desert" initiative is a great success story associated with the founder of UAE, Sheikh Zayed Al Nahyan. All Emirati are proud of it. All Abu Dhabi forests are considered the legacy of Sheikh Zayed Al Nahyan. But, some forests had a special value to him and are rated more highly.

- **Private Forests.** Forests owned by members of the Royal family and managed by EAD.

- **The Red Zone.** The Red Zone are those areas that have undergone significant reductions of groundwater where future supplies of groundwater are not assured. Forests in the Red Zone are more susceptible to loss of groundwater supply than those in other areas.

Environment Agency – Abu Dhabi considers this forest evaluation and classification as one of the most important steps toward achieving a high forest-management standard (EAD, 2016).

2.5 Current Actions

The EAD State of Environment report uses an assessment framework based on: Drivers; Pressures, State, Impacts, and Responses to arrive at an Outlook for its environmental themes and priority issues (EAD, 2017).

The key drivers for forestry are identified as the demand for ecosystem services, the cultural heritage of “Greening the Desert”, and land-use change. The prime pressures are groundwater depletion and salinization of soil and water. The state of the forests are generally good. The positive and negative impacts include; the carbon footprint of pumping irrigation water, groundwater use itself, carbon sequestration, and habitat provision. The responses are soil stabilization, irrigation, connection of forests with TSE, ecotourism, forest cancellation, and the development of a long-term forestry strategy based on evaluating the value of the various forest plantings.

Environment Agency – Abu Dhabi concludes that “… the outlook for forests in the Emirate of Abu Dhabi is uncertain. While they certainly have merit in terms of infrastructure protection, cultural heritage, amenity value, cultural value, and even some intrinsic value, this is at the expense of valuable water resources. With improved irrigation techniques and alternative sources of water such as TSE, it will be possible to reduce the demand for water, but how far remains to be seen” (EAD 2017).

2.5.1 Forest cancellation

In 2016, based on the 7 classification criteria listed in Section 2.4, EAD selected and cancelled 104 forests, and these covered 38,209 ha, being just 16% of the planted area. This followed an evaluation process of all forests to assess their value and consider their future sustainability. These forests were selected under the specified criteria above, using protocols agreed to by stakeholders and decision makers. The main operational activity of cancellation is that all irrigation and active tree management is stopped. The trees are left to survive on their own. Assessment of the consequences are awaited.

2.5.2 Reduction of irrigation amounts

By adopting irrigation schedules that consider the seasonality in the weather, and the idiosyncratic deciduous behaviours of the main tree species, water savings of between 30-40% should be possible with the use of groundwater for irrigation (Al Yamani et al., 2018).

The savings that will be possible, are however modest in relation to the scale of the reductions needed to protect groundwater.

2.6 Future options

The challenges ahead for managing the forests of Abu Dhabi are significant, as pressures to maintain habitat, infrastructure protection, and heritage are at odds with the pressures to reduce groundwater usage. These options will involve further cancellation of forests, strict application of the guidelines in Law 5, and increasing the usage of alternative water sources.

2.6.1 Forest Cancellation

Evaluation and assessment of the value of the various forests is likely to be an ongoing process. Decisions will need to be made in relation to any likely future cancellations of forests, or partial cancellations of parts of forests, as the inexorable pressures on groundwater mount. The goal is to achieve the right number of forests in the right place to ensure that all forests are fit-for-purpose, and use only the minimum amount of irrigation that is required to achieve that outcome. As outlined below, it is considered that if there is strict application of Law 5 on water scheduling of irrigation and the application of the minimum amount of groundwater, and if there is expanded use of TSE, then future forest cancellations can be avoided.

2.6.2 Application of Law 5

Law 5 was passed by the government of Abu Dhabi to regulate and protect groundwater. A forestry strategy prepared by EAD seeks to reduce usage of groundwater in Abu Dhabi forests mainly by using sustainable irrigation regimes that are tailored to plant needs. In 2016, the annual amount of groundwater used in Abu Dhabi forests was 188 Mm^3 and this was the base-line suggested in the Memorandum of Understanding between EAD and the Municipality in relation to the transfer of the management of the forests. The short-term target is to reduce groundwater usage to 37 Mm^3 by end of 2020. This dramatic reduction of 80% in groundwater usage in forestry will be challenging, but savings of up 50% should be possible, so the 188 Mm^3 of groundwater usage could be reduced to 94 Mm^3. Then fulfilment of the remaining gap of 57 Mm^3 would be needed through the application of TSE to achieve the target of just 37 Mm^3 of groundwater irrigation per year. It is understood that this amount of TSE is available.

Monitoring of irrigation usage at the well-head will be imperative to get the exact quantification of water consumption and to support EAD in their application of Law 5 to forestry. As the business academic Peter Drucker noted "… if you can't measure it, you can't improve it".

2.6.3 Alternative water sources

The annual water consumption of Abu Dhabi forests is estimated to be around 214 million m^3. The groundwater contribution is 82% of total consumption, and the remainder is shared equally between TSE and desalinated water (EAD, 2017). In order to minimize the pressure on groundwater, the alterative water sources are highly recommended. Environment Agency-Abu Dhabi is considering the usage of TSE to be the best solution to sustain forestry and increase their value. The use of desalinated water is costly in terms of energy, and furthermore there is the problem of brine disposal. In 2015, Abu Dhabi government started its plan by reducing the usage of desalinated water in 44 forests to bring it down to just 20 forests. On the other hand, 56 forests have been connected to TSE sources, with a plan to increase the share of TSE in forestry once the TSE reticulation networks are in place.

To meet EAD's goal for the reduction of groundwater consumption in forests to 37 Mm^3 y^{-1} by 2020, some 57 Mm^3 y^{-1} of TSE will be required.

As noted above, this 57 Mm^3 y^{-1} of TSE is considered to be available. Nonetheless, there is growing competition for this valuable waste resource. Furthermore, there needs to be reticulation systems built to connect the TSE supply with exiting irrigation distribution systems. Thankfully, however, the chemical composition of groundwater and TSE is not the same, for TSE has a much lower salinity ($\approx$ 0.5 dS m^{-1}) than groundwater ($\approx$ 5-10 dS m^{-1}). So schedules for TSE irrigation can use less water, as there is a positive plant response to the lower salinity TSE, and as well there is no requirement for a salt leaching fraction with TSE.

As noted, it should be possible to reduce the 188 Mm^3 y^{-1} of groundwater irrigation of forests to 94 Mm^3 y^{-1} by sustainable scheduling of irrigation. However, for a future scenario, where all irrigation of forests by groundwater might be prohibited, then this 94 Mm^3 y^{-1} would need to be entirely sourced from TSE.

2.7 Conclusions

The arid-forests of Abu Dhabi deliver valuable ecosystem services, and their continued existence is important. Yet, their continuation and functioning are critically dependent on a dwindling supply of groundwater that is becoming ever more saline. There are three emerging trends and actions that are seeking to sustain the arid forests of Abu Dhabi: forest cancellation, reduced groundwater irrigation, and replacement of groundwater by TSE for irrigation. Diligent application of the reduced groundwater irrigation schedules in Law 5, and expansion of the reticulation systems to take advantage of the growing volumes of TSE, should in sum be sufficient to reduce groundwater consumption by forests from today's 188 $Mm^3\ y^{-1}$, down to EAD's stated goal of 37 $Mm^3\ y^{-1}$ by the end of 2020.

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CHAPTER
3 Literature Review

As described in Chapter 2, there are 20 million trees covering 242,000 hectares in Abu Dhabi which consume 214 Mm^3 of groundwater for irrigation every year. Here the physiology of four of the major native species is described (Table 2.1, Chapter 2). Next, the current irrigation-management practices in the forests of Abu Dhabi are described. Finally, there is a brief description and review of the tools and techniques that were used to achieve the Objectives of this thesis (Section 3.1, Chapter1)

3.1 The Physiology and Phenology of Key Native Desert Species of the UAE

3.1.1 Al Ghaf

Al Ghaf is the local Arabic name for the *Prosopis cineraria* tree (Khan, 1999). It is an indigenous species of the Arabian Desert. Al Ghaf is a drought-tolerant evergreen tree that can tolerate the harsh climate of the desert environment. It also can withstand high salinity levels up to 4,500 ppm as reported by Dr Mohammed Ali Khan in his detailed study about indigenous trees of the UAE in 1999. However, in the current situation many Al Ghaf trees can survive even when irrigated with high levels of salinities. Nevertheless, the high level of salinity does affect their natural growth, health and colour.

Al Ghaf trees can be found growing naturally in the Abu Dhabi desert, either as individuals, or in small clusters. As well they are grown in large numbers in managed forests. The natural Al Ghaf trees depend mainly on the availability of groundwater, besides any scarce rainfall. Thus their roots can grow as deep as 30 meters to access groundwater. This is not the case with Al Ghaf in managed forests. Here they are irrigated mainly with pumped groundwater, and their roots are not deep enough to reach deep aquifers. This means their survival now depends on irrigation.

3.1.1.1 General description

Al Ghaf tree has a straight unbranched trunk for the first few meters before the branching starts. Some ungrazed trees in soft sandy soil can take the shape of a pyramid, as with the trees in the forest experiment near Madinat Zayed. Grazing and pruning can affect this shape and so make it have a circular, or cylindrical shape.

3.1.1.2 Leaf description

The leaves of the Al Ghaf tree are feathery, binnate, and tiny. The leaves are about one centimeter long, and arranged on central stalks in 7 to 16 pairs. Their colour of the leaves is pale green (Figure 3.1). The size of a leaf varies depending on the availability of water to the plant. The leaflets drop when there is no enough water available to maintain leaf water potential.

Figure 3.1. The Al Ghaf trees in the experimental plot near Madinat Zayed. The inset shows the leaf form and the nature of the flowers.

3.1.1.3 Flower and Fruit description

Al Ghaf is a monoecious tree. The flowers are yellow in colour, and their colour becomes brighter in areas with a higher quality of water. The flowers grow as spikes (Figure 3.1). The flowering season is during autumn (October-November) as we have noticed on field. The fruit is a slightly curved pod, varying in colour from brown to yellow.

3.1.2 Sidr

Sidr is the local Arabic name for the *Ziziphus spina-christi* tree (Khan, 1999). It is a widely distributed tree which can be found naturally growing and as a cultivated forest. The reason behind its wide range distribution in UAE, is because it can grow well in sandy, gravelly or silty soils across the wadis and plains. Also, it is tolerant to harsh conditions such as salt, drought, desert climate and heavy grazing.

3.1.2.1 General description

Sidr grows up to approximately 10 meters or so. The trunk maybe undivided, or divided near the base. The stem is multi-branched. Spines occur in opposite pairs, one long and straight up to 15 mm, the other is shorter and recurved at the base of leaf stalks (Figure 3.2).

3.1.2.2 Leaf description

Sidr is an evergreen tree but once a year it loses its leaves during summer as can be seen in Figure 3.3. The leaf is dark green in colour, with three clean veins, and it measures up to 8 cm. The leaves are coriaceous and their tips are pointed or obtuse.

Figure 3.2. The Sidr trees in the experimental plot near Madinat Zayed. The inset shows the leaf form and the nature of the flowers.

Figure 3.3. The Sidr tree in full leaf (left) and following defoliation of during early summer deciduous leaf fall (right).

3.1.2.3 Flower and Fruit description

Sidr flowers twice a year, in summer and in winter. Flowering during summer is more successful, as stated by Dr Mohammed in his book. Sidr flowers are monoecious, light green or creamy in colour, star-shaped and small in size about less than 1 cm in diameter.

Sidr fruits in forests are generally found to be round in shape with a short stalk. The common colour of the ripened fruit is orange.

3.1.3 Samr

Samr is the local Arabic name for *Acacia tortilis* (Khan, 1999). It is probably the most abundant wild tree in UAE. It is long lived, and distributed on silty, clayey and gravelly soils. It cannot grow naturally in coastal areas, because Al Samr is only mildly salt-tolerant.

3.1.3.1 General Description

Al Samr tree is a multi-stemmed halophytic xerophyte. Multiple branches emanate from the tree's base at the soil surface and are without leaves for the first metre, or so (Figure 3.4). It is the spiniest tree in UAE. The overall shape of this tree is umbrella-like. The bark is even and not cracked as for the Al Ghaf tree. The roots are so strong that they can break the hard rocks in which they grow.

Figure 3.4 The Samr trees in the experimental plot near Madinat Zayed.

3.1.3.2 Leaf Description

The leaves are small and bipinnate with up to 6 pinnae, and with 6-10 leaflets on each pinna (**Figure 3.5**). The trees are deciduous with a major leaf-fall in spring followed by flowering into early summer.

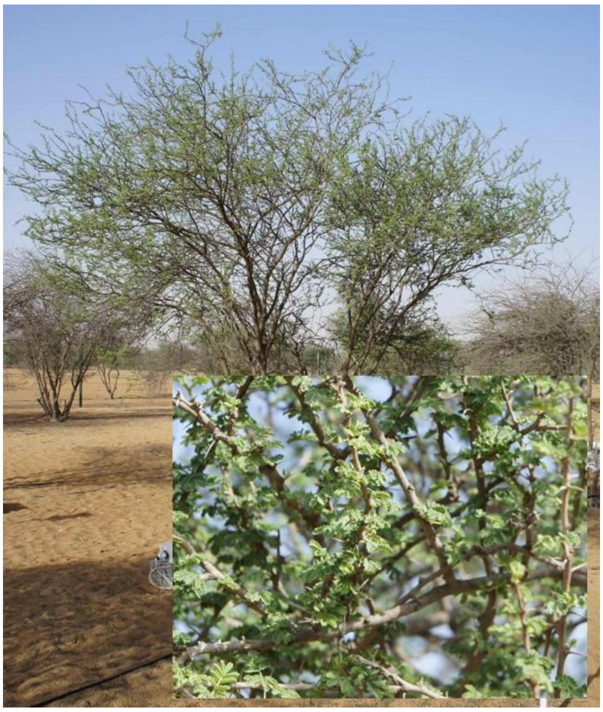

Figure 3.5 The Samr trees in the experimental plot near Madinat Zayed. The inset shows the leaf form and the long spines.

3.1.3.3 Flower and Fruit Description

Al Samr tree has small flowers in creamy-white or yellowish colour. Flowering starts in spring season and continues until early summer. The fruits are about 9 cm in length, they are spirally twisted and have yellow to brown colour.

3.1.4 Arak

Al Arak is the local Arabic name for *Salvadora persica* (Khan, 1999). It is also known as toothbrush plant. It is commonly distributed in sandy areas, as well as in lower slopes of the mountains. It can withstand high winds and salinity and that is why it is used as windbreak. It is also used as desert sand barrier and ornamental hedge.

The Arak tree possesses a tortuous pattern of many small stems which would make application of the CHPM impossible (Figure 3.6).

3.1.4.1 General Description

Arak can be found as either as an overgrown shrub, or as straggling bush up to 10 m high. It can even be found as a small tree (Figure 3.6).

3.1.4.2 Leaf Description

Arak leaves have a pale green or blue green colour. They are simple, opposite and glabrous. They have short stalks with either acute or obtuse tips.

3.1.4.3 Flower and Fruit Description

The flowers are minute, 3mm, aromatic and creamy- green with a short pedicel. Arak trees look pale green in colour during the flowering season.

The Arak fruit is a spherical berry, small in size about 3-6 mm, reddish or pinkish in colour. Arak fruits are edible.

Figure 3.6. An Arak tree in the Barari-managed Khub Al Dhas forest near Madinat Zayed. The inset shows the complex and twisted nature of the branching of the trunks.

3.2 Water Use and Irrigation in Forests

The management of the irrigation of arid forests is now described.

3.2.1 Current practices and the basis for irrigation amounts and timings

The establishment of arid forests in Abu Dhabi was based on the setup of suitable irrigation systems (Figure 2.5). These steps to achieve this were summarized early in the 1990s by Abu Dhabi Municipalities in their UAE Desert book (Municipality , Abu Dhabi, 1990). It was mentioned there that the drip-irrigation technique was preferred in forestry, usually by using 1 or 2 drippers under each tree so as to provide an average quantity of 10 gallons (or 38 litres) per tree per day (Municipality , Abu Dhabi, 1990). Groundwater was the only source for irrigation water in forestry at that time. (Municipality , Abu Dhabi, 1990). Different types of wells and pipelines were used, and these sometimes covered long distances to reach a good sources of groundwater. This continued through until 2009 (Barari, 2014)

Current irrigation practices have not changed that much. The drip irrigation technique is still preferred and it is applied for arid-forest trees, but usually by using only one dripper. Different types of drippers have, from time to time, been experimented with to apply the best and most suitable wetting on a larger scale so as to maintain water use efficiency. An average of 8 litres per day, with no irrigation on the Holy Day of Friday, is provided for each tree, through 6 hours of operation throughout all seasons. The quantity of irrigated water is calculated and controlled through pressure controlled drippers via a manual irrigation system. Of course many challenges remain in trying to provide each tree with the planned amount of water. Huge operational and maintenance efforts are required when considering alternatives due to groundwater depletion. This will influence the schedule of irrigation.

Groundwater is still the main source of irrigation in forestry. However, there are two other resources which have been used recently. Recycled water, or Treated Sewage Effluent (TSE), was introduced into forestry in 2010. Desalinated water was introduced in 2013 (Barari, 2014). Both are still been used in forestry, with plans for a rapid increase in the usage of TSE in future. An 80% reduction in groundwater use has been proposed (EAD, 2016b).

The total amount of irrigation water consumed by forestry under Barari contracts for all the regions in 2014 was reported to be approximately 148 million cubic meters. This has increased, since it was last reported in 2012/13, by about more than 8 million cubic meters. And it was expected to increase in 2015 due to an increase in the number of forests which are in the process of being transferred to Barari contracts (Barari, 2014). On the other hand, there are number of initiatives and future plans to reduce the amount of ground water used by forestry through following better management practices, as well as by the replacement, or removal, of certain types of tree species which are known to have high water consumption (EAD, 2016b).

3.3 Measuring Tree Water Use

There are many techniques available for measuring tree water-use (Kirkham, 2014). Each is fit for its specific purpose. These include using resolution of the water balance, or meteorological approaches via the Bowen Ratio method, or eddy covariance. Meteorological approaches require a uniform upwind surface, with a fetch-height ratio exceeding 30. In the experimental set-up used here with TSE applied to individual trees, a technique such as the Bowen-Ratio (Hou et al. 2010) would not be feasible. The paper by Hou et al. (2010) is a rare case of a forestry study in an extremely dry region, but their Bowen-Ratio methodology is inappropriate here, as it would not be possible to monitor ET_c from just a short line of six trees irrigated with TSE . Zait et al. (2018) carried out a detailed pot trial on the acclimation of xerophytic *Ziziphus spina-christi* to drought, salinity and temperature. This research revealed new physiological knowledge about the function of Sidr, and showed what the implications of climate change might be. However, despite this new physiological understanding there were no measurements of whole-tree transpiration, as would be required here for redesigning irrigation practices in the field. Heat-tracer techniques are another method for measuring tree transpiration, and include the heat balance approach, the Granier method, and the heat-pulse technique. Heat-based methods offer promise for understanding water use patterns and dynamics of individual trees, and by replication, of forest transpiration.

3.3.1 Heat Methods

There are several available methods of measuring plant water use that trace the ascent of sap through the vascular system of the plant. These methods are based on different principles such as electricity, magneto-hydrodynamic, nuclear magnetic resonance and thermodynamics. The latter one is commercially available in various forms, and has been used widely since its first use in Amazonian lianas by Huber in the 1930's (Huber, 1932). Five main methods based on the thermodynamics of sap flow have been developed, and they have been applied in different types of trees. These are

- The Compensation Heat Pulse Velocity method CHPV (Marshall, 1958; Green & Clothier, 1988),
- The Trunk Segment Heat Balance THB; Cermak (1995)
- The Stem Heat Balance SHB (Sakuratani 1981),
- The Heat Dissipation Approach HD; Granier (1985),
- The Heat Field Deformation Method HFD (Nadezhdina et al. 1998)

All of these five methods use heat as a tracer to measure the rate of sap flow in trees. Three of them: CHPV, THB and HD have been widely used in forests. Studies of water use in forests have been conducted in alpine beech forests in New Zealand (Swanson et al. 1979), temperate forests in France (Granier, 1985), semi-arid Eucalyptus forests in Western Australia (Burgess et al. 2001), semi-arid Grevillea forests in Kenya (Smith et al. 2002), and semi-arid poplar plantations in China (Wang et al. 2018). To the best of my knowledge, there are no published reports of field-use of heat pulse techniques in arid-forest species in a hyper-arid environment.

The CHPV method has been widely used, and equipment is commercially available from Tranzflo NZ (www.tranzflo.co.nz). It is based on thermodynamic measurements of heat to infer sap flow, and relies on quantifying the heat-pulse velocity and inferring the sap velocity in order to obtain total transpiration flow rates.

A diagrammatic representation of this method is shown in Figure 3.7.

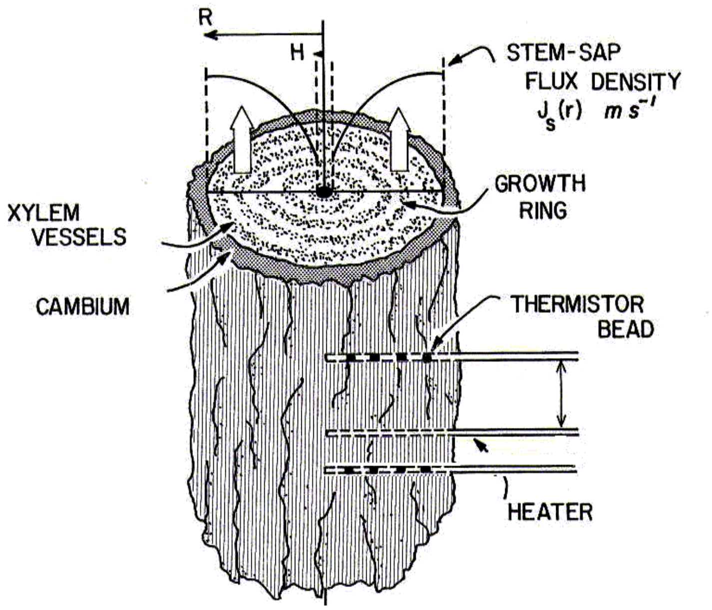

Figure 3.7. The set-up of the Compensation Heat Pulse Velocity (CHPV) method.

With the CHPV method, temperature sensors are placed asymmetrically above and below a heater needle to measure the convectively induced flow by the ascending sap of heat. From this heat velocity a sap-flux density profile through the trunk can be calculated. Integration of this profile provides the volume flux of transpiration in L/hr.

3.4 Conclusions

A more detailed description of the application of the compensation heat pulse method for Al Ghaf is given in Chapter 4. These tools and techniques were then used to measure the water use of Al Sidr (Chapter 5), and Al Samr (Chapter 7) irrigated with GW, as well as these trees irrigated with TSE (Chapters 6 and 7).

3.5 References

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Chapter 4

4 Sap Flow in Al Ghaf Trees Growing in the Hyper-Arid Desert of Abu Dhabi

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Chapter 4 presents the details of the results from the use of the heat-pulse method to measure actual water use by Al Ghaf trees. The same technique was then used to measure the tree water use in Al Sidr and Al Samr as well, and I will illustrate those results in Chapters 5, 6 and 7. The Ghaf trees were irrigated with saline groundwater of about 8-10 dS m^{-1}. Sap flow data of tree water use, *ET*c, were compared with the reference evapotranspiration (*ET*o). It was found that Al Ghaf trees use less water during summer than expected, and thus the diurnal pattern of sap flow is less than the *ET*o, as a result of stomatal control. Al Ghaf trees followed the same seasonal pattern during the three experimental years, which supported this adaptive response of Al Ghaf during summer. The heat-pulse technique proved its ability to realise good data on the trees' water use in response to the prevailing microclimate. The technique worked well on these desert species and in challenging hyper-arid conditions of the Abu Dhabi desert.

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4.1 Abstract

The arid forests of Abu Dhabi provide a variety of valuable provisioning, regulating and cultural ecosystem services. However, given the hyper-arid environment, they also require irrigation for the trees' survival. Our research goal here is to establish how much water the trees use when irrigated by groundwater (GW). We are carrying out experiments at Madinat Zayed in the western desert on a range of forest species. We report results from Al Ghaf trees (*Prosopis cineraria)* planted on a 7m x 7m grid. Tree water use is measured using the compensation heat-pulse method (CHPM) with sensors implanted into the trunks of four trees. Irrigation is supplied via in-line drippers (two per tree) using saline groundwater with an electrical conductivity (*EC*) of about 8-10 dS m^{-1}. Data are presented to illustrate the daily patterns of tree water use in response to the prevailing microclimate. During the cooler times of the year, when maximum air temperatures (Tmax ~ 30° C) and vapour pressure deficits (VPD ~ 3 kPa) are lower, the diurnal pattern of sap flow follows the potential evaporative demand (*ET*o). During the hottest times of the year, when Tmax is approaching 50° C and VPD > 6 kPa, we observe a mid-day depression of sap flow relative to *ET*o. Stomatal control appears to be an important adaptive response used by Al Ghaf trees to reduce their water loss during periods of high evaporative demand.

4.2 Introduction

Managed forests were established across the Emirate of Abu Dhabi more than 35 years ago. Today these arid forests provide valuable ecosystem services with benefits to both the environment and the community. The total area planted in forestry is 102,852 hectares and this comprises more than 19 million trees (EAD, 2016). Each of the managed forests are reliant on irrigation for the trees' survival. The source of irrigation water is predominantly from groundwater (GW) which is a non-renewable resource. Over-extraction of groundwater currently threatens the sustainability of agricultural and forest production which, when combined, account for about 95% of the total groundwater usage.

The Environment Agency – Abu Dhabi (EAD) has been mandated to protect and enhance groundwater resources in the Emirate. They recently passed Law 5 to restrict groundwater takes to conserve groundwater. To support their decision-making process, EAD are conducting research to quantify the water use and irrigation demands of a range of forest species including Al Ghaf (Prosopis cineraria) which is an important indigenous species of the Arabian Desert.

This species is a drought-tolerant, evergreen, leguminous tree which can tolerate the harsh climate of the desert environment and can survive even when irrigated with highly saline groundwater.

The main objective of our research is to quantify the water consumption and irrigation needs of these arid-forest species. The results will enable the development of strategies for improving the use of saline water in agriculture and address the institutional and regulatory aspects of agricultural water management through Law 5.

4.3 Material and Methods

4.3.1 Study area

The experimental site is located in the Khub al Dahs Forest (23.51º N, 53.75º E) near Madinat Zayed in the western desert of Abu Dhabi. The climate of Abu Dhabi is hyper-arid, with very high summer temperatures, annual rainfall of less than 100 mm, and a potential evapotranspiration loss of around 2000 mm, on average. The soil is classified as a Typic Torripsamment, mixed, hyperthermic (Soil AD158) (EAD, 2009). This is a deep, sandy soil with mixed mineralogy. It is widely distributed across Abu Dhabi with more than 50% of the Emirate having this soil type.

A research plot was set up in December, 2014, comprising twelve Al Ghaf trees. Six trees were irrigated with groundwater (GW), and another six were irrigated with treated sewage effluent (TSE). The GW has a salinity of around 8-10 dS/m, whereas the TSE has a salinity of less than 1 dS/m. An automatic irrigation system was installed to control and manage the irrigation using water sourced from two large tanks (22,730 litres) filled with GW or TSE. Irrigation is applied daily using two pressure-compensated drippers (4 L/h) per tree. Flow meters (Sensus 620, USA) are used to record the irrigation volumes.

4.3.2 Sap flow data

The compensation heat-pulse method (CHPM) was used to provide continuous monitoring of the trees' transpiration (Swanson & Whitfield, 1981; Green et al, 2003). Temperature probes were installed radially into the tree trunk, using a standard spacing of 5 mm upstream and 10 mm downstream from the linear heater probe. Each probe had four temperature sensors (model HP4TC, Tranzflo NZ Ltd, Palmerston North, NZ) located at depths of 10, 25, 40 and 55 mm below the cambium. Two sets of probes were installed in each of the 4 trees. A Campbell data logger (CR1000, Campbell Scientific, Logan, Utah, USA) was used to measure the time taken to achieve temperature equality between sensors located above and below the heater (t_Z, s) following the application of a 4.0 s heat pulse (30W).

Sap flow (L/h) was calculated from measurements of t_Z using the approach outlined by Green et al. (2003, 2009). These calculations included a correction for the effect of wounding. A wound diameter of 2.8 mm was used for the 2.0 mm diameter drill holes. Sap velocity was then deduced from the wound-corrected, heat-pulse velocity and the measured volumetric fractions of wood and water within the sapwood. Transpiration (T, L d^{-1}) was determined by multiplying sap velocity by the conducting wood area using the simple annulus approach suggested by Hatton, Catchpole, and Vertessy (1990). Data were collected at 30 min intervals starting from December 2014 through until December 2017.

4.3.3 Climate data

A weather station was installed in the Khub Al Dahs forest to record global shortwave radiation (LiCor Li-190), air temperature and relative humidity (Vaisala HMP 45C), wind speed at 5m (Maximum 3-cup anemometer), and rainfall (Pronamic 101). These weather data were used to estimate hourly and daily values of the reference evaporation (ET_o, mm hr^{-1}, or mm d^{-1}) using the standard approach of FAO-56 (Allen, 1998). The transpiration of the trees (ET_C, mm hr^{-1}, or mm d^{-1}) is then related to ET_O through the dimensionless crop-factor, K_C, which is calculated from the equation $ET_C = K_C \cdot ET_O$.

4.4 Results and Discussion

Here we present a selection of data (March 2016 and July 2016) from our three-year field study. Average climate data for these two months are summarized in Table 4.1. Corresponding values of daily irrigation volumes and daily tree water use are summarized in Table 2.

Table 4.1. Monthly climate data from Madinat Zayed. Here *R*g is global shortwave radiation, *T*max and *T*min are the maximum and minimum air temperatures, VPD is the vapour pressure deficit and W is the wind speed.

	Rg, MJ/m2/d	Tmax, °C	Tmin, °C	VPD, kPa	W, m/s
March					
Average	18.8	26.1	12.6	1.3	3.2
std dev	4.1	3.6	3.2	0.5	1
July					
Average	26	45	30.1	4.5	4.1
std dev	1.2	2.3	2.3	0.9	1.2

Table 4.2. A summary of daily irrigation volumes (IR) and the tree water use (*T*) of Al Ghaf trees at Madinat Zayed. The tree spacing is 7x7 m and the effective ground area is A=49 m2. The daily potential evaporation (*ET*o) is calculated using the FAO-56 Penman-Monteith model (Allen et al, 998). The crop factor (*K*c) = *ET*c/*ET*o and the crop transpiration (*ET*c) = *T*/*A*.

	IR, L/tree/d	T, L/tree/day	ETc, mm/d	ETo, mm/d	Kc
March					
Average	78	20.1	0.41	3.9	0.10
Std dev	29	5.7	0.12	1.0	0.03
July					
Average	63	35.6	0.73	6.4	0.11
Std dev	6	4.8	0.1	0.7	0.02

Firstly, we look at the diurnal patterns of sap flux density (SFD, cm/h) measured at the four radial depths below the cambium (Figures 4.1 & 4.2). These figures reveal the profiles of SFD that are integrated over the conducting sapwood area to provide an estimate of the tree's total volumetric sap flow, *T* (L/h) (Figures 4.3-4.5).

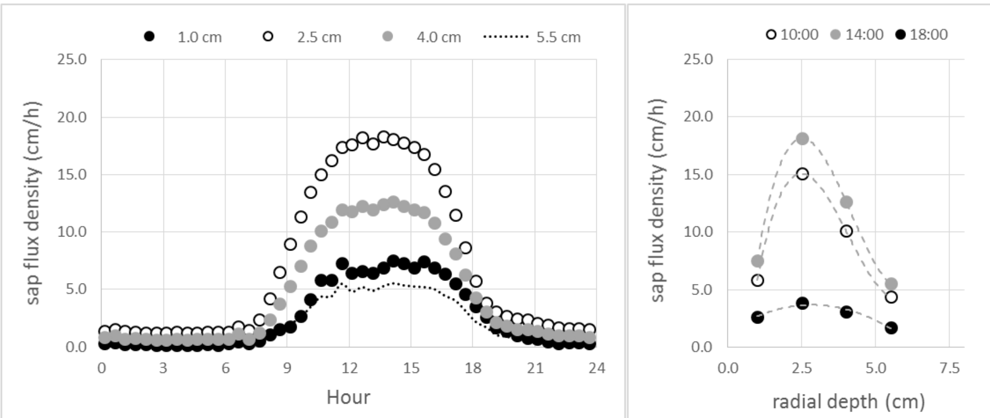

Figure 4.1. The left panel shows the diurnal pattern of sap flux density measured at four radial depths in the trunk of Al Ghaf trees from Khub Al Dhas forest, near Madinat Zayed, Abu Dhabi. The right panel shows the corresponding profile of sap flux density at three times of the day: mid-morning (10:00 h), mid-afternoon (14:00 h) and late afternoon (18:00 h). Each value is the average from four trees, as measured during the month of March.

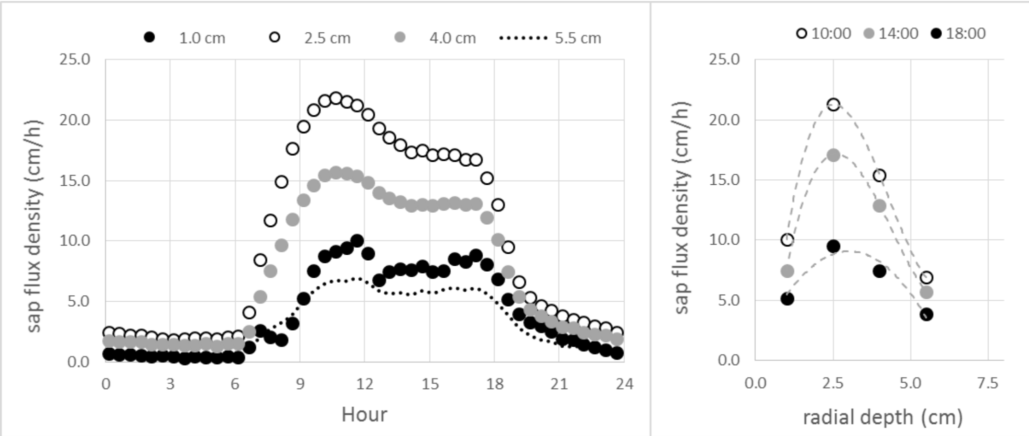

Figure 4.2. Same as Fig. 1, as measured during the month of July, 2016.

For the month of March (spring time), the diurnal pattern of SFD is quite symmetrical with peak fluxes occurring a few hours after mid-day (Figure 4.1). The SFDs during the mid-afternoon are slightly higher than during the mid-morning. The highest SFD was only about 18 cm/h, and this was observed at a radial depth of 2.5 mm below the cambium. Sap flow declines beyond the depth of 5.5 cm even during the hottest part of the day. In hindsight, we could have chosen slightly long sensors for these trees, but that would have made very little difference to the estimate of total volumetric flow, because of the radius-squared effect on the integration procedure. Very little sap flow was occurring after dark (1800 h) and this flow does not make a large contribution to the tree's daily water use (Figures 4.1 & 4.3). There is generally a very good correspondence between the diurnal pattern of sap flow and the corresponding pattern of ET_O (Figure 4.3).

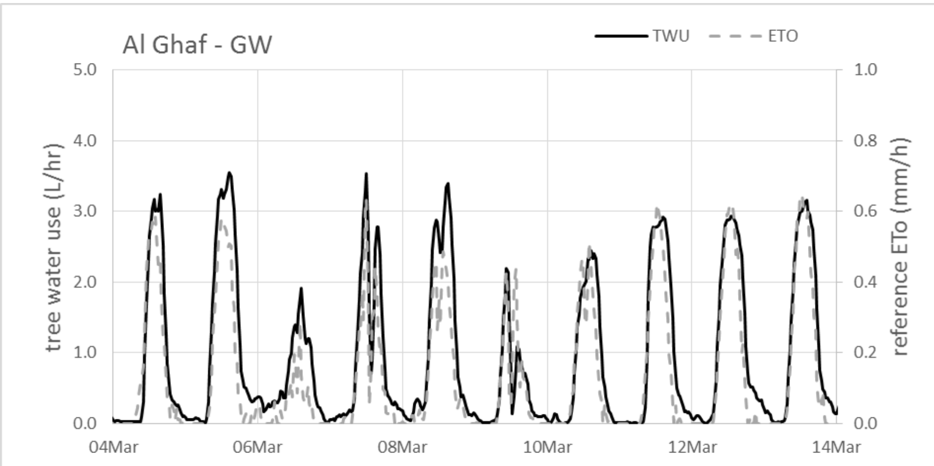

Figure 4.3. The black line shows the diurnal pattern of tree water use in Al Ghaf trees (n=4) at Khub Al Dhas forest near Madinat Zayed, Abu Dhabi, as determined from sap flow measurements. The broken line shows the corresponding value of the potential evapotranspiration (*ET*o, mm/h), as calculated using the FAO-56 Penman-Monteith

model (Allen et al, 1998). A total of 100 mm of rainfall was recorded between 6th and 10th of March, 2016. The average daily irrigation was 78.9 L/d/tree.

A large rainfall event occurred over the few days between March 6-10, 2016. This rainfall supressed the tree's water use, as expected, because of the lower evaporative demands on the cooler, cloudier days, and the leaves themselves would have been wet. Thereafter, the diurnal pattern of SFD essentially tracked the corresponding pattern of ET_O. Somewhat surprisingly, we did not observe large changes in tree water use following this rainfall (Figure 4.3). This result suggest the trees, in March 2016, were probably getting enough water from the supplemental irrigation.

In contrast, during the month of June-July 2016 (mid-summer) the diurnal pattern of SFD is no longer symmetrical (Figures 4.2 & 4.4). Peak flows now occur during mid-morning, around 1000 hours. There is a gradual decline in SFD throughout the afternoon, despite the increases in air temperature and VPD. Sap flow now also continues for several hours after dark, albeit at a very low rate and which becomes barely detectable beyond mid-night using CHPV method (Figure 4.4).

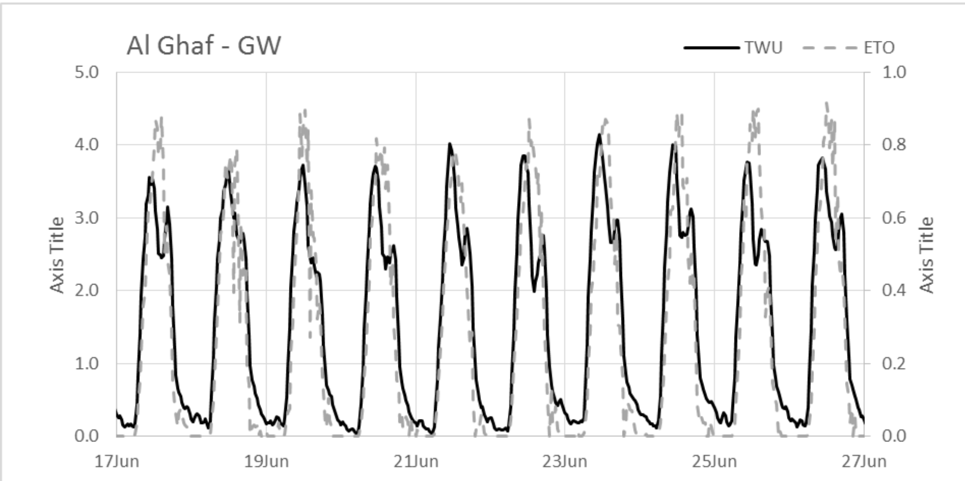

Figure 4.4. Same as Fig. 4.3, during the month of June, 2016. The average daily irrigation was 63.5 L/d/tree.

During July 2016 the trees were being irrigated at 63 L/day, on average, via two drippers that wetted only a very small surface area (about a radius of 20 cm) for 6-7 hours of the day, beginning at 0800 hours. The apparent suppression of sap flow during the mid-afternoon periods would indicate the trees were either becoming water stressed, due to an inadequate amount of readily-available water in the root zone soil, or they were exhibiting stomatal closure due to the elevated VPDs around 4.5 kPa during mid-summer (Table 4.2).

The following year (2017) the same trees received almost twice as much irrigation during June (110.4 L/d/ per tree). The VPDs were similar, yet we did not observe a suppression in sap flow during the afternoon. The trees responded to the increased irrigation volumes, exhibiting less-noticeable suppression of sap flow during the middle part of the day, and much larger nocturnal sap flows, even on nights when the evaporative demands were small (Figure 4.5).

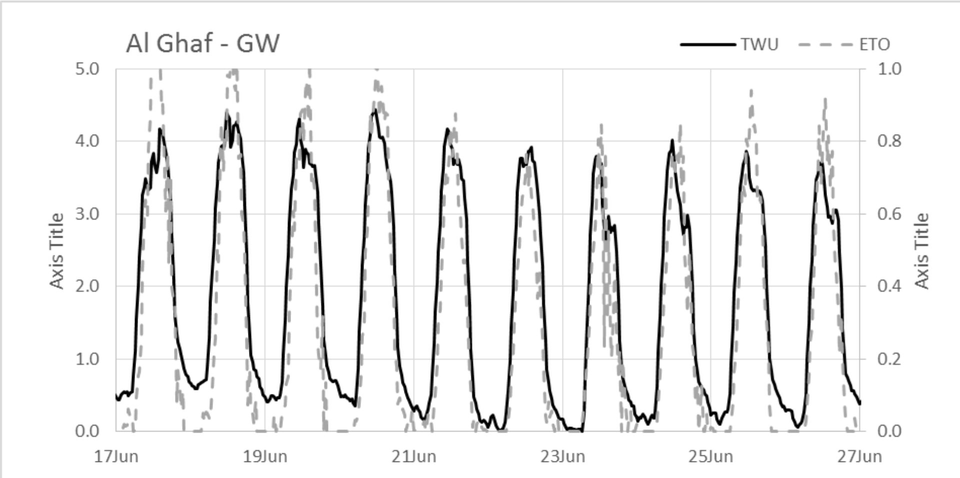

Figure 4.5. Same as Fig. 4.3, during the month of June, 2017. The average daily irrigation was set at 110.4 L/d/tree.

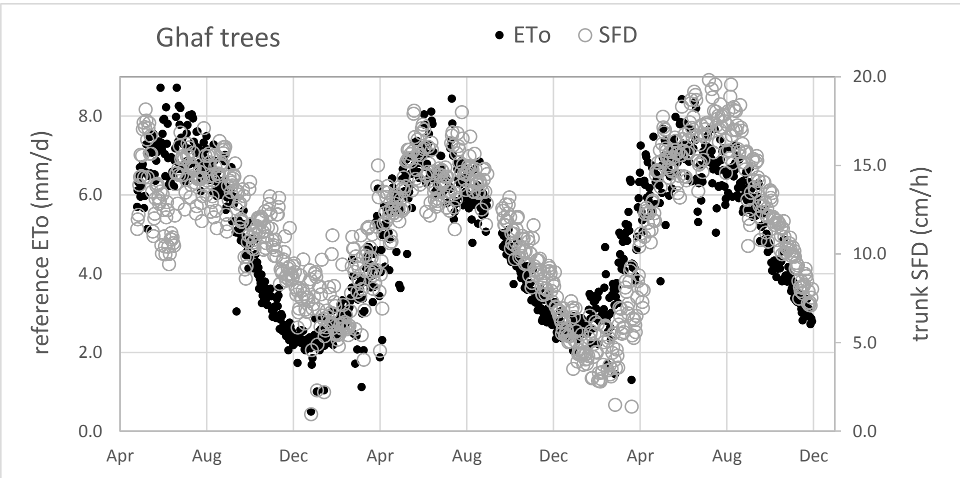

Figure 4.6. The black markers represents the daily pattern of the potential evapotranspiration (*ET*o, mm d-1), as calculated using the FAO-56 Penman-Monteith model (Allen et al, 1998). The grey markers represent average trunk sap flux density, as calculated from the tree's total daily sap flow (*T*, L d^{-1}) divided by the corresponding trunk cross-sectional area (*A*, cm^2) which ranged between 106 and 256 cm^2. For these calculations, *T* has been rescaled based on a 12 hour day.

4.5 Conclusion

The arid forests in the hyper-arid deserts of Abu Dhabi require irrigation. It seems there is a choice to make. Either, apply less irrigation during summer which will keep the trees alive, but their transpiration will be supressed and their productivity will also be curtailed; or conversely, apply more water to the trees, and even wet a larger rooted volume, which could help the trees to flourish better if that were sought. However, the implementation of Law 5 will be about applying the minimum amount of water to achieve the desired outcome of a range of ecosystem services. One can see this elevated water-use in the results of Fig 4.6. Focussing on just the June period, in the first two years only half as much irrigation water was applied as compared with the third season of our monitoring, and tree transpiration was about 20% lower. Stomatal control would appear to be an important adaptive response used by Al Ghaf trees to reduce their water loss during periods of high evaporative demand.

4.6 References

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CHAPTER 5

5 Water Use of Al Ghaf (*Prosopis cineraria*) and Al Sidr (*Ziziphus spina-christi*) Forests Irrigated with Saline Groundwater in the Hyper-Arid Deserts of Abu Dhabi

By extension of the analyses detailed in Chapter 4, the compensation heat-pulse technique (CHPM) was also used to measure water use or the actual evapotranspiration of Al Sidr, which is another native tree species. The conditions of the experiment were the same, and the Sidr trees were also irrigated with saline groundwater. Here in this chapter, I first give more details about the experimental sites in terms of soil, climate, irrigation water, and tree species. The CHPV method was used to measure sap flow to quantify tree water use of Al Ghaf and Al Sidr on a daily basis for almost 2.5 years. The results showed that the seasonal pattern of ET_o for the two species was different, and thus their crop factors, K_c, differed. Here I also provide recommendations on a new irrigation schedule which includes a 25% factor of safety, and a 25% salt-leaching fraction when groundwater is used for irrigation. These recommendations support Law 5, and would enable a 30% reduction on current practice for irrigation of Al Ghaf trees, and a 40% reduction for Al Sidr trees.

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5.1 Abstract

The arid forests of Abu Dhabi provide a variety of valuable provisioning, regulating and cultural ecosystem services. They require irrigating. And groundwater is the source. About 95 % of groundwater consumption is for agriculture and forestry. Over-extraction threatens groundwater resources. The Government of Abu Dhabi recently passed Law 5 to restrict groundwater abstraction. We have determined the minimum allocation required for the irrigation of two tree species. We carried out experiments at Madinat Zayed in the western desert on two arid-forest species: Al Ghaf (*Prosopis cineraria*) and Al Sidr (*Ziziphus spina-christi*), both planted on a 7m x 7m grid. We measured the actual evapotranspiration (*ET*c) using heat-pulse equipment in the trees. Saline groundwater with an electrical conductivity of about 8–10 dS m^{-1} was used for irrigation. Current practice is to drip irrigate with 60 L d^{-1}. Both species displayed distinct, and different, summer 'deciduous behaviours' that determine their seasonal pattern of *ET*c. A single crop-factor approach, using *ET*c predicted from *K*c.*ET*o, where *K*c is the crop factor and *ET*o is the reference evaporation, would not provide appropriate irrigation allocations. From our hourly measurements of *ET*c, made over 3 years, we quantified the seasonal pattern in *K*c. For Al Ghaf, *K*c ranged from 0.1 during February–July, to 0.15 in November–December; for the Sidr, *K*c was at a minimum of 0.06 in May, and rose to 0.16 in December. Daily irrigation requirements were provided for Law 5. With a 25% factor-of-safety, and a 25% salt-leaching requirement, irrigation requirements for Al Ghaf ranged from 24.4 L d^{-1} in January to 52.8 L d^{-1} in July. For Al Sidr the range was from 33.8 L d^{-1} in April to 53.5 L d^{-1} in September. These are a 40% saving on current practice.

5.2 Introduction

Groundwater (GW) is the main natural water-resource in Abu Dhabi. It is mostly a non-renewable resource (Murad et al., 2007; Al Mulla 2011). Groundwater has been extensively extracted to meet Abu Dhabi's water needs for various purposes. About 95 % of the total groundwater consumption is used by agriculture and forestry (EAD, 2016b). Over-extraction threatens groundwater sustainability. Abu Dhabi seeks to meet the increased demands for water and avoid further deterioration of groundwater quantity and quality (Murad, 2010; Dawoud, 2011). Environment Agency – Abu Dhabi (EAD) is the government entity mandated to protect and enhance groundwater resources in the Emirate. Their target by 2020 is to reduce the total volume of groundwater extracted annually from 2.198 Mm^3 to 1.82 Mm^3 (EAD, 2016b). The arid forests of Abu Dhabi consume some 11% of the Emirate's groundwater. Arid-forest tree species are also used in landscape amenity-plantings and these use some 14% of Abu Dhabi's groundwater.

The arid forest classification proposed by UNESCO divides arid zones into four categories, based on the ratio of the annual precipitation (P) to the annual potential evapotranspiration (PET). These are Hyper Arid Zones (P/PET ratio <0.03), Arid Zones (0.03<P/PET<0.2), Semi-arid zones (0.2<P/PET<0.5) and Semi-humid zones (0.5<P/PET<0.75) (De Pauw, Gobel, & Adam, 2000). Abu Dhabi is hyper-arid, with annual P at around 50 mm, and PET at 2000 mm.

All of the Abu Dhabi arid forests were established more than 35 years ago, and today they provide valuable ecosystem services and benefits to the environment and community. These roles and services provided by Abu Dhabi's arid forests include (FAO, 2010):

- Biodiversity Conservation
- Habitat provision
- Soil stabilization
- Erosion and desertification control
- Climate change mitigation and adaptation
- Providing ecosystem goods such as fodder, wood, herbs and medicines.

Over the last decade, EAD has managed the majority of government forests, along with some private forests in the Emirate of Abu Dhabi. Up until recently, the total planted area is 102,852 hectares and comprises more than 19 million trees (EAD, 2016a).

5.2.1 Groundwater protection and regulation

Unsustainable use of groundwater to irrigate these forests is one of the significant environmental challenges facing Abu Dhabi. It requires urgent intervention, and therefore EAD has made significant decisions. The Agency selected and cancelled some 105 forests in 2016. This is around one third of the number of forest sites and all operational activities, including irrigation, have been stopped in these forests.

Another key strategy for addressing Abu Dhabi's groundwater sustainability includes regulating for the responsible use of the remaining groundwater. In 2017, during the

International Water Summit (IWS), EAD announced the new Law No. 5, the Groundwater Organisation Law for Abu Dhabi Emirate, passed by HH Sheikh Khalifa bin Zayed Al Nahyan, the President of the United Arab Emirates. This law states that the Abu Dhabi Government owns the groundwater resources in the Emirate of Abu Dhabi. Also, under this law, groundwater abstraction and usage will be under EAD's control. Abu Dhabi is the first government in the Gulf region to state that it owns groundwater. The main objective of this new law is to ensure proper management of groundwater resources in the Emirate. The goal is to conserve groundwater and to allow the resources to replenish (EAD, 2017).

5.2.2 Research objectives

In order to achieve a reduction in the use of groundwater to irrigate the arid forests, it is necessary to determine first how much water the trees are actually using, and then determine how this might be reduced. For our research to answer this question we considered it best be undertaken by using direct sap-flow measurements of transpiration in these forests and then using this knowledge to develop irrigation management tools. The main objective of this research is to quantify the water consumption of two arid forest species, Al Ghaf and Al Sidr trees, irrigated with saline groundwater (GW) at salinities typical of the region, namely ≈ 10 dS/m, or 6,400 ppm.

Our results will enable the development of strategies for improving the use of saline water in agriculture and can address institutional and regulatory aspects of agricultural water management. We show how our results will be used by EAD in the regulations that have been promulgated through Law 5 in Abu Dhabi.

5.3 Materials & Methods

The major species in the arid forests of the Abu Dhabi desert are Al Ghaf, Al Sidr, Al Arak and Al Samar. These species were chosen in our broader project to be our experimental trees because they are the most widely distributed native plant species in Abu Dhabi forests, covering around 78% of forest plants in the emirate (EAD, 2016a). However, in this paper we will only cover the Ghaf and Sidr trees that have been irrigated with saline groundwater (GW). Further details for each of these tree species are provided below.

5.3.1 Research site and soil

During December 2014, experiments were set up on two plots of mature Al Ghaf and Al Sidr tree in the Khub al Dahs Forest (23.51º N, 53.75º E) near Madinat Zayed in the Al Dhafra region in the western desert of Abu Dhabi.

The soil type at the experimental site is classified as a Typic Torripsamment, mixed, hyperthermic (Soil AD158) (EAD, 2009). This type of soil is a deep, sandy soil with mixed mineralogy. It is widely distributed across Abu Dhabi with more than 50% of the Emirate having this soil type, and the majority of the arid forests in the Emirate are on this soil type.

A mini-disk infiltrometer (Decagon Devices Inc., Pullman, Washington, USA) was used to measure the soil's near-saturated hydraulic conductivity, K (mm hr^{-1}). The 3-D flow of water from the fritted disk of the mini-disk of radius r_o quickly approaches a steady state Q_∞ (m^3 s^{-1}). Wooding's equation (Wooding, 1968) describes this steady flow in relation to the disk's radius and the soil's hydraulic conductivity function – if it is of the form

$$K(h) = K_s \exp(\alpha h), \qquad [1]$$

Where h is the soil-water pressure head (mm), K_s is the saturated hydraulic conductivity when h=0, and α is the slope of the exponential $K(h)$ relationship.

Wooding's equation is

$$Q_\infty = K_s\left(\pi r_o^{\,2} + \frac{4 r_o}{\alpha}\right). \qquad [2]$$

Measurements of Q_∞ from a minidisk of radius r_o can be used to resolve the soil's hydraulic character. However, the equation contains two unknowns, K_s and α so multiple observations are required (Clothier, 2000). Ankeny et al. (1991) proposed a simultaneous solution of Wooding's equation based on a single permeameter and observations of steady infiltration at the two different heads h_1 and h_2. The infiltration commenced with h_2 first being -60 mm, and then with h_1 being -5 mm. Five replicate measurements of these were made. The structureless, wind-blown sand is spatially quite uniform. The sand was found to be very permeable. The slope α was found to be 0.02 mm^{-1}, and by extrapolation from h_1 to h=0 (Eq. 1) the saturated hydraulic conductivity K_s was found to be 9 m hr^{-1}.

5.3.2 Drip irrigation

Automatic irrigation systems were installed at both experimental sites to control and manage the irrigation. Two tanks of 22,730 litres, one at the Ghaf site and the other at the Sidr site, are filled continuously with GW with salinity of 8–10 dS m^{-1}. The water is then transferred into smaller tanks of 2,273 litres to help in the mixing of the water inside the tanks and reduce salinity variations. Each system was run for 7 hours daily, starting early in the morning. Flow meters record the actual amounts of irrigated water. Water is applied to trees using pressure-compensated drippers with two 4 L hr^{-1} drippers per tree. Thus each tree would receive just under 60 L d^{-1}, every day of the year.

Because of the permeable nature of this coarse sand, we sought to understand what size the wetted volume of soil would be when irrigated by dripper at 4 L hr^{-1} for 7 hours. To do this we used Philip's (1984) analytical solution for steady-state travel times away from a surface point source discharging at rate Q (L hr^{-1}). This is reasonable, as steady-state conditions develop rapidly during 3-D infiltration, especially close to the emitter (Clothier, 1984). Philip's (1984) solution also assumed an exponential hydraulic conductivity function with slope α (Eq. 1). The solution depends only on Q,α, and the soil's average water content θ (m^3 m^{-3}).

(Philip, 1984) provided a simple solution, especially the radius of wetting, R, at the surface (depth Z=0), where the expansion of the wet-front with time, T^*, will be:

$$T^*(R, 0) = 2 \exp(R) (1 - R + R^2/2) - 2, \qquad [3]$$

and for penetration of the wet-front directly under the dripper (R=0):

$$T^*(0, Z) = Z^2/2 - Z + \ln(1 + Z). \qquad [4]$$

Here the non-dimensional lengths are $Z=\alpha z$, where z is the depth (m) below the dripper, and $R=\alpha r$ where r (m) is the radial distance from the dripper

The non-dimensional travel time T^* from the origin is

$$T^* = \alpha^3 Qt/(16\pi\theta). \qquad [5]$$

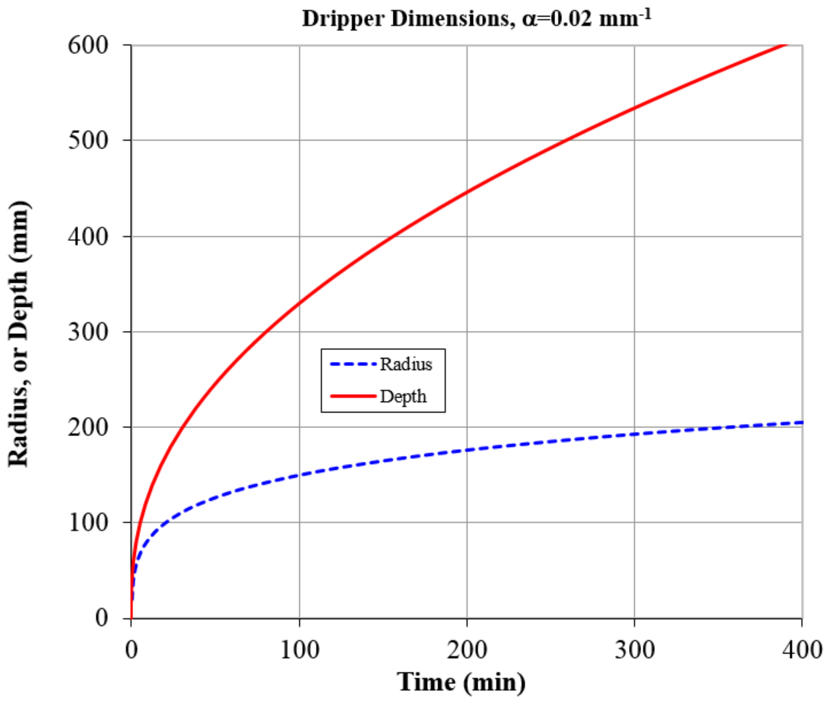

Figure 5.1 Predictions using Philip's (1984) theory for the development of the wet-front across the soil surface (Eq 3) and below a dripper (Eq 4) discharging at 4 L hr^{-1} onto the surface of sand in the Khub al Dahs forest near Madinat Zayed.

The wet-front penetration predictions using Eqs [3] and [4] are shown in Figure 5.1 for Q = 4 L hr^{-1}, and an average water content in the transmission zone of 0.2 m^{3}m^{-3}, and α = 0.02 mm^{-1}. It can be seen that during the 7 hour irrigation the wet-front at the surface could be expected to reach about 200 mm away from the dripper. This is what we observed in the field. Underneath the dripper, the wet-front would be expected to extend beyond 0.6 m. So the drippers would wet the soil to some considerable depth, enabling the trees to take up water from deeper down to meet the atmospheric demand for water.

5.3.3 Soil water and salinity monitoring

Two Campbell CS655 soil-water content reflectometers were installed in the drip zone of both the Ghaf and Sidr plots. One probe was inserted in the drip zone of a GW-irrigated tree and the other in that of a tree irrigated with treated sewage effluent (TSE). The CS655 measures the soil-water content, θ, and bulk electrical conductivity (EC_b, dS m^{-1}). In a separate laboratory test, we calibrated the CS655 probe to infer the soil-solution EC from both θ and EC_b. The calibration for EC was found to be linear with EC_b and parabolic with θ (A. Al-Muaini, *pers. comm.*, 2016).

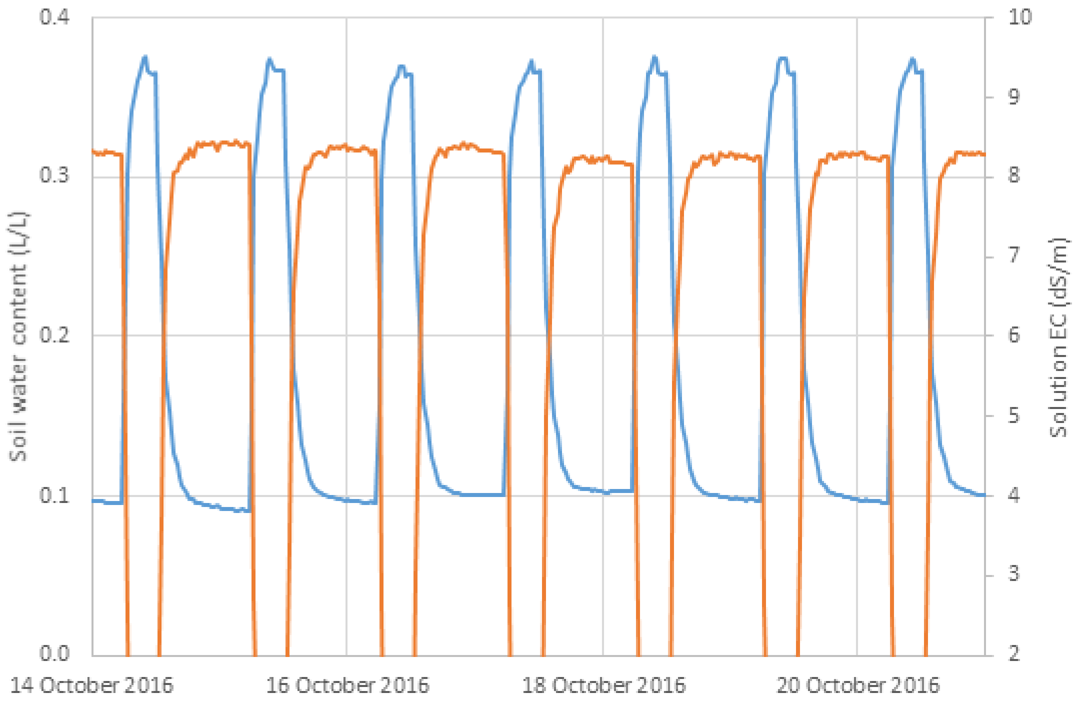

Figure 5.2 The diurnal pattern of soil water content, *θ*, (left axis, blue), and solution *EC*, (Right axis, red) inferred from the bulk EC_b and *θ* measured by a Campbell CS655 soil-water reflectometer in the drip zone of a Ghaf tree irrigated with saline groundwater (GW).

In Figure 5.2 we show the daily pattern of *θ* and *EC* during the irrigation period (0630–1330) for the GW irrigated Al Ghaf that was instrumented with the CS655 probe. The rapid rise and fall of *θ* reflects the highly permeable nature of this sand, and rootzone uptake of water to meet the atmosphere's demand on the tree for water. The calibration equation for *EC* provides erroneous values when the soil is at saturation. After the free-water drains away from the drip zone, the *EC* can be seen to rise to just over 8 dS m^{-1}, being about the salinity of the applied water. Here, and throughout the year, at this irrigation rate of about 60 L per tree per day, there is no change in the solution *EC* value, showing that there is effective flushing of excess salts from the rootzone.

5.3.4 The tree species

There are 12 trees in each of the 2 plots for Al Ghaf and Al Sidr, and within each plot six trees have been irrigated with GW, and six with treated sewage effluent (TSE). The GW has a salinity of around 10 dS m^{-1}, whereas the TSE has a salinity of less than 1 dS m^{-1}. Here we report only on the GW results. Our focus here is to develop water-management protocols for saline groundwater.

The Ghaf, or Al Ghaf, is the local Arabic name for *Prosopis cineraria*. Al Ghaf tree has a straight unbranched trunk for the first few metres. Then the branching starts. It is an indigenous species of the Arabian Desert. Al Ghaf is a drought-tolerant, evergreen, leguminous tree which can tolerate the harsh climate of the desert environment. However, the Ghaf trees in managed forests are all dependent upon irrigation. Al Ghaf trees can survive even when irrigated with highly saline groundwater. Nevertheless, the degree of salinity does affect their natural growth and health. Despite being evergreen, Al Ghaf undergoes cycles of leaf fall, fruiting and leaf renewal (Khan, 1999).

The Sidr, or Al Sidr, is the local Arabic name for *Ziziphus spina-christi*. The trunk may be undivided or divided near the base. The Sidr tree is frequently multi-branched. Sidr is tolerant to harsh conditions such as salt, drought, desert heat, and even heavy grazing by gazelles and camels (Khan, 1999; EAD, 2006).

5.3.5 Sapflow monitoring of transpiration

We installed heat-pulse devices in four trees per treatment to provide continuous monitoring of the trees' transpiration (T) using the compensation heat pulse velocity (CHPV) method (Green, Clothier, & Jardine, 2003). We used a standard spacing of the temperature probes of 5 mm upstream and 10 mm downstream from the heater probe. For the larger single-trunk Ghaf trees the temperature sensors in the probes were located at 10, 25, 40 and 55 mm below the cambium. Two sets of devices were installed in each of the four trees. For the thinner and multi-stemmed Sidr trees only two sensors per probe were used and these were located at 5 and 12 mm below the cambium. Four stems were instrumented in each of the four monitored Al Sidr trees.

A Campbell data logger (CR1000, Campbell Scientific, Logan, USA) was used to measure the time taken to achieve temperature equality between sensors located above and below the heater (t_Z, s) following the application of a 2.5 s heat pulse. Data were collected at 30 min intervals. Sap flow (L h^{-1}) was calculated from measurements of t_Z using the approach outlined by Green et al. (2003; 2009). These calculations included a correction for the effect of wounding. A wound diameter of 2.8 mm was used for the 2.0 mm diameter drill holes. Sap velocity was then deduced from the wound-corrected heat-pulse velocity and measured volumetric fractions of wood and water within the sapwood. The fractions of wood (Fm) and water (Fl) in the sapwood were determined gravimetrically from core samples (Fm = 0.35 and Fl = 0.60). Transpiration (T, L d^{-1}) was determined by multiplying sap velocity by the conducting wood area using the simple annulus approach suggested by Hatton et al. (1990).

This equipment was installed in the Al Ghaf trees during December 2014, and during February 2015 in the Sidr trees. The experiments have continued through into 2018.

5.3.6 Weather monitoring

The weather station at Khub Al Dahs forest records sub-hourly climate data comprising global shortwave radiation (LiCor 1200), air temperature and relative humidity (Vaisala HMP 45C), wind speed at 3m (RM Young), and rainfall (TE525 MM-L, Texas Electronics).

These weather data are used to estimate hourly and daily values of the reference evaporation (ETo, mm hr^{-1}, or mm d^{-1}) using the standard approach of FAO-56 (Allen, 1998). The transpiration of the trees (ETc, mm hr^{-1}, or mm d^{-1}) is then related to ET_O through the dimensionless crop-factor, K_C:

$$ET_c = K_c \, . \, ET_o \quad . \qquad [6]$$

5.4 Results and Discussion

5.4.1 Al Ghaf transpiration

Sap flow data for the four GW irrigated Ghaf trees began on 12 December 2014, and continued through until 2017. The four trees are of different sizes, and so we would expect the crop factor, Kc, to vary between trees. In Figure 5.3 (top) we show the hourly transpiration of Tree 3 (in L hr^{-1}), one of the largest, in relation to the reference ETo (mm hr^{-1}), over a period of nearly 3 weeks in the spring of 2014. The vertical axes have been scaled so the traces overlap each other. That the traces do overlap indicates that a single crop factor (Eq. 6) is appropriate for describing this data set. We have repeated this ‘scaling’ procedure for the smallest GW-irrigated Ghaf tree (#2), and this is shown in Figure 3 (bottom). Note the different scales of the right hand axes, which reflects the smaller crop factor for the smaller tree.

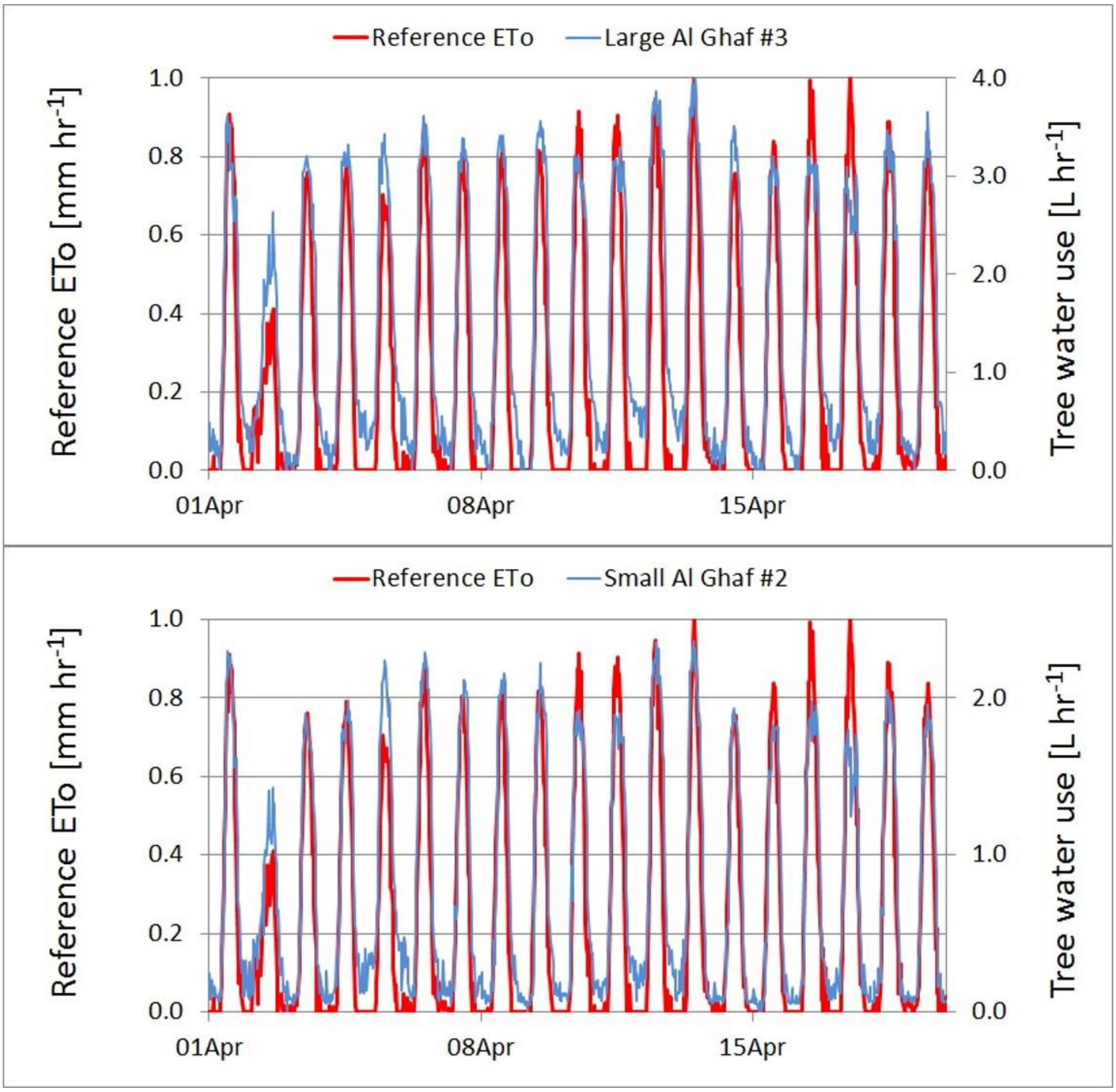

Figure 5.3 Top: The measured pattern of the half-hourly tree water use, *T* (L hr^{-1}, right axis), of a large Al Ghaf tree (#3) during the spring of 2015 in relation to the reference *ET*o (mm hr^{-1}, left axis). Bottom: As above, but for a small Al Ghaf (#2) tree. Note the different scale of the right-hand axes between the top and bottom graphs.

The daily value of the crop factor can be quantified by regressing tree water use, *T* in L d^{-1}, against the reference *ET*o in mm d^{-1}. Using a year's data set for both trees from 12 December 2014 until 24 November 2015, we found the slope of the regressions to be 4.55 for the large tree (Tree #3) and 2.88 for the smaller Tree #2 (Figure 5.4). Since the trees are planted on a 7 m by 7 m grid, these slopes turn into crop factors of 0.09 (=4.55/(7x7)) for Tree 3, and 0.059 (=2.88/(7x7)) for Tree 2. However, it is clear from the scatter of both plots, that a single annual crop factor, *K*c, would not enable a good prediction of the seasonal pattern of daily tree water use, *ET*c. Indeed, the correlation coefficient for the regressions are -0.29 and -1.22 respectively for Tree 3 and Tree 2, which suggests a simple arithmetic, annual-average for *T*, adjusted to the different tree sizes, would be better than using a unitary crop factor and a time-varying *ET*o!

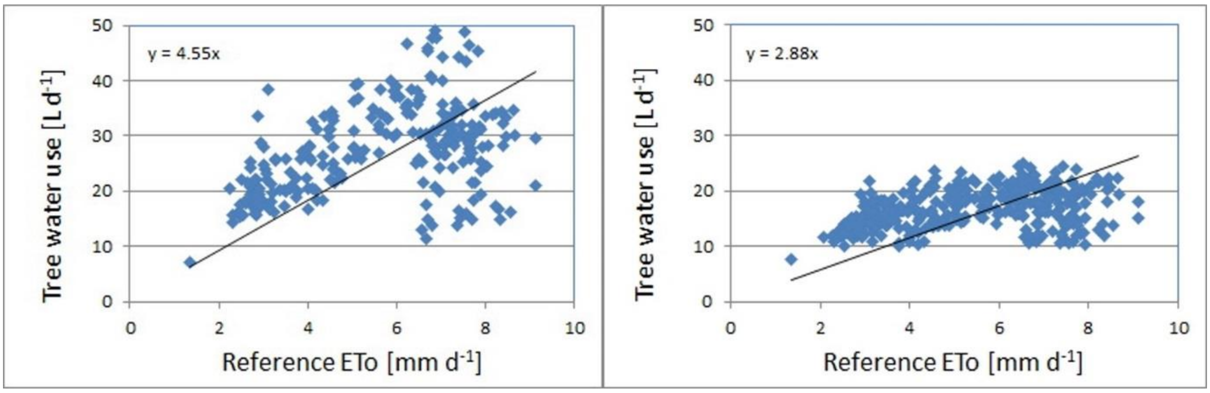

Figure 5.4 Left. The regression of the measured daily water-use by Tree 3, *T* in L d^{-1}, against the daily reference *ET*o, in mm d^{-1}. The data set covers 12/12/2014 until 24/11/2015. The slope of the regression is 4.55. Right. As above, but for the smaller Tree 2. The regression slope is 2.88.

It is instructive therefore to examine the seasonal pattern of daily tree water use, *T*, in relation to daily *ET*o, for all four monitored trees, and over the period of nearly 2.5 years of measurement. These data are shown in Figure 5 here as the red dots, with *ET*o in blue.

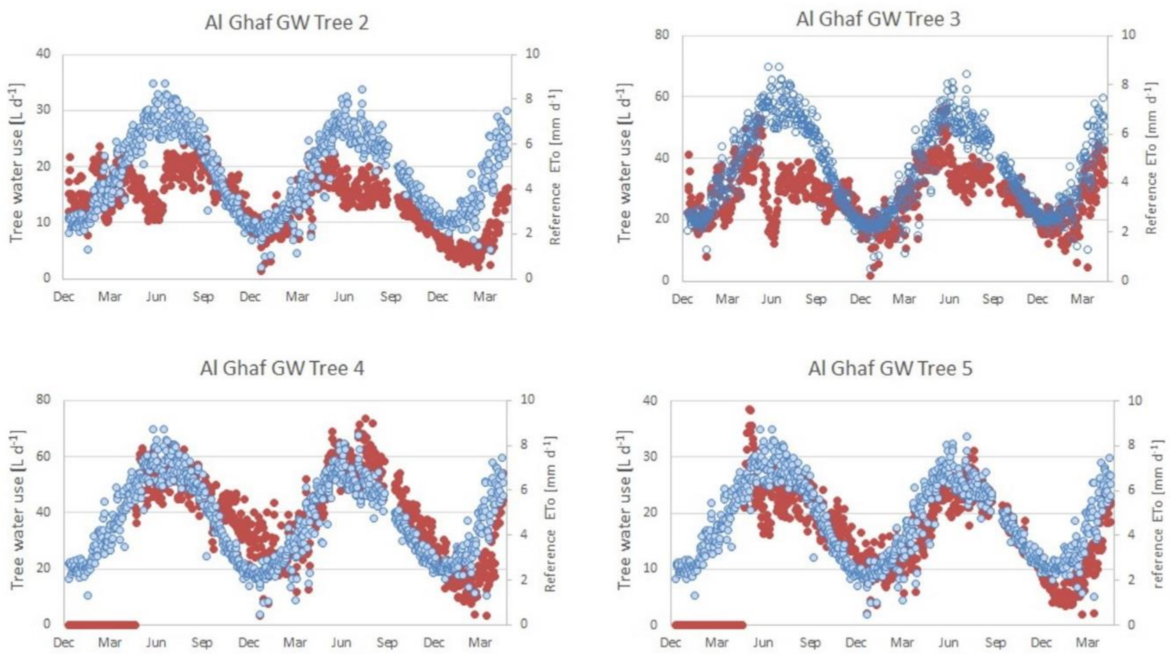

Figure 5.5 The seasonal pattern of measured daily water-use *T* (red dots, left axis) for all 4 GW irrigated Al Ghaf trees in relation to *ET*o (blue circles, right axis). The periods cover from late 2015 through until early 2017. Top left: Tree 2; Top right: Tree 3; Bottom left: Tree 4; Bottom right: Tree 5. Note the different scales on left-hand axes for transpiration *T*, in L d^{-1}, due to the different sizes of the four trees.

The left-hand axes in Figure 5.5 all have different scales, as the tree water use, *T*, of the two smallest trees (Trees 2 and 5) do not exceed 40 L d^{-1}, whereas the two larger trees use between 60 and 80 L d^{-1}. As alluded to in Figure 5.4, the pattern of *T* diverges from *ET*o at distinct times of the year due to the deciduous behaviour of Al Ghaf. There is a period of leaf loss during June, which is most noticeable in Tree 3, and also in Trees 2 and 5. This is not quite so evident with Tree 4. Furthermore, the magnitude of this dip in *T* is different between years. For Tree 3 in 2015, the period of both leaf loss, and leaf regrowth in June was very sharp, covering about 25 days. Tree 4 in both years showed only weak deciduous behaviours. This complex and asynchronous behaviour leads to difficulties in applying a crop-factor approach to *ET*c prediction.

However, given the variation due to tree sizes, both within our experimental trees, and throughout the forest stand, an aggregated approach to defining *K*c was adopted. The sap flow data from all four monitored trees was aggregated into average tree water-use values over the 2 years of experimentation, and these are shown in relation to *ET*o (Figure 5.6). The linked patterns of *T* in L d^{-1} and *ET*o in mm d^{-1} can be used to determine the temporal pattern of the crop factor. The impact of the varying asynchrony of leaf fall, flowering and new leaf growth, leads to a muted average pattern of *T* in relation to *ET*o.

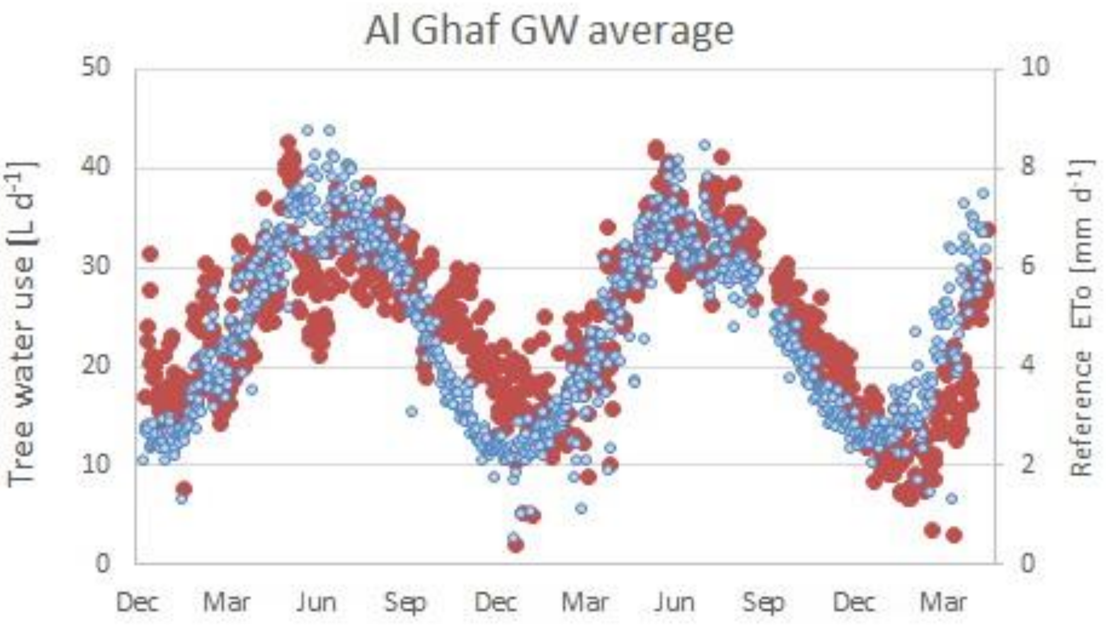

Figure 5.6 The seasonal pattern of average of the measured daily water-use *T* (red dots, left axis) for all four GW irrigated Al Ghaf trees in relation to *ET*o (blue circles, right axis).

The phenology of Al Ghaf trees is typically that new leaves appear just before, or simultaneously with, the fall of the old leaves. Flowering typically begins just after the flush of new leaves. This pattern of new foliage, flowering and fruiting occurs during the hottest period of the year between March and August. However, we have found that the relative strengths of the vegetative and flowering cycles varies in any given year between trees, and is due to the biennial bearing characteristic displayed by fruiting trees. In Figure 5.7 we show photos of two neighbouring trees, Tree 3 (left) and Tree 4 (right), taken on the same day in 2017. Tree 3 can be seen to be having an ‘on’ year in relation to flowering, whereas as Tree 4 was having an ‘off’ for flowering. The relative vegetative vigour of the trees is different with Tree 4 showing a surge of new leaf growth. Elsewhere in our experimental plot of eight instrumented trees, four GW irrigated and four TSE irrigated, we observed five trees to be having ‘on’ years of flowering, and three with ‘off’ years of flowering. It is this asynchrony that leads to the muted seasonally deciduous pattern in the average *T* in relation to *ET*o (Figure 5.6).

Figure5. 7 Photographs of two Al Ghaf trees taken on the same day, the 26th of April 2017. The tree on the left (Tree 3) had lost many leaves, showed little emergence of new leaves, and was beginning to flower heavily. The tree on the right (Tree 4) was showing no signs of flowering, but was undergoing a surge in new-leaf growth.

We can scale-up to the forest stand using the average pattern of *T*, relative to *ET*o, to compute the average crop factor *K*c. This is shown in Figure 8. There is a weak seasonal deciduous pattern, on average. The crop factor drops in February–March as the trees begin to lose leaves as they initiate flowering. Then *K*c remains effectively constant until new leaf growth lifts the crop factor in September to its peak in December. This pattern in the average *K*c enables us to predict irrigation requirements for stands of Al Ghaf trees, as we show later.

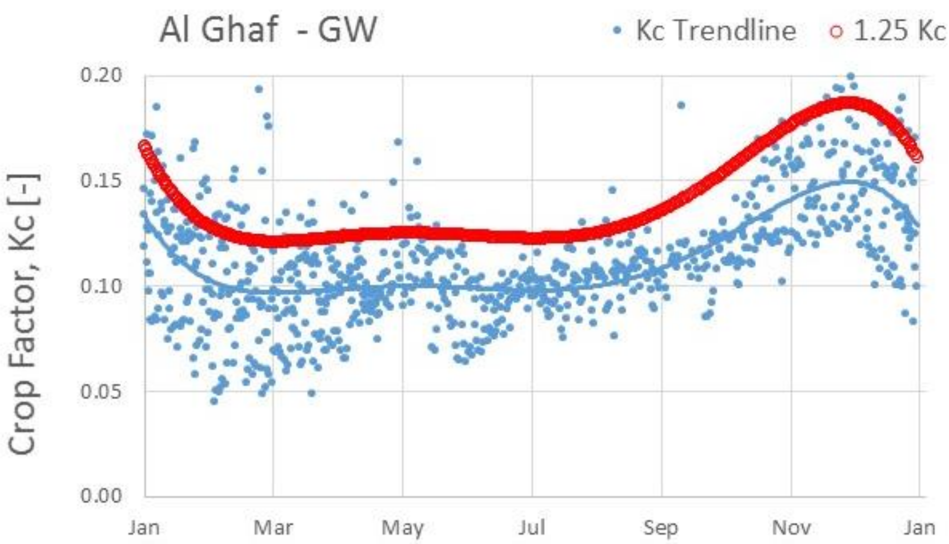

Figure 5.8 The average daily crop-factor, *K*c, for the four instrumented Ghaf trees over the year, computed from nearly 2.5 years of individual tree water-use *ET*c. The blue line is the fitted trendline using a 5th order polynomial. The red line is the fitted line with a 25% add-on as a 'factor-of-safety'.

5.4.2 Al Sidr transpiration

Our measured *ET*c for each of the four multi-stemmed Sidr trees is computed using our baseline measurements of sapflow in four measured stems. The flow in the measured stems was scaled to a flux density using the trunk cross-sectional area of the measured stems. The trees were then surveyed to find the diameters of all of the stems. The total trunk cross-sectional area of the whole tree was computed and the sap-flux density applied to this to compute the tree's total water use. The pattern of tree water use, *T*, is shown for Al Sidr trees 3 and 5 in Figure 5.9, along with the seasonal pattern over two years of *ET*o.

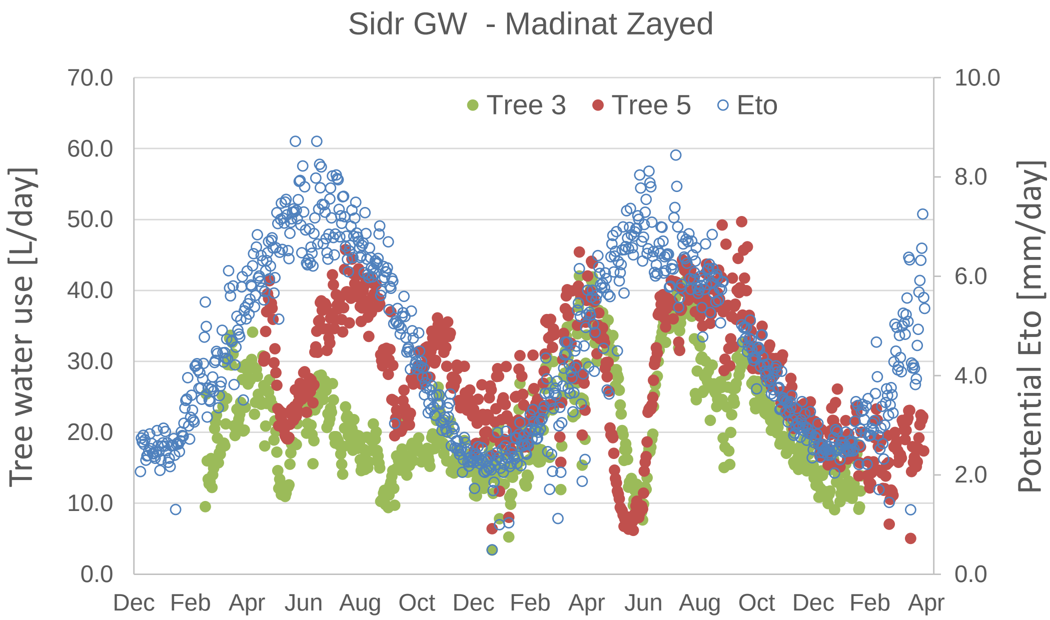

Figure 5.9 The seasonal pattern of tree water use, *T* (L d^{-1}) by two Sidr trees (3 and 5) being irrigated with groundwater (GW), shown in relation to *ET*o (mm d^{-1}) over 2 years beginning in 2015.

The impact of the deciduous behaviour of the Sidr trees is distinct and synchronous. There is a rapid loss of leaves in April, followed by rapid new leaf growth in May. There is a second, less distinct, period of leaf-loss in August with regrowth during September. Our measurements, and observations in the forest stand, reveal a greater degree of synchrony between trees, with less evidence of biennial bearing. In Figure 5.10 we show how significant the deciduous behaviour in spring can be. On the left of Figure 5.10 we show Sidr Tree 4 at the full-leaf stage in January 2017. By April, the tree has no leaves at all (Figure 5.10, right). In the background of the April photo, it can be seen that most trees have either no leaves, or just a few.

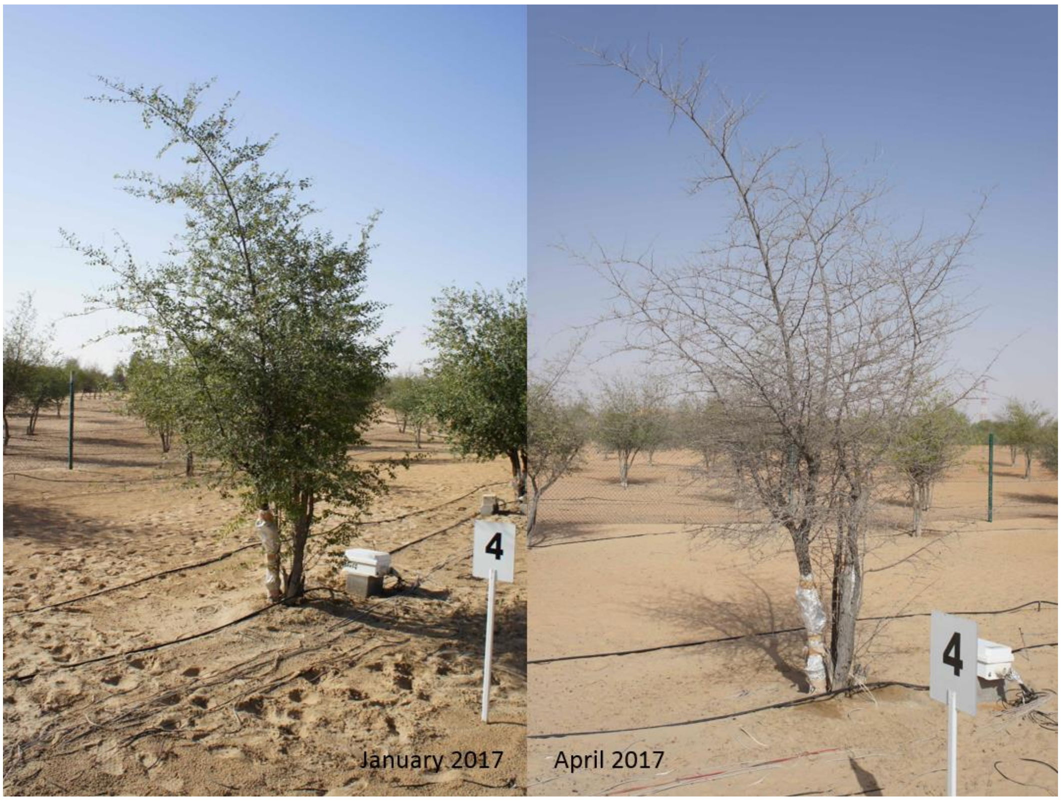

Figure 5.10 The groundwater (GW) irrigated Sidr Tree 4 at full leaf in January 2017 (left). The same tree is shown in April on the right.

The average crop factor *K*c was computed for all four trees, and the seasonal pattern over the year is shown in Figure 5.11, using over two years of sapflow measurements. A strong seasonal pattern is found, albeit with a degree of variability due to some weak asynchrony and tree-to-tree variation. A 4^{th} order polynomial was fitted to the data, and is shown in Figure 5.11. The amplitude in the seasonal pattern of the average *K*c is large, ranging from 0.16 in December/January, down to 0.06 in summer. In contrast, the average *K*c for the Ghaf trees ranged from just 0.10 to 0.15.

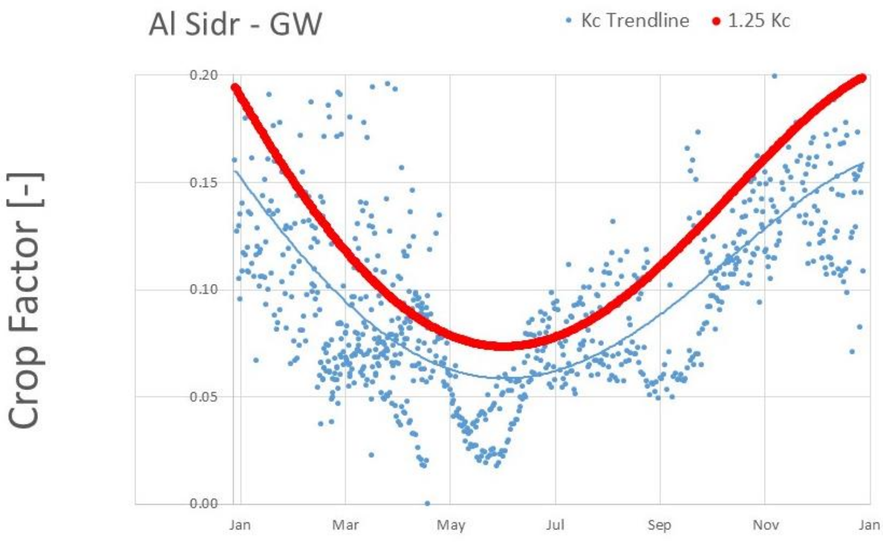

Figure 5.11 The average daily crop-factor, *K*c, for the four instrumented Sidr trees over the year, computed from over 2 years of individual tree water-use *ET*c. The blue line is the fitted trendline using a 4th order polynomial. The red line is the fitted line with a 25% add-on as a 'factor-of-safety'.

5.4.3 Irrigation allocation and Law 5

Current practice is to irrigate both the Ghaf and Sidr trees with 60 L d^{-1} of groundwater. Implementation of Abu Dhabi's Law 5 requires that irrigation be allocated at the minimum amount required to achieve the desired goal. Our results here are being used to define the irrigation allocation under Law 5 for amenity plantings of Al Ghaf and Al Sidr trees. We use our fitted values of *K*c, broken down by the maximum value for every month, to determine firstly the water use of the trees with what we consider to be an equitable 25% factor-of-safety (Table 5.1). Because the trees are irrigated with GW at a salinity of 8–10 dS m^{-1} we recommended that the irrigation allocation be at 1.5 *ET*c, so as to provide a 25% salt-leaching fraction.

Table 5.1. The seasonal pattern in average daily, *ET*o (mm d^{-1}), broken down by month at Madinat Zayed in the western desert of Abu Dhabi. For Al Ghaf trees (left) is shown the monthly maximum value of the crop factor, *K*c, along with the irrigation monthly requirements (L d^{-1}) considering a 25% factor-of-safety (1.25 *K*c. *ET*o) and a 25% salt-leaching factor (1.5 *K*c. *ET*o) for saline groundwater. On the right is shown these values for Al Sidr trees. The respective annual-average daily values are given at the foot of the table.

		Al Ghaf			Al Sidr		
Month	**Average ETo (mm/day)**	**Maximum *K*c [-]**	**1.25 [*K*c .ETo] (L/day)**	**1.50 [*K*c .ETo] (L/day)**	**Maximum *K*c [-]**	**1.25 [*K*c .ETo] (L/day)**	**1.50 [*K*c .ETo] (L/day)**
January	2.55	0.13	20.3	24.4	0.16	25.0	30.0
February	3.37	0.10	20.6	24.8	0.12	24.8	29.7
March	4.55	0.10	27.9	33.4	0.10	27.9	33.4
April	5.74	0.10	35.2	42.2	0.08	28.1	33.8
May	6.67	0.10	40.9	49.0	0.06	24.5	29.4
June	7.15	0.10	43.8	52.6	0.06	26.3	31.5
July	7.10	0.10	43.5	52.2	0.07	30.4	36.5
August	6.53	0.11	44.0	52.8	0.08	32.0	38.4
September	5.60	0.12	41.2	49.4	0.10	34.3	41.2
October	4.51	0.14	38.7	46.4	0.13	35.9	43.1
November	3.59	0.15	33.0	39.6	0.14	30.8	36.9
December	3.26	0.15	30.0	35.9	0.16	31.9	38.3
	Annual Average (L/day)		34.9	41.9		29.3	35.2

We have assessed whether a salt-leaching fraction of 25%, with a factor-of-safety of 25%, is sufficient by monitoring the rootzone salinity of an Al Ghaf, and Al Sidr tree, during 2017, after imposing a monthly irrigation schedule of 1.5 *ET*c. We present the results for the Ghaf tree in Figure 5.12. The irrigation schedule tracked 1.5 times the measured *ET*c, and the bulk electrical conductivity can be seen to rise from around 0.5-1 dS m^{-1}, prior to irrigation, up to about 1-2 dS m^{-1}. The pattern depends on the season due to the varying rootzone dynamics of wetting by irrigation, and extraction by the tree. However, there is no progressive rise in the bulk EC of the soil, as the bulk EC in January 2018 was the same as it was in January 2017. This indicates that an irrigation rate of 1.5 *ET*c is sufficient to flush excess salts from the rootzone.

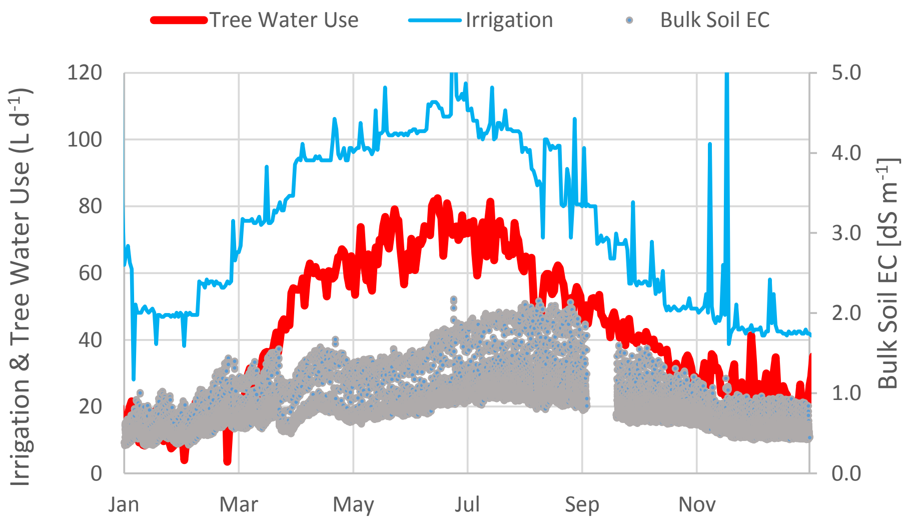

Figure 5.12. The measured daily irrigation rate applied to Al Ghaf tree #4 from 25 January 2017 to 25 January 2018 (blue line), along with the tree water-use measured by sap-flow monitoring (*ET*c – red line). The monthly schedule was set to achieve an irrigation rate of 1.5 *ET*c to ensure a salt leaching fraction of 25%, with a factor-of-safety of 25%. The pattern in the bulk-soil electrical conductivity (EC), as measured by a CS 655 probe under the dripper, is also shown (grey dots).

The monthly pattern of irrigation requirements at 1.5 *ET*c shows that Al Ghaf trees will need, on average, just 24 L d^{-1} during winter, and up to 53 L d^{-1} in summer (Figure 5.6). The annual-average daily water requirements will be 42 L d^{-1}, a saving of 30% on the current practice of 60 L d^{-1}. For the smaller Sidr trees, the water requirements are less, with the lowest water needs occurring in May at 30 L d^{-1}, and rising to 43 L d^{-1} in October (Figure 5.9). On annual average, the water requirement for Al Sidr is just 35 L d^{-1}, an annual saving of over 40% on current practice.

5.5 Conclusions

The arid forests in the hyper-arid deserts of Abu Dhabi require irrigating. Saline groundwater is the predominant source for the irrigation water, and current practice is to irrigate Al Ghaf and Al Sidr trees with a designated quantity of 60 L of groundwater every day of the year. Over-extraction of the Emirate's aquifers threatens groundwater sustainability. Consequently, Law 5 has been passed in Abu Dhabi to restrict groundwater takes for irrigation to protect the subterranean reserves of water. Law 5 will prescribe allocation limits so that only the minimum amount of water is used to achieve the desired outcome. We have carried out experiments on Al Ghaf and Al Sidr trees in the western desert of Abu Dhabi using sap flow measurements to monitor tree water use over 2.5 years. These results were used to quantify the seasonal pattern in the crop factor, *K*c, for these two deciduous arid-forest species. The seasonal patterns between the two species are quite different, due to their idiosyncratic patterns of leaf fall, flowering and leaf regrowth. By predicting tree water-use, *ET*c, as 1.5 *K*c.*ET*o, we could provide the regulations for Law 5 with irrigation allocation recommendations that included a 25% factor-of-safety, and a 25% salt-leaching fraction. These recommendations represent a 30% reduction on current practice for the groundwater irrigation of Al Ghaf trees, and a 40% saving for Al Sidr trees.

5.6 References

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CHAPTER 6

6 The Impact of Replacing Groundwater by Treated Sewage Effluent on the Irrigation Requirements of Al Ghaf (*Prosopis cineraria*) and Al Sidr (*Ziziphus spina-christi*) Forests in the Hyper-Arid Deserts of Abu Dhabi

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Two major objectives are discussed in this chapter;

First, the proposed allocation schedule for irrigation using saline groundwater for Al Ghaf and Al Sidr is tested. Details about this schedule were given in Chapter 5 and it is based on 1.5 *ET*c, with ETc being the trees' actual water use. Here the results of applying it for one year are presented. The heat-pulse method was used to monitor the tree water use, *ET*c, as was presented earlier in Chapters 4 and 5.

Second, treated sewage effluent (TSE) was introduced into our experiment. Currently GW is the main water source for irrigation in forestry. However, the Abu Dhabi government is looking into using alternative sources such as TSE to conserve groundwater. The TSE is 'sweeter', in the sense of salt, and it has an electrical conductivity of < 1 dSm^{-1}. Under the same experimental conditions for both Al Ghaf and Sidr, TSE was provided to half of the experimental trees and their *ET*c was monitored, and the seasonal patterns in water-use for the GW and TSE- irrigated trees were found. Al Ghaf and Al Sidr both showed better and healthier response to TSE relative to GW, and this is due to major salinity difference between the two water sources. There was no difference in the nutrient levels between the two water sources. A 50-60 % reduction in irrigation water can be achieved when using the proposed GW schedule and even more with TSE. Results from laboratory analyses of the soil, the irrigation waters, and the leaves for trees irrigated with GW and TSE are also discussed in this Chapter.

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6.1 Abstract

The arid forests of Abu Dhabi are valuable but they require irrigating. Currently groundwater (GW) is the source of this water, but these subterranean reserves are being over-exploited. Law No 5 of 2016 on the regulation of GW has been passed by the Government of Abu Dhabi to reduce GW abstraction. Abu Dhabi has a supply of tertiary-treated sewage effluent (TSE) that could be used as an alternative for irrigation. We set up experiments near Madinat Zayed in the Al Dhafra region of Abu Dhabi on two arid-forest species: Al Ghaf (*Prosopis cineraria*) and Al Sidr (*Ziziphus spina-christi*). The trees were planted at 7m x 7m spacing. The TSE is significantly 'sweeter' than GW, as its electrical conductivity is < 1 dS m^{-1}, whereas GW is 8-10 dS m^{-1}. The GW in this region is very high in nitrates (38.4±9.2 mg-NO_3 L^{-1}), and this was not significantly different from the TSE (53.7±11.8 mg-NO_3 L^{-1}). We monitored the actual tree water-use (*ET*c, L h^{-1}) via heat-pulse devices in both the GW and TSE-irrigated trees. We quantified the differences in the *ET*c patterns for both the GW and TSE-irrigated trees of both species over 3 years. Both species showed positive growth-responses to TSE, relative to the GW, and we consider this to be due to the lower electrical conductivity of the TSE water. Because of this growth response the water use of the TSE by Ghaf trees was, on annual average 17% higher than GW, and for the Sidr it was 39%. Our results were corroborated by stomatal porometry and leaf-area inferences. But for TSE there is no need for a salt-leaching fraction. Furthermore, to achieve the same tree-health outcome as with the GW, even less TSE need be applied. Irrigation requirements for TSE are at least 25% less than for GW.

6.2 Introduction

Abu Dhabi's arid forests are located in a hyper-arid desert, where annual precipitation is less than 50 mm, and annual potential evapotranspiration exceeds 2000 mm. Despite these harsh desert conditions, the first president of the United Arab Emirates (UAE), H.H Sheikh Zayed Al Nahyan sought to establish many forests to realise the valuable ecosystem services delivered by the trees. Abu Dhabi's forests now cover about 3.5% of the Emirate. The total number of trees is around 20 million trees, and thanks to irrigation with groundwater (GW), some 80% of these forests are classified in good condition.

The annual GW consumption for irrigation of the current forests is estimated to be about one quarter of total GW extractions. Meanwhile, conserving GW is imperative for food security, cultural heritage, and the environment of Abu Dhabi. In November 2016, the General Secretariat of the Executive Council of the Abu Dhabi Government issued Law No. 5, officially declaring that the Emirate of Abu Dhabi owns the GW reserves, and that its extraction and use would be governed by the rules, standards and conditions set out by Environment Agency – Abu Dhabi (EAD). Law No.5 will help to manage the demand for GW and ensure the reserves into the future (EAD, 2017).

In an earlier paper (Al Yamani et al., 2018) we described our experiments on the irrigation of Al Ghaf and Al Sidr by saline GW with an electrical conductivity of EC of 8-10 dS m^{-1}. From our results and analyses we provided EAD with new GW irrigation allocations for Law 5 based on direct measurements of tree water use (*ET*c), plus a factor-of-safety of 25%, and a salt-leaching fraction of 25% (Al Yamani et al., 2018). Adoption of this allocation regime will result in GW savings of up to 40% in forest irrigation.

6.3 Treated Sewage Effluent

However, even greater savings are required to protect GW reserves, so the Abu Dhabi government has recently started new initiatives to understand better the status and the pressure on the more than 100,000 groundwater wells in the Emirate. This strategic assessment now involves seeking ways to reduce pressure on GW by finding alternative sources for irrigation. The UAE has been collecting and treating sewage since 1973, and this tertiary-treated TSE is derived from desalinated water. Treated sewage effluent is 'sweeter' than GW, in the sense of salt. The EC of TSE is generally < 1 dS m^{-1}, some tenfold lower than GW. The TSE comes from residential and municipal sources, trade water-use, plus some storm-water runoff and rainfall. There are more than 60 wastewater treatment plants in the UAE, and the majority of these are in Abu Dhabi. Most of these treatment plants use advanced technologies to treat the sewage water to a tertiary level. Currently some TSE is used for irrigation of amenity vegetation, but still a significant volume of TSE is disposed of into the Arabian Gulf. The Government has a plan to achieve full usage of TSE for irrigation.

6.4 Objectives

The goal of the work outlined here was to provide EAD with guidelines to aid in the implementation of Law 5 in terms of irrigation requirements, impacts on tree health, and GW savings, through the use of TSE to irrigate two major species of arid forest: Al Ghaf (*Prosopis cineraria*) and Al Sidr (*Ziziphus spina-christi*). The research objective was to quantify the water-use (ET_c, L d^{-1}, or mm d^{-1}) of Al Ghaf and Al Sidr trees irrigated with TSE, so that new allocation guidelines can be developed for Law 5 for this alternative water source. The ET_c of the TSE-irrigated trees is compared to that of those GW trees previously described in Al Yamani et al. (2018). We also sought to determine what controls the differences in the ET_c between the GW and TSE-irrigated trees, and to quantify the impact of TSE on both tree performance and soil health. In Al Yamani et al. (2018) we provided irrigation allowances that would minimise the use of GW to irrigate the trees, and here we sought to do the same for TSE so that maximum benefit can be made of this valuable alternative source of water. Furthermore, we describe the use of our 'light stick' to infer the fractional light interception (*LI*) of the GW and TSE trees. This *LI* enables their crop factor, K_c, to be estimated, so that the FAO-56 model (Allen et al. 1998) can be used to predict the tree's ETc simply from the reference ET_o using K_c ET_o.

6.5 Materials & Methods

The major native species of the hyper-arid forests of the Abu Dhabi desert are the Ghaf, Sidr, Arak and Samr. Here we discuss irrigation experiments on mature plots of Al Ghaf and Al Sidr trees. Both tree species in our experimental plots were irrigated either with GW or TSE.

6.5.1 Research site

This research was carried out within the Khub Al Dahs forest (23.51° N, 53.75° E) near Madinat Zayed in the Al Dhafra region of the western desert of Abu Dhabi. Al Yamani et al. (2018) have provided a complete description of the site and the experimental set-up, so only salient details are repeated here. The soil is a Typic Torripsamment, mixed, hyperthermic (Soil AD158) (EAD, 2009; Shahid et al., 2014). It is a deep, sandy soil that is widely distributed across 75% of the UAE. A large proportion of the managed forests in the UAE are on this type of soil.

Two experimental sites were established. There were 12 trees in each of the two plots for Al Ghaf and Al Sidr. Within each plot six trees in a single row were irrigated with GW, and in the neighbouring row six trees were irrigated with TSE. The botanical details of the Ghaf and Sidr trees are provided in Al Yamani et al. (2018). Also, as described in Al Yamani et al. (2018), sapflow sensors were installed in four trees of each treatment to provide a continuous record of the trees' transpiration (ET_c, L d^{-1}) using the compensation heat pulse velocity method (Green, Clothier, & Jardine, 2003). The sapflow devices were installed in the Ghaf trees in December 2014, and during February 2015 for the Sidr trees. The TSE treatments on both tree species began on 18 May 2015.

Automated irrigation systems were used at both experimental sites to control the irrigation using GW and TSE. Two tanks, each of 22,730 litres, were located at both the Ghaf and Sidr sites. One tank at both sites was continuously filled with GW having a salinity of 8–10 dS m^{-1}. The other tank at both sites were filled every month with TSE provided by the Abu Dhabi Sewerage Services Company. The source of the TSE was domestic TSE from the city of Madinat Zayed, and the EC of this water was always much less than 1 dS m^{-1}. The water from both of these large header tanks was then transferred separately to smaller tanks each of 2,273 litres to help with the mixing of the water to reduce salinity variations. Each system was operated daily for 6 hours, beginning early in the morning. Flow meters were used to monitor the applied aliquots of water. Pressure-compensated drippers were used with two 4 L h^{-1} drippers per tree. Thus, each tree received about 60 L d^{-1}, on each day throughout the year. The irrigation strategy was however changed in the last year of the experiment, 2017, as we discuss later.

6.5.2 Weather monitoring

Khub Al Dahs forest has a meteorological station that records high-frequency weather data including global shortwave radiation (LiCor 1200), air temperature and relative humidity (Vaisala HMP 45C), wind speed at 3m (Maximum 3-cup anemometer), and rainfall (Pronamic 101 rain gauge).

These weather data were used to compute the hourly and daily values of the reference evaporation (ET_o, mm hr^{-1}, or mm d^{-1}) using the FAO-56 approach of Allen et al. (1998). The transpiration rate of the trees (ET_c, mm hr^{-1}, or mm d^{-1}), as measured by the sapflow sensors, was then related to ET_O via the crop-factor, K_C [-] using

$$ET_c = K_c \,.\, ET_o \quad . \qquad [1]$$

6.5.3 Soil, water, and leaf analyses

Samples of the soil, irrigation water, and the leaves were collected from both the GW and TSE trees at appropriate times. Chemical and microbiological analyses on the soil and water sampled were carried out by the commercial company Exova Ltd in Dubai (www.exova.com). Leaf samples were analysed by United Arab Emirates University in Al Ain.

6.5.4 GW and TSE water analyses

There are more than 40 wells in Khub Al Dahs forest. The GW in Al Ghaf experimental site is pumped from a different well than the one in Al Sidr experimental site.

Water samples were collected directly from dripper outlets while the irrigation was on. Two water samples were collected from both the GW and TSE lines at the Al Ghaf and Al Sidr sites in 2015 at the initiation of the TSE application, and a second sampling was done at the end of 2017.

6.5.5 Soil analyses

The first soil samples, labelled as the reference, were taken in February 2015. These were taken inside the same forest, and close to, but just outside of the experimental plots. We collected a total of six soil samples, three of them were taken directly under the dripper at depths of 10, 20 and 40 cm, and the other three samples were taken on the edge of the wet zone around the dripper.

Soil samples were collected three more times during the experiments: in December 2015; December 2016; and finally in December 2017. These soil samples were also collected from directly under the dripper and at the edge of the wetted zone. They were taken from around two guard trees located at the respective ends of the experimental rows, so as to avoid disturbing the soil around the experimental trees. The guard trees were under the same irrigation regime as the experimental trees.

6.5.6 Chemical Analyses

After examining the results of the soil chemistry obtained between the guard trees, and between the edge of the drip-zone and directly under it, we decided to group the results as there were no differences between these groupings.

6.5.7 Microbiological Analyses

Soil samples were taken directly under the two drippers, and at the edge of the two drip-zones, of the two guard trees of each treatment during December 2017, some 2.5 years after the TSE treatments were imposed on both the Ghaf and Sidr trees. Laboratory analyses were carried out for Enterococci (CFU 100 mL^{-1}), faecal coliforms (CFU 100 mL^{-1}), and helminth eggs (eggs L^{-1}) to assess the risks of the use of TSE on human health.

6.5.8 Leaf Analyses

Leaf samples from Al Ghaf and Al Sidr were collected from the experimental trees. We took a random selection of leaves, about 10-20 from each tree, from around each quadrant of each tree. Leaf Sampling was done at four times: in 2015, 2016, 2017 during the period of April-June, and the final group of samples were taken on December 2017.

6.5.9 Stomatal Conductance.

A diurnal sequence of stomatal conductance, g_c (mmol m^{-2} s^{-1}), was carried out of the Sidr trees on the 26 September 2017, as this was the time at which trees' leaf area was near its maximum. The measurements were made from mid-morning through to mid-afternoon using a steady-state porometer (LI-1600, Licor) to measure the g_c. Because of the small and pinnate nature of the leaves of Al Ghaf, it was not possible to measure the g_c of those leaves. The coriaceous Sidr leaves are hypostomatous, with the stomata present only on the lower surface of the leaves.

6.5.10 The Light Stick

Given the lower EC, we anticipated that the TSE would most likely have a beneficial impact on tree growth and tree health. Our measurements of tree water-use, ET_c, would, we hypothesised, reflect this change in tree performance. However, we also sought a simpler means of inferring this response, and one that would have greater utility by measuring the tree canopy characteristics that might be affected by TSE. This would also extend to assess the impact of GWs of different salinities.

Lang (1987) developed a method of using the transmittance of the sun's beam through a tree's canopy to infer the canopy leaf area. Canopy radiation interception can be estimated from static, or mobile, arrays of quantum sensors using Beer's Law. Extending the method of Lang and McMurtrie (1992), we have developed a small, hand-held 'light stick' that can be used in an understory transit to record the percentage of light being transmitted through the canopy. The light-intercepted fraction (*LI*) from these light stick measurements provides a measure of the canopy density. The small light stick (Tranzflo NZ Ltd, Palmerston North, and NZ) is 200 mm long, with 4 equi-spaced quantum sensors that are sensitive to photosynthetically active radiation (PAR). The light stick was used to 'sweep out' the interior of each tree's shadow area, so that the light transmittance could be determined. The length and breadth of the perimeter of each tree's shadow area were measured at the same time. From time-of-day, the zenith angle of the sun is known, and it is then possible to compute the effective tree-shadow area. From the light stick we can infer the *LI* created by the leaves and woody structures that have intercepted the incoming radiation. Both the TSE and GW trees were measured for both species and this was carried out April, May, September, and December. These dates would enable us to capture the changing leaf areas of the trees at the beginning of leaf-fall, the maximum defoliation, and the maximum leaf area, respectively.

The light stick was used here to determine the impact of TSE on the changed growth habit of the Ghaf and Sidr trees that had previously been irrigated with GW. Also the *LI* is linked here to the crop factor, Kc, we inferred directly from the sap flow measurements.

6.6 Results and Discussion

6.6.1 Water, soil and leaf results

6.6.2 Water

The main differences between GW and TSE waters lay in their salt chemistries. The electrical conductivity of the TSE was less than 10% of that of the GW. The anion and cation chemistries reflected the high content of salts in the GW (Table 6.1).

Interestingly, especially from the perspective of plant growth, there is no significant difference between the nitrate contents in the GW and TSE. Both were very high, and well in excess of health guidelines for potable water. Fragaszy and McDonnell (2016) reported that high levels of nitrate occur naturally in the groundwater around Liwa, due to the low rates of plant uptake, high leaching, and the accumulation of precipitation-derived evaporites.

Table 6.1. The average properties of both the groundwater (GW) and treated sewage effluent (TSE) used for the irrigation of the Al Ghaf and Al Sidr trees. Samples were collected from the irrigation lines in both in 2015 and again in 2017. Here ns is statistically 'not significant' (P>0.05) and * is high significance (P<0.001).**

Al Ghaf and Al Sidr Water Analyses		**Groundwater**	**Treated Sewage Effluent**	
Inorganic Parameters	Units	Mean and Standard Deviation		
Conductivity	mS/cm	7.5 (0.9)	0.8 (0.04)	***
pH Value @ 20°C	pH units	7.9 (0.1)	7.9 (0.3)	ns
Anions				
Bicarbonate	mg/L	67.1 (4.7)	73.2 (4.0)	ns
Carbonate	mg/L	5.0 (0.1)	2.2 (0.3)	***
Nitrate	mg/L	38.4 (9.2)	53.7 (11.8)	ns
Sulphate	mg/L	778.3 (38.7)	65.3 (19.5)	***
Chloride	mg/L	1972.5 (372.1)	126.0 (13.1)	***
Cations				
Calcium	mg/L	189.5 (29.5)	31.8 (4.6)	***
Magnesium	mg/L	77.0 (14.8)	4.5 (0.6)	***
Sodium	mg/L	1272.0 (189.4)	95.9 (3.7)	***
Potassium	mg/L	48.2 (7.5)	12.0 (1.2)	***
Phosphorus	mg/L	-	2.6 (0.2)	
SAR		19.8 (3.4)	4.8 (0.9)	***

6.6.3 Soil

6.6.3.1 Chemistry

The key results for the salt chemistry found on saturated paste extracts are given in Table 6.2.

Table 6.2. The salt chemistry for the soil samples under the drippers of the groundwater (GW) and treated sewage effluent (TSE) irrigated Al Ghaf and Al Sidr trees. Here ECe is the electrical conductivity of the saturated paste extract, and SAR is the sodium adsorption ratio. Here ns is statistically 'not significant' (P>0.05), * is low significance (P<0.05), ** is medium significance (P<0.01), and * is high significance (P<0.001).**

		pH		ECe (dS/m)		SAR	
Ghaf	GW	7.6 (0.2)	ns	6.3 (3.7)	***	10.9 (3.6)	**
	TSE	7.5 (0.3)		2.4 (2.6)		5.4 (7.5)	
Sidr	GW	7.9 (0.3)	*	8.4 (9.4)	**	16.1 (14.6)	***
	TSE	7.7 (0.3)		1.9 (1.4)		4.4 (2.8)	

The salinity and the sodicity (Sodium Adsorption Ratio, SAR) values for soil samples taken under Al Ghaf and Al Sidr trees are higher in the soil irrigated with GW, than in the soil irrigated with TSE. This is to be expected because of the different salt chemistries of the two irrigation sources (Table 6.1). An interesting finding from the soil salinity values is that there is no build-up of salinity in the soil around the drippers. This confirms the *in situ* findings using EC probes we described in Al Yamani *et al.* (2018). The salt leaching fraction of 25%, with a factor-of-safety of 25%, appeared effective at leaching the salts from the dripzones of the GW-irrigated trees.

In addition to this salt chemistry, we determined the total nitrogen content of the soil wetted by the respective irrigation waters (Table 6.3). There were no differences in soil nitrogen content between the GW-irrigated soil, and the TSE-irrigated soil, and this was the same for both the Al Ghaf and Al Sidr trees. The high amounts of soil nitrogen reflect the high concentrations of nitrate in both the GW and the TSE waters, and the similarity in the nitrate concentration between these two irrigation sources. Thus it is not possible to attribute any differences in plant growth and performance to nitrogen nutrition.

Table 6.3. The total nitrogen concentration in the soil measured on saturated paste extracts for the wetted soil under the groundwater (GW) and treated sewage effluent (TSE) irrigated Al Ghaf and Al Sidr trees. Here ns is statistically 'not significant' (P>0.05).

		Total Nitrogen (mg/kg)	
Ghaf	GW	443 (189)	ns
	TSE	495 (389)	
Sidr	GW	326 (141)	ns
	TSE	334 (127)	

We also carried out analyses of the soil content of heavy metals and metalloids (Table 6.4). The results were equivocal. The only differences between the GW and TSE soil contents for the Ghaf were for zinc, chromium and fluoride, and all were highly statistically significant. The only differences between the soils at the Sidr site were for chromium (low significance) and fluoride (medium significance). In all cases, the GW-irrigated soil had the higher concentrations.

Table 6.4. The soil concentration (mg kg^{-1}) of various metals and metalloids in the groundwater (GW) irrigated soil, and the treated sewage effluent (TSE) irrigated soil under both the Al Ghaf trees and Al Sidr trees. Here ns is statistically 'not significant' (P>0.05), * is low significance (P<0.05), ** is medium significance (P<0.01), and * is high significance (P<0.001).**

Element (mg/ kg)		Zn		V		Mn		Pb		Cu		Co		Cr		As		F		Fe		Al		Ni	
Ghaf	GW	30.8 (17.8)	***	10.2 (2.2)	ns	112.4 (21.8)	ns	2.0 (0.4)	ns	5.6 (2.3)	ns	2.0 (0.3)	ns	21.0 (7.4)	***	1.4 (0.3)	ns	2.3 (1.1)	***	3238.0 (579.3)	ns	2703.5 (423.0)	ns	11.3 (1.9)	ns
	TSE	15.0 (8.9)		9.5 (1.5)		110.5 (16.1)		2.5 (2.3)		4.6 (2.8)		1.9 (0.2)		14.3 (4.3)		1.3 (0.2)		1.1 (0.3)		3177.5 (447.2)		2630.0 (370.8)		11.5 (1.9)	
Sidr	GW	15.6 (7.0)	ns	9.7 (1.8)	ns	110.5 (21.6)	ns	1.7 (0.2)	ns	4.2 (1.4)	ns	2.0 (0.3)	ns	15.7 (2.7)	*	1.2 (0.2)	ns	1.3 (0.9)	**	3207.0 (514.4)	ns	2644.5 (350.0)	ns	10.9 (1.7)	ns
	TSE	14.9 (8.5)		8.9 (2.1)		107.1 (23.7)		1.6 (0.3)		3.5 (0.8)		1.8 (0.4)		13.2 (4.2)		1.3 (0.2)		0.7 (0.2)		2994.0 (562.1)		2429.5 (420.2)		10.3 (1.8)	

6.6.3.2 Soil microbiology

No helminth eggs were found in the wetted soil of either treatment. Enterococci and faecal coliforms were found in virtually all samples from both treatments. There were no significant differences between the concentrations of either the Enterococci and faecal coliforms between the GW and TSE treatments. Thus, it would seem that the Enterococci and faecal coliforms are naturally occurring, and not derived from human sources via just the TSE. This forest is home to herds of desert gazelles, and there is abundant bird-life. These would seem to be the origin of these microbes. However, both plots had been fenced off for three years. So it would seem that the communities of these microbes are now living autonomously in the soil, as has been found elsewhere (Byappanahalli and Fujioka, 1998). Hartz et al. (2008) reported on the survival potential of Enterococci and faecal coliforms in sub-tropical beach sand. From our results, it now seems that they can also survive in the drip-zones of irrigated desert sands. The use TSE for irrigation of amenity forests would therefore seem not to pose a risk to human health.

6.6.4 Leaf

The bulked results in relation to the leaf macro-nutrients are given in Table 6.5.

Table 6.5. Analysis of the nutrient status of leaves sampled from both Al Ghaf and Al Sidr trees irrigated with either groundwater (GW) and treated sewage effluent (TSE). Here ns is statistically 'not significant' (P>0.05), and * is low significance (P<0.05)

		Al Ghaf			Al Sidr		
		Groundwater	Treated Sewage Effluent		Groundwater	Treated Sewage Effluent	
Leaf Nutrients	Units	Mean and Standard Deviation					
Nitrogen	mg/kg	1.9 (0.3)	1.9 (0.3)	ns	2.4 (0.3)	2.1 (0.5)	*
Phosphorus	mg/kg	1056 (304)	1129 (268)	ns	1056 (244)	1121 (252)	ns
Potassium	mg/kg	6396 (1388)	6937.8 (1485.5)	ns	7317 (1972)	8030 (1753)	ns

There were no significant differences in P and K values between the irrigation treatments for both Al Ghaf and Al Sidr. There was a difference of low statistical significance between the leaf N concentrations in Al Sidr trees. But it was the GW-irrigated trees that had the higher N amounts. Thus we conclude that any differences that we observed between the TSE and GW irrigated trees were not due to the amounts of nutrients in the TSE-irrigated trees.

6.6.5 Al Ghaf transpiration – GW and TSE

Sap flow data for the four GW irrigated Ghaf trees began on 12 December 2014, and continued over three years through until early 2018 (Figure 6.1). The daily measured tree water use values, *ET*c (L d^{-1}), are presented along with the daily values of the reference evapotranspiration, *ET*o (mm d^{-1}) The first two years of these data were presented by Al Yamani et al. (2018), and we present the extended three-year data set here for completeness to enable comparison with the TSE values (Figure 6.2). The TSE treatment began on 18th May 2015.

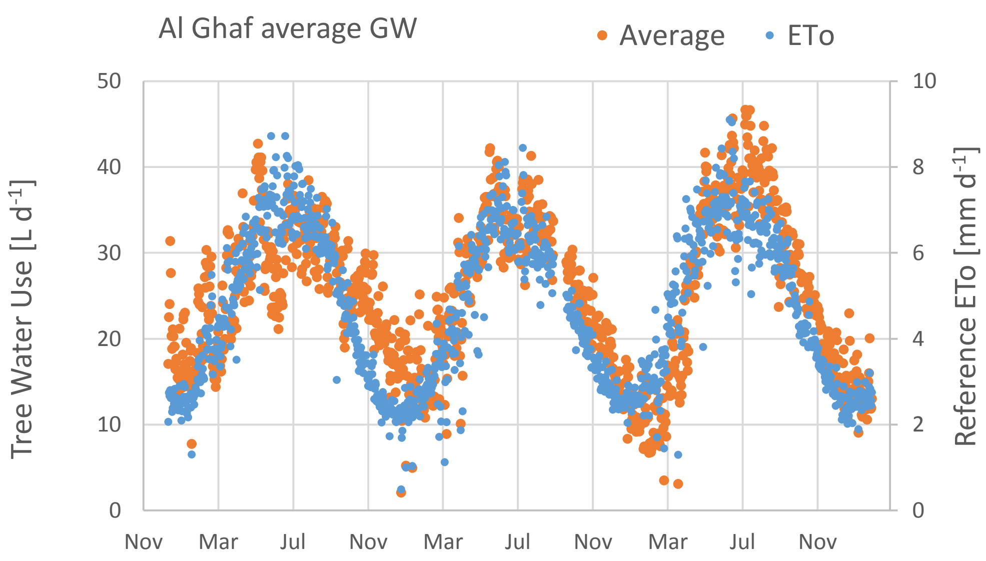

Figure 6.1. The seasonal pattern from 2015 to early 2018 of the average of the daily water-use *ET*c (red dots, left axis in L d^{-1}) from measurements made every 30 minutes on all four groundwater (GW) irrigated Al Ghaf trees in relation to the reference evapotranspiration *ET*o (blue circles, right axis in mm d^{-1}). This GW water-use data extends by the year the results presented by Al Yamani *et al.* (2018).

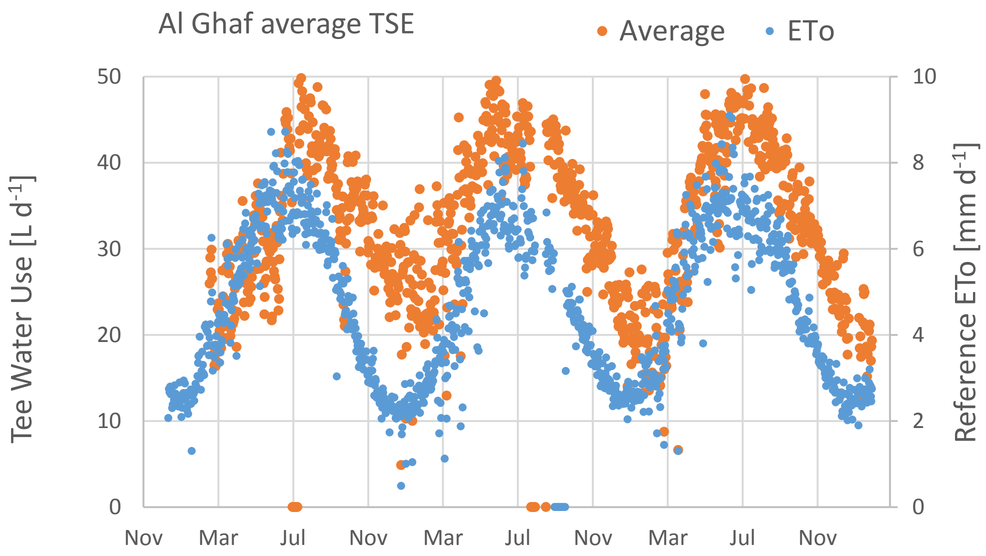

Figure 6.2. The seasonal pattern from 2015 to early 2018 of the average of the daily water-use *ET*c (red dots, left axis in L d^{-1}) from measurement made every 30 minutes on all four treated sewage effluent (TSE) irrigated Al Ghaf trees in relation to the reference evapotranspiration *ET*o (blue circles, right axis in mm d^{-1}).

Over the last 7 months of 2015, despite the TSE being applied to the treatment trees, there was no difference in their *ET*c relative to that of the GW trees. Both the GW and TSE patterns of *ET*c tracked *ET*o. However, during the early months of 2016, the TSE trees' *ET*c increased relative to previous tracking with *ET*o, and became relatively greater than the *ET*c of the GW trees. This divergence became clearer when we calculated and compared the crop factors, *K*c, for the GW and TSE trees. In Figure 3 is shown the annual variation in the *K*c of the GW trees and this data set comprises over 3 years of daily measurements, which is one more year than the equivalent data set previously presented by Al Yamani *et al.* (2018). There was a muted seasonal pattern due to the asynchrony of the deciduous behaviours of the various trees. Peak leaf area occurred in December-January, and there was leaf fall in February. Over the 3 years the annual average *K*c for the GW trees was 0.110 (±0.03, n=1127).

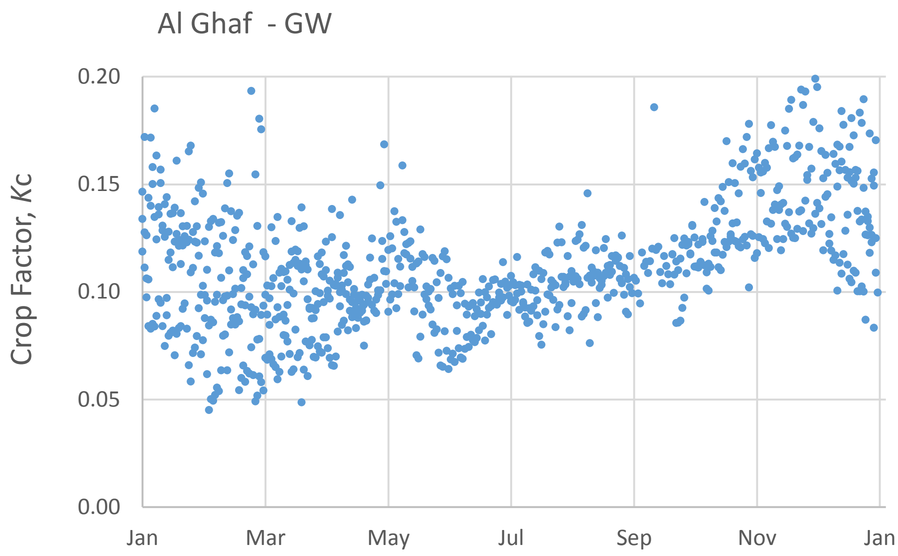

Figure 6.3. The average daily crop-factor, *K*c (=*ET*c/*ET*o), for the Ghaf trees irrigated with groundwater (GW) over the three years of 2015 through to early 2018. These *K*c data include an extra year's results from those presented by Al Yamani *et al.* (2018).

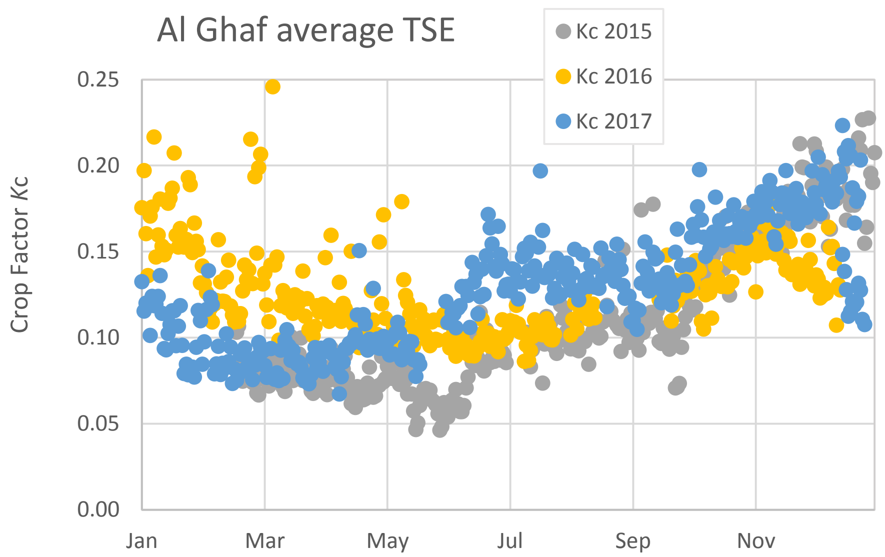

Figure 6.4. The average daily crop-factor, *K*c (=*ET*c/*ET*o), for the Ghaf trees irrigated with treated sewage effluent (TSE) over each of the years 2015 (grey dots), 2016 (yellow dots), and 2017-early 2018 (blue dots). The TSE irrigation began in May 2015, and previously the trees had been irrigated with groundwater (GW).

The annual seasonal patterns in the *K*c values for the TSE trees are shown in Figure 6.4 for the calendar years of 2015, 2016 and 2017. Unlike for the GW trees (Figure 6.3) there was a separation in behaviours between years for the TSE trees (Figure 6.4). The annual average *K*c for 2015 for the TSE trees was 0.112 (±0.03, n=309), which was no different from that of the

GW trees. However, in the year after beginning TSE irrigation there was greater vegetative vigour, and less defoliation, especially during January-May 2016. The 2016 annual average *K*c was 0.127 (±0.027, n=310) which was significantly (P<0.001) higher than the 2015 average value. For 2017, the annual average *K*c was 0.129 (±0.035, n-358), which was not significantly different from the 2016 value.

Thus our sap-flow measurements have revealed that TSE increased the trees' leaf growth such that the *K*c of the TSE trees became 17% higher than that of the GW trees. We were not able to discern any visual differences between the treatment trees, and this difference was made detectable only through our sap-flow measurements.

6.6.6 Al Sidr transpiration – GW and TSE

Our measured *ET*c for each of the four multi-stemmed Sidr trees was computed using our baseline measurements of sapflow in the four monitored trees of each treatment. Before we began to analyses the impact of TSE on the water use of the Sidr trees, we re-visited the crop-factor results of Al Yamani et al. (2018) for the GW-irrigated trees. Al Yamani et al. (2018) presented the 2015 and 2016 *K*c data as one, here we have split the two years to show the difference in the vegetative vigour between the years (Figure 6.5). It can be seen that in January to April 2015 was an 'on' fruiting year, with low vegetative vigour, whereas 2016 was an 'off' fruiting year, with high vegetative vigour. The 'on-off' year behaviour in 2015 and 2016 affected the comparison we wished to make with the TSE trees immediately upon commencement of the treatment.

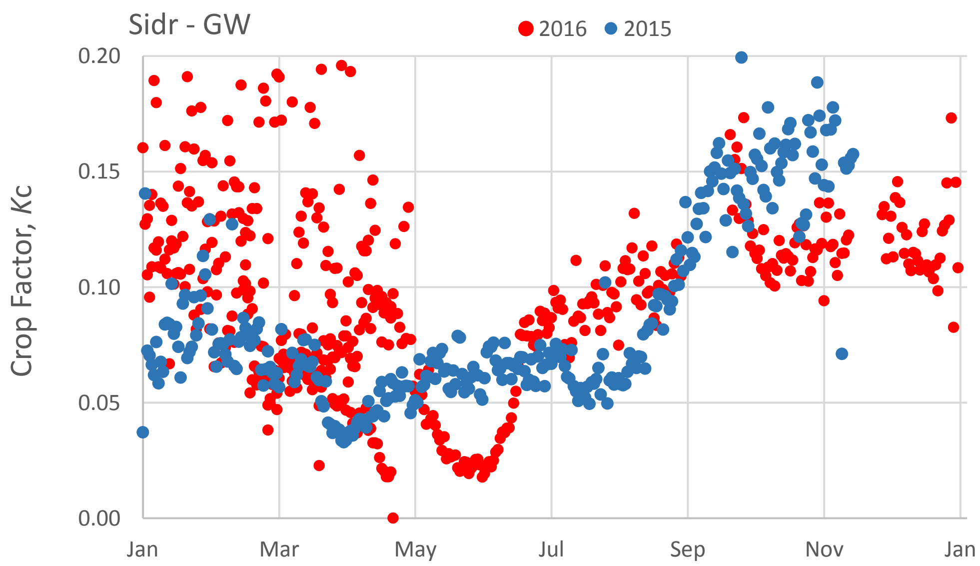

Figure 6.5. The average daily crop-factor, *K*c (=*ET*c/*ET*o), for the Sidr trees irrigated with groundwater (GW) over each of the years 2015 (blue dots), and 2016 (red dots). These 2015-2016 data were presented by Al Yamani *et al*. (2018) without separating the years. Here we have separated the years 2015 and 2016 to show the difference in the *K*c during an 'on' year for vegetative vigour (2016) and an 'off' year for vegetative vigour (2015).

In Figures 6.6 and 6.7 we present the actual average tree water uses, *ET*c (L d^{-1}), of the GW and TSE Sidr trees, Also shown in these figures are the actual daily amounts of irrigation applied to each of the trees, noting that a zero value does not always mean 'no irrigation' because sometimes there was a flowmeter malfunction. By comparison of Figures 6.6 and 6.7, it can be seen that in early 2015 the *ET*c of the TSE trees was already greater than that of the GW trees before the TSE treatment was commenced on 18th May. This difference was due to the lower vegetative vigour of the GW trees in the 'off' fruiting year of 2015 (Figure 6.5).

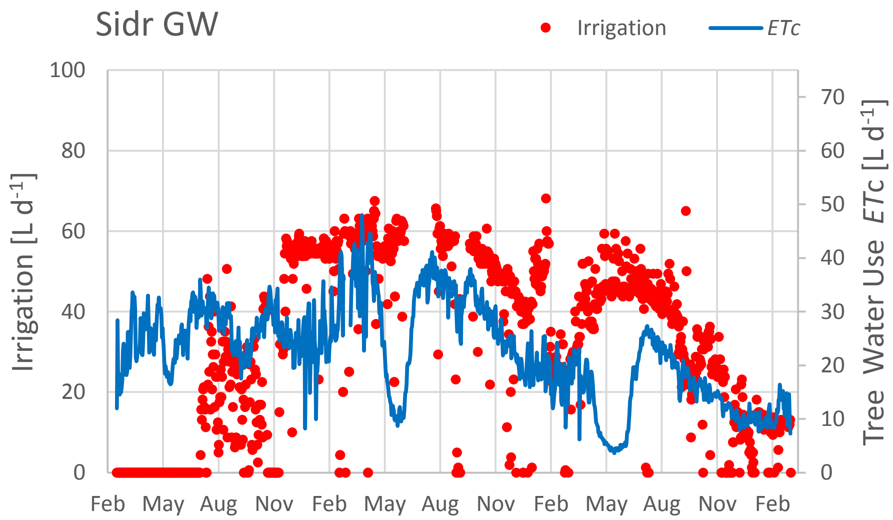

Figure 6.6. The daily average water-use of the groundwater (GW) irrigated Sidr trees, *ET*c (blue line, L d^{-1}), from measurements every 30 minutes made over the years 2015 until early 2018. Also shown is the amount of water applied on average to each of the trees (red dots) as measured using an in-line flowmeter. A zero reading here often indicates a flowmeter malfunction rather than an absence of irrigation.

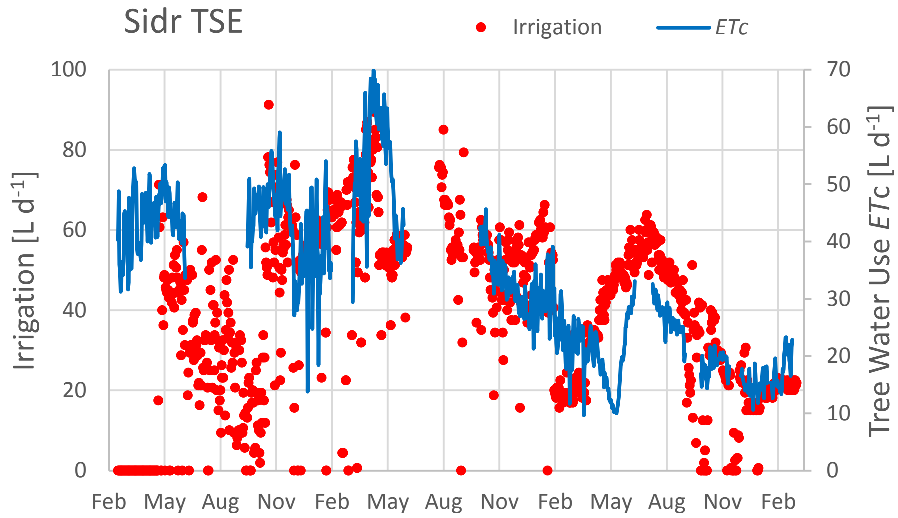

Figure 6.7. The daily average water-use of the treated sewage effluent (TSE) irrigated Sidr trees, *ET*c (blue line, L d^{-1}), from measurements every 30 minutes made over the years 2015 until early 2018. Also shown is the amount of water applied on average to each of the trees (red dots) as measured using an in-line flowmeter. A zero reading here often indicates a flowmeter malfunction rather than an absence of irrigation. The TSE irrigation began in May 2015, and previously the trees had been irrigated with groundwater (GW).

During 2016, we provided EAD with advice that considered the sustainable irrigation of arid forest trees would be at the rate of 1.5 *ET*c, allowing for a factor-of-safety of 25%, and a salt-leaching fraction of 25%. We decided to test this schedule experimentally on the Sidr trees in 2017. Figures 6.6 and 6.7 shows the reduced rates of irrigation with a summer peak rate of irrigation dropping to about 45 L d^{-1}.

Thus the 2017 data provide us with a good comparison of the impact of TSE of Al Sidr tree water use. Over the year from 1 March 2017 to 1 March 2018, we applied an average of 30 L d^{-1} of irrigation to the GW trees, and 33 L d^{-1} to the TSE trees. So within our ability to manage the irrigation, we essentially applied the same amount of water to both treatments of around 30 L d^{-1}, being half of what is current practice of 60 L d^{-1}. Over that year, the GW trees transpired on annual average 14.4 (± 3.0) L d^{-1}, whereas the TSE trees transpired on average 20.0 (± 7.2) L d^{-1}, a rate that was 39% higher. Therefore, TSE irrigation could be even further reduced below 30 L d^{-1}, to achieve a similar ‘tree-health’ outcome as the GW trees.

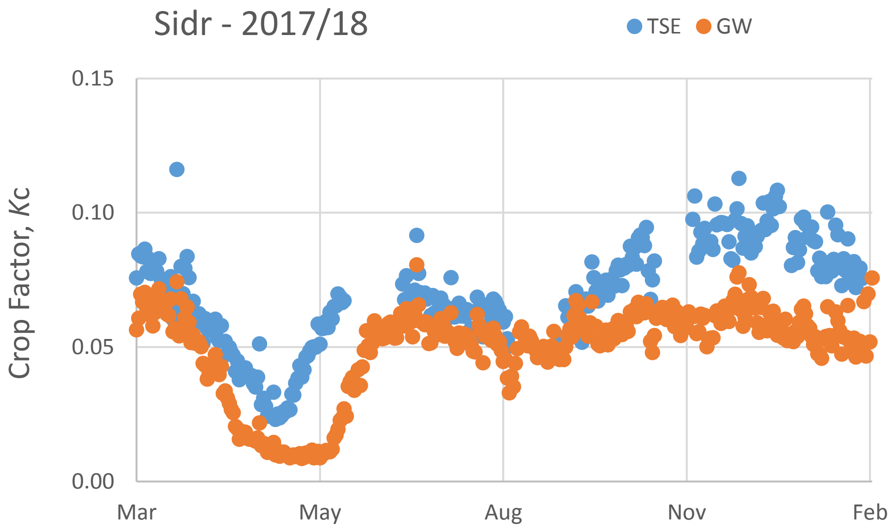

Figure 6.8. The average daily crop-factor, *K*c (=*ET*c/*ET*o), for the Sidr trees irrigated with groundwater (GW - orange dots) and treated sewage effluent (TSE – blue dots) over of the year 2017 and early 2018. The TSE irrigation began in May 2015, and previously the trees had been irrigated with GW. During this year 2017-18, irrigation was restricted to both trees at a rate of 1.5 *ET*c, on monthly average.

In Figure 6.8, we show the seasonal trend in the respective crop factors over 2017-18 for the GW and TSE-irrigated trees. As expected the *K*c for the TSE trees was always higher than that of the GW trees. Furthermore, the deciduous loss of leaves in early April was not as severe for the TSE trees, and the re-emergent leaf growth occurs sooner, and more vigorously, in May. Under this reduced-irrigation regime, the annual average *K*c for the GW trees was 0.056, whereas it was 0.070 for the TSE trees.

In Figure 6.9, we show the comparison between two trees and their maximum deciduous defoliation. Tree 5 (left) is a GW-irrigated tree, and Tree 8 (right) is TSE irrigated. There were more viable and green leaves on the TSE tree at this time. In Figure 6.10, we show these same two trees at a time when they were approaching their maximum leaf area in late September. The greater leaf area of the TSE tree is obvious, and we draw attention to the differing sizes and light 'densities' of the respective tree shadows.

Figure 6.9. Left. Sidr Tree 5 that is groundwater irrigated (GW). Right. Sidr Tree 8 which is treated sewage effluent irrigated (TSE). These photographs were taken on 26th April 2017 at a time of deciduous leaf fall.

Figure 6.10. Left. Sidr Tree 5 that is groundwater irrigated (GW). Right. Sidr Tree 8 which is treated sewage effluent irrigated (TSE). These photographs were taken on 26th September 2017 at a time of maximum canopy leafiness.

6.6.7 Stomatal Conductance, g_c

During mid-morning to mid-afternoon on the 25 September 2017 we carried out measurements of g_c on the GW and TSE Sidr trees. For the TSE trees we found the average g_c to be 17.7 mmol m^{-2} s^{-1} (SE ±2.2, n= 19) and that for the GW trees was 8.1 mmol m^{-2} s^{-1} (SE ±1.5, n= 17). The difference was significant ($P<0.05$). The GW trees had a lower g_c, presumably as a result of their lower and more negative osmotic water potential resulting from the irrigation with more saline groundwater. This difference in g_c would explain the different tree productivities (Figures 9 and 10). Both these conductance values are very low, as befits a xerophytic halophyte like Sidr (*Ziziphus*) growing under conditions of high temperatures combined with very low atmospheric humidity. The relative humidity was around 10% at noon and the air temperatures were > 45C. Arndt *et al.* (2011) reported low g_c values for *Ziziphus rotundafolia* growing under controlled conditions in pots. For their severe water-stress treatment water was withheld, and the leaf water potential dropped to -2

MPa after 20 days, at which time the osmotic potential was -2.3 MPa. Between 15 and 28 days, they measured the stomatal conductance of these stressed *Ziziphus* trees to be between 5-15 mmol m^{-2} s^{-1}. Although our stomatal conductance measurements were carried out only over a single day, they do indicate that the GW trees were under greater water stress than the TSE trees that were irrigated with lower salinity water. This difference in stomatal conductance would seem to account for the greater productivity of the TSE trees.

6.6.8 Light Stick and the Crop Factor

The *LI* results are presented in Table 6.6. For the GW-irrigated Ghaf trees the *LI* was at its lowest of 0.26-0.28 during leaf-fall in April-May, and rose to 0.30 in December at the time of maximum leafiness. There was also a seasonal change in the TSE-irrigated Ghaf trees, albeit somewhat muted. The TSE trees had a significantly greater ($P < 0.05$) *LI* than the GW trees by 11%.

A similar seasonal pattern in *LI* was found the Sidr trees for both treatments (Table 6.6). The *LI* for the TSE trees was twice that of the GW trees, and this difference was significant ($P < 0.0001$).

Table 6.6. Calculations of the trees' shadow areas from length and breadth measurements in mid-morning, and the fractional light interception (*LI*) obtained using the light-stick at various times during 2016 and 2017. These measurements are the average for the four treatment trees of each treatment for the Ghaf and Sidr experiments.

Al Ghaf: Groundwater		
Date	Shadow area (m^2)	Light interception fraction, *LI*
25 April 2017	22	0.26
26 April 2017	22	0.28
25 May 2016	22	0.27
25 September 2017	22	0.30
26 September 2017	22	0.30
9 December 2017	22	0.28
	Average (± SD)	0.28 (±0.02)
Al Ghaf: Treated Sewage Effluent		
Date	Shadow area (m^2)	Light interception Fraction, *LI*
26 April 2017	23	0.30
25 May 2016	23	0.30
25 September 2017	23	0.31
26 September 2017	23	0.31
9 December 2017	23	0.31
	Average (± SD)	0.31 (±0.01)

Al Sidr: Groundwater		
Date	Shadow area (m^2)	Light interception fraction, *LI*
26 April 2017	8	0.08
25 May 2016	8	0.09
25 September 2017	8	0.10
26 September 2017	8	0.09
27 September 2017	8	0.10
10 December 2017	8	0.10
	Average (± SD)	0.09 (±0.01)
Al Sidr: Treated Sewage Effluent		
Date	Shadow area (m^2)	Light interception fraction, *LI*
26 April 2017	14	0.18
25 September 2017	14	0.18
26 September 2017	14	0.18
27 September 2017	14	0.19
10 December 2017	14	0.19
	Average (± SD)	0.19 (±0.004)

The light stick has clearly picked up the leaf-growth responses to TSE by both species through measuring *LI*. However, the seasonal changes in *LI* were less than anticipated from our visual observations of the changing leafiness (Figure 9 and 10). This is due to the characteristic canopy architecture of both species. The leaves of Al Ghaf and Al Sidr (Figures 9 and 10) are small and numerous on the many structural branches of the trees. So even during leaf fall there was a substantial degree of light interception by the woody branches of the tree (Figure 9, left). This woodiness explains the muted seasonal response in the measured *LI* despite the changing leaf area.

Studies have linked the easily-measured value of *LI* to the crop factor *K*c in order to predict tree water-use, *ETc*, using the inferred *K*c in the formula: $ETc = Kc \cdot ETo$. The ratio $Kc\ LI^{-1}$ has been found to be in the range of 1-1.2 for well-watered trees horticultural trees (Goodwin *et al*., 2006; O’Connell et al. 2008; Goodwin et al., 2015; Al Muaini et al., 2018).

The annual average *K*c values of the Ghaf trees in 2017 were 0.110 and 0.129 for the GW and TSE treatments respectively. So the $Kc\ LI^{-1}$ values are 0.39 and 0.42, much less than the 1-1.2 that has been reported. For the Sidr trees the *K*c values were 0.056 and 0.07 for the GW and TSE treatments. Their $Kc\ LI^{-1}$ values are therefore 0.62 and 0.37, which are again much less than those already reported.

We consider there are two reasons why these *K*c LI^{-1} values are less than half of those reported by others. Firstly, as noted above, there was a significant contribution of the woody branches of these arid-forest species in the measured *LI*. This woody infrastructure does not contribute to transpiration, and is not reflected in the *K*c. Secondly, both Al Ghaf and Sidr are xerophytic halophytes, and would have been under salt stress under our treatments. We measured very low stomatal conductances for Al Sidr, which we considered to be typical of *Ziziphus* trees at low water potentials (≈ -2 MPa) and low osmotic potentials (≈ - 2 MPa) (Arndt et al., 2001). Thus the ratio *K*c LI^{-1} is much lower for our arid-forest trees than the well-watered value of 1-1.2 for horticultural trees, because of water stress resulted in a lower *K*c, and because our *LI* value was higher though the influence of non-leaf interception of light by the woody parts of the trees.

Nonetheless, the consistent values of *K*c $LI^{-1} \approx 0.4\text{-}0.6$ for these arid-forest species does appear to provide a simple basis for using the light-stick measurements to infer the crop factor. We are examining this further for another arid-forest species; Al Samr.

6.6.9 Irrigation requirements

Current practice at Khub Al Dhas forest is to irrigate both the Ghaf and Sidr trees with 60 L d^{-1} of groundwater. Implementation of Abu Dhabi's Law 5 requires that irrigation be allocated at the minimum amount required to achieve the desired goal. In Yamani *et al*. (2018) we provided an irrigation allocation schedule for GW to both the Ghaf and Sidr trees which suggested a monthly schedule of 1.5 *ET*c, and was based on 25% factor-of-safety, and a 25% salt-leaching fraction. Our results here show that with TSE, the 25% requirement for a salt-leaching fraction could be dispensed with. So for TSE the suggested schedule now becomes the 1.25 *ET*c column in Table 1 of Al Yamani *et al*. (2018). That means that on an annual average basis, the Al Ghaf trees only need 34.9 L d^{-1} of TSE, and the Sidr trees only need 29.3 L d^{-1}. Furthermore, if the desire were to use TSE to achieve the same tree productivity as for the GW trees (Figures 9 and 10), then this rate of TSE could be even reduced further because of the beneficial impact of the 'sweeter' TSE.

6.7 Conclusions

The arid forests in the hyper-arid deserts of Abu Dhabi require irrigating. Saline groundwater is the predominant source for the irrigation water, and the current practice is to irrigate Al Ghaf and Al Sidr trees using 60 L of groundwater every day of the year. In Al Yamani et al.

(2018) we proposed an allocation schedule for irrigation using saline GW that was based on 1.5 *ET*c accounting for a 25% factor-of-safety and a 25% salt leaching fraction.

We now update these recommendations for TSE. These irrigated arid forests require considerably less water than current practices for both GW and TSE. The low salt content of the TSE means that far less extra water is required when using TSE instead of GW, to achieve similar plant growth to that achieved with current irrigation. These changes represent a 50-60% reduction in water application from current practices. In addition, using an alternative water source like TSE will reduce the drawing down of the finite groundwater reserves and protect the remaining aquifer stocks of water.

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CHAPTER 7

7 Water Use of Al Samr (*Acacia tortilis*) Forests Irrigated with Saline Groundwater and Treated Sewage Effluent in the Hyper-Arid Deserts of Abu Dhabi.

Al Samr is the third native species considered in this research. To complete the work from Chapter 6 on Al Ghaf and Al Sidr, here the water use of Al Samr is measured under the same experimental conditions using the same techniques. Al Samr trees have a very low leaf area, and more woody infrastructure than the Ghaf or the Sidr, thus the maximum *ET*c of Al Samr was found to be around 10 L d^{-1}. This is a very low value compared to the other studied species. Therefore, it is recommended that the irrigation allocation for Al Samr, when using GW, should be just 15 L d^{-1}. When using TSE this needs to be just 12.5 L d^{-1} for there is no need for the 25% salt-leaching fraction.

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7.1 Abstract

The arid forests planted in Abu Dhabi provide a variety of valuable ecosystem services. The forests need to be irrigated, and currently groundwater (GW) provides the bulk of this water. However GW recharge is very low, and reserves are rapidly dwindling and becoming more saline. In 2016, Law 5 was passed in Abu Dhabi with the objective to set GW extraction limits and define irrigation-usage allowances. Here we sought to define the usage allowance for Al Samr trees, and this work complements our previous research on Al Ghaf and Al Sidr forests. We have measured tree water-use, *ET*c, using sapflow monitoring of GW-irrigated trees, and trees irrigated with treated sewage effluent (TSE). Maximum rates of tree water-use, *ET*c, were found to around 10 L d^{-1}, and there are two distinct deciduous periods where *ET*c briefly dropped below 2- L d^{-1}. The total annual water use of the TSE-irrigated trees was 2.2 kL y^{-1}, which is about 25% higher than the 1.8 kL y^{-1} for the GW-irrigated trees.

For Law 5, we recommend that the irrigation allocation for Al Samr trees be simply based on a constant *ET*c of 10 L d^{-1}. So for GW irrigation, allowing for a 25% factor-of-safety, and a 25% salt-leaching fraction, the recommended allocation would be 15 L d^{-1}. This represents a saving of 75% from the current practice of irrigation 60 L d^{-1}. For TSE, without the need for salt leaching, the irrigation allocation would only need to be 12.5 L d^{-1}.

Research Highlights

- Al Samr forests in the hyper-arid deserts of Abu Dhabi require groundwater irrigation
- Through Law 5 groundwater (GW) allocation for forest irrigation is being controlled
- Measured water use of Al Samr is low at 3-10 L d^{-1}, < 15% of that being applied now
- Water use of Al Samr irrigated with treated sewage effluent is 25% higher than GW
- We show proximal sensing of tree shadows can be used to predict Al Samr water use
- We recommend that irrigation allocation for GW be 15 L d^{-1}, and 12.5 L d^{-1} for TSE

7.2 Introduction

In the 1970s, the late Sheikh Zayed bin Sultan Al Nahyan, the founding father of the United Arab Emirates, embarked on a programme of greening of the desert. The planted forests provide a variety of valuable ecosystem services. However, the forests need to be irrigated. They are in a hyper-arid environment where annual evapotranspiration exceeds 1900 mm y^{-1} and rainfall is often less than 60 mm y^{-1}. The main source of the water for irrigation is currently groundwater (GW). However GW recharge is very low, and reserves are rapidly dwindling and becoming more saline. In 2016, Law 5 was passed in Abu Dhabi with the objective to set GW extraction limits and define usage allowances. Our work here seeks to provide Law 5 with the GW irrigation allowance for Al Samr forests, and this complements our previous GW allocation work on Al Ghaf and Al Sidr forests (Al Yamani et al. 2018a).

There are some 93,000 ha of planted forests in Abu Dhabi, comprising some 20 million trees. Al Samr forests contain over 800,000 trees, or about 15% of the planted forest trees. Al Samr is the fourth most-planted forest species, yet the second most prevalent natural species.

Treated sewage effluent (TSE) is being considered as an alternative to groundwater (GW). Here we also assess the irrigation requirements of Al Samr trees for TSE. This TSE work complements that by Al Yamani et al. (2018b) on Al Ghaf and Al Sidr forests.

As well, we show how proximal sensing of the shadow cast by the trees' canopy using a light-stick can be used to predict tree-water use and irrigation requirements.

7.3 Materials and Methods

The experiments carried out over 2016-2017 with the Al Samr trees took place near Madinat Zayed within the same forest of Khub al Dahs (23.51º N, 53.75º E) as the research carried by Al Yamani et al. (2018 a,b) on Al Ghaf and Al Sidr. Although this work was carried out over about one year, the results from Al Yamani et al. (2018 a,b) show that in this hyper-arid desert environment, the year-to-year variation in weather is negligible, especially in relation to the large within-year variation in water-use due to the trees' different phenological stages.

7.3.1 Soil and species

The soil is a Typic Torripsamment, mixed, hyperthermic (Soil AD158) (EAD, 2009).

The Al Samr tree is a multi-stemmed halophytic xerophyte. Multiple branches emanate from the tree's base at the soil surface and are without leaves for the first metre, or so (Figure 7.1). The leaves are small and bipinnate with up to 6 pinnae, and with 6-10 leaflets on each pinna. The trees are deciduous with a major leaf-fall in spring followed by flowering into early summer.

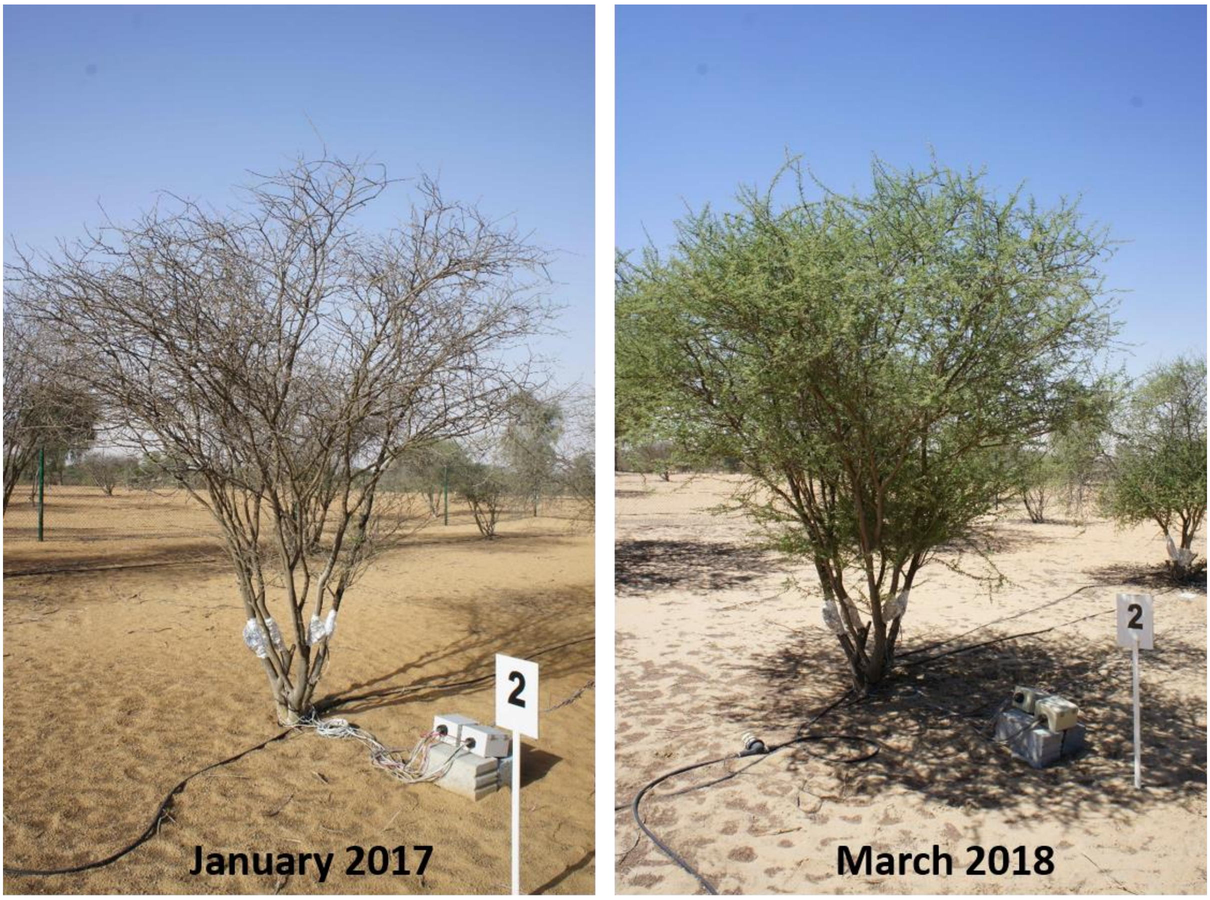

Figure 7.1. Left. Tree 2, which is irrigated with treated sewage effluent (TSE), is shown after leaf-fall in January 2017. Four sets of heat-pulse probes can be seen wrapped in protective aluminium foil in the branches. The tree shadow area to the right can be seen to be dominated by the woody infrastructure of the tree. Right. The same tree seen at

full leaf in March 2018. The increased density of the tree's shadow area can be seen as a result of the leafiness.

7.3.2 Sapflow and Light-Stick

Three GW-irrigated trees were instrumented, as were three TSE-irrigated trees. Details of the sapflow-measurement technique are given in Al Yamani et al. (2018a). Like our earlier measurements on the multi-stemmed Al Sidr trees (Al Yamani et al. 2018b), either 3 or 4 sets of probes were installed in the branches of each instrumented Al Samr tree, as can be seen in Figure 1. The measured flow in each stem was turned into a flux density using the stem cross-sectional area. All the branches of each tree were then measured to find the diameters of each of the stems. The total water use of the tree was then calculated from the measured total cross-sectional areas of all the branches and the measured sap-flux density.

We used the small light-stick described in Al Yamani et al. (2018b) to measure the light interception by the trees' canopies, *LI* (%). These *LI* data will be used to infer the crop factor, $K\text{c} = ET\text{c} / ET\text{o}$, where *ET*c is the trees' water use (mm d^{-1}) and *ET*o is the reference evapotranspiration (mm d^{-1}) (Allen et al. 1998). So from the measured *LI* and *ET*o, it will be possible to predict, using proximal sensing with the light stick, Al Samr tree water-use *ET*c via an inferred *K*c.

7.4 Results and Discussion

7.4.1 Water Use and the Measured Crop Factor

The seasonal pattern in the reference evapotranspiration, *ET*o, is shown in Figures 7.2 and 7.3. The weather is virtually always cloud-free, and rainfall is negligible, so there is annual trend that is dominated by the seasonal pattern of incident radiation.

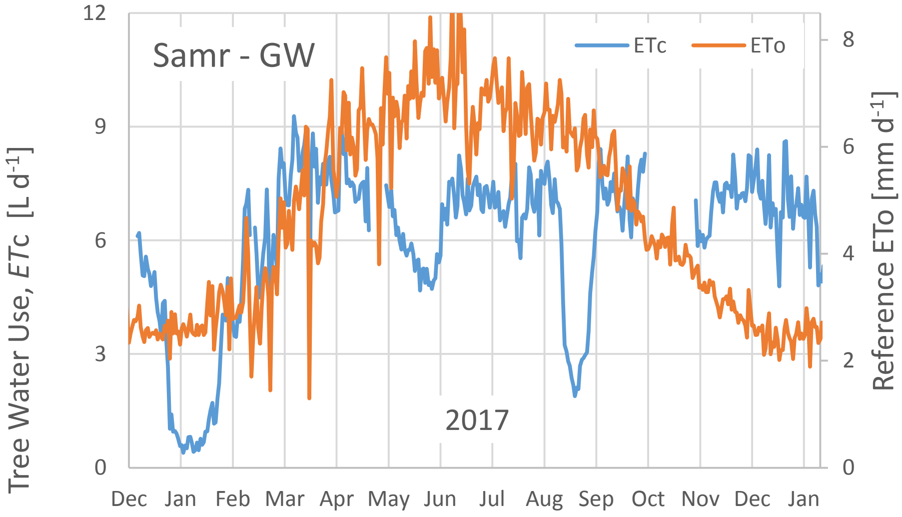

Figure 7.2. The seasonal pattern in the reference evapotranspiration, *ET*o (mm d^{-1}), is shown as the red line, and the measured average tree water-use, *ET*c (L d^{-1}) of the three instrumented Samr trees irrigated with groundwater (GW) is shown as the blue line.

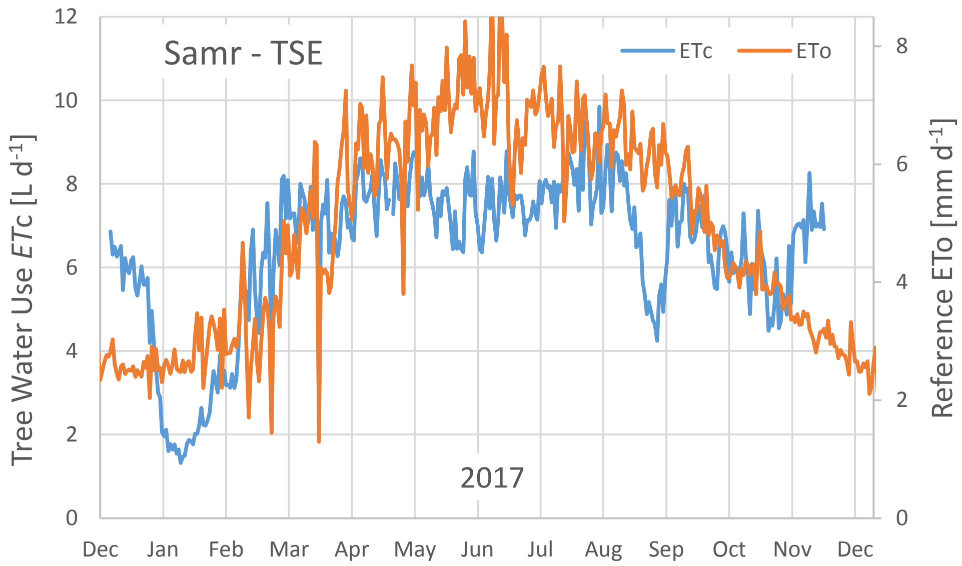

Figure 7.3. The seasonal pattern in the reference evapotranspiration, *ET*o (mm d^{-1}), is shown as the red line, and the measured average tree water-use, *ET*c (L d^{-1}) of the three instrumented Samr trees irrigated with treated sewage effluent (TSE) is shown as the blue line.

The seasonal pattern of Al Samr tree water-use, *ET*c, for the GW-irrigated trees (Figure 7.2) and TSE-irrigated trees (Figure 7.3) is not directly connected with that of *ET*o. There is a distinct drop-off in *ET*c for both treatments during early January, as the trees lose their leaves prior to flowering (Figure 1). There is also a secondary, but lesser, deciduous loss of leaves in late August-early September. We have observed a similar bi-modal deciduous behaviour in Al Sidr trees (Al Yamani et al., 2018a).

In addition, we observed a drop in *ET*c only for the GW-irrigated trees in May (Figure 7.2). This, we consider, is due to leaf-eating pests. Al Samr trees are known to be a target for leaf-defoliating pests such as the *Julodis* sp. of beetle, and the Lepidoptera *Baralade similes*. It will be unlikely that such drops in *ET*c could be incorporated in irrigation allocations for Law 5, and we report this here as an interesting observation.

Irrespective, the measured water-use values of both treatments is very low, being between 3-10 L d^{-1}. This is well less than the current practice of applying 60 L d^{-1} of irrigation. Substantial water savings are possible. The water use by the GW trees over the year was 1.8 kL y^{-1}, whereas the TSE used 2.2 kL y^{-1}, and increase of 25% due to the lower salinity of the TSE, which is a similar response to that we found for the Al Ghaf and Al Sidr trees (Al Yamani et al., 2018b).

From the measured water-uses by the GW and TSE trees, *ET*c, we can compute the crop factor, *K*c, using the monitored weather data of the reference *ET*o. These results are shown in Figure 7.4, and seasonal patterns reflect the deciduous phenology of the Samr trees, and the likely effect of leaf defoliation of the GW trees by pests. These are very low *K*c values, reflecting the wide spacing and low leaf area of the trees. The annual average *K*c values for the GW trees is 0.019, and 0.021 for the TSE trees (Table 7.1).

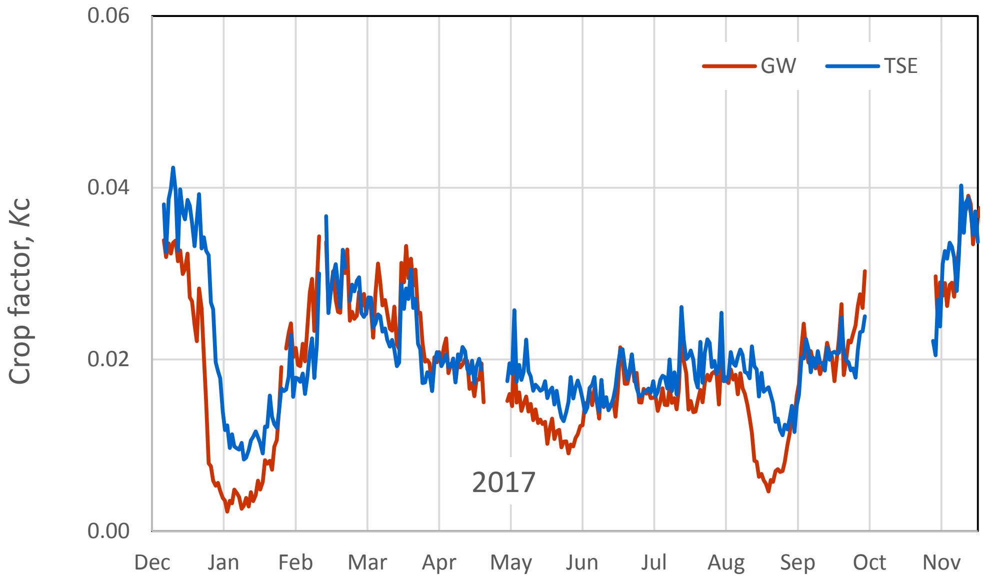

Figure 7.4. The average seasonal pattern in the crop factor, *K*c (= *ET*c / *ET*o), for the three Samr trees irrigated with groundwater (GW) (red line), in relation to the three Samr trees irrigated with treated sewage effluent (TSE) (blue line).

7.4.2 Predicting the Crop Factor

The challenge for implementation of Law 5 is to predict tree water use, *ET*c, and infer irrigation requirements without having to carry out such detailed sapflow measurements as we have done here. Proximal sensing of the trees' light interception provide a means to infer the crop factor *K*c and permit prediction of *ET*c. Goodwin et al. (2015) and O'Connell et al. (2008) found the relationship between the ratio of *K*c and *LI* to be 1-1.2 for pears and apples, respectively, and Al Muaini et al. (2018) found it to be 1-1.1 for dates in Dubai. Using this empirical link, it is then possible to predict the crop factor from the proximally sensed *LI* to predict the seasonal variation in *ET*c from *ET*o measurements made at a weather station. For the halophytic xerophytes of Al Ghaf and Al Sidr, Al Yamani et al. (2018b) from the $Kc\ LI^{-1}$ ratio to be lower at 0.4-0.6, due to the smaller nature of the leaves relative to the woody infrastructure of the trees, and also due to the level of salt and water stress of these irrigated tree species near Madinat Zayed.

We present in Table 1 our measurements of the seasonal trend in *LI* for both the GW and TSE-irrigated Al Samr trees. There is a very muted seasonal pattern, as the woody infrastructure of the tree, with its small leaves, dominates the trees' shadow pattern, as can be seen by comparison of the two trees shown in Figure 7.1. There is a very low light-interception of just 0.17-0.18 by the Samr trees, with no significant difference between the treatments.

Table 7.1. The light interception fraction (*LI*) measured using the light stick on 5-6 occasions under the three groundwater-irrigated (GW) trees, and the three treated sewage effluent (TSE) irrigated trees. Also shown is the annual average crop factor, *K*c, measured for these treatment trees, along with the annual average ratio of *K*c LI^{-1}.

	Groundwater	**Treated Sewage Effluent**
Date	Light Interception, *LI* (-)	Light Interception, *LI* (-)
26-Apr-17	0.16	0.16
25-May-16		0.17
25-Sep-17	0.17	0.18
26-Sep-17	0.17	0.18
27-Sep-17	0.17	0.19
10-Dec-17	0.18	0.19
Mean *LI* (-)	**0.17**	**0.18**
Crop factor, *Kc*	0.019	0.021
***Kc* LI^{-1}**	**0.111**	**0.118**

The ratio *K*c LI^{-1} we have found for the Al Samr trees is very low, being just 0.11. This is even lower than that we found for Al Ghaf and Al Sidr. This low ratio reflects the low leaf area of the trees in relation to their woody infrastructure, and is also a consequence of the xerophytic nature of this hardy desert species in a saline environment. The rates of *ET*c of both treatment trees is between 3-10 L d^{-1}, well less than the 60 L d^{-1} of GW irrigation that is being used currently. Savings of up to 75% are possible.

7.5 Conclusions

We found through our sapflow measurements that the xerophytic Al Samr trees use very little water, for despite their substantial woody infrastructure, they possess a low leaf area. Maximum rates of tree water-use, *ET*c, were around 10 L d^{-1}, and there are two distinct deciduous periods where *ET*c briefly dropped below 2-4 L d^{-1}. The total annual water use of the TSE-irrigated trees was 2.2 kL y^{-1}, which was about 25% higher than the 1.8 kL y^{-1} for the GW-irrigated trees.

For simplicity, we suggest that under Law 5, the irrigation allocation for Al Samr trees be based on a constant *ET*c of 10 L d^{-1}. So, for GW irrigation, allowing for a 25% factor-of-safety, and a 25% salt-leaching fraction, the recommended allocation would be 15 L d^{-1}. This represents a saving of 75% from the current practice of irrigation 60 L d^{-1}. For TSE, without the need for salt leaching, the irrigation allocation would only need to be 12.5 L d^{-1}.

The relationship we have found between the crop factor, *K*c, and the light interception, *LI*, sensed proximally using the light stick, will enable extrapolation of these irrigation allocation results to Al Samr forests of different ages and different tree spacing.

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CHAPTER 8

8 Conclusions and Suggestions for Future Research

8.1 Synopsis

In Chapter 2, both the historical basis and future options for native plant-species in the hyper-arid forests of Abu Dhabi were outlined.

The Abu Dhabi State of the Environment Report (EAD 2017) concluded that the outlook for forests of Abu Dhabi is uncertain. But EAD hoped that "... with improved irrigation techniques and alternative sources of water such as TSE it will be possible to reduce the demand for water, but how far remains to be seen".

To assist in achieving EAD's goal the research described in this thesis sought to

- Directly measure the water use of major arid-forest species irrigated with either saline GW or TSE.
- Understand the complex relationships between tree water use, the prevailing weather, and the phenological characteristics of the trees.
- Develop a relationship between the crop factor, K_c, and the canopy characteristics of the tree species as inferred using a light-stick to measure the percentage light interception by the trees' canopy.
- Develop guidelines for Law 5 for the water-allocation limits for three of the arid-forest species for GW and TSE.

8.2 Conclusions

The key findings of my study are now listed.

8.2.1 Measuring water use of trees irrigated with groundwater and treated sewage effluent

The heat-pulse technique was used successfully to measure the water use of Al Ghaf, Al Sidr and Al Samr trees. Currently all trees are irrigated with 60 L d^{-1} on every day of the year, except on Fridays.

The seasonal pattern of tree water use *ET*c was found to range from 15 L d^{-1} in winter, to 40 L d^{-1} for Al Ghaf irrigated with groundwater. For Al Sidr this range was from 10 L d^{-1} to 50 L d^{-1}. The range for Al Samr was just from 3 L d^{-1} to 12 L d^{-1}.

With the 'sweeter' TSE, there was a growth response in the TSE-irrigated trees such that the water use of the Ghaf trees increased by 17 % for Al Ghaf, 39% for Al Sidr, and 25% for Al Samr. The differing responses to the lower salinity water reveals the different salt tolerances of these three tree species.

8.2.2 The relationship between tree-water use, weather and phenology

These arid-forest trees were found to have different deciduous behaviors as found by their different seasonal patterns of measured *ET*c in relation to *ET*o. The crop factor, *K*c, is the ratio of *ET*c to *ET*o, and its seasonal pattern reflects the variation in the canopy leaf area of the trees.

For the GW irrigated trees the *K*c for Al Ghaf ranged from 0.1 in March up to 0.15 in December reflecting the spring deciduous leaf fall and the autumnal growth of new leaves. As noted above, the TSE trees had *K*c values that were 17% higher, and followed the same seasonal pattern.

The seasonal pattern in the *K*c of the Sidr trees possessed a sharp dip in April-May with a strong pattern of deciduous leaf fall. The GW-irrigated Sidr has a *K*c of about 0.6 throughout the year, except in April-May when it dropped to 0.01. The *K*c for the TSE-irrigated Sidr followed the same pattern, but was about 40% higher.

The Samr trees possess two periods of deciduous leaf-fall, the first and largest occurs in January, with a secondary loss of leaves in September. The leaf area of the Samr trees was very low, such that for most of the year the GW-irrigated trees had a *K*c of around just 0.02. The *K*c increased to 0.035 in December and then rapidly dropped to 0.01 in January, before recovering to 0.025 in February. The *K*c for the TSE-irrigated trees followed the same pattern, but was some 25% higher.

Quantification of the *K*c is critical, as this enables the seasonal pattern of tree water-use, *ET*c, to be predicted from *K*c.*ET*o. The *K*c is however dependent on tree spacing and tree management practices, so it would be useful if it were possible to use proximal, or even remote sensing to predict the *K*c of a forest stand.

8.2.3 Develop a relationship between tree water-use, weather and the trees' canopy measured using a light-stick

As part of the involvement of Plant & Food Research in the EAD-funded project, a light stick was developed (Chapter 3.3.3) to enable measurement of the light interception, *LI* (%), of the trees canopy. Following the work of Goodwin et al. (2006), the relationship between the measured *LI* and the measured *K*c was explored. Goodwin et al. (2006) found that the ratio of *K*c to *LI* was 1-1.2 for temperate horticultural tree crops. It was found that this did not hold for these halophytic and xerophytic arid forest species.

For Al Ghaf the $K\text{c}\ LI^{-1}$ ratio was found to be 0.39 and 0.42 for the GW and TSE-irrigated trees. For Al Sidr the respective values were 0.62 and 0.37. So, for these species it would seem reasonable to use a value of 0.4-0.6 to infer *K*c from *LI*. It was noted in Chapter 4 (Figure 4.2) that the Al Ghaf trees exhibit stomatal control as an adaptive mechanism during summer, and this accounts for the lower-than-expected values of $K\text{c}\ LI^{-1}$ for Al Ghaf. In Chapter 5, measurements of stomatal conductance on both the GW and TSE Al Sidr trees revealed low levels of *g*s, well-below those expected for well-watered trees. This also accounts for their low values of $K\text{c}\ LI^{-1}$ relative to those presented by Goodwin et al. (2006 for well-watered horticultural crops.

The Samr trees have a very low leaf area, and a substantial area of woody infrastructure. They are also xerophytic halophytes. Here we found $K\text{c}\ LI^{-1}$ to be even lower at just 0.11.

8.2.4 Guidelines values for Law 5 in relation to irrigation allocation for arid forest species.

In Chapter 5 (Table 5.1) and Chapter 6 (Section 6.6.9) guideline irrigation values were presented for Law 5 for Al Ghaf and Al Sidr based on the seasonal pattern of *ET*c. The values for Al Samr were presented in Chapter 7 (Section 7.5). For the GW-irrigated trees, the rule for seasonal irrigation allocation was based on 1.5 *ET*c, reflecting a 25% factor-of-safety and a 25% salt leaching fraction. For the TSE irrigated trees, there was considered no need for salt leaching and so the allocation rule was 1.25 *ET*c. The key findings are presented in Table 8.1 below.

	*ET*c Maximum (L d^{-1})	*ET*c Minimum (L d^{-1})	*K*c	Irrigation water savings (%)	*ET*c increase with TSE (%)
Al Ghaf	40	15	0.1-0.15	35	17
Al Sidr	50	10	0.01-0.6	70	39
Al Samr	12	3	0.01-0.035	75	25

Table 8.1 The key findings in relation to Law 5 in terms of maximum and minimum water use (*ET*c), the crop factor (*K*c), the percentage water savings and the percentage increase in *ET*c when the trees were irrigated with treated sewage effluent (TSE)

8.3 Suggestions for Future Research

The research described in this thesis has already answered many of the goals sought by the EAD-funded project. Nonetheless, in answering these goals, further questions were raised, and it is suggested that future research could focus on the following topics.

8.3.1 Detailed evaluation of ecosystem services

Quantification of the value of ecosystem services delivered by Abu Dhabi forests should be carried out. An evaluation process was done to support the cancellation of lower quality forests and to classify the forests into certain groups for managing operational tasks. But there is a need for better information in terms of the value of all four types of ecosystem services. Water allocation should be prioritized and allocated to forests depending on the value of the ecosystem service that they provide. The use of TSE enables increases in tree growth and forest health. The impacts and trade-offs of this growth and health increment needs to be assessed in order to distribute TSE in the most effective way. In addition, understanding the value of Abu Dhabi forests will support EAD in developing a strategic plan which clarifies the future outlook of forests, including under climate-change, taking into consideration the additional opportunities that could emerge through a sustainable afforestation program. These might include: local employment and educational development, fuel supply, microclimate change, plus food and fiber production.

The suggested appropriate methodology for evaluation of the ecosystem services of Abu Dhabi forests, would be to develop a linked two-fold economic analysis by first assessing the costs and then assessing the benefits. This approach is presented diagrammatically below in Figure 8.1.

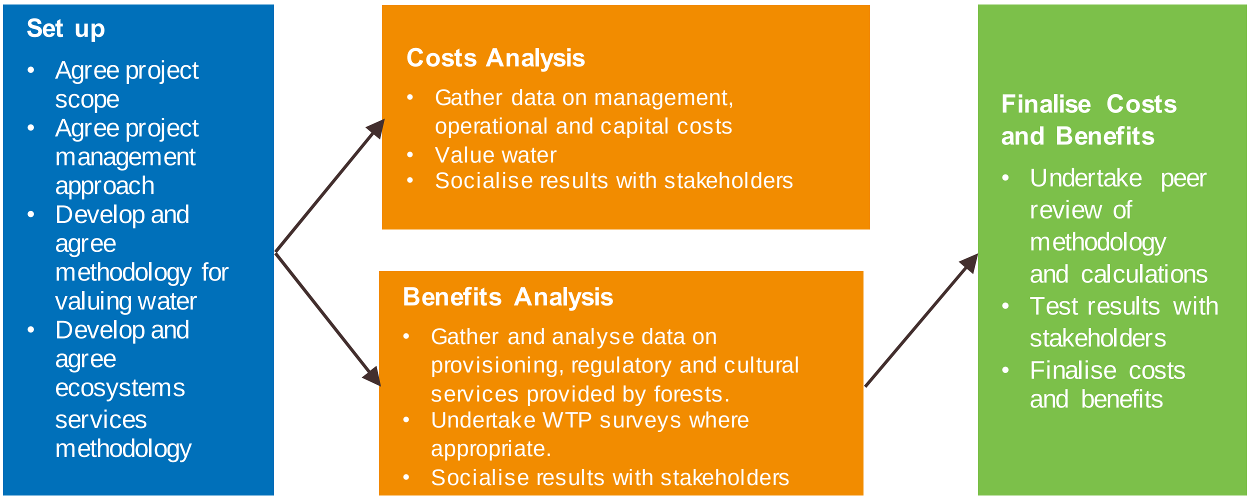

Figure 8.1 Proposed approach for a cost-benefit analysis of Abu Dhabi forests. Here WTP is the willingness-to-pay

8.3.2 Arak

As noted there were technical difficulties with the lysimeter set-up intended to be used to measure the water use of Al Arak, and assess the impact of TSE. Completion of the task to include Al Arak in a decision support tool will now be carried out by Plant & Food Research under their contract with EAD. The stomatal porometry measurements I did manage to make on the Arak trees suggest that the stomatal behaviours of Arak are similar to those of Al Sidr (Chapter 6.6.7). So it would seem that choosing a value of $Kc\ LI^{-1}$ of around 0.5 would be appropriate for turning proximal measures of *LI* from the light stick into a *Kc* for predicting Arak tree water use. Furthermore, the biomass of the GW and TSE trees was measured during the decommissioning of the experiment. The wet weights of the excised tree canopies were 2.0 (±0.9) and 3.0 (±0.5) for the GW and TSE treatments, respectively. This result is significant at $P<0.05$. So this biomass ratio could be used to infer the impact of TSE, for biomass is linearly related to water use.

8.3.3 Groundwater recharge and impacts under GW and TSE irrigation.

Most of the GW drawn to irrigate the arid forests comes from confined fossil water reserves. Therefore, any drainage and leaching from irrigation is unlikely to recharge to underlying aquifer from which the water is taken. It is likely that the drainage will either create, or recharge, shallow groundwater tables. Since the proposed irrigation regime for GW includes a 25% salt leaching fraction, there will be the export of salts from the rootzone which will end up in the shallow groundwater. It is likely that this will eventually lead to the creation, or exacerbation of surface salt scalds, which are locally known as sabkha. This salinization of groundwater is an emerging global concern (Foster et al. 2018). With the increasing use of TSE, this problem should diminish, and might even lead to amelioration of sabkha.

8.3.4 Carbon sequestration

A regulating ecosystem service provided by arid forests is carbon sequestration. This services delivers value through climate-change mitigation. The trees capture carbon through photosynthesis and sequester it in their woody biomass, and also they increase the carbon content of the soil in their rootzone. It would worthwhile to understand better the magnitude of carbon sequestration in arid forests, and assess it value for climate-change mitigation. It is anticipated that this might, however, be quite small.

8.3.5 Implementation of decision support tool

Through the EAD-Plant & Food contract a decision support tool (DST) will be developed for management of irrigation in forests. However, future work will be needed on the implementation of this tool.

Law 5 requires that all GW wells used for irrigation must be monitored to provide accurate water abstraction data. Linking this data set with the water-use allocations provided by the DST will be critical, and useful in future extension work with farmers and forest managers.

8.3.6 Education about Treated Sewage Effluent

Earlier attempts by the government to provide TSE to private farms for free have met with resistance. Even though these farms were close to the treatment plants, the owners refused to use TSE in their farms. The expanded use of TSE in the agriculture sector is being limited by public acceptance, rather than management or regulatory restrictions. For forestry, thankfully this is less so. So forestry could be used as an example for the safe use of TSE. However, the real challenge in forestry, is the availability of infrastructure needed for widespread TSE supply to forests in remote areas.

8.4 References

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APPENDIX A

9 Appendix A.1 Published Papers

9.1 Papers – Wafa Al Yamani:

1. **Al Yamani**, Wafa, Steve Green, Rommel Pangilinan, Steve Dixon, Shabbir Shahid, Peter Kemp, and Brent Clothier. 2018. Water Use of Al Ghaf and Al Sidr Forests Irrigated With Saline Groundwater in the Hyper-Arid Deserts of Abu Dhabi. *Agricultural Water Management* 203:105-114.

2. Rahmati, Mehdi, Lutz Weihermüller, Jan Vanderborght, Yakov A. Pachepsky, Lili Mao, Seyed Hamidreza Sadeghi, Niloofar Moosavi, Hossein Kheirfam, Carsten Montzka, Kris Van Looy, Brigitta Toth, Zeinab Hazbavi, **Wafa Al Yamani**, Ammar A. Albalasmeh, Ma'in Z. Alghzawi, Rafael Angulo-Jaramillo, Antônio Celso Dantas Antonino, George Arampatzis, Robson André Armindo, Hossein Asadi, Yazidhi Bamutaze, Jordi Batlle-Aguilar, Béatrice Béchet, Fabian Becker, Günter Blöschl, Klaus Bohne, Isabelle Braud, Clara Castellano, Artemi Cerdà, Maha Chalhoub, Rogerio Cichota, Milena Císlerová, Brent Clothier, Yves Coquet, Wim Cornelis, Corrado Corradini, Artur Paiva Coutinho, Muriel Bastista de Oliveira, José Ronaldo de Macedo, Matheus Fonseca Durães, Hojat Emami, Iraj Eskandari, Asghar Farajnia, Alessia Flammini, Nándor Fodor, Mamoun Gharaibeh, Mohamad Hossein Ghavimipanah, Teamrat A. Ghezzehei, Simone Giertz, Evangelos G. Hatzigiannakis, Rainer Horn, Juan José Jimenez, Diederik Jacques, Saskia Deborah Keesstra, Hamid Kelishadi, Mahboobeh Kiani-Harchegani, Mehdi Kouselou, Madan Kumar Jha, Laurent Lassabatere, Xiaoyan Li, Mark A. Liebig, Lubomír Lichner, María Vitoria López, Deepesh Machiwal, Dirk Mallants, Micael Stolben Mallmann, Jean Dalmo de Oliveira Marques, Miles R Marshall, Jan Mertens, Félicien Meunier, Mohammad Hossein Mohammadi, Binayak P Mohanty, Mansonia Pulido Moncada, Suzana Montenegro, Renato Morbidelli, David Moret-Fernández, Ali Akbar Moosavi, Mohammad Reza Mosaddeghi, Seyed Bahman Mousavi, Hasan Mozaffari, Kamal Nabiollahi, Mohammad Reza Neyshabouri, Marta Vasconcelos Ottoni, Theophilo Benedicto Ottoni Filho, Mohammad Reza Pahlavan Rad, Andreas Panagopoulos, Stephan Peth, Pierre-Emmanuel Peyneau, Tommaso Picciafuoco, Jean Poesen, Manuel Pulido, Dalvan José Reinert, Sabine Reinsch, Francis Parry Roberts, David Robinson, Jesús Rodrigo-Comino, Otto Corrêa Rotunno Filho, Tadaomi Saito, Hideki Suganuma, Carla Saltalippi, Renáta Sándor, Brigitta Schütt, Manuel Seeger, Nasrollah Sepehrnia, Ehsan Sharifi Moghaddam, Manoj Shukla, Shiraki Shutaro, Ricardo Sorando, Ajayi Asishana Stanley, Peter Strauss, Zhongbo Su, Ruhollah Taghizadeh-Mehrjardi, Encarnación Taguas, Wenceslau Geraldes Teixeira, Ali Reza Vaezi, Mehdi Vafakhah, Tomas Vogel, Iris Vogeler, Jana Votrubova, Steffen Werner, Thierry Winarski, Deniz Yilmaz, Michael H. Young, Steffen Zacharias, Yijian Zeng, Ying Zhao, Hong Zhao, Harry Vereecken. 2018. Development and Analysis of Soil Water Infiltration Global Database. *Earth System Science Data* [submitted – under review].

3. **Al Yamani Wafa**, Steve Green, Rommel Pangilinan, Steve Dixon, Shabbir Shahid, Peter Kemp, and Brent Clothier. 2019. The Impact of Replacing Groundwater by Treated Sewage Effluent on the Irrigation Requirements of Al Ghaf (*Prosopis cineraria*) and Al Sidr (*Ziziphus spina-christi*) Forests in the Hyper-Arid Deserts of Abu Dhabi. *Agricultural Water Management* 214:28-37.

4. **Al Yamani Wafa**, Steve Green, Rommel Pangilinan, Steve Dixon, Shabbir Shahid, Peter Kemp, and Brent Clothier. 2019. Water Use of Al Samr (*Acacia tortilis*) Forests Irrigated with Saline Groundwater and Treated Sewage Effluent in the Hyper-Arid Deserts of Abu Dhabi. *Agricultural Water Management* 216:361-364

5. **Al Yamani, Wafa**, Steve Green, Rommel Pangilinan, Steve Dixon, Peter Kemp, and Brent Clothier. Sap flow in Al Ghaf trees growing in the Hyper-Arid Desert of Abu Dhabi. *Acta Horticulturae.* 1222: 207-213. ISHS 2018. DOI 10.17660/ActaHortic.2018.1222.28 Proc. of the X International Workshop on Sap Flow Eds.: L.S. Santiago and H.J. Schenk.

6. **Al Yamani**, W., S.R. Green, I. McCann, B.E. Clothier, M. Abdelfattah and R. Pangilinan 2017. Water use of date palms in the saline desert soils of the United Arab Emirates. *Acta Horticulturae*. DOI 10.17660/ActaHortic.2017.1178.12 XXIX IHC – Proc. International Symposium on Tropical Fruit. Eds.: S.K. Mitra and R. Nissen. p 67-74.

7. **Al Yamani**, W., S. Green, R. Pangilinan, S. Dixon and B. Clothier, 2016. Sustainable Irrigation of Arid Forests in Abu Dhabi using Groundwater and Treated Sewage Effuent. In: Integrated nutrient and water management for sustainable farming. (Eds L.D. Currie and R.Singh). http://flrc.massey.ac.nz/publications.html. Occasional Report No. 29. Fertilizer and Lime Research Centre, Massey University, Palmerston North, New Zealand. 12 pages.

8. **Al Yamani**, W., Steve Green, Rommel Pangilinan, Steve Dixon, Peter Kemp, & Brent Clothier, 2017. The impact of using treated sewage effluent to irrigate arid forests in the hyper-arid deserts of Abu Dhabi. In: Science and policy: nutrient management challenges for the next generation. (Eds L. D. Currie and M. J. Hedley). http://flrc.massey.ac.nz/publications.html. Occasional Report No. 30. Fertilizer and Lime Research Centre, Massey University, Palmerston North, New Zealand. 10 pages.

9. **Al Yamani,** Wafa, Lesley Kennedy, Steve Green, and Brent Clothier. 2019. The historical basis and future options for native plant-species in the hyper-arid forests of Abu Dhabi. Journal of Land Use Policy [accepted pending revision]

9.2 Presentations & Workshops

Date	Presenters	Topic	Attendees
10 June 2014	Wafa Al Yamani (with Lesley Kennedy)	Executive presentation on the NZ Partnership programme – overview of all projects – establishment of sap flow project for Forests discussed	EAD Executive team Executives from ADFCA and ICBA EAD Forestry and ground water team EAD Fisheries team NZ Ambassador to UAE NZ G2G representatives
13 December 2015	Wafa al Yamani (with Dr Steve Green, Dr Brent Clothier, Steve Dixon)	Presentation on forestry project progress	EAD forestry team, ground water team, ADFCA, Barari, and FSC
19 January 2016	Dr Brent Clothier (with Wafa Al Yamani)	TechTalk at the International Water Summit (IWS)	IWS attendees
20 January 2016	Dr Brent Clothier, Dr Shaikha Hosani, Wafa Al Yamani	IWS presentation	IWS attendees
8 February 2016	Wafa Al Yamani	Presentation of the paper" SUSTAINABLE IRRIGATION OF ARID FORESTS IN ABU DHABI USING	FLRC at Massey University, New Zealand

		GROUNDWATER AND TREATED SEWAGE EFFLUENT”	
10 October 2016	Lesley Kennedy (with Wafa Al Yamani)	Executive Presentation – NZ Partnership projects, progress update	EAD Executive team Executives from ADFCA and ICBA EAD Forestry and ground water team EAD Fisheries team NZ Ambassador to UAE NZ G2G representatives
26 September 2016	Wafa Al Yamani (with Dr Steve Green, Dr Brent Clothier)	Presentation on forestry project progress	NZ G2G, EAD, Forestry and Information management teams
4 December 2016	Wafa Al Yamani (with Dr Steve Green, Steve Dixon, Dr Brent Clothier)	Workshop at Al Salamat with Barari on forestry data	Dr Mahmoud Al Hassan & the Barari science team
19 January 2017	Wafa Al Yamani (with Dr Steve Green, Dr Brent Clothier, Lesley Kennedy)	Presentation of research findings to date on Forestry; and presentation on the prototype DST	Dr Fred Launay, Eva Ramos, Peter Fippinger, ADFCA representatives, Dr Dakheel (ICBA), Barari
8 February 2017	Wafa Al Yamani	Presentation of the paper “ THE IMPACT OF USING TREATED SEWAGE EFFLUENT TO IRRIGATE ARID FORESTS IN THE HYPER-ARID	FLRC at Massey University, New Zealand

		DESERTS OF ABU DHABI"	
14 March 2018	Wafa Al Yamani (with Dr Steve Green, Dr Brent Clothier, Steve Dixon)	Presentation on updated findings of the forestry project.	Groundwater team, ADFCA, ICBA
18 July 2018	Dr Brent Clothier	Invited keynote address "*Minimising the use of groundwater and the use of alternative water sources for the irrigation of arid forests in the deserts of Abu Dhabi*"	Symposium on Ecological Restoration and Efficient Utilization of Water Resources in Semi-arid Regions, Zhangjiakou, Hebei province, China.
5 December 2018	Dr Brent Clothier (with Wafa Al Yamani)	Invited keynote address "*Soil, Carbon, and Water: Natural Capital Delivering Valuable Ecosystem Services*"	NZ Soil Science Society Conference, Napier

APPENDIX B

10 Appendix B: Declaration

The funding for this project on the use of groundwater (GW) and treated sewage effluent (TSE) to irrigate the arid-forests of Abu Dhabi, was provided by my employee, Environment Agency – Abu Dhabi (EAD). This four-year project commenced in December 2014, and was resourced by EAD at the level of AED 4.992 million, or NZ$ 1.10 million.

As an employee of EAD, I was granted full-time study leave to pursue my PhD through Massey University on this project. Professor Peter Kemp and Dr Brent Clothier provided academic supervision.

This was a complex project, involving over NZ $100,000 in high-technology electronic sensing technologies, and plus more on detailed soil and plant analyses. Furthermore there were many partners in this detailed and important project: EAD, Plant & Food Research Ltd, Massey University, Maven International, Barari Forest Management, and Exova Analytical Laboratories.

From EAD's perspective, I was the project leader. I managed all the interactions between the teams. The leadership of this project was mine.

Nonetheless, the outcomes of this project, and the intellectual achievements are shared between the participants, as would be expected for such a complex and substantially resourced job.

I make this declaration:

- The technology used in this project in relation to sapflow, soil measurements using time domain reflectometry (TDR), the light stick, the soil and plant analyses, were all derived from organisations who have proprietary claims to their technology and the analysis software that was used to provide the results purchased through this project. These companies provided results and spreadsheets that were purchased under the contracts. I understand the principles of the technology employed, but I am not an expert in their analyses, I am a user of the knowledge provided by these technologies.

- The data generation and the raw analyses were proprietary, as expected for the complex analyses of sapflow, TDR light interception, and soil and plant analyses that were sought in this project. Whereas I understand the biophysical and chemical principles of theses proprietary analyses, I have sought to interpret and apply these knowledge advances.

- My role was in the interpretation of the results provided via the proprietary software, and the application of these to the practical objectives set out under multi-party contracts with EAD, and the academic goals of my doctoral research.

- Necessarily, the publications emanating from my research have many authors, all of whom have provided valuable support an insights into my project. I provided the leadership
- The leadership and academic interpretations of my research is mine, and has been developed in conjunction with the many colleagues in my team.

I conclude by noting that the practical and intellectual outcomes of this work has provided value to EAD, increased the knowledge-base concerning the sustainable management of arid forests, better enabled the protection of the Emirates' water resources through usage of alternative water sources, and helped strongly in my developing my scientific career.

Wafa Al Yamani

APPENDIX D

11 Appendix D: Statements of Contribution for Publications

MASSEY UNIVERSITY
GRADUATE RESEARCH SCHOOL

STATEMENT OF CONTRIBUTION
TO DOCTORAL THESIS CONTAINING PUBLICATIONS

(To appear at the end of each thesis chapter/section/appendix submitted as an article/paper or collected as an appendix at the end of the thesis)

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

Name of Candidate: Wafa Faisal Al Yamani

Name/Title of Principal Supervisor: Prof. Peter Kemp

Name of Published Research Output and full reference:

Al Yamani, Wafa, Lesley Kennedy, Steve Green, and Brent Clothier. 2019. The historical basis and future options for native plant-species in the hyper-arid forests of Abu Dhabi. [Manuscript readied for submission to the Journal of Arid Land]

In which Chapter is the Published Work: Chapter 2

Please indicate either:

- The percentage of the Published Work that was contributed by the candidate: 95%

  and / or

- Describe the contribution that the candidate has made to the Published Work:

  Kindly refer to Appendix B for details

Wafa Al Yamani Digitally signed by Wafa Al Yamani Date: 2018.11.30 11:47:54 +13'00'

Candidate's Signature

30.11.2018

Date

Digitally signed by Peter D Kemp Date: 2018.11.30 17:16:51 +13'00'

Principal Supervisor's signature

30/11/2018

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MASSEY UNIVERSITY
GRADUATE RESEARCH SCHOOL

STATEMENT OF CONTRIBUTION
TO DOCTORAL THESIS CONTAINING PUBLICATIONS

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Name/Title of Principal Supervisor: Prof. Peter Kemp

Name of Published Research Output and full reference:

Al Yamani, Wafa, Steve Green, Rommel Pangilinan, Steve Dixon, Peter Kemp, and Brent Clothier. Sap flow in Al Ghaf trees growing in the Hyper-Arid Desert of Abu Dhabi. Acta Horticulturae [in press], 10th ISHS Sap Flow Symposium, Fullerton, California, 22-26 May 2017.

In which Chapter is the Published Work: Chapter 4

Please indicate either:

- The percentage of the Published Work that was contributed by the candidate: 70%

  and / or

- Describe the contribution that the candidate has made to the Published Work:

  Kindly refer to Appendix B for details

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30.11.2018

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Digitally signed by Peter D Kemp Date: 2018.11.30 17:18:10 +13'00'

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STATEMENT OF CONTRIBUTION
TO DOCTORAL THESIS CONTAINING PUBLICATIONS

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Name/Title of Principal Supervisor: Prof. Peter Kemp

Name of Published Research Output and full reference:

Al Yamani, Wafa, Steve Green, Rommel Pangilinan, Steve Dixon, Shabbir Shahid, Peter Kemp, and Brent Clothier. 2018. Water Use of Al Ghaf and Al Sidr Forests Irrigated With Saline Groundwater in the Hyper-Arid Deserts of Abu Dhabi. Agricultural Water Management 203:105-114.

In which Chapter is the Published Work: Chapter 5

Please indicate either:

- The percentage of the Published Work that was contributed by the candidate: 85%

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- Describe the contribution that the candidate has made to the Published Work:

  Kindly refer to Appendix B for details

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Digitally signed by Peter D Kemp Date: 2018.11.30 17:19:18 +13'00'

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Date

MASSEY UNIVERSITY
GRADUATE RESEARCH SCHOOL

STATEMENT OF CONTRIBUTION
TO DOCTORAL THESIS CONTAINING PUBLICATIONS

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Name/Title of Principal Supervisor: Prof. Peter Kemp

Name of Published Research Output and full reference:

Al Yamani Wafa, Steve Green, Rommel Pangilinan, Steve Dixon, Shabbir Shahid, Peter Kemp, and Brent Clothier. 2018. The Impact of Replacing Groundwater by Treated Sewage Effluent on the Irrigation Requirements of Al Ghaf (Prosopis cineraria) and Al Sidr (Ziziphus spina-christi) Forests in the Hyper-Arid Deserts of Abu Dhabi. Agricultural Water Management [accepted pending revision].

In which Chapter is the Published Work: Chapter 6

Please indicate either:

- The percentage of the Published Work that was contributed by the candidate: 90%

  and / or

- Describe the contribution that the candidate has made to the Published Work:

  Kindly refer to Appendix B for details

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STATEMENT OF CONTRIBUTION
TO DOCTORAL THESIS CONTAINING PUBLICATIONS

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Name/Title of Principal Supervisor: Prof. Peter Kemp

Name of Published Research Output and full reference:

Al Yamani Wafa, Steve Green, Rommel Pangilinan, Steve Dixon, Shabbir Shahid, Peter Kemp, and Brent Clothier. 2018. Water Use of Al Samr (Acacia tortilis) Forests Irrigated with Saline Groundwater and Treated Sewage Effluent in the Hyper-Arid Deserts of Abu Dhabi. Agricultural Water Management [under review].

In which Chapter is the Published Work: Chapter 7

Please indicate either:

- The percentage of the Published Work that was contributed by the candidate: 85%

  and / or

- Describe the contribution that the candidate has made to the Published Work:

  Kindly refer to Appendix B for details

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