SCOPING STUDY AND A BASELINE UNDERSTANDING OF POMEGRANATE ORCHARD WATER USE IN SELECTED PRODUCTION AREAS

Report

to the Water Research Commission

by

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The survey was co-funded by the Pomegranate Producers' Association of South Africa, through the Alternative Crops Fund of the Western Cape Department of Agriculture, and the Agricultural Research Foundation. Their contributions are gratefully acknowledged.

We also thank participating producers and their farm managers for making their orchards available for the survey and for supplying assistance on request.

EXECUTIVE SUMMARY

MOTIVATION AND RATIONALE

Global warming-induced climatological changes are expected to impact negatively on the already limited water resources of the Western Cape, and water restrictions for agriculture are already an inevitable fact during the drought years. Increased temperature will result in an increased demand for irrigation for deciduous fruit orchards, but the irrigation volume for the agricultural sector is unlikely to increase as the Department of Water Affairs has capped agricultural allocations at current levels. It is furthermore predicted that the western region of South Africa will have a significant reduction in streamflow, with potentially sombre implications for irrigated agriculture. Water demand and supply forecasts for the Berg and the Olifants-Doorn water management areas, respectively, indicate a severe (-20% to -80%) and moderate (0% to -20%) gap between the supply in 2010 and the projected demand by 2030. Improved agricultural water use efficiency and productivity are considered necessities to provide the water needed for the projected increased water demand for human consumption and industrial production by 2030. Such limited water resource availability makes maximising net income per unit of water used a prerequisite for sustainable farming.

One way to cope with this situation is to invest in more suitable crops for the potential future climate, such as drought-tolerant pomegranate trees. Although the pomegranate industry in South Africa is small, it is growing, with 81, 10 and 7% of plantings (1,024 ha) in the Western Cape, Limpopo and Northern Cape, respectively. Production started in the early 2000s, and South Africa is presently an international role player in production and exports from the southern hemisphere to various countries in the northern hemisphere. In 2019, about 1,123,027 equivalent cartons of fruit (3.8 kg) were exported and 553,133 cartons were processed. Hortgro forecast exports of about 1.377 million cartons and the processing of almost 678,239 cartons for the industry by 2024. Research and development by the Pomegranate Producers' Association of South Africa (POMASA) is currently focused on the improvement of production practices. Although pomegranate trees are considered drought tolerant, irrigation is required during the dry summer months to optimise growth, yield and fruit quality for commercial production. The skilful management of limited water resources will be a necessity if optimal production and fruit quality are to be retained for a total farm unit.

Correct irrigation system selection, design and maintenance are very important for efficient in-field water management, but efficient irrigation scheduling is the key to achieving high irrigation water use efficiency. Although there are general POMASA guidelines with regard to the irrigation of pomegranates, no local research results are available to guide producers with regard to the effect of different levels of soil water depletion on pomegranate tree growth, yield and fruit quality under local conditions. Such research can provide guidelines with regard to the best water use efficiency without compromising the quality of fruit that is destined for the export market.

However, first and foremost, baseline information is needed regarding current irrigation practices and related tree water status, growth, yield and fruit quality to direct more detailed research for the pomegranate industry. The Agricultural Research Council (ARC) can utilise information obtained by the survey that forms part of this report to motivate for co-funding in future for more detailed irrigation research to be conducted to enable producers to achieve the high water use productivity that the latest South African Irrigation Water Strategy requires. Such research will be in support of the Water Research, Development and Innovation Roadmap and will focus, in particular, on the water demand aspect, through the Water Research Commission (WRC) Climate Change, the Water-Energy-Food Nexus and Sustainable Water Behaviour Lighthouses, as set out in the WRC's Corporate Plan of 2018/19-2022/23.

AIMS AND OBJECTIVES

The general aim of this study is to identify future pomegranate irrigation research needs from local survey observations and baseline data to ultimately empower South African producers to achieve the high economic water use productivity that is required. The first specific aim entails conducting an extensive literature survey on the water use and irrigation management of pomegranate trees. The second specific aim is to analyse data from a local survey, including weather, soil, water and crop baseline information from pomegranate orchards under drip- or micro-irrigation in different production areas to identify research gaps that can direct future pomegranate irrigation research.

METHODS

The ARC, in collaboration with the pomegranate industry (POMASA), co-funded by the Alternative Crop Fund (ACF) of the Western Cape Department of Agriculture, conducted a survey over two seasons (2017/18 and 2018/19) on the irrigation and performance of pomegranate trees. Data collected at nine full-bearing pomegranate (Wonderful cultivar) orchards on commercial farms in four pomegranate production areas in the Western Cape (Bonnievale, Gouda, Wellington and Wolseley) was analysed to identify research gaps to direct future pomegranate water use and irrigation research. Three farms were within the boundaries of the Berg water management area (WMA), and three farms were within the Breede WMA. Sites selected included orchard variability currently present in the industry, comprising different degrees of water quality (non-saline or saline), tree spacing (416 to 1,111 trees per hectare), sandy or heavier soil, level or ridged gradients, planted with or without nets, and irrigated with micro-sprinklers or drip-irrigation (single or double line). Soil profiles were characterised, research infrastructure was installed, weather data was collected, irrigation was applied, and soil water dynamics and plant response were monitored. The collection of tree data included growth stages, tree water status, shoot and fruit growth, yield and fruit quality. Fruit marketability and gross farm income earned were assessed. Water use efficiency (kilogram of fruit produced per hectare per mm of water used) and productivity (income earned per hectare per mm of water used) were calculated based on the irrigation water applied and the total of the effective rainfall and irrigation water applied.

RESULTS AND DISCUSSION

The water and soil resources of production areas were assessed, taking into account the quality of the irrigation water and the available soil water (soil water-holding capacity and root zone distribution). Water salinity, measured in terms of electrical conductivity, ranged between 5 and 71 mS m^{-1} for five sites, and sodium content ranged between 4.4 and 91 mg l^{-1}. Based on electrical conductivity, these waters can practically be considered non-saline (electrical conductivity < 70 mS m^{-1}). Borehole water from Wellington, though, was moderately saline and had an electrical conductivity of 224 mS m^{-1} and a sodium content of c. 421 mg ℓ^{-1}.

According to the Water Quality Decision Support System, it was predicted that the equilibrium between root zone salinity and water quality for all the orchards was ideal for irrigation, with mostly negligible effects of salinity on crop yield expected. The exception was the borehole at Wellington, the water salinity of which was in the tolerable range, which can potentially salinise the root zone to levels that restrict the yield of many crops. Depending on cultivar, pomegranate trees are considered to be moderately sensitive to moderately tolerant to salinity.

Based on the interaction between the electrical conductivity of irrigation water and the sodium adsorption ratio (SAR) of the topsoil, the degree of reduced soil surface infiltrability for the different orchards ranged from none to moderate. The SAR in the soil water was, in most cases, less than 3 and was associated with low soil water salinity of between 20 and 40 mS m^{-1}, which may result in moderately reduced hydraulic conductivity in sensitive soils.

In cases where the SAR was less than 3 and the salinity less than 20 mS m^{-1}, the hydraulic conductivity could decrease severely. In Wellington, in the single-line drip-irrigated orchard, soil water SAR values of more than 12 and a saturated soil water electrical conductivity (EC_e) of less than 50 may result in a severe reduction of the hydraulic conductivity of the topsoil, but deeper in the soil where the soil water salinity is c. 150 mS m^{-1}, hydraulic conductivity may only decrease moderately. In the 300-600 mm soil layer of the ridged double-line drip-irrigated orchard, an SAR of c. 12, in combination with an EC_e of c. 94 mS m^{-1}, may also moderately reduce the hydraulic conductivity.

Crop growth and yield are affected by salinity (which reduces the ability of crops to absorb water from the soil), as well as by accumulation of potentially toxic ions, namely sodium (Na), chloride (Cl) and boron (B), in the root zone. For the orchards in Bonnievale irrigated by micro-sprinkler, a relative yield decrease of c. 18, 36, 8 and 1% was predicted due to salinity and high levels of sodium, chloride and boron, respectively. In the double-line drip-irrigated orchards in Wellington, the relative yield could decrease by 10 and 19% due to the salinity and sodium content of the irrigation water. The effect of the high salinity, sodium and chloride in irrigation water used in the single-line drip-irrigated orchard in Wellington on the relative yield of a sensitive crop was extreme (i.e. no yield). However, since pomegranate is considered to be moderately sensitive to moderately tolerant to salinity, relative yield should be less affected.

According to the Langelier Index, the potential for irrigation water to result in irrigation equipment corrosion ranged between none (ideal) and unacceptable (Langelier Index < -2) between orchards, whereas no problem with scaling was foreseen. With regard to emitter clogging, the pH value appears to be too high at all orchards, while manganese and iron content did not pose a problem or was acceptable.

According to the soil water-holding capacity between -10 and -100 kPa (estimated from soil texture analysis, Bemlab), the heavier soils in Bonnievale had the highest soil water-holding capacity, i.e. between 144 and 165 mm m^{-1}, whereas it was slightly lower for the sandy loam with c. 21% stone (117 mm m^{-1}). The soil water-holding capacity of the sandy Gouda soils was the lowest and, on average, c. 50% of that available in the micro-sprinkler-irrigated orchards in Bonnievale. The soil water-holding capacity in the netted and open orchards, respectively, was c. 69 mm m^{-1} (profile average stone 23% v/v) and 84 mm m^{-1} (profile average stone c. 15% v/v). The water-holding capacity of the sandy soil in Wolseley and the sandy loam and loamy sand in the Wellington area was 93, 88 and c. 100 mm m^{-1}, respectively. The soil water-holding capacity of the drip-irrigated soils was, on average, 40% less than that of the micro-irrigated soils. With respect to soil water-holding capacity in the production regions, Gouda, Wolseley and Wellington, respectively, had, on average, 46, 34 and 32% less water available between -10 and -100 kPa than the Bonnievale soils. Differences in the soil water-holding capacity of the heavier vs lighter soils require different irrigation intervals to adequately meet the tree water requirements.

The root systems of seven of the nine orchards developed up to a depth of 1.2 m. At Bonnievale, the root depth of the double-line drip-irrigated sandy loam orchard was limited to 600 mm by an impermeable layer, and at Wolseley, in the single-line drip-irrigated sand under net, by a clay layer at 1 m depth. The root density to a 600 mm depth was, on average, c. 45% lower in the micro-sprinkler-irrigated orchards compared to that in the drip-irrigated orchards. Root distribution perpendicular to the tree row indicated that, for the drip-irrigated orchards, most of the roots were concentrated in a c. 1 m radius from the tree, whereas, for micro-irrigated orchards, roots were distributed across the whole area allotted to the tree. The drought tolerance of pomegranate trees can partially be explained by the presence of deep root systems that penetrated even very stony soil layers.

The evaporative demand that drives water use and irrigation water requirements in the production areas ranged from c. 942 to 1,250 mm for the 2017/18 and 2018/19 seasons. The amount of irrigation water applied ranged from 237 to 834 mm in 2017/18, and from 272 to 867 mm in 2018/19.

If effective rainfall is also taken into account, the total amount of effective rainfall and irrigation ranged from 409 to 1,001 mm for 2017/18, and from 381 to 1,161 mm for 2018/19. In comparison, in California, where annual evaporative demand reached 1,379 mm, six-year-old Wonderful trees that were surface drip-irrigated according to a scientific schedule received c. 1,100 mm of rainfall and irrigation. On average for soil type, 68 and 47% more water was applied from 1 September to the end of May in the 2017/18 and 2018/19 seasons, respectively, to clayey and sandy loam soils compared to loamy sand and sandy soils. Micro-sprinkler-irrigated orchards received 80 and 53% more water than drip-irrigated orchards in the two respective seasons. In Gouda, the drip-irrigated open orchard received 45 and 27% more water than the netted orchard. However, the lower amount of irrigation water applied under net cannot be contributed solely to the effects of the net since the emitter spacing differed for the two orchards and the borehole that supplied the netted orchard occasionally ran dry in the 2017/18 season. Water restrictions due to the drought in the Western Cape hampered the application of irrigation according to tree water requirements, and orchards were irrigated according to the producer's practice. The amount of water applied does therefore not necessarily accurately reflect the water requirements of these orchards. Soil water dynamics indicated instances of under- and over-irrigation during the two seasons. It was not necessarily restricted to specific orchards or production areas.

Shoot growth rate increased non-linearly with higher rates of effective rainfall and irrigation applied until the fruit set, but only in the second season. During the critical drought in 2017/18, water application rates were very low, and no vegetative growth response was evident. Tree water status indicated that the Gouda and Wellington orchards were subjected to either moderate or severe levels of water stress during the fruit growth and ripening stages, which impacted negatively on fruit growth rate. The relative fruit growth rate tended to increase with an increased amount of effective rainfall and irrigation water applied during the fruit set and ripening phases. The total yield for the two seasons varied between 14.2 and 67.7 t ha^{-1}. Statistical analyses showed the significant effects of the rate of effective rainfall and irrigation applied from September until harvest or until the end of the season on tree yield, individual fruit weight, relative income and several fruit quality variables. Trends for most fruit quality variables were not consistently significant in both seasons. This was most likely due to the effect of the rainfall that occurred during ripening in the second season. The final fruit size of 20 fruit sampled per orchard for maturity analysis (fruit weight, length and diameter), as well as yield and average fruit weight for five trees per orchard, related positively to increased irrigation rate until harvest for the entire season.

Fruit skin moisture content and firmness, aril weight and moisture content, and the percentage of fruit with dark-red arils also tended to increase with increased irrigation rate until harvest, but the trends were not significant for all variables in both seasons. The red colouration of the fruit's skin tended to decrease with an increased rate of irrigation until harvest. The fruit of all orchards conformed to the ripeness standards expected for export. The titratable acidity of pomegranate juice tended to increase, whereas the total soluble solids, pH and Maturity Index decreased with an increased rate of irrigation until harvest in the first season, but not in the second. Effective rainfall and irrigation applied until harvest did not affect fruit blemishes or cracking, but increased the rates of water application during the period from the end of linear fruit growth until harvest, and decreased sunburn. The percentage of sunburnt fruit at harvest tended to decrease with improved tree water status during the fruit growth stage. There were no significant trends between physiological disorders (scuff marks, russeting, cork around the pedicel, internal decay) and the rate of effective rainfall and irrigation applied until harvest.

Fruit that was suitable for export during the 2017/18 and 2018/19 seasons, respectively, was 75 and 81% for Bonnievale; 74 and 63% for Wolseley; 50 for 73% for Wellington; and 38 and 75% for Gouda. However, there was no simple relationship between effective rainfall and irrigation applied, and the marketability of the fruit. The maximum water use efficiency among the orchards was high compared to some published data for pomegranate from other countries and cultivars.

Water use efficiency based on irrigation water applied varied between 59.4 and 125.5 kg ha^{-1} mm^{-1} for the 2017/18 season, and between 31.1 and 91.3 kg ha^{-1} mm^{-1} for the 2018/19 season. If effective rainfall is also taken into account, the water use efficiency ranged from 36.6 to 85.9 kg ha^{-1} mm^{-1} in the first, and from 22.4 to 73. kg ha^{-1} mm^{-1} in the second season. Water use efficiency with effective rainfall and irrigation taken into account was the highest in Bonnievale for both seasons, with that in Wellington, Gouda and Wolseley being c. 7 and 8%; 31 and 26%; and 45 and 66% less efficient in the respective seasons.

The relative income of pomegranate orchards (expressed vs maximum income earned) increased with more effective rainfall and irrigation applied in both seasons. Bonnievale also had the best relative water productivity (gross farm income per hectare per mm of water used) for both seasons for scenarios where only irrigation water or the total of effective rainfall and irrigation water applied was taken into consideration (data not shown). In 2017/18 and 2018/19, respectively, water productivity based on effective rainfall and irrigation applied in Wellington, Gouda and Wolseley was 36 and 12%; 55 and 21%; and 34 and 44% less compared to Bonnievale.

CONCLUSIONS

There is potential for irrigation-related research to improve the water use efficiency and productivity of some pomegranate production areas or individual orchards. There is, indeed, a clear-cut need for water use and irrigation research, and potential spin-offs for the industry and South Africa as a whole.

Recommendations for future research on water use and irrigation

Based on the data collected and trends established between effective rainfall and irrigation water applied, pomegranate yield and quality parameters, the following research needs were identified:

- Decreased availability of adequate volumes of high-quality water for agricultural purposes or during drought periods requires the optimisation of irrigation and production practices that include saline water. According to the literature, pomegranate cultivars are moderately salt sensitive to moderately salt tolerant. Research in this regard is needed under local conditions to ensure sustainable production over the long term.
- There is potential for some production areas to increase their yield and fruit quality through improved irrigation scheduling. Since there are no local crop coefficients available for irrigation scheduling purposes and they are actually orchard-specific, research is required on the water use (transpiration and evapotranspiration) of a range of pomegranate orchards to develop a model that will enable the practical estimation of water use for individual orchards on-farm. Such a model will enable producers to schedule irrigation according to tree water requirements and prevent over- or under-irrigation, which impacts on the environment (leaching of fertilizers and water losses) and the performance of fruit trees (yield and quality). Such research may also be used to validate water use estimates of the satellite-based Fruitlook, which is currently being promoted by the Western Cape Department of Agriculture as a water-saving tool. Research may be necessary for different cultivars and in different provinces. Although most plantings are currently in the Western Cape, there are indications of increased interest and orchard establishment in Limpopo.
- Research is needed on deficit irrigation and other water-saving strategies (e.g. mulches) for pomegranate orchards to save water and optimise yield and fruit quality under drought conditions. Crop phenological stages that are the least vulnerable to drought should be identified to develop these strategies. Although literature indicated that the stage from bud break until fruit set has the potential to save water without negative impacts on yield, our survey indicated that fruit growth rate during this stage increased with higher rates of effective rainfall and the application of irrigation. The effect of different levels of water stress on fruit set and development under local conditions during this stage needs to be researched further and compared to that applied during linear fruit growth and ripening until harvest.

- Although the abovementioned research regarding deficit irrigation strategies will address fruit quality aspects as well, there are specific fruit quality issues that impact greatly on the marketability and profitability of pomegranates. These are highlighted separately. The amount of water application through rainfall and irrigation appears to have the opposite effect on quality-related consumer preferences such as red skin colour and dark-red arils, with more water resulting in a poorer red colouration of the skin, but a better red colouration of the arils. Research regarding irrigation and/or production strategies that may result in a better red colouration of both the skin and the arils is needed. If that is not possible, the economic feasibility of production for specific markets should be examined.
- The effect of irrigation, trellis systems and cover alternatives on pomegranate tree performance and fruit quality should be researched. Sunburn and windmarks are quality defects of pomegranate fruit that, depending on the degree of these defects, can decrease export volumes. Inadequate irrigation may lead to tree water stress and increased sunburn of fruit. Additional measures to curb sunburn are the use of appropriate trellis systems or to enclose the fruit after final fruit set in cloth or paper bags until shortly before harvest. The latter is a labour-intensive exercise. Another alternative, and one that is probably a more cost-effective solution to curb sunburn and wind damage, could be the use of drape netting, as is currently practiced in apple orchards. Less sunburnt and chafed fruit could increase export volumes and foreign or local income earned by commercial and/or smallholder farmers.
- Additional requests from pomegranate producers included the following:
  - Research on the effect of over-irrigation on root-related diseases and their management, especially in young orchards.
  - The treatment of highly saline water to improve quality before application through other means than reverse osmosis, which requires a reservoir on site.

RELEVANCE

Future research, based on research gaps identified in this project, will aim to provide the necessary information to support sustainable farming amid climate change (i.e. higher temperatures and changing rainfall patterns) and increasingly limited water resources. Knowledge of water-efficient production practices (e.g. accurate irrigation scheduling, appropriate irrigation systems, mulches and water-saving irrigation strategies) will allow producers to use limited water resources more efficiently and produce quality fruit for the local and export markets. High water use productivity and increased income from quality export fruit may improve the economic welfare of the community, i.e. producers and their farm workers will benefit from a positive impact on the economy. Pomegranate is a versatile fruit that can be marketed fresh, or it can be processed to provide ready-to-eat convenience foods and juice, whereas parts of the fruit can be used in pharmaceutical products. Processing plants, supported by a large enough industry, may create new job opportunities and promote economic development. Higher production may also lead to more job opportunities.

Research will aim to address the achievement of maximum water use efficiency and/or water use productivity at the farm level, and, as such, generate relevant information that can inform national government policy and decision making in the water sector. It is expected that temperature increases due to climate change will impact on Africa to a greater extent than Europe. The successful production of a drought-tolerant crop may provide sustainable income and work opportunities in future when crops currently produced become unproductive or fail. Water savings in agriculture will make more water available to other sectors, which is critical during drought. With regard to the environment, proper irrigation management will promote the efficient use of limited water resources and reduce the leaching of fertilizers, which impact on the quality of groundwater. The use of poor-quality water for production may be a viable option for pomegranate production in areas where other water resources are not available. Pomegranate trees are relatively tolerant to salinity, and careful management will be necessary to ensure the sustainable use of soils where saline irrigation water is applied over the long term.

Irrigation research requires substantial funding due to the specialised equipment needs, especially for the measurement of evapotranspiration, transpiration and soil water, and salinity status. It is envisioned that national agricultural and water sectors, which have to address adaption to climate change, could co-fund the future water use and irrigation-related research of the pomegranate industry. Such research would not only benefit the pomegranate industry and its dependents, but also the South African economy. Taking into account the high water use efficiency acquired locally in some production areas compared to that achieved internationally, as well as job creation and the economic potential of the crop, the WRC is requested to strongly consider a call to fund research on water use of and/or water-saving irrigation strategies and/or the use of saline irrigation water for the irrigation of pomegranate trees.

The extent to which the contract objectives have been met

The contract objectives have all been met and were exceeded in the case of the second specific aim by the inclusion of two years of survey data instead of only data for 2017/18.

Knowledge dissemination is ongoing until March 2020:

- One popular article was published in *SA Fruit Journal,* outlining the scope and purpose of the survey on the current irrigation practices and tree performance of pomegranate:
  Volschenk, T & Mulidzi, AR (2019) Pomegranate tree performance during critical drought, *SA Fruit Journal* 18(3):65-67.
- The literature survey is currently being reviewed at ARC Infruitec-Nietvoorbij before being submitted as two articles for publication in a South African journal.
- A final report was submitted to POMASA regarding the outcomes of the survey.
- A poster on the effect of irrigation on pomegranate tree performance in the Western Cape, South Africa, was presented at the Food and Agriculture Organisation of the United Nations' Water Productivity Conference in Tunisia (4-6 December 2019).
- A scientific article is still to be published – provided it is accepted by a credible journal.
- A voice note was submitted to RSG Landbou regarding climate change, irrigation and pomegranate tree performance. The broadcast date is still due (refer to Eloise Pretorius).

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SYMBOLS

a*	Red colouration
A_n	Net photosynthesis
B	Boron
C*	Chroma
Ca	Calcium
Cl	Chloride
Cu	Copper
EC_e	Saturated soil water extract
EC_{iw}	Irrigation water salinity
E_p	Pan evaporation
ET_o	Penman-Monteith reference evapotranspiration
ET_c	Crop evapotranspiration
fc	Fractional canopy ground cover
Fe	Iron
g_s	Stomatal conductance
K	Potassium
K_c	Crop coefficient
K_p	Class A pan factor
L*	Lightness
Mg	Magnesium
Mn	Manganese
N	Nitrogen
Na	Sodium
P	Phosphate
$Rain_{eff}$	Effective rainfall
RDIripe	Regulated deficit irrigation during ripening
T_r	Transpiration rate

$WP_{Irrigation}$	Water productivity based on irrigation applied
$WP_{Raineff + Irrigation}$	Water productivity based on effective rainfall and irrigation applied
$WUE_{Irrigation}$	Water use efficiency based on irrigation applied
$WUE_{Irrigation+Raineff}$	Water use efficiency based on effective rainfall and irrigation applied
Zn	Zinc
Ψ_s	Stem water potential

ABBREVIATIONS

ACF	Alternative Crop Fund
ARC	Agricultural Research Council
DI	Deficit irrigation
EC	Electrical conductivity
FC	Field capacity
FCM	False codling moth
FI	Full irrigation
FN	Fruit number
FS	Fruit size
FSA	Full surface area
IWUE	Intrinsic leaf water use efficiency
LAI	Leaf Area Index
MDS	Maximum daily trunk shrinkage
MI	Maturity Index
POMASA	Pomegranate Producers' Association of South Africa
PRD	Partial rootzone drying
RDI	Regulated deficit irrigation
RWC	Relative water content
SDI	Sustained deficit irrigation
SAR	Sodium adsorption ratio
TSS	Total soluble solids

TA	Titratable acidity
TAC	Total anthocyanin content
TEAC	Trolox equivalent antioxidant activity
TPC	Total phenolic compounds
WER	Water evaporation replenishment
WMA	Water management area
WP	Water productivity
WRC	Water Research Commission
WUE	Water use efficiency

CHAPTER 1: INTRODUCTION

1.1 MOTIVATION

Global warming-induced climatological changes are expected to impact negatively on the already limited water resources of the Western Cape (WCDoA and WCDEA&DP, 2016), and water restrictions for agriculture are an inevitable fact during drought years. Increased temperatures will result in an increased demand for irrigation for deciduous fruit orchards, but the irrigation volume for the agricultural sector is unlikely to increase as the Department of Water Affairs has capped agricultural allocations at current levels. It is furthermore predicted that the western region of South Africa will have a significant reduction in streamflow, with potentially sombre implications for irrigated agriculture. Water demand and supply forecasts for the Berg and the Olifants-Doorn WMAs, respectively, indicate a severe (-20% to -80%) and moderate (0% to -20%) gap between the supply in 2010 and the projected demand in 2030. Improved agricultural water use efficiency and productivity are considered necessities to provide the water needed for the projected increased water demand for human consumption and industrial production by 2030. Such limited water resource availability makes maximising net income per unit of water used a prerequisite for sustainable farming.

One way to cope with this situation is to invest in more suitable crops for the potential future climate (DEA, 2016), such as drought-tolerant pomegranate trees. Although the pomegranate industry in South Africa is small, it is growing, with 81, 10 and 7% of plantings (1,024 ha) in the Western Cape, Limpopo and Northern Cape, respectively. Production started in the early 2000s, and South Africa is presently an international role player in production and exports from the southern hemisphere to various countries in the northern hemisphere. In 2019, about 1,123,027 equivalent cartons of fruit (3.8 kg) were exported and 553,133 cartons were processed. Hortgro forecast exports of about 1.377 million cartons and the processing of almost 678,239 cartons for the industry by 2024. Research and development by POMASA is currently focused on the improvement of production practices. Although pomegranate trees are considered drought tolerant, irrigation is required during the dry summer months to optimise growth, yield and fruit quality for commercial production. The skilful management of limited water resources will be a necessity if optimal production and fruit quality is to be retained for a total farm unit.

Correct irrigation system selection, design and maintenance are very important for efficient in-field water management, but efficient irrigation scheduling is the key to achieving high irrigation water use efficiency. Although there are general POMASA guidelines with regard to the irrigation of pomegranates, no local research results are available to guide producers with regard to the effect of different levels of soil water depletion on pomegranate tree growth, yield and fruit quality under local conditions. Such research can provide guidelines with regard to the best water use efficiency without compromising the quality of fruit that is destined for the export market.

However, first and foremost, baseline information is needed regarding current irrigation practices and related tree water status, growth, yield and fruit quality information to direct more detailed research for the pomegranate industry. The ARC can utilise information obtained by the survey that forms part of this report to motivate for co-funding in future for more detailed irrigation research to achieve the high water use productivity that the latest South African Irrigation Water Strategy requires. Such research will be in support of the Water Research, Development and Innovation Roadmap and will focus, in particular, on the water demand aspect, through the WRC Climate Change, the Water-Energy-Food Nexus and Sustainable Water Behaviour Lighthouses as set out in the WRC's Corporate Plan of 2018/19-2022/23.

1.2 AIMS AND OBJECTIVES

The general aim of this study is to identify future pomegranate irrigation research needs from local survey observations and baseline data to ultimately empower South African producers to achieve the high economic water use productivity that is required. The first specific aim entails conducting an extensive literature survey on the irrigation management of pomegranate trees. The second specific aim is to analyse data from a local survey, including weather, soil, water and crop baseline information from pomegranate orchards under drip- or micro-irrigation in different production areas to identify research gaps that can direct future pomegranate irrigation research.

1.3 APPROACH

The relevance of the scoping study, and the aims and objectives set are described in Chapter 1. In Chapter 2, the literature review provides international research information on pomegranate tree water use, its response to water deficits and salinity, and potential water management strategies for use under limited water supply. In Chapter 3, South African data regarding current irrigation practices and tree performance collected at nine full-bearing pomegranate (Wonderful cultivar) orchards on commercial farms in four pomegranate production areas in the Western Cape (Bonnievale, Gouda, Wellington and Wolseley) are presented. Sites selected included orchard variability currently present in the industry, comprising different degrees of water quality, sandy or heavier soil, level or ridged gradients, planted with or without nets, and irrigated with micro-sprinklers or drip-irrigation (single or double line). Chapter 4 provides a synopsis of survey results. The study concludes with recommendations for future research on water use and irrigation for the pomegranate industry (Chapter 5).

1.4 REFERENCES

DEA (2016) *South Africa National Adaptation Strategy*. Draft for comments. https://www.environment.gov.za/sites/default/files/docs/nas2016.pdf. Accessed 02/05/2018.

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CHAPTER 2: LITERATURE REVIEW ON WATER USE AND IRRIGATION MANAGEMENT

2.1 INTRODUCTION

Although there are general POMASA guidelines with regard to the irrigation of pomegranates (POMASA, 2013), there are no local research results available to guide producers with regard to the effect of different levels of soil water depletion on pomegranate tree growth, yield and fruit quality under local conditions. A review of international pomegranate research is warranted to provide guidance until local research generates guidelines for South African producers on how to achieve the best water use productivity without compromising fruit quality. This review focuses on irrigation methods, the crop's water requirements and sensitivity to water deficits, and salinity and water management strategies under limited water supply (irrigation and orchard management).

2.2 METHODS OF IRRIGATION

Most of the large commercial orchards in Israel, India and the USA use drip-irrigation methods, although some producers prefer sprinklers (Holland et al., 2009). In California, though, most pomegranate orchards are irrigated using flood or furrow methods, with few farmers using high-frequency surface or subsurface drip (Wang et al., 2015; Zhang et al., 2017). In India, it is general practice to irrigate crops by conventional methods, i.e. flood, furrow and ring basin methods, with – in 2013 – only about 28% of the micro-irrigated crops in India being drip-irrigated (Singh and Sharma, 2013). In South Africa, drip- (single and double line) and micro-sprinkler irrigation are also practiced, whereas overhead irrigation is not advised for pomegranates (POMASA, 2013).

The benefits of drip-irrigation compared to conventional irrigation in Indian pomegranate orchards included c. 42% increased yield and c. 38% higher net returns of farmers. According to Kumar et al. (2013), drip-irrigation in pomegranate orchards saved a substantial amount of irrigation water (c. 32%) compared to surface methods. In comparison to surface irrigation systems, drip-irrigation increased water productivity (water productivity = yield/irrigation water applied) by 82% (53.2 kg ha^{-1} mm^{-1}), while net profit per mm of water applied for drip almost doubled. Frequent drip-irrigation, furthermore, limited variation in soil water availability and decreased pomegranate fruit cracking by 10-15%, which increased marketable yield. Ghosh et al. (2013) also found that drip-irrigated plants had less cracking than basin-irrigated plants.

Potential advantages of drip-irrigation over conventional methods (i.e. flood, furrow and ring basin) include a saving of up to 50% of water through reduced transpiration and evaporation losses, less labour costs related to weed control and the application of fertilizers and pesticides, and better control of water application on sloping terrains and variable soils (Singh and Sharma, 2013). The benefits of well-managed surface and subsurface drip-irrigation systems include eliminated or reduced runoff and deep drainage, minimised surface soil and plant evaporation, reduced transpiration of drought-tolerant crops and reduced fertilizer losses (Ayars et al., 1999). Compared to surface drip-irrigation on a sandy loam soil in California, subsurface drip-irrigation resulted in some years of significant increases in the yield of prime (good colour, diameter > 80 mm, minimal cracking with no open cracks) and/or sub-prime (suitable for juice, green, open cracked) fruit (Ayars et al., 2017; Wang et al., 2015). The total yield was consistently higher in the subsurface drip-irrigation system compared to the surface system, but due to an additional 10% of water being applied to the surface drip-irrigation treatment to compensate for evaporative water loss and weed growth, there were no significant differences (Ayars et al., 2017). The use of a subsurface drip-irrigation system resulted in reduced weed pressure compared to surface drip-irrigation. Water productivity (yield/water applied in mm) ranged from c. 51.5 to 55.8 kg ha^{-1} mm^{-1} and 59.7 to 60.4 kg ha^{-1} mm^{-1} for the surface and subsurface drip-irrigation systems, respectively.

Although subsurface drip-irrigation systems have their advantages, there are also some disadvantages to take into account (Lamm, 2002). These include, among others, wetting pattern issues on coarse soils, difficulties in monitoring and evaluating system operation and application efficiency, emitter discharge rates and water redistribution disparities, restricted plant root development and its role in irrigation and fertilization, and crop water stresses, even when the root zone is well watered. Although subsurface drip-irrigation can be used for pomegranate trees (Ayars et al., 2017), one needs to keep in mind that it entails high-frequency irrigation on a sandy loam soil. Applying irrigation after 1 mm of water use resulted in between 10 and 12 irrigations per day during peak water use (Ayars et al., 2017).

2.3 WATER REQUIREMENTS

Information on the water requirements of crops is needed to decide whether the production of a certain crop is viable in a specific region. Crop water requirements are the amount of water that needs to be supplied to replace water lost through evapotranspiration from the orchard. Crops' water requirements can be determined by directly measuring the water use (energy balance and micrometeorological methods, soil water balance and lysimeters) or it can be estimated indirectly using mathematical models.

2.3.1 Reference evapotranspiration and crop coefficients

For purposes of irrigation scheduling, crop evapotranspiration (ET_c) is frequently estimated according to the guidelines of FAO56 (Allen et al., 1998) using weather data-based Penman-Monteith reference evapotranspiration (ET_o) and crop coefficients (K_c). To calculate ET_o, one needs data on solar radiation, air temperature, humidity and wind speed measured at 2 m (or converted to that height) above an extensive surface of green grass, shading the ground and with no shortage of water. The ET_o can be estimated for hourly, daily or ten-day to monthly time steps using the appropriate calculations. Reference evapotranspiration can also be quantified using other less accurate models that require less extensive weather data sets (Meshram et al., 2011) or by monitoring Class A pan evaporation (Allen et al., 1998; Bhantana and Lazarovitch, 2010). Class A pan factor (K_p) is used for the conversion of Class A pan evaporation to ET_o (Allen et al, 1998). Long-term meteorological data has also been used to estimate ET_o for some of the pomegranate irrigation research done in India (Meshram et al., 2010a; Meshram et al., 2010b; Meshram et al., 2011; Bhagat and Popale, 2016), Iran (Parvizi et al., 2014) and Egypt (Seidhom and Abd-El-Rahman, 2011).

Although FAO56 (Allen et al., 1998) contains K_c values for various crops, data is not listed for pomegranate trees. Crop coefficients are experimentally determined ratios of ET_c/ET_o and K_c based on Class A pan evaporation, which are not interchangeable with those developed using ET_o. Crop coefficients can be determined based on ET_c measured accurately using weighing or drainage lysimeters (Ayars et al., 2017; Bhantana and Lazarovitch, 2010; Zhang et al., 2017) or deriving it from the soil water balance (Allen et al., 1998). Alternatively, the K_c of pomegranate can be estimated from site-specific empirical relationships of K_c versus the day of the year (Ayars et al., 2017; Parvizi et al., 2014), or from fractional canopy ground cover (Meshram et al., 2010a; Meshram et al., 2011; Zhang et al., 2017), as indicated in Figure 2.1.

Zhang et al. (2017) developed different mathematical relationships between K_c and fractional canopy ground cover for bushy (UC-KARE) and vase-shaped (USDA_ARS) pomegranate (Wonderful cultivar) trees in California. Comparison of these pomegranate-specific K_c estimates to those for peach (Ayars et al., 2003), grapevine (Williams and Ayars, 2005) and the general deciduous fruit equation used by Meshram et al. (2011) indicated that the Wonderful cultivar tended to have lower K_c values at comparable fractional ground cover (also measured as shaded area cast on the ground) than these crops (Figure 2.1). The differences in slopes and intercepts of these relationships are ascribed to differences in methods used to determine ET_c and the shaded areas, and dissimilarities in cultivation practices, specifically irrigation amounts and frequencies (Williams and Ayars, 2005).

For pomegranate, from the sources used in this review, only the K_c values generated by research of Ayars et al. (2017), Bhantana and Lazarovitch (2010) and Zhang et al. (2017) are based on lysimeter measurements. Those of Bhantana and Lazarovitch (2010) were intended for use with Class A pan evaporation and are suitable for a range of irrigation water salinities between 0.8 and 8 dS m^{-1}. The Class A pan crop coefficients for non-saline conditions for one-year-old Wonderful plants were 0.16 at bud break and 0.64 at 120 days after bud break. In California, the maximum K_c for use with the Penman-Monteith-derived ET_o increased for subsurface drip-irrigated Wonderful pomegranate trees from 0.85 for four-year-old trees to between 1 and 1.2 for six-year-old trees, bearing c. 33.2 and 50.4 t ha^{-1} fruit, respectively (Ayars et al., 2017). Intrigliolo et al. (2011a) adapted K_c values based on those of Bhantana and Lazarovitch (2010) for Spanish research conditions (Intrigliolo et al., 2012; Intrigliolo et al., 2013), whereas Buesa et al. (2012) initially used the farmer irrigation schedule and experimentally developed crop coefficients using soil water content and stem water potential measurements as a calibration aid. Bugueño et al. (2016) based their research on young pomegranate trees on the K_c value of Bhantana and Lazarovitch (2010) and recommended an upward adjustment since trunk growth rate was higher at 130% ET_c compared to 100% ET_c treatment.

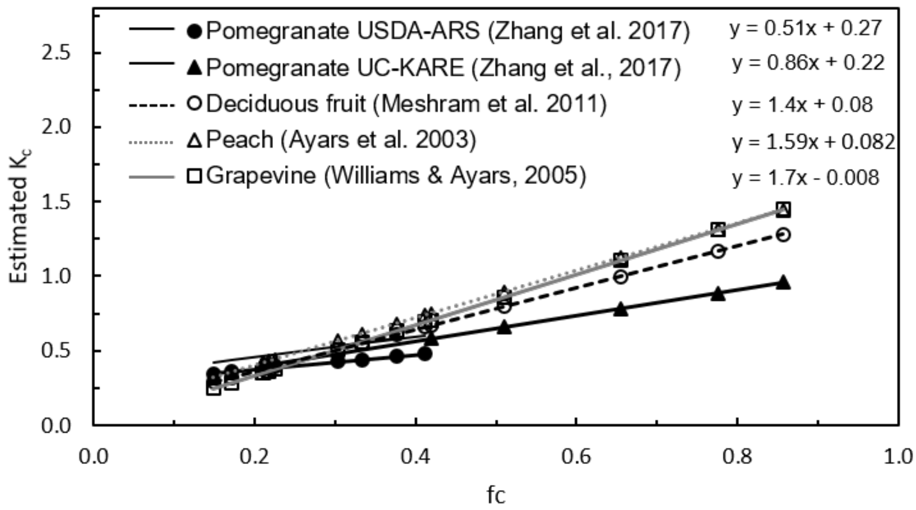

Figure 2.1: Comparison between crop coefficient (K_c) estimates from fractional canopy ground cover for bearing pomegranate (Zhang et al., 2017), general deciduous fruit (Meshram et al., 2010a), peach trees (Ayars et al., 2003) and grapevine (Williams and Ayars, 2005).

2.3.2 Crop evapotranspiration

From the articles sourced in this review, the only lysimeter-measured daily ET_c data for young pomegranate orchards was available from Israel (Bhantana and Lazarovitch, 2010). Daily ET_c of one-year-old *Punica granatum* L. plants during 2008 ranged from 0.23 to 5 mm d^{-1} from bud burst to peak season. The Class A pan evaporation during this period ranged from c. 3.1 to 9.2 mm d^{-1}. The young tree's peak water use is about half that measured in the Mediterranean climate of the Central Valley of California for bearing six-year-old Wonderful pomegranate trees (10.5 mm d^{-1}) (Ayars et al., 2017). There were minor cultivar-related differences in the daily ET_c of the one-year-old Wonderful and SP-2 varieties and their response to a range of irrigation water salinities between 0.8 and 8 dS m^{-1} (Bhantana and Lazarovitch, 2010). Salinity significantly reduced the daily ET_c of the pomegranate plants, which should be taken into account during irrigation scheduling to prevent excessive leaching.

The seasonal ET_c (March to November) for one-year-old Wonderful and SP-2 plants irrigated with low-salinity water in Israel during 2008 was 544 and 557 mm, respectively, amounting to about a third of the 1,521 mm cumulative Class A pan evaporation (Bhantana and Lazarovitch, 2010).

The irrigation of these trees with water with a salinity of 1.4, 3.3, 4.8 and 8 dS m^{-1}, respectively, reduced the seasonal ET_c relative to that of trees irrigated with 0.8 dS m^{-1} water by 15, 23, 44 and 66%. In 2010 and 2012 in California, the yearly ET_c of one- and three-year-old Wonderful subsurface drip-irrigated plants was c. 4% (c. 53 mm) and c. 35% (483 mm) of the c. 1,263 and c. 1,387 mm ET_o, respectively (Ayars et al., 2017). The yearly ET_c of bearing four-, five- and six-year old trees was c. 683, c. 912 and c. 953 mm, respectively, which amounted to 49, 62 and 69% of the cumulative ET_o.

Actual seasonal evapotranspiration of nine-year-old Manfalouty pomegranate trees grown in sandy desert soils in the El-Maghara region in Egypt was determined by measuring soil moisture content gravimetrically (Seidhom and Abdel-Rahman, 2011). The ET_c of trees drip-irrigated every second day totalled c. 483 mm on average over three years from February to October, with a maximum daily water use of 2.7 mm d^{-1} during the season. The ET_o for the 2008 to 2010 seasons, on average, amounted to 1,334 ± 16 mm. Soil water balance determined the seasonal evapotranspiration of six-year-old Hicaznar pomegranate trees planted in 1.2 m deep loamy soil in Turkey to range between 775.2 and 825.6 mm during three seasons, whereas the ET_o amounted to 751.5 (± 34.4) (Dinc et al., 2018).

2.3.3 Irrigation water requirement

In addition to ET_c, the irrigation water requirement takes effective rainfall into account and may include extra water to compensate for irrigation system efficiencies and/or the leaching of salts (Allen et al., 1998). Methods for the estimation of ET_c and the irrigation water requirements differed widely between countries and research studies sourced in this review due to site-specific differences in, among other factors, evaporative demand, orchard spacing, cultivars, tree canopy cover, soil type, wetted area and irrigation water salinity. However, the measured amounts of irrigation water applied to the well-watered control treatments of drip-irrigated irrigation research projects conducted in young to full-bearing orchards in various countries gives an indication of the variation in the irrigation water requirement of pomegranate orchards (Figure 2.2).

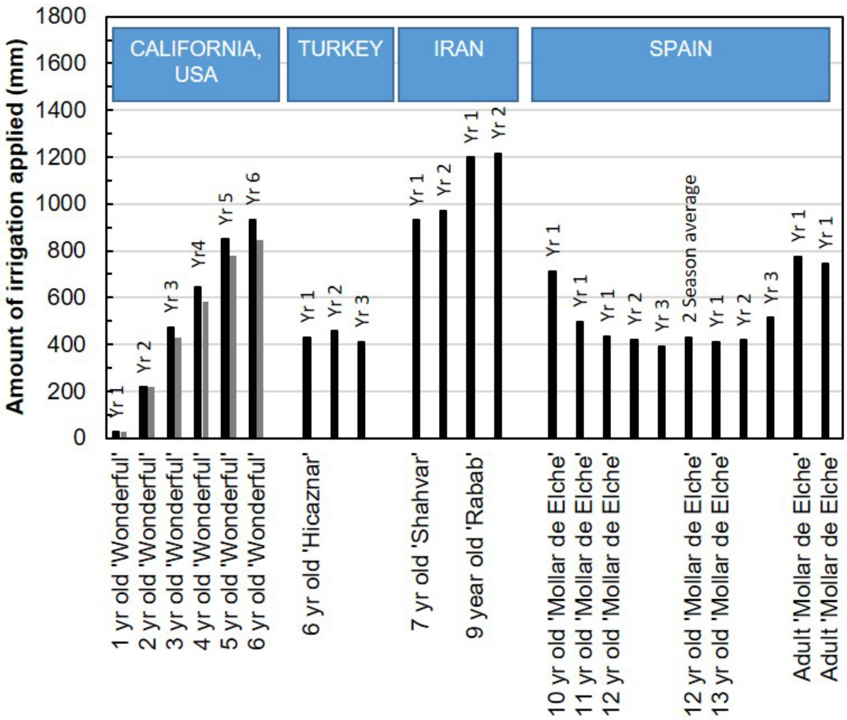

Figure 2.2: Amounts of irrigation applied to well-watered control treatments of drip-irrigation research projects for selected pomegranate cultivars varying in age and irrigated period in California, Turkey, Iran and Spain. The grey bars indicate subsurface drip-irrigation. Data labels indicate experimental year.

On fine sandy loam in the first and second season in California, non-bearing Wonderful trees received 25 and 216 mm drip-irrigation, respectively (Ayars et al., 2017). The amount increased in subsequent seasons for bearing three-, four-, five- and six-year-old subsurface drip-irrigated pomegranate trees to 427, 584, 780 and 843 mm for irrigation water, and to 472, 645, 848 and 932 mm for surface drip-irrigated trees of a similar age. In Turkey, irrigation applied in loamy soil to double-line drip-irrigated Hicaznar trees amounted to 430, 455.5 and 410 mm (Dinc et al., 2018). The maximum irrigation applied to the pomegranate cultivars Shahvar and Rabab grown on loam and fine sandy loam soils in Iran was 972 and 1,214 mm, respectively (Parvizi et al., 2014; Selahvarzi et al., 2017). The amount of irrigation water applied to the Mollar de Elche cultivar grown on sandy loam to silt loam soils in Spain ranged from 392 to 776 mm (Buesa et al., 2012; Intrigliolo et al., 2011a; Intrigliolo et al., 2012; Intrigliolo et al., 2013; Mellisho et al., 2012; Mena et al., 2013; Peña-Estévez et al., 2015; Peña-Estévez et al., 2016).

With regard to the canopy cover of these orchards, no information was available for the non-bearing trees in California. However, maximum canopy ground cover for the surface drip-irrigated three-, four- and five-year old Wonderful orchards, respectively, was c. 20.9, 46.2 and 81.3%, compared to c. 21.1, 51 and 85.7% for the subsurface irrigated trees (Zhang et al., 2017). Canopy cover of the Shavar cultivar in Iran is given as c. 50% (Selahvarzi et al., 2017), whereas the canopy diameter of the Rabab cultivar was 2 m in an orchard spaced 5 m x 4 m (Parvizi et al., 2014). The full canopy ground cover of most of the Spanish Mollar de Elche orchards between 11 and 13 years old ranged between 48 and 56% (Buesa et al., 2012; Intrigliolo et al., 2011a; Intrigliolo et al., 2012; Intrigliolo et al., 2013).

2.4 RESPONSES TO WATER DEFICITS AND SALINITY

Limited water supplies or the application of alternative irrigation management strategies in orchards can cause water deficits in fruit trees. Water stress can be induced deliberately by withholding irrigation or by applying less water than plants use, a method called regulated deficit irrigation (RDI) (Mitchell et al., 1984). To effectively apply RDI as a strategic tool to reduce vegetative growth and pruning costs, or to manipulate fruit quality, an understanding of plant response to water stress is important. Knowledge of tree and fruit growth patterns is a prerequisite to apply RDI successfully. This tool is usually applied during a period of slow fruit growth, when shoot growth is rapid, and after harvest in early-maturing varieties (Goodwin and Boland, 2002).

Most of the research consulted in this review regarding the effect of water deficits on pomegranate tree performance formulated deficit irrigation (DI) or partial rootzone drying (PRD) treatments relative to E_p (pan evaporation), ET_o (Afria et al., 1998; Dinc et al., 2018; Galindo et al., 2014a; Mellisho et al., 2012) or ET_c (Bartual et al., 2015a; Bartual et al., 2015b; Haneef et al., 2014; Intrigliolo et al., 2012; Intrigliolo et al., 2013; Laribi et al., 2013; Noitsakis et al., 2016; Parvizi et al., 2014; Parvizi et al., 2016;. Parvizi and Sepaskhah, 2015; Selahvarzi et al., 2017). Others withheld water for varying periods before harvest (Galindo et al., 2014b; Galindo et al., 2017a), applied different volumes of water per season (Khattab et al., 2011) or varied irrigation intervals without or in combination with soil management practices (Dinc et al., 2018; Ghosh et al., 2013; Seidhom and Abd-El-Rahman, 2011). Only a few studies quantified soil water content in addition to monitoring plant water status or water deficit-related stress indicators (Ayars et al., 2017; Buesa et al., 2012; Bugueño et al., 2016; Intrigliolo et al., 2013; Hepaksoy et al., 2016; Parvizi et al., 2016).

Large variability in and incompatibility of research results of different deficit irrigation studies for different orchards can partially be attributed to the use of ET_o or estimated ET_c as a reference base to induce treatments, since the magnitude of the deficit induced, even for orchards of similar properties, depends on the ET_o variation. Also, if the actual soil water deficit is not quantified, it becomes very difficult to compare stress levels induced in different studies. Galindo et al. (2017b) stressed, among other key constraints for the application of RDI, the requirement for new and more precise criteria to define a water deficit for a range of different growing conditions (species, weather, soil depth, fruit load and rootstock).

The effect of irrigation strategies on trees may differ depending on the timing and level of water deficit applied, its duration, the climatic conditions of the area and the drought tolerance of the crop via avoidance and tolerance mechanisms. Although the extent of the root system plays an important role in the drought tolerance of a crop, the inherent physiological traits of plants also determine their responses to water deficits and productivity under limited water supply (Pinheiro et al., 2005). Apart from the research of Rodrígues et al. (2012) and Galindo et al. (2014b) on the Mollar de Elche cultivar, there is a lack of information on the leaf water relations of different pomegranate cultivars that mechanistically explain the leaf-level response of trees to water deficits.

2.4.1 Physiology

Pomegranate trees are considered to be drought resistant. Under water-deficit conditions, trees decrease stomatal conductance (g_s) to control water loss via transpiration to avoid leaf turgor loss (Rodrígues et al., 2012; Parvizi et al., 2016). In addition, in response to severe long-term stress (i.e. water withheld for up to four weeks), active osmotic adjustment occurred in Mollar de Elche leaves, enabling it to maintain turgor (Rodrígues et al., 2012). According to Rodrígues et al. (2012), drought-tolerance characteristics of leaves such as high apoplastic soil water content (42 to 58%) may aid in the retention of water at low leaf water potentials. At turgor loss point, the Mollar de Elche leaves had osmotic potential of between -2.49 and -3.27 MPa, while still having a relatively high relative water content (RWC) (on average, c. 84%). No elastic adjustment occurred in these leaves as a result of water stress. Fruit peel osmotic potential increased, whereas that of arils was not affected by water deficits (Galindo et al., 2014b). Fruit peel turgor loss occurred at a fruit water potential of -2.25 MPa (an estimated midday stem water potential of -1.95 MPa), and aril turgor loss at a fruit water potential of -2.69 MPa (an estimated midday stem water potential of -2.46 MPa). Decreased marketable yield and fruit size was attributed to fruit turgor loss for a period of more than six days during the end of fruit growth and ripening, despite compensative fruit growth that occurred after a rainfall event.

Leaf water potential, pre-dawn and during the day, as well as stem water potential (Ψ_s), is frequently used in irrigation research to indicate the water status of fruit trees and vines. Crop, and even cultivar-specific, thresholds of these indicators are linked to degrees of water constraints that impact on crop physiology and fruit quality to a lesser or more severe extent (Tejero and Zuazo, 2018; Myburgh, 2018). Since the minimum (midday) Ψ_s incorporates the effects of atmospheric demand, as well as the soil water on the tree (Ebel et al., 2001), it is frequently used commercially to schedule the irrigation of woody crops. Itrigliolo et al. (2011a), though, considered Mollar de Elche photosynthesis and stomatal conductance to be more sensitive indicators of water deficits than midday Ψ_s. Pomegranate Ψ_s is affected by several factors, which include soil water content, irrigation water salinity, climate variables and crop load. The stem water potential of the Rabab cultivar decreased with increased evaporative demand as the season progressed, as well as with increasing soil water deficit. Different slopes of linear regression relationships between midday Ψ_s and the soil water deficit for two sequential seasons was ascribed to the effects of higher crop load and differences in mean air temperature (Parvizi et al., 2016). In contrast, no significant relationship was found between Mollar de Elche's Ψ_s and its soil water content in the root zone up to a depth of 0.5 m (Intrigliolo et al., 2013). In this case, the linear regression relationships between midday Ψ_s and the midday vapour pressure deficit of different seasons was affected by irrigation water salinity, whereas increased crop load also decreased Ψ_s.

For Mollar de Elche in well-watered control treatments in Spain, g_s associated with a seasonal minimum midday Ψ_s of between -0.98 and -1.6 MPa ranged between 400 and 220 mmol m^{-2} s^{-1} (Figure 2.3a). The stomatal conductance was much lower under Iranian conditions for the Rabab and Shavar cultivars, the maximum being 41 and 105 mmol m^{-2} s^{-1} at a seasonal minimum midday Ψ_s of -2.6 and -1.2 MPa, respectively. The low Ψ_s values of the fully irrigated Rabab trees, compared to values of about -1.1 MPa for adequately irrigated Mollar de Elche trees (Galindo et al., 2013; Intrigliolo et al., 2013) were attributed to differences between cultivars and environmental conditions during measurement (Parvizi et al., 2016).

During fruit development in California in summer, a relatively low mean pre-dawn and midday Ψ_s of -0.825 and -2.420 MPa was measured using the shoots of four pomegranate cultivars irrigated three times a week (Chater et al., 2018). In this case, there was a time delay between the pruning of the shoots placed in plastic bags and the measurement of Ψ_s. Mean maximum temperatures reported for California in August (35.6 °C) were comparable to the 35.9 °C reported for the Rabab growing season in Iran (Parvizi et al., 2016). Over two seasons, mean stomatal conductance of the four cultivars ranged between 100 and 180 mmol m^{-2} s^{-1} in the morning, and decreased to between 40 and 70 mmol m^{-2} s^{-1} in the afternoon (Chater et al., 2018).

The midday stem water potential of several commercially well-known Iranian cultivars subjected to 14 days of drought in a greenhouse study decreased to values of between -5.35 and -6.63 MPa, with that of the control ranging between -1.2 and -1.8 MPa (Pourghayoumi et al., 2017a). The most drought-tolerant cultivar had higher leaf RWC, stem water potential and intrinsic leaf water use efficiency (IWUE), and a greater ability for osmotic adjustment compared to the other cultivars. Pourghayoumi et al. (2017b) found clear differences in metabolite contents and antioxidant enzyme activity among the cultivars differing in drought tolerance. Cultivars also differed with regard to the ability to physiologically recover after rehydration (Pourghayoumi et al., 2017a; Pourghayoumi et al., 2017b) and more research regarding the mechanism that allows fast recovery after rehydration and the prevention of photoinhibitory damage in plants subjected to drought stress is needed (Catola et al., 2016).

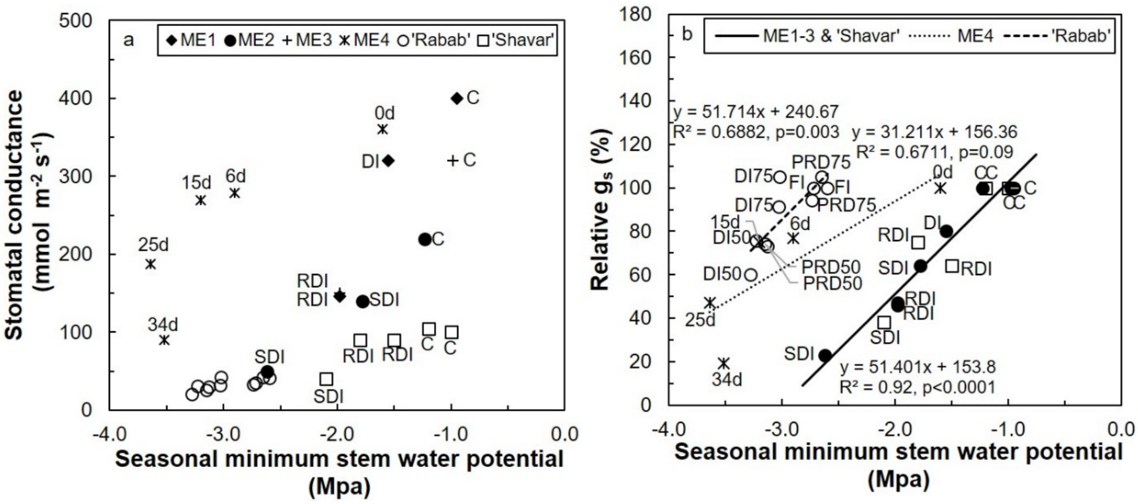

Figure 2.3: Seasonal minimum midday stem water potential and corresponding actual (a) and relative (b) stomatal conductance for three pomegranate cultivars subjected to full irrigation (C or FI), sustained, regulated or other deficit irrigation strategies (SDI, RDI, DI), including partial rootzone drying (PRD). Separate regression relationships were applied for the Mollar de Elche (ME) cultivar subjected to deficit irrigation (ME1-3) and where water was withheld for different periods (ME4). Graphs were drawn from data adapted from Galindo et al. (2013), Galindo et al. (2014a), Galindo et al. (2014b), Mellisho et al. (2012), Mena et al. (2013), Parvizi et al. (2016) and Selahvarzi et al. (2017).

In general, the stomatal conductance (g_s) of Mollar de Elche trees that received no irrigation for different time periods before harvest was higher at lower seasonal minimum midday Ψ_s (between -2.9 and -3.64 MPa) compared to that of studies of the same cultivar where RDI or sustained deficit irrigation (SDI) treatments were applied (Figure 2.3a). Although these differences may partially be attributed to the site-specific effects of climate, crop load and irrigation water salinity, it is possible that plant water deficits develop physiologically differently when water is withheld completely for a continuous period compared to where the crop is pre-conditioned for water deficits, i.e. where less than the crop water demand is applied daily or periodically.

The seasonal minimum midday Ψ_s in deficit irrigated (DI/RDI/SDI) Mollar de Elche trees ranged between -1.55 and -2.6 MPa, whereas, in Shavar trees, it reached -1.5 to -2.8 MPa (Figure 2.3a) (Selahvarzi et al., 2017). For Rabab trees subjected to various PRD and DI treatments over two seasons, the minimum midday seasonal Ψ_s varied between -2.65 and -3.28 MPa (figures 2.3a and 2.3b). The stomatal conductance of Rabab trees reduced linearly with decreasing stem water potential, and non-linearly with increasing vapour pressure deficit until 7 kPa, after which it dropped sharply in response to increasing vapour pressure deficit (Parvizi et al., 2016).

Apparently, pomegranate cultivars differ in their ability to control their water status under water deficit conditions. The leaf RWC of Shishehgap decreased at a greater rate than that of Rabab with increasing water stress up to 25% of field capacity (Ebtedaie and Shekafandeh, 2016).

Table 2.1: The effect of deficit irrigation strategies on tree water status and the associated relative reduction in the midday stomatal conductance of different pomegranate cultivars of varying ages produced in various countries. Water status is indicated by minimum seasonal midday stem water potential (Ψ_s), pre-dawn or midday leaf water potential (Ψ_{pd} or Ψ_l). An asterisk indicates significant differences compared to a well-watered control. Data values (water potential and stomatal conductance) were obtained from text or derived from graphs.

Cultivar	Country	Age	Irrigation strategy	Irrigation levels	Minimum water potential (MPa)	Decrease in g_s relative to control (%)	Author
Mollar de Elche	Spain	10	Control RDI	T0: 105% ET_o T1: Withheld water for 34 days during second half of rapid fruit growth, reirrigated for six days.	Ψ_s -0.98 Ψ_s -1.98*	 c. 53%*	Galindo et al. (2013)
Mollar de Elche	Spain	Adult	DI RDI	T0: 105% ET_o T1: Second half of rapid fruit growth to last harvest 33% ET_o	Ψ_s -1.02 After two weeks Ψ_s c. -1.5 Ψ_s c. -1.5 Ψ_s -2.18*	 After two weeks: c. 28% After c. six weeks: c. 42% After c. eight weeks: c. 13%	Galindo et al. (2014a)
Mollar de Elche	Spain	Adult	Water withheld before harvest (days)	0 6 15 25 34	Ψ_s -1.6 Ψ_s -2.9* Ψ_s- -3.2* Ψ_s -3.64* Ψ_s -3.52*	 c. 23%* c. 25%* c. 53%* c. 81%*	Galindo et al. (2014b)
Mollar de Elche	Spain	10	Control	60% ET_o –117% ET_o – 99% ET_o until first half of linear fruit growth phase, second half of linear fruit growth phase and during end of fruit growth and ripening, respectively	Ψ_s -1 Ψ_{pd} -0.45 Ψ_l -2.2		Mellisho et al. (2012) Rodrígues et al. (2012)
			Grower's criteria (DI)	32% ET_o – 74% ET_o – 36% ET_o until first half of linear fruit growth phase, second half of linear fruit growth phase and during end of fruit growth and ripening, respectively	Ψ_s -1.6* Ψ_{pd} -0.6* Ψ_l -2.6	c. 19%*	

Cultivar	Country	Age	Irrigation strategy	Irrigation levels	Minimum water potential (MPa)	Decrease in g_s relative to control (%)	Author
			RDI	32% ET_o – NI – 99% ET_o until first half of linear fruit growth phase, second half of linear fruit growth phase and during end of fruit growth and ripening, respectively	Ψ_s -2* Ψ_{pd} -1.2* Ψ_l -2.9*	c. 53%*	
Mollar de Elche	Spain	Adult	Control	75% ET_o	Ψ_s -1.23		Mena et al. (2013)
			SDI	43% ET_o	Ψ_s -1.78*	36%*	
			SDI	12% ET_o	Ψ_s -2.62*	77%*	
Rabab	Iran	9	FI	100% ET_c	Ψ_s-2.72, -2.6		Parvizi et al. (2016)
			DI	75% ET_c DI	Ψ_s -3.03*, -3.02*	8.6%, -4.9%	Two seasons: 2011, 2012
			PRD	75% ET_c PRD	Ψ_s -2.74, -2.65	5.7%, -4.9%	
			DI	50% ET_c DI	Ψ_s -3.28*, -3.23*	40%*, 24.4%*	
			PRD	50% ET_c PRD	Ψ_s -3.15*, -3.13*	25.7%, 26.8%*	
Shavar	Iran	7	Control	100% ET_c	Ψ_s -1.2, -1		Selhavarzi et al. (2017)
			RDI fruit set	No irrigation until end fruit set, 100% ET_c rest of season	Ψ_s -1.5*, -1.8*	36%*, 25%*	Two seasons: 2014, 2015
			SDI	50% ET_c throughout season	Ψ_s -2.1*, -2.8* (week thereafter -2.5)	62%*, 12.5% (week thereafter 70%*)	
Wonderful	Greece	12	Control	100% ET_c starts two months after bud break	Ψ_{pd} -0.29		Noitsakis et al. (2016)
			PRD1	100% ET_c one side of tree	Ψ_{pd} -0.26*	13%*	
			PRD2	50% ET_c one side of tree	Ψ_{pd} -0.55*	39%*	

At 50% of field capacity, the RWC of Shishehgap leaves was c. 30% less than that of the control, while this reduction was only 12.5% in Rabab leaves. Better control of plant water status in Rabab is attributed to a stronger antioxidant system to tolerate drought-related oxidative stress and a more effective accumulation of soluble carbohydrates for osmotic adjustment (Ebtedaie and Shekafandeh, 2016).

In general, the lowest seasonal stomatal conductance for the RDI and SDI treatments coincided with the seasonal minimum midday Ψ_s (Galindo et al., 2013; Galindo et al., 2014b; Mellisho et al., 2012; Mena et al., 2013), making a comparison of relative stomatal conductance at minimum midday Ψ_s relevant. However, in some cases, the stomatal conductance of the well-watered Mollar de Elche decreased substantially later in the season, resulting in only a minor decrease of RDI-relative stomatal conductance (13%) by the time it reached the seasonal minimum midday Ψ_s of -2.18 MPa (Table 2.1) (Galindo et al., 2014a). Earlier in the season, the effect of RDI on the relative g_s proved to be much more pronounced, being reduced by c. 42% at a Ψ_s of c. -1.5 MPa. For Shavar in the second season of SDI, a substantial reduction in g_s was measured about a week after the seasonal minimum midday Ψ_s of -2.8 MPa had been recorded (Selahvarzi et al., 2017). These data points have therefore been excluded from the regression relationships and water stress classification in the following paragraphs.

The relative g_s of Mollar de Elche and Shavar had similar linear regression relationships with seasonal minimum midday Ψ_s. According to a combined linear regression relationship (Figure 2.3b), the relative stomatal conductance of these cultivars decreased by 26 and 51% at minimum midday Ψ_s values of -1.5 and -2 MPa, respectively, under their respective experimental conditions. Water stress in Mollar de Elche trees developed differently where RDI and/or SDI was applied (Galindo et al., 2013; Galindo et al., 2014a; Mellisho et al., 2012; Mena et al., 2013) compared to where water was withheld completely once-off before harvest (Galindo et al., 2014b) (figures 2.3a and 2.3b). In the latter case, the mathematical relationship between relative stomatal conductance and minimum midday Ψ_s was poorer, and relative stomatal conductance decreased at a lower rate compared to where RDI or SDI was practiced. For Rabab, data for two seasons combined indicated that stomatal conductance decreased at a similar rate to that of Mollar de Elche and Shavar, even though the range of Ψ_s differed greatly.

In several deficit irrigation studies, the stomatal response of the trees was used to rank the water stress to which the trees were subjected (Table 2.1). In general, a relative reduction in midday stomatal conductance of between 19 and 36% was considered mild or moderate, whereas a decrease of between 53 and 77% was considered severe (Table 2.2). A moderate water deficit of -1.55 MPa during the second half of linear fruit growth was considered enough to affect the yield, final fruit size and fruit quality characteristics of Mollar de Elche (Mellisho et al., 2012). The classifications of Galindo et al. (2014b) and Parvizi et al. (2016) did not fit in with those of the other studies, and were excluded from Table 2.2. In the case of Galindo et al. (2014b), Mollar de Elche's midday stem water potential of -2.9 MPa, -3.2 and lower than -3.5 MPa (Table 2.1) was classed as mild, severe and very severe water stress. Parvizi et al. (2016) described water deficits occurring at the end of the fruit growth stage with seasonal minimum stem water potentials (Table 2.1) of between -2.65 and -3.03 MPa as mild (trees irrigated at 75% ET_c), and between -3.13 and -3.28 MPa as severe (trees irrigated at 50% ET_c).

Table 2.2: Classification of the degree of water stress for deficit irrigated treatments from selected research studies according to seasonal minimum midday stem water potential and associated reduction in stomatal conductance relative to a well-watered control. Adapted from Galindo et al. (2013; 2014a), Mellisho et al. (2012), Mena et al. (2013), Rodrígues et al. (2012) and Selahvarzi et al. (2017).

Seasonal minimum midday stem water potential (MPa)	Relative reduction in stomatal conductance	Degree of water stress
-0.98 to -1.23	-	Well-watered
-1.5 to -1.8	19 to 36%	Mild/moderate
-1.98 to -2.8	53 to 77%	Severe/strong

The stem water potential of Rabab trees irrigated every four days at 100% ET_c (six drippers per tree) and 75% ET_c PRD (irrigation on alternate sides of the tree, three drippers per tree) was more or less comparable in both seasons, whereas, in the 75 and 50% ET_c DI (irrigation on one side of the tree, three drippers per tree) and 50% ET_c PRD treatments, it was notably lower after about 80 days from bud burst compared to the aforementioned two treatments (Parvizi and Sepaskhah, 2015). Stem water potential in the PRD irrigation strategies was significantly higher compared to that in the corresponding DI strategies. Irrigation at 50% ET_c reduced stem water potential compared significantly to that in the 75 and/or 100% ET_c treatments about three months after bud break. Stem water potential decreased linearly as soil water deficit increased, albeit at a steeper slope during the second season, which was attributed to differences in weather conditions and higher crop load. The progressive seasonal decrease in stem water potential in all irrigation strategies until early fruit ripening (i.e. 170 days after bud burst) was attributed to increased water demand due to tree and fruit growth, air temperature increases and decreased air humidity. Applying severe water stress with PRD and DI strategies affected gas exchange parameters significantly compared with full irrigation (FI) and mild water stress (Parvizi et al., 2016). The PRD strategies had higher leaf water use efficiency (transpiration efficiency or A_n/T_r) than DI, due to higher net photosynthesis (A_n) at comparable transpiration rates (T_r), and transpiration efficiency was increased by increasing the level of water stress (i.e. from irrigating at 75 to 50% ET_c). The fully irrigated trees had lower IWUE (A_n/g_s) compared to the other irrigation strategies, with no notable differences in IWUE for PRD and DI strategies in both levels of water stress.

In Greece, applying 100% ET_c to one side of the root zone (PRD) instead of to the whole root zone significantly increased the pre-dawn leaf water potential of Wonderful pomegranate trees on several occasions (Noitsakis et al., 2016). Irrigation applied to one side of the root zone at 50% ET_c significantly decreased pre-dawn leaf water potential after the first month of treatment and for the remainder of the season compared to the control and 100% ET_c PRD treatment, decreasing beyond -0.5 MPa at some stage (Table 2.1). During this period, stomatal conductance, transpiration rate, and, to a lesser degree, net photosynthesis decreased significantly with a decrease in the amount of irrigation water applied and with a smaller area of application (i.e. full root zone vs one side of the root zone). Lower stomatal conductance in the 100% ET_c PRD treatment, despite higher pre-dawn leaf water potential values compared to the control, was attributed to chemical signals involved in stomatal regulation. The authors hypothesised that, in the absence of or under mild drought conditions, the primary signals controlling stomatal conductance are root chemical signals, whereas under intense drought conditions, tree water status plays a more important role. This is in direct contrast to Rodrígues et al. (2012), who considered the process to operate and vice versa. In this regard, Parvizi et al. (2016) hypothesised that the pomegranate's response to water stress is mainly based on weather conditions so that, in arid conditions with high vapour pressure deficit (their study), hydraulic signalling, and in humid conditions with low vapour pressure deficit (Intrigliolo et al., 2011a), non-hydraulic signalling possibly contributed to stomatal control.

2.4.2 The effects on phenological development

In Egypt, during two subsequent seasons, increasing the application of irrigation to 20-year-old Manfalouty pomegranate trees from 280 to 600 mm per season resulted in c. 24 to 34% more flowers per shoot, c. 10% higher fruit set and 8.6% less fruit drop (Khattab et al., 2011). In Spain, mild plant water stress (Ψ_s less than -1.4 MPa) applied early in the season through RDI (25% ET_c during flowering, fruit set and early fruit growth, 100% ET_c during the remainder of the season) and SDI (50% ET_c throughout the season) decreased the drop of fruit and flowers in Mollar de Elche trees (Intrigliolo et al., 2013).

In Iran, though, a more severe level of RDI (no irrigation until the end of fruit set, 100% ET_c for the remainder of the season) applied to seven-year-old Shavar pomegranate trees in two sequential seasons resulted in minimum Ψ_s values of c.-1.5 and c.-1.8 MPa near the end of fruit set (Selahvarzi et al., 2017). The RDI decreased the number of lateral flowers on average over two seasons by c. 38% compared to where irrigation was applied at 100% ET_c, and increased fruit set on the lateral flowers compared to the 100% ET_c and SDI (50% ET_c throughout the season) treatments.

In addition, the RDI treatment shortened the flowering period compared to that of fully watered and SDI trees by c. 42 and 49%, respectively. The delayed first and advanced second and third flowering waves were attributed to RDI that may have induced earlier completion of current year shoot growth or modified plant hormonal balance, which promoted earlier blooming. The trees that were subjected to SDI had a comparable number of lateral flowers and fruit set in the first season compared to the 100% ET_c trees. In the second season, though, the lateral flowers decreased by 17% and fruit set by c. 37% compared to the well-watered trees. The SDI trees had less water stress at the end of fruit set compared to the RDI trees, but reached a minimum midday Ψ_s of c. -2.1 and c. -2.8 MPa later in the season in the two respective seasons.

The SDI treatments with their longer duration not only affected the current season's production, but also fruit bud development in the following season. The degree of impact is determined by the severity of the water deficit that develops during the season. Additional research is needed to determine the effect of water stress (timing, degree and duration) on the bud differentiation and fruit set of pomegranates.

2.4.3 Vegetative growth

Although the response of trees to water deficits differs between those in pots and those in orchards, greenhouse studies can give an indication of how the trees may respond in the field. Soil water depletion of two-litre pots to 60, 40 and 20% of fully watered status reduced the vegetative growth of one-year-old Chinese pomegranate seedlings significantly relative to a fully watered control (Figure 2.4) (Xie et al., 2015). Several variables, including plant height (c. 13 to 43% of 89.7 cm), stem diameter (c. 22 to 46% of 14.6 mm) and shoot dry weight (c. 16 to 57%), decreased, whereas root dry weight tended to increase (c. 10 to 25%). The root-to-shoot ratio increased significantly from 0.16 in the control plants to 0.26 and 0.47 in plants at 40 and 20% water content, respectively.

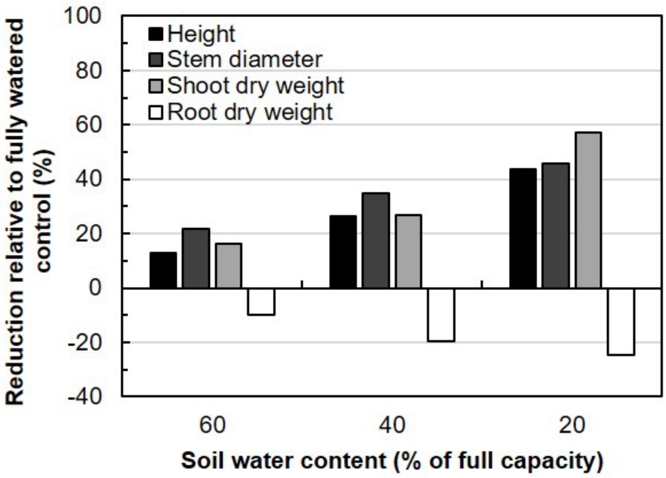

Figure 2.4: The effect of soil water deficits on the vegetative growth of potted one-year-old Chinese pomegranate seedlings (adapted from Xie et al., 2015).

In a greenhouse study in Iran, Ebtedaie and Shekafandeh (2016) found that pomegranate cultivars may differ in sensitivity to water stress at the biochemical level, which affects their water status and growth. The irrigation of one-year-old Shishehgap pomegranates at 50 and 25% of field capacity (FC) reduced new shoot growth relative to the 100% FC treatment by 21 and 50%, respectively. However, Rabbab was less sensitive to water deficits, and shoot growth decreased by 4 and 23% for the respective treatments. Likewise, high water deficit (25% FC) induced less severe leaf necrosis and leaf drop in Rabbab compared to Shishegap. The RWC of the Rabbab leaf decreased less, whereas leaves had a stronger antioxidant system and accumulated more soluble carbohydrates compared to Shishegap, allowing it to withstand more water stress.

In Chile, where only 30% ET_c was applied to newly planted Wonderful pomegranate trees in a sandy loam soil orchard, water deficits during only the second season reduced canopy volume, trunk growth rate and trunk cumulative growth compared to where 100 and/or 130% ET_c was applied (Bugueño et al., 2016). Trees receiving 70% ET_c tended to have lower canopy volume and trunk cumulative growth compared to trees where 130% ET_c was applied, indicating the onset of some plant stress. In young trees, the trunk growth rate was a more sensitive indicator of water deficits than maximum daily trunk shrinkage (MDS) and a 33% decrease in optimal trunk growth rate was considered to indicate sub-optimal growth or stressed conditions for young Wonderful pomegranate plants (Bugueño et al., 2016). In Spain, MDS is accepted as a more suitable indicator of water stress for full-bearing pomegranate trees (Intrigliolo et al., 2011b; Galindo et al., 2013). In general, for full-bearing Mollar de Elche trees in Spain, MDS increased in response to water stress with increasingly negative stem water potential (Intrigliolo et al. 2011b; Galindo et al., 2013). However, more research in this regard is needed as different relationships are applied earlier and later in fruit growth (Intrigliolo et al., 2011b). Galindo et al. (2013) found a sharp decrease in MDS above a Ψ_s of -1.67 MPa.

With regard to young bearing pomegranate trees, there appears to be a fine balance between plant available water and the competition between different types of vegetative growth and yield for assimilates. In India, the yield of three-year-old Ganesh trees increased with increasing area per leaf (Figure 2.5a), but both area per leaf and yield decreased when plant height exceeded c. 179 cm in treatments that replaced more than 40% of evaporated water (Figure 2.5b) (Afria et al., 1998). For every 10 cm increase in plant height beyond 179 cm, the estimated leaf area decrease was c. 4% and the yield loss was 10.8%. A wetter irrigation regime for such young orchards may therefore promote tree structure development rather than leaf photosynthetic capacity and yield, whereas drier conditions may secure a first harvest, but restrict tree growth.

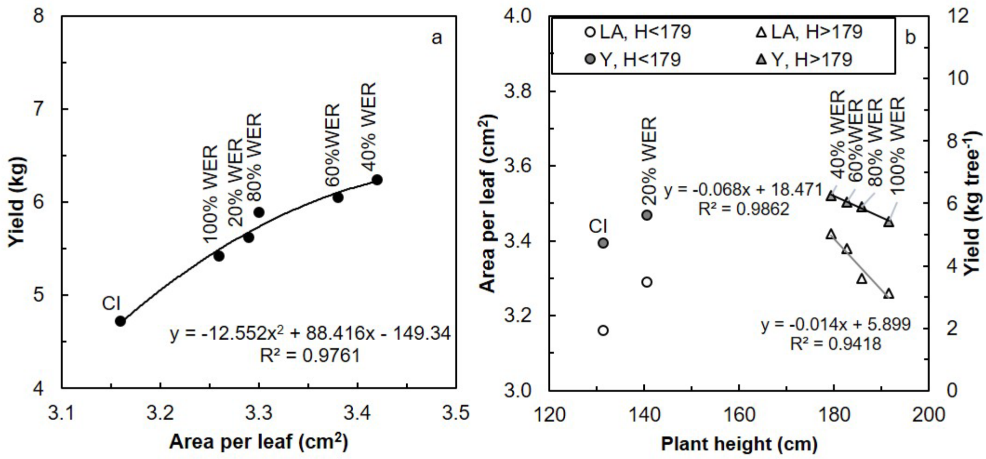

Figure 2.5: The effect of a) area per leaf on yield and b) plant height (H) on area per leaf (LA) and yield (Y) of conventionally irrigated (CI) and drip-irrigated three-year-old Ganesh pomegranate trees in India (adapted from Afria et al., 1998). [WER = water evaporation replenishment]

However, the yield of a four-year-old Bhagwa high-density planting subjected to different degrees of water deficit for one season decreased linearly with tree height (R^2 = 0.9636, data not shown) and leaf area index (R^2 = 0.9971, data not shown) (Haneef et al., 2014). Drip-irrigating the plants on alternate days at 75 and 50% of the crop water requirement reduced tree height by c. 8 and 13%, plant spread by c. 9 and 14% and leaf area index by c. 14 and 28%, respectively, relative to where 100% of the water requirement was applied. In this case, the detrimental effect of water deficits on vegetative growth was reflected directly in the yield response.

Depending on the degree and duration, water deficits applied over several seasons can have a cumulative effect on canopy development and, in the long term, affect orchard productivity. In California, deficit irrigation of Wonderful trees at 35 and 50% ET_c in the first season only tended to decrease the canopy size relative to the 75 and 100% ET_c treatments (i.e by 13%) (Zhang et al., 2017). In the second and third year of deficit irrigation (fourth and fifth growing seasons), though, the trees under severe or medium stress were significantly smaller, having 19% less canopy cover than those fully irrigated or under mild stress.

Likewise, in Turkey, the canopy volume of six-year-old Hicaznar trees subjected to SDI at 50% E_p decreased progressively more during three subsequent seasons. Canopy volume was reduced by 8.3 and 9.4%; 10.9 and 11.8%; and 14 and 14.9% compared to where 100 or 125% E_p was replaced, respectively (Dinc et al., 2018). The canopies of trees irrigated at an SDI of 75% E_p only became significantly smaller compared to the well-watered trees from the second season onwards, but the size difference (c. 10.7%) remained similar over seasons. Increasing the irrigation interval from three to six days decreased canopy volume in the first season of SDI by c. 16%. Although the effect was significant, it was much less (< 5%) in the second and third seasons. The total trunk cross-sectional area of the 75% E_p and 50% E_p trees tended to be and were significantly less, respectively, compared to that of trees irrigated at 100 or 125% E_p from only the second season onwards. Total trunk cross-sectional area appears to be a coarser indicator of water deficit than canopy volume, since it is also not affected by irrigation interval.

In contrast, during a three-year experimental period in Spain, the SDI treatment (50% ET_c) reduced the trunk growth of mature Mollar de Elche trees by 26% compared to control trees irrigated at 100% ET_c (Intrigliolo et al., 2013). In the first and second season of deficit irrigation, canopy volume was only reduced in the SDI treatment compared to the control, whereas in the third season, RDI treatments (25% ET_c) applied during flower and fruit set, and ripening, respectively, had a significant reduction in canopy volume compared with control trees. The canopy volume reduction in the third year was more pronounced in the SDI trees (up to 30%) than in the RDI treatments compared to the control.

The RDI treatment is used as a tool in high-density fruit orchards to limit excessive vegetative growth (Chalmers et al., 1984). In Iran, withholding irrigation from seven-year-old Shahvar trees from the beginning of the growing season until the end of fruit set stage (RDI) over two seasons delayed initial vegetative growth by c. 10 days and reduced the growth rate compared to trees irrigated at 100% ET_c (Selahvarzi et al., 2017). The RDI midday Ψ_s during this period decreased to c. -1.5 and c. -1.8 MPa in the two respective seasons, whereas midday Ψ_s of the fully irrigated trees remained between -0.3 and -1.2 MPa. The final shoot length of $RDI_{fruit\ set}$ compared to the control dropped by 31.7 and 12.6% in the first and second seasons, respectively.

For trees irrigated at 50% ET_c throughout the season (SDI), shoot elongation was similar to that of the well-watered control in the first growing season for about the first two months. During this period, the SDI midday Ψ_s was mostly above c. -1 MPa, with a minimum of c. -1.3 MPa (values obtained from graph). The shoot elongation rate decreased during the last month with midday Ψ_s during this period decreasing to c. -1.5 and even beyond -2 MPa. Poorer growth of SDI shoots compared to that of the 100% ET_c treatment from the beginning of the second season may be partially due to significant water status differences between the trees. The midday Ψ_s in the well-watered trees was above -1 MPa for the greatest part of the shoot growth period until the end of fruit set, whereas that of the SDI trees was generally below -1 MPa.

Also in Iran, applying 50% ET_c via PRD or DI decreased the leaf area index (LAI) of nine-year-old Rabab trees on average by 22% compared to trees where 100% ET_c or 75% ET_c PRD or DI was applied (Parvizi et al., 2016). The LAI tended to be higher in the PRD compared to the DI strategies, but it was not significantly higher. The leaf senescence of deficit irrigated trees started earlier compared to that of fully and PRD treated trees.

The water deficit-related reduction in vegetative growth in two sequential seasons impacted on yield, which decreased linearly with LAI measured at 134 and 135 days after bud break in the two respective seasons (data not shown, $R^2 = 0.8316$, $p = 0.031$; and $R^2 = 0.8965$, $p = 0.015$) (Parvizi et al., 2016).

The positive effect of ample irrigation on pomegranate vegetative growth was confirmed during two experimental seasons in Egypt, where new shoot length, leaf number per shoot and area per leaf of 5 x 5 m-spaced 20-year-old Manfalouty pomegranate trees (n = 3, ten shoots per tree) increased as irrigation water applied in sandy soil per season increased from 280 mm (7 m^3 per tree) to 600 mm (15 m^3 per tree) (Khattab et al., 2011). Linear regression relationships using the data of two sequential seasons combined indicated that yield increased with longer shoots, more leaves per shoot and greater area per leaf (figures 2.6a, 2.6b and 2.6c). Under the experimental conditions for the specific cultivar, yield increased by 1 t ha^{-1} per cm in shoot length, 1.6 t ha^{-1} for each additional leaf per shoot and 4.3 t ha^{-1} per cm in area per leaf.

Different relationships between yield and area per leaf for the young Ganesh and mature Manfalouty trees may be due to the effect of cultivar, age and/or crop management differences on leaf size (figures 2.5 and 2.6c). It should be noted that pomegranate is highly sensitive to continuous, overly wet soil conditions, which lead to root rot and fungal diseases (Hepaksoy et al., 2016; Jamadar et al., 2011). The excessive irrigation of pomegranates should therefore be avoided, and special attention should be paid to irrigation management, especially in heavy and poorly drained soils.

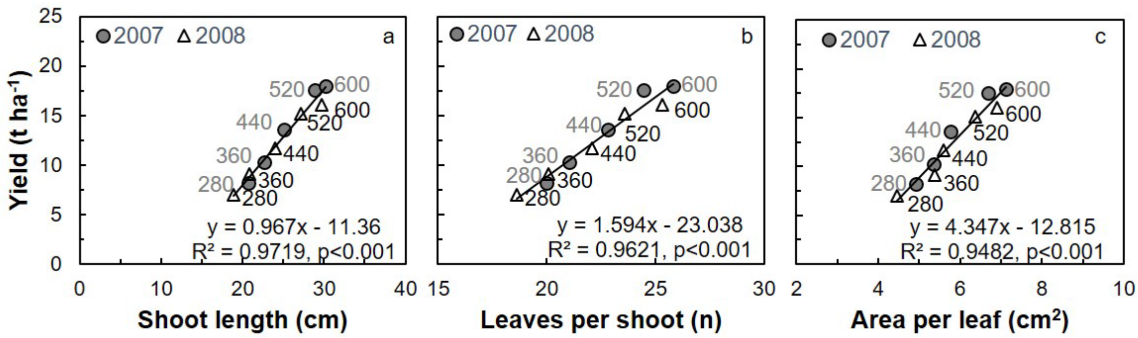

Figure 2.6: The effect of current-season vegetative growth on the yield of mature Manfalouty pomegranate trees, drip-irrigated with different amounts of water in sandy soil in Egypt. Regression relationships on data of two sequential seasons combined include data between yield and a) shoot length, b) leaves per shoot and c) area per leaf, respectively. Data labels indicate the seasonal amount of irrigation water applied in mm (adapted from Khattab et al., 2011).

2.4.4 Fruit growth

Pomegranate fruit is a fleshy berry (Holland et al., 2009). The fruit growth curve can differ between cultivars (Shulman et al., 1984; Al-Yahyai et al. and references therein, 2009). In Israel, under two different climatic conditions, Shulman et al. (1984) reported a single sigmoidal growth pattern for the Mule's Head cultivar compared to a more linear one for Wonderful trees, whereas, in Spain, Mollar de Elche also had a sigmoidal growth pattern (Intrigliolo et al., 2012). The length of the fruit's growth period also varies between cultivars – in Spain, the young fruit development of Mollar de Elche took about 17 days, after which fruit growth continued for 90 days, followed by 35 days of ripening (Melgarejo et al., 1997). In Iran, the development of Rabab during these respective periods took 10-20 days, 110-120 days and 23-28 days (Pavizi et al., 2016). Publications sourced in this review that included information on the seasonal shoot and fruit growth of pomegranate were limited to that of Galindo et al. (2017b) for Mollar de Elche. If RDI is to be used as a water-saving and fruit quality manipulation tool, such information is critical for decision making – at least for the most important cultivars in different countries.

The absolute fruit growth rate of Mollar de Elche during linear fruit growth and harvest ranged between 0.25 and 0.6 mm d^{-1} (Intrigliolo et al., 2013). Growth rates of fruit subjected to 25% ET_c RDI during linear fruit growth only reduced significantly during the middle of the deficit irrigation period compared to that of the 100% ET_c treatment. According to Parvizi et al. (2016), applying severe water stress (i.e. irrigation at 50% ET_c) with both PRD and DI strategies reduced the fruit growth rate compared to trees irrigated at 100% ET_c, 75% ET_c PRD or DI strategies, but only until 190 days after bud break, after which the fruit growth rate did not differ between treatments until harvest.

2.4.5 Effects on yield

The yield of pomegranate trees originating from different countries increased linearly per tree from 19.9 to 93.9 kg, and per hectare from as low as 14.2 to 52 t ha^{-1} as the total amount of precipitation and irrigation water applied to various cultivars increased from 200 to 1,214 mm (figures 2.7a and 2.7b). Yield per tree and per hectare increased by c. 6.4 kg or c. 3.1 ton, respectively, for each 100 mm of irrigation water and precipitation added. Multiple linear regression of yield with irrigation and precipitation entered as separate variables (data not shown) improved the coefficient of determination of the yield estimates per tree (R^2 = 78.96, p < 0.0001) and per hectare (R^2 = 63.78, p < 0.0001).

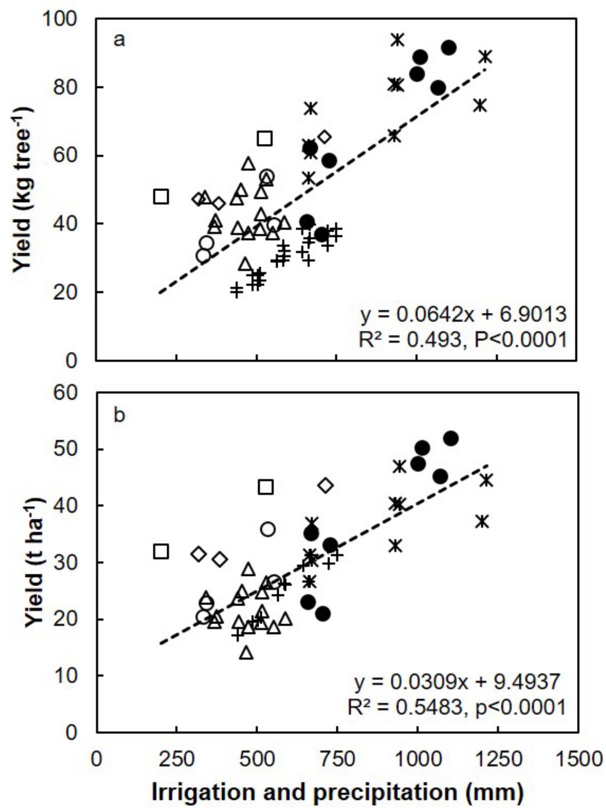

Figure 2.7: The effect of total irrigation applied and precipitation on yield per tree (a) and per hectare (b) of various pomegranate cultivars from different countries. Data from Iran (asterisks), Spain (□, Δ, ○), Turkey (+) and California, USA (●) was used to compile the figure (Ayars et al., 2017; Cano-Lamadrid et al., 2018; Dinc et al., 2018; Galindo et al., 2014a; Intrigliolo et al., 2012; Intrigliolo et al., 2013; Mellisho et al., 2012; Parvizi et al., 2014; Parvizi et al., 2016).

Precipitation accounted for a mere 1.9 and 2.5% of the variability in yield, the balance being due to differences in irrigation applied in the various research experiments. Yield per hectare increased linearly with ET_c, whereas the relative yield response to ET_c was non-linear (figures 2.8a and 2.8b). Maximum yield was achieved where between 721 and 952.5 mm of water evapotranspired, below which yield decreased as ET_c diminished.

There was no simple relationship between yield, which ranged between 14.2 and 47 t ha^{-1}, and seasonal minimum stem water potential with values of between -0.99 and -3.64 MPa (Figure 2.9). The water potential dataset of the majority of authors, which included the cultivars Mollar de Elche, Shavar and Wonderful, ranged from -0.99 to -2.8 MPa, with a general decreasing trend in yield as stem water potential decreased. In the case of Galindo et al. (2014b) and Parvizi et al. (2016), maximum yield for Mollar de Elche and Rabab realised at much lower stem water potentials, and, except for one value of -1.6 MPa, the combined data set ranged from -2.6 to -3.64 MPa. Yield of Rabab trees decreased linearly in two consecutive seasons with seasonal minimum stem water potential. If the data of Intrigliolo et al. (2013) with limited yield response to deficit irrigation is omitted from the first data group, relative yield also decreased linearly with seasonal minimum stem water potential (Figure 2.10). The estimated relative yield decrease if the seasonal minimum stem water potential drops from -1 to -1.5, -2 and -2.5 MPa, respectively, amounts to 15, 29 and 44% (Figure 2.10). Early-season midday stem water potential for several well-irrigated (no stress) fruit trees typically falls between -0.4 and -1 MPa, and during mid- to late-season, between -0.5 and -1.2 MPa (Fereres et al., 2012). In general, for all the pomegranate cultivars discussed above, relative yield decreased by 24, 34 and 45% if the seasonal minimum midday stem water potential decreased by -0.5, -1 and -1.8 MPa relative to that of the well-watered trees (Figure 2.11).

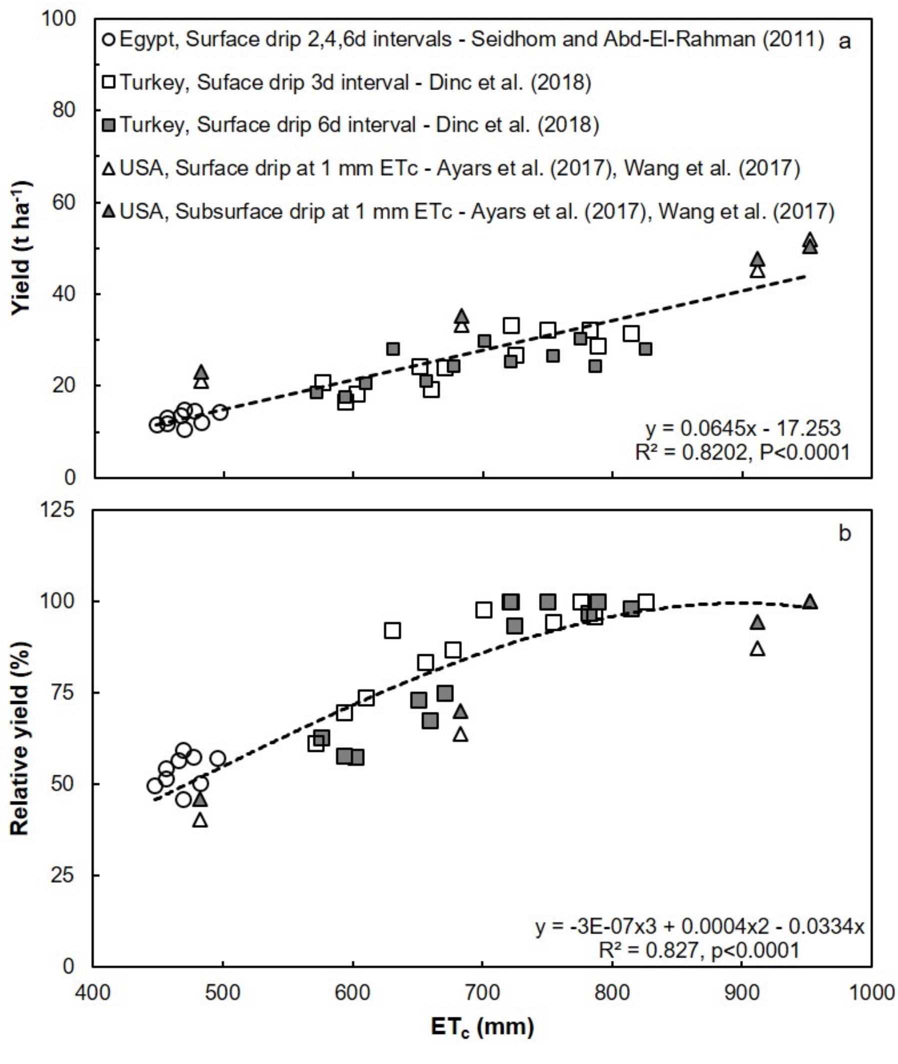

Figure 2.8: The relationship of seasonal (Seidhom and Abd-El-Rahman, 2011: February to October; Dinc et al., 2018: March to November) and annual (Ayars et al., 2017) evapotranspiration to a) yield and b) relative yield. Data from Egypt, Turkey and the USA are for several seasons for drip-irrigated Manfalouty, Hicaznar and Wonderful pomegranate trees, respectively.

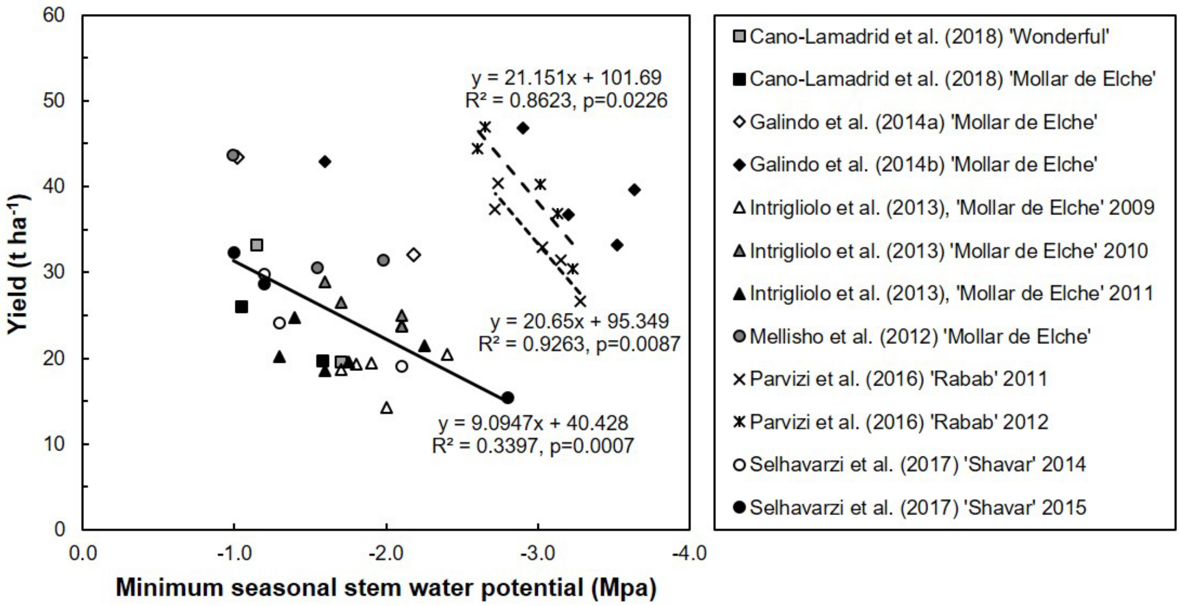

Figure 2.9: Comparison of yield to seasonal minimum stem water potential for several pomegranate cultivars produced in Spain and Iran (x, asterisks, ○, ●). Data was obtained from text or derived from graphs.

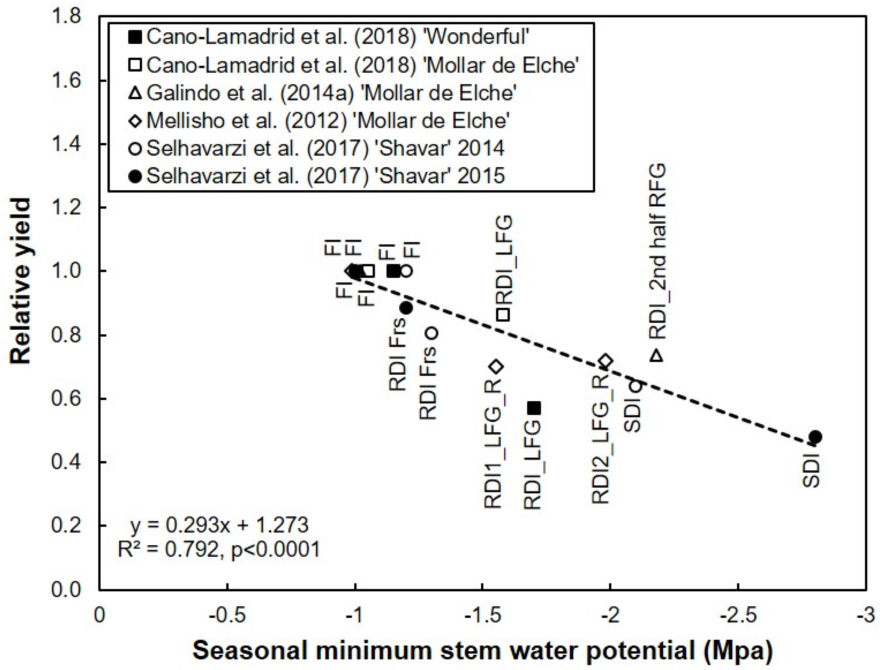

Figure 2.10: The effect of deficit irrigation on relative pomegranate yield and seasonal minimum stem water potential obtained from selected pomegranate deficit irrigation research studies for the cultivars Mollar de Elche, Shavar and Wonderful. Data labels indicate full irrigation (FI), regulated deficit irrigation (RDI) applied during fruit set (Frs), linear or rapid fruit growth (LFG or RFG) or ripening (R) and sustained deficit irrigation (SDI).

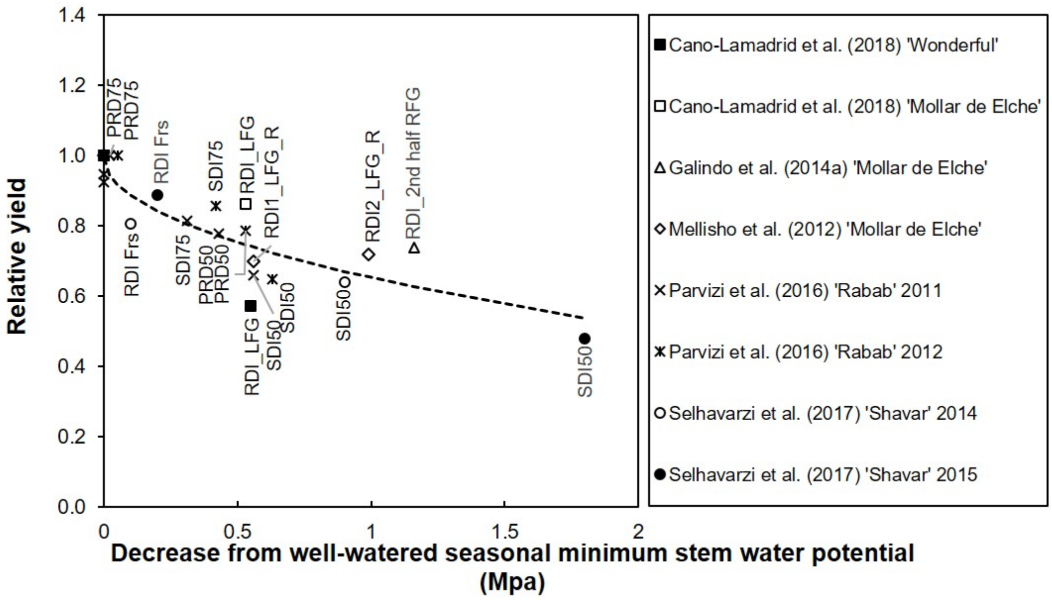

Figure 2.11: The relative yield response of several deficit irrigated pomegranate cultivars to a decrease from the seasonal minimum stem water potential of well-watered trees. Data labels indicate regulated deficit irrigation (RDI) applied during fruit set (Frs), linear or rapid fruit growth (LFG or RFG) or ripening (R), partial rootzone drying (PRD) and sustained deficit irrigation (SDI). The percentage ET_c supplied by irrigation during PRD and SDI is also indicated.

Several deficit irrigation strategies decreased pomegranate yield due to a reduction in fruit number and/or fruit weight, whereas some resulted in a yield increase relative to well-watered trees (tables 2.3 and 2.4). Regulated deficit irrigation of 10-year-old Mollar de Elche trees near Murcia in Spain decreased the total yield of a well-watered control (43.7 t ha^{-1}) by between 28 and 30% (Mellisho et al., 2012). Withholding irrigation during the second part of linear fruit growth and irrigating at 99% ET_o during end fruit growth and ripening decreased the marketable yield by 23% compared to the control, whereas irrigation at 74 and 36% ET_o during these phases (growers' criteria) did not decrease yield significantly. Seasonal midday stem water potential as low as -1.98 MPa in trees not irrigated during the second part of linear fruit growth probably contributes to decreasing the individual fruit weight of the first and second harvest by 13.8 and 20.4%, respectively, compared to the well-watered control.

Minimum seasonal midday stem water potential in the trees irrigated according to the growers' criteria reached -1.5 MPa, with individual fruit weight being comparable to the control at first harvest, but at second harvest, it was 9.8% less. Fruit of trees subjected to no irrigation during the second half of linear fruit growth did not display compensatory fruit growth after rewatering, resulting in smaller fruit compared to that of well-watered trees at harvest (Mellisho et al., 2012). For the same cultivar, Intrigliolo et al. (2013) also noted the absence of compensatory fruit growth when full irrigation was restored, where 25% ET_c was applied during linear fruit growth. In this regard, where irrigation was withheld for 15, 25 and 34 days before harvest, the marketable yield (c. 88% of total yield for the control) of Mollar de Elche pomegranate trees decreased by 38, 49 and 69%, whereas it was comparable to the well-watered control and where irrigation was withheld for six days (Table 2.3) (Galindo et al., 2014b). Part of the yield decrease was due to significantly lower fruit weight (c. 14%) in these treatments compared to fruit in the control, which weighed 293 g per fruit. Reduced expansion of fruit was attributed to severe water deficits, which resulted in fruit turgor loss. Likewise, irrigating adult Mollar de Elche pomegranate trees daily at 33% ET_o during the second half of rapid fruit growth until the last harvest resulted in a minimum seasonal stem water potential of -2.18 MPa, and decreased total yield, fruit number and average fruit size, respectively, relative to the unstressed treatment by 26.2, 11.7 and 16.5 (Galindo et al., 2014a).

Table 2.3: Effect of irrigation strategies on the relative reduction in yield, fruit number (FN) and fruit weight of mature drip-irrigated Mollar de Elche pomegranate trees in Spain. The maximum plant water deficit achieved during the season is indicated in terms of minimum stem water potential (SWP) reported in the text or derived from graphs. An asterisk indicates significant differences in yield and its components relative to the well-watered control. Marketable yield is indicated in brackets.

Author	Irrigation strategy	Irrigation levels	Control yield (t ha^{-1})	Decrease relative to control (%)			SWP (MPa)
				Yield	FN	FW	
Cano-Lamadrid et al. (2018)	Control	120% ET_c	26				-1.05
	RDI	120% ET_c until fruit set, 60% ET_c during fruit growth and ripening		24.1*	N/A	6.1	-1.6
Galindo et al. (2014a)	Control	T0: 105% ET_o	43.5				<-1
	RDI	T1: Second half of rapid fruit growth to last harvest 33% ET_o		26.2*	11.7*	16.5*	-2.18
Galindo et al. (2014b; 2017a)	Water withheld before harvest (days)	0	42.9				-1.6
		6		-9.0 (2.3)	N/A	11.9	-2.9
		15		14.6* (38.0*)	N/A	14.0*	-3.2
		25		7.6 (49.1*)	N/A	15.0*	-3.64
		34		22.7*(68.7*)	N/A	13.7*	-3.52
Intrigliolo et al. (2012; 2013)	Control	100% ET_c whole season	21.8				-1.6
	SDI	50% ET_c whole season		2.3	-28.2*	22.4*	-2.1
Three-season average	RDIfl-fr.set	25% ET_c flowering, fruit set, early fruit growth, 100% ET_c rest of season		-11.5*	-19.1*	6.8*	-1.6
	RDIfr.gr	25% ET_c linear fruit growth,100% ETc rest of season		5.5	0.8	5.6*	-1.9
	RDIripe	25% ET_c last part of fruit growth and ripening, 100% ET_c rest of season		7.3	5.3	1.8	-2.1
Mellisho et al. (2012)	Control	60% ET_o – 117% ET_o – 99% ET_o until first half of linear fruit growth phase, second half of linear fruit growth phase and during the end of fruit growth and ripening, respectively	33.2; 10.5				<-1
Two harvests	Grower's criteria	32% ET_o – 74% ET_o – 36% ET_o until first half of linear fruit growth phase, second half of linear fruit growth phase and during the end of fruit growth and ripening, respectively		14.7; 78.6*	N/A	2.7; 9.8*	-1.5
	RDI	32% ET_o – NI – 36% ET_o until first half of linear fruit growth phase, second half of linear fruit growth phase and during the end of fruit growth and ripening, respectively		23.0*; 44	N/A	13.8*; 20.4*	-1.98

Table 2.4: Effect of irrigation strategies on the relative reduction in yield, fruit number (FN) and fruit weight of different pomegranate cultivars of varying ages produced in various countries. An asterisk indicates significant differences in yield and its components relative to the well-watered control

Cultivar	Country	Age	Irrigation strategy	Irrigation levels	Control yield (t ha^{-1})	Decrease relative to control (%)			Author and comment
						Yield	FN	FW	
Rabab	Iran	9	FI	100% ET_c	37.3; 44.5				Parvizi et al. (2014)
			DI	75% ET_c DI		11.8*; 9.4*	11.1*; 9.9*	8.1*	Two seasons
			PRD	75% ET_c PRD		-8.3*; -5.6*	-10.7*; -8.5*	-1.3	
			DI	50% ET_c DI		28.6* ;31.5*	22.6*; 27.7*	19.7*	
			PRD	50% ET_c PRD		15.8*; 17*	11.5*; 13.5*	11.1*	
Shavar	Iran	7	Control	100% ET_c	24.9; 26.9				Selhavarzi et al. (2017)
			RDI fruit set	No irrigation until end of fruit set, 100% ET_c rest of season		19.3 and 11.3	18.1* and 19.3*	-28.8*	Two seasons
			SDI	50% ET_c throughout season		36* and 52.1*	14.3* and 39.3*	17.4*	
Wonderful	Greece	12	Control	100% ET_c starts two months after bud break	N/A				Noitsakis et al. (2016)
			PRD1	100% ET_c one side of tree		N/A	N/A	-8.6	
			PRD2	50% ET_c one side of tree		N/A	N/A	5.2*	
Wonderful	Spain	6	Control	120% ET_c	33.1				Cano-Lamadrid et al. (2018)
			RDI	120% ET_c until fruit set, 60% ET_c during fruit growth and ripening		41*	N/A	3.9	
Wonderful	USA	5	DI	100% ET_c	17.8				Zhang et al. (2017)
				75% ET_c		-3.5*	-5.3	2.6	Third season
				50% ET_c		5.4	-1.3	7.4	
				35% ET_c		34.4*	16	21.6*	

In contrast, 25% ET_c RDI during linear fruit growth, which resulted in a seasonal minimum stem water potential of -1.9 MPa, had, on average, no significant effect on yield over three seasons and decreased fruit weight by a mere 5.6% (Intrigliolo et al., 2012; Intrigliolo et al., 2013). Also, 25% ET_c RDI during the last part of fruit growth and ripening resulted in a minimum stem water potential of -2.1 MPa in trees, with no significant effect on yield, fruit number or weight. The lack of response to the RDI treatment may be due to crop load being half that of trees from the other studies mentioned above (Table 2.3). Cano-Lamadrid et al. (2018) found that fruit thinning increased the weight of Molar de Elche and Wonderful fruit significantly. Although 60% ET_c RDI during fruit growth and ripening decreased the yield of Mollar de Elche and Wonderful by 24.1 and 41%, respectively, it had no significant effect on fruit weight (tables 2.3 and 2.4). Seasonal minimum midday stem water potential in these trees reached c.-1.6 and c. -1.7 MPa, respectively, with the deviation from the mean stem water potential for Wonderful almost reaching -2 MPa. Water stress during the second half of the linear fruit growth stage is therefore considered to be detrimental to the fruit growth of Mollar de Elche pomegranate trees.

However, 50% ET_c SDI and 25% ET_c RDI applied to Mollar de Elche during flowering and fruit set resulted in comparable or increased yield, respectively, relative to trees irrigated at 100% ET_c throughout the season (Intrigliolo et al., 2012; Intrigliolo et al., 2013; Laribi et al., 2013). Mild water stress during flowering and fruit set increased the number of Mollar de Elche fruit by c. 28 and c. 19% concurrent to a fruit weight decrease of c. 22 and c. 7% for the respective treatments. In contrast, in Iran, for the slightly higher yielding seven-year-old Shavar, no irrigation until the end of fruit set, followed by irrigation at 100% ET_c for the rest of the season, resulted in yield losses of between 11.3 and 19.3% during two seasons (Table 2.4). The number of fruit decreased by c. 19%, whereas an increase of almost 29% in average fruit weight was reported relative to that of well-watered trees (Selhavarzi et al., 2017). In this case, 50% ET_c SDI resulted in yield decreases of between 36 and 52.1%, relative to the 100% ET_c treatment, with both the number and size of the fruit being affected negatively (Table 2.4).

Also in Iran, treatment over two seasons with 75% ET_c PRD with a four-day irrigation interval increased the yield of Rabab by c. 7% on average, compared to trees that received 100% ET_c (Parvizi et al., 2014). The yield increase was mainly due to more fruit (c. 9.6%) of comparable size than that of well-watered trees. However, 75 and 50% ET_c SDI applied to one side of the tree only and the application of 50% ET_c PRD decreased yield by 10.6, 16.4 and 30%, respectively, compared to the application of 100% ET_c, which decreased the number of fruit between 10.5 and 25.2% and the weight by up to 19.7% (Table 2.4) (Parvizi et al., 2014). In Greece, 50% ET_c PRD applied to only one side of Wonderful trees from two months after bud break also decreased fruit weight significantly, compared to the application of 100% ET_c to the full root zone (Noitsakis et al., 2016).

In California, the yield of deficit irrigated Wonderful trees from bearing stage was not affected until the third year of treatment (Centofanti et al., 2017b; Zhang et al., 2017). The 75% ET_c SDI increased the yield of the then five-year-old trees, which were compared marginally to a 100% ET_c control, whereas 50% ET_c SDI did not have any significant effect (Table 2.4) (Zhang et al., 2017). However, the 35% ET_c SDI decreased yield by 34.4% compared to the 100% ET_c due to an almost 22% decrease in fruit weight and 16% less fruit compared to the fully irrigated trees.

The difference in the yield response of trees in the various research studies in relation to the 50% ET_c SDI treatment may be attributed to differences in cultivar drought tolerance, crop load and climatic conditions, but also to irrigation management practices and the resultant soil water availability. No information on the drip-irrigation frequency applied by Selahvarzi et al. (2017) is available for the Shavar cultivar. However, in the studies of Centofanti et al. (2017b) and Zhang et al. (2017), for example, drip-irrigation was applied at different depletion levels with percentage daily use accumulated to a threshold of 4 mm ET_c. Irrigation at a similar depth was therefore applied to the whole root zone at different frequencies for different treatments.

In the case of Parvizi et al. (2014), irrigation was only applied to one side of the tree every four days for different durations to realise the treatment ET_c levels. In the research of Intrigliolo et al. (2012), the irrigation frequency was changed during the season from once a week in spring to five times a week in summer, but was similar for treatments for which irrigation duration was varied to realise different ET_c levels. Such differences should be kept in mind when the results of different research studies are compared.

Apart from RDI and SDI applied relative to ET_c or ET_o (tables 2.3 and 2.4), Table 2.5 lists research studies that defined irrigation levels relative to pan evaporation (Afria et al., 1998; Dinc et al., 2018; Haneef et al., 2014) or applied different amounts of water with or without soil conditioner (Khattab et al., 2011; Khattab et al., 2014). Other researchers evaluated the effect of irrigation interval and/or duration in combination with soil management practices (Ghosh et al., 2013; Seidhom and Abd-El-Rahman, 2011). The yield of four-year-old high-density planted Bhagwa trees decreased by c. 11 and c. 24% when irrigation replaced only 75 and 50% of pan evaporation every second day, instead of 100% (Haneef et al., 2014). The yield decrease was due to c. 9 and c. 21% less fruit and a reduced fruit weight of 2.6 and 5.7% in the respective treatments compared to the application of 100% of the water requirement.

In Turkey, during three subsequent seasons, SDI at 50% E_p (E_{pan}) reduced the yield of Hicaznar trees that were irrigated at either three- or six-day intervals by between 34 and 37% (Dinc et al., 2018). The yield of trees irrigated at 75% as opposed to 125% E_p decreased by 18.5 and 23.7% in the first and third seasons, and was not significantly lower in the second season (Table 2.5). Fruit weight did not differ significantly between the different well-watered (100 and 125% E_p) and SDI (75 and 50% E_p) treatments and averaged 473, 494 and 555 g during the three experimental seasons. The lower yield of the SDI trees was attributed to less fruit of more or less comparable mass in comparison to those of the 100 and 125% E_p trees.

In Egypt, during two subsequent seasons, increasing the application of irrigation to 20-year-old Manfalouty pomegranate trees from 280 to 600 mm per season resulted in c. 55% more fruit, while yield more than doubled (Khattab et al., 2011). Also in Egypt, a comparison of the effects of three irrigation intervals (2, 4 and 6 days, 20 ℓ h^{-1} emitters) and three soil mulching practices under the trees (control without mulch, bitumen mulch and olive pomace mulch) on nine-year-old Manfalouty pomegranates indicated that the highest yield was obtained with olive pomace mulch and an irrigation interval of six days (Seidhom and Abdel-Rahman, 2011).

In India, a comparison of three drip-irrigation treatments of different durations at two-day intervals with or without mulch, basin irrigation and a life-saving irrigation with straw mulching found that the fruit yield of seven-year-old Ruby trees was the highest at three hours of drip-irrigation without mulch (Ghosh et al., 2013).

2.4.6 Water use efficiency and water productivity

In general, there is inconsistency regarding the use of the terms water use efficiency and water use productivity in the research surveyed in this review, and these terms cannot necessarily be used interchangeably. Higher water productivity (WP) (yield per ha divided by mm of applied water) for subsurface, as opposed to surface, drip-irrigated pomegranate trees was due to a higher yield and less water applied to the subsurface irrigated trees (Ayars et al., 2017). The WP for four-, five- and six-year-old trees was 60.4, 61 and 59.7 kg ha^{-1} mm^{-1} for the subsurface drip-irrigated trees and 51.5, 53.5 and 55.8 kg ha^{-1} mm^{-1} for the surface drip-irrigated trees. Deficit irrigation resulted in increasing the water use efficiency (WUE) (fruit yield divided by irrigation applied plus rainfall) of Mollar de Elche pomegranate trees (Intrigliolo et al., 2013). The increase in WUE on average over three years relative to the control (39.5 kg ha^{-1} mm^{-1}) was particularly noticeable in the SDI (59.6 kg ha^{-1} mm^{-1}) treatment and in the application of RDI during flowering and fruit set (48.9 kg ha^{-1} mm^{-1}). The SDI and RDI treatments were successful in increasing WUE and WP (economic yield value divided by irrigation applied), maintaining the yield value at levels similar to the control (Intrigliolo et al., 2013). However, SDI had a definite impact on fruit size, and – consequently – on the farmers' income.

Deficit irrigation and PRD strategies increased WP (fruit yield divided by water used) on average over two seasons by 21 and c. 45% compared to trees irrigated at 100% ET_c (WP 4.2 kg m^{-3}) (Parvizi et al., 2014). Irrigation applied at 75% ET_c increased WP by 26.6%, and at 50% ET_c by 39% relative to the 100% ET_c treatment. However, these values should be interpreted carefully because they do not reflect economic water productivity, which determines farmer profit at the end of the day. However, the PRD 75% ET_c strategy increased WP by 38%, mainly through increased fruit number and comparable fruit weight relative to the fully irrigated trees. In the first and second seasons, an RDI strategy (no irrigation until the end of fruit set, 100% ET_c for the remainder of the season) applied to seven-year-old Shavar pomegranate trees in Iran (Selahvarzi et al., 2017) increased WP (fruit yield divided by water applied) relative to that of the control (2.15 and 2.45 kg m^{-3}) by c. 50 and 39%, respectively. Although the SDI treatment increased WP by c. 59% in the first season relative to the control, the detrimental long-term effect of severe water deficits on trees reduced the SDI WP in the second season to levels similar to those of the control.

The WUE of 20-year-old Manfalouty pomegranate trees in Egypt was calculated as the scheduled amount of water per treatment divided by the yield (Khattab et al., 2011). The treatment that received 520 mm per season had the highest WUE, i.e. 3.22 and 2.91 kg m^{-3} of water applied. The WUE decreased significantly, with the amounts of water applied being less or more than 520 mm. The underlying reason for the drier treatments may be water stress-related yield decreases, and for the wetter treatment, inefficient water use.

In Turkey, the WUE (yield divided by evapotranspiration) of several irrigation treatments, including SDI treatments, was not statistically significant (Dinc et al., 2018). During three seasons, WUE ranged from 28 to 46 kg ha^{-1} mm^{-1}. The irrigation WUE (yield divided by irrigation) ranged from 59.5 to 106.6 kg ha^{-1} mm^{-1}.

Table 2.5: The effect of irrigation strategies on the relative reduction in yield, fruit number (FN) and fruit weight of different pomegranate cultivars of varying ages produced in various countries. An asterisk indicates significant differences in yield and its components relative to the well-watered control. [CEP = cumulative pan evaporation; CWM = control without mulch; BEM = bitumen emulsion mulch; OPM = olive pomace mulch; SDI = sustained deficit irrigation]

Cultivar	Country	Age	Irrigation strategy	Irrigation levels	Control yield t ha^{-1}	Decrease relative to control (%)			Author and comment
						Yield	FN	FW	
Bhagwa	India	4	Irrigation levels	100% E_p	24.2				Haneef et al. (2014)
				75% E_p		11.4*	8.9*	2.6*	
				50% E_p		24.4*	21.4*	5.7*	
Ganesh	India	3	Conventional water evaporation replenishment (WER)	Replace 75 mm CEP	4.72 kg $tree^{-1}$				Afria et al. (1998)
				20% WER		-19.1*	N/A	N/A	
				40% WER		-32.2*	N/A	N/A	
				60% WER		-28.2*	N/A	N/A	
				80% WER		-24.8*	N/A	N/A	
				100% WER		-14.8*	N/A	N/A	
Hicaznar	Turkey	6	Control	125% E_p	29.8; 31.3; 26.6				Dinc et al. (2018)
			SDI	100% E_p		1.3; -0.3; 1.9	0.1; -7.8; 3.8	1.2;7; -2	Three seasons
			SDI	75% E_p		18.5*; 16.3; 23.7	15.3; 11.6; 25.6	3.8; 5.3; -2.6	FN = Y/FM
			SDI	50% E_p		34.2*; 36.7*; 35.3*	33.5; 36; 34.4	1.1; 1.2; 1.4	
Manfalouty	Egypt	20	Irrigation level	600 mm	17.9, 16.0				Khattab et al. (2011) Khattab et al. (2014)
				520 mm		2.2*; 5.6*	3.9*, 2.7*	-1.8; 3	Two seasons
			Farm control	440 mm		24.4*; 27.2*	16.3*; 19.7*	9.7; 9.3	FW=Y/FN
				360 mm		42.8*; 43.0*	24.6*; 26.6*	24.2; 22.3	for 520 and 600 mm
				280 mm		54.3*; 56.6*	34.5*; 36.1*	30.3; 32.1	

Cultivar	Country	Age	Irrigation strategy	Irrigation levels	Control yield	Decrease relative to control (%)			Author and comment
					t ha^{-1}	Yield	FN	FW	
Manfalouty	Egypt	9	Irrigation interval and mulch	2 days CWM	10.7; 12.2; 14.4				Seidhom and Abd-El-Rahman (2011)
				2 days BEM		-11.9; -11.8; -26.8			Three seasons
				2 days OPM		-34.8; -39.4; -34.7*			Limited statistics
				4 days CWM		-12.7; -12.6; -1.0			
				4 days BEM		-52.4; -52.4; -36.6			
				4 days OPM		-62.9; -62.9; -46*			
				6 days CWM		-8.6; -8.6; -4.1			
				6 days BEM		-51.5; -51.4; -45.8			
				6 days OPM		-117.8; -99; -75.1*			
Ruby	India	7	Irrigation interval and mulch (M)	Drip 2 days 1 hour		40.5			Ghosh et al. (2013)
				Drip 2 days 2 hours		22.6			Two-season average
				Drip 2 days 3 hours	18.6	-			*No statistics*
				Drip 2 days 1 hour + M		27.4			
				Drip 2 days 2 hours + M		35.7			
				Drip 2 days 3 hours + M		38.7			
				Basin once a week + M		51.8			

2.4.7 Fruit and product quality

Water deficits can affect pomegranate fruit and product quality by changing its appearance, taste and/or beneficial health effects, thereby impacting on its marketability. Three main markets exist for pomegranate fruit: fresh consumption, processing (mainly arils and juice) and for the medicinal industry (Alcaraz-Mármol et al., 2017). For producers to be profitable, different consumer preferences need to be complied with (Borochov-Neori et al., 2009). Apart from high antioxidant capacity, important fruit quality attributes include size, colour, juiciness, taste, flavour and seed hardness (Fawole and Opara and references therein, 2013), whereas aril colour, total soluble solids and titratable acidity are generally used to assess fruit quality (Fawole and Opara and references therein, 2013; Holland et al., 2009).

2.4.7.1 Appearance

<u>Colour</u>

Reasons for increased fruit colour in trees that have experienced water stress during ripening may be increased soluble solids content that may be related to increased anthocyanin synthesis and reduced vegetative growth, which may improve the exposure of fruit to sunlight – leading to a higher red-coloured appearance and water stress per se, which may have promoted colour pigment synthesis (Laribi et al., 2013). Mollar de Elche trees that were irrigated daily at 33% ET_o during the second half of rapid fruit growth until the last harvest had fruit that was a darker, more reddish, more bluish and more intense garnet colour than trees irrigated at 105% ET_o (Galindo et al., 2014a).

Likewise, moderate water stress, induced by RDI growers' practice (Table 2.1), increased the red peel colour of marketable fruit from the first harvest from three-fold to five-fold compared to the control, and where no irrigation was applied during the second half of linear fruit growth, reflecting earlier ripening (Mellisho et al., 2012). In addition, the red colouration of the arils was between 29 and 39% higher compared to these treatments, with the red colour of arils from fruit where irrigation was withheld during the second half of linear fruit growth being the poorest. Cano-Lamadrid et al. (2018) found a poorer red colour of juice for both Mollar de Elche and Wonderful trees that had been subjected to mild water stress after been irrigated at 60% ET_c during fruit growth and ripening.

Bartual et al. (2015a), comparing a control (100% ET_c throughout the season), SDI (50% ET_c) and RDI (25% ET_c during flowering and fruit set, linear fruit growth and ripening, respectively, followed by 100% ET_c during the rest of the season), found that SDI fruit skin had the reddest colour, followed by that subjected to RDI during ripening. The SDI resulted in redder and darker fruit at harvest and during the refrigerated storage period, but during shelf-life, the fruit colour tended towards an overall yellow colour, although the SDI fruit was still redder than that subjected to other treatments (Laribi et al., 2013).

Likewise, Mena et al. (2013) found that fruit under moderate water stress (43% ET_o SDI) had juice that was more yellow in colour, whereas the juice of fruit under severe water stress was even more yellow in colour, with a less intense red colour and higher luminosity than fruit irrigated at 75% ET_o or 43% ET_o SDI (Mena et al., 2013). Peña-Estévez et al. (2015) also found that the colour of the arils of fruit that was subject to the withholding of irrigation for 16 and 26 days prior to harvest was less saturated and turned slightly red-orange compared to the fruit of trees that had been irrigated at 120% ET_o. In contrast to the findings of Bartual et al. (2015a; 2015b), the fruit peel of young bearing Wonderful trees was lighter with a lower red-greenness when the trees had been subjected to 35% ET_c SDI compared to the application of irrigation at 100, 75 and 50% ET_c levels (Centofanti et al., 2017b).

In conclusion, moderate stress during the second part of fruit growth generally has positive effects on fruit skin and aril colour, whereas severe water deficits may result in poor aril colour and the yellowing of fruit juice.

Juice yield and rind thickness

Water deficits, with a few exceptions, appeared to decrease the thickness of the pomegranate peel and reduce fruit juice content. For Manfalouty, the percentage of the fruit peel increased significantly with the application of 280 mm irrigation water per season compared to 360 and 440 mm (Khattab et al., 2014). In the case of Rabab, DI and PRD strategies (75% and 50% ET_c) did not affect aril or peel percentages or juice density compared to a fully irrigated control (Parvizi and Sepaskhah, 2015). However, irrigating high-density four-year-old Bhagwa trees at 75 and 50% E_p reduced juice content by 10.2 and 20.2% and decreased rind thickness by 15.1 and 38.1%, compared to the application of 100% E_p (Haneef et al., 2014). For Shavar, the aril-to-peel ratio increased significantly where RDI was applied until fruit set (no irrigation) and 50% ET_c SDI, compared to that of trees receiving 100% ET_c throughout the season (Selahvarzi et al., 2017). Severe drought stress during fruit growth resulted in reduced peel weight, which increased the aril-to-peel ratio (Selhavarzi et al., 2017). According to Mellisho et al. (2012), irrigating Mollar de Elche according to growers' practice by applying 74% ET_o during the second half of linear fruit growth and 36% ET_o at the end of fruit growth and inducing ripening reduced the fruit's peel content at the second harvest compared to the control.

However, this deficit irrigation strategy did not affect the moisture content of the fruit relative to the well-watered control (Mellisho et al., 2012). Compared to fruit from trees receiving 100% ET_c during the whole season, juice yield of the same cultivar was also not affected by 50% ET_c SDI or 25% ET_c RDI during various phenological phases, followed by 100% ET_c during the remainder of the season (Laribi et al., 2013). For Rabab, juice percentage was significantly higher in the fruit of trees that had been subjected to 75 or 50% ET_c PRD compared to 50% ET_c DI applied to one side of the root zone, whereas it tended to be higher when compared to the fruit of the well-watered control (Parvizi and Sepaskhah, 2015). Juice density was not significantly affected by DI or PRD strategies. The juice percentage of Manfalouty fruit also decreased when the amount of seasonal irrigation was reduced from 440 and 360 mm to 280 mm (Khattab et al., 2014). The juice percentage of Wonderful fruit that had been subjected to the application of 100% ET_c and 50% ET_c to one side of the root zone was not affected relative to that of trees applying 100% ET_c to the whole root zone (Noitsakis et al., 2016). In contrast to the aforementioned research, the juice percentage of Shavar fruit that had been subjected to RDI (no irrigation until fruit set, 100% ET_c for the remainder of the season) increased by c. 10% compared to the fruit of trees receiving 100% ET_c and 50% ET_c SDI (Selahvarzi et al., 2017). The decreased juice percentage of the SDI treatment of fruit was attributed to less arils and lower juiciness as a result of water deficits.

Organoleptic rating

Sensory analysis showed that Mollar de Elche arils from trees where water was withheld for 16 and 26 days before harvest showed higher visual appearance and overall quality scores than for arils from fully irrigated trees, whereas deficit irrigation appeared to increase the shelf-life of arils by four days compared to 14 days for fully irrigated trees (Peña-Estévez et al., 2015). The arils of Mollar de Elche that had been subject to the withholding of irrigation for 16 days prior to harvest also had a 9% higher firmness compared to that of trees irrigated at 120% ET_c or where irrigation was withheld for 26 days (Peña-Estévez et al., 2015). On the other hand, the arils of fruit that had been subject to the withholding of water for 26 days prior to harvest had higher colour scores compared to those where water had been withheld for 16 days or that were fully irrigated, and had similar scores (Peña-Estévez et al., 2015). Comparing growers' RDI practice to non-limiting soil water conditions, sensory analysis also indicated that fruit that had been subjected to deficit irrigation treatment had a better visual appearance, colour, flavour and overall sensory quality after storage for 14 days at 5 °C than that of fully irrigated trees, independent of the pre-processing storage period (Peña-Estévez et al., 2016). In contrast, deficit irrigation had a detrimental effect on the quality of the young high-density planted Bhagwa fruit. The organoleptic rating of trees irrigated at 75 and 50% E_p decreased by 13 and 23.6%, respectively, compared to the application of 100% E_p (Haneef et al., 2014).

Cracking

The main physiological disorder of pomegranate is fruit cracking, which occurs when the fruit peel or cuticle fractures or splits (Khadivi-Khub and references therein, 2015). Fruit cracking may be triggered by irregular and insufficient irrigation or by excessive rainfall, especially during fruit ripening. Cracks reduce marketability and provide access to pests and diseases, causing significant income loss in the fresh market and processing industries. The morphological properties of pomegranate fruit that are significantly related to fruit cracking include fruit volume and shape (oblate vs spheroid), the skin-to-fruit weight ratio, as well as the aril-to-fruit weight ratio, but not skin thickness (Saei et al., 2014). Larger fruit, fruit with a ratio of fruit length-to-diameter of less than 1 and fruit containing more or larger seeds was more susceptible to cracking. In addition, calcium affects the biomechanical behaviour of the fruit skin, and excessive calcium content may increase the cracking rate. According to Galindo et al. and references therein (2014b), water stress can alter the peel's mechanical properties, resulting in less extensibility and increased stiffness and thickness. Mellisho et al. and references therein (2012) also indicated that decreased peel content may be related to the incidence of fruit splitting. Pomegranate cultivars differ in sensitivity to cracking (Hepaksoy et al., 2000; Khadivi-Khub and references therein, 2015) with some crack-resistant varieties displaying higher leaf-level WUE compared to sensitive ones (Hepaksoy et al., 2000).

Intrigliolo et al. (2013) found minimal cracking of Mollar de Elche fruit over three seasons (2-6% of fruit per tree), with 25% ET_c RDI during fruit growth only in the second season, increasing cracking significantly relative to the 100% ET_c treatment. In contrast, the percentage of Mollar de Elche fruit with cracked peels, relative to total yield, progressively increased with the water-withholding period before harvest for 6, 15, 25 and 34 days, was c. 21, c. 28, c. 51 and c. 64%, respectively (Galindo et al., 2014b). The cracking of fruit was attributed to an asymmetric increase in fruit turgor pressure after 88.4 mm of rainfall had occurred 10-12 days before harvest, the turgor pressure of the arils increasing to a much greater extent than the turgor pressure of the peel, resulting in cracking.

For Wonderful trees, applying 100% ET_c to only one side of the root zone (PRD) caused a relatively stable plant water status during the growing period, which reduced fruit cracking from c. 11%, where irrigation was applied to the whole root zone at 100% ET_c or to only one side of the root zone at 50% ET_c, to c. 8% of the fruit (Noitsakis et al., 2016). According to Makus et al. (2014), the increased drip-irrigation of Wonderful trees also increased the amount of superficially cracked and split fruit. For Rabab, the fruit cracking of trees irrigated at 75 or 50% ET_c PRD was slightly less or comparable, respectively, to that of trees irrigated at 100% ET_c (6.1% of fruit) (Parvizi et al., 2014). However, 75 and 50% ET_c DI applied to only one side of the tree increased fruit cracking relative to the well-watered trees by 1.5 and 4%, respectively. In Egypt, during two subsequent seasons, increasing the application of irrigation to 20-year-old Manfalouty trees from 280 to 520 mm per season decreased fruit cracking gradually from 8.6 and 9% by up to c. 2.9% less, whereas the application of 600 mm per season only reduced cracking by 0.3 and 0.7%, relative to the driest treatment (Khattab et al., 2011). In both seasons, the treatment that received the least water had the highest fruit cracking (8.6 and 9% respectively), followed by the treatment that received the most water. In Iran, for the Post Sefid Darjazin cultivar, the application of irrigation during two subsequent seasons at 14-day intervals resulted in 19.9 and 32.8% cracking compared to 7.1 and 11% where irrigation was applied at seven-day intervals (Ghanbarpour et al., 2019).

Sunburn

Research regarding the effect of irrigation on sunburn levels of pomegranate fruit was very limited and varied with seasons. Where Mollar de Elche trees were subjected to 25% ET_c RDI during different phenological phases or to 50% ET_c SDI during three seasons, the effect of deficit irrigation on sunburn was not clear-cut (Intrigliolo et al., 2013).

In the second season of treatment, SDI fruit had higher sunburn levels (c. 16% of fruit) compared to the well-watered control (13% of fruit), and where RDI was applied during ripening (12.9% of fruit). However, during the third season, fruit subjected to RDI during flowering and fruit set had higher sunburn levels compared to the control, whereas it was comparable in the SDI and control trees.

Physiological disorders and incidence of decay

Laribi et al. (2013) and Bartual et al. (2015a), in comparing a well-watered control, 50% ET_c SDI and 25% ET_c RDI treatments during flowering until fruit set, linear fruit growth and ripening, respectively, found no significant differences among treatments with regard to rind sinking after eight weeks at 5 °C and a shelf-life of seven days at 20 °C, but SDI fruit was less susceptible to external pitting and blemishes than the RDI and control treatments. After 19 weeks of cold storage and a subsequent week of shelf-life at 20 °C, SDI reduced external physiological disorders that manifested as peel pitting, blemishes and sinking to between slight and moderate, whereas, for the rest of the treatments, external physiological disorders manifested as moderate to severe.

Aril browning was significantly lower in SDI fruit compared to the other treatments. Irrigation treatments had no effect on the incidence of decay. Weight loss increased with storage time, and after 19 weeks at 5 °C plus the complementary shelf-life period. Fruit from SDI and RDI applied during ripening showed the lowest weight loss values compared to the control treatment (Bartual et al., 2015a; Laribi et al., 2013).

2.4.7.2 Taste

Total soluble solids

In terms of total soluble solids (TSS) content, 1 °Brix is considered a meaningful increment in the perception of fruit flavour (Laribi et al. and references therein, 2013). Deficit irrigation applied to only one side of the root zone and PRD strategies applying 50% ET_c increased the TSS of Rabab fruit significantly, but by a mere 0.4 to 0.6 °Brix compared to a fully irrigated control and 75% ET_c DI and PRD strategies (Parvizi and Sepaskhah, 2015). For Wonderful fruit, the application of 100% ET_c to only one side of the root zone instead of to the whole root zone increased TSS by 0.8 °Brix, whereas applying 50% ET_c to one side of the root zone did not significantly affect the TSS relative to the control (Noitsakis et al., 2016).

The TSS of fruit from fully irrigated young bearing Wonderful trees was significantly higher in the first season of deficit irrigation under conditions of recurrent drought and high temperatures compared to trees subjected to 75, 50 and 35% ET_c SDI, with no differences in TSS during the following season (Centofanti et al., 2017b). In India, the TSS of the juice of young Ganesh trees was the highest in cases where 40 and 60% of evaporable water was replaced by drip-irrigation, with significantly lower TSS where 80 and 100% was applied, and even lower TSS where 20% evaporable water was replaced or conventional irrigation applied (Afria et al., 1998).

The TSS of the juice of three-year-old Ganesh trees increased with increasing area per leaf (data not shown, R^2 = 0.7974), but similar to the relationships of area per leaf and yield, respectively, to plant height (Figure 2.5b), decreased when plant height exceeded c. 179 cm in treatments that replaced more than 40% of evaporated water.

The TSS of the juice of adult Mollar de Elche trees irrigated daily at 33% ET_o during the second half of rapid fruit growth until the last harvest only tended to be higher relative to the 16.4 °Brix of well-watered trees at the first harvest, but increased by 1.4 and 1.7 °Brix relative to the 16.2 °Brix of the control at the two following harvests (Galindo et al., 2014a). For the same cultivar, when irrigation was withheld from 26 days before harvest, the TSS of the juice was slightly higher (4%) compared to that from fully irrigated trees, whereas withholding irrigation from 16 days prior to harvest did not have a significant effect (Peña-Estévez et al., 2015).

When Mollar de Elche trees were subjected to 50% ET_c SDI and 25% ET_c RDI during various phenological phases, the TSS ranged at harvest from 16.5 to 17.5 °Brix and decreased during storage (Bartual et al., 2015a; Laribi et al., 2013). The SDI and RDI irrigation strategy applied during ripening resulted in the highest TSS at harvest, as well as after cold storage for eight and 19 weeks, respectively, followed by a seven-day shelf-life period (Bartual et al., 2015a). At the end of the storage and shelf-life period, the TSS increased relative to the well-watered control by 0.7 °Brix for fruit from RDI during the fruit growth and ripening stages, respectively, and by 0.9 °Brix for SDI treatment.

The irrigation of 10-year-old Mollar de Elche trees according to the growers' RDI strategy increased fruit TSS at the first harvest by 1.4 and 1.2 °Brix compared to that of a well-watered control (15.5 °Brix) and trees where irrigation was withheld during the second half of linear fruit growth (15.7 °Brix), reflecting earlier ripening (Mellisho et al., 2012). This trend was not present in fruit of the second harvest, for which TSS ranged between 16.1 and 16.6 °Brix. The TSS of pomegranate arils processed at harvest increased after 14 days' shelf-life for the growers' RDI strategy by 4.1% relative to TSS at harvest, whereas that of well-watered trees increased by just more than 0.4% relative to the initial TSS value (Peña-Estévez et al., 2016). Reduced fruit metabolism during extended cold storage probably caused the lack of differences in the TSS of arils processed after 30, 60 and 90 days of storage at 5 °C and subjected to different shelf-life periods.

In contrast to the studies above, the TSS of fruit from adult Mollar de Elche trees was not affected by SDI, resulting in moderate (43% ET_o) and severe (12% ET_o) water deficits (Mena et al., 2013). Furthermore, irrigation applied at 125, 100, 75 and 50% of E_p at three- and six-day irrigation intervals did not significantly affect the TSS of the juice of six-year-old Hicaznar fruit, although the TSS values tended to increase as less irrigation water was applied (Dinc et al., 2018). Decreasing the seasonal irrigation of Manfalouty trees during two seasons from 440 to 280 mm did not affect fruit TSS significantly, whereas total acidity increased (Khattab et al., 2014).

The TSS of Mollar de Elche and Rabab, in general, increased with greater water deficits as indicated by lower seasonal minimum stem water potential (Figure 2.12). Parvizi and Sepaskhah (2015) had previously indicated that, on average over two seasons, TSS increased as mean stem water potential decreased during the fruit growth stage (i.e. 105 days from bud burst until harvest).

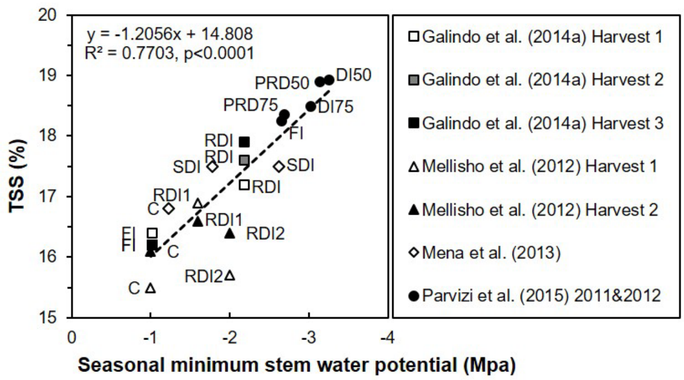

Figure 2.12: The effect of seasonal minimum stem water potential on the TSS of Mollar de Elche and Rabab (circles) pomegranate juice at harvest. Data labels indicate whether trees were well watered (C or FI) or where partial rootzone drying (PRD), regulated deficit irrigation (RDI) or sustained deficit irrigation (SDI) was applied. RDI 1 and RDI 2 refer to different seasonal RDI strategies, whereas PRD 75 and PRD 50 refer to the percentage of ET_c applied.

Titratable acidity

In general, the titratable acidity (TA) of pomegranate juice was either not affected or increased as a result of deficit irrigation. Several RDI and SDI strategies did not significantly affect the TA of Mollar de Elche fruit juice at harvest (Galindo et al., 2014a; Mellisho et al., 2012; Mena et al., 2013; Peña-Estévez et al., 2016), nor after the pre-processing storage of arils at 5 ºC for 30, 60 or 90 days, respectively (Peña-Estévez et al., 2016). However, withholding irrigation from 26 days before harvest increased the TA of Mollar de Elche arils at harvest by 8% compared to those from fully irrigated trees, while withholding irrigation for 16 days had an insignificant effect (Peña-Estévez et al., 2015). Furthermore, applying 50% ET_c SDI throughout the season or 25% ET_c RDI during flower and fruit set, fruit growth and ripening respectively, significantly increased the TA of the juice at harvest compared to trees receiving 100% ET_c, but with no differences in TA discernible after storage (Bartual et al., 2015; Laribi et al., 2013). For Rabab, the TA increased with increasing mean soil water deficit during the fruit growth stage (Parvizi and Sepaskhah, 2015). The TA of fruit from trees irrigated according to a 50% ET_c DI strategy was significantly higher compared to that of fully irrigated trees and those irrigated according to a 75% ET_c PRD strategy. In contrast, Noitsakis et al. (2016) found no effect of PRD strategies applying 100% ET_c and 50% ET_c to one side of the tree on the juice TA of Wonderful fruit.

The pH balance

In response to a variety of water deficits, fruit juice pH increased (Mellisho et al., 2012), was not affected (Centofanti et al., 2017b; Dinc et al., 2018; Noitsakis et al., 2016; Parvizi and Sepaskhah, 2015) or decreased (Mena et al., 2013; Peña-Estévez et al., 2015; Peña-Estévez et al., 2016). The fruit juice pH of Rabab increased linearly with soil water deficit (Parvizi and Sepaskhah, 2015), whereas that for Hicaznar tended to decrease as less irrigation water was applied (Dinc et al., 2018). For Mollar de Elche, where irrigation was withheld during linear fruit growth, fruit juice pH was not affected at the first harvest, but tended to be higher or was significantly higher at the second harvest compared to the control or trees irrigated according to growers' RDI criteria, respectively (Mellisho et al., 2012). For trees irrigated according to the growers' RDI criteria compared to those of well-watered trees, Peña-Estévez et al. (2016) found that arils processed at harvest had a significantly lower pH, and the pH level decreased with an increasing shelf-life period up to 14 days.

The difference in the aril pH of deficit irrigated and well-watered fruit stored and processed at 30, 60 and 90 days varied with no definite trend with regard to shelf-life period (Peña-Estévez et al., 2016). Similarly, when irrigation was withheld from 26 days before harvest, aril pH decreased by 6% compared to that of fully irrigated trees, with no significant effect when irrigation was withheld for 16 days (Peña-Estévez et al., 2015). The juice pH of Mollar de Elche subjected to severe water stress (12% ET_o SDI) also decreased slightly, but significantly, compared to trees subjected to no or moderate (43% ET_o SDI) water stress (Mena et al., 2013). In contrast, the pH level of fruit juice from six-year-old Hicaznar trees was not significantly affected by irrigation applied at 125, 100, 75 and 50% E_p at three- and six-day irrigation intervals (Dinc et al., 2018). Likewise, DI and PRD strategies irrigated at 50 or 75% ET_c did not affect the juice pH of Rabab trees compared to a control irrigated at 100% ET_c (Parvizi and Sepaskhah, 2015). Furthermore, no significant effect of water deficits was found on the pH of Wonderful fruit juice where PRD strategies applied 100 and 50% ET_c, respectively, to one side of the root zone instead of 100% ET_c to the whole root zone (Noitsakis et al., 2016) or where deficit irrigation was applied to young bearing trees at 75, 50 or 35% ET_c (Centofanti et al., 2017b).

Maturity Index

The Maturity Index (MI) (TSS:TA) of several SDI and RDI treatments increased relative to well-watered trees, whereas, in some cases, it was not affected. Irrigating Mollar de Elche trees daily at 33% ET_o during the second half of rapid fruit growth until the last harvest increased the MI of the juice at first harvest by 22.6%, and at third harvest by 9.6% compared to the control (Galindo et al., 2014a).

For the same cultivar, the MI of fruit irrigated according to the growers' RDI practice (Table 2.1) reflected earlier ripening – being significantly higher at first harvest than in a well-watered control, whereas withholding irrigation during the second half of linear fruit growth only tended to increase the MI relative to the control (Mellisho et al., 2012). Bartual et al. (2015a) found similar MI values at harvest for trees receiving 100% ET_c and 50% ET_c SDI, with significantly higher TSS and TA in the SDI compared to the 100% ET_c treatment. The MI was significantly higher than in all 25% ET_c RDI treatments applied during different phenological phases, with the lowest MI found where RDI was applied during flowering and fruit set. In contrast to these studies, the MI of Mollar de Elche fruit was not affected by SDI, resulting in moderate (SDI applied at 43% ET_o) and severe (SDI applied at 12% ET_o) water deficits (Mena et al., 2013).

For high-density planted four-year-old Bhagwa trees, applying 75 and 50% E_p increased the MI by 25 and 43.8% compared to the application of 100% E_p (Haneef et al., 2014). Also, for Shavar, no irrigation until the end of fruit set and 50% SDI increased the MI by 26.5 and 14.3% compared to that of trees receiving 100% ET_c throughout the season (Selahvarzi et al., 2017). The MI of trees subjected to 50 and 75% ET_c PRD tended to be higher, and that of trees subjected to 50 and 75% ET_c DI treatments tended to be lower, compared to the application of 100% ET_c (Parvizi and Sepaskhah, 2015). The MI of Manfalouty trees decreased during two seasons with less irrigation water applied due to a significant increase in the acidity of the fruit, with minor differences in TSS (Khattab et al., 2014).

2.4.7.3 Health

The beneficial effects of pomegranate fruit juice and arils are associated with the fruit's exceptionally high antioxidant capacity, which correlates strongly with its high content and distinctive composition of phenolic compounds (Fawole and Opara and references therein, 2013). The high levels of polyphenol antioxidants have the ability to oppose oxidation caused by free radicals that lead to cell damage, some degenerative disorders and other diseases in which inflammation plays a critical role (Fawole et al. and references therein, 2012). Arils from deficit irrigated trees, in some cases, resulted in better quality and healthier attributes during shelf-life than those from trees irrigated according to non-limiting soil water conditions (Peña-Estévez et al., 2016), whereas, in others, juice from trees subjected to SDI was of a lower quality and less healthy than that from trees without water stress (Mena et al., 2013).

<u>Total phenolic compounds</u>

Deficit irrigation strategies increased (Selahvarzi et al., 2017), did not affect (Cano-Lamadrid et al., 2018; Centofanti et al., 2017b; Galindo et al., 2014a; Mellisho et al., 2012) or decreased (Mena et al., 2013; Peña-Estévez et al., 2016) total phenolic compounds (TPC) in fruit juice and arils. In Iran, for seven-year-old Shavar trees, RDI during fruit set and 50% ET_c SDI, on average over two seasons, increased the TPC of the fruit relative to the control by 9.7 and 33.6%, respectively (Selhavarzi et al., 2017). In contrast, TPC decreased by c. 43% in fruit of trees subjected to SDI (43 and 12% of ET_o) relative to that of trees irrigated at 75% ET_o throughout the season (Mena et al., 2013). Arils from Mollar de Elche trees subjected to growers' RDI had, at harvest, 18% lower total phenolic contents than the well-watered control, but after 90 days of pre-processing storage, had c. 30% more (Peña-Estévez et al., 2016). Arils from deficit irrigated fruit had limited or no reduction in phenolic compounds during shelf-life and, in some cases, had higher concentrations than those in well-watered trees. According to Peña-Estévez et al. (2016), the behaviour of individual phenolics depends on irrigation treatment and the duration of cold storage.

<u>Anthocyanins</u>

Anthocyanins are considered to be responsible for the colour of the pomegranate skin and arils, and are an important commercial quality trait (Laribi et al., 2013). With regard to total anthocyanin content (TAC), water stress, in addition to sunlight exposure and temperature, may control anthocyanin biosynthesis (Mena et al. and references therein, 2013). For Shavar, RDI until the end of fruit set and 50% ET_c SDI had no effect on the TAC of fruit (Selhavarzi et al., 2017). Irrigating Mollar de Elche trees daily at 33% ET_o during the second half of rapid fruit growth until the last harvest (Galindo et al., 2014a) or applying a growers' RDI (Mellisho et al., 2012; Peña-Estévez et al., 2016) did not affect the fruit juice TAC of the first harvest relative to well-watered trees either.

However, for the same cultivar, the TAC of fruit decreased by 3 and 7% for trees subjected to withholding water for 16 and 26 days prior to harvest, respectively, compared to fully irrigated trees (Peña-Estévez et al., 2015). In contrast, where 25% ET_c RDI was applied during linear fruit growth, the TAC of the juice at harvest and after cold storage increased significantly compared to that of well-watered trees or those subjected to 25% ET_c RDI applied during flowering until fruit set or ripening, respectively, or to 50% ET_c SDI (Bartual et al., 2015b; Laribi et al., 2013). The colour of the fruit peel and juice were affected differently by deficit irrigation. The timing of water stress for Mollar de Elche should therefore be taken into account with regard to anthocyanin accumulation (Laribi et al., 2013). Irrigation strategies such as SDI and RDI during ripening increased fruit skin colouration, whereas RDI during linear fruit growth resulted in the highest concentration of juice anthocyanins. For Manfalouty fruit, applying more irrigation water per season decreased the total anthocyanins in fruit (Khattab et al., 2014). In contrast, SDI at 75, 50 or 35% ET_c was found to have no effect on the concentration of several anthocyanin compounds over two sequential seasons for young bearing Wonderful trees (Centofanti et al., 2017b).

Total antioxidant capacity

Deficit irrigation did not affect (Galindo et al., 2014a; Mellisho et al., 2012; Peña-Estévez et al., 2016), decreased (Mena et al., 2013) or increased (Selahvarzi et al., 2017) the total antioxidant capacity of pomegranate fruit juice. Daily irrigation of Mollar de Elche trees at 33% ET_o during the second half of rapid fruit growth until the last harvest did not affect the antioxidant capacity of the fruit juice at marketing stage, compared to that of trees irrigated at 105% ET_o (Galindo et al., 2014a) nor did growers' RDI have a significant effect relative to that of well-irrigated trees (Mellisho et al., 2012). However, according to Peña-Estévez et al. (2016), the total antioxidant capacity of arils from well-watered Mollar de Elche trees was 1.4-fold higher at harvest than that of deficit irrigated fruit. During a shelf-life of up to 14 days, though, the total antioxidant capacity of the control fruit decreased, whereas that of the deficit irrigated fruit increased, with nearly the same total antioxidant capacity for both irrigation treatments at the end of cold storage. In contrast, the total antioxidant capacity of the juice of trees subjected to moderate (irrigated at 43% ET_o SDI) and severe water stress (irrigated at 12% ET_o SDI) decreased on average by c. 25% compared to that of trees subjected to no water stress (irrigated at 75% ET_o) (Mena et al., 2013). In contrast, the antioxidant activity of Shavar fruit over two seasons increased on average by 43% in a 50% ET_c SDI treatment relative to the control, whereas the RDI treatment of withholding irrigation until fruit set had no significant effect (Selahvarzi et al., 2017).

Sugars, acids and other phenolic substances

Peña-Estévez et al. (2016) found that Mollar de Elche fruit that was subjected to deficit irrigation (growers' practice) had 13 and 21% higher glucose and fructose contents, respectively, at harvest than the well-watered control. Overall, deficit irrigation had a positive effect on the sugar content of pomegranate arils from fruit stored for 30, 60 and 90 days (Peña-Estévez et al., 2016). In contrast, according to Cano-Lamadrid et al. (2018), water deficit induced by applying 60% ET_c during fruit growth and ripening did not affect the sugars of Mollar de Elche fruit, whereas it increased glucose and fructose in Wonderful fruit. Mellisho et al. (2012), though, reported no irrigation treatment effect on the sucrose, glucose, fructose, citric acid or malic acid content of pomegranate arils. Punicalagin content, which can contribute significantly to the antioxidant activity in pomegranate juice (Mena et al. and references therein, 2013), decreased as water stress increased in moderate (irrigated at 43% ET_o SDI) and severe water stress (irrigated at 12% ET_o SDI) treatments, being 36 and 73% less than in the control at harvest. This decrease in punicalagin concentration, despite no change in ellagic acid (punicalagin hydrolysed compound) concentration, could indicate that moderate and severe water stress levels inhibit punicalagin biosynthesis (Mena et al., 2013). In this regard, Cano-Lamadrid et al. (2018) found that mild water stress had no effect on the punicalagin content of Mollar de Elche and Wonderful fruit. In Manfalouty fruit, total sugar was significantly increased by reducing the irrigation water applied from 440 to 360 mm and 280 mm per season (Khattab et al., 2014).

At harvest, Mollar de Elche arils that were subjected to growers' RDI practice had a significantly higher total Vitamin C content compared to that of well-watered trees, with ascorbic acid being 28% of the total compared to 35% for the control (Peña-Estévez et al., 2016). Irrigation had no effect on ascorbic acid content during shelf-life, except for the arils processed after a pre-processing storage period of 60 days, which showed higher ascorbic acid losses compared to the control. According to Cano-Lamadrid et al. (2018), the level of water stress in Mollar de Elche and Wonderful trees irrigated at 60% ET_c during fruit growth and ripening was too low to affect the citric acid and ascorbic acid content of the fruit. The seasonal minimum stem water potential in these two cultivars reached c. -1.6 MPa. The Vitamin C content of Manfalouty fruit decreased by increasing the amount of seasonal water applied from 280 and 360 mm to 440 mm (Khattab et al., 2014). In contrast, the Vitamin C content of Bagwa fruit was significantly less where trees were subjected to 50% ET_c DI compared to fully irrigated trees (100% ET_c), or trees subjected to 75% ET_c DI or PRD treatment (Parvizi and Sepaskhah, 2015). The Vitamin C concentration of the juice decreased with mean stem water potential during the fruit growth stage.

Conflicting results of water deficits on bioactive compounds and antioxidant activity may be due to differences in cultivars, the age of the trees, harvest time and drought severity (Selahvarzi et al., 2017). In addition, differences in the mechanical fruit juice extracting process (Centofanti et al., 2017a; Centofanti et al., 2017b; Mphahlele et al., 2016) and agro-environmental conditions may also play a role (Centofanti et al., 2017b).

2.5 WATER MANAGEMENT STRATEGIES UNDER LIMITED WATER SUPPLY

2.5.1 Irrigation management

Selected research regarding irrigation strategies for pomegranate trees and the advantages and disadvantages of the strategies are listed in tables 2.6 and 2.7. Water savings relative to a well-watered control ranged between c. 14 and 100% for a range of experimental periods pertaining to the different studies. Studies that focused largely on the effect of water deficits during linear fruit growth and/or ripening of Mollar de Elche include those of Cano-Lamadrid et al. (2018), Galindo et al. (2014a; 2014b; 2017a) and Mellisho et al. (2012). However, the effect of SDI (Intrigliolo et al., 2013; Mena et al., 2013) and RDI at different phenological stages (Intrigliolo et al., 2013) (Table 2.7) on the performance of the cultivar was evaluated as well.

Fruit ripening is a critical period for Mollar de Elche as irrigation is required during most of this phenological period to achieve maximum yield (Galindo et al., 2017a). However, withholding water for six days before harvest saved 14% of water relative to well-watered trees, while it increased fruit peel colour and enhanced bioactive compound content, with no negative impact on marketable yield (37.1 t ha^{-1}) or fruit size (tables 2.2 and 2.6). Advanced harvest time may result in earlier market access and improved fruit prices. For producers interested in the processing market, the red colour of juice improved, whereas fruit size at harvest decreased by c. 14% when water was withheld for 25 and 34 days before harvest, using 62 and 100% less water compared to the well-watered trees. Total yield decreased by c. 8 and 23% for these two scenarios, and marketable yield decreased by 49 and 69% (Table 2.2).

According to Peña-Estévez et al. (2015), withholding water from 16 and 26 days before harvest saved c. 6 and 11% water and increased the shelf-life of arils by four days compared to a well-watered control. Arils from deficit irrigated fruit had greater visual appearance and overall quality, but had lower anthocyanin content and a slightly red-orange colour. The TSS when water was withheld for 26 days was slightly higher, whereas withholding water for 16 days had no effect relative to that of the control. In contrast to the findings of Galindo et al. (2017a), Intrigliolo et al. (2013) found that 25% ET_c RDI applied to Mollar de Elche trees during ripening did not affect yield, fruit number, fruit weight or economic yield value, whereas the strategies saved 18% of water and tended to have increased water productivity relative to the control (Table 2.7).

Table 2.6: Summary of the effect of various irrigation strategies on Mollar de Elche pomegranate fruit marketability-related variables and water saved relative to well-watered trees. [FN = fruit number; FS = fruit size; NE = no significant effect; TAC = total anthocyanin content; TEAC = Trolox equivalent antioxidant activity; TPC = total phenolic compounds; TSS = total soluble solids; WS = water savings relative to well-watered control].

Author	Irrigation strategy	Irrigation levels	Advantages	Disadvantages	WS (%)
Cano-Lamadrid et al. (2018)	RDI	120% ET_c until fruit set, 60% ET_c during fruit growth and ripening	NE FS	< Yield 24% < Juice red colour NE sugars and organic acids NE TPC or punicalagin	39.1
Galindo et al. (2014a)	RDI	105% ET_c until first half of fruit growth, second half of rapid fruit growth to last harvest 33% ET_o	>Juice red colour >TSS and MI Advanced optimal harvest time 7-8 days	< Yield 26%, < FN, < FS NE bioactive quality	68.6
Galindo et al. (2014b; 2017a)	Withhold irrigation before harvest (days)	6	NE marketable yield and FS > Bioactive compounds > Peel red colour Advanced harvest time > Fruit price	< TPC	14.1
		15	> Peel red colour	< Marketable yield 38% and FS << TPC	32.8
		25 and 34	> Peel red colour > Juice red colour	< Marketable yield 49 and 69% and FS << TPC	61.7 and 100

Author	Irrigation strategy	Irrigation levels	Advantages	Disadvantages	WS (%)
Mellisho et al. (2012) Peña-Estévez et al. (2016)	Growers' criteria	32% ET_o – 74% ET_o – 36% ET_o until first half of linear fruit growth phase, second half of linear fruit growth phase and during end of fruit growth and ripening, respectively	> Peel and aril red colour >TSS and MI, glucose and fructose at harvest >TSS increase after 14 days storage at 5 ºC > Overall sensory quality at shelf-life Beneficial phenolics effect during storage >Quality and health attributes during shelf-life	< Yield 30% < FS < Peel content second harvest	46.3
	RDI	32% ET_o – NI – 99% ET_o until first half of linear fruit growth phase, second half of linear fruit growth phase and during end of fruit growth and ripening, respectively	NE fruit moisture content	< Yield 28% and <FS (14 and 20%) NE Peel red colour < Aril red colour NE TSS and MI < TAC NE TEAC, sugars and organic acids	55.1
Mena et al. (2013)	SDI	43% ET_o	NE TSS or MI	>Yellowish juice colour < TPC and punicalagin < Antioxidant activity NE total anthocyanin	42.3
	SDI	12% ET_o	NE TSS or MI	> Yellowish juice colour, less intense red colour < TPC and TAC < Punicalagin and antioxidant activity	84.7

Table 2.7: Summary of the effect of sustained and regulated deficit irrigation applied during different phenological phases on Mollar de Elche pomegranate fruit marketability-related variables and water saved relative to well-watered trees (adapted from data for three seasons from Bartual et al., 2015; Intrigliolo et al., 2012; Intrigliolo et al., 2013; Laribi et al., 2013). [MI = Maturity Index; NE = no significant effect; WUE = yield/(irrigation applied + rainfall); WP = economic yield value/irrigation applied; WS = water savings relative to well-watered control]

Irrigation strategy	Irrigation levels	Advantages	Disadvantages	WS (%)
SDI	50% ET_c whole season	< Vegetative growth NE yield > FN (28%) NE MI at harvest >TSS at harvest and 19 weeks after cold storage + shelf-life > Peel red colour at harvest and during storage + shelf-life >>Juice anthocyanins after 19 weeks' storage + shelf-life >> WUE >> WP < Skin sinking after 19 weeks' storage + shelf-life < Skin pitting and blemishes after 19 weeks' storage + shelf-life < Aril browning after cold storage + shelf-life < Fruit weight loss after 19 weeks' storage + shelf-life	< FS (22%) << Economic yield value (28%) Sunburn Long-term tree productivity NE juice anthocyanins at harvest NE juice anthocyanins after eight weeks' storage + shelf-life > Yellow peel colour after storage + shelf-life NE antioxidant capacity at harvest and after 19 weeks' storage + shelf-life	44
RDIfl-fr.set	25% ET_c flowering, fruit set, early fruit growth, 100% ETc rest of season	> Yield > FN NE TSS NE economic yield value > WUE > WP < Skin sinking after 19 weeks' storage + shelf-life < Skin pitting and blemishes after 19 weeks' storage + shelf-life	Slightly < FS (7%) << MI at harvest NE juice anthocyanins after eight weeks' storage + shelf-life NE antioxidant capacity at harvest and after 19 weeks' storage + shelf-life	12

Irrigation strategy	Irrigation levels	Advantages	Disadvantages	WS (%)
RDIfr.gr	25% ET_c linear fruit growth, 100% ET_c rest of season	> Aril anthocyanins > TSS after 19 weeks' storage + shelf-life NE economic yield value > WP > Juice anthocyanins at harvest >>Juice anthocyanins after eight weeks' storage + shelf-life >>>Juice anthocyanins after 19 weeks' storage + shelf-life	Slightly < FS (6%) < MI at harvest Fruit cracking NE WUE NE antioxidant capacity at harvest and after 19 weeks' storage + shelf-life	24
RDIripe	25% ET_c last part of fruit growth and ripening, 100% ETc rest of season	NE on yield/ FN/FS >TSS at harvest, after eight and 19 weeks' storage > Peel red colouration > Higher sugar content Accelerated fruit ripening date NE economic yield value and WP > Juice anthocyanins after eight and 19 weeks' storage + shelf-life < Skin sinking after 19 weeks' storage + shelf-life < Fruit weight loss after 19 weeks' storage + shelf-life	< MI at harvest NE WUE NE antioxidant capacity at harvest and after 19 weeks' storage + shelf-life	18

Fruit was furthermore compared to well-watered trees, higher TSS levels at harvest and throughout eight and 19 weeks of cold storage, enhanced red colour of the peel and more anthocynanins in the juice after eight and 19 weeks of cold storage. Fewer external physiological disorders and less fruit weight loss occurred after 19 weeks of storage and a seven-day shelf-life period. However, RDI applied during ripening may, in some seasons, result in increased fruit cracking. The differences in the outcomes of this research regarding RDI during ripening, compared to that of Galindo et al. (2014b; 2017a), may partially be explained by differences in crop load (c. 49% lower yield), the level of water stress that developed (Table 2.2) and the fact that water was not completely withheld before harvest.

Among the SDI and various RDI treatments, the best strategy for Mollar de Elche was a 25% ET_c application during the main flower and reproductive organ drop period only, with 100% ET_c applied during the rest of the season (Intrigliolo et al., 2013). This strategy saved c. 12% water relative to the 100% ET_c treatment, and increased yield via more fruit of a slightly lower weight (tables 2.2 and 2.7). Water deficits did not affect the TSS (Intrigliolo et al., 2013). The economic yield value was not affected, but WUE and WP increased relative to the control. External physiological disorders after cold storage were less compared to the control. Disadvantages of this strategy are that it decreased MI at harvest and had no positive effect on the juice anthocyanins or antioxidant capacity. The 25% ET_c RDI applied during the linear fruit growth only reduced fruit weight by c. 6% and saved 24% of water relative to the control. This strategy had no effect on the economic yield value, but increased WP. The TSS of the juice, compared to the control, increased after 19 weeks of storage and a seven-day shelf-life, although the MI was lower at harvest. Juice anthocyanins increased relative to the control at harvest and notably after eight and 19 weeks of storage and shelf-life. Fruit irrigated according to this strategy may, in some seasons, be susceptible to cracking.

Although 50% ET_c applied for three years during the entire growing season (SDI) saved 44% of water relative to the 100% ET_c treatment, it had no negative impact on yield in the Mediterranean area of southeastern Spain (Table 2.7). On average over three years, trees were bearing c. 28% more fruit of c. 22% lower weight, which decreased the economic yield value relative to the control by 28% (Table 2.2) (Intrigliolo et al., 2013). The red colour of the fruit peel was enhanced at harvest and throughout cold storage and shelf-life, but turned yellowish at the end of storage and shelf-life. Despite the latter, fruit still had a greater red colouration than in the case of the other irrigation treatments (Laribi et al., 2013). Juice anthocyanins increased notably relative to the control after 19 weeks of storage and over the following shelf-life period. Taking the smaller fruit size and its marketability into account, the SDI strategy may be more suitable for producers prioritising the juice industry (Intrigliolo et al., 2013).

Fruit had fewer external physiological disorders and less aril browning, and less fruit weight loss after cold storage and shelf-life compared to a well-watered control. Furthermore, the SDI reduced vegetative growth markedly, which may, in the long term, affect tree productivity – especially if trees are still young when the strategy is imposed (Intrigliolo et al., 2013). The fruit of trees subjected to the SDI strategy may, in some seasons, also be prone to increased sunburn compared to well-watered trees. Of all the irrigation strategies evaluated in this research, SDI increased WUE and WP the most, relative to the control. According to Bartual et al. (2015a), SDI and, to a lesser extent, 25% ET_c RDI during ripening, could be used as tools to accelerate the fruit ripening date of Mollar de Elche fruit due to faster sugar accumulation. This has important implications for the marketing of pomegranate fruit. The red colouration and higher sugar content may advance harvest time if the cultivar is picked according to external colouration with the prospect to fetch better prices if one can get to the market earlier (Laribi et al., 2013).

With regard to Wonderful, 75% ET_c SDI increased yield relative to trees irrigated at 100% ET_c in the third year that deficit irrigation was applied (Zhang et al., 2017). However, there is a paucity of data regarding the quality of the fruit and the exact amount of water applied (Table 2.8). Indications during the second year of deficit irrigation were that irrigation at 35% ET_c SDI may have a detrimental effect on fruit colour (Centofanti et al., 2017b). Irrigation at 60% ET_c during fruit growth and ripening also had a detrimental effect on the colour of the juice and reduced yield by 41% (Cano-Lamadrid et al., 2018), whereas applying 100% ET_c to only one side instead of to the full root zone may reduce the incidence of cracking (Noitsakis et al., 2016).

Table 2.8: Summary of the effect of sustained and regulated deficit irrigation (SDI and RDI) or partial rootzone drying (PRD) on Wonderful pomegranate fruit marketability-related variables and water saved relative to well-watered trees. [FN = fruit number; FW = fruit weight; NE = no significant effect; N/A = not available; TSS = total soluble solids; WS = water savings relative to well-watered control].

Cultivar	Country	Age	Irrigation strategy	Irrigation levels	Advantages	Disadvantages	WS (%)	Author
Wonderful	Greece	12	PRD1	Two months from bud break, 100% ET_c one side of tree	NE FW < Cracking >TSS		N/A	Noitsakis et al. (2016)
			PRD2	Two months from bud break, 50% ET_c one side of tree		< FW	N/A	
Wonderful	Spain	6	RDI	120% ET_c until fruit set, 60% ET_c during fruit growth and ripening	NE FW > Sugars	< Yield 41% < Juice red colour NE total phenolic compounds NE punicalagin NE organic acids	38.6	Cano-Lamadrid et al. (2018)
Wonderful	USA	5	SDI	75% ET_c	>Yield, NE FN, FW		N/A	Zhang et al. (2017)
				50% ET_c	NE yield, FN, FW		N/A	
				35% ET_c	NE FN	<Yield, FW	N/A	

Table 2.9: Summary of the effect of sustained and regulated deficit irrigation (SDI and RDI) or partial rootzone drying (PRD) on pomegranate fruit marketability-related variables and water saved relative to well-watered trees in Iran. [FN = fruit number; FW = fruit weight; MI = Maturity Index; NE = no significant effect; N/A = not available; TPC = total phenolic compounds; TSS = total soluble solids; WUE = yield/(rainfall and/or irrigation applied); WP = economic yield value/irrigation applied); WS = water savings relative to well-watered control].

Cultivar	Country	Age	Irrigation strategy	Irrigation levels	Advantages	Disadvantages	WS (%)	Author
Rabab	Iran	9	SDI	75% ET_c DI One side of tree	NE juice content >WUE	< Yield, FN, FW < MI NE TSS, Vitamin C > Cracking	22.4	Parvizi et al. (2014; 2016) Parvizi and Sepaskhah (2015)
			PRD	75% ET_c PRD	> Yield and FN, NE FW > Juice content >>> WUE	NE Vitamin C NE TSS, MI	22.4	
			SDI	50% ET_c DI One side of tree	> TSS >> WUE	<< Yield, FN, FW < Vegetative growth < Juice content, MI, Vitamin C >> Cracking	44.8	
			PRD	50% ET_c PRD	> Juice, TSS >>>> WUE	< Yield, FN, FW < Vegetative growth NE Vitamin C	44.8	
Shavar	Iran	7	RDI fruit set	No irrigation until end fruit set, 100% ET_c rest of season	< Vegetative growth NE yield, > FW > Compact flowering > Fruit set > Juice content > Aril:peel ratio; MI > WUE first season, NE second season > TPC	< FN NE total anthocyanin content NE antioxidant activity Decrease hermaphrodite:male flower ratio	18	Selhavarzi et al. (2017)
			SDI	50% ET_c throughout season	> Aril:peel ratio; MI > WUE first season, NE second season >> TPC, > Antioxidant activity	< Vegetative growth < Yield, FN, FW < Flowers second season, NE TAC	50	

Research from Iran for Rabab indicated positive effects of 75% ET_c PRD on yield and juice content, with c. 22% water saved relative to a well-watered control (Parvizi et al., 2014; Parvizi et al., 2016). This irrigation strategy increased WUE significantly compared to a well-irrigated control and trees that were deficit irrigated at 75 and 50% ET_c on one side of the root zone only (Table 2.9). One has to keep in mind, though, that the PRD strategy can increase labour or irrigation system costs. In contrast to the findings of Noitsakis et al. (2016) regarding cracking for Wonderful, fruit cracking increased for Rabab relative to a well-watered control where irrigation was applied at 75 or 50% ET_c to one side of the root zone. Also in Iran, for Shavar, no irrigation applied from the beginning of the season until fruit set, followed by irrigation at 100% ET_c during the remainder of the season, resulted in reduced vegetative growth with a compact flowering period, improved fruit set and weight, with no effect on yield and increased total phenolic compounds compared to the control (Table 2.9) (Selahvarzi et al., 2017). On the contrary, SDI, applied at 50% ET_c, decreased yield and had negative carry-over effects on vegetative growth and flowering in the second season, although fruit juice had higher total phenolic compounds and antioxidant activity compared to the control. The RDI strategy applied c.18% less water compared to the control, and the SDI strategy 50% less. Both strategies had higher WUE compared to the control treatment in the first season, but were comparable to that of well-watered trees in the second season.

Based on the current sourced research (tables 2.6 to 2.9), SDI may supply a market for smaller pomegranates with increased red skin and/or juice. However, an SDI strategy applying 50% ETc or less in dry and arid regions may, in most cases, not be sustainable and cannot be recommended over the long term for profitable pomegranate production. In this regard, more research is needed that addresses the carry-over effects of water deficits on vegetative growth and reproductive bud development between seasons.

2.5.2 Orchard management

In Egypt, for Manfalouty trees in sandy soils, ET_c decreased and yield increased as the drip-irrigation interval increased from two to four to six days (Seidhom and Abd-El-Rahman, 2011). In addition, plant residues applied as olive pomace mulch decreased ET_c compared to where no mulch (plus weeds) or petroleum applied as bitumen emulsion mulch was applied. Olive pomace mulched trees had the highest yield, followed by the bitumen emulsion mulched trees, with trees with no mulch having the lowest yield. Irrespective of mulching treatment, yield increased as the irrigation interval increased (Figure 2.13). Yield increases relative to the crop without mulch ranged between 12 and 40% for the bitumen emulsion mulch, and between 35 and 101% for the olive pomace mulch. The positive effect of the olive pomace mulch may be associated with pronounced increases in soil temperature, which may increase both water and nutrient consumption by tree roots, which, in turn, affects crop yield. The highest WUE (crop yield/seasonal ET_c) was obtained for a combination of a six-day irrigation interval and olive pomace mulch. The WUE increased as trees aged, amounting to 5.55, 5.59 and 5.65 kg m^{-3} for three respective seasons. Similarly, the water economy (crop yield/irrigation applied) equalled 4.14, 4.31 and 4.49 kg m^{-3} during the three seasons. The positive effect of mulches on pomegranate fruit yields have been previously reported, whereas mulching also reduced fruit cracking (Seidhom and Abd-El-Rahman and references therein, 2011).

However, straw mulching in drip-irrigated pomegranates did not improve WUE, but the ineffectiveness of mulch treatments was attributed to water infiltration problems, especially during dry months (Ghosh et al., 2013). The use of new mulches for soil water conservation in arid regions has been introduced as an alternative to conventional (plastic) mulches (Farzi et al., 2017). Different mulch materials differed in efficiency on soil water conservation and reduced evaporation relative to bare soil by between 35 and 63%. De-oiled olive pomace mulch and pistachio shell mulch – as new mulch materials – seem more favourable for conserving soil water compared to the other materials (Figure 2.14).

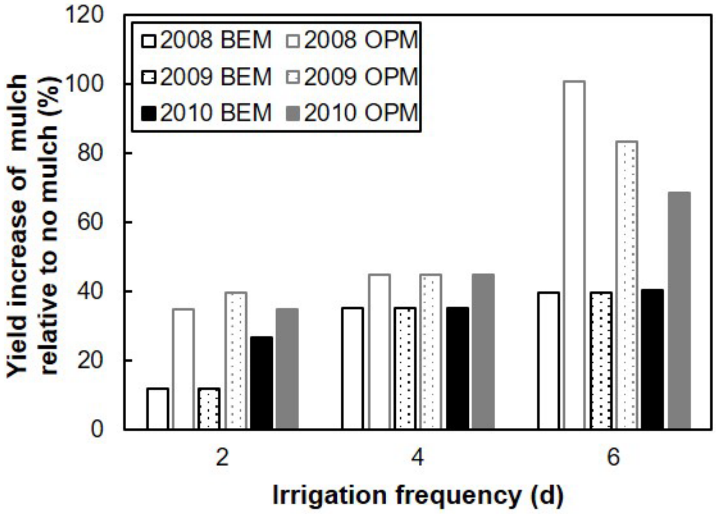

Figure 2.13: The yield increase of Manfalouty pomegranate trees mulched with bitumen emulsion (BEM) and olive pomace (OPM) relative to where no mulch was applied, drip-irrigated at different irrigation frequencies during three subsequent seasons (adapted from Seidhom and Abd-El-Rahman, 2011).

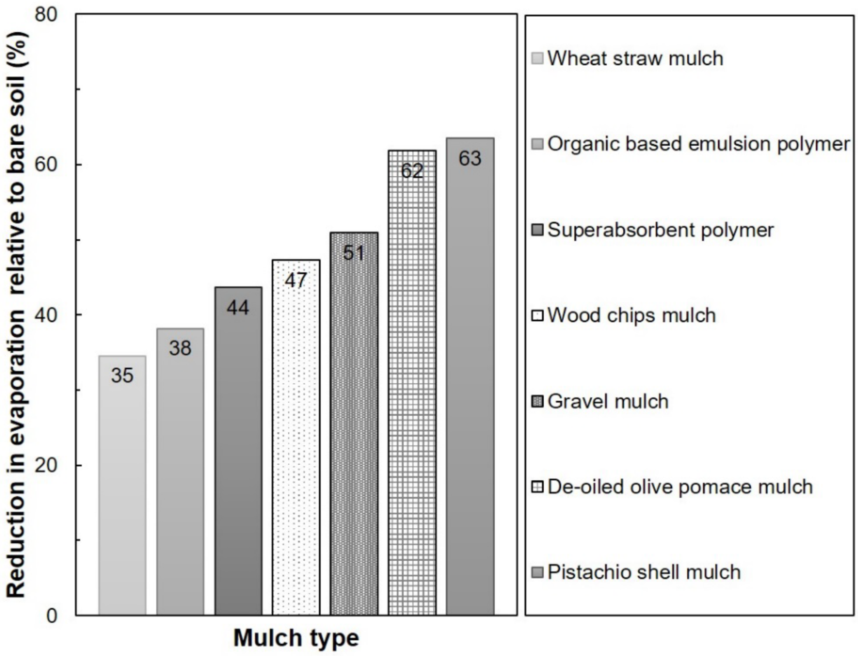

Figure 2.14: The effect of mulch type on evaporation relative to bare soil (adapted from Farzi et al., 2017).

Makus et al. (2014) found in-row durable white plastic to be beneficial to retain soil water, reduce chemical weed control required, increase total fruit yield (by c. 20%) and improve the colour of pomegranate juice. White plastic improved midday orchard floor reflectance, reduced surface temperatures and decreased variability in soil temperatures at several depths up to 300 mm. White plastic had no significant effect on the colour of the peel. Trees grown under white plastic had more basal sucker production at the end of the season, whereas irrigation rate also increased sucker frequency and size.

None of the articles sourced in this review addressed the use of cover crops in pomegranate orchards. However, weeds appear to be problematic in several pomegranate orchards. In this regard, the research of Fourie et al. (2017) on the use of cover crops to control weeds in vineyards may be informative.

2.6 CONCLUSIONS

With regard to irrigation systems, drip-irrigation appears to be favoured above the more conventional types of irrigation. Management challenges of subsurface drip-irrigation systems should be taken into account, though, if this type of irrigation is considered. The ET_c of subsurface irrigated pomegranate orchards in arid regions for one- to six-year-old trees ranged from 53 to 953 mm and orchard water requirements may increase depending on the irrigation system used and whether weeds are present in the orchard. Comparison of mathematical relationships to determine crop coefficients from fractional ground cover indicated that Wonderful trees tended to have lower K_c values at comparable canopy cover to grapevine, peach and other deciduous fruit. In general, for pomegranate trees, mild and severe water deficits were related to seasonal minimum stem water potential values of between -1.5 and -1.8 MPa and between c. -2 and -2.8 MPa, respectively, which could decrease stomatal conductance by between 19 and 36%, and between 53 to 77% relative to well-watered trees.

Water deficits affected vegetative growth. Applied over several seasons, this can have a cumulative effect on canopy development, depending on its degree and duration. In the long term, this can affect orchard productivity. Depending on cultivar, pomegranates have a linear to sigmoidal fruit growth pattern. Severe water deficits, in particular, affect fruit growth rate compared to that of well-watered trees with minor differences late in the fruit growth stage. Maximum yield of pomegranate was achieved where between 721 and 953 mm ET_c occurred, below which level yield decreased with ET_c. In general, relative yield for selected cultivars decreased by 24, 34 and 45% if seasonal minimum midday stem water potential decreased by -0.5, -1 and -1.8 MPa relative to that of well-watered trees. Yield typically decreased due to less fruit and/or fruit of lower weight.

With regard to fruit and product quality, the appearance, taste and health properties of fruit were affected by various deficit irrigation strategies. For selected cultivars, the TSS in fruit juice increased as seasonal minimum midday stem water potential decreased. With regard to fruit skin, juice colour and bioactive compounds, deficit irrigation studies, in some cases, had conflicting results. Water deficits during ripening and sustained deficit irrigation throughout the season, in some cases, resulted in an improved red colour of the skin and/or juice, but with a negative effect on fruit weight and economic income. A comparison of the advantages and disadvantages of several irrigation strategies identified the potential of some to optimise farmer profitability and comply with customer requirements. Sustained deficit irrigation at low levels of ET_c replacement is not considered a sustainable strategy for pomegranate orchards over the long term. In terms of orchard management, olive pomace mulch increased yield and decreased orchard water use. Different types of mulches can be considered to reduce soil evaporation water losses, whereas cover crops should be investigated as a means to control weeds.

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CHAPTER 3: IRRIGATION AND POMEGRANATE TREE PERFORMANCE – A SURVEY

3.1 INTRODUCTION

The ARC, in collaboration with the pomegranate industry (POMASA), co-funded by the Alternative Crop Fund of the Western Cape Department of Agriculture, conducted a survey over two seasons (2017/18 and 2018/19) on the irrigation and performance of pomegranate trees. Baseline information regarding current irrigation practices and related tree water status, growth, yield and fruit quality was collected to direct more detailed research for the pomegranate industry to enable producers to achieve the high water use productivity that the latest South African Irrigation Water Strategy requires. This chapter addresses the second specific aim of the scoping study: to analyse data from a local survey, including weather, soil, water and crop baseline information from pomegranate orchards under drip- or micro-irrigation in different production areas to identify research gaps that can direct future pomegranate water use and irrigation research.

3.2 METHODOLOGY

Data collected at nine full-bearing pomegranate (Wonderful cultivar) orchards on commercial farms in four pomegranate production areas in the Western Cape (Bonnievale, Gouda, Wellington and Wolseley) was analysed. Sites selected include orchard variability currently present in the industry, comprising sandy or heavier soil, level or ridged gradients, planted with or without nets and irrigated with micro-sprinklers or drip-irrigation (single or double line). The cultivar selected (Wonderful) is an important role player in the export market (POMOSA, 2013).

A water and soil sample for chemical status analyses was taken to assess the suitability of the sites for the experiment. Soil samples were taken at depths of 0-300 mm and 300-600 mm in the tree row. A profile pit was made for each orchard to describe soil properties and determine the extent of the root zone. This information was used to determine the depths and positions for the installation of soil water content monitoring equipment. Soil samples were taken for soil particle size analyses (five fraction) at three representative depth increments, and the soil texture determined. Manual water meters were installed in-line for each orchard to monitor the amount of water applied by irrigation for a section of five trees. Decagon 5TM and/or ECH$_2$O soil water content sensors were installed in the irrigated area of two trees at at least two depths each – representing the middle and bottom end of the root zone. Meteorological data of each orchard obtained from the nearest weather station was used to characterise atmospheric conditions. Irrigation applied was monitored by reading the manual water meters at the end of each of four phenological phases (flowering to fruit set, fruit growth, ripening and post-harvest). Soil water dynamics was measured hourly at two trees per orchard, except in one orchard where IRRICON monitored the soil water content (one tree). The producers applied standard orchard practices.

The plant response was monitored by determining tree water status at three selected fruit growth stages (i.e. flowering to fruit set, fruit growth and ripening) using the pressure chamber technique. Midday stem water potential was measured on one short shoot per tree for each of five trees per orchard. Individual leaf petioles were too short to fit the available equipment. Shoot length (10 shoots per tree of five trees per orchard) was measured as an indication of vegetative growth. Leaves were sampled for nutrient analysis at a commercial laboratory (Bemlab) at the end of January. Fruit size (10 fruit per tree of five trees per orchard) was measured at the beginning and/or end of the three selected fruit growth stages. Yield was quantified at harvest (fruit per tree of five trees per orchard counted and weighed).

To determine fruit quality at harvest, the fruit of five trees per orchard were evaluated for sunburn, cracking, blemishes, crown rot, external decay and false codling moth (FCM). More detailed fruit quality evaluation at harvest (four fruit per tree of five trees per orchard) included fruit length and diameter, fruit skin colour, the colour of the arils and TSS, pH and the TA of the pomegranate juice. The susceptibility of fruit to external (e.g. decay, cracking) and internal (e.g. browning, pitting of arils and internal teguments and surfaces, paleness of arils, decay) physiological disorders was done. Physiological disorders that only develop during cold storage were not reported.

A commercial laboratory (Bemlab) determined the fruit mineral nutrient content on a sample of two fruit per tree of five trees per orchard. In addition, all fruit harvested was classified according to the norms below to compare fruit marketability (Table 3.1) and to determine gross farm income. Gross farm income per orchard was determined per marketing class based on the average amounts paid out by a local export company for exported fruit during 2017 and 2018. Based on specific count groups, Extra Class and Class 1 fruit were paid out per 3.8 kg carton, whereas fruit for processing was paid out per kilogram. It was assumed that fruit classed as waste (Fallout Class) did not contribute to income.

Table 3.1: Pomegranate fruit marketing classification norms

Quality variable	Division	Marketing class			
		Extra Class	Class 1	Processing	Waste/ fallout
Weight (kg)		≥ 0.18	≥ 0.18	≥ 0.18	< 0.180
Skin colour (colour chart)		1 to 2	3 to 6	7 to 9	Not applicable
Sunburn	Colour	N = none	LB = light brown	LDB = light and dark brown	BL = black
	Degree	N = none	L10 = ≤ 10% surface	M10 = >10% surface	L10 or M10
Cracking		N = none	N = none	INT = up to integument	ARIL = up to arils
Blemishes		N = none	EL10 = 10% surface	EL25 = 25% surface	M25 = > 25% surface
False codling moth		N = none	N = none	N = none	FCM

3.3 RESULTS AND DISCUSSION

3.3.1 Plot selection

POMASA identified 28 farm owners or managers who were potentially interested in participating in the research. The selection of farms was further refined according to basic information supplied to POMASA by consultants and/or farm managers regarding climate, crop, soil, irrigation water source, irrigation system, irrigation scheduling method and crop management. Ten farms were visited and 14 potential orchards with full-bearing Wonderful blocks on sandy or heavier soil were considered. The nine orchards selected for the purpose of this survey are located on six farms: three farms (five orchards) in the Berg WMA and three in the Breede WMA (four orchards) (figures 3.1 and 3.2). Three orchards are in the Bonnievale production area, two in Gouda, one in Wolseley and three in Wellington (Table 3.1; Figure 3.1). Producer soil and water analysis records were used at first to assess the suitability of the sites for the experiment. Orchards on sandy soil outnumbered those on heavier soils. However, sandy orchards included different irrigation management scenarios (Table 3.2). One orchard that was irrigated with poor quality water (data not shown) has been included to record its effects on tree performance.

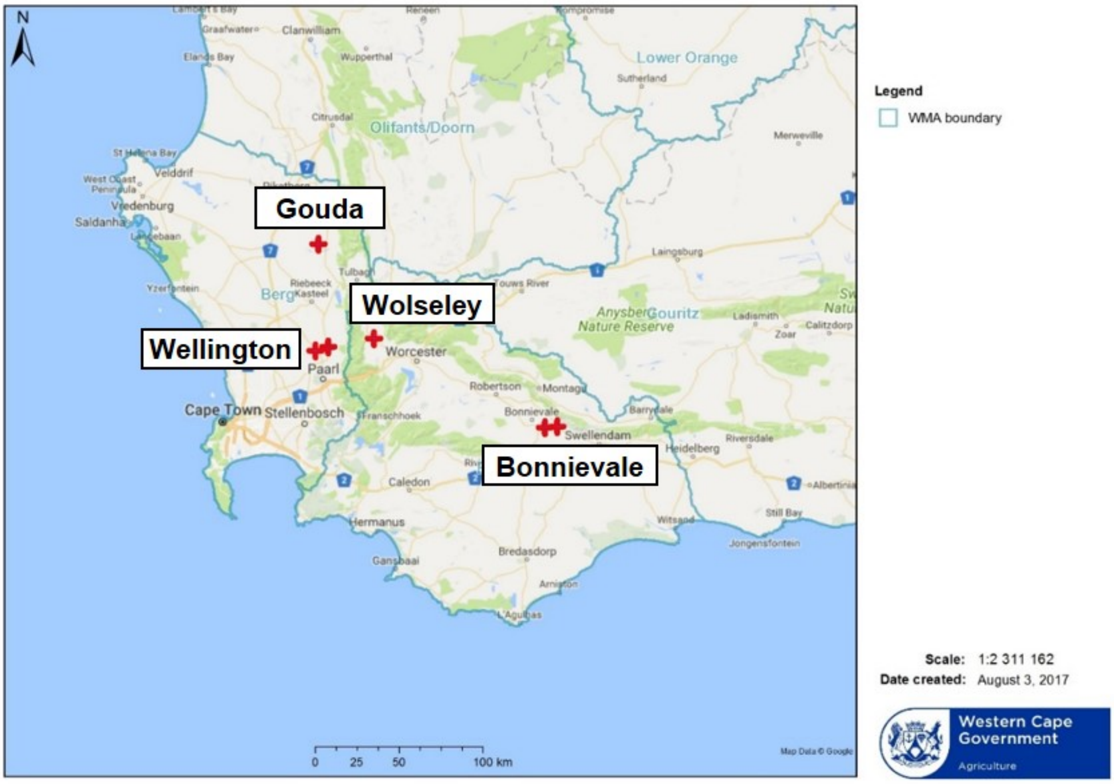

Figure 3.1: The location of farms selected for a survey on irrigation and pomegranate tree performance in four production areas in the Western Cape

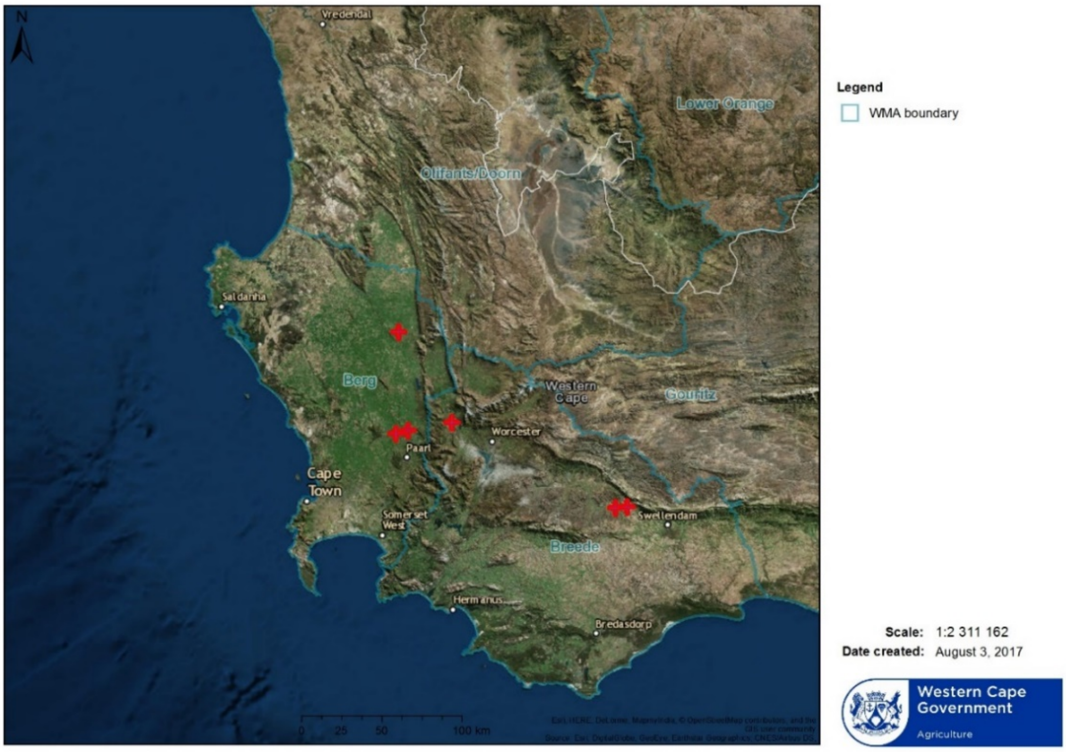

Figure 3.2: The location of farms selected for a survey on irrigation and pomegranate tree performance within the boundaries of the Berg and the Breede WMAs in the Western Cape

3.3.2 Orchard characteristics

Orchard characteristics and an indication of tree size are summarised in tables 3.2 and 3.3. Orchards included three with single, and six with multi-trunk trees (Table 3.3). The single tree's perimeter varied between 24 and 73 cm, and the multi-trunk tree varied between 49 and 86 cm. Tree height ranged from 2.1 to 3.5 m. The percentage orchard area covered by the trees (estimated as solid area per full surface area) ranged between 32 and 72%. The solid area estimate of trees was based on mid-canopy diameter measurements at the linear fruit growth stage.

3.3.3 Water and soil resources

3.3.3.1 Irrigation water quality

An irrigation water quality decision support system (Du Plessis et al., 2017) and chemical analysis data of irrigation water and soils sampled in August 2017 were used to determine the fitness of water for use. This was done by assessing the potential effect of the water quality on root zone salinity (Table 3.4), soil infiltrability (Table 3.5), hydraulic conductivity (Table 3.6), relative crop yield of sensitive crops (Table 3.7) and irrigation equipment (Table 3.8). As a first approach, the assessment is conservative and is done for soils sensitive to a reduction in infiltration rate and hydraulic conductivity. The estimated impact may be less on sandy soils, which are considered to be relatively tolerant to physical deterioration due to SAR and electrical conductivity interactions.

Effects on soil quality

According to the predicted equilibrium root zone salinity, water quality for all orchards was ideal for irrigation with mostly negligible effects of salinity on crop yield expected (Table 3.4). The exception was the borehole at Wellington, the water quality of which was in the tolerable range that can potentially salinise the root zone to levels that restrict the yield of many crops. The infiltration of water into soil depends on the interaction between the EC_{iw} (Table 3.4) and SAR of the top soil (Table 3.5), among other factors. The degree of reduced surface infiltrability for the different orchards ranged between none and moderate.

Hydraulic conductivity refers to the movement of water through the bulk soil. The SAR in the soil water was, in most cases, less than 3 and associated with low soil water salinity of between 20 and 40 mS m^{-1} (Table 3.4), which may result in moderately reduced hydraulic conductivity in sensitive soils (Table 3.6). In cases where SAR was less than 3 and salinity less than 20 mS m^{-1}, the hydraulic conductivity could decrease severely. In Wellington, in the single-line drip-irrigated orchard, soil water SAR values of more than 12 and EC_e values of less than 50 may result in severe reduction in hydraulic conductivity in the top soil, but deeper in the soil, where the soil water salinity was c. 150 mS m^{-1}, hydraulic conductivity may decrease only moderately. In the 300-600 mm soil layer of the ridged double-line drip-irrigated orchard, an SAR of c. 12, in combination with an EC_e of c. 94 mS m^{-1}, may also reduce hydraulic conductivity moderately.

Effects on yield

Crop growth is affected by salinity, which reduces the ability of crops to absorb water from the soil, as well as the accumulation of potentially toxic ions, namely, sodium, chloride and boron in the root zone. The potential effects of the salinity and ion concentrations of the irrigation water on the relative crop yield of a sensitive crop are summarised in Table 3.7. For the micro-sprinkler-irrigated orchards in Bonnievale, a relative yield decrease of c. 18, 36, 8 and 1% is predicted due to the salinity and high levels of sodium, chloride and boron, respectively. In the double-line drip-irrigated orchards in Wellington, relative yield could decrease by 10 and 19% due to the salinity and sodium content of the irrigation water. The effect of the high salinity, sodium and chloride in irrigation water used in the single-line drip-irrigated orchard in Wellington on the relative yield of a sensitive crop is extreme. However, since pomegranate is considered to be moderately sensitive to moderately tolerant to salinity (Allen et al., 1998; Bhantana and Lazarovitch, 2010), relative yield should be less affected.

Table 3.2: Details of orchards selected for the irrigation and pomegranate tree performance survey

Production area	Year planted	Orchard spacing	Open/ netted	Level/ ridged	Ridge height (m)	Soil type*	Irrigation system	Micro-sprinkler/ emitter spacing (m)	Double line drip – emitter position
Bonnievale	2006	4 m x 6 m	Open	Ridged	c. 0.3 m	Clay	Micro-sprinklers	2	N/A
	2007	4 m x 6 m	Open	Ridged	c. 0.3 m	Loam	Micro-sprinklers	2	N/A
	2011	2 m x 5 m	Open	Ridged	c. 0.23 m** c. 0.43 m***	Clay	Double-line drip-irrigation	0.6	Staggered
Gouda/Porterville	2008	2.5 m x 5 m	Open	Level	N/A	Sand	Double-line drip-irrigation	0.75	Even
	2008	2.5 m x 5 m	Netted	Level	N/A	Sand	Double-line drip-irrigation	0.75 and 0.5	Staggered
Wolseley/ Worcester	2009	2.4 m x 4.5 m	Netted	Level	N/A	Sandy loam on clay loam	Single-line drip-irrigation	0.6	N/A
Wellington	2012	3.5 m x 5 m	Open	Ridged	Ripped	Sand on clay	Single-line drip-irrigation	0.6	N/A
	2010	2 m x 4.5 m	Open	Level	N/A	Sand	Double-line drip-irrigation	0.75	Staggered
	2008	2 m x 4.5 m	Open	Ridged	c. 0.62 m	Sand	Double-line drip-irrigation	0.75	Even

* According to producer records/experience

** Upslope

*** Downslope

Table 3.3: Orchard characteristics in the Bonnievale, Gouda, Wolseley and Wellington production areas. The soil texture class, irrigation system, year of planting, planting density, trunk nature and mean (± standard deviation) trunk base perimeter, tree height and estimated solid area per full surface area at linear fruit growth stage are indicated. Soil texture classes include clay (Cl), loam (Lm) and sand (Sa). Irrigation systems include micro-sprinkler (MS) or single-line (1LD) or double-line drip-irrigation (2LD). The presence of a ridge (R), ripped ridge (RR) or net are also indicated.

Production area	Soil texture class	Irrigation	Year planted	Planting density (trees/ha)	Trunk nature	Base[1] (cm)	Height (m)		Estimated solid area per full surface area (%)	
							2018	2019	2018	2019
Bonnievale	SaClLm	MS R	2006	416	Single	73 ± 16	3.2 ± 0.7	3.2 ± 0.3	63.0 ± 6.9	59.2 ± 3.4
	LmSa/SaLm	MS R	2007	416	Single	58 ± 7	3.1 ± 0.4	3.2 ± 0.4	42.5 ± 4.9	49.2 ± 4.2
	SaLm	2LD R	2011	1 000	Multi	49 ± 7	2.9 ± 0.4	3.0 ± 0.1	32.1 ± 3.4	51.9 ± 3.3
Gouda	Sa	2LD + net	2008	800	Multi	58 ± 10	3.1 ± 0.3	3.4 ± 0.1	58.9 ± 8	54.3 ± 6.7
	Sa	2LD	2008	800	Multi	54 ± 4	2.6 ± 0.2	3.0 ± 0.1	46.9 ± 6.7	53.0 ± 5.8
Wolseley	Sa	1LD + net	2009	571	Multi	86 ± 17	2.9 ± 0.5	3.5 ± 0.2	58.4 ± 5.4	62.7 ± 2.6
Wellington	SaLm/SaClLm/Cl	1LD RR	2012	571	Multi	60 ± 12	2.3 ± 0.2	2.1 ± 0.2	45.3 ± 4.3	32.0 ± 3.4
	LmSa	2LD	2010	1 111	Single	24 ± 2	2.4 ± 0.1	2.5 ± 0.2	47.1 ± 4.7	46.1 ± 5.6
	LmSa	2LD R	2008	1 111	Multi	63 ± 10	3.3 ± 0.2	2.6 ± 0.2	72.2 ± 3.2	66.3 ± 8.6

[1] Trunk base perimeter measured at the beginning of October 2017.

Table 3.4: Irrigation water salinity (EC_{iw}), predicted equilibrium root zone salinity and fitness for use of irrigation water available in the different pomegranate production areas

Production area	Irrigation water source	Irrigation system	EC_{iw} (mS m^{-1})	Predicted equilibrium root zone salinity (mS m^{-1})	Fitness for use	Root zone salinity range (mS m^{-1})
Bonnievale	Canal	Micro-sprinkler	71	133	Ideal	0-200
	Borehole	Double-line drip-irrigation	15	28	Ideal	0-200
Gouda	Borehole	Double-line drip-irrigation	46	9	Ideal	0-200
Wolseley	River	Single-line drip-irrigation	5	9	Ideal	0-200
Wellington	Borehole	Single-line drip-irrigation	224	421	Tolerable	400-800
	River/dam	Double-line drip-irrigation	58	109	Ideal	0-200

Table 3.5: Sodium adsorption ratio (SAR) of the top 300 mm of soil and potential degree of reduced surface infiltrability to irrigation water in the different pomegranate production areas. Soil texture classes include clay (Cl), loam (Lm) and sand (Sa).

Production area	Irrigation system	Soil texture	Surface SAR (mmol $\ell^{-1})^{0.5}$	Degree of reduced surface infiltrability
Bonnievale	Micro-sprinkler	SaClLm	1.7	None
	Micro-sprinkler	LmSa/SaLm	1.9	None
	Double-line drip-irrigation	SaLm R	5.9	Severe
Gouda	Double-line drip-irrigation	Sa + net	1.9	None
	Double-line drip	Sa	3.5	Moderate
Wolseley	Single-line drip-irrigation	Sa + net	0.3	Slight
Wellington	Single-line drip-irrigation	SaLm/SaClLm/Cl	19.2	Slight
	Double-line drip-irrigation	LmSa	3.7	Moderate
	Double-line drip-irrigation	LmSa	5.4	Moderate

Table 3.6: Sodium adsorption ratio (SAR), electrical conductivity of the soil water (EC_e) and the estimated degree of reduced hydraulic conductivity in the 0-300 mm and 300-600 mm soil layers in different pomegranate production areas. Soil texture classes include clay (Cl), loam (Lm) and sand (Sa). [1LD = single-line drip-irrigation; 2LD = double-line drip-irrigation].

Production area	Irrigation system	Soil texture	Depth increment (mm)	SAR of soil layer (mmol $\ell^{-1})^{0.5}$	EC_e (mS m^{-1})	Degree of reduced hydraulic conductivity
Bonnievale	Micro-sprinkler	SaClLm R	0-300	1.7	21.4	Moderate
			300-600	2.0	23.5	Moderate
	Micro-sprinkler	LmSa/SaLm R	0-300	1.9	33.0	Moderate
			300-600	2.2	33.6	Moderate
	2LD	SaLm R	0-300	5.9	57.6	Moderate
			300-600	8.3	52.1	Moderate
Gouda	2LD	Sa + net	0-300	1.9	23.2	Moderate
			300-600	1.2	19.7	Severe
	2LD	Sa	0-300	3.5	36.8	Moderate
			300-600	3.2	10.1	Severe
Wolseley	1LD	Sa + net	0-300	0.3	12.0	Severe
			300-600	0.4	9.7	Severe
Wellington	1LD	SaLm/SaClLm/Cl RR	0-300	19.2	26.3	Severe
			300-600	33.8	153.4	Moderate
	2LD	LmSa	0-300	3.7	26.0	Severe
			300-600	2.8	10.2	Severe
	2LD	LmSa R	0-300	5.4	114.9	Slight
			300-600	11.8	93.7	Moderate

Table 3.7: Predicted effect of irrigation water salinity (EC_{iw}), boron (B), chloride (Cl) and sodium (Na) content on relative crop yield of salt-sensitive crops. [MS = micro-sprinkler; 1LD = single-line drip-irrigation; 2LD double-line drip-irrigation].

Production area	Irrigation system	EC_{iw} (mS m^{-1})	Na mg/l	Cl mg/l	B mg/l	Predicted relative crop yield (%) as affected by			
						Salinity	Na	Cl	B
Bonnievale	MS	71	91.0	197.4	0.16	82	64	92	99
	2LD	15	14.4	35.6	< 0.08	100	100	100	100
Gouda	2LD	46	41.1	133.3	< 0.08	100	100	100	100
Wolseley	1LD	5	4.4	19.2	0.14	100	100	100	100
Wellington	1LD	224	420.9	779.7	0.40	0	0	0	90
	2LD	58	61.7	115.5	0.09	90	81	100	100

Effects on equipment

The potential for irrigation water, according the Langelier Index, to result in irrigation equipment corrosion ranged between none (ideal) and unacceptable (Langelier Index < -2) between orchards, whereas no problems with scaling are foreseen (Table 3.8). With regard to emitter clogging, pH appears to be too high at all orchards, while manganese and iron content did not pose a problem or was acceptable (data not shown).

Table 3.8: Irrigation water fitness-for-use classification for potential irrigation equipment corrosion/scaling and clogging of drippers due to pH. [MS = micro-sprinkler; 1LD = single-line drip-irrigation; 2LD = double-line drip-irrigation].

Production area	Irrigation system	Irrigation equipment		Emitter clogging	
		Corrosion	Scaling	pH	
		Fitness	Fitness	Units	Fitness
Bonnievale	MS	Acceptable	Ideal	7.9	Tolerable
	2LD	Tolerable	Ideal	8.6	Unacceptable
Gouda	2LD	Acceptable	Ideal	9.4	Unacceptable
Wolseley	1LD	Unacceptable	Ideal	7.9	Tolerable
Wellington	1LD	Acceptable	Ideal	7.5	Tolerable
	2LD	Ideal	Ideal	9.1	Unacceptable

3.3.3.2 Available soil water

Soil water-holding capacity according to texture

Soil particle size analyses (five fraction) were done for soils sampled at 0-300, 300-600 and 600-900 mm depth increments to determine soil texture. The average clay, silt and sand contents up to 900 mm depth and soil texture classes for the nine orchards are indicated in Figure 3.3, whereas the soil water-holding capacity between -10 and -100 kPa (estimated from soil texture analysis at Bemlab) is displayed in Figure 3.4. The average for the sandy loam soil in Bonnievale is only up to 600 mm depth as deeper sampling was not possible due to a restrictive layer.

Soil classification according to soil texture analysis indicated that the micro-sprinkler-irrigated orchards in the Bonnievale production area had deep, heavier soils with no coarse fraction, i.e. a sandy clay loam and loamy sand to sandy loam soil. The drip-irrigated orchard had sandy loam soil up to only c. 600 mm deep where soil depth was limited by shallow dorbank. The soil contained c. 24% (v/v) and c. 19% (v/v) stone in the 0-300 and 300-600 mm depth increments. The sandy double-line drip-irrigated Gouda soils had a similar particle size, but the coarse fraction in the netted orchard increased in the 0-300, 300-600 and 600-900 mm depth increments, respectively, from c. 8 to c. 26 to c. 35%. In the open orchard, the very stony layer occurred a bit deeper as the coarse fraction increased from c. 6 to c. 9 and c. 31% for the respective layers mentioned above. In Wolseley, the sandy soil in the single-line drip-irrigated orchard contained no stones and had c. 20% less coarse sand and c. 5 and c. 15% more fine and medium sand, respectively, than the Gouda soils. In the Wellington production area, the single-line drip-irrigated orchard had sandy loam soil in the top 0-300 mm, which changed to sandy clay loam and clay in the 300-600 and 600-900 mm depth increments. The soil was considerably stony in the 0-300 mm (c. 27% v/v) and 300-600 mm (c. 37% v/v) depth increments. The double-line drip-irrigated orchards (level and ridged) had loamy sand with similar particle size distribution, c. 4% (v/v) stones in the top 300 mm and up to c. 13% (v/v) stones in the deeper soil layers.

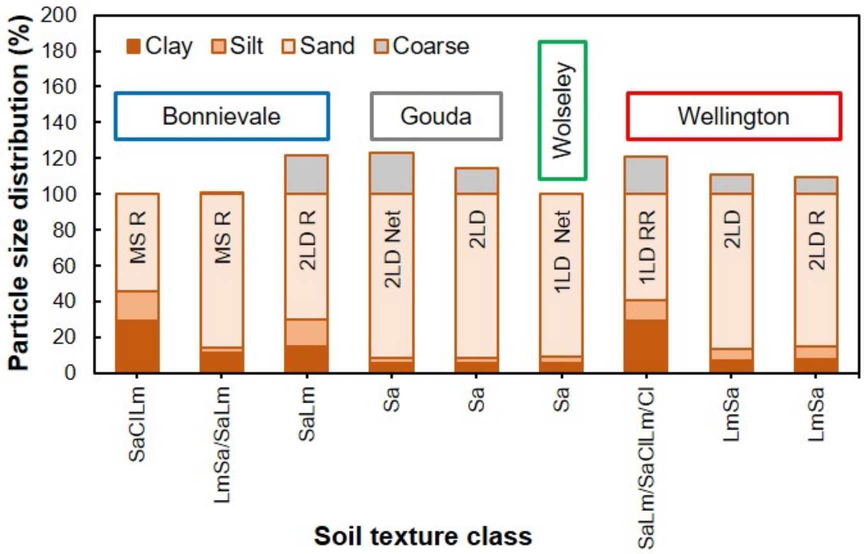

Figure 3.3: Soil particle size distribution of open or netted (net), micro-sprinkler (MS), single-line (1LD) or double-line (2LD) drip-irrigated orchards in the Bonnievale, Gouda, Wolseley and Wellington production areas. Ridged (R) or ripped ridge (RR) is indicated where applicable. The 100% total of the finer fractions are used as a baseline (x-axis) for the coarse fraction percentage (v/v). The soil texture classes include sand (Sa), clay (Cl) and loam (Lm).

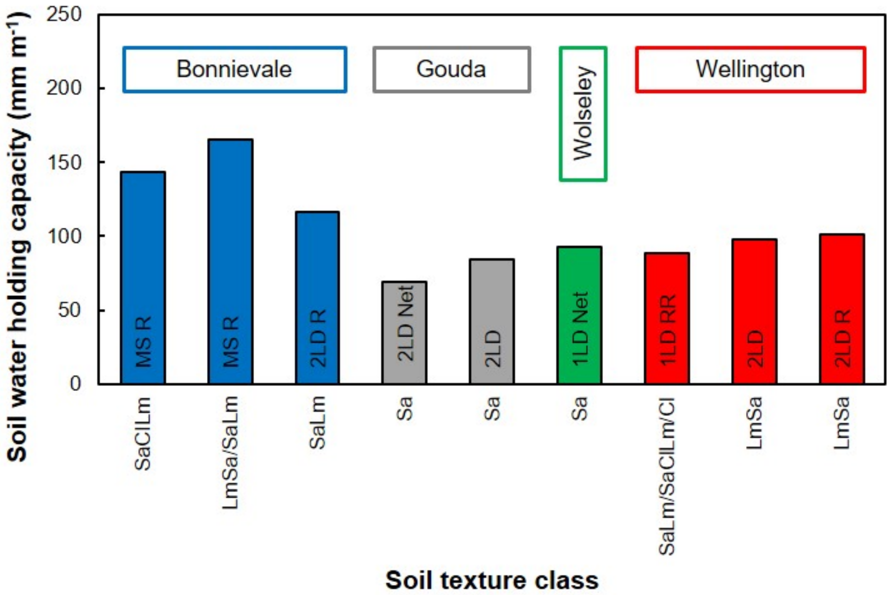

Figure 3.4: The soil water-holding capacity of soils in open or netted (net), micro-sprinkler (MS), single-line (1LD) or double-line (2LD) drip-irrigated orchards in the Bonnievale, Gouda, Wolseley and Wellington production areas. Ridged (R) or ripped ridge (RR) is indicated where applicable. The soil texture classes include sand (Sa), clay (Cl) and loam (Lm).

According to the soil water-holding capacity between -10 and -100 kPa (Figure 3.4), the heavier soils in Bonnievale had the highest soil water-holding capacity, i.e. between 144 and 165 mm m^{-1}, whereas it was slightly lower for the sandy loam with c. 21% stone (117 mm m^{-1}). The soil water-holding capacity of the sandy Gouda soils was the lowest and, on average, c. 50% of that available in the micro-sprinkler-irrigated orchards. The soil water-holding capacity in the netted and open orchards, respectively, was c. 69 mm m^{-1} (profile average stone 23% v/v) and 84 mm m^{-1} (profile average stone c. 15% v/v).

The water-holding capacity of the sandy soil in Wolseley and the sandy loam and loamy sand in the Wellington area were 93, 88 and c. 100 mm m^{-1}, respectively. The soil water-holding capacity of the drip-irrigated soils were, on average, 40% less than that of the micro-irrigated soils. With respect to soil water-holding capacity in production regions, Gouda, Wolseley and Wellington, respectively, had, on average, 46, 34 and 32% less water available between -10 and -100 kPa than the Bonnievale soils.

Root zone distribution

One soil profile pit was made per orchard to determine the extent of the root zone and to determine the placement of soil water-monitoring equipment. The root systems of seven of the nine orchards developed up to a depth of 1.2 m (Figure 3.5). At Bonnievale, the root depth of the double-line drip-irrigated sandy loam orchard was limited to 600 mm by an impermeable layer (Figure 3.5a), and at Wolseley, in the single-line drip-irrigated netted sandy orchard, by a clay layer at 1 m depth (Figure 3.5b). The root density to a depth of 600 mm was, on average, c. 45% lower in the micro-sprinkler-irrigated orchards compared to that in the drip-irrigated orchards. The highest root density in the top 600 mm of soil was found in the ridged loamy sand orchard in Wellington (429 roots m^{-2}) and the lowest in the single-line drip-irrigated ripped ridge sandy loam/sandy clay/loam on clay orchard in Wellington (125 roots m^{-2}). At Gouda, in the double-line drip-irrigated sandy soils, roots were prevalent deeper in the soil (Figure 3.5b) despite stone content exceeding 30% at the 600-900 mm depth increment. Root distribution perpendicular to the tree row (Figure 3.6) indicated that, for drip-irrigated orchards, most roots were concentrated in a c. 1 m radius from the tree, whereas for micro-irrigated orchards, roots were distributed in the whole area allotted to the tree.

3.3.4 Evaporative demand of production areas

Weather stations representative of the orchards in the different pomegranate production areas were selected (Table 3.9) to compare various climate variables (e.g. radiation, temperature, relative humidity and wind speed; data not shown), the evaporative demand and rainfall (Figure 3.7).

Table 3.9: Weather stations representative of orchards in the Bonnievale, Gouda, Wolseley and Wellington production areas. Orchards are identified by their irrigation systems and soil texture classifications. [MS = micro-sprinkler; 1LD = single-line drip-irrigation; 2LD = double-line drip-irrigation; Sa = sand; Cl = clay; Lm = loam; R = ridged; RR = ripped ridge].

Production area	Orchard	Station name	Latitude	Longitude	Altitude
Bonnievale	MS SaClLm R	Merwespont	-33.9729	20.1552	117
	MS LmSa/SaLm R	Merwespont	-33.9729	20.1552	117
	2LD SaLm R	Boesmanspad	-33.9222	20.20251	191
Gouda/Porterville	2LD Sa + net	Porterville: De Hoek	-33.1552	19.03216	126
	2LD Sa	Porterville: De Hoek	-33.1552	19.03216	126
Wolseley/Worcester	1LD Sa + net	La Plaisant	-33.4527	19.2154	283
Wellington	1LD SaLm/SaClLm/Cl RR	Diemerskraal	-33.568	18.90825	113
	2LD LmSa	Landau	-33.5778	18.96795	126
	2LD LmSa R	Landau	-33.5778	18.96795	126

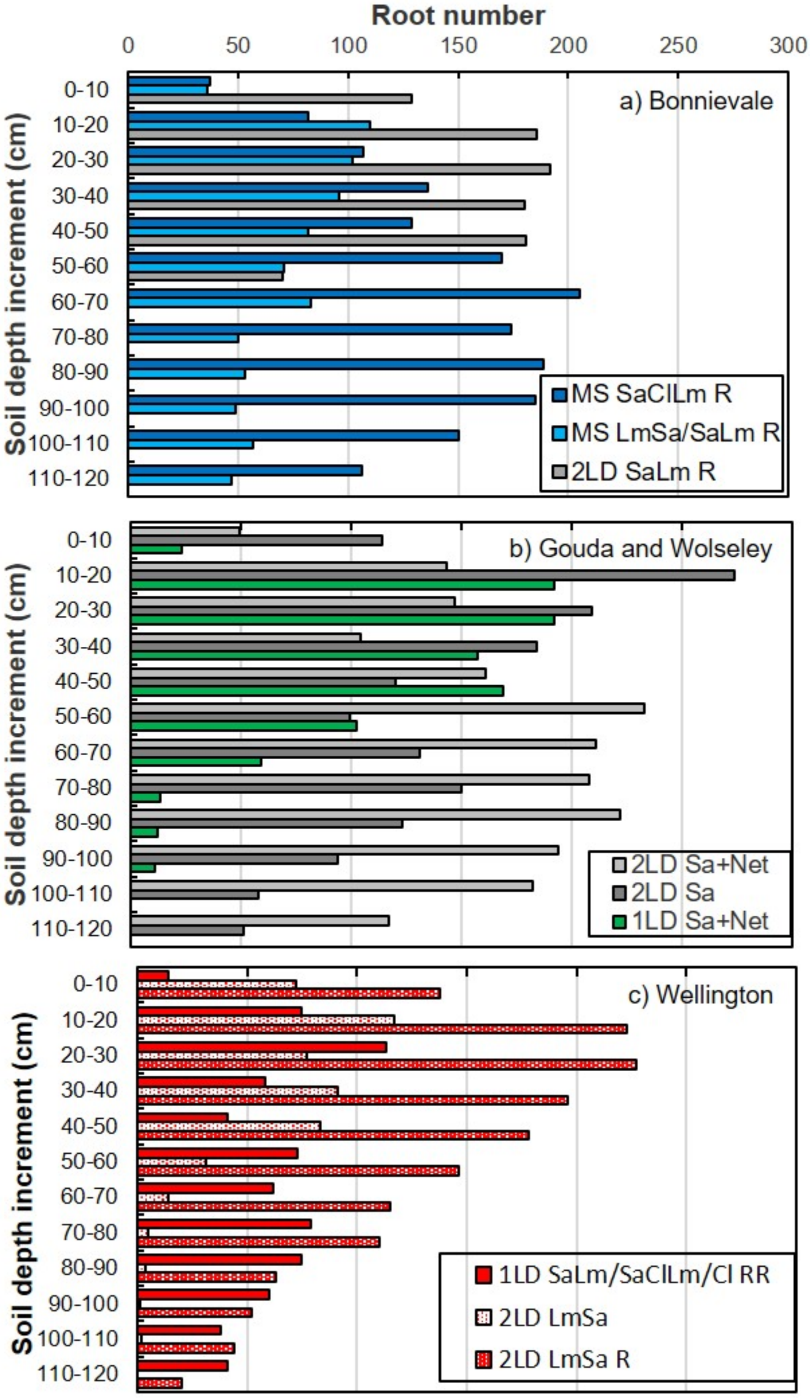

Figure 3.5: **Vertical root profile distribution of full-bearing Wonderful pomegranate orchards in the Bonnievale (a), Gouda and Wolseley (green bars) (b) and Wellington (c) production areas during the 2017/18 season. [MS = micro-sprinkler; 1LD = single-line drip-irrigation; 2LD = double-line drip-irrigation; R = ridged; RR = ripped ridge]. The soil texture classes include sand (Sa), clay (Cl) and loam (Lm).**

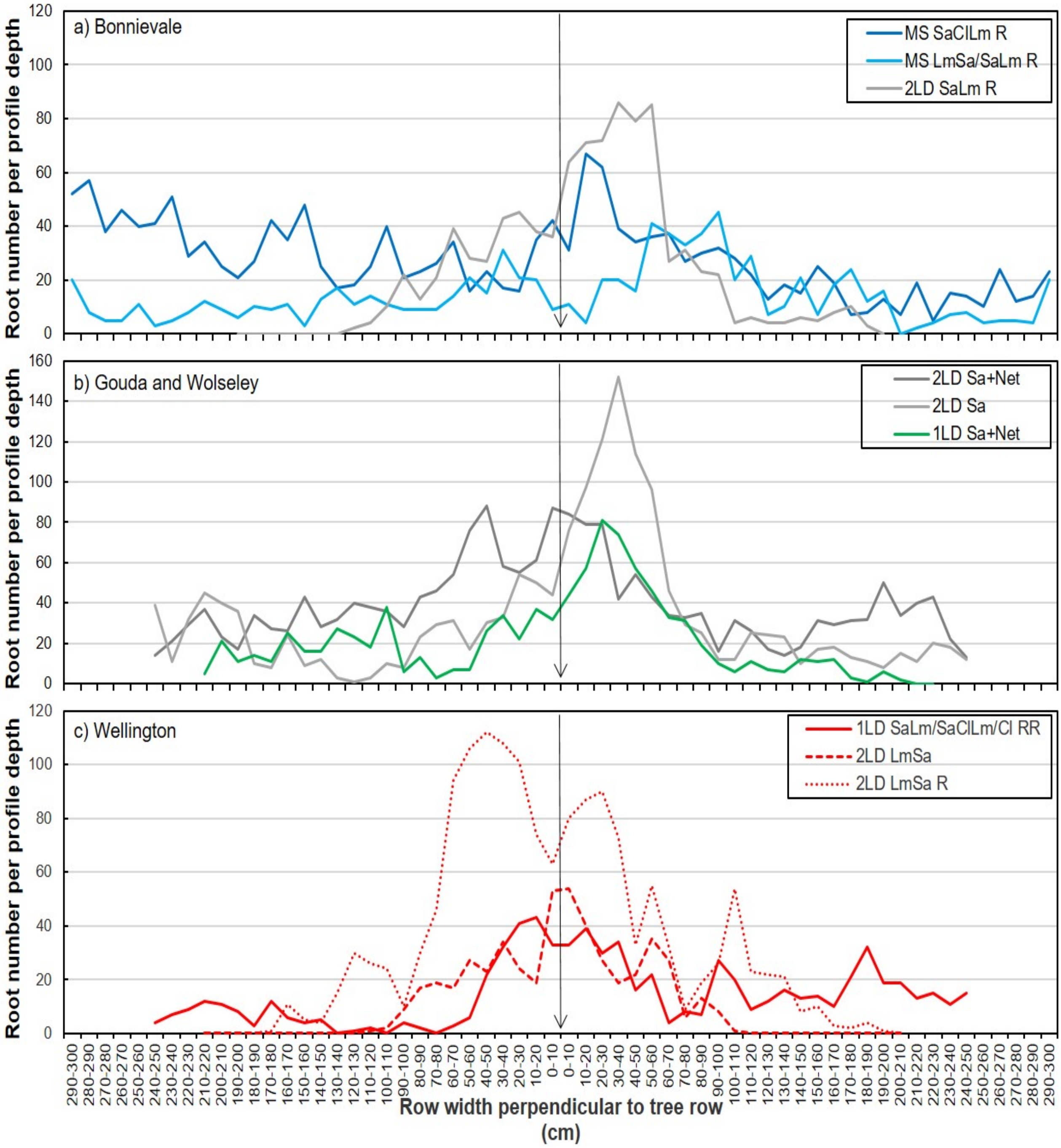

Figure 3.6: Root distribution perpendicular to the tree row of full-bearing pomegranate (Wonderful) orchards in the Bonnievale (a), Gouda and Wolseley (green line) (b) and Wellington (c) production areas during the 2017/18 season. The tree row is indicated by the arrow. [MS = micro-sprinkler; 1LD = single-line drip-irrigation; 2LD = double-line drip-irrigation; R = ridged; RR = ripped ridge]. The soil texture classes include sand (Sa), clay (Cl) and loam (Lm).

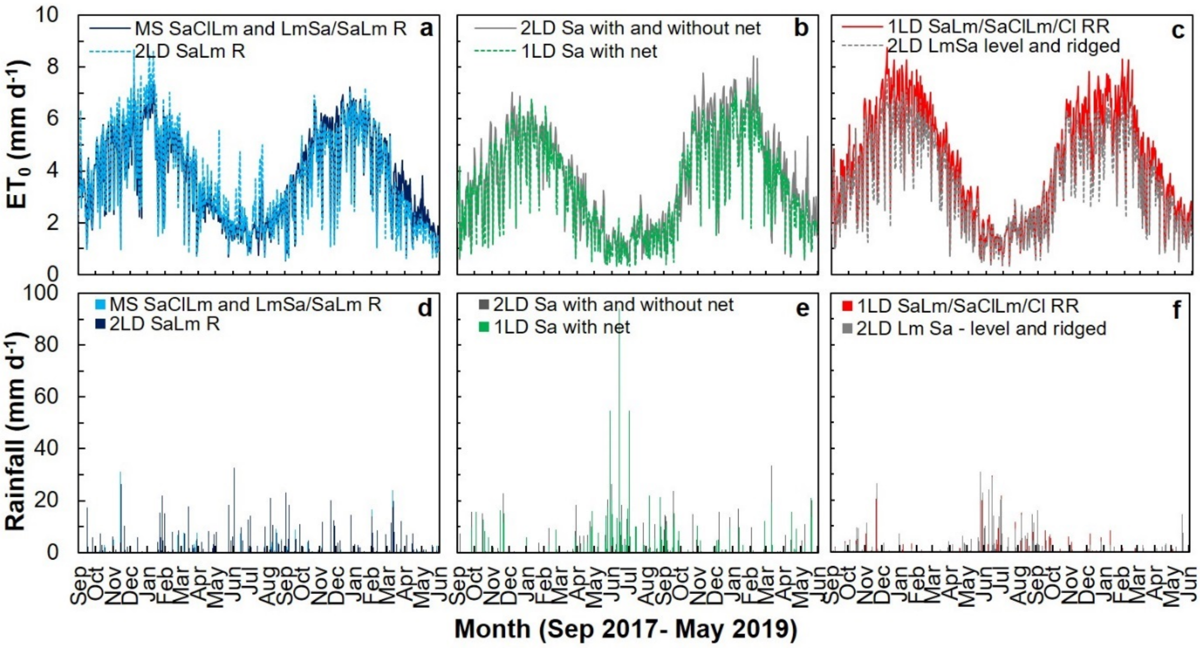

Figure 3.7: Daily Penman-Monteith reference evapotranspiration (ET_o, a, b, c) and rainfall (d, e, f) from September 2017 to May 2019 for pomegranate (Wonderful) orchards in the Bonnievale (a and d), Gouda (grey) and Wolseley (green) (b and e) and Wellington (c and f) production areas. Orchards are identified by their irrigation system and soil texture classifications. [MS = micro-sprinkler; 1LD = single-line drip-irrigation; 2LD = double-line drip-irrigation; R = ridged; RR = ripped ridge]. The soil texture classes include sand (Sa), clay (Cl) and loam (Lm).

The water use of orchards is driven by the evaporative demand of the atmosphere, which can be quantified by the Penman-Monteith reference evapotranspiration or ET_o (Allen et al., 1998). In general, the daily ET_o increased from August until January, after which it started to decline gradually in all production regions towards June (Figure 3.7a to Figure 3.7c). During the two seasons, the monthly averaged ET_o peaked in December and/or January and ranged between c. 5.4 and c. 5.7 mm d^{-1} for the micro-sprinkler-irrigated orchards in Bonnievale, and between c. 5.6 and c. 6 mm d^{-1} for the drip-irrigated orchard (Figure 3.7a). In Wellington, the monthly averaged ET_o for these months reached values of between 6.5 and 6.8 mm d^{-1} for the single-line drip-irrigated orchard, with lower values of 5.5 to 5.7 mm d^{-1} recorded for the double-line drip-irrigated orchards (Figure 3.7c).

In Gouda, the monthly averaged ET_o ranged between 5.3 and 6.2 mm d^{-1}, with that in Wolseley reaching c. 5.9 and 6.1 mm d^{-1} (Figure 3.7b). In all production areas, rainfall events during the period September to May was – with a few exceptions – less than 25 mm d^{-1}. Although all orchards received limited rainfall during December 2017 (Figure 3.7d to Figure 3.7f), this trend extended until February 2018 for Gouda and Wolseley (Figure 3.7e) and until May 2018 in both seasons for Wellington (Figure 3.7f). The average daily ET_o per growth stage was the highest during linear fruit growth and ripening (Figure 3.8). In 2017/18, the average ET_o tended to remain higher in the Wellington orchards during ripening compared to the other production areas, whereas in 2018/19, the ET_o decreased for all orchards relative to the linear fruit growth stage. However, during the second season, the ET_o in the Gouda and Wolseley orchards was higher during ripening compared to the Bonnievale orchards, and higher than or comparable to that of Wellington towards the end of the season. Both the Gouda and Wolseley production areas had higher ET_o rates during 2018/19 compared to 2017/18. The total ET_o for the period from September to May is indicated for 2017/18 and 2018/19 in Figure 3.9.

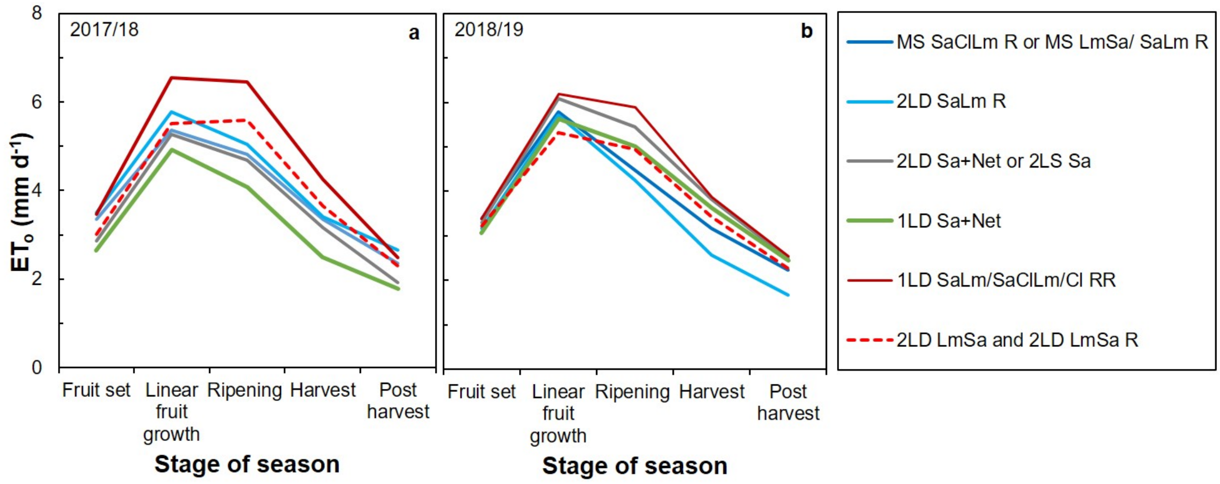

Figure 3.8: Average daily Penman-Monteith reference evapotranspiration (ET_o) for the fruit set, linear fruit growth, ripening, harvest and post-harvest stages for pomegranate (Wonderful) orchards during the 2017/18 and 2018/19 growing seasons in the Bonnievale (blue), Gouda (grey), Wolseley (green) and Wellington (red) production areas. Orchards are identified by their irrigation systems and soil texture classifications. [MS = micro-sprinkler; 1LD = single-line drip-irrigation; 2LD = double-line drip-irrigation; R = ridged; RR = ripped ridge]. The soil texture classes include sand (Sa), clay (Cl) and loam (Lm).

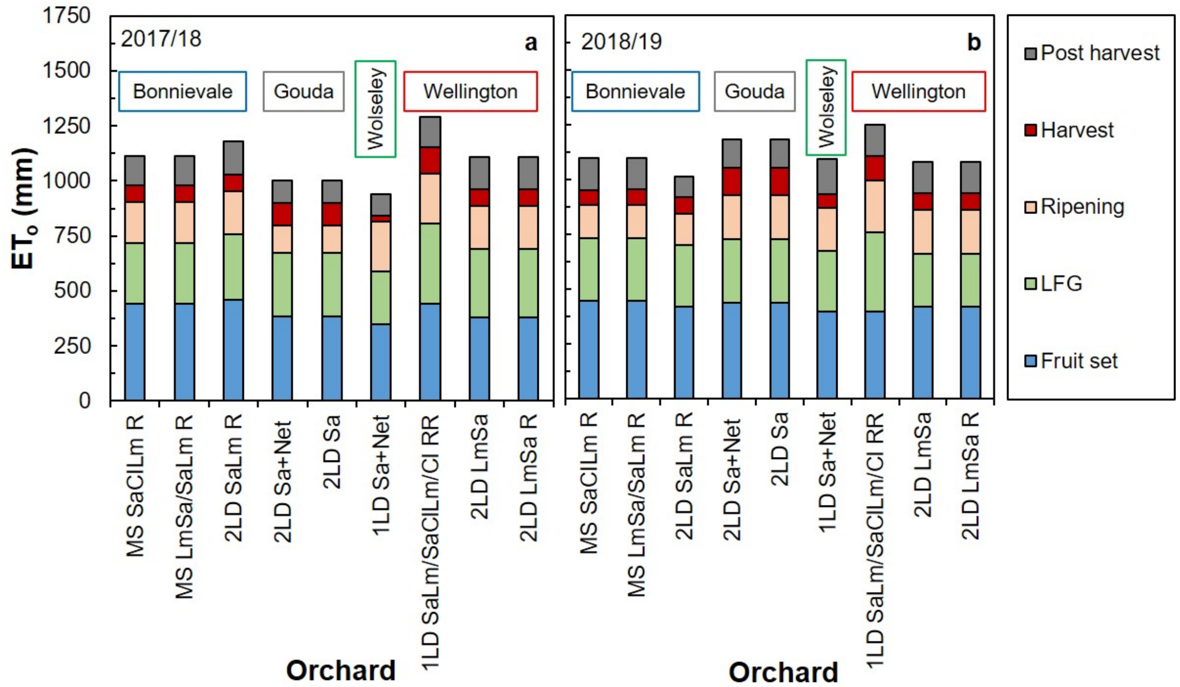

Figure 3.9: Total Penman-Monteith reference evapotranspiration (ET_o) for the fruit set, linear fruit growth, ripening, harvest and post-harvest stages for pomegranate (Wonderful) orchards during the 2017/18 and 2018/19 growing seasons in the Bonnievale, Gouda, Wolseley and Wellington production areas. Orchards are identified by their irrigation systems and soil texture classifications. [MS = micro-sprinkler; 1LD = single-line drip-irrigation; 2LD = double-line drip-irrigation; R = ridged; RR = ripped ridge]. The soil texture classes include sand (Sa), clay (Cl) and loam (Lm).

In 2017/18, the total ET_o for the period September to May was, on average, c. 1,168, 1,092, 1,003 and 942 mm (Figure 3.9a) for Wellington, Bonnievale, Gouda and Wolseley, respectively. The evaporative demand in the Bonnievale, Gouda and Wolseley areas was therefore c. 7, c. 14 and c. 19% less compared to Wellington.

In 2018/19, though, differences in total ET_o between production regions diminished, with that for Bonnievale (1,070 mm) and Wolseley (1,095 mm) being 6 and 4% less, and that for Gouda (1,184 mm) becoming c. 4% more than for Wellington (1,137 mm) (Figure 3.9b). The total ET_o from 1 September to 31 May in 2018/19 compared to 2017/18 decreased by 3 and 2% for Wellington and Bonnievale, whereas it increased by 18 and 16% for Gouda and Wolseley respectively.

Evaporative demand was relatively similar for the different growth stages during the two seasons, being, on average, 416, 288, 186, 84 and 134 mm for the production regions over the seasons from the beginning of September until fruit set, from fruit set until linear fruit growth, from linear fruit growth to ripening, from ripening to harvest, and from post-harvest until the end of May, respectively (Figure 3.9). The evaporative demand for these respective stages relative to the seasonal total ET_o (1,106 mm) was likewise comparable between seasons and, on average, 38, 26, 17, 8 and 12% of the total ET_o (Figure 3.10). The evaporative demand for the 2017/18 growing season was 86% of the annual ET_o from 1 September 2017 until the end of August 2018 for the Bonnievale area, and, on average, 89% for the other production regions.

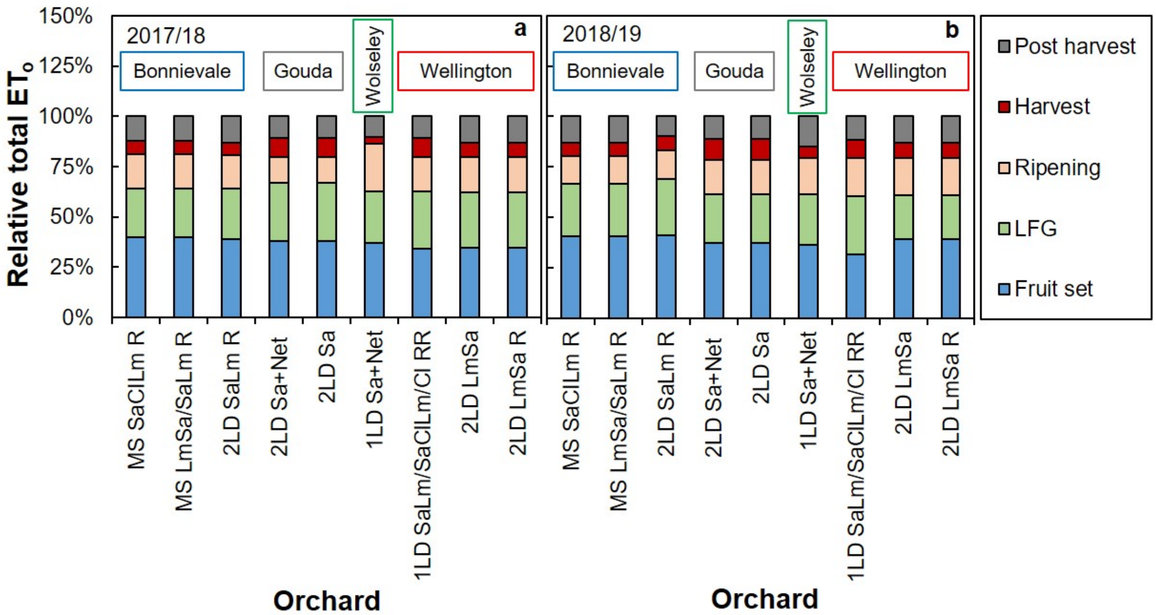

Figure 3.10: Relative total Penman-Monteith reference evapotranspiration (ET_o) for the fruit set, linear fruit growth, ripening, harvest and post-harvest stages for pomegranate (Wonderful) orchards during the 2017/18 and 2018/19 growing seasons in the Bonnievale, Gouda, Wolseley and Wellington production areas. Orchards are identified by their irrigation systems and soil texture classifications. [MS = micro-sprinkler; 1LD = single-line drip-irrigation; 2LD = double-line drip-irrigation; R = ridged; RR = ripped ridge]. The soil texture classes include sand (Sa), clay (Cl) and loam (Lm).

Rainfall, in addition to irrigation, supplies the water requirements of trees. The total amount of rainfall received from 1 September 2017 to the end of May 2018 ranged between 202 mm (micro-sprinkler-irrigated orchards) and 305 mm (double-line drip-irrigated orchard) for Bonnievale, 306 mm for Gouda, 244 mm for Wolseley and 174 mm (single-line drip-irrigated orchards) and 204 mm (double-line drip-irrigated orchards) for Wellington. During winter 2018 (June to August), the respective orchards received 114, 152, 252, 326, 242 and 256 mm rainfall. The total amount of rainfall received from September 2018 to May 2019 ranged between 241 and 327 mm for the micro-sprinkler and drip-irrigated Bonnievale orchards, respectively. Rainfall for the same period amounted to 314 mm for Gouda, 196 mm for Wolseley, and 128 and 107 mm for the single- and double-line drip-irrigated orchards in Wellington.

During the 2018/19 season, the micro-sprinkler and drip-irrigated orchards in Bonnievale received c. 20 and 7% more rainfall, respectively, and the Gouda orchards received c. 3% more, compared to 2017/18. However, the orchard in Wolseley and the single- and double-line orchards in Wellington received c. 20, c. 27 and c. 47% less rainfall, respectively, in the second season compared to the first.

3.3.5 Irrigation management

3.3.5.1 Irrigation water applied

The amount of irrigation water applied to the nine full-bearing Wonderful pomegranate orchards from the first week in September until the end of May ranged between 237 and 834 mm in 2017/18, and between 272 and 867 mm in 2018/19 (Figure 3.11). In both the 2017/18 and 2018/19 seasons, most of the water was applied in Bonnievale (688 and 775 mm), followed by Gouda (426 and 492 mm), Wolseley (385 and 456 mm) and Wellington (243 and 346 mm). On average over the seasons, Gouda, Wolseley and Wellington applied 63, 57 and 40% of that applied in the Bonnievale area. Irrigation applied in the 2018/19 season was 13, 15, 19 and 42% more in the 2018/19 season than in the 2017/18 season for Bonnievale, Gouda, Wolseley and Wellington, respectively. In addition to the irrigation applied during the growing season, some orchards were also irrigated from June to August. In Bonnievale, the micro-sprinkler-irrigated ridged sandy clay loam and loam sand on sandy loam orchards received 29 and 50 mm of irrigation, respectively, whereas 7.6 mm was applied to the double-line drip-irrigated orchard. In Wellington, the single-line drip-irrigated orchard received 2.6 mm irrigation water during this period.

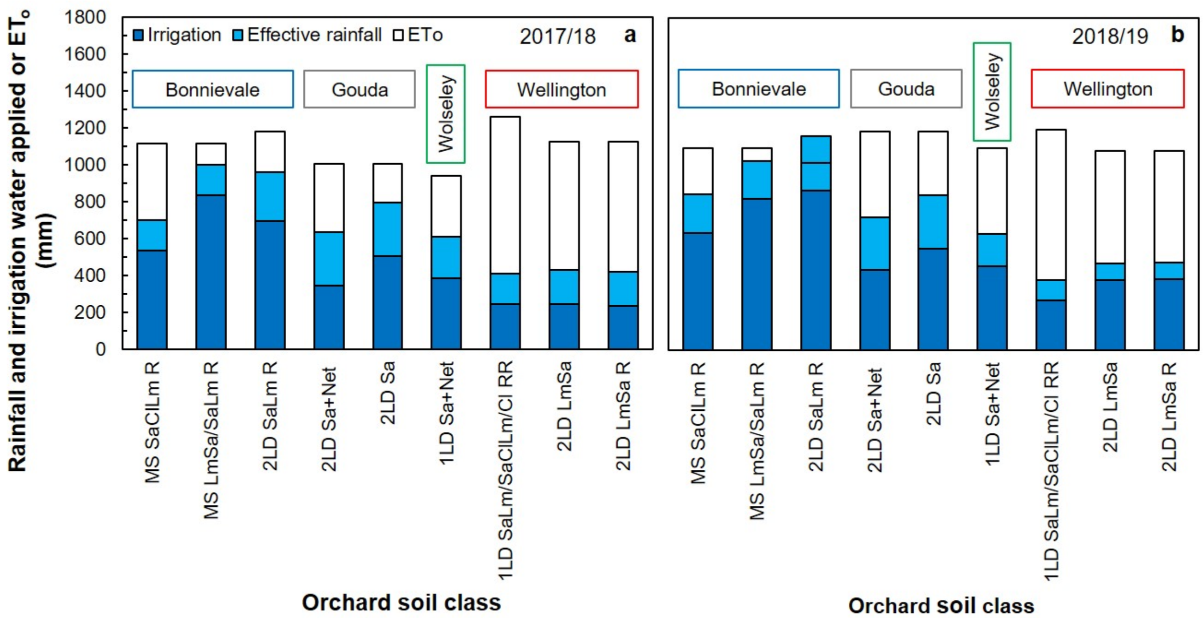

Figure 3.11: Reference evapotranspiration (ET_o), effective rainfall and irrigation water applied to full-bearing Wonderful pomegranate orchards in the Bonnievale, Gouda, Wolseley and Wellington production areas from September until May during the 2017/18 and 2018/19 seasons. [MS = micro-sprinkler; 1LD = single-line drip-irrigation; 2LD = double-line drip-irrigation; R = ridged; RR = ripped ridge]. The soil texture classes include sand (Sa), clay (Cl) and loam (Lm).

On average for soil type, 68 and 47% more water was applied from 1 September to the end of May in the 2017/18 and 2018/19 seasons, respectively, to clay and sandy loam soils compared to the loam-sand and sandy soils. Micro-sprinkler-irrigated orchards received 80 and 53% more water than drip-irrigated orchards in the two respective seasons. In Gouda, the open drip-irrigated orchard received 45 and 27% more water than the netted orchard.

However, the lower amount of irrigation water applied under net cannot be contributed solely to the effects of the net since the emitter spacing differed for the two orchards and the borehole supplying the netted orchard occasionally ran dry in the 2017/18 season. Orchards were irrigated according to producer practice and the amount of water applied does not necessarily accurately reflect the water requirements of these orchards.

3.3.5.2 Effective rainfall

Effective rainfall was obtained by correcting rainfall for estimated evaporation losses (Allen et al., 1998), but not by taking the effect of soil water content into account. Effective rainfall during the 2017/18 and 2018/19 growing seasons, respectively, amounted, on average, to 201 and 236 mm; 289 and 288 mm; 226 and 177 mm; and 173 and 95 mm for Bonnievale, Gouda, Wolseley and Wellington (Figure 3.11). Effective rainfall that occurred from the beginning of September until fruit set, from fruit set until linear fruit growth, from linear fruit growth to ripening, from ripening to harvest, and from post-harvest until the end of May was, on average, 77 and 93 mm; 20 and 18 mm; 8 and 16 mm; 19 and 32 mm; and 92 and 36 mm over the production regions for the 2017/18 and 2018/19 seasons, respectively (Figure 3.12).

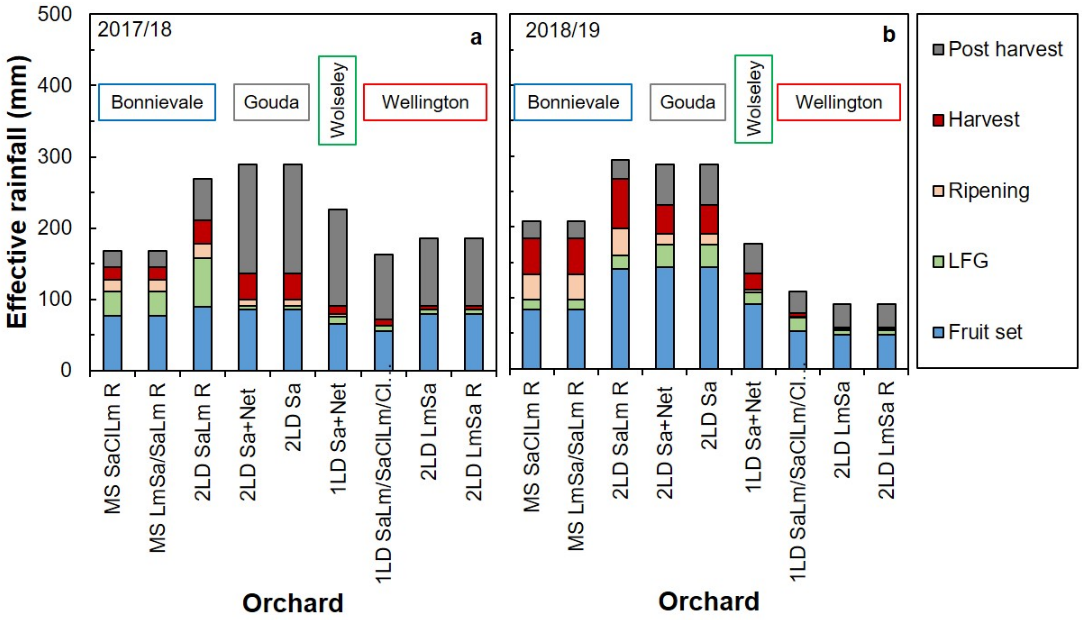

Figure 3.12: Total effective rainfall for the fruit set, linear fruit growth, ripening, harvest and post-harvest stages for pomegranate (Wonderful) orchards during the 2017/18 and 2018/19 growing seasons in the Bonnievale, Gouda, Wolseley and Wellington production areas. Orchards are identified by their irrigation systems and soil texture classifications. [MS = micro-sprinkler; 1LD = single-line drip-irrigation; 2LD = double-line drip-irrigation; R = ridged; RR = ripped ridge]. The soil texture classes include sand (Sa), clay (Cl) and loam (Lm).

Effective rainfall that occurred from the beginning of September until fruit set, from fruit set until linear fruit growth, from linear fruit growth to ripening, from ripening to harvest, and from post-harvest until the end of May was, on average, 37 and 48%; 10 and 9%; 4 and 7%; 8 and 14%; and 41 and 22% of the total rainfall that fell during the growing season over the production regions for the 2017/18 and 2018/19 seasons, respectively, (Figure 3.13). The effective rainfall for the production regions, on average, increased in the second season during fruit set, ripening and harvest, and decreased post-harvest compared to the first season.

The Bonnievale area compared to the other production regions tended to receive a larger portion of the effective rainfall during linear fruit growth until harvest, although the difference between areas became somewhat smaller in the 2018/19 season. In 2017/18 and 2018/19, respectively, 42 and 47%; 18 and 30%; 11 and 24%; and 7 and 16% of the seasonal total effective rainfall occurred during linear fruit growth until harvest for the Bonnievale, Gouda, Wolseley and Wellington production areas.

The risk for the cracking/splitting of fruit for Bonnievale increased in 2018/19 compared to the previous season as 25% of the seasonal effective rainfall occurred during harvest, compared to 11% in the previous season. Effective rainfall post-harvest, in both seasons, was less in the Bonnievale area compared to the other production areas. For Bonnievale, Gouda, Wolseley and Wellington, respectively, effective rainfall during the 2017/18 growing season was 63, 54, 41 and 42% of the annual effective rainfall that occurred from 1 September 2017 until the end of August 2018.

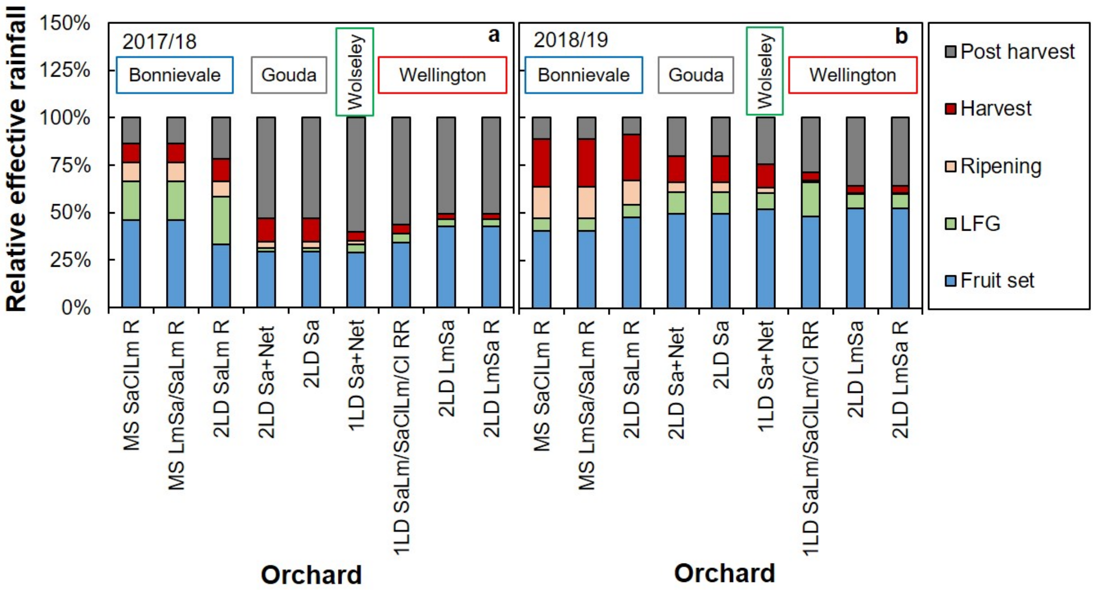

Figure 3.13: Effective rainfall for the fruit set, linear fruit growth, ripening, harvest and post-harvest stages relative to the growing season total for pomegranate (Wonderful) orchards during the 2017/18 and 2018/19 growing seasons in the Bonnievale, Gouda, Wolseley and Wellington production areas. Orchards are identified by their irrigation systems and soil texture classifications. [MS = micro-sprinkler; 1LD = single-line drip-irrigation; 2LD = double-line drip-irrigation; R = ridged; RR = ripped ridge]. The soil texture classes include sand (Sa), clay (Cl) and loam (Lm).

3.3.5.3 Total irrigation and effective rainfall

The total amount of effective rainfall and irrigation water applied from the first week in September until the end of May to the nine full-bearing Wonderful pomegranate orchards ranged between 409 and 1,001 mm in 2017/18, and between 381 mm and 1,161 mm in 2018/19 (Figure 3.11). As in the case for irrigation (refer to section 3.3.5.1), the total of effective rainfall and irrigation in both seasons was the highest in Bonnievale (889 and 1,011 mm), followed by Gouda (715 and 780 mm), Wolseley (611 and 633 mm) and Wellington (421 and 443 mm). On average, over the seasons, the total effective rainfall and irrigation for Gouda, Wolseley and Wellington was 79, 66 and 46% that for the Bonnievale area. The total of effective rainfall and irrigation for Bonnievale, Gouda, Wolseley and Wellington for the 2018/19 season, respectively, was 14, 9, 4 and 5% more than for the 2017/18 season. The total effective rainfall and irrigation for the 2017/18 and 2018/19 seasons, respectively, equalled 78 and 94%; 71 and 66%; 65 and 58%; and 36 and 39% of the seasonal total ET_o for the Bonnievale, Gouda, Wolseley and Wellington production areas, respectively.

The total effective rainfall and irrigation exceeding ET_o at the drip-irrigated orchard in Bonnievale in 2018/19 can partially be attributed to higher rainfall during fruit set and harvest compared to the micro-sprinkler-irrigated orchards and the application of slightly more irrigation. The effectivity of large rainfall events or significant amounts of rainfall occurring on subsequent days may have been over-estimated.

3.3.5.4 Soil water dynamics

Data obtained from soil water content sensors was converted to volumetric soil water content using the factory calibration equation supplied or a calibration equation obtained from previous research for comparable soil types. No temperature corrections have been applied to the data. Graphs in this report reflect general trends in volumetric soil water content.

In Bonnievale, the volumetric soil water content at the micro-irrigated ridged sandy clay-loam orchard indicated the largest fluctuation from October 2017 to May 2018 at the 300 and 600 mm depths (Figure 3.14a). There was also oscillation in soil water content at the 900 and 1,200 mm depths at the beginning of the season, which levelled off at the 900 mm depth from December as it became drier compared to initial soil water content. Soil water content at the 1,200 mm depth had a less steep, but definite downward trend towards the end of the season – pointing to drier subsoil conditions, compared to that in October. Rainfall and/or irrigation replenished soil water content at all depths during winter 2018, and in the 2018/19 season, soil water content fluctuated similarly at all depths until 23 March 2019, after which the soil gradually began to dry at all depths. The soil water content increased a few times more at the 300, 600 and 900 mm depths, but was not refilled at the 1.2 m depth before measurement ended.

The soil water dynamics of the ridged loamy sand on sandy loam soil orchard was similar to that of the sandy clay loam orchard from October 2017 to May 2018 as the most soil water content fluctuation occurred at the 300 and 600 mm depths (Figure 3.14b). It appears as if oscillations were of more or less the same magnitude throughout the season until harvest, which was not always the case in Figure 3.14a. Soil water content at 900 mm depth reflected irrigations or rainfall, but appeared to remain almost constant throughout the season, while that at the 1,200 mm depth fluctuated, but started to dry out from February onwards. Rainfall or irrigation increased the soil water content in the two topsoil layers during winter, but there was a gradual drying trend present at all depths. Data was not available for the 900 mm depth during this time due to equipment problems. There was a large increase in soil water content at the 300 mm depth on 17 October, and at the 600 mm depth on 11 November. Soil water content at the 1,200 mm depth gradually increased from 11 November until 27 February, after which it started to decrease again towards the end of the season.

In the 2017/18 season, the sandy loam double-line drip-irrigated orchard appeared to have fluctuations in soil water content at all levels up to a depth of 800 mm (Figure 3.14c). Root studies indicated that the roots of trees may be restricted by an impermeable layer to about 600 mm (Figure 3.5a) and that the soil contains a large percentage of coarse material (Figure 3.3). It is possible that roots penetrated the soil deeper at the soil water content measurement site where a drill was used to install the soil water measurement probe. Soil water content at all levels increased during February to March, and it levelled off at a maximum at a depth of 800 mm. This may be an indication of over-irrigation during this period. The soil water content at a depth of 800 mm decreased from 8 April until 9 September 2018, after which it reached levels similar to the previous season. The soil water content did not remain that high as frequently, though. There was an overall trend for soil water content at the 100, 200, 400 and 600 mm soil layers to increase from October 2017 until May 2019.

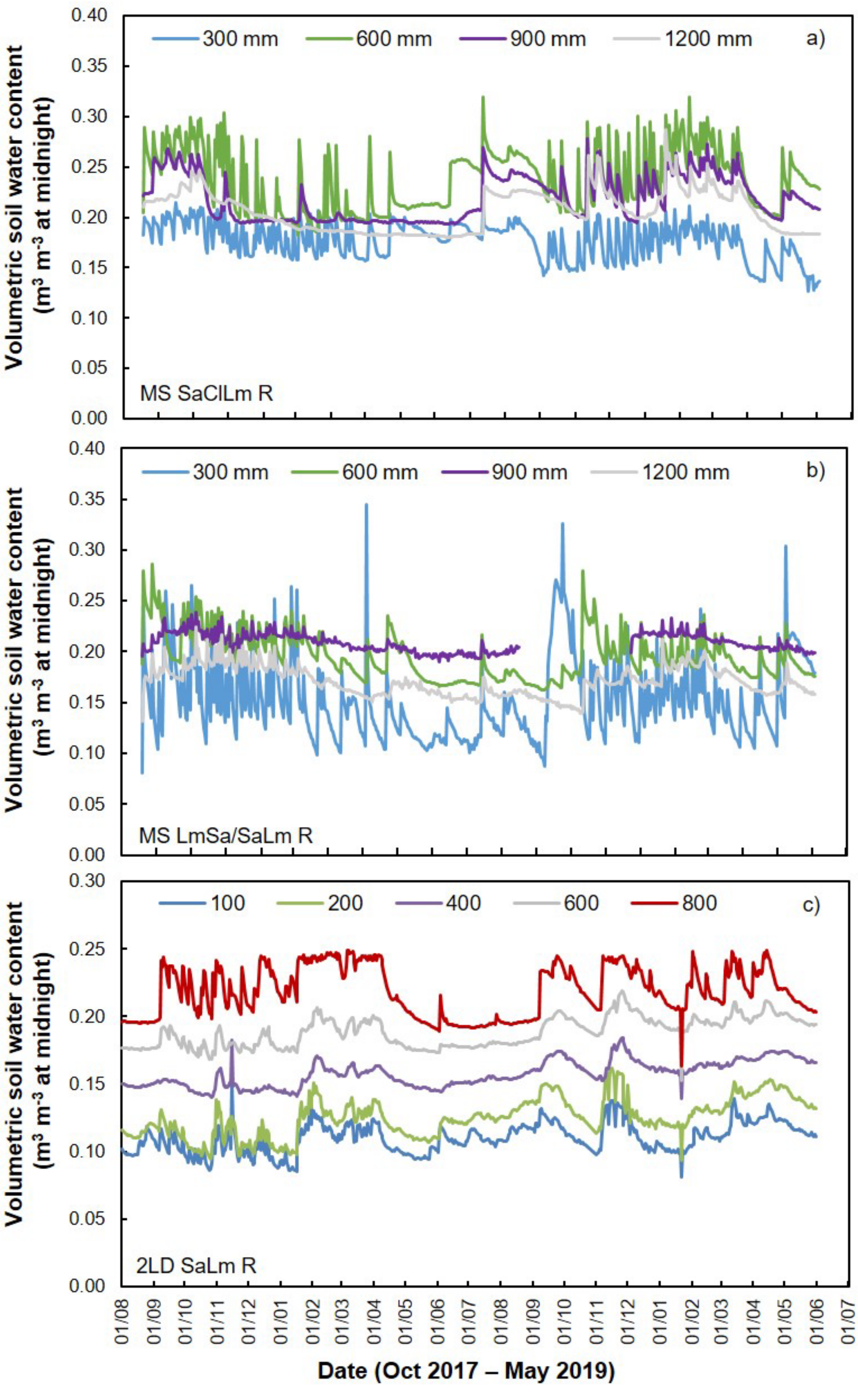

Figure 3.14: Soil water dynamics of the pomegranate (Wonderful) orchards in the Bonnievale production area from October 2017 until May 2019. Soil water status at selected depths are indicated for the micro-sprinkler-irrigated ridged sandy clay loam (a) and loamy sand/sandy loam (b) orchards, as well as for a double-line drip-irrigated ridged sandy loam orchard (c).

In the netted orchard in Gouda, the soil water content of the sandy soil in the root zone at a depth of 300 mm was very low, but fluctuated and reflected irrigation or rain throughout the 2017/18 season (Figure 3.15a).

The soil water content at the bottom of the root zone became very dry and levelled off as early as the end of November 2017. Roots in this orchard proliferated in the deeper gravelly part of the soil profile (Figure 3.5b). The borehole supplying this orchard at times ran dry during the season due to the drought, and the near mid-April soil water content at both the 300 and 1,100 mm depths were levelled off at the low end. During winter in 2018, a water table was present at the 1,100 mm depth, which gradually decreased from about 6 September until 4 October, with a drastic decrease until 15 November 2018 (Figure 3.15a). Soil water content at the 300 mm depth decreased from about 19 September until 5 December, after which it gradually increased towards mid-March. It is possible that, in addition to irrigation, 10.9 mm rainfall on 8 March, combined with a total of 37.5 mm on 19 and 20 March, increased the soil water content up to below the root zone. In the 2017/18 season, the soil water content of the sandy soil in the root zone at 400 and 1,200 mm in the open orchard fluctuated until mid-January, after which the soil water content at the 1,200 mm depth levelled off until near the end of February, and again after 25 March (Figure 3.15b). It appears as if a temporary water table was present up to a depth of 400 mm during winter. Frequent fluctuations of soil water content at the 1,200 mm depth most likely indicate the preferential flow of irrigation water from the sandy topsoil to the gravelly subsoil.

At Wolseley, the volumetric soil water content at a depth of 500 mm in the root zone reflected clear oscillations, becoming drier, in general, before irrigation or rainfall from February 2018 onwards (Figure 3.15c). There was limited movement in soil water content at the 1,000 mm depth below the root zone, except for a period in December 2017 and January 2018 when the soil water was probably replenished by over-irrigation, since no significant rainfall occurred shortly before this increase. During winter, a water table developed up to the 500 mm depth. Fluctuation at the 1,000 mm depth during the 2018/19 season indicated irrigation beyond the root zone from the end of December until 4 March 2019, after which the subsoil gradually dried out towards the end of the season.

In Wellington, in the single-line drip-irrigated sandy loam/sandy clay loam/clay irrigated orchard, the volumetric soil water content at the 300 mm depth was relatively high until the end of November, after which it dropped considerably as irrigation was not being applied due to a broken pump (Figure 3.16a). Hereafter, soil water content was increased gradually by limited rainfall and/or irrigation until it was finally restored to its initial levels by mid-March. The soil water in the clayey layer at the bottom of the root zone (1,200 mm) gradually decreased from November and levelled off at a low by the end of January. The soil water at this level was restored by rainfall in May 2018. After winter 2018, soil water content at the 300 mm depth remained at levels similar to that in the previous season, until the beginning of March when it increased significantly, and remained more or less similar until the end of April, after which it decreased towards the end of the season. Soil water content at a depth of 1,200 mm decreased from about 20 October 2018 until the end of April 2019, after which it gradually increased. The subsoil became less dry in the 2018/19 season compared to 2017/18.

In the level double-line drip-irrigated loamy sand orchard, the volumetric soil water content fluctuated at the 400 mm depth, the depletion level before irrigation remaining more or less similar throughout the season (Figure 3.16b). The soil water content at the 800 mm depth started to decrease gradually from the beginning of November 2017 until it reached its driest point by 9 March 2018. During winter 2018, a water table appeared to develop at the 800 mm depth, which gradually decreased from 9 October towards the end of the season. Soil water dynamics at the 400 mm depth appeared to be similar in 2018/19 compared to that of the previous season.

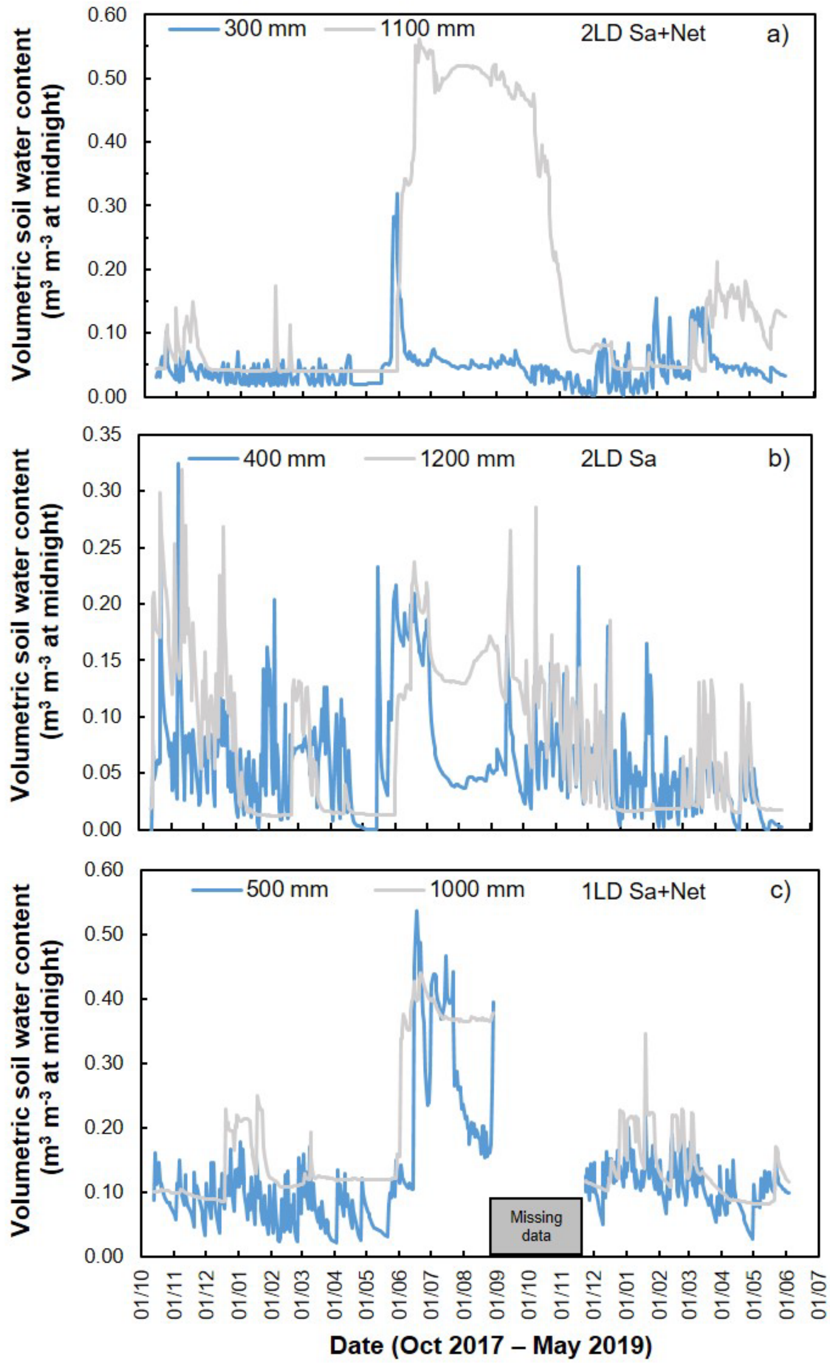

Figure 3.15: Soil water dynamics of the pomegranate (Wonderful) orchards in the Gouda and Wolseley production areas from October 2017 to June 2019. Soil water status in the main root zone (blue line) and bottom of/below the root zone (grey line) are indicated for the Gouda sandy double-line drip-irrigated orchards with (a) and without net (b) and the Wolseley sandy single-line drip-irrigated orchard (c).

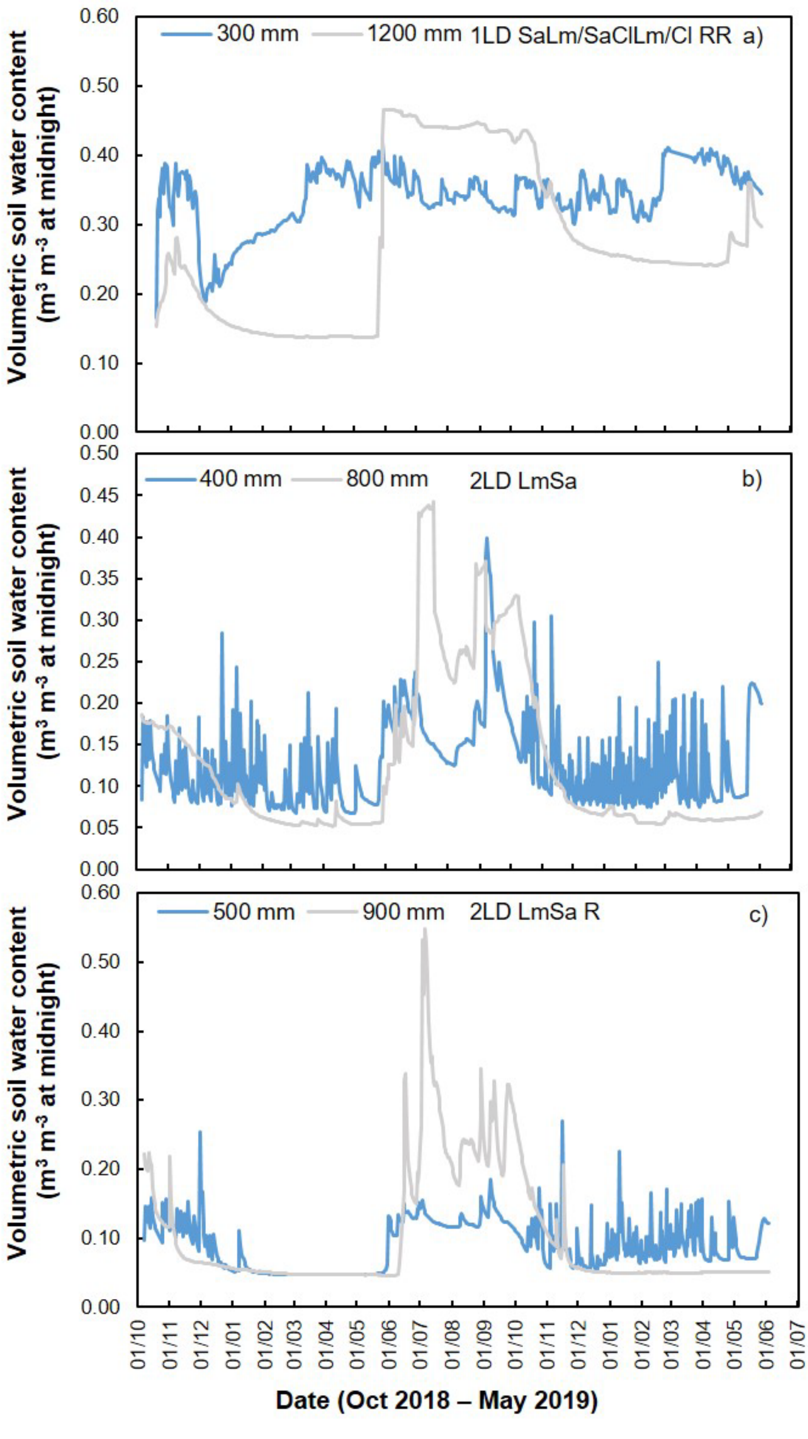

Figure 3.16: Soil water dynamics of pomegranate (Wonderful) orchards in the Wellington production area from October 2017 until May 2019. Soil water status in the main root zone (blue line) and bottom of/below the root zone (grey line) are indicated for the single-line drip-irrigated ripped ridge sandy loam/sandy clay loam/clay orchard (a), the level double-line drip-irrigated loamy sand (b) and ridged double-line drip-irrigated loamy sand (c) orchards.

In the ridged double-line drip-irrigated loamy sand orchard, the volumetric soil water content at which irrigation refill occurred decreased from the beginning of November 2017 until the end of January 2018 and was only restored at the end of May 2018 (Figure 3.16c). During the 2018/19 season, the soil water content at a 500 mm depth clearly fluctuated in response to irrigation.

The soil water content at the 900 mm depth decreased gradually from the beginning of November 2017 and levelled off at a low near the beginning of January 2018. It only increased significantly by 16 June 2018. During the 2018/19 season, the soil water content at 900 mm depth decreased from about 25 September until the end of November, after which it remained low until the end of the season.

3.3.6 Tree response

3.3.6.1 Growth stages

Tree shoot length, fruit diameter and canopy dimensions were measured near the end of the three phenological growth stages: fruit set, fruit growth and ripening in the 2017/18 and 2018/19 seasons (Table 3.10). In 2017/18, for the orchards on average, the duration of the stages from the beginning to the end of fruit set (relative to 1 September), fruit growth and ripening was 101 ± 3, 53 ± 2 and 36 ± 6 days. From ripening until the first harvest, 13 ± 5 days elapsed, followed by the second harvest 12 ± 2 days later. In 2018/19, the duration of the stages was similar to that in the first season, i.e. for fruit set, fruit growth and ripening, it was 100 ± 5, 49 ± 4 and 37 ± 3 days. From ripening until the first harvest, 14 ± 4 days elapsed, followed by a second harvest 12 ± 4 days later, and, in some cases a third harvest after another 9 ± 2 days.

3.3.6.2 Tree water status

Tree water status in the different production areas was determined during 2017/18 and 2018/19 at flowering to fruit set, fruit growth and ripening. Orchards in each production area were measured on the same day per growth stage, with one exception (fruit set in Wellington in 2018/19; Table 3.11). Current season shoots were enclosed in stem water potential bags up to the fourth node two hours before measurements were taken. The xylem (stem) water potential of shoots selected at a height of between 0.7 and 1.22 m was determined between 12:00 and 14:30. Weather conditions and time elapsed after irrigation application varied between stages, production areas and between orchards within production areas, which made direct comparisons between orchards difficult or invalid (Table 3.12). The xylem water potential values therefore only indicate whether the trees were experiencing water stress at the time of measurement, and are not necessarily indicative of conditions directly foregoing irrigation. In 2017/18, weather conditions during fruit set stage included c. 80-100% cloud cover in the Bonnievale area, no cloud cover in Gouda and c. 10% cloud cover in Wolseley and Wellington. Conditions during the fruit growth stage for both seasons were ideal, i.e. full sun. In 2017/18, during ripening, there was light high-level cloud in Bonnievale and Gouda, and none in Wolseley and Wellington. In 2018/19, weather conditions during the fruit set stage were sunny with high cloud cover in the Bonnievale area, and no cloud cover in Gouda, Wolseley and Wellington. During ripening, there were cloudy conditions in Gouda and Wolseley, and full sun conditions in Bonnievale and Wellington.

In Spain, midday stem water potential values of Mollar de Elche pomegranate trees without water stress in several experiments ranged between -0.6 and -1.6 MPa, but could become as low as -1.8 MPa (Intrigliolo et al., 2011; Intrigliolo et al., 2013; Mena et al., 2013). Trees subjected to moderate and severe sustained water deficits have been reported to reach minimum stem water potential values of -1.78 and -2.62 MPa, respectively (Mena et al. 2013). Due to a lack of stem water potential norms for Wonderful pomegranate, the Mollar de Elche indicator values are used to interpret our shoot xylem water potential measurements. It must be taken into account that weather conditions also affect stem water potential values.

Table 3.10: Dates at fruit set, linear fruit growth and ripening during which shoot length, fruit diameter and canopy dimensions* were measured, as well as the dates of sequential harvests in different pomegranate (Wonderful) production areas in the 2017/18 and 2018/19 seasons. [MS = micro-sprinkler; 1LD = single-line drip-irrigation; 2LD = double-line drip-irrigation; R = ridged; RR = ripped ridge]. The soil texture classes include sand (Sa), clay (Cl) and loam (Lm). *Only linear fruit growth stage. ** Harvest 3.

Season	Production Area	Orchard	Stage				
			Fruit set	Fruit growth	Ripening	Harvest 1	Harvest 2 and 3
2017/18	Bonnievale	MS SaClLm R	2017/12/12	2018/02/01	2018/03/12	2018/03/20	2018/04/03
		MS LmSa/SaLm R	2017/12/12	2018/02/01	2018/03/12	2018/03/21	2018/04/03
		2LD SaLm R	2017/12/12	2018/02/01	2018/03/12	2018/03/22	2018/04/04
	Gouda	2LD Sa + net	2017/12/14	2018/02/07	2018/03/06	2018/03/27	2018/04/06
		2LD Sa	2017/12/14	2018/02/07	2018/03/06	2018/03/27	2018/04/06
	Wolseley	1LD Sa + net	2017/12/11	2018/01/29	2018/03/26	2018/04/05	-
	Wellington	1LD SaLm/SaClLm/Cl RR	2017/12/07	2018/01/30	2018/03/08	2018/03/23	2018/04/05
		2LD LmSa	2017/12/07	2018/01/30	2018/03/08	2018/03/19	N/A
		2LD LmSa R	2017/12/07	2018/01/30	2018/03/08	2018/03/19	2018/03/29
2018/19	Bonnievale	MS SaClLm R	2018/12/12	2019/01/30	2019/03/05	2019/03/13	2019/03/27
		MS LmSa/SaLm R	2018/12/12	2019/01/30	2019/03/05	2019/03/19	2019/03/28
		2LD SaLm R	2018/12/12	2019/01/30	2019/03/05	2019/03/26	2019/04/03
	Gouda	2LD Sa + net	2018/12/13	2019/01/29	2019/03/07	2019/03/20	2019/04/09
		2LD Sa	2018/12/13	2019/01/29	2019/03/07	2019/03/20	2019/04/02 2019/04/09**
	Wolseley	1LD Sa + net	2018/12/10	2019/01/28	2019/03/08	2019/03/25	-
	Wellington	1LD SaLm/SaClLm/Cl RR	2018/11/28	2019/01/25	2019/03/06	2019/03/18	2019/03/25 2019/04/04**
		2LD LmSa	2018/12/11	2019/01/25	2019/03/06	2019/03/18	2019/03/29
		2LD LmSa R	2018/12/11	2019/01/25	2018/03/06	2019/03/18	2019/03/29

Table 3.11: Xylem water potential measurement dates during fruit set, fruit growth and ripening in different Wonderful pomegranate production areas in the Western Cape during 2017/18 and 2018/19

Season	Growth stage	Production area			
		Bonnievale	Gouda	Wolseley	Wellington
2017/18	Fruit set	13/11/2017	10/11/2017	29/11/2017	09/11/2017
	Fruit growth	01/02/2018	07/02/2018	29/01/2018	31/01/2018
	Ripening	18/03/2018	06/03/2018	26/03/2018	08/03/2018
2018/19	Fruit set	12/12/2018	13/12/2018	10/12/2018	28* and 30/11/2018
	Fruit growth	05/02/2019	29/01/2019	28/01/2019	24/01/2019
	Ripening	05/03/2019	07/03/2019	08/03/2019	06/03/2019

*1LD SaLm/SaClLm/Cl RR

Table 3.12: Weather conditions prevailing during xylem water potential measurements during fruit set, fruit growth and ripening in different Wonderful pomegranate production areas in the Western Cape during 2018/19

Season	Growth stage	Production area			
		Bonnievale	Gouda	Wolseley	Wellington
2017/18	Fruit set	Cloudy	Clear	Cloudy	Cloudy
	Fruit growth	Clear	Clear	Clear	Clear
	Ripening	Cloudy	Cloudy	Clear	Clear
2018/19	Fruit set	Cloudy	Clear	Clear	Clear
	Fruit growth	Clear	Clear	Clear	Clear
	Ripening	Clear	Cloudy	Cloudy	Clear

During fruit set in 2017/18, the xylem water potential of all the orchards was equal to or below -1 MPa, except for the micro-sprinkler-irrigated sandy clay loam in Bonnievale, which had a xylem water potential of c. -1.4 MPa (Table 3.13). It appears as if the water supply in all the orchards was adequate during this stage. During the fruit growth stage, xylem water potential ranged between -1.035 and -2.28 MPa. Moderate water deficits may have occurred in Gouda, with the ridged double-line drip-irrigated loamy sand orchard in Wellington being subjected to severe water stress before irrigation. The xylem water potential in the other two Wellington orchards was approaching the moderate water deficit range. There was no difference in the xylem water potential of the netted and open orchards at Gouda during this stage. During ripening, the xylem water potential ranged between -1.06 and -2.723 MPa. The Bonnievale orchards, the open Gouda orchard and the Wolseley orchard were irrigated the morning before/during measurement, which explains the higher xylem water potential values compared to the orchards that were not irrigated. The exception was the Wellington single-line drip-orchard, which still displayed a moderate degree of water deficit after 20 minutes of irrigation before tree water status was determined. This specific orchard is irrigated with saline water (Table 3.4) and salinity may, in addition to water deficits, further decrease stem water potential. According to their water status, the trees in the Wellington orchards were either on the brink of moderate water stress or experiencing moderate or severe water deficits. The netted Gouda orchard was also subject to moderate water deficits. In 2018/19, during fruit set, the xylem water potential of all the orchards was equal to or below -1.1 MPa, except for the double-line drip-irrigated sandy loam orchard in Wellington, which had a xylem water potential of c. -1.3 MPa (Table 3.13).

Table 3.13: Pomegranate (Wonderful) xylem water potential (± standard error (SE)) measured during fruit set, fruit growth and ripening in different Western Cape production areas in the 2017/18 and 2018/19 seasons. [MS = micro-sprinkler; 1LD = single-line drip-irrigation; 2LD = double-line drip-irrigation; R = ridged; RR = ripped ridge]. The soil texture classes include sand (Sa), clay (Cl) and loam (Lm).

Season	Production area	Orchard	Shoot xylem water potential (MPa)					
			Fruit set		Fruit growth		Ripening	
			Average	SE	Average	SE	Average	SE
2017/18	Bonnievale	MS SaClLm R	-1.390	0.033	-1.200	0.016	-1.210	0.062
		MS LmSa/SaLm R	-0.900	0.091	-1.040	0.043	-1.060	0.073
		2LD SaLm R	-0.950	0.032	-1.050	0.038	-1.260	0.062
	Gouda	2LD Sa + net	-0.950	0.050	-1.915	0.024	-1.830	0.030
		2LD Sa	-0.800	0.032	-1.890	0.033	-1.230	0.058
	Wolseley	1LD Sa + net	-0.830	0.020	-1.035	0.038	-1.180	0.124
	Wellington	1LD SaLm/SaClLm/Cl RR	-0.970	0.044	-1.665	0.050	-1.790	0.037
		2LD LmSa	-0.960	0.073	-1.540	0.116	-1.670	0.132
		2LD LmSa R	-1.000	0.042	-2.280	0.041	-2.730	0.090
2018/19	Bonnievale	MS SaClLm R	-1.050	0.187	-0.973	0.081	-0.983	0.080
		MS LmSa/SaLm R	-0.930	0.091	-0.860	0.107	-0.985	0.120
		2LD SaLm R	-1.050	0.117	-1.166	0.058	-0.965	0.070
	Gouda	2LD Sa + net	-0.980	0.057	-1.724	0.099	-1.114	0.143
		2LD Sa	-0.910	0.074	-1.655	0.121	-1.178	0.150
	Wolseley	1LD Sa + net	-0.670	0.076	-0.907	0.089	-0.666	0.049
	Wellington	1LD SaLm/SaClLm/Cl RR	-0.960	0.055	-1.180	0.182	-1.232	0.163
		2LD LmSa	-1.315	0.065	-1.740	0.173	-1.412	0.159
		2LD LmSa R	-1.144	0.072	-1.398	0.194	-1.636	0.123

Orchards appeared to be watered adequately during this stage. During the fruit growth stage, xylem water potential ranged between -0.86 and -1.74 MPa. The greatest water deficits occurred in Gouda, and in the double-line drip-irrigated loamy sand in Wellington, approaching the moderate water deficit range.

During ripening, the xylem water potential ranged between -0.666 and -1.636 MPa, which is much higher compared to the minimum xylem water potential of -2.7 MPa (i.e. severe stress) reported during the critical drought of the previous season. Despite variability between sites, shoot xylem water potential at fruit growth stage in 2017/18 and in 2018/19 tended to increase (i.e. became less negative) non-linearly and linearly, respectively, with an increase in the average rate of effective rainfall and irrigation water applied per day from fruit set to the end of the fruit growth stage (figures 3.17a and 3.17b).

For data of both seasons combined, the overall trend was for shoot xylem water potential at fruit growth stage to increase non-linearly with greater rates of effective rainfall and irrigation applied (Figure 3.17c). Data of orchards omitted as outlying values in 2018/19 were excluded based on the impact of heavy winter pruning on trees or questionable tree health. Under the conditions of the research conducted, the application of micro-sprinkler-irrigation of between 6.2 and 7 mm d^{-1} or drip-irrigation of between 5.3 and 5.6 mm d^{-1} resulted in shoot stem water potential values of between -0.95 and -1.1 MPa, which can be considered indicative of well-watered trees.

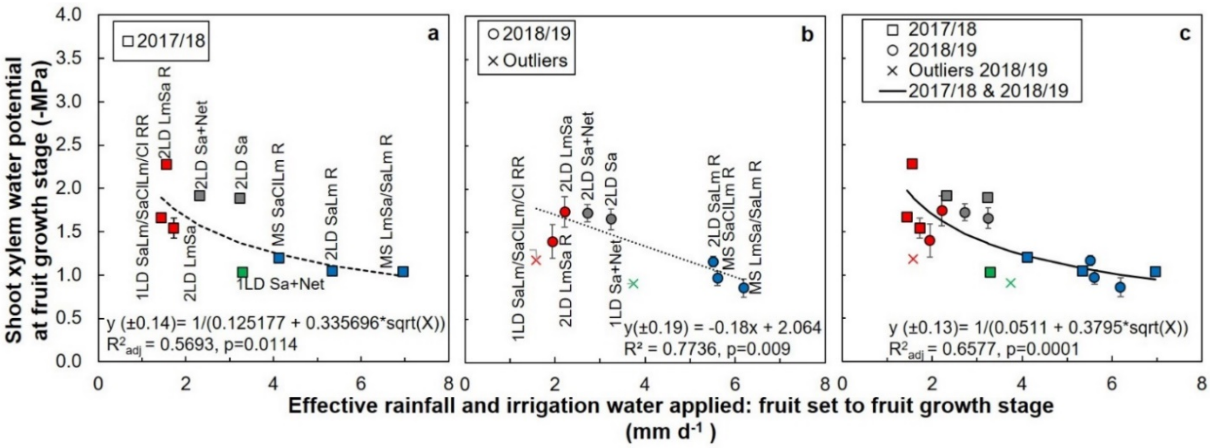

Figure 3.17: The relationship between shoot xylem water potential (± standard error) and effective rainfall and irrigation water applied to full-bearing Wonderful pomegranate orchards in the Bonnievale (blue markers), Gouda (grey markers), Wolseley (green marker) and Wellington (red markers) production areas during 2017/18 (a) and 2018/19 (b) and for seasons combined (c). [MS = micro-sprinkler; 1LD = single-line drip-irrigation; 2LD = double-line drip-irrigation; R = ridged; RR = ripped ridge]. The soil texture classes include sand (Sa), clay (Cl) and loam (Lm).

3.3.6.3 Vegetative growth

Shoot growth on current season shoots varied from bud break to linear fruit growth stage between 243 and 442 mm in 2017/18 and between 211 and 624 mm in 2018/19 (figures 3.18a and 3.18b). In 2017/18, more than 94% of the shoot growth was completed by the end of fruit set. Exceptions were the double-line drip-irrigated clay soil in Bonnievale and sand in Gouda, for which 84 and 66%, respectively, of the total shoot growth was completed at the fruit set stage. In 2018/19, 90% or more of the shoot growth was completed by the end of fruit set for the majority of orchards. Exceptions were the micro-sprinkler-irrigated ridged loamy sand/sandy loam soil orchard in Bonnievale and the heavily winter-pruned sandy loam/sand clay loam/clay orchard in Wellington, for which 78% of the total shoot growth was completed at fruit set stage. The latter, originally freestanding trees were trained onto a trellis system in the 2018/19 season.

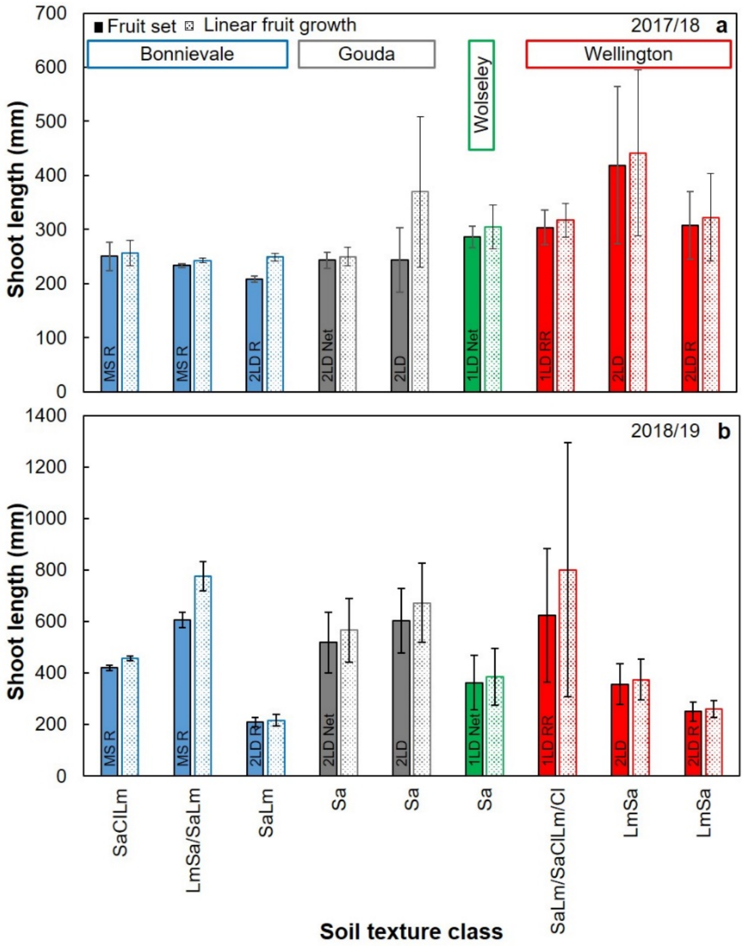

Figure 3.18: Shoot growth from bud break until fruit set (solid bars) and linear fruit growth stage (patterned bars) of full-bearing Wonderful pomegranate orchards in the Bonnievale (blue bars), Gouda (grey bars), Wolseley (green bars) and Wellington (red bars) production areas during the 2017/18 (a) and 2018/19 (b) seasons. [MS = micro-sprinkler; 1LD = single-line drip-irrigation; 2LD = double-line drip-irrigation; R = ridged; RR = ripped ridge]. The soil texture classes include sand (Sa), clay (Cl) and loam (Lm).

In 2017/18, the rate of effective rainfall and irrigation applied from the beginning of September until the end of the fruit set fruit growth stage amounted to less than 2.5 mm d^{-1}, whereas, in 2018/19, the amount ranged from 1.5 to 3.7 mm d^{-1} (figures 3.19a and 3.19b). In the first season, there was no clear relationship between the effective rainfall and the amount of water applied per day from 1 September until the end of the fruit set stage and shoot growth rate (Figure 3.19a). In 2018/19, though, shoot growth rate increased logarithmically from 2.5 to 5.9 mm d^{-1}, with more effective rainfall and irrigation applied, provided two outlying values were excluded (Figure 3.19b).

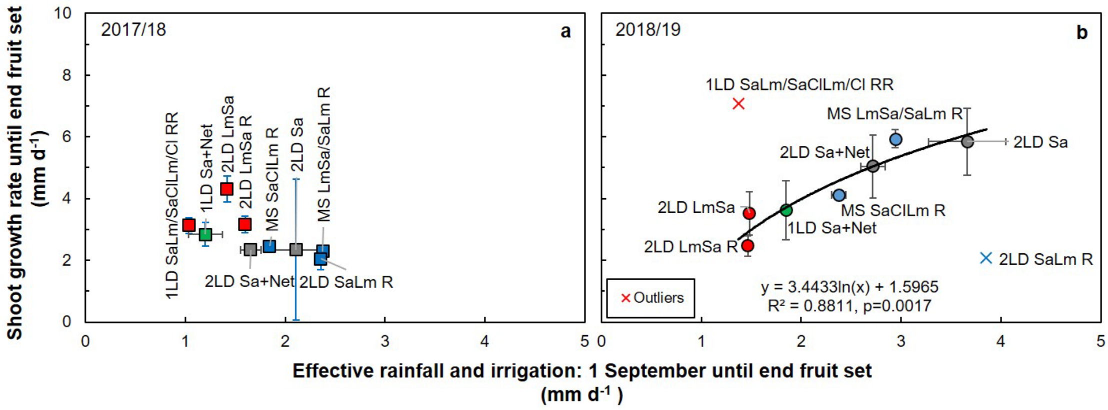

Figure 3.19: Shoot growth rate from bud break until the end of fruit set vs daily irrigation applied from 1 September until the fruit set stage for Wonderful pomegranate orchards in the Bonnievale (blue markers), Gouda (grey markers), Wolseley (green marker) and Wellington (red marker) production areas during a) the 2017/18 and b) the 2018/19 seasons. [MS = micro-sprinkler; 1LD = single-line drip-irrigation; 2LD = double-line drip-irrigation; R = ridged; RR = ripped ridge]. The soil texture classes include sand (Sa), clay (Cl) and loam (Lm).

The excessive growth of the single-line drip-irrigated orchard on sandy loam/sandy clay loam/clay in Wellington was considered as a response to heavy pruning. In the ridged double-line drip-irrigated orchard on sandy loam in Bonnievale, vegetative growth of the trees was adequate according to the farm manager and tree height increased notably. The only explanation for the apparently poor growth was that the shoots selected for measurement at mid-canopy height did not represent the actual growth of the trees. Shoot growth rate for the period between 1 September and the end of linear fruit growth increased exponentially with increasing rates of effective rainfall and irrigation applied (data not shown, y (SE ± 0.19) = exp(0.176 + 0.35x), R^2 = 0.767, p = 0.0098).

For production regions, on average, in 2017/18, Wellington had the highest shoot growth rate from 1 September until linear fruit growth (3.5 mm d^{-1}), followed by Wolseley, Gouda and Bonnievale (20, 34 and 36%, respectively, less than the Wellington average). In 2018/19, though, Gouda had the highest shoot growth rate during this period (5.4 mm d^{-1}), followed by Wellington, Bonnievale and Wolseley (20, 26 and 33%, respectively, less than the Gouda average). On average for soil type, the shoot growth rate of trees on clayey and sandy loam soils was c. 18% less in the first season compared to those on sandy and loamy sand soils (2.7 mm d^{-1}). In the second season, the shoot growth rate of trees on clayey and sandy loam soils was once again lower (7%) compared to those on sandy and loamy sand soils, where shoot growth rate averaged 4.4 mm d^{-1}.

Pruning mass, as an indicator to compare vegetative growth between orchards, was discarded since one orchard was severely pruned to adopt a different training system. Some orchards were not pruned at all, while others were pruned without notifying the research team.

3.3.6.4 Fruit growth

Fruit diameter was measured at the end of fruit set, during linear fruit growth and at ripening. In 2017/18, at the end of fruit set, the fruit of the micro-sprinkler-irrigated orchard on ridged loamy sand and the double-line drip-irrigated ridged sandy loam orchard in Bonnievale had, on average, fruit of c. 57 mm in diameter, which was c. 15% larger than the fruit of all the other orchards, on average (Figure 3.20a). Based on fruit diameter, the micro-sprinkler-irrigated orchards in Bonnievale had c. 13% larger fruit compared to all the other orchards at both linear fruit growth (average fruit diameter c. 78 mm) and ripening stage (average fruit diameter c. 93 mm) (Figure 3.20).

The smallest fruit was from Wolseley (Figure 3.20b) and the orchards in Wellington (Figure 3.20c). At Gouda, fruit under net was between 2 and 6% smaller until the first harvest (Figure 3.20b), and at the second harvest, it was 12% smaller compared to fruit produced in open orchards (data not shown).

At the end of fruit set in 2018/19, the fruit of most orchards was comparable and, on average, c. 59 mm in diameter (figures 3.20d to 3.20f). Notably, smaller fruit was present in the Wolseley orchard (51 mm; Figure 3.20e) and in the double-line drip-irrigation lime sandy orchard in Wellington (55 mm; Figure 3.20f). Significantly smaller fruit in the single-line drip-irrigation sandy clay/clay loam/clay ripped ridge orchard (46 mm; Figure 3.20f) could be due to earlier onset of the end of fruit set in the 2018/19 season and/or a carry-over effect of severe winter pruning applied to train the previously free-standing trees on a trellis system.

By linear fruit growth stage, though, these fruit overcame the initial small size and the orchard had of the largest fruit (96 mm) at ripening stage (Figure 3.20f). Fruit diameter at ripening was, on average, (± standard deviation) 91 ± 3.5 mm for all orchards, with fruit from the netted single-line drip-irrigated orchard in Wolseley (Figure 3.20e; 86 mm) and the double-line drip-irrigated loamy sand orchard in Wellington (Figure 3.20f; 87 mm) being the smallest.

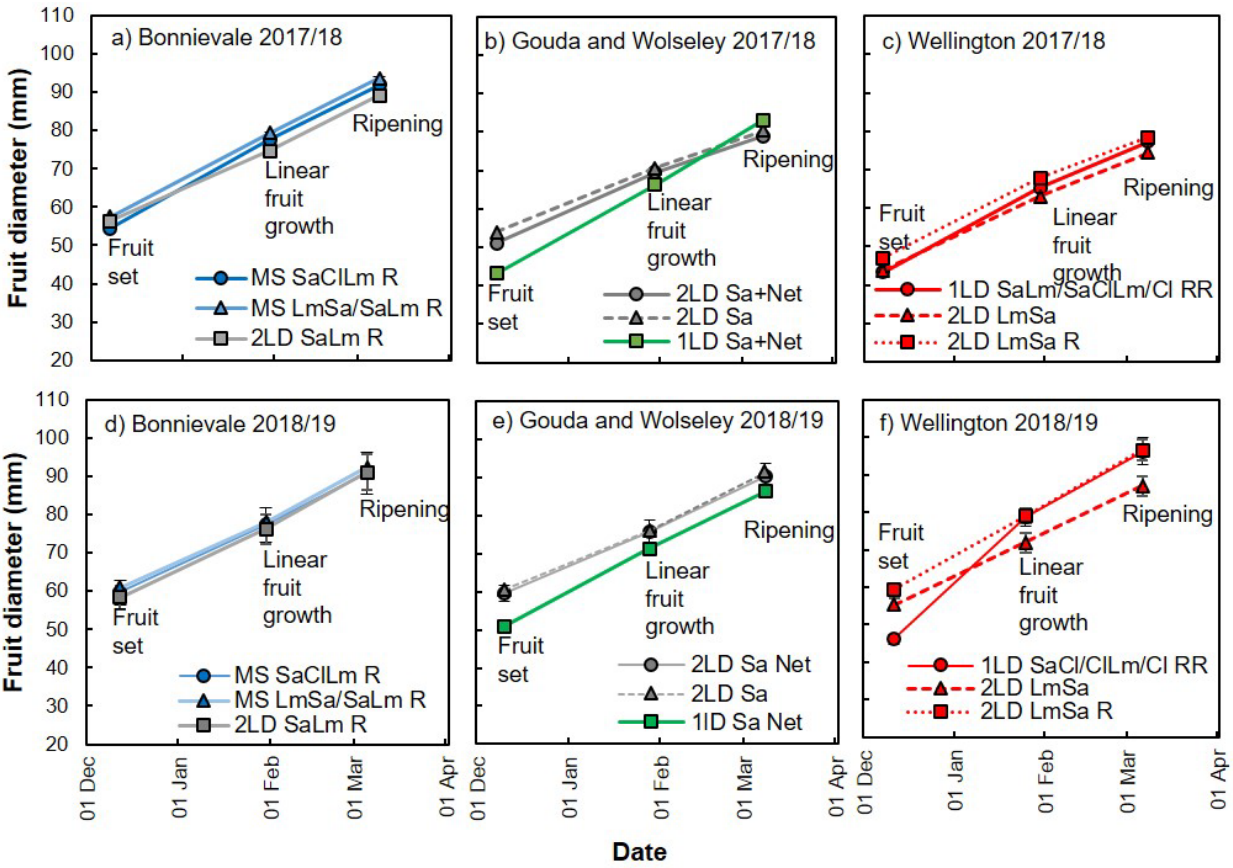

Figure 3.20: Fruit diameter of full-bearing Wonderful pomegranate orchards measured during fruit set, linear fruit growth and ripening in the Bonnievale (a, d), Gouda and Wolseley (green line) (b, e) and Wellington (c, f) production areas during the 2017/18 (a, b, c) and 2018/19 (d, e, f) seasons. [MS = micro-sprinkler; 1LD = single-line drip-irrigation; 2LD = double-line drip-irrigation; R = ridged; RR = ripped ridge]. The soil texture classes include sand (Sa), clay (Cl) and loam (Lm).

With regard to production areas, at fruit set in 2017/18, Bonnievale had 6, 23 and 20% larger fruit (diameter c. 54 mm) compared to Gouda, Wolseley and Wellington, respectively (Figure 3.21). At linear fruit growth stage, fruit in the respective areas was 9, 14 and 15% smaller, compared to fruit at Bonnievale (c. 75 mm in diameter) and 13, 9 and 16% smaller during ripening (c. 92 mm in diameter). Fruit diameter based on all fruit at first harvest at Bonnievale (c. 90 mm), and Gouda and Wolseley (c. 88 mm) was comparable, but still 10% smaller at Wellington (c. 81 mm) compared to Bonnievale. Fruit from the second harvest was also smaller at Gouda (8%) and Wellington (13%) compared to that at Bonnievale (c. 86 mm). At Wolseley, all fruit was removed during one harvest. The diameter of fruit from micro-sprinkler-irrigated trees was c. 13% larger at fruit set, linear fruit growth and ripening stages compared to drip-irrigated orchards. At both the first and second harvests, though, fruit diameter (based on all fruit harvested) was only 5% more compared to that of fruit from drip-irrigated orchards.

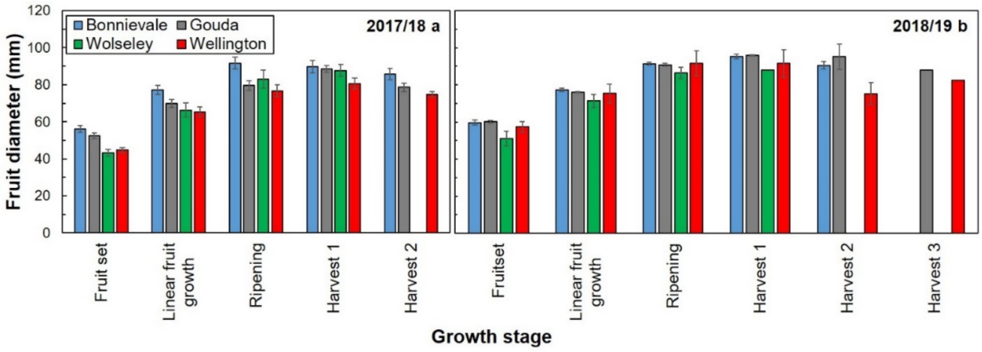

Figure 3.21: Fruit diameter (± standard deviation) of full-bearing Wonderful pomegranate orchards measured during fruit set, linear fruit growth, ripening and the first, second and third harvest in the Bonnievale, Gouda, Wolseley and Wellington production areas during the 2017/18 (a) and 2018/19 (b) seasons. The average fruit diameter at different fruit growth stages until ripening is for 50 fruit per orchard, and at harvest for all fruit, excluding cracked or split fruit.

In 2018/19, at fruit set, linear fruit growth stage and ripening, fruit at Bonnievale, Gouda and Wellington was comparable (diameter c. 59, 76 and 91 mm on average) and c. 14, 6.3 and 5.5 larger compared to fruit at Wolseley at these respective stages (Figure 3.21). At first harvest, fruit from Bonnievale and Gouda had comparable diameters (96 mm on average), whereas fruit from Wellington was, on average, 92 mm and that of Wolseley 88 mm. There was large variability in fruit size for the Wellington area compared to that of the other areas. Fruit diameter at the second harvest was similar to that at the first harvest for Bonnievale and Gouda, on average, with that for Wellington being c. 26% smaller. Fruit from the third harvest at Gouda and Wellington was, on average, 88 and 83 mm diameter, respectively. Fruit from micro-sprinkler-irrigated orchards was c. 8% larger than drip-irrigated fruit at fruit set, but the size difference became smaller later in the season, with fruit being of comparable size at the first harvest, and only 5% larger at the second harvest. At Gouda, there were only small differences (i.e. less than 3%) between fruit diameter under net compared to that grown in open orchards, except for the second harvest, where fruit under net was 10% smaller than that grown in the open orchard. The diameter of fruit from orchards with clay loam or sandy loam soils was between 5 and 7% more than those from orchards with loamy sand or sandy soils.

The fruit growth rate for the fruit set phase was calculated relative to 1 September, since exact dates of flowering were not available for the different orchards. Fruit growth rate during 2017/18 and 2018/19 was 0.56 and 0.47; 0.38 and 0.39; and 0.35 and 0.41 mm d^{-1}, on average, during the fruit set, linear fruit growth and ripening phases, respectively. The fruit growth rate during fruit set tended to increase with more effective rainfall and irrigation applied in both seasons, but the relationship for the linear fruit growth and ripening phases was less clear (figures 3.22a to 3.22c).

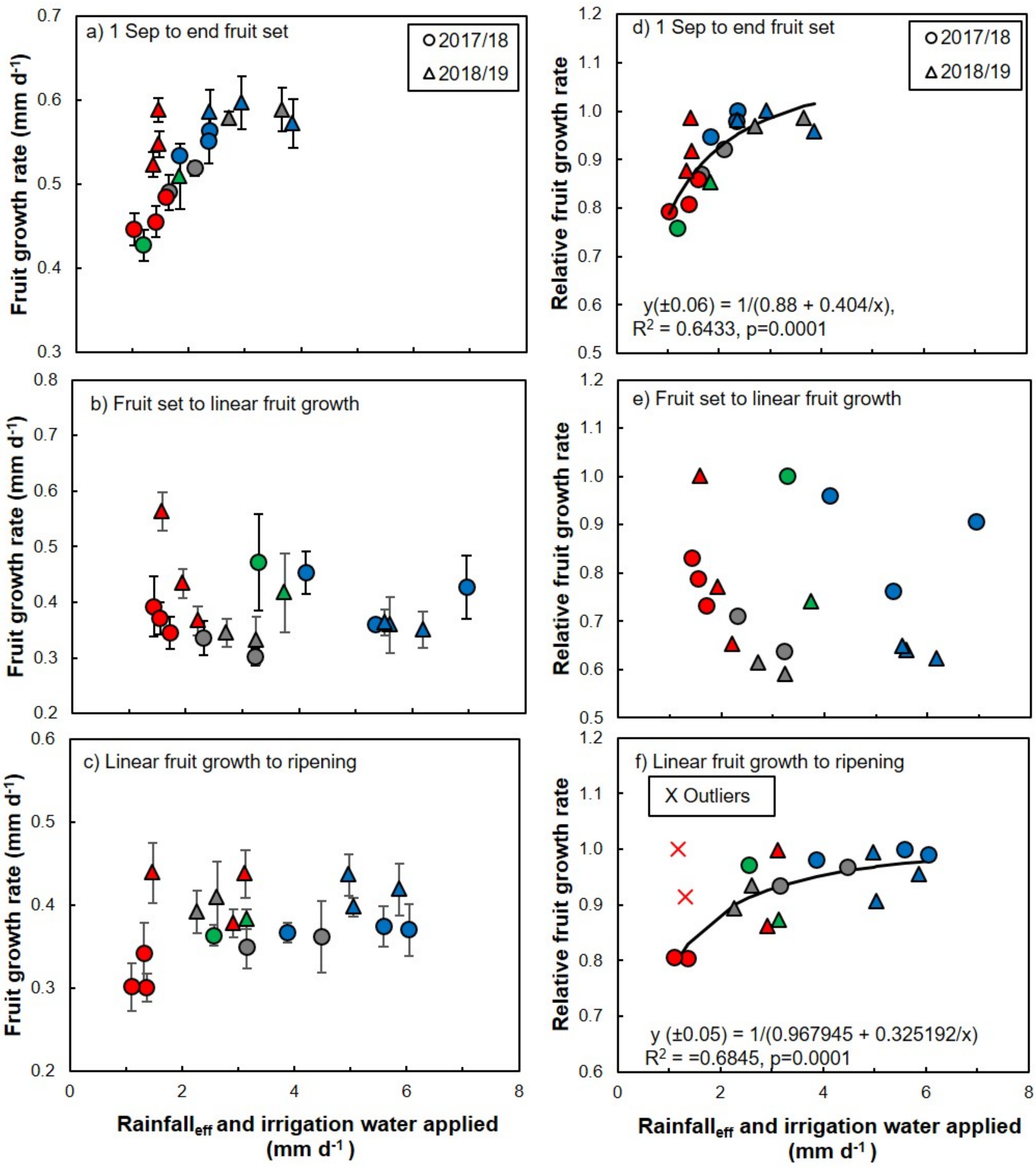

Figure 3.22: The absolute (± standard deviation) (a to c) and relative (d to f) fruit growth rate of full-bearing Wonderful pomegranate orchards measured during fruit set (a and c), linear fruit growth (b and e) and ripening (c and f) in the Bonnievale (blue markers), Gouda (grey markers), Wolseley (green marker) and Wellington (red markers) production areas during the 2017/18 and 2018/19 seasons.

Relative fruit growth rate during fruit set (Figure 3.22d) and ripening (Figure 3.22f) tended to increase non-linearly with an increased amount of effective rainfall and irrigation water applied daily. The relative fruit growth rate of the single-line drip-irrigated orchard in Wellington during ripening was identified as an outlier for both seasons, deviating by more than two standard deviation points from the mathematical model (Figure 3.22f). There was no simple relationship between the daily effective rainfall and the amount of water applied, and the absolute or relative fruit growth rate during linear fruit growth (figures 3.22b and 3.22e).

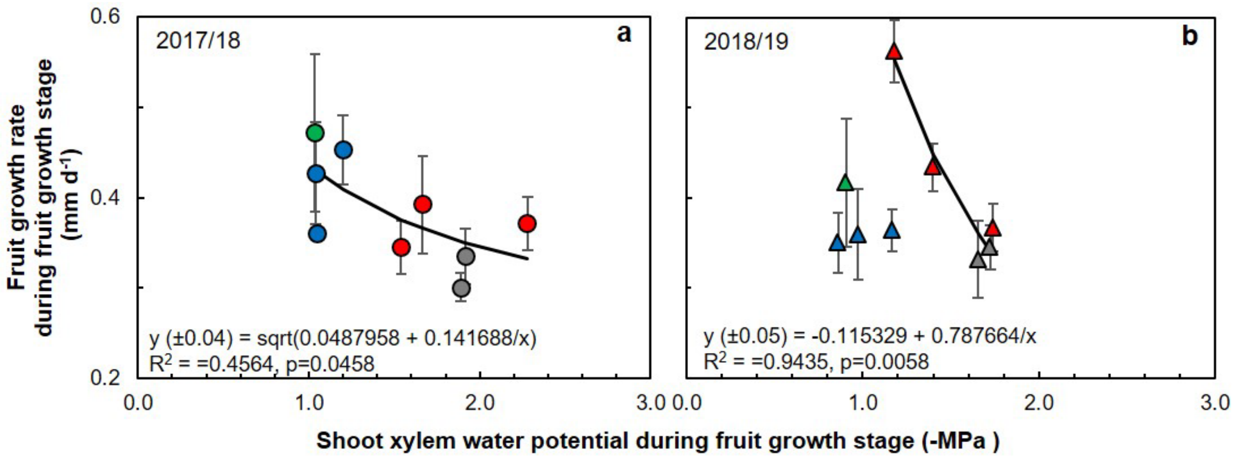

Figure 3.23: The relationship between fruit growth rate (± standard deviation) and shoot xylem water potential during the fruit growth stage of full-bearing Wonderful pomegranate orchards in the Bonnievale (blue markers), Gouda (grey markers), Wolseley (green marker) and Wellington (red markers) production areas during the 2017/18 season. The mathematical relationship in 2018/19 only applies to Gouda and Wellington.

However, fruit growth rate during the linear fruit growth stage tended to improve with higher (i.e. less negative) shoot xylem water potential in 2017/18 (Figure 3.23a). In 2018/19, though, it was not possible to fit one mathematical relationship for all orchards (Figure 3.23b). The fruit growth rate in Gouda and Wellington decreased non-linearly with stem water potential between -1.18 and -1.74 MPa. The lack of correlation between fruit growth rate and stem water potential for the Bonnievale area may be related to the effect of more than 20 mm of rainfall that occurred between two and five days before the measurements were made. The Wolseley stem water potential data point was previously identified as an outlying data point in comparison to effective rainfall and irrigation applied (refer to Figure 3.17b).

3.3.6.5 Leaf nutrient analysis

Leaf macro- and micronutrient contents are summarised in Table 3.14. In 2017/18, according to norms for pomegranate trees (refer to Bemlab, Table 3.14), the leaf nitrogen and phosphate levels from the Bonnievale micro-irrigated orchards were very high, whereas nitrogen was deficient in four of the drip-irrigated orchards, especially the netted Wolseley orchard . The phosphate levels were low in all the drip-irrigated orchards in Wellington and in the open drip-irrigated Gouda orchard, but they were very high in the Wolseley orchard. In 2017/18, leaves from all orchards indicated potassium deficiency, but calcium levels were adequate. Leaf magnesium levels were deficient in Wolseley and in the level double-line drip-irrigated loam sand orchard in Wellington.

Table 3.14: Macro- and micronutrient content of leaves sampled at the end of January/beginning of February from the middle of the current-year shoots of full-bearing Wonderful pomegranate trees in different Western Cape production areas. Macronutrients, including nitrogen (N), phosphate (P), potassium (K), calcium (Ca) and magnesium (Mg). Micronutrients include sodium (Na), manganese (Mn), iron (Fe), copper (Cu), zinc (Zn) and boron (B), are indicated. Symbols in columns indicate whether nutrient concentrations are deficient (D), low (L), high (H), very high (V) or toxic (T).

Season	Production area	Orchard	N	P	K	Ca	Mg	Na	Mn	Fe	Cu	Zn	B
			Percentage					mg kg^{-1}					
2017/18	Bonnievale	MS SaClLm R	2.42V	0.20V	0.81D	1.85	0.37	111	40T	148	721T	16D	14D
		MS LmSa/SaLm R	2.27V	0.22V	0.74D	1.52	0.40V	106	32	162	625T	12D	13D
		2LD SaLm R	1.68D	0.17	0.57D	1.22	0.53V	69	132T	149	487T	21D	12D
	Gouda/Porterville	2LD Sa + net	1.08D	0.15	0.85D	1.31	0.38	89	72T	185	136T	71H	15D
		2LD Sa	1.74	0.13D	0.73D	1.31	0.57V	66	58T	130	104T	74H	15D
	Wolseley	1LD Sa + net	0.44D	0.19V	0.84D	1.14	0.24D	57	47T	109	7D	11D	13D
	Wellington	1LD SaLm/SaClLm/Cl RR	1.87	0.12D	0.67D	1.25	0.32	108	43T	111	86H	13D	13D
		2LD LmSa	1.76	0.12D	0.85D	1.28	0.26D	66	119T	130	12	18D	15D
		2LD LmSa R	1.69D	0.13D	0.84D	1.36	0.37	84	37	119	102T	18D	16D
2018/19	Bonnievale	MS SaClLm R	2.19V	0.20V	1.07	2.38	0.41V	52	43T	246	446T	16D	20D
		MS LmSa/SaLm R	2.02V	0.19V	1.21V	1.63	0.43V	125	36	155	436T	11D	19D
		2LD SaLm R	1.96V	0.22V	1.01	1.57	0.56V	139	117T	219	410T	34L	20D
	Gouda/Porterville	2LD Sa + net	1.81	0.17	1.13	1.75	0.44V	83	93T	190	95H	22D	21D
		2LD Sa	2.01V	0.18V	1.24V	1.43	0.51V	142	79T	173	90H	52H	23D
	Wolseley	1LD Sa + net	1.24D	0.29V	1.33V	1.81	0.35	110	39	214	9L	24D	29L
	Wellington	1LD SaLm/SaClLm/Cl RR	1.64D	0.15	0.97	1.61	0.32	164	50T	223	262T	13D	18D
		2LD LmSa*	1.60D	0.12D	0.95	1.95	0.32	58	35	136	79H	20D	18D
		2LD LmSa R	1.51D	0.13D	1.07	1.61	0.41V	60	46T	161	60H	31L	20D
		Norm: Low	***1.7***	***0.14***	***0.9***	***1***	***0.3***	**0**	**20**	**45**	**9**	**30**	**25**
		Norm: High	***1.9***	***0.18***	***1.2***	***2.5***	***0.4***	**300**	**40**	**150**	**20**	**35**	**35**

Magnesium levels were very high in the leaves of the open Gouda orchard, and in Bonnievale, in the micro-sprinkler-irrigated loam sand/sandy loam and the sandy loam drip- irrigated orchard (Table 3.14). In 2018/19, leaves from the Bonnievale and Gouda areas tended to have normal to high levels of nitrogen, phosphate and magnesium. The Wolseley orchard was deficient in nitrogen, but had very high levels of phosphate and potassium. Leaves of all the Wellington orchards were nitrogen deficient, with the double-line drip-irrigated loamy sand orchards indicating a phosphate deficiency as well. Potassium levels in leaves of the Wellington orchards were adequate. Leaves of the ridged double-line drip-irrigated loamy sand orchard in Wellington contained very high levels of magnesium. In both seasons, the calcium levels in the leaves of all the orchards were adequate.

Leaf surfaces were not washed before analysis and high levels of certain micronutrients may therefore be due to spray residues. Sodium was within the norms for both seasons (Table 3.14). Manganese and copper reached toxic levels in the leaves of most orchards, with the exception of the leaves in the Wolseley orchards, which were deficient in copper in 2017/18 and had low levels in 2018/19. Iron levels tended to be high in the Bonnievale orchards and in the open Gouda orchard in 2017/18, but in 2018/19, iron levels were exceeding the high norm in all orchards but one. In 2017/18, leaves of all orchards were deficient in boron and zinc, except for the Gouda orchards, which had high zinc levels. In 2018/19, leaves of all the orchards were once again boron deficient, except for Wolseley, which had low levels of this micronutrient. All orchards also had either low or deficient levels of zinc, except for the double-line drip-irrigated open orchard in Gouda, which contained high levels of zinc in the leaves.

For most leaf macro- and micronutrients, there was no significant relationship between leaf nutrient content and effective rainfall and irrigation until the end of linear fruit growth when leaves were sampled. Leaf phosphate and magnesium content increased either non-linearly or linearly with higher rates of effective rainfall and irrigation applied until the end of linear fruit growth, provided outlying values were omitted in some seasons (Figure 3.24).

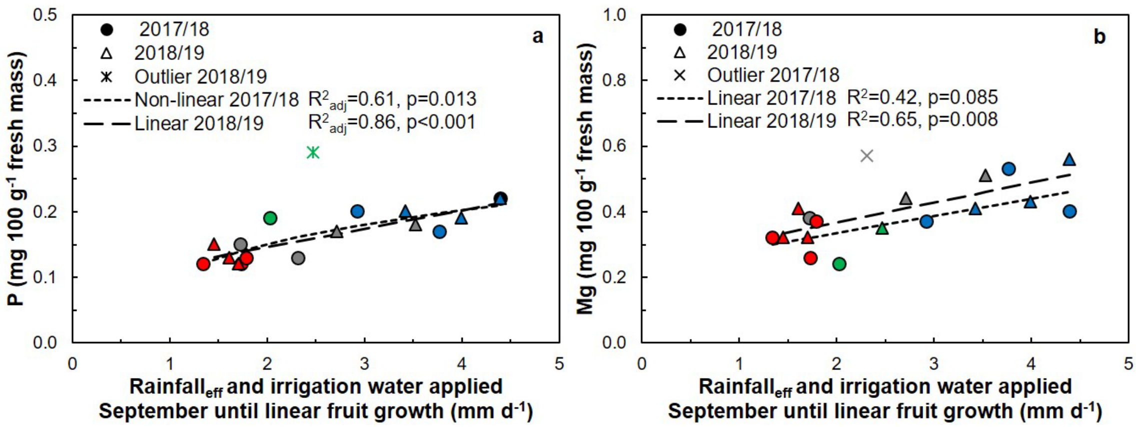

Figure 3.24: The effect of effective rainfall and irrigation applied until linear fruit growth on the a) phosphate (P) and b) magnesium (Mg) content of Wonderful pomegranate leaves in the Bonnievale (blue markers), Gouda (grey markers), Wolseley (green markers) and Wellington (red markers) production areas during the 2017/18 and 2018/19 seasons.

3.3.6.6 Yield

In 2017/18, orchards were harvested from 19 March until 5 April 2018. Total yield for the 2017/18 season varied between 20 kg per tree (21.9 t ha^{-1}) and 145 kg per tree (60.3 t ha^{-1}) (Table 3.15). The highest yield (Bonnievale micro-sprinkler-irrigated sandy clay/loam ridged orchard) was c. 63% more than the lowest (Wellington double-line drip-irrigated ridged loamy sand orchard). Total yield for the level Wellington double-line drip-irrigated sandy loam orchard was not available since the second commercial harvest was completed without notification.

Data of this orchard is omitted from comparisons between areas, soils and irrigation systems. The harvesting norms differed between farms, and the mass of fruit harvested during the first harvest varied between 18 and 86% of the total, except for Wolseley, which was harvested once-off. The Bonnievale area, on average, had the highest yield (59.4 t ha^{-1}), with 35, 26.4 and 22.9 t ha^{-1} for the Gouda, Wellington and Wolseley production areas, respectively. Yield for Bonnievale was therefore 41, 56 and 62% higher than Gouda, Wellington and Wolseley. Total yield on the heavier soils (sandy clay loam, sandy loam) was 52.3 t ha^{-1}, i.e. 45% higher than the yield on the lighter soils (sand and loamy sand). Yield of micro-sprinkler-irrigated orchards was, on average, 59.7 t ha^{-1}, 43% higher than that of the drip-irrigated orchards. In Gouda, the netted orchard realised 50% of the yield of the open orchard. In 2018/19, orchards were harvested from 13 March until 9 April 2019. Between one and three harvests occurred, depending on the orchard (Table 3.15). Total yield for the 2018/19 season varied between 15 kg per tree (14.2 t ha^{-1}) and 162 kg per tree (67.7 t ha^{-1}). The highest yield occurred once more in the Bonnievale micro-sprinkler-irrigated sandy clay/loam ridged orchard and was c. 79% more than the lowest (Wolseley single-line drip-irrigated netted sandy soil orchard). The Bonnievale area, on average, also had the highest yield for the second season (60.5 t ha^{-1}), followed by Gouda (38 t ha^{-1}), Wellington (27.2 t ha^{-1}) and Wolseley (14.2 t ha^{-1}). The yield in Bonnievale was therefore 37, 55 and 77% higher compared to Gouda, Wellington and Wolseley. Total yield on the sandy clay loam and sandy loam soils was 49.5 t ha^{-1}, i.e. 28% higher than the yield on loamy sand and sandy soils. The yield of micro-sprinkler-irrigated orchards was, on average, 61.2 t ha^{-1}, 46% higher than that of the drip-irrigated orchards.

In Gouda, the netted orchard realised 55% of the yield of the open orchard. The high total yield at the Bonnievale sandy clay/loam orchard in both the 2017/18 and 2018/19 seasons was a combination of a high number of fruit per tree (444 and 423), with an average weight of c. 0.328 and 0.385 kg per fruit, respectively (Figure 3.25; Table 3.16). In 2017/18, the poor yield of the Wellington double-line drip-irrigated ridged loamy sand orchard was due to less fruit per tree and smaller fruit (c. 0.2 kg), whereas, in Wolseley, low fruit number dictated total yield (tables 3.15 and 3.16). In 2018/19, Wolseley had the lowest yield and 40% less fruit than in 2017/18, although fruit was slightly larger compared to the previous season. The low yield for the single-line drip-irrigated orchard in Wellington in 2018/19 may be related to the heavy winter pruning to which the trees were subjected, and the first season of training on a trellis system. In 2017/18, the Bonnievale orchards had 56% more fruit than those in Gouda and Wellington, and 78% more than those in Wolseley (Table 3.16). Trees on heavier soils had 61% more fruit per tree compared to those on lighter soils, while micro-irrigated orchards bore 66% more fruit per tree than drip-irrigated orchards (Figure 3.25a). In Gouda, the netted orchard had c. 36% less fruit than the open orchard. Fruit losses due to FCM in the orchard were not quantified, but c. 64% of the fruit of trees under net was infested with FCM compared to c. 27% in the open orchard. Less severe FCM infestations occurred in the single-line drip-irrigated orchards in Wellington (6%) and Wolseley (2.9%).

In 2018/19, the Bonnievale orchards had 60, 64 and 72% more fruit than those in Gouda, Wolseley and Wellington, respectively (Table 3.16). The orchards with clay and sandy loam soils had 61% more fruit than the orchards with loamy sand and sandy soils. The micro-irrigated orchards had 73% more fruit than the drip-irrigated orchards (Figure 3.25a).

Table 3.15: Yield (± standard deviation or SD) per tree and per hectare of full-bearing pomegranate orchards in the Bonnievale, Gouda, Wolseley and Wellington production areas during the 2017/18 and 2018/19 seasons. [MS = micro-sprinkler; 1LD = single-line drip-irrigation; 2LD = double-line drip-irrigation; R = ridged; RR = ripped ridge]. The soil texture classes include sand (Sa), clay (Cl) and loam (Lm).

Production area	Orchard ID	Harvest	Yield (kg/tree)				Yield (t/ha)			
			2017/18		2018/19		2017/18		2018/19	
			Mean	SD	Mean	SD	Mean	SD	Mean	SD
Bonnievale	MS SaClLm R	1	124	22.9	64.6	22.5	51.7	9.6	26.9	9.4
		2	21	14.8	97.7	21.8	8.6	6.2	40.7	9.1
		Total	**145**	**12.9**	**162.4**	**12.7**	**60.3**	**5.4**	**67.7**	**5.3**
	MS LmSa/SaLm R	1	70	29.5	56.5	10.7	29.1	12.3	23.6	4.5
		2	72	28.5	74.4	22.5	29.9	11.9	31.0	9.4
		Total	**142**	**33.2**	**131.0**	**30.6**	**59.0**	**13.8**	**54.6**	**12.8**
	2LD SaLm R	1	11	3.9	32.2	12.7	10.8	3.9	13.4	5.3
		2	48	4.8	27.1	8.4	48.1	4.8	11.3	3.5
		Total	**59**	**5.9**	**59.3**	**11.5**	**58.9**	**5.9**	**59.3**	**11.5**
Gouda	2LD Sa + net	1	17	2.4	12.7	1.3	13.7	1.9	10.1	1.1
		2	12	4.3	21.4	7.7	9.6	3.4	17.1	6.1
		Total	**29**	**4.9**	**34.1**	**7.8**	**23.2**	**3.9**	**27.3**	**6.2**
	2LD Sa	1	26	5.4	14.6	5.0	20.6	4.3	11.7	4.0
		2	33	16.1	21.5	4.2	26.2	12.9	17.2	3.3
		3	**-**	**-**	25.6	19.7	**-**	**-**	20.5	15.8
		Total	**58**	**14.3**	**61.7**	**18.0**	**46.7**	**11.5**	**49.3**	**14.4**
Wolseley	1LD Sa + net	**Total**	**25**	**7.0**	**15.3**	**5.2**	**22.9**	**6.5**	**14.2**	**4.8**
Wellington	1LD SaLm/SaClLm/Cl RR	1	19	12.3	14.2	7.1	11.0	7.0	8.1	4.1
		2	35	7.7	9.6	4.2	19.9	4.4	5.5	2.4
		3	**-**	**-**	4.6	3.1	**-**	**-**	2.6	1.8
		Total	**54**	**14.0**	**28.4**	**11.9**	**30.9**	**8.0**	**16.2**	**6.8**
	2LD LmSa	1	16	6.1	28.4	4.6	17.4	6.8	31.6	5.1
		2	N/A	N/A	2.7	1.4	N/A	N/A	3.0	1.5
		Total	**N/A**	**N/A**	**31.2**	**5.6**	**N/A**	**N/A**	**34.6**	**6.3**
	2LD LmSa R	1	14	4.3	17.1	8.1	15.5	4.8	19.1	9.0
		2	6	1.1	10.5	2.0	6.5	1.3	11.7	2.3
		Total	**20**	**5.0**	**27.7**	**7.3**	**21.9**	**5.6**	**30.8**	**8.1**

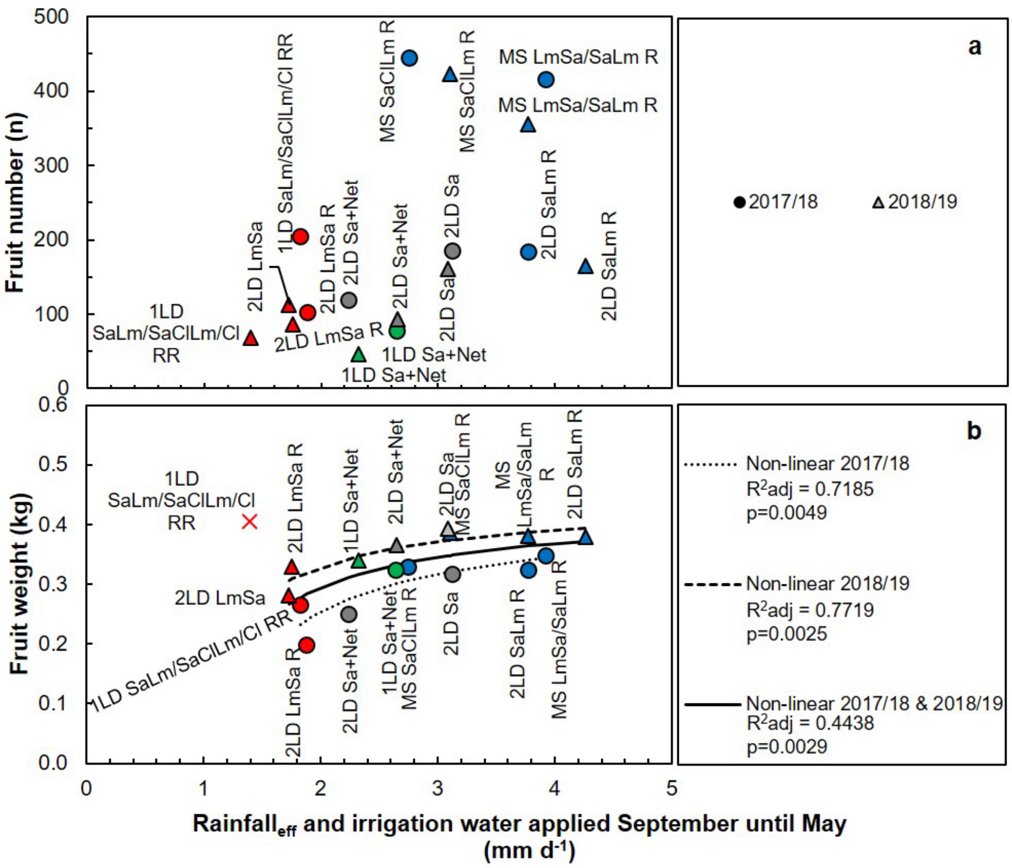

Figure 3.25: The relationship between (a) fruit number per tree and (b) mean fruit weight of full bearing Wonderful pomegranate orchards in the Bonnievale (blue markers), Gouda (grey markers), Wolseley (green markers) and Wellington (red markers) production areas and the amount of effective rainfall (Rainfall$_{eff}$) and irrigation water applied from 1 September until the end of May during the 2017/18 and 2018/19 seasons. Data for 2018/19 for the single-line drip-irrigated orchard from Wellington was considered an outlier (X).

In Gouda, the netted orchard had c. 42% less fruit than the open orchard, with no FCM-infested fruit for the second season. In 2017/18, the Bonnievale area had, on average, the heaviest fruit (c. 315 g), with that in Gouda, Wolseley and Wellington weighing 15, 3 and 30% less (Table 3.16). Fruit weight from trees on heavier soils was c. 14% more than on lighter soils, while that of micro-irrigated trees was c. 17% more than those that were drip-irrigated. In Gouda, the fruit from the netted orchards weighed, on average, 21% less than those from the open orchards.

In 2018/19, fruit from Bonnievale and Gouda had a similar weight (c. 380 g), whereas that from Wolseley and Wellington weighed c. 11% less. Fruit weight from trees on heavier soils was c. 12% more than that from lighter soils, while that of micro-irrigated trees was c. 7% more than those that were drip-irrigated. In Gouda, the fruit from the netted orchards weighed, on average, 7% less than those from the open orchards. Mean fruit weight (based on measured individual fruit weight) and yield tended to increase with the amount of effective rainfall and irrigation water applied from 1 September until the end of May during both seasons (figures 3.25b and 3.26). There was no clear trend with regard to fruit number and the amount of water applied from September until the end of May (Figure 3.25a).

Table 3.16: The average (± standard deviation or SD) fruit number per tree and fruit weight of full-bearing Wonderful pomegranate orchards in the Bonnievale, Gouda, Wolseley and Wellington production areas during the 2017/18 and 2018/19 seasons. [MS = micro-sprinkler; 1LD = single-line drip-irrigation; 2LD = double-line drip-irrigation; R = ridged; RR = ripped ridge]. The soil texture classes include sand (Sa), clay (Cl) and loam (Lm).

Production area	Orchard ID	Harvest	Fruit number (n)				Fruit weight (kg)			
			2017/18		2018/19		2017/18		2018/19	
			Mean	SD	Mean	SD	Mean	SD	Mean	SD
Bonnievale	MS SaClLm R	1	371	89.0	164	58.4	0.338	0.017	0.394	0.019
		2	73	44.5	259	67.7	0.266	0.035	0.380	0.023
		Total	**444**	**62.8**	**423**	**47.5**	**0.328**	**0.015**	**0.385**	**0.021**
	MS LmSa/SaLm R	1	195	87.0	141	37.3	0.362	0.028	0.407	0.042
		2	220	94.2	213	81.6	0.332	0.031	0.362	0.043
		Total	**415**	**119.4**	**354**	**114.3**	**0.347**	**0.030**	**0.380**	**0.043**
	2LD SaLm R	1	33	16.6	81	40.6	0.351	0.050	0.419	0.050
		2	151	17.9	83	17.2	0.319	0.023	0.338	0.065
		Total	**184**	**28.3**	**164**	**50.5**	**0.323**	**0.026**	**0.378**	**0.049**
Gouda	2LD Sa + net	1	58	4.4	32	6.2	0.294	0.021	0.391	0.048
		2	60	23.6	61	20.1	0.201	0.025	0.350	0.056
		Total	**118**	**29.1**	**93**	**22.4**	**0.249**	**0.027**	**0.365**	**0.050**
	2LD Sa	1	71	13.8	37	13.7	0.360	0.012	0.404	0.024
		2	113	51.3	47	11.5	0.285	0.015	0.458	0.039
		3	-	-	76	55.0	-	-	0.327	0.027
		Total	**185**	**46.0**	**160**	**53.6**	**0.316**	**0.004**	**0.393**	**0.033**
Wolseley	1LD Sa + net	**Total**	**77**	**25.9**	**46**	**18.3**	**0.324**	**0.027**	**0.338**	**0.031**
Wellington	1LD SaLm/SaClLm/Cl RR	1	55	33.5	31	15.4	0.338	0.024	0.464	0.062
		2	149	33.8	25	9.1	0.235	0.005	0.390	0.058
		3	-	-	16	11.1	-	-	0.270	0.031
		Total	**204**	**45.5**	**68**	**30.4**	**0.265**	**0.021**	**0.404**	**0.047**
	2LD LmSa	1	71	29.8	97	13.2	0.225	0.022	0.295	0.030
		2	N/A	N/A	15	5.3	N/A	N/A	0.183	0.026
		Total	**N/A**	**N/A**	**112**	**17.1**	**N/A**	**N/A**	**0.281**	**0.025**
	2LD LmSa R	1	69	30.5	42	21.9	0.211	0.024	0.412	0.025
		2	33	6.8	43	9.7	0.177	0.015	0.251	0.031
		Total	**102**	**35.9**	**85**	**21.0**	**0.198**	**0.018**	**0.328**	**0.030**

A relatively poor mathematical fit was obtained for the relationship between yield per tree and the effective rainfall and irrigation, since the micro-sprinkler-irrigated orchards had yields of between 131 and 164 kg per tree, whereas the drip-irrigated orchards yielded only 61.7 kg per tree or less (Figure 3.26a). Yield per hectare and relative yield increased non-linearly with more effective rainfall and irrigation applied if data from netted orchards was considered as outlying values (figures 3.26b and 3.26c). Based on the mathematical relationship between relative yield and effective rainfall and irrigation (Figure 3.26c), it is estimated that 1,165 mm of water is needed from September until the end of May to obtain maximum yield.

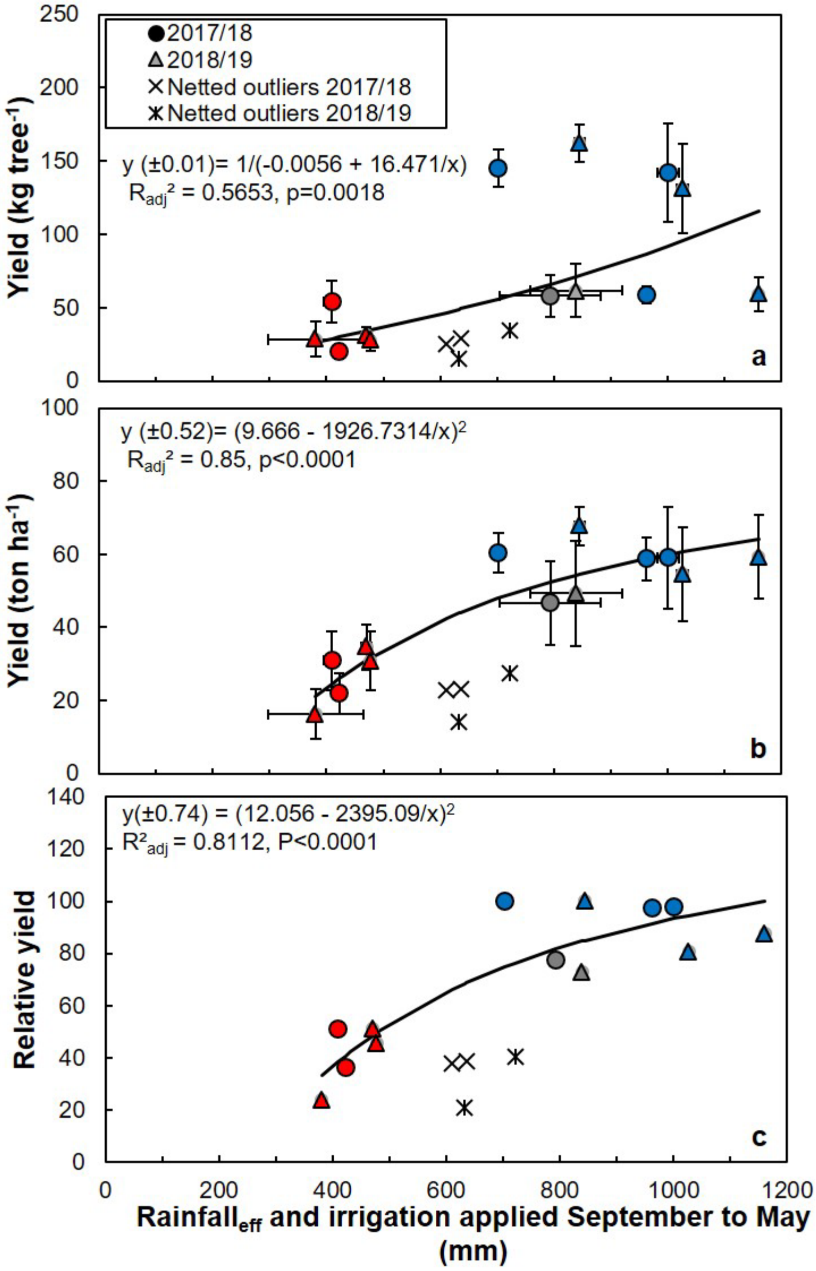

Figure 3.26: The relationship between yield (± standard error) per tree (a), per hectare (b) and relative yield (c) of full-bearing Wonderful pomegranate orchards in the Bonnievale (blue markers), Gouda (grey markers) and Wellington (red markers) production areas and the amount of effective rainfall ($Rainfall_{eff}$) and irrigation water applied from 1 September until the end of May during the 2017/18 and 2018/19 seasons. Mathematical models are based on data of both seasons and netted orchards were omitted as outlying values.

3.3.6.7 Fruit quality

<u>Fruit physico-chemical analysis</u>

Fruit dimensions and moisture content

Fruit weight, length and diameter increased linearly or non-linearly with irrigation rate until harvest, albeit with different trends for the two seasons, or for data of both seasons combined (figures 3.27a to 3.27c). An exception is fruit diameter, for which there was no significant trend with irrigation rate until harvest for the 2018/19 season (Figure 3.27c). Fruit peel moisture content increased non-linearly with higher rates of irrigation applied until harvest for fruit from both seasons, with a linear trend for data of the two seasons combined (Figure 3.27d).

There was no clear trend with regard to peel thickness (range 4.2 mm to 6.6 mm) and rate of effective rainfall and irrigation applied until harvest during both seasons (data not shown). Fruit firmness increased non-linearly and linearly in 2017/18 and 2018/19, respectively, provided some data was omitted as outliers (Figure 3.28). Outlying data points were statistically identified as the netted orchards in Wolseley and Gouda for 2017/18 and the level double-line drip-irrigated loamy sand orchard in Wellington for both seasons. Aril weight of the 2017/18 season increased non-linearly with increased irrigation rate until harvest, with no significant relationship for fruit of the second season (Figure 3.29a). Data of the netted orchard at Gouda was identified as an outlying value. Aril moisture content of fruit of the first season increased non-linearly with increased irrigation rate until harvest, with no significant trend for the second season (Figure 3.29b).

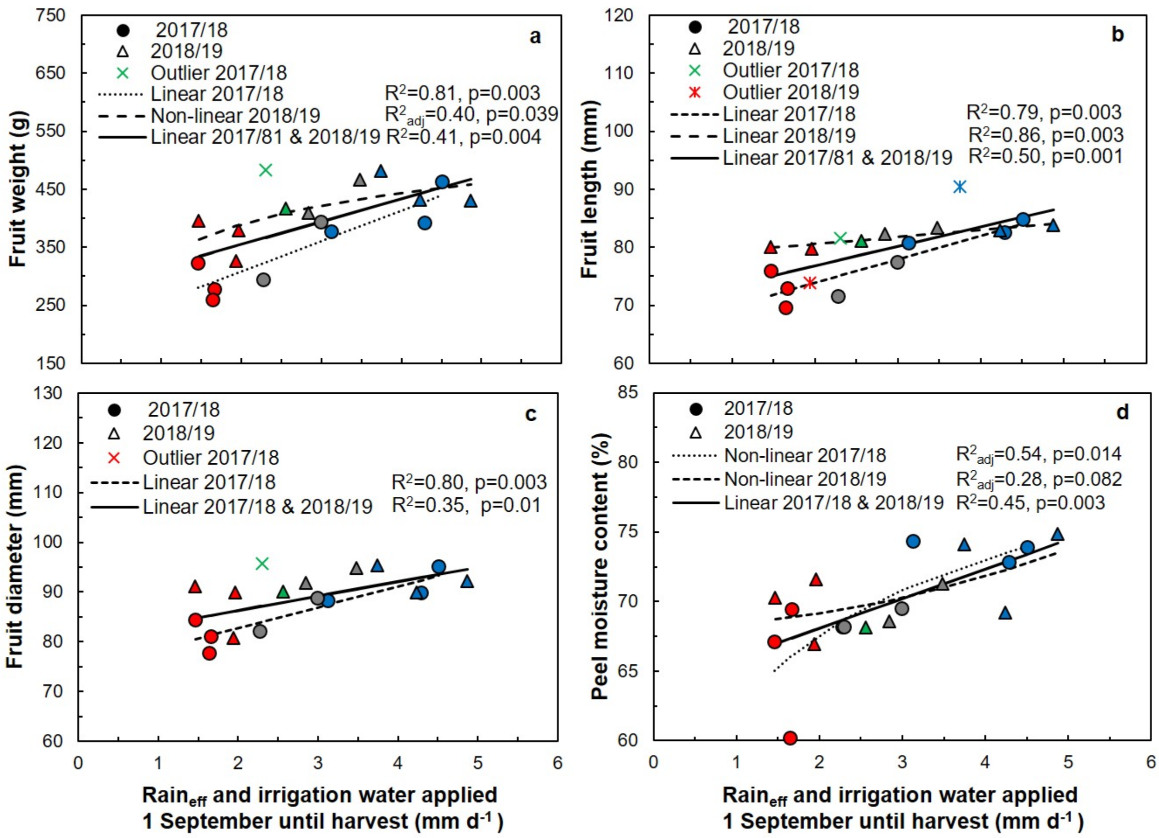

Figure 3.27: Pomegranate (cv. Wonderful) fruit weight (a), length (b) and diameter (c), as well as peel moisture content of fruit on average for all harvests vs effective rainfall and irrigation water applied until harvest in the 2017/18 and 2018/19 seasons. Fruit is from orchards harvested in the Bonnievale (blue markers), Gouda (grey markers), Wolseley (green marker) and Wellington (red markers) production areas.

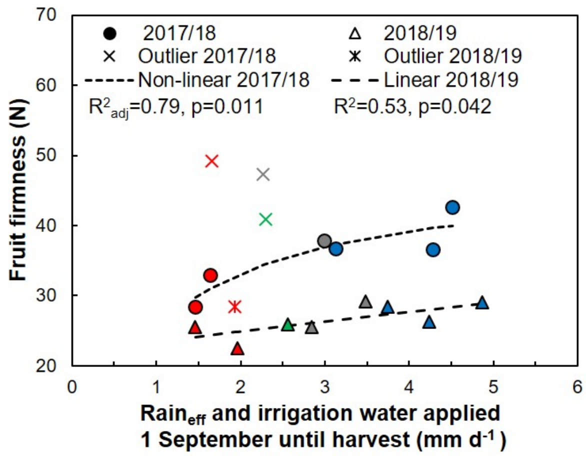

Figure 3.28: Pomegranate (Wonderful) fruit firmness vs effective rainfall and irrigation water applied until harvest in 2017/18 and 2018/19. Fruit was harvested in the Bonnievale (blue markers), Gouda (grey markers), Wolseley (green marker) and Wellington (red markers) production areas.

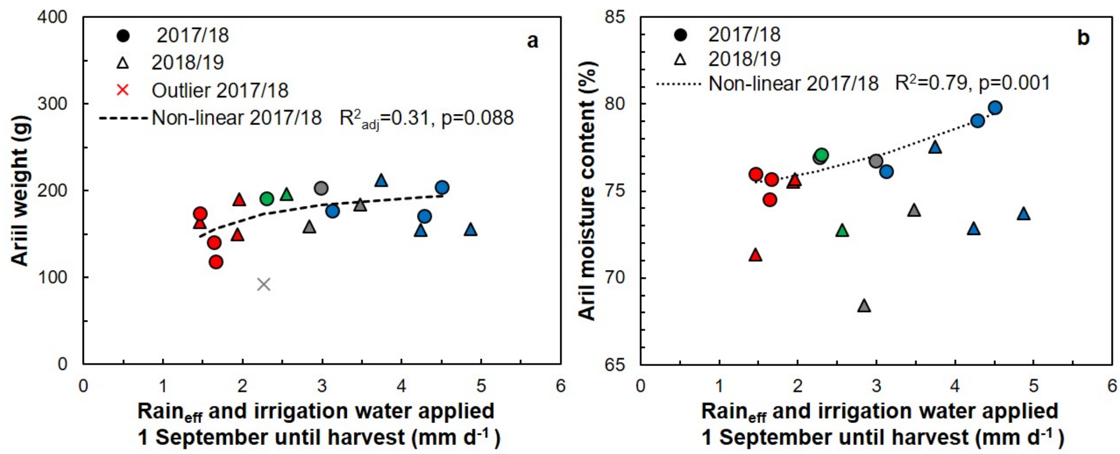

Figure 3.29: Pomegranate (Wonderful) aril weight (a) and aril moisture content (b) of fruit on average for all harvests in 2017/18 and 2018/19. Fruit was harvested in the Bonnievale (blue markers), Gouda (grey markers), Wolseley (green marker) and Wellington (red markers) production areas.

Fruit colour

With regard to fruit peel colour measured with a chromameter, lightness (L*) and hue° tended to increase non-linearly in the first season with higher rates of effective rainfall and irrigation applied, with no significant trend for the second season (figures 3.30a and 3.30c). For data of both seasons combined, hue° also increased non-linearly as rates of effective rainfall and irrigation increased, whereas no significant trend was found for lightness due to divergent data patterns in the two seasons. Red colouration (a*) decreased with increased rate of effective rainfall and irrigation in both seasons and for the combined data set (Figure 3.30b). Chroma tended to decrease with a higher rate of effective rainfall and irrigation applied in the first season, with no significant trend for the second season or in the combined dataset for both seasons. Data for fruit from the double-line drip-irrigated orchard in Bonnievale was identified statistically as outliers for all variables in the first season, and in the case of red colouration, in the second season as well. These values were excluded from the mathematical relationships between fruit colour parameters and the rate of effective rainfall and irrigation applied until harvest, as discussed above. Specific production practice information such as canopy manipulation and fertilizer application for the different orchards that can also affect fruit colouration was not considered in this report and it has to be taken into account that the maturity samples only contained 20 randomly sampled fruit per harvest.

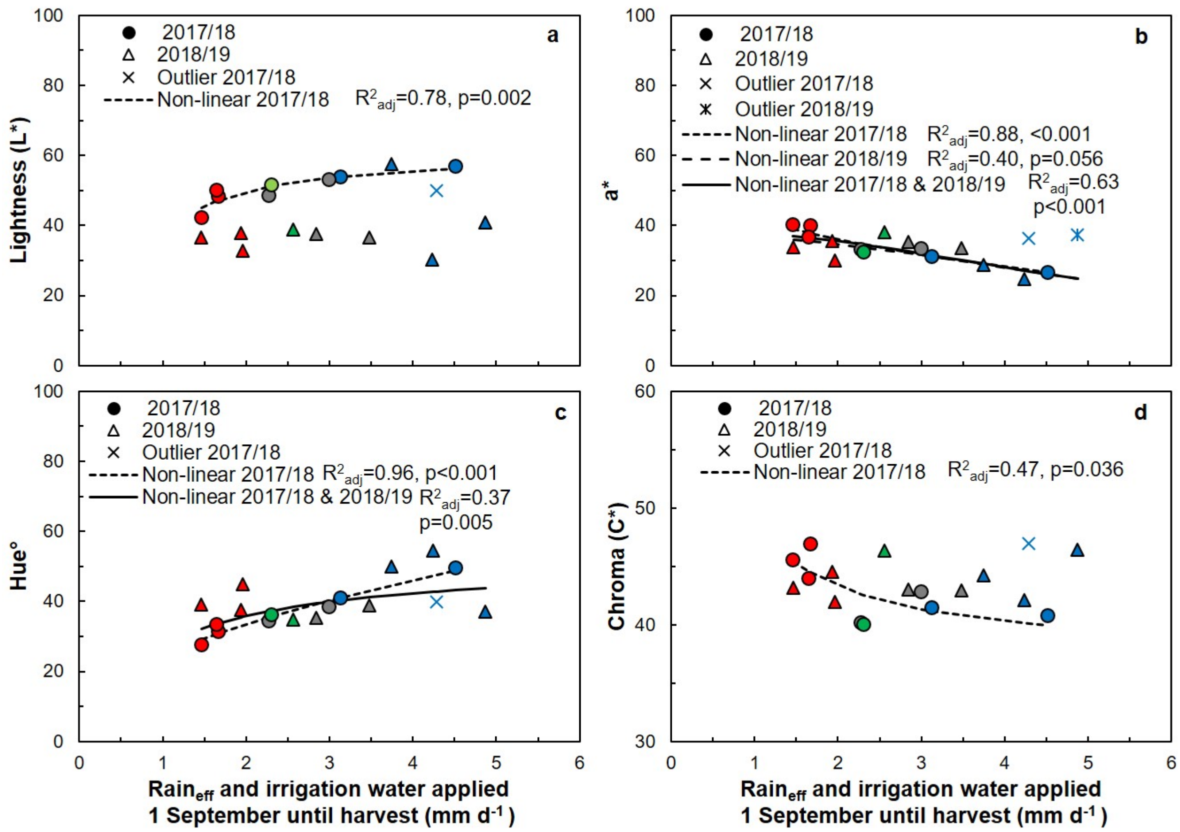

Figure 3.30: Pomegranate (Wonderful) fruit skin lightness, red colour or a* (b), hue (c) and chroma (d) of fruit from 2017/18 and 2018/19. Fruit was harvested in the Bonnievale (blue markers), Gouda (grey markers), Wolseley (green marker) and Wellington (red markers) production areas. Values represent the average of all harvests.

According to Galindo et al. (2017), L* and hue° values of pomegranate peel tended to decrease with accumulated water stress, while a* and C* values increased, resulting in fruit peel with higher redness and darkness values. Likewise, the significant trends in our survey, which were mostly confined to the first season with critical drought, indicated a decrease in L* and hue° and an increase a* and C* with lower rates of effective rainfall and irrigation applied (figures 3.30a to 3.30d).The percentage of fruit with dark-red arils varied between 42 and 97% in 2017/18, and between 50 and 100% in 2018/19 (figures 3.31a and 3.31b). On average for production regions in 2017/18, Bonnievale had the largest number of fruit with a dark-red colour (c. 95% of fruit), followed by Wolseley (c. 85%), Gouda (76%) and Wellington (70%). In 2018/19, though, the average was comparable for Bonnievale and Gouda (c. 84%), followed by Wellington (73%), with the least fruit with a good aril colour from Wolseley (50%).

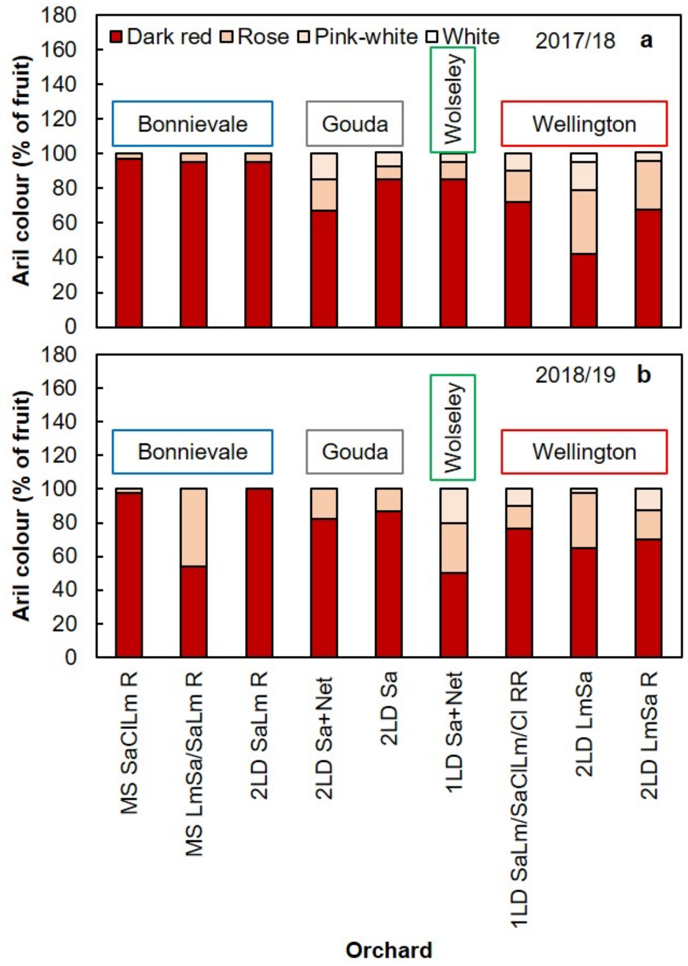

Figure 3.31: Pomegranate (Wonderful) aril colour during the 2017/18 (a) and 2018/19 (b) seasons. Data for the double-line drip-irrigated loamy sand orchard in Wellington for 2017/18 is for Harvest 1 only. [MS = micro-sprinkler; 1LD = single-line drip-irrigation; 2LD = double-line drip-irrigation; R = ridged; RR = ripped ridge]. The soil texture classes include sand (Sa), clay (Cl) and loam (Lm).

The micro-sprinkler-irrigated sandy clay loam orchard from Bonnievale had more than 97% of fruit with dark-red arils in both seasons, whereas 90 and 100% of fruit from the double-line drip-irrigated sandy loam orchard had a sought-after aril colour for the two respective seasons. Orchards producing the least fruit with good aril colour in 2017/18 included the Gouda double-line drip-irrigated sand under net and the Wellington ridged double-line drip-irrigated loamy sand (c. 68% of fruit) (Figure 3.31a). In 2018/19, the single-line drip-irrigated orchard under net in Wolseley and the micro-sprinkler-irrigated loamy sand/sandy loam orchard in Bonnievale had the least fruit with dark-red arils (Figure 3.31b).

In 2017/18, about 96% of fruit from micro-sprinkler-irrigated orchards had dark-red arils compared to 79% of fruit from drip-irrigated orchards, whereas the percentages were comparable in 2018/19. In the two respective seasons, of the fruit produced on heavier soils, 90 and 82% had dark-red arils compared to 76 and 72% of fruit produced on lighter soils. In Gouda in 2017/18, the netted orchard had 21% less fruit with dark-red arils than the open orchard, with only a 5% difference between orchards in the second season. In both seasons, the percentage of fruit with dark-red arils tended to become higher and those with rose-coloured arils became less, with an increased rate of effective rainfall and irrigation until harvest (figures 3.32a and 3.32b).

Data for the micro-sprinkler-irrigated loamy sand/sandy loam ridged orchard in Bonnievale in 2018/19 was statistically identified as an outlier and omitted from the mathematical relationships established.

The high percentage of fruit with dark-red arils for the Bonnievale area compared to Wellington may therefore be partially explained by the higher rate of effective rainfall and irrigation applied.

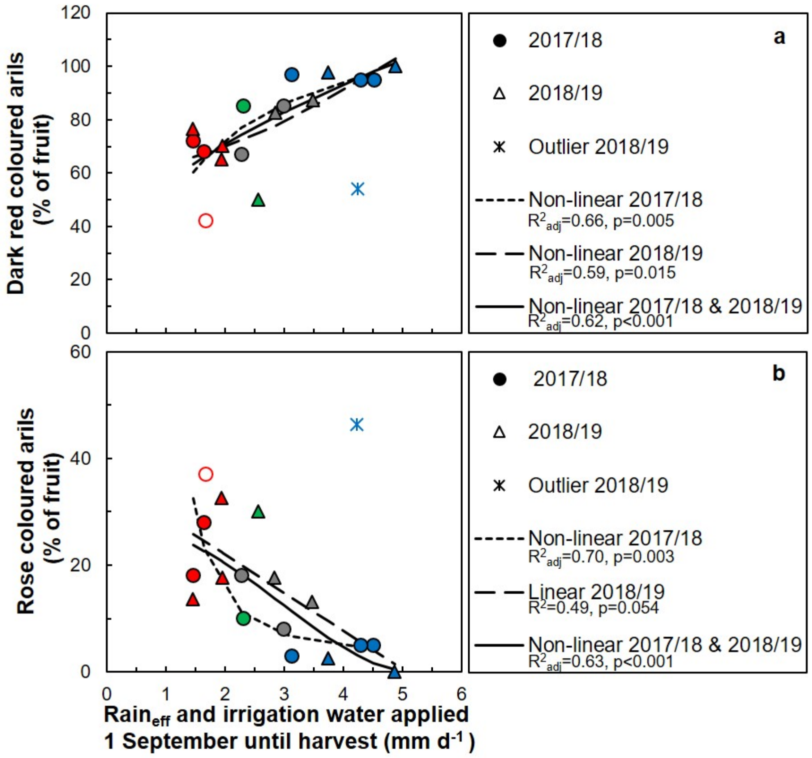

Figure 3.32: The effect of rate of effective rainfall and irrigation until harvest on the percentage of fruit with a) dark-red and b) rose-coloured arils during the 2017/18 and 2018/19 seasons. Fruit is from orchards harvested in the Bonnievale (blue markers), Gouda (grey markers), Wolseley (green marker) and Wellington (red markers) production areas. Data indicated by non-filled red markers are for Harvest 1 only. [MS = micro-sprinkler; 1LD = single-line drip-irrigation; 2LD = double-line drip-irrigation; R = ridged; RR = ripped ridge]. The soil texture classes include sand (Sa), clay (Cl) and loam (Lm).

Total soluble solids, total titratable acidity and pH

The ripeness of all fruit harvested during both seasons conformed to the minimum ripeness requirements of the Department of Agriculture, Forestry and Fisheries for export (14 °Brix) and the more stringent requirements of some export companies (16 °Brix) (Figure 3.33a).The pomegranate mean (± standard error) TSS for 2017/18 ranged between 16.4 (± 0.05) °Brix and 19.3 (± 0.27) °Brix, which was comparable to values of between 15.8 (± 0.05) °Brix and 18.8 (± 0.32) °Brix for the 2018/19 season.

The minimum total TA in fruit juice was c. 25% lower in the second season than the first season (0.74 (± 0.02) g 100 g^{-1}) with the maximum being similar (1.44 (± 0.14) g 100 g^{-1} malic acid). Juice pH for the two seasons was comparable and ranged between 2.1 (± 0.01) and 3.1 (± 0.11). These pH values are considerably lower than the pH of 4.9 reported for Mollar de Elche produced in Spain (Galindo et al., 2017). The MI (ratio of TSS:TA) ranged between 11.4 and 25.5 in 2017/18 and between 11.9 and 30.1 in 2018/19.

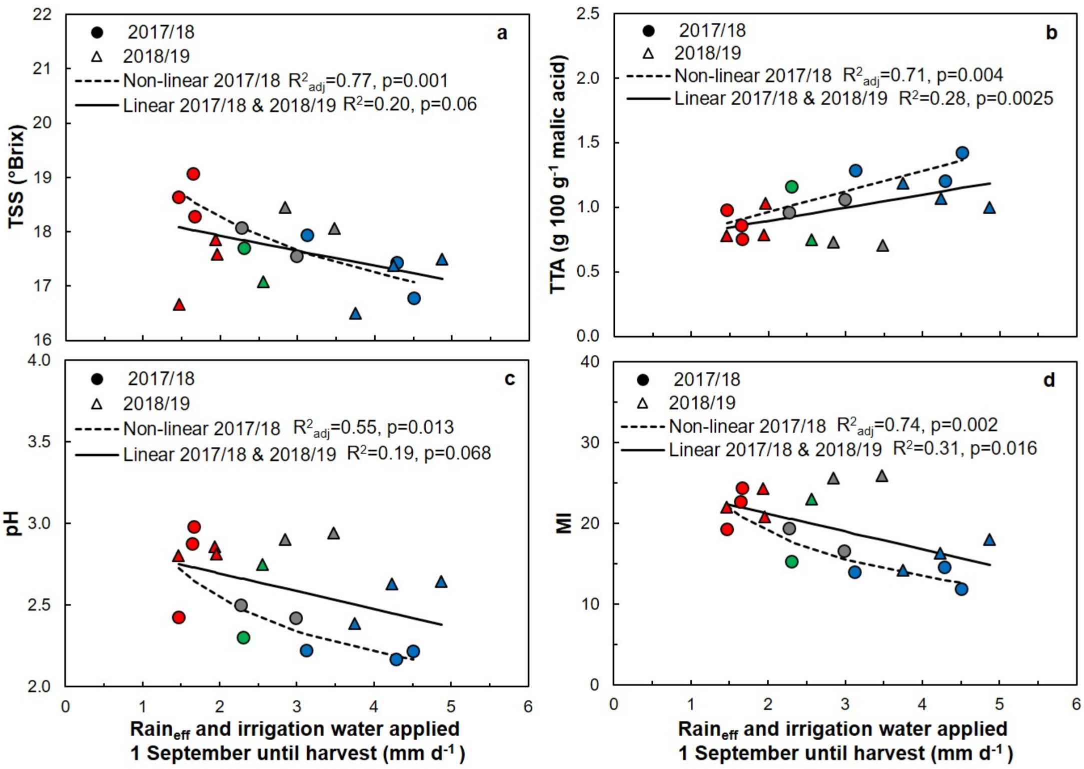

Figure 3.33: The relationship between mean pomegranate (Wonderful) juice a) total soluble solids (TSS), b) titratable acids (TA), c) pH and d) maturity index (MI), respectively, and effective rainfall and irrigation water applied until harvest during the 2017/18 and 2018/19 seasons. Fruit is from orchards harvested in the Bonnievale (blue markers), Gouda (grey markers), Wolseley (green marker) and Wellington (red markers) production areas. Data points are averages of all harvests per season.

With regard to production areas, in 2017/18, the TSS of pomegranate juice was the lowest in Bonnievale (c. 17.5 °Brix), Gouda and Wolseley (c. 17.8 °Brix), with juice from Wellington having the highest sugar content (c. 18.7 °Brix). In 2018/19, the TSS of pomegranate juice was the lowest in Bonnievale and Wolseley (c. 17.1 °Brix) and Wellington (c. 17.3 °Brix), with juice from Gouda having the highest sugar content (c. 18.2 °Brix). For the respective seasons, micro-sprinkler-irrigated orchards had lower pomegranate juice TSS (c. 17.4 and 16.9 °Brix) compared to that of drip-irrigated orchards (c. 18.2 and c. 17.5 °Brix). Fruit juice from orchards on heavier soils also had lower sugar levels (c. 17.7 and c. 16.9 °Brix) than that from orchards on lighter soils (c. 18.2 and c. 17.9 °Brix). The TA of pomegranate juice tended to increase, whereas the TSS, pH and MI decreased with increased rates of irrigation until harvest for the 2017/18 season and for data of both seasons combined (figures 3.33a to 3.33d)). However, in 2018/19, there were no significant statistical relationships between the maturity variables and the rate of effective rainfall and irrigation applied until harvest. The occurrence of rainfall during the harvest period in 2018/19 (figures 3.12 and 3.13) could possibly explain the lack of trends in the second season.

Fruit mineral content

There were no noteworthy significant statistical relationships between macro- or micronutrients in the fruit (Table 3.17) and leaves (tables 3.14 and 3.15) for either season or for the first season with soil sampled during August 2017 (data not shown). In 2017/18, fruit nitrogen, phosphate, potassium, calcium and magnesium content (mg 100 g^{-1} fresh mass) ranged from 185 to 321; 42 to 78; 261 to 429; 20 to 63; and 19 to 28, respectively. Fruit sodium, manganese, iron, copper, zinc and boron content (mg kg^{-1} fresh mass) varied from 22 to 97; 1.6 to 10.3; 4.2 to 68.9; 0.9 to 14.1; 2.3 to 21.6; and 3.3 to 17.

In 2018/19 compared to 2017/18, the content ranges for fruit nitrogen and calcium were slightly higher, and those for phosphate and potassium lower, with the range for magnesium remaining more or less the same. In 2018/19, the fruit sodium content range was between 38 and 77 mg kg^{-1} fresh mass, with that for the other micronutrients being similar to that of the previous season. There was no significant effect of effective rainfall and irrigation that occurred until harvest on fruit nutrient content, except for magnesium in the 2017/18 season. Fruit magnesium content tended to increase non-linearly with a higher rate of effective rainfall and irrigation until harvest (data not shown, $R^2 = 0.40$, $p = 0.066$). If two outlying values were omitted, the magnesium content of fruit increased linearly with effective rainfall and irrigation applied (data not shown $R^2 = 0.96$, $p < 0.001$, $n = 7$).

External and internal physiological disorders

In 2017/18, scuffmarks were most prevalent for the Bonnievale micro-sprinkler-irrigated sandy clay loam orchard (68% of fruit) and the open double-line drip-irrigated orchard on sand in Gouda (60% of fruit), and the least prevalent in the netted single-line drip-irrigated orchard in Wolseley (5%) (Figure 3.34a). The Bonnievale, Gouda and Wellington production areas had, on average, 52, 42 and 34% fruit with scuffmarks. Micro-sprinkler-irrigated orchards had almost double (58%) the percentage of fruit with scuffmarks compared to drip-irrigated orchards (33%), while orchards on heavier soils produced 47% of fruit with scuff marks compared to 31% produced on lighter soils. In Gouda, the netted orchard had 23% fruit with scuffmarks, compared to 60% in the open orchard.

In 2018/19, the prevalence of scuffmarks in all orchards, on average, was about a third compared to the 40% of fruit for 2017/18 (figures 3.34a and 3.34b). It was once again most prevalent in the Bonnievale micro-sprinkler-irrigated sandy clay loam orchard, but the occurrence was less than half that of the previous season (33% of fruit). The least scuffmarks occurred in the netted double-line drip-irrigated orchard in Gouda (3%), which was 10% less compared to the open orchard. For the other orchards, fruit with scuffmarks amounted to 15% or less of the total. The Bonnievale, Gouda, Wolseley and Wellington production areas had, on average, 18, 8, 10 and 11% fruit with scuffmarks. Micro-sprinkler-irrigated orchards had 19% fruit with scuffmarks compared to 11% for drip-irrigated orchards, while orchards on heavier soils produced 17% fruit with scuff marks compared to 8% produced on lighter soils.

Russeting occurred in 2017/18 and 2018/19, on average, for all orchards on 42 and 37% of fruit, respectively (figures 3.34c and 3.34d). The occurrence in orchards ranged between 10 and 73% of fruit in 2017/18, and between 8 and 58% of fruit in 2018/19. Russeting appeared to be more severe in the second season, since, on average, for all orchards, 35, 43 and 21% of the fruit had slight, moderate and severe russeting in 2017/18, compared to 6, 16 and 78%, respectively, in 2018/19. In 2017/18, a more or less similar trend was found for russeting as for scuffmarks, since the same orchards that had the highest and lowest scuffmarks were scored as having the highest russeting, although the single-line drip-irrigated orchard in Wellington had more russeting (55%) than scuffmarks (Figure 3.34c). On average for the Bonnievale, Gouda, Wellington and Wolseley production regions, russeting occurred on 58, 50, 41 and 10% of fruit. Micro-sprinkler-irrigated orchards had 46% more fruit with russeting compared to drip-irrigated orchards, and orchards on heavier soils had 65% more fruit with russeting than those on lighter soils. In Gouda, the netted orchard had about half the percentage of fruit with russeting compared to the open orchard. In 2018/19, on average, for the Bonnievale, Gouda, Wellington and Wolseley production regions, russeting occurred on 22, 50, 46 and 40% of fruit. In contrast to the previous season, micro-sprinkler-irrigated orchards had 31% less fruit with russeting compared to drip-irrigated orchards (45%), and orchards on heavier soils had 14% less russeting than those on lighter soils. In Gouda, the netted orchard had 16% more russeting compared to the open orchard, whereas it was less compared to the open orchards in the previous season.

Table 3.17: Pomegranate (Wonderful) macro- and micronutrient content of fruit harvested in 2018 in the Bonnievale, Gouda, Wolseley and Wellington production areas. Fruit nitrogen (N), phosphate (P), potassium (K), calcium (Ca), magnesium (Mg), sodium (Na), manganese (Mn), iron (Fe), copper (Cu), zinc (Zn) and boron (B) content is displayed. [MS = micro-sprinkler; 1LD = single-line drip-irrigation; 2LD = double-line drip-irrigation; R = ridged; RR = ripped ridge]. The soil texture classes include sand (Sa), clay (Cl) and loam (Lm).

Season	Production area	Orchard	Macronutrients					Micronutrients					
			N	P	K	Ca	Mg	Na	Mn	Fe	Cu	Zn	B
			(mg 100 g^{-1} fresh mass)					(mg kg^{-1} fresh mass)					
2017/18	Bonnievale	MS SaClLm R	277	73.5	358	27.2	24.2	62.6	9.8	68.9	14.1	21.6	15.3
		MS LmSa/SaLm R	289	73.3	308	23.5	27.8	29.2	3.8	9.7	2.4	4.6	6
		2LD SaLm R	321	73.4	301	25.4	27.4	30.2	6.8	10.2	3.2	5	4.4
	Gouda	2LD Sa + net	291	47.0	324	41.2	20.8	51.1	2.5	5.3	0.9	2.5	3.3
		2LD Sa	288	42.0	334	36	22.6	46.3	1.9	4.2	1.1	2.3	5.2
	Wolseley	1LD Sa + net	185	54.8	429	62.8	27.6	43.6	1.6	4.3	1	2.5	4.6
	Wellington	1LD SaLm/SaClLm/Cl RR	296	48.2	261	20.4	20	22	3.7	7.8	2.3	4.3	4.1
		2LD LmSa*	257	55.9	300	22.1	18.7	97	10.3	37.1	7.7	21.2	17
		2LD LmSa R	299	78.0	348	29.5	26.1	55.1	9.9	37.7	9.6	21.3	11.6
2018/19	Bonnievale	MS SaClLm R	248	44.94	404	61.4	23.5	62.6	9.8	68.9	14.1	21.6	15.3
		MS LmSa/SaLm R	368	37.54	348	29.3	17.1	42.2	1.5	12.7	2.0	2.5	3.5
		2LD SaLm R	204	52.80	99	60.7	25.1	38.2	1.8	6.1	1.2	3.0	5.2
	Gouda	2LD Sa + net	266	64.00	100	59.1	25.6	44.1	2.4	6.7	1.4	3.1	4.1
		2LD Sa	286	48.71	91	50.6	30.5	47.1	2.4	6.9	1.3	3.1	5.0
	Wolseley	1LD Sa + net	199	35.81	269	28.1	15.6	42.5	1.3	3.9	1.4	2.2	3.0
	Wellington	1LD SaLm/SaClLm/Cl RR	324	53.94	113	58.3	27.5	77.4	2.6	18.8	2.1	3.8	5.8
		2LD LmSa	256	37.42	91	59.8	22.4	40.6	2.0	35.4	1.2	2.8	5.4
		2LD LmSa R	226	43.07	115	75.4	30.5	39.7	2.0	39.1	1.4	3.2	6.2

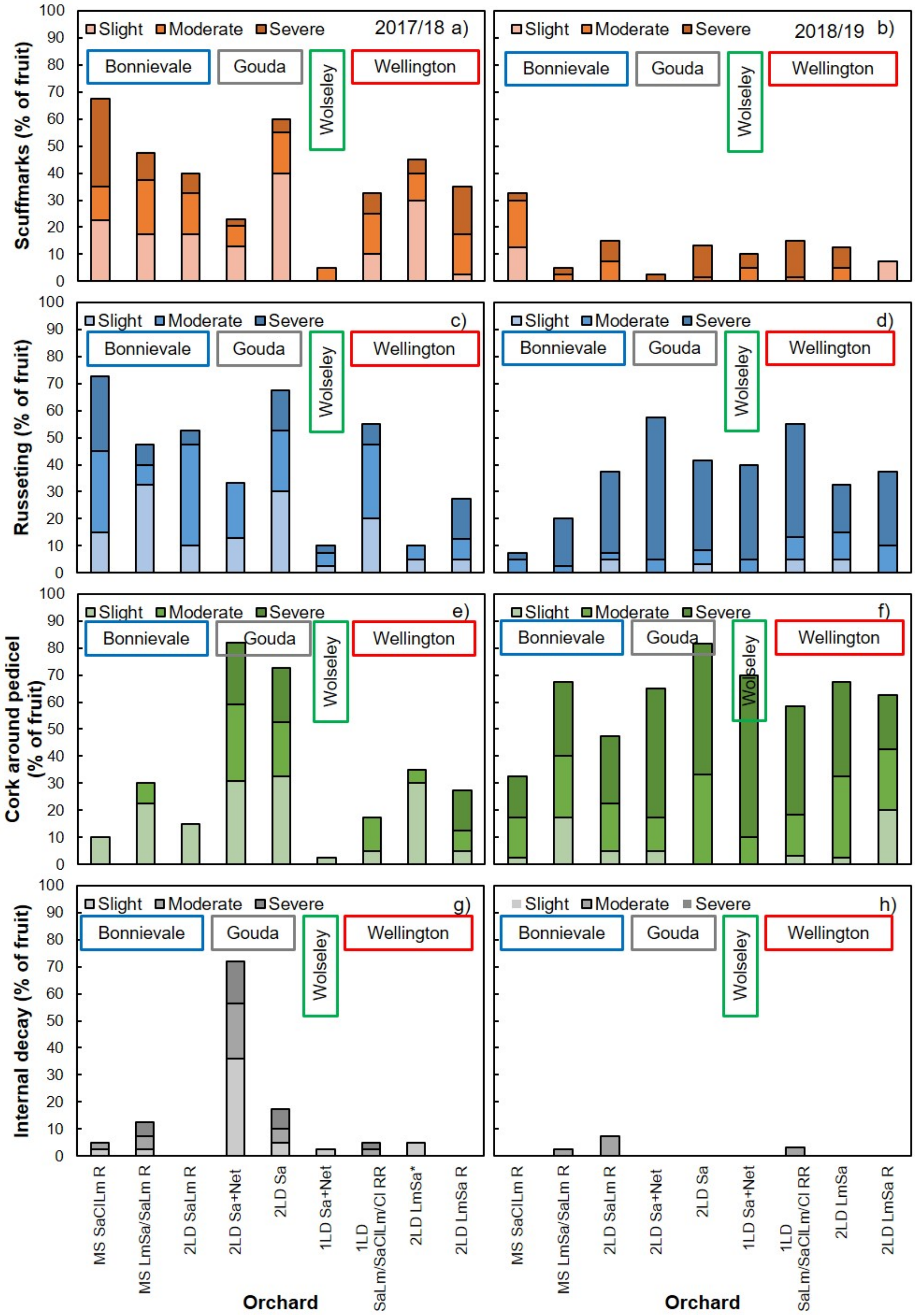

Figure 3.34: External and internal physiological disorders of pomegranate (Wonderful) orchards harvested in the Bonnievale, Gouda, Wolseley and Wellington production areas during the 2017/18 (a, c, e, g) and 2018/19 (b, d, f, h) seasons. Data for the orchard marked with an asterisk is for Harvest 1 only. [MS = micro-sprinkler; 1LD = single-line drip-irrigation; 2LD = double-line drip-irrigation; R = ridged; RR = ripped ridge]. The soil texture classes include sand (Sa), clay (Cl) and loam (Lm).

In 2017/18, cork around the pedicel (Figure 3.34e) was clearly a problem in the Gouda production area (77% of fruit), whereas, in 2018/19, the problem appeared to be more widespread between orchards (Figure 3.34f). Cork around the pedicel occurred in 2017/18 and in 2018/19, on average, for all orchards on 32 and 61% of fruit, respectively. The occurrence in orchards ranged between 3 and 82% of fruit in 2017/18, and between 33 and 82% of fruit in 2018/19. Cork around the pedicel also appeared to be more severe in the second season, since, on average, for all orchards, 52, 28 and 20% of the fruit had slight, moderate and severe degrees of cork around the pedicel in 2017/18, compared to 10, 32 and 58%, respectively, in 2018/19. The Bonnievale, Gouda, Wolseley and Wellington production areas, respectively, had, on average, 18, 77, 3 and 23% of fruit with cork around the pedicel in 2017/18, and 49, 73, 70 and 60% in 2018/19. In 2017/18, micro-sprinkler-irrigated fruit had c. 20% fruit with cork around the pedicel, compared to 36% in fruit in drip-irrigated orchards, and 21 and 40%, respectively, in 2018/19. In both seasons, the disorder tended to be found less on heavier soils (18 and 27% of fruit) compared to lighter soils (46 and 44% of fruit). In Gouda, the netted orchard had 13% more fruit with cork around the pedicel in 2017/18 than the open orchard, and in 2018/19, it had 17% less.

In 2017/18, except for those in Gouda and the micro-sprinkler-irrigated sandy loam/loamy sand orchard in Bonnievale, orchards had 5% or less fruit with internal decay (Figure 3.34g), and in 2018/19, they had less than 8% (Figure 3.34h). In 2017/18, about 40% of the sampled fruit from the netted Gouda orchard was infested with FCM, and 72% of all fruit had internal decay, compared to 18% of the fruit from the open orchards, and 12% in the Bonnievale orchard mentioned above. The netted Gouda orchard is also the only one in which fruit with cracks in the fruit skin was reported (c. 5% of fruit). This was also only for the 2017/18 season, with no occurrence in any of the orchards in 2018/19. There were no significant trends between the physiological disorders discussed above and the rate of effective rainfall and irrigation applied until harvest for both seasons (data not shown).

Marketability

Based on the individual fruit weight of all nine orchards combined, c. 88% of fruit was eligible for export (i.e. > 180 g) for the 2017/18 season (n = 8,995), and c. 93% was eligible for the 2018/19 season (n = 7,524). According to colour classification, using the POMASA fruit colour chart, 19.7 and 7.3% of fruit were classified as Extra Class (photographs 1 and 2 on the POMASA fruit colour chart), c. 63.5 and 60.3% were classified as Class 1 (photographs 3 to 6) and c. 16.8 and 32.4% were classified as Processing Class (photographs 7 to 9) in the two respective seasons. In both seasons, about 69% of the fruit did not have sunburn (Class 1), c. 12% had light- and dark-brown sunburn (Processing Class) and c. 6% had black sunburn (Fallout Class), whereas, in the 2018/19 season, fruit had slightly more light-brown sunburn (c. 16%) compared to 2017/18 (c. 11%). The degree of sunburn was fairly similar for the two seasons and occurred on less than 10% of the surface (Class 1) for about 15% of fruit and on more than 10% of the fruit surface (Processing) for c. 14% of fruit. Cracking in 2017/18 and 2018/19, respectively, was limited to c. 4.7 and 1.8% of fruit having cracks up to the integument, and c. 7 and c. 2% of fruit having cracks reaching the arils. With regard to blemishes for the two respective seasons, c. 37 and 33% of fruit were Extra Class (no blemishes), c. 37 and 35% were Class 1 (blemishes on less than or equal to 10% of the fruit surface), c. 14% and 18% were Processing Class (blemishes on more than 10%, but less than or equal to 25% of the fruit surface) and c. 12 and 14% were Fallout Class (blemishes on more than 25% of the fruit surface).

Please note that, for the 2017/18 season, means of variables for production areas, micro-sprinkler vs drip-irrigated and heavier vs light soils exclude data of the level double-line drip-irrigated orchard in Wellington. Harvest data was not complete and quality data in graphs depicts only the first harvest. Heavier soils refer to soils that include sandy clay loam, sandy loam or clay in their classification, whereas lighter soils refer to loamy sand and sandy soils.

Individual fruit weight

Based on individual fruit weight, more than 85% of fruit from six of the nine orchards was suitable for export (i.e. weighed > 180 g) in 2017/18, whereas, in 2018/19, more than 83% of fruit from all orchards qualified for export (figures 3.35a and 3.35b). The exceptions in 2017/18 were the micro-sprinkler-irrigated ridged sandy clay loam orchard of Bonnievale, and the level and ridged double-line drip-irrigated loamy sand orchards of Wellington, of which c. 76, c. 70 and c. 53% of fruit, respectively, were eligible for export (Figure 3.35a). With regard to the different production areas, c. 88% of Bonnievale and Gouda fruit, c. 86% of Wolseley fruit and c. 74% of Wellington fruit were suitable for export based on an individual fruit weight of more than 180 g in 2017/18. In 2018/19, more fruit from Bonnievale (c. 95%), Gouda (c. 92%) and Wellington (c. 90%) passed the export standard, whereas the situation remained similar for Wolseley. Although there was no real difference in the percentage of exportable fruit based on fruit weight between micro-irrigated and drip-irrigated orchards in 2017/18, the former had 5% more fruit for export in 2018/19 than the latter. Of fruit produced on heavier soils (sand clay loam, sandy loam) in the respective seasons, c. 89 and 95% qualified for export, compared to 79 and 88% on lighter (sand, loamy sand) soils. At Gouda, the netted orchard had c. 4% more fruit that qualified for export in 2017/18 than the open orchard, and 2% less in 2018/19.

Fruit skin colour

According to skin colour, the micro-sprinkler-irrigated orchards in Bonnievale had the least fruit (c. < 8% and c. <1%, respectively) suitable for Extra Class (photographs 1 and 2 on the POMASA fruit colour chart) (figures 3.35c and 3.35d) in both seasons. In 2017/18, about half the fruit of the Wellington single-line drip-irrigated sandy loam/sandy clay loam/clay ripped ridge orchard had an excellent colour, but in 2018/19, the first season's trees had been trained on a trellis system. This decreased to 14% of fruit (Figure 3.28b). For this orchard, though, 87 and 96% of fruit was either Extra Class or Class 1 (Figure 3.32d) in the first and second seasons, respectively. The saline irrigation water used in this orchard (Table 3.4) may have an improved fruit colour. Borochov-Neori et al. (2014) found that anthocyanin accumulation in the pomegranate (Wonderful) peel increased as irrigation water salinity increased from 100 to 600 mS m^{-1}. The high percentage of Extra Class fruit for the level Wellington sandy loam orchard (c. 57%) only reflects fruit quality of the first harvest in 2017/18 (Figure 3.35c). For the other orchards, about a quarter (c. 23%) of fruit was suitable for Extra Class in the first season. In 2018/19, the Gouda orchards had, on average, 22% of Extra Class fruit, with the drip-irrigated orchards in Bonnievale, Wolseley and Wellington having less than 15%.

In 2017/18, based on colour, the micro-sprinkler-irrigated orchards in Bonnievale had between 72 and 77% Class 1 fruit, followed by the netted single-line drip-irrigated sandy soil orchard in Wolseley (c. 68%) (Figure 3.35c). The drip-irrigated orchards in Bonnievale and Gouda had, on average, c. 60% Class 1 fruit, and the single-line drip-irrigated orchard on sandy loam/sandy clay loam/clay in Wellington had c. 36% Class 1 fruit. The Wellington ridged double-line drip-irrigated loamy sand orchard, which was subjected to severe water deficits (refer to Table 3.13), had c. 50% Class 1 fruit and the most fruit for processing due to poor colour development (i.e. c. 25%). In 2018/19, the Wellington single-line drip-irrigated sandy loam/sandy clay loam/clay ripped ridge orchard had the most Class 1 fruit (81%), followed by the drip-irrigated sandy loam orchard in Bonnievale (74%) and the level double-line drip-irrigated loamy sand orchard in Wellington (71%) (Figure 3.35d).

The micro-sprinkler-irrigated sandy clay loam orchard of Bonnievale had 68% Class 1 fruit, compared to 44% for trees on the loamy sand/sandy loam. The netted Gouda orchard had 63% Class 1 fruit compared to 60% for the open orchard. Both the Wolseley and the double-line drip-irrigated ridged loamy sand orchard in Wellington had 14% less Class 1 fruit compared to the previous season. More than half of the fruit (56%) from the latter orchard and the micro-sprinkler-irrigated loamy sand/sandy loam orchard in Bonnievale was only suitable for processing due to poor colour development.

Shoot growth rate of the loamy sand/sandy loam orchard in Bonnievale was of the highest in 2018/19 and dense canopies may partially explain poor colour development. However, this was not the case for the Wellington orchard (Figure 3.15b).

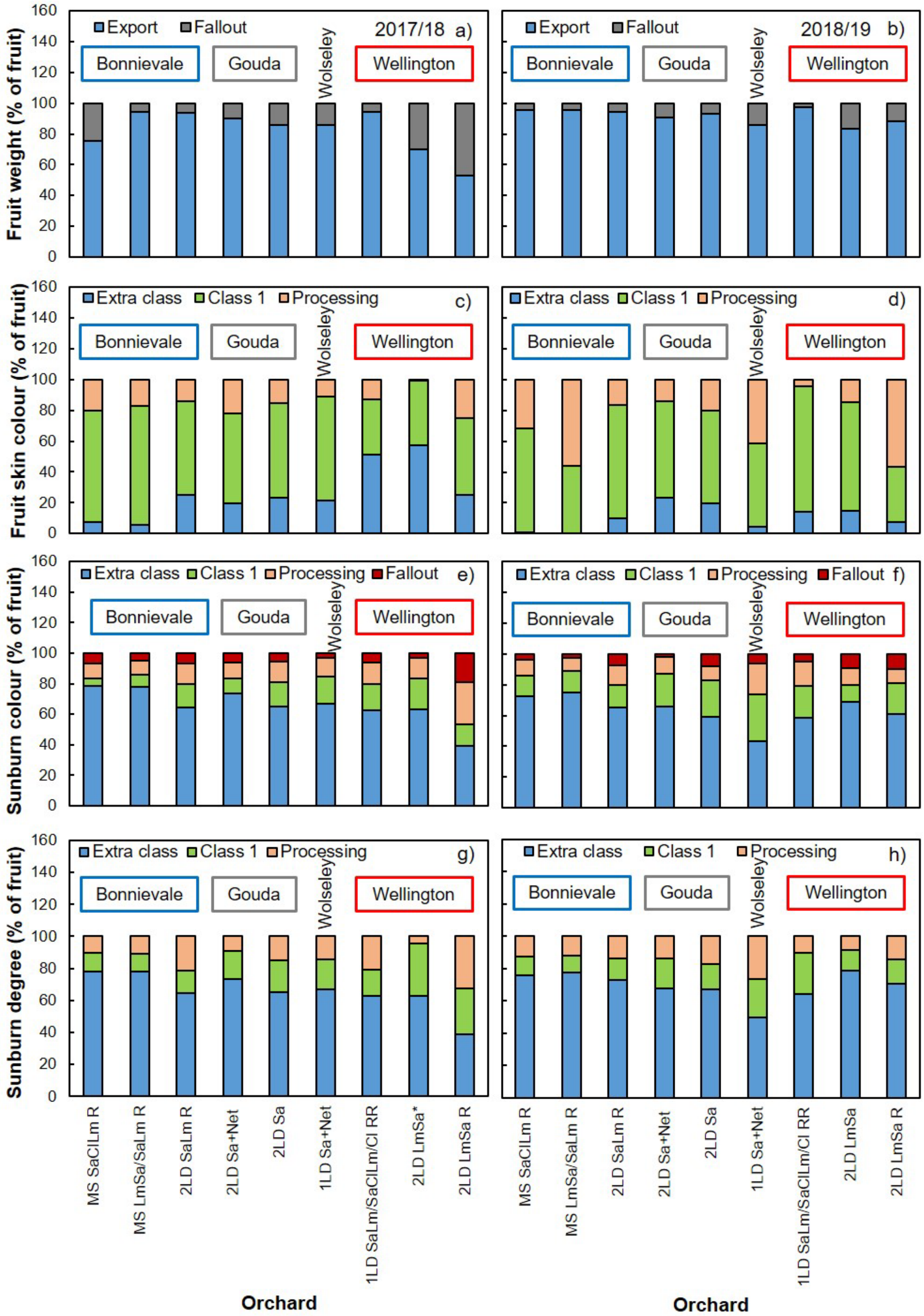

Figure 3.35: Fruit marketability classification (Extra Class, Class 1, Processing and Fallout) for pomegranate (Wonderful) orchards harvested in the Bonnievale, Gouda, Wolseley and Wellington production areas during the 2017/18 (a, c, e, g) and 2018/19 (b, d, f, h) seasons for individual fruit weight (a, b), fruit skin colour (c, d), sunburn colour (e, f) and sunburn degree (g, h). Data for the orchard marked with an asterisk is for Harvest 1 only. [MS = micro-sprinkler; 1LD = single-line drip-irrigation; 2LD = double-line drip-irrigation; R = ridged; RR = ripped ridge]. The soil texture classes include sand (Sa), clay (Cl) and loam (Lm).

Based on colour, in 2017/18, the netted orchard in Gouda had c. 4% less Extra Class, c. 2% less Class 1 and c. 6% more Processing fruit compared to the open orchard (Figure 3.35c). In 2018/19, the netted orchard had c. 3% more Extra Class (23%) and Class 1 (63%) fruit, respectively, and c. 6% less Processing fruit compared to the open orchard (Figure 3.35d).

With regard to the different production areas in the 2017/18 and 2018/19 seasons, c. 13 and 4% of Bonnievale fruit, c. 21 and 22% of Gouda fruit, 21 and 4% of Wolseley fruit, and c. 38 and 12% of Wellington fruit had Extra Class colour, with c. 70 and 60%; 60 and 61%; c. 68 and 54%; and 43 and 63% of fruit in the respective areas being Class 1. In 2017/18, the Wolseley orchard, even though it was under net, had the least poorly coloured fruit (c. 11%), with Bonnievale having c. 17% and Gouda and Wellington having c. 19% of Processing fruit based on colour. In contrast to the previous season, in 2018/19, Wolseley had the most Processing fruit based on colour (41%), followed by Bonnievale (34%), Wellington (25%) and Gouda (17%). In 2017/18, the majority of fruit from the micro-irrigated orchards was Class 1 (c. 75%), with a mere c. 6% Extra Class. In 2018/19, though, only 56% was Class 1, with less than 1% Extra Class. Fruit from drip-irrigated orchards appeared to have a better colour, as c. 28 and 13% of fruit was Extra Class and c. 56 and 63% was Class 1 in 2017/18 and 2018/19, respectively. There was, on average, no meaningful difference in colour classification for fruit from heavier and lighter soils, respectively, in 2017/18. However, in 2018/19, heavier soils had 10% more Class 1 fruit (67%) and 8% less Extra Class fruit (6%) compared to fruit from lighter soils, with no real difference in the amount of Processing fruit (on average, c. 28%).

Sunburn colour

Sunburn per orchard varied between c. 22 and 61% of harvested fruit in the 2017/18 season, and between 25 and 57% in 2018/19. In 2017/18, the micro-irrigated orchards in Bonnievale and the netted double-line drip-irrigated sandy soil orchard at Gouda had the least sunburnt fruit (c. 22 and c. 27%, respectively), with between c. 5 and 10% of fruit having light-brown (Class 1) and c. 10% light- and dark-brown sunburn (Processing) (Figure 3.35e). The percentage of sunburnt fruit in the other drip-irrigated orchards ranged between 33 and 37%, except for the ridged double-line drip-irrigated loamy sand orchard in Wellington, which had c. 61% of fruit with various degrees of sunburn.

In 2018/19, the micro-irrigated orchards in Bonnievale once again had the least sunburnt fruit (on average, c. 26%) with between c. 14% of fruit having light-brown sunburn (Class 1), c. 10% light- and dark-brown sunburn (Processing) and 3% black sunburn (Fallout) (Figure 3.35f). The drip-irrigated orchard in Bonnievale had 35% sunburnt fruit, of which c. 14% had light-brown sunburn (Class 1), c. 12% had light- and dark-brown sunburn (Processing) and 8% had black sunburn (Fallout). The netted and open double-line drip-irrigated sandy soil orchards at Gouda had 34 and 41% sunburnt fruit, respectively. The open orchard had 6% more black sunburnt fruit than the netted orchard (2%). The Wellington ridged double-line drip-irrigated level and ridged loamy sand orchards, as well as the single-line drip-irrigated sandy loam/sandy clay loam/clay ripped ridge orchard had 31, 39 and 41% of sunburnt fruit, respectively. The amount of black sunburn in the loamy sand orchards amounted to c. 10%, and in the single-line drip-irrigated orchard, it amounted to 5%. Wolseley had the highest number of sunburnt fruit, which increased by 24% compared to the previous season (33%), with 30% being light brown, 20% being light and dark brown and 7% being black. The percentage of light-brown sunburnt fruit in orchards ranged between 14.5 and c. 18% in the first season, and between 11 and 30% in the second season.

In 2017/18, the number of light- and dark-brown sunburnt fruit was between c. 12 and 14%, except for the ridged double-line drip-irrigated loamy sand orchard in Wellington, which had about double the amount of Processing fruit (c. 28%). It is most likely that severe water deficits in the latter orchard (refer to Table 3.13) contributed to the c. 19% of fruit with unacceptable levels of sunburn (i.e black) compared to between c. 3 and c. 6% in the other orchards.

In 2018/19, the number of light- and dark-brown sunburnt fruit ranged between 9 and 12%, except for the single-line drip-irrigated orchards in Wellington and Wolseley, where it reached 16 and 20%, respectively. The percentage of sunburnt fruit at harvest increased with lower (i.e. more negative) shoot xylem water potential during the fruit growth stage, provided that two outlying values were omitted from statistical analysis in 2018/19 (Figure 3.36). Further research is needed to confirm the effect of tree water status on the amount of fruit with sunburn at harvest. Although there was large variation, the total percentage of fruit with sunburn decreased with an increased rate of effective rainfall and irrigation between the fruit growth stage and harvest (Figure 3.37).

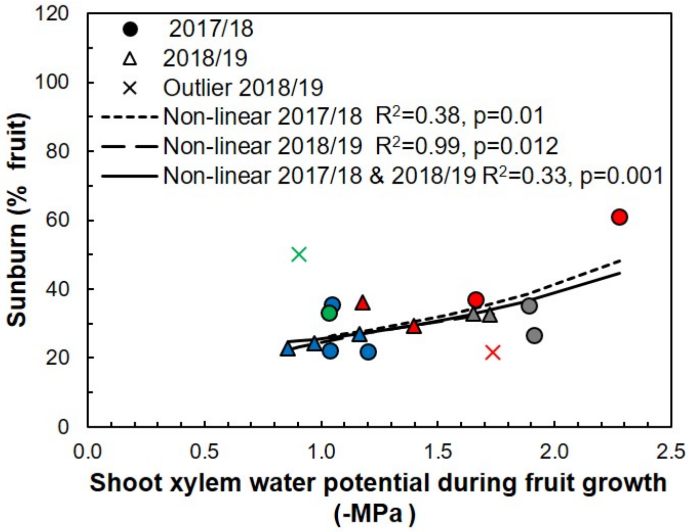

Figure 3.36: The relationship between the percentage of sunburnt fruit at harvest and shoot xylem water potential of pomegranate trees (Wonderful) during the fruit growth stage in 2017/18 and 2018/19. The Bonnievale (blue markers), Gouda (grey markers), Wolseley (green marker) and Wellington (red markers) production areas are indicated.

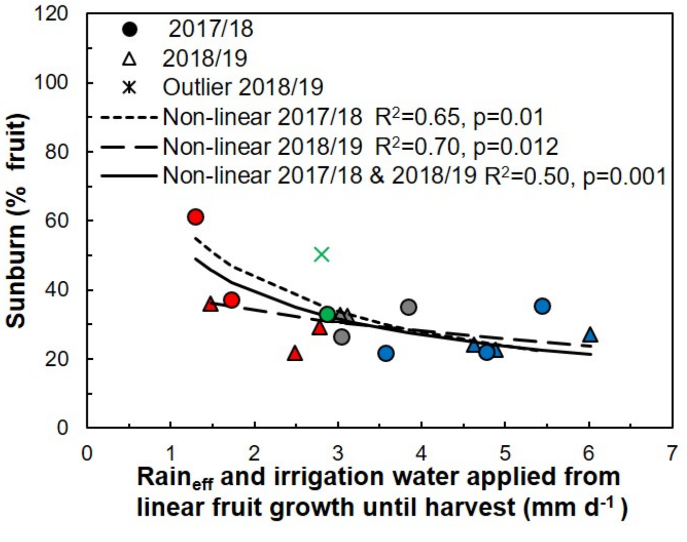

Figure 3.37: The relationship between the percentage of sunburnt fruit of pomegranate trees (Wonderful) at harvest and the rate of effective rainfall and irrigation from linear fruit growth until harvest of the 2017/18 and 2018/19 seasons. The Bonnievale (blue markers), Gouda (grey markers), Wolseley (green marker) and Wellington (red markers) production areas are indicated.

For the different production areas, in 2017/18 and 2018/19, on average, c. 26 and 29% of Bonnievale, 31 and 38% of Gouda, c. 33 and 57% of Wolseley, and c. 49 and 37% of Wellington fruit had some sunburn. In the respective areas and seasons, c. 9 and 14%; 13 and 22%; 18 and 30%; and 16 and 17% of these fruit were light brown, whereas, for both seasons, c. 12 and 10%; c. 12 and 20%; and c. 21 and 12% was light- and dark-brown. The percentage Fallout (i.e. black fruit) in 2017/18 and 2018/19, respectively, was the highest in Wellington (c. 12 and 8%), with that in Bonnievale and Gouda being 6 and 5%, and that in Wolseley being 3 and 7%. Micro-sprinkler-irrigated trees had 16 and 13% less sunburnt fruit than drip-irrigated orchards in the two seasons. The micro-sprinkler-irrigated orchards had 9 and 6% less Class 1; 5 and 3% less Processing; and 2 and 4% less Fallout fruit than drip-irrigated trees in the 2017/18 and 2018/19 seasons, respectively. Likewise, trees on heavier soils had 10 and 8% less sunburnt fruit compared to those on lighter soils in the two respective seasons. The orchards with heavier soils had 3 and 6% less Class 1; 4% less or similar Processing; and 3 and 2% less Fallout fruit than orchards on lighter soils. In the 2017/18 and 2018/19 seasons, the netted Gouda orchard had 9 and 7% less sunburnt fruit, respectively, than the open orchard. The netted orchard had 6 and 2% less Class 1, 4% less and 2% more Processing, and 0.7% more and 6% less Fallout fruit than the open orchard.

Sunburn degree

In 2017/18, as in the case of sunburn colour, the micro-sprinkler-irrigated orchards in Bonnievale had the lowest degree of sunburn, with almost similar amounts of fruit being Class 1 and Processing (c. 11%) (Figure 3.35g). In 2017/18, in the other orchards, the Class 1 degree of sunburn and fruit having sunburn on more than 10% of the fruit surface (Processing fruit) varied between c. 14 and 21%, except for the netted orchard, which had only 9% fruit destined for processing due to sunburn. The other exception was the ridged double-line drip-irrigated loamy sand orchard in Wellington, of which c. 29% of the fruit had sunburn on less than or equal to 10% of the fruit surface and c. 31% of fruit had sunburn on more than 10% of the fruit surface.

In 2018/19, the degree of sunburn was once again of the lowest in the Bonnievale micro-sprinkler-irrigated orchards, i.e. c. 23%, with c. 11% being Class 1 and 12% being Processing fruit. In the second season, though, it was the lowest in the Wellington level double-line drip-irrigated loamy sand orchard (22%), with 13% of fruit being Class 1 and 9% being suitable for processing. For the rest of the orchards, the Class 1 degree of sunburn ranged from c. 13 to 26%, with fruit having sunburn on more than 10% of the fruit surface (Processing fruit) varying between 10 and 17%. The total percentage of fruit with sunburn ranged between 27 and 36%. The netted single-line drip-irrigated orchard in Wolseley had the highest number of fruit with sunburn, i.e. 50%, of which 23% was Class 1 fruit and 27% was Processing fruit.

With regard to the different production areas, in 2017/18 and 2018/19, c. 12% of Bonnievale; 19 and 17% of Gouda; c. 19 and 23% of Wolseley; and c. 22 and 18% of Wellington had sunburn on less than or equal to 10% of the fruit surface in the respective seasons. In 2017/18, the percentage of fruit with sunburn on more than 10% of the surface ranged between c. 12 and c. 14% for the Bonnievale, Gouda and Wolseley areas, but increased to c. 27% in the Wellington area. In 2018/19, though, fruit suitable for processing was 13, 16, 27 and 11% of the total in the respective areas. According to the degree of sunburn in 2017/18, micro-sprinkler-irrigated compared to drip-irrigated orchards had c. 8% less fruit destined for Class 1 and Processing, respectively. In 2018/19, micro-sprinkler-irrigated orchards had 7% less Class 1 and 3% less Processing fruit than the drip-irrigated orchards. In 2017/18 and 2018/19, respectively, orchards on heavier soils had 8 and 3% less Class 1 fruit and 2 and 4% less Processing fruit compared to orchards on lighter soils. In Gouda, in the two respective seasons, the netted orchard had c. 3% less and 4% more Class 1 fruit, and c. 6 and 3% less Processing fruit, compared to the open orchard.

Blemishes

Although blemishes are not a direct effect of the application of irrigation water, they may increase with excessive vegetative growth, which may occur under conditions of luxurious irrigation combined with the presence of wind. The percentage of fruit with blemishes ranged from 45 to 79% between orchards (figures 3.38a and 3.38b) for the two seasons. Netted orchards had the lowest percentage of blemishes in 2017/18 (c. 45%), but in 2018/19, blemishes in the Wolseley orchard increased to 63%, with that in Gouda being comparable to that of the first season.

In 2017/18, the orchards with the highest percentage of blemishes included the micro-sprinkler-irrigated sandy clay loam orchard in Bonnievale and the ridged double-line drip-irrigated loamy sand orchard in Wellington (Figure 3.38a). Both these orchards had more than 40% Class 1 fruit (blemishes < 10% of the fruit surface) and c. 17% of fruit unsuitable for export (blemishes > 25% of the fruit surface). In 2018/19, the micro-sprinkler-irrigated sandy clay loam orchard in Bonnievale once again had the highest percentage of blemishes (73%) with 41% of fruit being Class 1 and 13% of fruit not being suitable for export. The Gouda double-line drip-irrigated sandy soil orchard had 71% of fruit with blemishes, of which 29% was Class 1 and 23% was not suitable for export. For the rest of the orchards, blemishes ranged from 64 to 68% of fruit with between 11 and 18% of fruit not being suitable for export. In the 2017/18 and 2018/19 seasons, the micro-irrigated orchards had 12 and 6% more blemishes than the drip-irrigated orchards, with the orchards on heavy soils having a mere 4 and 7% more blemishes than the orchards on lighter soils. In Gouda, the netted orchard had 15 and 26% less fruit with blemishes in the respective seasons than the open orchard, of which c. 10 and 14% was attributed to less fallout.

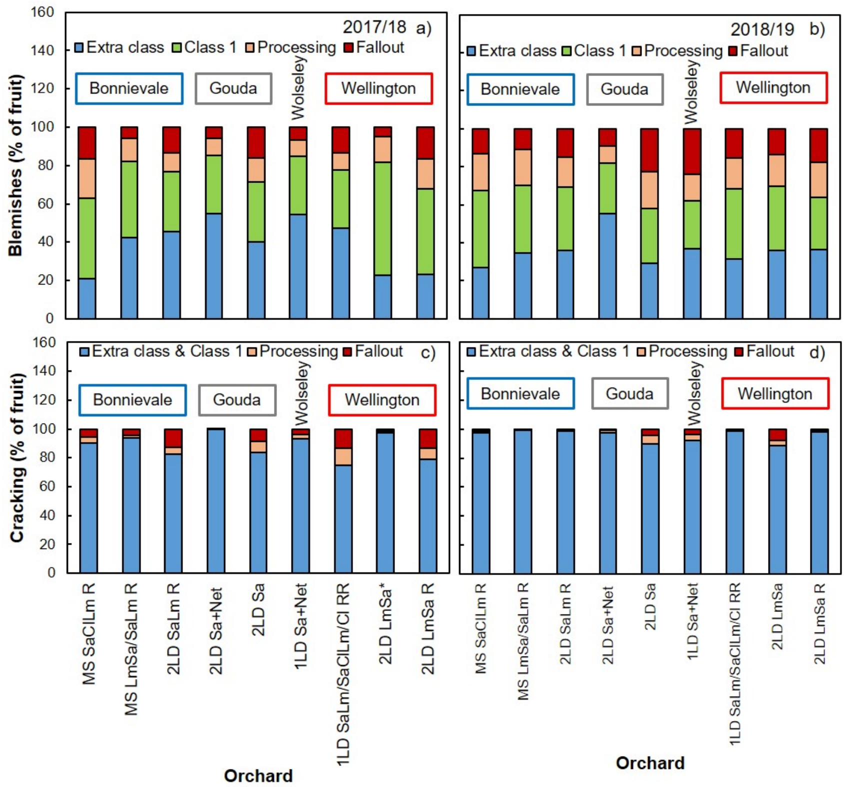

Figure 3.38: Fruit marketability classification (Extra Class, Class 1, Processing and Fallout) for pomegranate (Wonderful) orchards harvested in the Bonnievale, Gouda, Wolseley and Wellington production areas during the 2017/18 (a, c) and 2018/19 (b, d) seasons for blemishes (a, b) and cracking (c, d) of fruit. Data for the orchard marked with an asterisk is for Harvest 1 only. [MS = micro-sprinkler; 1LD = single-line drip-irrigation; 2LD = double-line drip-irrigation; R = ridged; RR = ripped ridge]. The soil texture classes include sand (Sa), clay (Cl) and loam (Lm).

Cracking

In 2017/18, the amount of cracking in orchards ranged between less than 1% to c. 25%, and in 2018/19, between 1 and 12% (figures 3.38c and 3.38d). In 2017/18, orchards where the cracking of fruit was the least included the micro-sprinkler-irrigated orchards in Bonnievale (between c. 6 and c. 10% of fruit) and the netted orchards in Gouda (0.5% of fruit) and Wolseley (c. 6.5% of fruit). The percentage of fruit with cracks in the other orchards ranged between 16.5 and c. 25% (Figure 3.38a). In 2018/19, although cracking was 3% or less in all orchards except for Wolseley (8%), the open double-line drip-irrigated orchard at Gouda (10%) and the level double-line drip-irrigated orchard in Wellington (12%) (Figure 3.38b). With regard to the cracking of fruit in the different production areas in 2017/18 and 2018/19, Wolseley, Gouda, Bonnievale and Wellington, respectively, had c. 6 and 8%; c. 8 and 6%; c. 11 and 2%; and c. 23 and 5% of cracked fruit in the respective seasons.

Micro-sprinkler-irrigated compared to drip-irrigated orchards had, on average, c. 7% less cracked fruit, with c. 3% less in Class 1 and c. 4% less fruit destined for processing. In 2018/19, the difference in cracking between micro-sprinkler and drip-irrigated orchards was minor and amounted to only 3%. In 2017/18, orchards on heavier soils had c. 4% more cracked fruit than those on lighter soils, of which c. 3% were Processing Class. In 2018/19, though, orchards on heavier soils had 5% less cracked fruit than those on lighter soils, of which c. 2% were Processing Class. In 2017/18, the netted orchard in Gouda had c. 16% less cracked fruit compared to that in the open orchard, with equal amounts of fruit from the open orchard classed as Processing and Fallout (c. 8%). In 2018/19, the netted orchard had 7% less cracked fruit than the open orchard, with 6 and 4% of fruit from the open orchard being classed as Processing and Fallout.

Collective quality

The marketability of fruit, taking individual fruit weight, fruit skin colour, sunburn (colour and degree), degree of cracking and blemishes collectively into account, is depicted in Figure 3.39. In 2017/18, the highest percentage of exportable fruit (c. 83%) came from the micro-sprinkler-irrigated loamy sand/sandy loam orchard in Bonnievale, compared to c. 23% of exportable fruit in the Gouda double-line drip-irrigated sandy orchard. A very high percentage of Fallout from the latter orchard was due to FCM infestation.

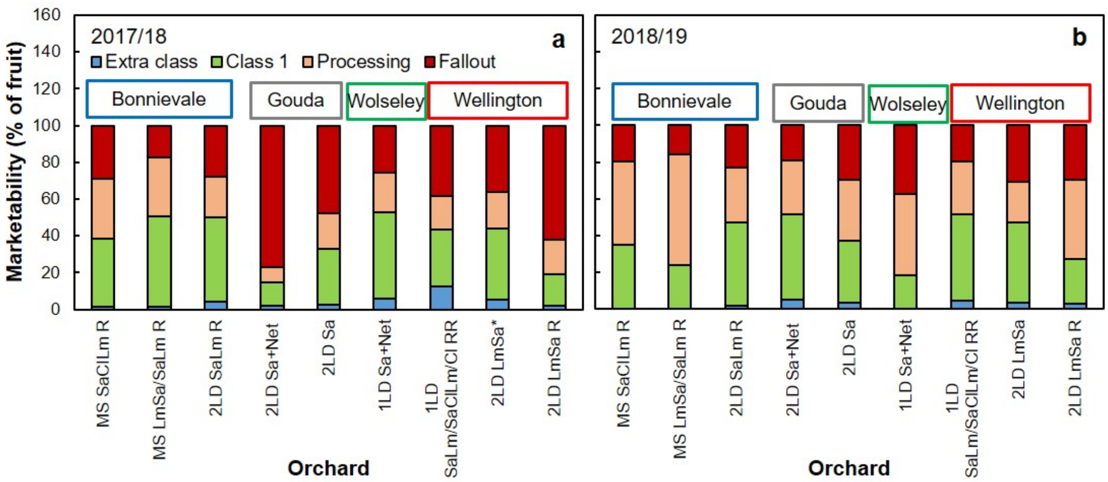

Figure 3.39: Fruit marketability classification (Extra Class, Class 1, Processing and Fallout) for pomegranate (Wonderful) orchards harvested in the Bonnievale, Gouda, Wolseley and Wellington production areas during the 2018/19 and 2019/20 seasons. Data for the orchard marked with an asterisk is for Harvest 1 only. [MS = micro-sprinkler; 1LD = single-line drip-irrigation; 2LD = double-line drip-irrigation; R = ridged; RR = ripped ridge]. The soil texture classes include sand (Sa), clay (Cl) and loam (Lm).

However, the low percentage of exportable fruit in the ridged double-line drip-irrigated loamy sand orchard in Wellington (c. 38%) can most likely be attributed to the indirect effects of water deficits (figures 3.17a, 3.23a and 3.36) on individual fruit weight (figures 3.25b, 3.27a and 3.35a) and sunburn (figures 3.35e, 3.36 and 3.37). In 2018/19, the same orchard from Bonnievale had the most fruit for export (84%), whereas the lowest export percentage was for the Wolseley orchard (63%). The latter orchard had the least Class 1 fruit (19%) and the most Fallout (37%), most likely due to the effect of blemishes (Figure 3.35b). The percentage fruit in Extra Class was, in general, below 6% for all orchards in both seasons, except for the single-line drip-irrigated orchard in Wellington (12.7%), which had more favourable fruit colour in 2017/18 (Figure 3.35c).

The percentage of Class 1 fruit in 2017/18 was the highest in the Bonnievale micro-sprinkler-irrigated loamy sand/sandy loam orchard (49.5%), followed by the netted single-line drip-irrigated orchard in Wolseley (47%) and the double-line drip-irrigated sandy loam orchard in Bonnievale (45.7%) (Figure 3.39). For the other orchards, the percentage of Class 1 fruit ranged from c. 30 to c. 38%, except for the netted Gouda orchard (c. 13%) and the ridged double-line drip-irrigated loamy sand Wellington orchard (c. 17%). In 2018/19, the single-line drip-irrigated orchard in Wellington had the most Class 1 fruit (47%), followed closely by the netted double-line drip-irrigated orchards in Gouda (46%), Bonnievale (45%) and the level loamy sand orchard in Wellington (44%). The better performance of the single-line drip-irrigated orchard in Wellington is probably due to favourable fruit weight and colour (figures 3.35b and 3.35d). The micro-sprinkler-irrigated orchards had 35 and 24% Class 1 fruit for the sandy clay loam and the loamy sand/sandy loam orchards, respectively. The rest of the orchards had between 19 and 33% Class 1 fruit.

In 2017/18, the percentage of fruit exported for processing ranged from 18.3 to 22.2%, except for the Bonnievale micro-sprinkler-irrigated orchards, which had c. 32%, and the Gouda netted orchard, which had c. 8% (Figure 3.39). In 2018/19, the micro-irrigated loamy sand/sandy loam orchard had 60% of fruit for processing, most likely due to poor fruit colour (Figure 3.35d). The amount of Processing fruit exported for the other orchards varied between 22 and 45% (Figure 3.39). The percentage fruit in the Fallout Class was quite high in 2017/18 (i.e. between 25.7 and 77.2%), except for the Bonnievale micro-sprinkler-irrigated loamy sand/sandy loam orchard (c. 18%). The percentage of fruit not suitable for export was less in 2018/19, compared to the previous season, and ranged from 16 to 37%. The Wolseley orchard had the highest percentage of Fallout and the micro-sprinkler-irrigated loamy sand/sandy loam orchard in Bonnnievale had the least. Fallout Class included fruit weighing less than 180 g (figures 3.35a and 3.35b), fruit with black sunburn (figures 3.35c and 3.35d), blemishes on more than 25% of the fruit surface (figures 3.38a and 3.38b) and cracking up to the arils (figures 3.38c and 3.38d).

In 2017/18, with regard to production areas, Bonnievale and Wolseley had the highest percentage of exportable fruit (c. 75%), followed by that in Wellington (50%) and Gouda (38%). The FCM infestation was the main reason behind the poor marketability of the Gouda fruit. In 2018/19, the number of fruit for export, relative to the previous season, increased for Bonnievale (81%), Wellington (73%) and Gouda (75%), and decreased for Wolseley (63%). In the two seasons, micro-irrigated-orchards had c. 77 and 82% fruit that was suitable for the export market, compared to 54 and 73% (Gouda orchards excluded for 2017/18, 61%) from drip-irrigated orchards. In both seasons, drip-irrigated orchards had about double the percentage Fallout of micro-irrigated orchards (Gouda orchards excluded for 2017/18, c. 40% more). Of the fruit produced on heavier soils in the respective seasons, 72 and 80% could be exported, compared to 47 and 71% on lighter soils (Gouda orchards excluded for 2017/18, 56%). In Gouda, 23 and 81% of the fruit from the netted orchard could be exported, compared to 52 and 70% of fruit produced on the open orchards.

3.3.6.8 Water use efficiency and productivity

Water use efficiency (kg of fruit produced per hectare per mm of water used) and water productivity (gross farm income per hectare per mm of water used) were calculated. Both indices were expressed on the basis of irrigation water applied, as well as on the total of efficient rainfall and irrigation applied. The WUE based on irrigation applied ($WUE_{Irrigation}$) appeared to be higher in the first season compared to the second season, with the exception of the micro-sprinkler-irrigated loamy sand/sandy loam orchard in Bonnievale (Figure 3.40). In 2017/18, the single-line drip-irrigated orchard in Wellington had the highest $WUE_{Irrigation}$, followed by that of the micro-sprinkler-irrigated sandy clay loam (Figure 3.40a). The $WUE_{Irrigation}$ of the open double-line drip-irrigated orchards in Bonnievale, Gouda and Wellington ranged from c. 85 to 93 kg ha^{-1} mm^{-1}. The micro-sprinkler-irrigated loamy sand on a sandy loam orchard in Bonnievale had a somewhat lower efficiency (c. 70 kg ha^{-1} mm^{-1}). However, the double- and single-line netted drip-irrigated orchards in Gouda and Wolseley, respectively, had the lowest $WUE_{Irrigation}$, i.e. c. 67 and 59 kg ha^{-1} mm^{-1}. The latter value was comparable to the $WUE_{Irrigation}$ for four-, five- and six-year old subsurface drip-irrigated trees in California, which amounted to 60.4, 61 and 59.7 kg ha^{-1} mm^{-1} (Ayars et al., 2017). The $WUE_{Irrigation}$ for surface drip-irrigated trees of a similar age in the same experimental orchard amounted, respectively, to 51.5, 53.5 and 55.8 kg ha^{-1} mm^{-1}.

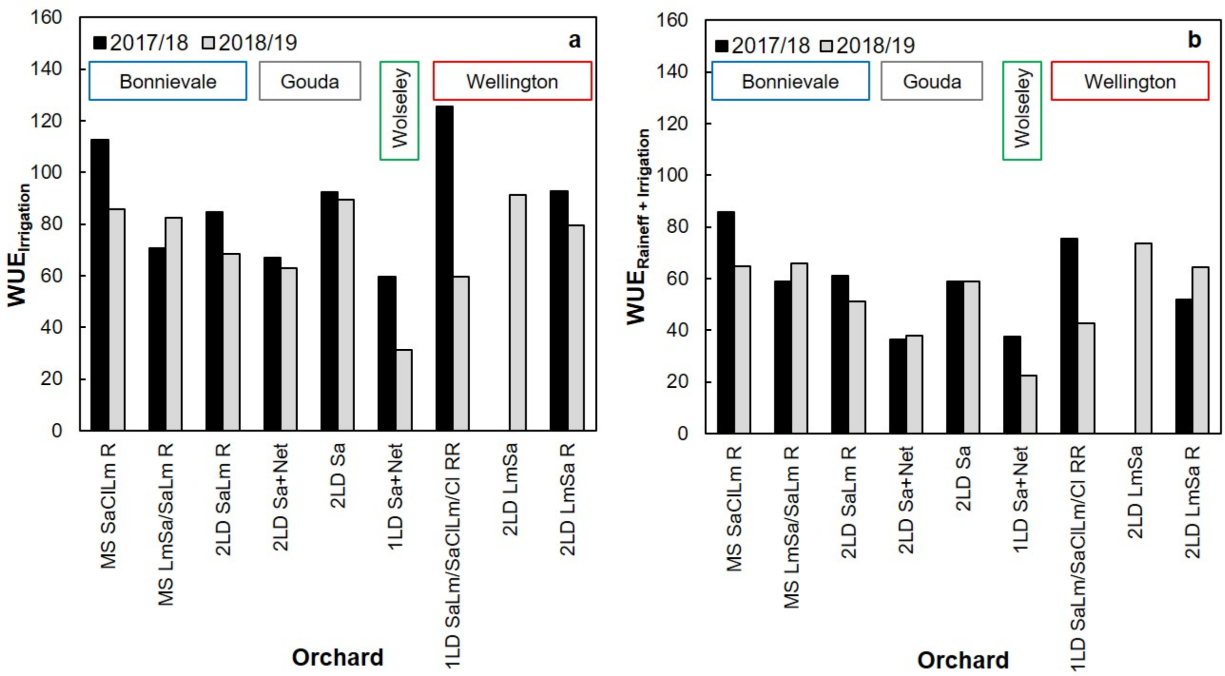

Figure 3.40: Water use efficiency (WUE) based on yield per a) irrigation applied ($WUE_{Irrigation}$) and b) effective rainfall and irrigation applied ($WUE_{Raineff\ +\ Irrigation}$) for pomegranate (Wonderful) orchards harvested in the Bonnievale, Gouda, Wolseley and Wellington production areas during the 2017/18 and 2018/19 seasons. Data values are relative to the maximum water productivity achieved. [MS = micro-sprinkler; 1LD = single-line drip-irrigation; 2LD = double-line drip-irrigation; R = ridged; RR = ripped ridge]. The soil texture classes include sand (Sa), clay (Cl) and loam (Lm). Data is not available for the 2LD LmSa orchard for 2017/18.

In 2018/19, the $WUE_{Irrigation}$ of the single-line drip-irrigated orchard was impacted on negatively by a change in orchard training system, reducing it by more than 50% (Figure 3.40a). The highest $WUE_{Irrigation}$ was obtained in the level double-line drip-irrigated orchards on loamy sand in Wellington and on sand in Gouda (c. 90 kg ha^{-1} mm^{-1}), followed closely by the micro-irrigated orchards in Bonnievale with a $WUE_{Irrigation}$ of 83 and 86 kg ha^{-1} mm^{-1}. The $WUE_{Irrigation}$ of the ridged double-line drip-irrigated orchards in Wellington and Bonnievale was about 80 and 68 kg ha^{-1} mm^{-1}, respectively.

The lower $WUE_{Irrigation}$ of the latter orchard, compared to the previous season, may be attributed to the application of more irrigation water in the second season (Figure 3.11), since yield was fairly similar during the two seasons (Table 3.15). The $WUE_{Irrigation}$ of the double- and single-line netted drip-irrigated orchards in Gouda and Wolseley, respectively, was 63 and 31 kg ha^{-1} mm^{-1}. The lower $WUE_{Irrigation}$ of the Wolseley orchard, compared to the previous season, was due to lower yield, as a result of less fruit, not smaller size, and the application of about 19% more irrigation water (Table 3.16; figures 3.22a and 3.22b).

If effective rainfall is also taken into account in the WUE ($WUE_{Raineff + Irrigation}$), the micro-sprinkler-irrigated sandy clay loam orchard of Bonnievale had the highest $WUE_{Raineff + Irrigation}$ (c. 86 kg ha^{-1} mm^{-1}) in the first season, followed by the single-line drip-irrigated orchard in Wellington with c. 76 kg ha^{-1} mm^{-1} (Figure 3.40b). The $WUE_{Raineff + Irrigation}$ for the open double-line drip-irrigated orchards in Bonnievale and Gouda was similar to that of the micro-sprinkler-irrigated orchard with loamy sand on sandy loam, ranging from c. 59 to 61 kg ha^{-1} mm^{-1}. The ridged double-line drip-irrigated orchard in Wellington had $WUE_{Raineff + Irrigation}$ of c. 52 kg ha^{-1} mm^{-1}, whereas that for the netted orchards in Gouda and Wolsley was c. 37 kg ha^{-1} mm^{-1}. In 2018/19, the level double-line drip-irrigated orchard in Wellington had the highest $WUE_{Raineff + Irrigation}$ (c. 74 kg ha^{-1} mm^{-1}), whereas it was comparable for the ridged double-line drip-irrigated orchard in Wellington and the micro-sprinkler-irrigated orchards in Bonnievale (c. 65 kg ha^{-1} mm^{-1}). The $WUE_{Raineff + Irrigation}$ for the double-line drip-irrigated orchard in Bonnievale dropped by 20% in the second season, and that for the single-line drip-irrigated orchard in Wellington dropped by c. 78%. The reasons for these decreases have been explained in the foregoing paragraph. The $WUE_{Raineff + Irrigation}$ for the netted orchards remained the lowest of all, with that in Wolseley decreasing further in the second season to 22 kg ha^{-1} mm^{-1}. In Spain, deficit irrigation resulted in increasing WUE (fruit yield divided by irrigation applied + rainfall) of Mollar de Elche trees (Intrigliolo et al., 2013). The increase in WUE, on average, over three years relative to the control (39 kg ha^{-1} mm^{-1}), was particularly noticeable in the sustained deficit irrigation (59 kg ha^{-1} mm^{-1}) treatment and where regulated deficit irrigation was applied during flowering and fruit set (49 kg ha^{-1} mm^{-1}). The sustained deficit irrigation and regulated deficit irrigation treatments were successful in increasing WUE and water productivity.

The relative income of the pomegranate orchards of the Western Cape increased with more effective rainfall and irrigation applied in both seasons, and for the data of both seasons combined (figures 3.41a, 3.41b and 3.41c). The higher income of the Bonnievale area, compared to the other areas, is most likely due to the high yield obtained in these orchards (Table 3.16) and the high percentage of exportable fruit (refer to "collective quality" in section 3.3.6.7). In 2017/18, Extra Class fruit earned between 2 and 9% of the relative income for orchards, except for the single-line drip-irrigated orchard in Wellington, which had 21% Extra Class fruit (Figure 3.42a), mainly due to the excellent fruit colour (Figure 3.35c). In the second season, though, only six orchards had Extra Class fruit, which contributed a maximum of 8% to the relative income (Figure 3.42b). Class 1 fruit tended to be the main earner of income (i.e. between 58 and 77%) in both seasons, with few exceptions in 2018/19. These included the micro-sprinker-irrigated orchard on loamy sand/sandy loam soil in Bonnievale and the single-line drip-irrigated orchard in Wellington. More fruit of the Bonnievale orchard was destined for processing due to its poor colour (Figure 3.35d), whereas the change of the training system in the Wellington orchard probably impacted negatively on the Class 1 income through the smaller fruit size and lower fruit numbers (Table 3.16). Relative income earned by Class 1 fruit tended to increase linearly in 2017/18 with the application of more effective rainfall and irrigation, but in the second season, there were no consistent trends (data not shown). Relative income earned by Processing fruit ranged from 16 to 37% of the total per orchard in the two seasons, except for the two orchards discussed above, for which fruit that was only suitable for processing exceeded 50% in the second season (Figure 3.42).

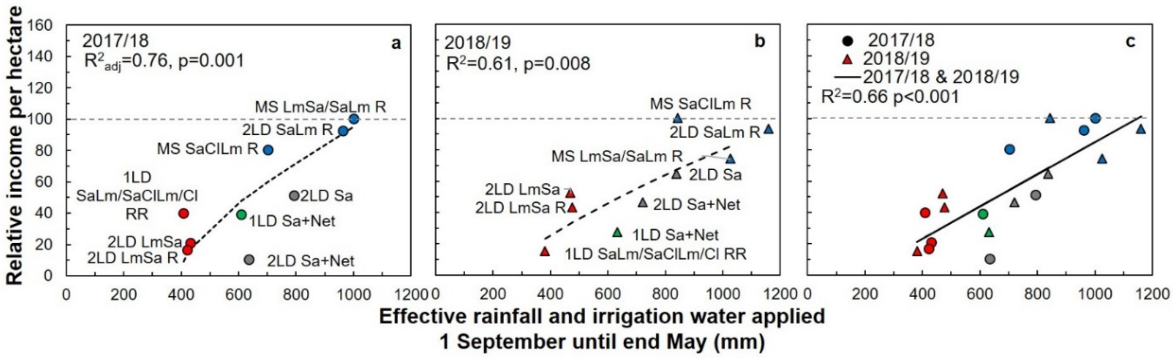

Figure 3.41: Relative income for pomegranate (Wonderful) orchards harvested in the Bonnievale blue markers), Gouda (grey markers), Wolseley (green markers) and Wellington (red markers) production areas during the 2018/19 (a) and 2019/20 (b) seasons. [MS = micro-sprinkler; 1LD = single-line drip-irrigation; 2LD = double-line drip-irrigation; R = ridged; RR = ripped ridge]. The soil texture classes include sand (Sa), clay (Cl) and loam (Lm). Income is expressed relative to the maximum income earned.

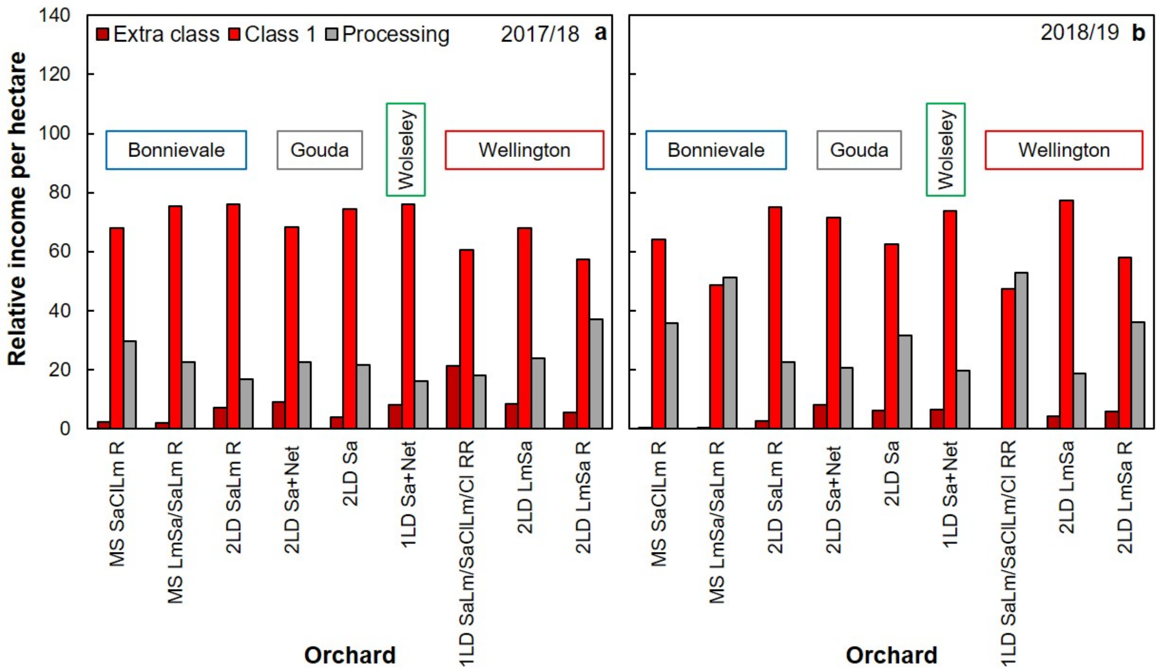

Figure 3.42: Relative income per quality class for pomegranate (Wonderful) orchards harvested in the Bonnievale, Gouda, Wolseley and Wellington production areas during the 2018/19 (a) and 2019/20 (b) seasons. [MS = micro-sprinkler; 1LD = single-line drip-irrigation; 2LD = double-line drip-irrigation; R = ridged; RR = ripped ridge]. The soil texture classes include sand (Sa), clay (Cl) and loam (Lm). Data for the double-line loam-sandy orchard for 2017/18 only reflects Harvest 1.

In the first season, relative WP based on irrigation applied or $WP_{Irrigation}$ (Figure 3.43a) was the highest in the single-line drip-irrigated orchard in Wellington, followed closely by the Bonnievale orchards (74 to 93%) and the netted Wolseley orchard (63%). Although the Gouda orchards were affected by FCM infestation in the first season, the open orchard also achieved 63% relative $WP_{Irrigation}$, whereas the $WP_{Irrigation}$ of the netted Gouda orchard was severely affected (18%). Poor relative $WP_{Irrigation}$ of the ridged double-line drip-irrigated orchard in Wellington (43%) was probably due to sunburnt fruit with more fruit classed as Processing and Fallout (figures 3.35c, 3.35e and 3.41a). In the second season, the relative $WP_{Irrigation}$ of the single-line drip-irrigated orchard in Wellington dropped to 36% due to a change in orchard training system, which required severe winter pruning (Figure 3.43a).

In the 2018/19 season, the micro-sprinkler-irrigated orchard on sandy clay loam in Bonnievale and the level double-line drip-irrigated orchard in Wellington (88%) had the highest relative $WP_{Irrigation}$. The relative $WP_{Irrigation}$ for the double-line drip-irrigated orchards in Bonnievale and Gouda, and the ridged orchard in Wellington ranged from 68 to 75%. The low relative $WP_{Irrigation}$ of the Wolseley orchard (38%) was probably due to low fruit numbers (Table 3.16) combined with poor fruit colour development and sunburn on 57% of the fruit (figures 3.35d and 3.35f), as well as some degree of blemishes on 63% of the fruit (Figure 3.38b).

Either Bonnievale or Wellington had the best $WUE_{Irrigation}$ (i.e. between 77 and 109 kg ha^{-1} mm^{-1}), on average, in the two seasons, with that in Gouda being c. 10% less than that in Wellington (Table 3.18). However, the $WUE_{Irrigation}$ for Wolseley was 34 and 63% lower compared to Bonnievale for 2017/18 and 2018/19, respectively. If rainfall is taken into account, Bonnievale had the highest $WUE_{Raineff + Irrigation}$ for both seasons, with that in Wellington, Gouda and Wolseley being c. 7 and 8%; 31 and 26%; and 45 and 66% less efficient in the respective seasons. Bonnievale also had the best relative $WP_{Irrigation}$ and $WP_{Raineff + Irrigation}$ for both seasons (Table 3.18). In 2017/18 and 2018/19, respectively, the relative $WP_{Irrigation}$ for Wellington, Gouda and Wolseley was 18 and 14%; 42 and 8%; and 20 and 41% less compared to that of Bonnievale. The $WP_{Raineff + Irrigation}$ for the respective seasons in Wellington, Gouda and Wolseley was 36 and 12%; 55 and 21%; and 34 and 44% less compared to Bonnievale. Wolseley and Wellington had comparable $WP_{Irrigation}$ and $WP_{Raineff + Irrigation}$ for the first season, but it decreased for Wolseley by 27 and 32%, respectively, compared to Wellington in the second season.

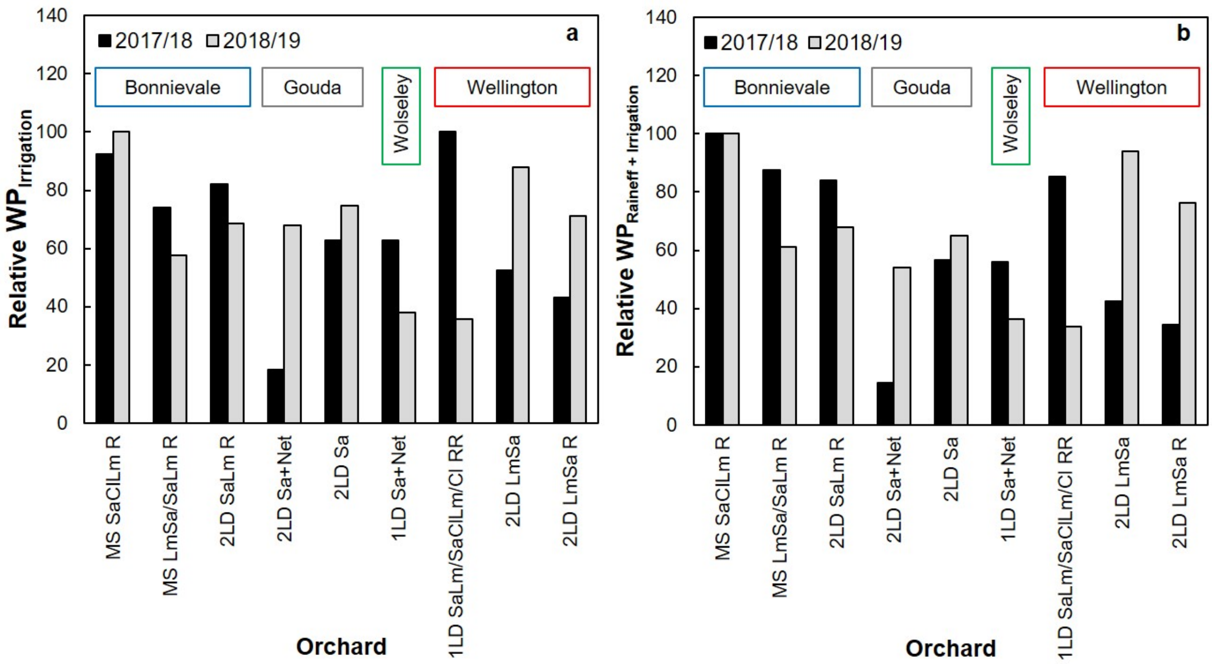

Figure 3.43: Relative water productivity (WP) based on income (R) per a) irrigation applied and b) effective rainfall (Raineff) and irrigation applied for pomegranate (Wonderful) orchards harvested in the Bonnievale, Gouda, Wolseley and Wellington production areas during the 2018/19 and 2019/20 seasons. Data values are relative to the maximum water productivity achieved. [MS = micro-sprinkler; 1LD = single-line drip-irrigation; 2LD = double-line drip-irrigation; R = ridged; RR = ripped ridge]. The soil texture classes include sand (Sa), clay (Cl) and loam (Lm). Data for the 2LD LmSa orchard for 2017/18 only reflects Harvest 1.

Table 3.18: Comparison of mean water use efficiency (WUE) and water productivity (WP) based on irrigation applied (Irrigation) or effective rainfall and irrigation applied (Raineff + Irrigation) for pomegranate (Wonderful) orchards harvested in the Bonnievale, Gouda, Wolseley and Wellington production areas during the 2018/19 and 2019/20 seasons. Relative data values are compared to the maximum achieved.

Group mean	$WUE_{Irrigation}$ (kg ha^{-1} mm^{-1})		$WUE_{Raineff + Irrigation}$ (kg ha^{-1} mm^{-1})		Relative $WP_{Irrigation}$		Relative $WP_{Raineff + Irrigation}$	
	2017/18	2018/19	2017/18	2018/19	2017/18	2018/19	2017/18	2018/19
Bonnievale	89	84	69	65	83	79	90	80
Gouda	80	76	48	48	41	71	35	59
Wolseley	59	31	37	22	63	38	56	36
Wellington	109	77	64	60	65	65	54	68
Micro-sprinkler	92	84	72	65	83	79	94	80
Drip-irrigation	87	69	54	50	60	63	53	61
Heavier soils	98	74	70	56	87	65	89	66
Lighter soils	78	71	46	51	48	68	41	65
Net (Gouda)	67	63	37	38	18	68	14	54
Open	93	90	59	59	63	75	57	65

The $WUE_{Irrigation}$ for micro-sprinkler orchards, compared to that for drip-irrigated orchards, was 5 and 18% higher in 2017/18 and 2018/19, whereas the $WUE_{Raineff + Irrigation}$ for the respective seasons was 26 and 23% higher for micro-sprinkler vs drip-irrigation. Likewise, micro-sprinkler-irrigation increased the $WP_{Irrigation}$ and $WP_{Raineff + Irrigation}$ for orchards compared to drip-irrigation by 23 and 15%, respectively, in 2017/18, and by 40 and 19%, respectively, in 2018/19. In this survey, the micro-sprinkler-irrigated orchards were planted on heavier soils, which, on average, had a higher WUE compared to the lighter soils, especially in the first season. In the first season, the $WP_{Irrigation}$ and $WP_{Raineff + Irrigation}$ of orchards on heavier soils were 39 and 48% higher, respectively, compared to that on lighter soils, with minor differences in the second season. The greater water-holding capacity of heavier soils (Figure 3.4) may have contributed to higher WP, especially during a season of critical drought, such as the 2017/18 season. If the first season, where FCM infestation most likely impacted on tree performance, is ignored, the netted orchard had 29% lower $WUE_{Irrigation}$ and 37% lower $WUE_{Raineff + Irrigation}$ compared to the open orchard. In the second season, $WP_{Irrigation}$ and $WP_{Raineff + Irrigation}$ was 7 and 11% less, respectively, for the netted orchard compared to the open orchard.

3.4 CONCLUSIONS

Water restrictions due to the Western Cape drought prevented pomegranate producers from supplying irrigation according to the tree water requirements. Despite this, valuable information was obtained regarding the local production areas and the effect of the application of irrigation on yield and fruit quality. For all practical purposes, water sources were non-saline, except for one case where moderately saline water may have affected pomegranate tree performance.

Production practices should take irrigation water quality and soil properties into account, especially on more clayey soils, to ensure that adequate water infiltration and hydraulic conductivity occur in soil profiles that promote sustainable production in the long term.

The evaporative demand that drives water use and irrigation water requirements for the 2017/18 and 2018/19 seasons (September to May) in Wellington, Bonnievale, Gouda and Wolseley was c. 1,168 and 1,137 mm; 1,092 and 1,070 mm; 1,003 and 1,184 mm; and 942 and 1,095 mm, respectively.

In 2017/18 the evaporative demand in the Bonnievale, Gouda and Wolseley areas was therefore, c. 7, c. 14 and c. 19% less compared to Wellington. In 2018/19, though, differences in total ET_o between production regions diminished, with that for Bonnievale and Wolseley being 6 and 4% less, and that for Gouda becoming c. 4% more than that for Wellington. The total ET_o from 1 September to 31 May in 2018/19, compared to 2017/18, decreased by 3 and 2% for Wellington and Bonnievale, whereas it increased by 18 and 16%, respectively, for Gouda and Wolseley.

With regard to irrigation management, soil water dynamics indicated instances of under- and over-irrigation during the two seasons. The amount of irrigation water applied to the nine full-bearing Wonderful pomegranate orchards during the season ranged between 237 and 834 mm in 2017/18, and between 272 and 867 mm in 2018/19. In both the 2017/18 and 2018/19 seasons, most water was applied in Bonnievale (688 and 775 mm), followed by Gouda (426 and 492 mm), Wolseley (385 and 456 mm) and Wellington (243 and 346 mm). On average over the seasons, Gouda, Wolseley and Wellington applied 63, 57 and 40% of the irrigation applied to the Bonnievale area. Irrigation applied in 2018/19 compared to 2017/18 was 13, 15, 19 and 42% more for Bonnievale, Gouda, Wolseley and Wellington, respectively. Effective rainfall also supplies the crop water requirements. Rainfall corrected for evaporation losses amounted, on average, to 201 and 236 mm; 289 and 288 mm; 226 and 177 mm; and 173 and 95 mm for Bonnievale, Gouda, Wolseley and Wellington during the 2017/18 and 2018/19 growing seasons, respectively. For 2017/18, the total amount of effective rainfall and irrigation ranged from 409 to 1001 mm, and for 2018/19, it ranged from 381 to 1161 mm. As is the case for irrigation, Bonnievale had the highest total effective rainfall and irrigation in both seasons (889 and 1011 mm), followed by Gouda (715 and 780 mm), Wolseley (611 and 633 mm) and Wellington (421 and 443 mm). On average over the seasons, the total effective rainfall and irrigation for Gouda, Wolseley and Wellington was 79, 66 and 46% of that for the Bonnievale area. The total effective rainfall and irrigation for Bonnievale, Gouda, Wolseley and Wellington, respectively, for the 2018/19 season, was 14, 9, 4 and 5% more than for the 2017/18 season. The total effective rainfall and irrigation for the 2017/18 and 2018/19 seasons, respectively, equalled 78 and 94%; 71 and 66%; 65 and 58%' and 36 and 39% of the seasonal total ET_o for the Bonnievale, Gouda, Wolseley and Wellington production areas, respectively.

Tree water status indicated that the Gouda and Wellington orchards were subjected to either moderate or severe water stress levels during the fruit growth or ripening stages, which impacted negatively on fruit growth rate. Relative fruit growth rate during fruit set and ripening tended to increase non-linearly with an increased amount of effective rainfall and irrigation water applied daily. Increased rates of effective rainfall and irrigation applied from September until the end of fruit set enhanced shoot growth rate in the second season, but not in the first season, during which effective rainfall and irrigation rates were 2.5 mm d^{-1} or less. Effective rainfall and irrigation did not affect leaf macro- and micronutrients, except for leaf phosphate and magnesium content, which increased either non-linearly or linearly with higher rates of effective rainfall and irrigation applied until the end of linear fruit growth.

Final fruit size (fruit weight, length and diameter), also related positively with increased irrigation rate until harvest, and yield and average fruit weight with higher rates of water application for the total season. Total yield for the 2017/18 and 2018/19 seasons, respectively, varied between 21.9 and 60.3 t ha^{-1}, and between 14.2 and 67.7 t ha^{-1}. The Bonnievale area, on average, had the highest yield in the respective seasons (59.4 and 60.5 t ha^{-1}), followed by Gouda (35 and 38 t ha^{-1}), Wellington (26.4 and 27.2 t ha^{-1}) and Wolseley (22.9 and 14.2 t ha^{-1}). Yield for Bonnievale compared to Gouda, Wellington and Wolseley was 41 and 37%; 56 and 55%; and 62 and 77% higher in 2017/18 and 2018/19, respectively.

Fruit peel moisture content and fruit firmness tended to increase with higher rates of effective rainfall and irrigation until harvest. Aril weight and moisture content also tended to increase with increased effective rainfall and irrigation rate until harvest, but only in the first season. The percentage of fruit with dark-red arils increased with more effective rainfall and irrigation applied in both seasons.

In contrast, the red colouration of fruit skin tended to decrease with an increased rate of irrigation until harvest. The fruit of all the orchards conformed to the ripeness standards expected for export. The TA of pomegranate juice tended to increase, whereas the TSS, pH and MI decreased with increased rate of irrigation until harvest in the first season, but not in the second season. Rainfall occurring during harvest may partially explain the lack of significant trends for the second season. There were no significant trends between physiological disorders (scuffmarks, russeting, cork around the pedicel, internal decay) and the rate of effective rainfall and irrigation applied until harvest. The percentage of sunburnt fruit at harvest increased with lower tree water status during the fruit growth stage. Although there was large variation, the total percentage of fruit with sunburn decreased with an increased rate of irrigation between the fruit growth stage and harvest. There was no meaningful relationship between the amount of effective rainfall and irrigation applied until harvest and cracking or blemishes of fruit.

Fruit suitable for export during the 2017/18 and 2018/19 seasons, respectively, was 75 and 81% for Bonnievale, 74 and 63% for Wolseley, 50 for 73% for Wellington, and 38 and 75% for Gouda. However, there was no simple relationship between effective rainfall and irrigation applied and the marketability of the fruit. The WUE (kilogram of fruit produced per hectare per mm of water used) of the orchards was high in comparison to some of the published data for pomegranate from other countries and cultivars. Water use efficiency based on irrigation water applied varied between 59.4 and 125.5 kg ha^{-1} mm^{-1} for the 2017/18 season, and between 31.1 and 91.3 kg ha^{-1} mm^{-1} for the 2018/19 season. If effective rainfall is also taken into account, the WUE ranged between 36.6 and 85.9 kg ha^{-1} mm^{-1} in the first season, and between 22.4 and 73. kg ha^{-1} mm^{-1} in the second season. The WUE, with effective rainfall and irrigation taken into account, was the highest in Bonnievale for both seasons, with that in Wellington, Gouda and Wolseley being c. 7 and 8%; 31 and 26%; and 45 and 66% less efficient in the respective seasons.

The relative income of pomegranate orchards (expressed vs maximum income earned) increased with more effective rainfall and irrigation applied in both seasons. Bonnievale also had the best relative water productivity (gross farm income per hectare per mm of water used) for both seasons for scenarios where only irrigation water or the total of effective rainfall and irrigation water applied was taken into consideration. In 2017/18 and 2018/19, respectively, water productivity, based on effective rainfall and irrigation applied was 36 and 12%; 55 and 21%; and 34 and 44% less in Wellington, Gouda and Wolseley, compared to Bonnievale.

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CHAPTER 4: SYNOPSIS OF CURRENT RESEARCH

South African baseline information regarding pomegranate water use and irrigation practices is limited to that acquired by one survey done in the Western Cape. No information is available from any other provinces in this regard. The ARC, in collaboration with the pomegranate industry (POMASA), co-funded by the Alternative Crop Fund of the Western Cape Department of Agriculture, conducted a survey over two seasons (2017/18 and 2018/19) on the irrigation and performance of pomegranate trees. Data collected at nine full-bearing pomegranate (Wonderful cultivar) orchards on commercial farms in four pomegranate production areas in the Western Cape (Bonnievale, Gouda, Wellington and Wolseley) was analysed to identify research gaps to direct future research into pomegranate water use and irrigation. Three farms were within the boundaries of the Berg WMA, and three were within the Breede WMA. Sites selected included orchard variability currently present in the industry, comprising different degrees of water quality (non-saline or saline), tree spacing (416 to 1,111 trees per hectare), sandy or heavier soil, level or ridged gradients, planted with or without nets, and irrigated with micro-sprinklers or drip-irrigation (single or double line).

4.1 WATER AND SOIL RESOURCES

Water and soil resources, taking the quality of irrigation water and available soil water (soil water-holding capacity and root zone distribution) into account, as well as evaporative demand and irrigation management, were described for production areas. The quality assessment of irrigation water, according to the Irrigation Water Quality Decision Support System (Du Plessis et al., 2017), was conservative and took into account soils that were sensitive to a reduction in infiltration rate and hydraulic conductivity. The estimated impact may be less on sandy soils, which are considered relatively tolerant to physical deterioration due to SAR and electrical conductivity interactions. For five sites, the water salinity, measured in terms of electrical conductivity, ranged between 5 and 71 mS m^{-1}, and the sodium content ranged between 4.4 and 91 mg ℓ^{-1}, the water being practically non-saline. Borehole water from Wellington was moderately saline, though. It had an electrical conductivity of 224 mS m^{-1} and a sodium content of c. 421 mg ℓ^{-1}. According to the predicted equilibrium root zone salinity, the water quality of all the orchards was ideal for irrigation, with mostly negligible effects of salinity on crop yield expected. The exception was the borehole at Wellington, the water quality of which was in the tolerable range that can potentially salinise the root zone to levels that restrict the yield of many crops. Depending on cultivar, pomegranate trees are considered to be moderately sensitive to moderately tolerant to salinity.

Based on the interaction between the electrical conductivity of irrigation water and the SAR of the topsoil, the degree of reduced surface infiltrability for the different orchards ranged between none and moderate. The SAR in the soil water was, in most cases, less than 3, and associated with low soil water salinity of between 20 and 40 mS m^{-1}, which may result in moderately reduced hydraulic conductivity in sensitive soils. In cases where SAR was less than 3 and salinity was less than 20 mS m^{-1}, the hydraulic conductivity could decrease severely. In the single-line drip-irrigated orchard in Wellington, soil water SAR values of more than 12 and an EC_e of less than 50 may result in severe reduction in hydraulic conductivity in the topsoil, but deeper in the soil, where the soil water salinity was c. 150 mS m^{-1}, hydraulic conductivity may only decrease moderately. In the 300-600 mm soil layer of the ridged double-line drip-irrigated orchard, an SAR of c. 12, in combination with an EC_e of c. 94 mS m^{-1}, may also moderately reduce the hydraulic conductivity.

Crop growth is affected by salinity (which reduces the ability of crops to absorb water from the soil), as well as by the accumulation of potentially toxic ions, namely sodium, chloride and boron in the root zone. For the micro-sprinkler-irrigated orchards in Bonnievale, a relative yield decrease of c. 18, 36, 8 and 1% was predicted due to the salinity and high levels of sodium, chloride and boron, respectively.

In the double-line drip-irrigated orchards in Wellington, relative yield could decrease by 10 and 19% due to irrigation water salinity and sodium content. The effect of the high salinity, sodium and chloride in irrigation water used in the single-line drip-irrigated orchard in Wellington on the relative yield of a sensitive crop was extreme (i.e. no yield). However, since pomegranate is considered to be moderately salt-sensitive to moderately salinity-tolerant, relative yield should be less affected. The potential for irrigation water, according to the Langelier Index, to result in irrigation equipment corrosion ranged from none (ideal) to unacceptable (Langelier Index < -2) between orchards, whereas no problems with scaling was foreseen. With regard to emitter clogging, pH appears to be too high at all orchards, while manganese and iron content did not pose a problem or was acceptable.

According to the soil water-holding capacity between -10 and -100 kPa (estimated from the soil texture analysis, Bemlab), the heavier soils in Bonnievale had the highest soil water-holding capacity, i.e. between 144 and 165 mm m^{-1}, whereas it was slightly lower for sandy loam soils with c. 21% stone (117 mm m^{-1}). The soil water-holding capacity of the sandy Gouda soils was the lowest and, on average, c. 50% of that available in the micro-sprinkler-irrigated orchards from Bonnievale. The soil water-holding capacity in the netted and open orchards, respectively, was c. 69 mm m^{-1} (profile average stone 23% v/v) and 84 mm m^{-1} (profile average stone c. 15% v/v). The water-holding capacity of the sandy soil in Wolseley and the sandy loam and loamy sand in the Wellington area was 93, 88 and c. 100 mm m^{-1}, respectively. The soil water-holding capacity of the drip-irrigated soils were, on average, 40% less than that of the micro-irrigated soils. With respect to soil water-holding capacity in the production regions, Gouda, Wolseley and Wellington, respectively, had, on average, 46, 34 and 32% less water available between -10 and -100 kPa than the Bonnievale soils.

The root systems of seven of the nine orchards developed up to a depth of 1.2 m. At Bonnievale, the root depth of the double-line drip-irrigated sandy loam orchard was limited to 600 mm by an impermeable layer, and at Wolseley, in the single-line drip-irrigated sand under net, by a clay layer at a depth of 1 m. The root density to a depth of 600 mm was, on average, c. 45% lower in the micro-sprinkler-irrigated orchards compared to that in the drip-irrigated orchards. Root distribution perpendicular to the tree row indicated that, for the drip-irrigated orchards, most of the roots were concentrated in a c. 1 m radius from the tree, whereas for micro-irrigated orchards, roots were distributed in the whole area allotted to the tree.

4.2 EVAPORATIVE DEMAND AND IRRIGATION MANAGEMENT OF PRODUCTION REGIONS

For the 2017/18 and 2018/19 seasons, the evaporative demand that drives water use and irrigation water requirements in the production areas ranged between c. 942 and 1,291 mm (Table 4.1). In 2017/18, the amount of irrigation water applied ranged between 237 and 834 mm, and in 2018/19, it ranged between 272 and 867 mm.

Table 4.1: Penman-Monteith reference evapotranspiration (ET_o), irrigation applied and the total of effective rainfall ($Rain_{eff}$) and irrigation applied during the 2017/18 and 2018/19 growing seasons in four Western Cape pomegranate production areas during 2017/18 and 2018/19

Seasonal total amount (mm from September to May)						
Season	**Variable**	**Range**	**Production area**			
			Bonnievale	**Gouda**	**Wolseley**	**Wellington**
2017/18	ET_o	942-1291	1,137	1,003	942	1,168
	Irrigation	237-834	688	426	385	243
	$Rain_{eff}$ + irrigation	409-1,001	889	715	611	421
2018/19	ET_o	1015-1,250	1,070	1,184	1,095	1,137
	Irrigation	272-867	775	492	456	346
	$Rain_{eff}$ + irrigation	381-1,161	1,011	780	633	443
2018/19 vs 2017/18	ET_o		-2%	+18%	+16%	-3%
	Irrigation		+13%	+15%	+19%	+42%
	$Rain_{eff}$ + irrigation		+14%	+9%	+4%	+5%

If effective rainfall is also taken into account, the total amount of effective rainfall and irrigation ranged between 409 and 1,001 mm for 2017/18, and between 381 and 1,161 mm for 2018/19. In comparison, annual evaporative demand in California reached 1,379 mm, and six-year-old Wonderful trees received 1,099.8 mm of rainfall and irrigation according to a scientifically scheduled surface drip-irrigated programme (Ayars et al., 2017).

On average for soil type, 68 and 47% more water was applied from 1 September to the end of May in the 2017/18 and 2018/19 seasons, respectively, to clayey and sandy loam soils compared to loamy sand and sandy soils. Micro-sprinkler-irrigated orchards received 80 and 53% more water than drip-irrigated orchards in the two respective seasons. In Gouda, the open drip-irrigated orchard received 45 and 27% more water than the orchard under net. However, the lower amount of irrigation water applied under net cannot be contributed solely to effects of the net, since the emitter spacing differed for the two orchards and the borehole that supplied the netted orchard occasionally ran dry in the 2017/18 season. Orchards were irrigated according to producers' practice. The amount of water applied therefore does not necessarily accurately reflect the water requirements of these orchards. Soil water dynamics indicated instances of under- and over-irrigation during the two seasons, and it was not necessarily restricted to specific orchards or production areas.

4.3 TREE RESPONSE

Shoot growth rate increased non-linearly with higher rates of effective rainfall and irrigation applied until fruit set (R^2_{adj} = 0.88, p = 0.002), but only in the second season. During critical drought in 2017/18, water application rates were very low and no vegetative growth response was evident. Tree water status indicated that Gouda and Wellington orchards were subjected to either moderate or severe water stress levels during the fruit growth and ripening stages, which impacted negatively on fruit growth rate. Relative fruit growth rate tended to increase with an increased amount of effective rainfall and irrigation water applied during fruit set (R^2_{adj} = 0.64, p = 0.0001) and ripening (R^2_{adj} = 0.69, p = 0.0001).

Total yield for the two seasons varied between 14.2 and 67.7 t ha^{-1}. Statistical analyses showed significant effects of the rate of effective rainfall and irrigation applied from September until harvest or until the end of the season on yield, yield components and relative income (Table 4.2) and on several fruit quality variables (Table 4.3).

Table 4.2: Summary regarding the trend status of linear or non-linear regression relationships between rate of effective rainfall and irrigation applied from September until May and yield components, yield and relative income per hectare, respectively. *Netted orchards omitted as outlying values.

Variable	2017/18	Statistical indicator	2018/19	Statistical indicator	Seasons combined	Statistical indicator
Fruit number (n)	Not significant range: 77-444	-	Not significant range: 46-423	-	Not significant	-
Fruit weight (kg)	Increased range: 0.198-0.347	R^2_{adj} = 0.72 p = 0.005	Increased range: 0.281-0.404	R^2_{adj} = 0.77 p = 0.003	Increased	$R^2_{ad\,j}$= 0.44 p = 0.003
Yield* (t ha^{-1})	Increased range: 21.9-60.3	R^2 = 0.66 p = 0.014	Increased range: 14.2-67.7	R^2 = 0.81 p = 0.001-	Increased	R^2_{adj} = 0.85 p < 0.0001
Income per hectare (relative to maximum)	Increased	R^2_{adj} = 0.76 p = 0.001	Increased	R^2_{adj} = 0.61 p = 0.008	Increased	R^2_{adj} = 0.66 p < 0.001

Table 4.3: Summary regarding the trend status of linear or non-linear regression relationships between the rate of effective rainfall and irrigation applied from September until harvest and selected fruit physicochemical characteristics, maturity indicators and physiological disorders determined on a sample of 20 fruit. *Outliers omitted.

Variable	2017/18	Statistical indicator	2018/19	Statistical indicator	Seasons combined	Statistical indicator
Fruit weight	Increased	R^2 = 0.81 p = 0.003	Increased	R^2_{adj} = 0.40 p = 0.039	Increased	R^2 = 0.41 p = 0.004
Fruit length	Increased	R^2 = 0.79 p = 0.003	Increased	R^2 = 0.86 p = 0.003	Increased	R^2 = 0.50 p = 0.001
Fruit diameter	Increased*	R^2 = 0.80 p= 0.003	Not significant	-	Increased*	R^2 = 0.35 p = 0.01
Fruit firmness	Increased*	R^2_{adj} = 0.79 p = 0.011	Increased*	R^2 = 0.53 p = 0.042	Not significant	-
Peel thickness	Not significant	-	Not significant	-	Not significant	-
Peel moisture content	Increased	R^2_{adj} = 0.54 p = 0.014	Increased	R^2_{adj} = 0.28 p = 0.082	Increased	R^2_{adj} = 0.45 p = 0.003
Peel red colouration	Decreased*	R^2_{adj} = 0.88 p < 0.001	Decreased*	R^2_{adj} = 0.40 p = 0.056	Decreased*	R^2_{adj} = 0.63 p < 0.001
Aril weight	Increased*	R^2_{adj} = 0.31 p < 0.088	Not significant	-	Not significant	-

Variable	2017/18	Statistical indicator	2018/19	Statistical indicator	Seasons combined	Statistical indicator
Aril moisture content	Increased	$R^2_{adj} = 0.79$ $p = 0.001$	Not significant	-	Not significant	-
Fruit having dark red arils	Increased	$R^2_{adj} = 0.66$ $p = 0.005$	Increased*	R^2_{adj}, = 0.59 $p = 0.015$	Increased*	R^2_{adj}, = 0.62 $p < 0.001$
Fruit having rose-coloured arils	Decreased	$R^2_{adj} = 0.70$ $p = 0.003$	Decreased*	$R^2 = 0.49$ $p = 0.054$	Decreased*	$R^2_{adj} = 0.63$ $p < 0.001$
Total soluble solids	Decreased	$R^2_{adj} = 0.77$ $p = 0.001$	Not significant	-	Not significant	$R^2 = 0.20$ $p = 0.06$
Total titratable acids	Increased	$R^2_{adj} = 0.71$ $p = 0.004$	Not significant	-	Increased	$R^2 = 0.28$ $p = 0.003$
pH	Decreased	$R^2_{adj} = 0.55$ $p = 0.013$	Not significant	-	Not significant	$R^2 = 0.19$ $p = 0.068$
Maturity Index	Decreased	$R^2_{adj} = 0.74$ $p = 0.002$	Not significant	-	Decreased	$R^2 = 0.31$ $p = 0.016$
Scuffmarks	Not significant	-	Not significant	-	Not significant	-
Russeting	Not significant	-	Not significant	-	Not significant	-
Cork around pedicel	Not significant	-	Not significant	-	Not significant	-
Internal decay	Not significant	-	Not significant	-	Not significant	-

Trends for most fruit quality variables were not consistently significant in both seasons, most likely due to the effect of rainfall that occurred during ripening in the second season. The final fruit size of 20 fruit sampled per orchard for maturity analysis (fruit weight, length and diameter) (Table 4.4), as well as yield and average fruit weight for five trees per orchard (Table 4.3), related positively with increased irrigation rate until harvest for the entire season. Fruit skin moisture content and firmness, aril weight and moisture content, and the percentage of fruit with dark-red arils also tended to increase with increased irrigation rate until harvest, but the trends were not significant for all variables in both seasons (Table 4.3).

The red colouration of the fruit skin tended to decrease with increased rate of irrigation until harvest (Table 4.4). The fruit of all orchards conformed to the ripeness standards expected for export. The TA of pomegranate juice tended to increase, whereas the total soluble solids, pH and the MI decreased with an increased rate of irrigation until harvest in the first season, but not in the second season.

Effective rainfall and irrigation applied until harvest did not affect fruit blemishes or cracking, but increased rates of water application during the period from the end of linear fruit growth until harvest decreased sunburn in 2017/18 ($R^2_{adj} = 0.65$, $p = 0.01$), 2018/19 ($R^2_{adj} = 0.70$, $p = 0.012$) and for the data of both seasons combined ($R^2_{adj} = 0.50$, $p = 0.001$).

The percentage of sunburnt fruit at harvest tended to decrease with improved tree water status during the fruit growth stage. There were no significant trends between the physiological disorders (scuffmarks, russeting, cork around the pedicel, internal decay) and the rate of effective rainfall and irrigation applied until harvest.

4.4 WATER USE EFFICIENCY AND PRODUCTIVITY

Fruit that was suitable for export during the 2017/18 and 2018/19 seasons, respectively, was 75 and 81% for Bonnievale; 74 and 63% for Wolseley; 50 and 73% for Wellington; and 38 and 75% for Gouda. However, there was no simple relationship between effective rainfall and irrigation applied and the marketability of fruit. The maximum WUE (kilogram of fruit produced per hectare per mm water used) achieved locally was high in comparison to some published data for pomegranate from other countries and cultivars.

Water use efficiency based on irrigation water applied varied between 59.4 and 125.5 kg ha^{-1} mm^{-1} for the 2017/18 season, and between 31.1 and 91.3 kg ha^{-1} mm^{-1} for the 2018/19 season. If effective rainfall is also taken into account, the WUE ranged from 36.6 to 85.9 kg ha^{-1} mm^{-1} in the first season, and 22.4 to 73. kg ha^{-1} mm^{-1} in the second season. Water use efficiency, taking effective rainfall and irrigation into account, was the highest for both seasons in Bonnievale, with that in Wellington, Gouda and Wolseley being c. 7 and 8%; 31 and 26%; and 45 and 66% less efficient in the respective seasons.

The relative income of pomegranate orchards (expressed vs maximum income earned) increased with more effective rainfall and irrigation applied in both seasons (Table 4.3). Bonnievale also had the best relative water productivity (gross farm income per hectare per mm of water used) for both seasons for scenarios where only irrigation water or the total of effective rainfall and irrigation water applied was taken into consideration (data not shown). In 2017/18 and 2018/19, respectively, water productivity based on effective rainfall and irrigation applied was 36 and 12%; 55 and 21%; and 34 and 44% less in Wellington, Gouda and Wolseley, compared to Bonnievale.

4.5 REFERENCES

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CHAPTER 5: RECOMMENDATIONS FOR FUTURE RESEARCH ON WATER USE AND IRRIGATION

There is indeed a clear-cut need for irrigation research and potential spin-offs for the South African pomegranate industry and South Africa as a whole. Based on the data collected and trends established between effective rainfall and irrigation water applied, pomegranate yield and quality parameters, the following research needs were identified:

5.1 RESEARCH GAPS

- Decreased availability of adequate volumes of high-quality water for agricultural purposes or during drought periods requires the optimisation of irrigation and production practices that include saline water. According to the literature, pomegranate cultivars are moderately salt tolerant. Research in this regard is needed under local conditions to ensure sustainable production over the long term.

- There is potential for some production areas to increase their yield and fruit quality through improved irrigation scheduling. Since there are no local crop coefficients available for irrigation scheduling purposes and they are actually orchard-specific, research is required on the water use (transpiration and evapotranspiration) of a range of pomegranate orchards to develop a model that will enable the practical estimation of water use for individual orchards on-farm. Such a model will enable producers to schedule irrigation according to tree water requirements and prevent over- or under-irrigation, which impacts on the environment (leaching of fertilizers and water losses) and the performance of fruit trees (yield and quality). Such research may also be used to validate the water use estimates of the satellite-based Fruitlook, which is currently being promoted by the Western Cape Department of Agriculture as a water-saving tool. Research may be necessary for different cultivars and in different provinces. Although most plantings are currently in the Western Cape, there are indications of increased interest and orchard establishment in Limpopo.

- Research is needed on deficit irrigation and other water-saving strategies (e.g. mulches) for pomegranate orchards to save water and optimise yield and fruit quality under drought conditions. Crop phenological stages that are the least vulnerable to drought should be identified to develop these strategies. Although literature indicated that the stage from bud break until fruit set has the potential to save water without negative impacts on yield, our survey indicated that the fruit growth rate during this stage increased with higher rates of effective rainfall and the application of irrigation. The effect of different levels of water stress on fruit set and development under local conditions during this stage needs to be researched further and compared to that applied during linear fruit growth and ripening until harvest.

- Although the abovementioned research regarding deficit irrigation strategies will address fruit quality aspects as well, there are specific fruit quality issues that impact greatly on the marketability and profitability of pomegranates. These are highlighted separately. The amount of water application through rainfall and irrigation appears to have the opposite effect on quality-related consumer preferences such as red skin colour and dark-red arils, with more water resulting in a poorer red colouration of the skin, but a better red colouration of the arils. Research regarding irrigation and/or production strategies that may result in a better red colouration of both the skin and the arils is needed. If that is not possible, the economic feasibility of production for specific markets should be examined.

- The effect of irrigation, trellis systems and cover alternatives on pomegranate tree performance and fruit quality should be researched. Sunburn and windmarks are quality defects of pomegranate fruit that, depending on the degree of these defects, can decrease export volumes. Inadequate irrigation may lead to tree water stress and increased sunburn of fruit. Additional measures to curb sunburn are the use of appropriate trellis systems or to enclose fruit after final fruit set in cloth or paper bags until shortly before harvest. The latter is a labour-intensive exercise. Another alternative, and one that is probably a more cost-effective solution to curb sunburn and wind damage, could be the use of drape-netting, as is currently practiced in apple orchards. Less sunburnt and chafed fruit could increase export volumes and foreign or local income earned by commercial and/or smallholder farmers.

- Additional requests from pomegranate producers included the following:
  - Research on the effect of over-irrigation on root-related diseases and their management, especially in young orchards.
  - The treatment of highly saline water to improve quality before application through other means than reverse osmosis, which requires a reservoir on site.

5.2 RELEVANCE

Future research, based on research gaps identified in this project, will aim to provide the necessary information to support sustainable farming amid climate change (i.e. higher temperatures and changing rainfall patterns) and increasingly limited water resources. Knowledge of water-efficient production practices (e.g. accurate irrigation scheduling, appropriate irrigation systems, mulches and water-saving irrigation strategies) will allow producers to use limited water resources more efficiently and produce quality fruit for the local and export markets. High water use productivity and increased income from quality export fruit may improve the economic welfare of the community, i.e. producers and their farm workers will benefit from a positive impact on the economy. Pomegranate is a versatile fruit that can be marketed fresh or it can be processed to provide ready-to-eat convenience foods and juice, whereas parts of the fruit can be used in pharmaceutical products. Processing plants, supported by a large enough industry, may create new job opportunities and promote economic development. Higher production may also lead to more job opportunities.

Research will aim to address the achievement of maximum water use efficiency and/or water use productivity at the farm level, and, as such, generate relevant information that can inform national government policy and decision making in the water sector. It is expected that temperature increases due to climate change will impact on Africa to a greater extent than Europe. The successful production of a drought-tolerant crop may provide sustainable income and work opportunities in future when crops currently produced become unproductive or fail. Water savings in agriculture will make more water available to other sectors, which is critical during drought. With regard to the environment, proper irrigation management will promote the efficient use of limited water resources and reduce the leaching of fertilizers, which impact on the quality of groundwater. The use of poor-quality water for production may be a viable option for pomegranate production in areas where other water resources are not available. Pomegranate trees are relatively tolerant to salinity, and careful management will be necessary to ensure the sustainable use of soils where saline irrigation water is applied over the long term.

5.3 FUNDING FOR FUTURE RESEARCH

Irrigation research requires substantial funding due to the specialised equipment needs, especially for the measurement of evapotranspiration, transpiration and soil water, and salinity status. It is envisioned that national agricultural and water sectors and the pomegranate industry, probably via the Western Cape Department of Agriculture’s Alternative Crop Fund, could co-fund future water use and irrigation-related research. Such research would not only benefit the pomegranate industry and its dependents, but also the South African economy.

Potential primary funders for future pomegranate water use and irrigation research are depicted in Figure 5.1. In national government, the Department of Agriculture, Land Reform and Rural Development, and the Department of Water and Sanitation both reside in the Economic and Infrastructure Development Cluster. The ARC and the WRC are public entities nested in these two departments. The mission of the ARC is to be a premier science institution that conducts research with partners, develops human capital and fosters innovation to support and develop the agricultural sector.

The ARC's main functions are, among others, to undertake and promote research and cooperate with departments of the state, institutions, persons and other authorities for the promotion and conduct of research in agriculture, and its technology transfer. The ARC is aligned to national priorities and policies, including, among others, the National Development Plan (Vision 2030), contribution to employment and job creation, increasing agricultural production and productivity, food and nutrition security, and enabling the country to respond and adapt to climate change concerns.

The mission of the WRC is to be a global water knowledge node and South Africa's premier water knowledge hub active across the innovation value chain that informs policy and decision-making, creates new products, innovation and services for socio-economic development, develops human capital in the water science sector, empowers communities and reduces poverty, supports the national transformation and redress project, and develops sustainable solutions and deepens water research and development in South Africa, Africa and the developing world.

The Commission's mandate includes promoting coordination, cooperation and communication in the area of water research and development, establishing water research needs and priorities, stimulating and funding water research according to priority, promoting the effective transfer of information and technology, and enhancing knowledge and capacity building within the water sector. The contribution of the future research to the Water Research, Development and Innovation Roadmap and specifically the water demand aspect, through the WRC Climate Change, the Water-Energy-Food Nexus and Sustainable Water Behaviour Lighthouses, as set out in the WRC's Corporate Plan of 2018/19-2022/23, was already highlighted in the introduction to this report.

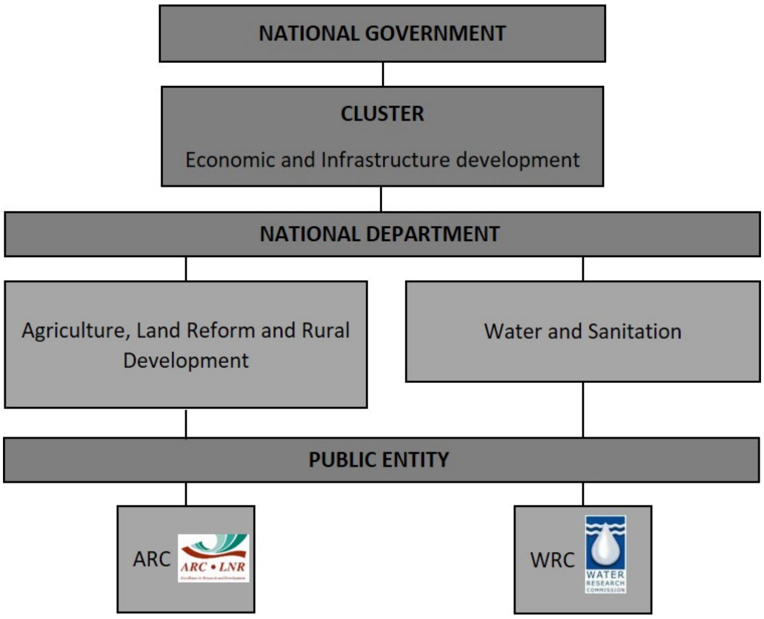

Figure 5.1: Diagram depicting national government-related potential funders for future pomegranate irrigation research

At provincial level, the Western Cape Department of Agriculture's Alternative Crop Fund has previously contributed, via POMASA, to the survey conducted to obtain baseline irrigation and water use information for pomegranate. The Alternative Crop Fund furthers exports and supports land reform. Alternative crops are mostly water-smart and would therefore be preferred crops against the current, and most probably drier and even continued drought conditions in the Western Cape and the rest of South Africa.

Promoting alternative crops is also one of the proposed actions of the Western Cape *SmartAgri* plan. However, the pomegranate industry is small and competes with several other alternative crops for Alternative Crop Fund research funds. The likelihood for future funding from this source is considered small. It is furthermore not clear if provincial government in other provinces such as Limpopo, the Northern Cape, the Eastern Cape and the Free State, where new plantings could also benefit from such research, will be interested in co-funding research and through which channels these departments should be approached. Optimised irrigation scheduling can aid in the sustainability of the water and soil resources for all the country's provinces.

Taking the high water use efficiency acquired locally in some production areas into account, compared to that achieved internationally, as well as job creation and the economic potential of the crop, the WRC is requested to strongly consider a research call to fund research on water use and/or water-saving irrigation strategies for pomegranate trees.