7-2019

Crop and climate suitability for irrigated agriculture in the Midlands area of Western Australia, 2nd edition

Leon van Wyk

Department of
Primary Industries and
Regional Development

GOVERNMENT OF
WESTERN AUSTRALIA

Crop and climate suitability for irrigated agriculture in the Midlands area of Western Australia

Second edition

Resource management technical report 415

Crop and climate suitability for irrigated agriculture in the Midlands area of Western Australia

Second edition

Resource management technical report 415

Leon van Wyk

ISSN 1039-7205

Cover: Seed potato crop near Dandaragan (photo: L van Wyk)

Recommended reference

van Wyk, L 2019, 'Crop and climate suitability for the Midlands area of Western Australia', 2nd edition, *Resource management technical report 415*, Department of Primary Industries and Regional Development, Perth.

Disclaimer

Copies of this document are available in alternative formats upon request.

3 Baron-Hay Court, South Perth WA 6151
Telephone: +61 (0)8 9368 3333
Email: enquiries@dpird.wa.gov.au
Website: dpird.wa.gov.au

Contents

Preface

The first edition of this report was updated after corrections were made in related reports, specifically Griffin et al. (2019a, 2019b). This second edition contains those corrections, and some outdated mapping has been replaced or removed. Other minor editorial changes have also been made in this edition. This edition replaces *Resource management technical report 405*.

Acknowledgements

Royalties for Regions funding made this investigation possible. It was conducted by the Department of Agriculture and Food, Western Australia (DAFWA), which was replaced by the Department of Primary Industries and Regional Development (DPIRD) on 1 July 2017. This investigation was part of the Midlands Water for Food Project, which aims to support the expansion of irrigated agriculture in the Northern Perth Basin.

I would like to thank my colleagues James Dee, Alec McCarthy and Angela Stuart-Street for the technical review of the report, and John Bruce for providing GIS support. Angela Rogerson and Kathryn Buehrig (KB Editing) edited this report.

Summary

The Midlands groundwater and land assessment is a $4.7 million Water for Food project. Its aim is to confirm groundwater availability at one or more focus areas that may form precincts of 2000–3000 hectares (ha) suitable for intensive irrigated horticulture. This report forms part of this project.

Firstly, this report describes the climate of the Midlands study area and highlights the subtle differences between the two selected focus areas, Irwin and Dinner Hill. It discusses the importance of climate in determining crop suitability. We also investigated the following additional factors that determine crop suitability:

- water quality
- water quantity
- land capability (soils)
- environmental impact.

Secondly, this report examines potential commercial horticultural crops for the Midlands area.

We found that the combination of climate and the range of soils in the study area would suit a wide range of horticultural crops. The main limiting factor for extensive horticultural development in the study area is the availability of water that is suitable for irrigation. High temperatures, wind and water quality are also important management considerations.

1 Introduction

1.1 Background

The expansion of irrigated agriculture has growers and investors searching for areas of suitable land with good groundwater resources. The Midlands groundwater and land assessment is a $4.7 million Water for Food project, seeking to confirm groundwater availability in focus areas that may form precincts of 2000–3000ha suitable for intensive irrigated horticulture between Perth and Geraldton.

Using a multi-criteria analysis process, the groundwater resources of the North Perth Basin were matched with a broad soil capability assessment of the Midlands area to identify potentially suitable locations. Details of this process are in the unpublished Department of Water report (2017a). Irwin and Dinner Hill were the two focus areas selected by the project team for more-detailed assessment.

This report details the crop and climate suitability analysis of the Midlands study area, focusing on the Irwin and Dinner Hill areas. It is accompanied by additional reports and mapping which will collectively assist future irrigated agricultural development in the Midlands area:

- soil and land capability report for the Irwin focus area and surrounding lands (Griffin et al. 2019a)
- soil, land capability and land management unit report for the Dinner Hill focus area (Griffin et al. 2019b)
- hydrology hazard assessment report (Speed & Killen 2018)

This information also complements the prospectivity mapping undertaken by the Department of Water (2017b) which identifies potential areas for groundwater in the region.

1.2 Study area

The Midlands Water for Food study area covers about 17 000 square kilometres (km^2). It is 120 kilometres (km) north of Perth and stretches along the coast from Dongara in the north to Lancelin in the south, and inland from Mingenew in the north to Moora in the south (Figure 1.1).

Historically, broadacre agriculture dominated the Midlands area; mainly cereal cropping and pastures for sheep and cattle. More recently, it is being recognised for its potential to support horticulture.

Today, horticulture in the Midlands area mainly produces annual vegetable crops, such as carrots, onions, potatoes and leafy vegetables. There are also perennial tree crops, such as citrus, nuts, mangos and olives.

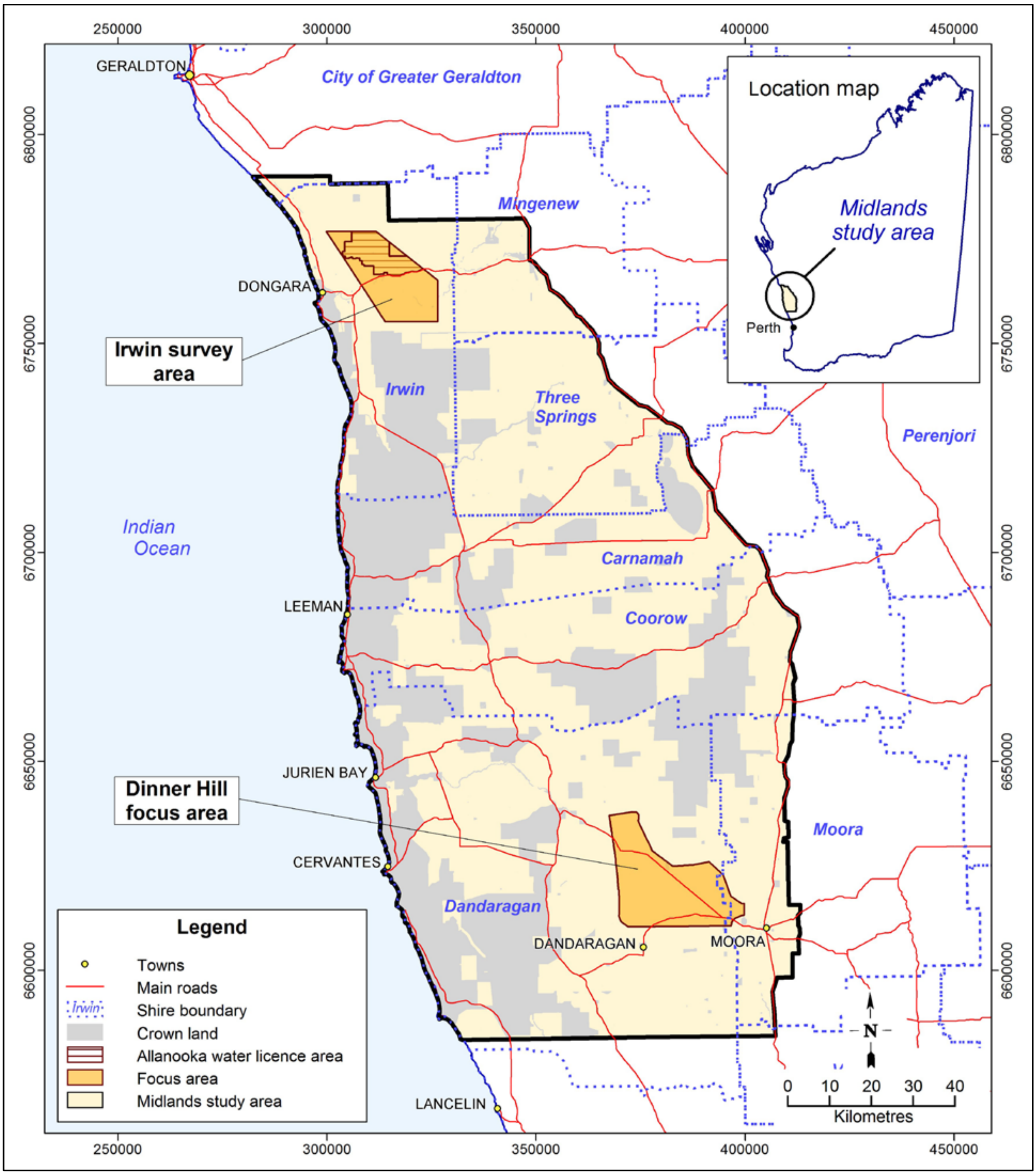
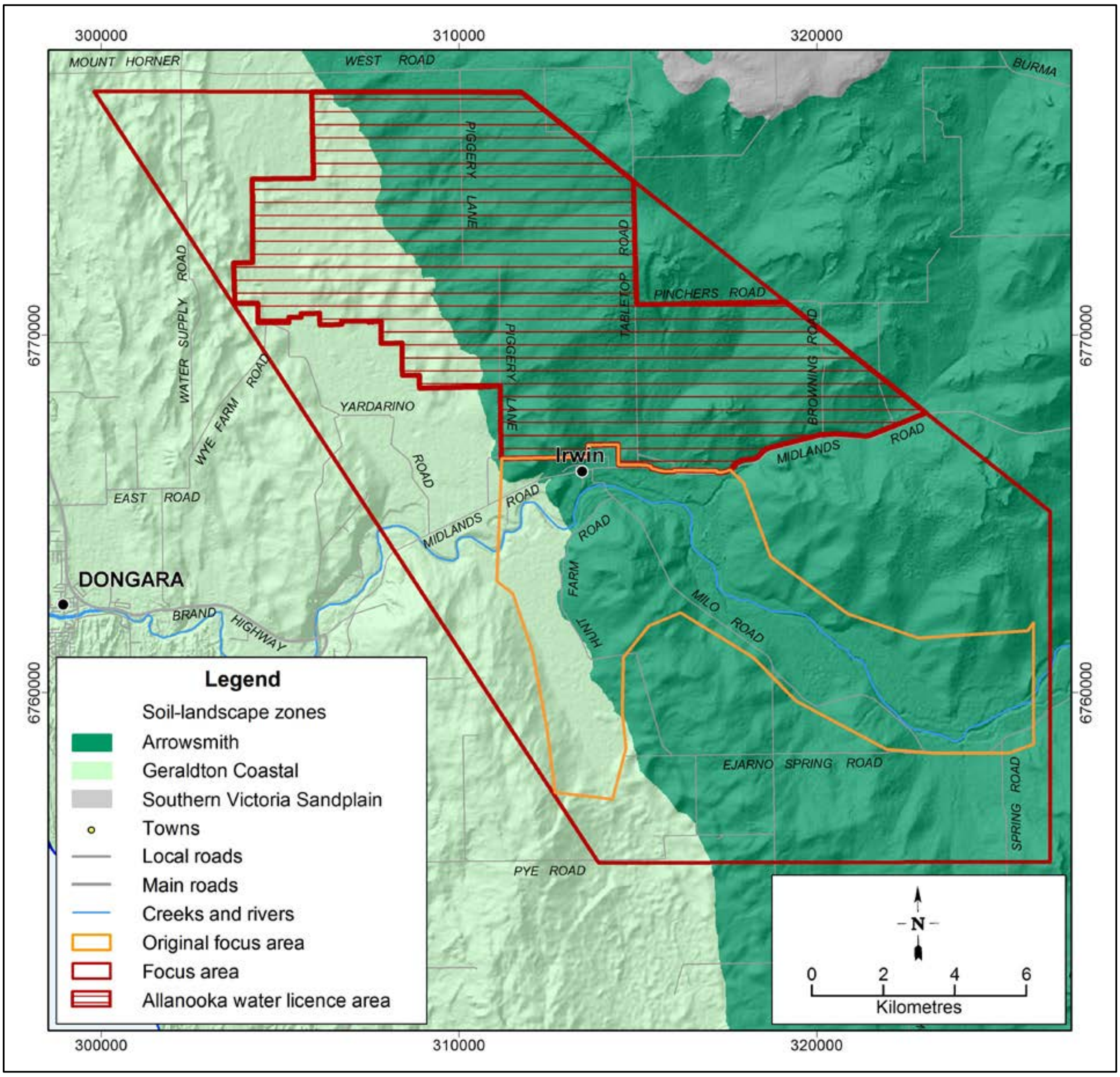


Figure 1.1 Midlands study area

1.2.1 Irwin focus area

The Irwin focus area is 15km east of Dongara and covers an area of about 33 700ha (Figure 1.2). Broadacre agriculture is still the dominant land use here, with only a small area of annual and perennial horticulture, including mangos and some irrigated pasture.

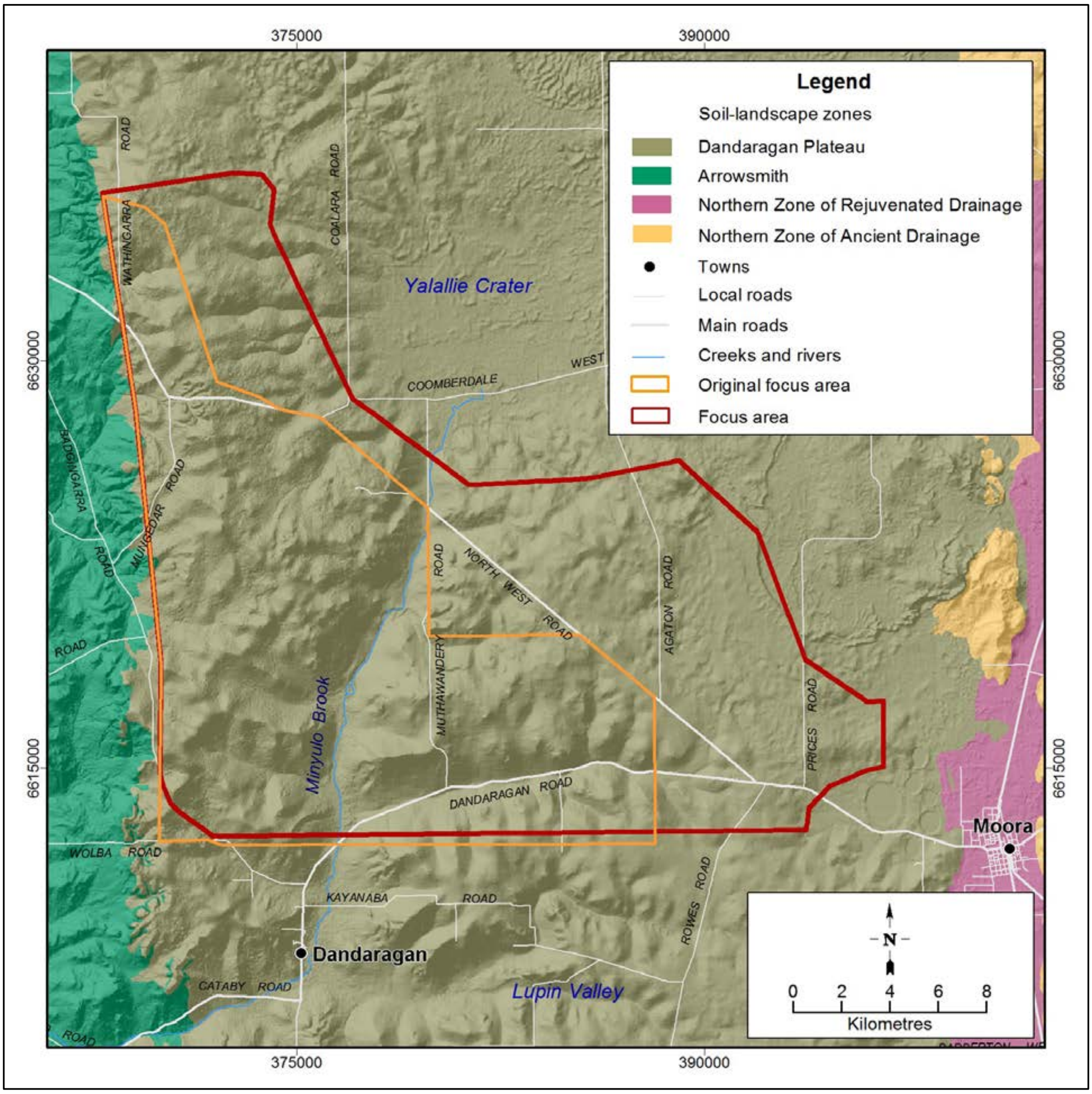


Source: Griffin et al. (2019a)

Figure 1.2 Irwin focus area

1.2.2 Dinner Hill focus area

The Dinner Hill focus area is between Badgingarra and Dandaragan and covers about 50 200ha (Figure 1.3). While broadacre agriculture still dominates in this area, there is also an established horticultural industry. The main vegetable crop is potatoes for the fresh and seed markets, while the main tree crops are citrus and olives. Other tree crops like mangos and stone fruits are also produced, but on a smaller scale.



Source: Griffin et al. (2019b)

Figure 1.3 Dinner Hill focus area

2 Climate

Climate is one of the most important considerations in assessing an area for its suitability for different crops. More-specific climate requirements for crops are presented in Chapter 3.1.

Overall, the Midlands study area has a Mediterranean-type climate with hot, dry summers and cool, wet winters. The average annual rainfall tends to decrease from south to north and west to east, with the highest rainfall of 600 millimetres (mm) at Lancelin and the lowest of 370mm at Mingenew (based on a 30-year average from 1981 to 2010). The area's rainfall is winter-dominant, with up to 80% of the annual total occurring between May and September. Summer is normally dry, except for some isolated thunderstorms and the occasional decaying cyclone (Bureau of Meteorology 2017).

Temperatures also vary across the region. This variation is mainly due to the influence of latitude and the Indian Ocean. In summer, the average maximum temperatures along the coast range from 30°C in the south to 32°C in the north, with the highest temperatures occurring in February. Moving east, there is an increase in the average maximum summer temperatures, ranging from 35°C in the south to 37°C in the north. The coastal influence is also apparent in the winter minimum temperatures, with a 9°C average minimum in July and August at the coast and a 7°C average minimum inland (Bureau of Meteorology 2017).

Prevailing winds have a strong influence on the climate of the area. In summer, the dominant wind in the morning is normally a warm easterly that ranges from 18 to 22 kilometres per hour (km/h). The summer afternoons are generally characterised by a sea breeze from a south-south-westerly direction. On the coast, these winds range from 26 to 31km/h and can reach as far inland as Eneabba, with sea breezes of 18km/h and to Badgingarra, with winds of up to 28km/h. The cooling summer breeze often reaches further inland later in the day.

The wind is more variable during winter as cold fronts approach from the Indian Ocean. The prevailing winds ahead of cold fronts come from the east to north-west and behind the fronts, the winds are generally from the west to south-west. The average wind speeds are generally lower than in summer and vary from 10 to 20km/h (Bureau of Meteorology 2017).

The coastal influence in the area is also evident in the difference in relative humidity between the coast and the inland areas. This is especially obvious during summer where the afternoon (3pm) relative humidity is higher or very close to the morning (9am) relative humidity in the coastal areas, while inland relative humidity is significantly lower in the afternoons (Bureau of Meteorology 2017).

2.1 Weather data

Long-term weather data for the area is available from seven Bureau of Meteorology weather stations. Four of these are within the study area and the other three are nearby (Figure 2.1). These stations all have more than 20 years of records, which has been essential to describe the climate of the area. See Appendix A for a summary of the long-term weather data.

DPIRD has an extensive network of weather stations in the study area, with real-time data that is essential for fine-tuning of irrigation scheduling. There are 12 stations within the study area and another 6 nearby (Figure 2.1; Department of Agriculture and Food, Western Australia 2017).

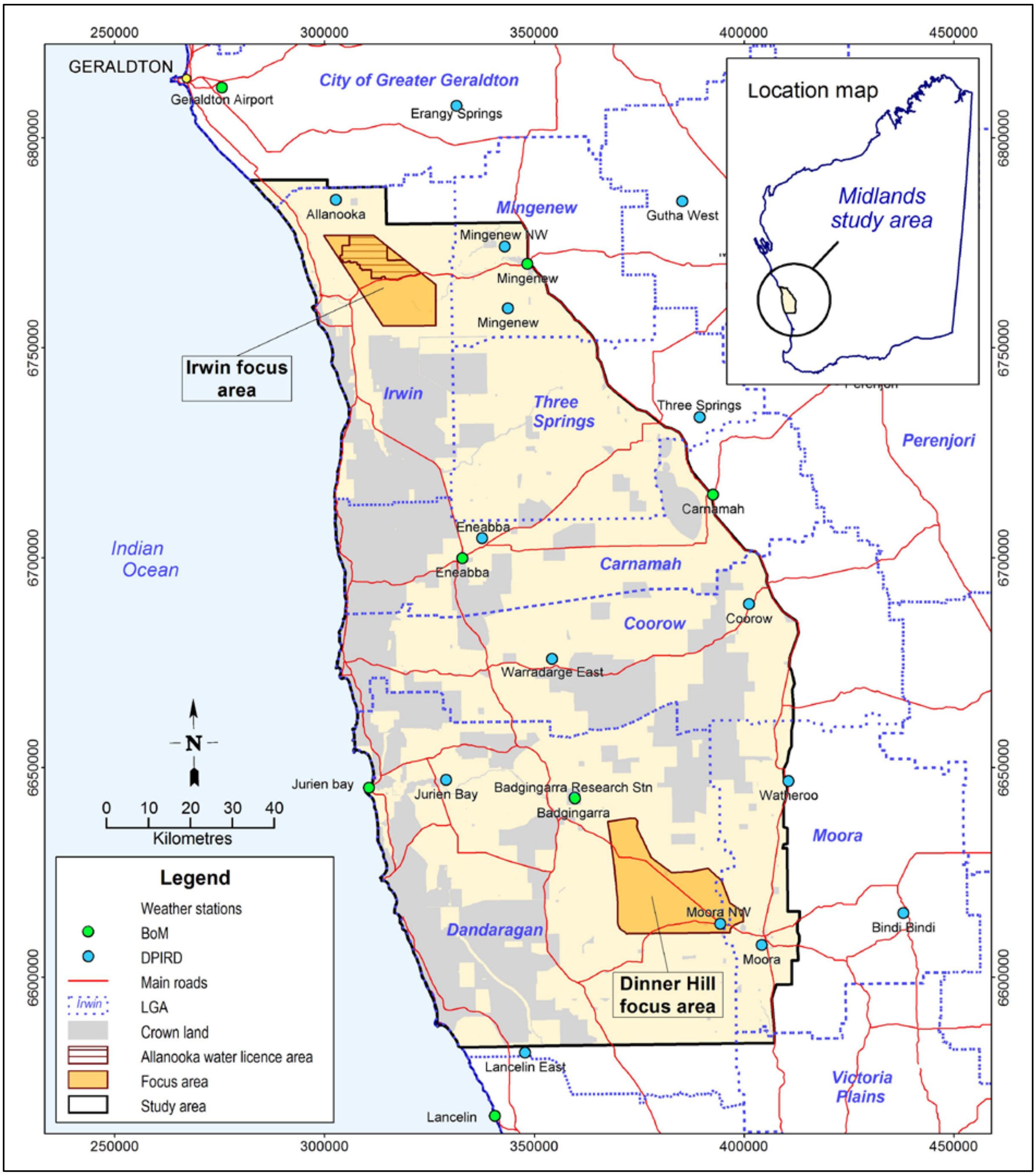


Figure 2.1 Weather stations in the Midlands study area

2.2 Crops and climate

A range of climatic factors influence crop growth, determining whether a crop will be suited to a specific area. The key climatic factors that influence crop growth are precipitation (rainfall), solar radiation, temperature, relative humidity and wind. These are discussed in the following sections. Evaporation, which is the result of a combination of climatic factors, is also discussed.

2.2.1 Rainfall

Rainfall in the study area occurs mostly in winter, therefore a limited number of crops (mainly broadacre) would thrive in the area on rainfall alone. The availability of suitable groundwater in the area hugely increases the range of crops, including horticultural crops, that can be successfully grown.

Almost all of the irrigation water in the study area is groundwater extracted from bores of varying depths. Surface water catchments and storages are not an attractive option because the study area experiences very high rates of evaporation and only receives 370–600mm of rain per year.

2.2.2 Solar radiation

Plants use the solar energy from the sun to fix carbon dioxide from the atmosphere, and in combination with water from the soil, convert this into carbohydrates to grow, reproduce and provide the grain and vegetation used as food by humans and animals. The solar energy available to plants is a function of sunshine intensity and duration.

Solar radiation is not a limiting factor for crop production within the study area.

2.2.3 Temperature

Plants can grow in a wide temperature range, from 5°C to 45°C. Plants are adapted to the area of their origin and will therefore have an optimum temperature range for growth. In general, plants that originate from tropical areas will be very sensitive to low temperatures, while plants that originate from colder climates will not tolerate high temperatures.

Some crops require cyclic temperature patterns to function properly. For example, many deciduous crops require a period of chill to initiate flowering, while others may just require a period of change in temperature and day length.

Soil temperature is also important because extremes can have a negative effect on crop establishment. Potato tubers are very sensitive to high soil temperature and when planted in these conditions (such as during summer), crop establishment will be very poor.

The presence of frost determines the range of crops that can be successfully grown. The timing of frost events is also important, as the effect of frost depends on what stage of growth the plant is at. Frost can occur as soon as the temperature falls below 2°C. In the study area, the risk of frost is lower on the coastal plain west of the Dandaragan Scarp than in the inland areas. The risk also reduces moving from south to north.

The Irwin focus area has a very low frost risk, while some parts of the Dinner Hill focus area experience frost almost every year. Microclimates, described in Chapter 2.3, are more of an issue in the Dinner Hill focus area than in the Irwin focus area.

2.2.4 Relative humidity

Relative humidity is the amount of moisture in the air expressed as a percentage of the amount the air can actually hold. Warmer air can hold more moisture than cooler air, which means that for a given amount of atmospheric moisture, relative humidity will be lower if air is warm than it would be if the air is cool (Bureau of Meteorology 2017).

Relative humidity has a direct influence on the water balance of a plant. It also indirectly affects growth, pollination, photosynthesis, yield and the occurrence of disease. Relative humidity will also affect fruit quality because the fruit of some plants are more susceptible to sun and heat damage during periods of low relative humidity.

Relative humidity is affected by the proximity of an area to the coast. This is evident in the study area. During summer, the afternoon (3pm) relative humidity is higher or very close to the morning (9am) relative humidity in the coastal areas, but it is significantly lower in the inland areas (Bureau of Meteorology 2017).

Relative humidity is different between the two focus areas, because Irwin is close to the coast and Dinner Hill is inland.

2.2.5 Wind

Wind can have physiological and mechanical effects on crops. Physiological effects include increased transpiration and drying of plants by hot dry winds. Mechanical effects include physical damage to plants, flowers and fruit and chilling injuries during cold winds. This damage can reduce the quality of crops or even result in a complete loss.

Wind is a significant climatological feature of the area, but there is a distinct difference between the coastal and inland areas. On the coast, during the summer months (December to February), the wind tends to increase in the afternoons, shifting from the south-south-east in the morning to a cooling sea breeze from the south-south-west in the afternoon. These cool sea breezes can reach inland as far as Eneabba and Badgingarra. In the inland areas, during December and January, the wind tends to drop off slightly in the afternoon and shift from east to south-south-west. In February, the dominant wind is from the east in the morning and afternoon and it is generally hot, having a drying effect on crops (Bureau of Meteorology 2017).

The winds in the Irwin focus area have a distinctive coastal nature and the area regularly experiences the cooling effect of a sea breeze, while in the Dinner Hill focus area the winds tend to have more of an inland nature.

Crops that are sensitive to wind damage should be protected via well-planned windbreaks (Maynard & Hochmuth 2007).

2.2.6 Evaporation

Evaporation is not a climatic factor, but is the result of a combination of climatic factors. Evaporation is a measure of the amount of water that evaporates from an open pan, called a 'Class A evaporation pan'. Evaporation is also calculated using weather station data, because the rate of evaporation depends on factors such as cloudiness (solar radiation), air temperature, relative humidity and wind speed (Bureau of Meteorology 2017).

As all these climatic factors determine the amount of water required for productive plant growth, it is evident that evaporation values are required to determine the amount of water used by actively growing crops (Department of Primary Industries and Regional Development [DPIRD] 2017a).

In the study area, annual evaporation is considerably higher than annual rainfall. This emphasises the importance of irrigation for successful horticultural production. The relationship between monthly rainfall and evaporation shows that rainfall only exceeds evaporation for three months of the year in the southern coastal areas (Figure 2.2), while in the northern inland areas, evaporation always exceeds rainfall (Figure 2.3). Appendix B includes graphs for all available DPIRD weather stations.

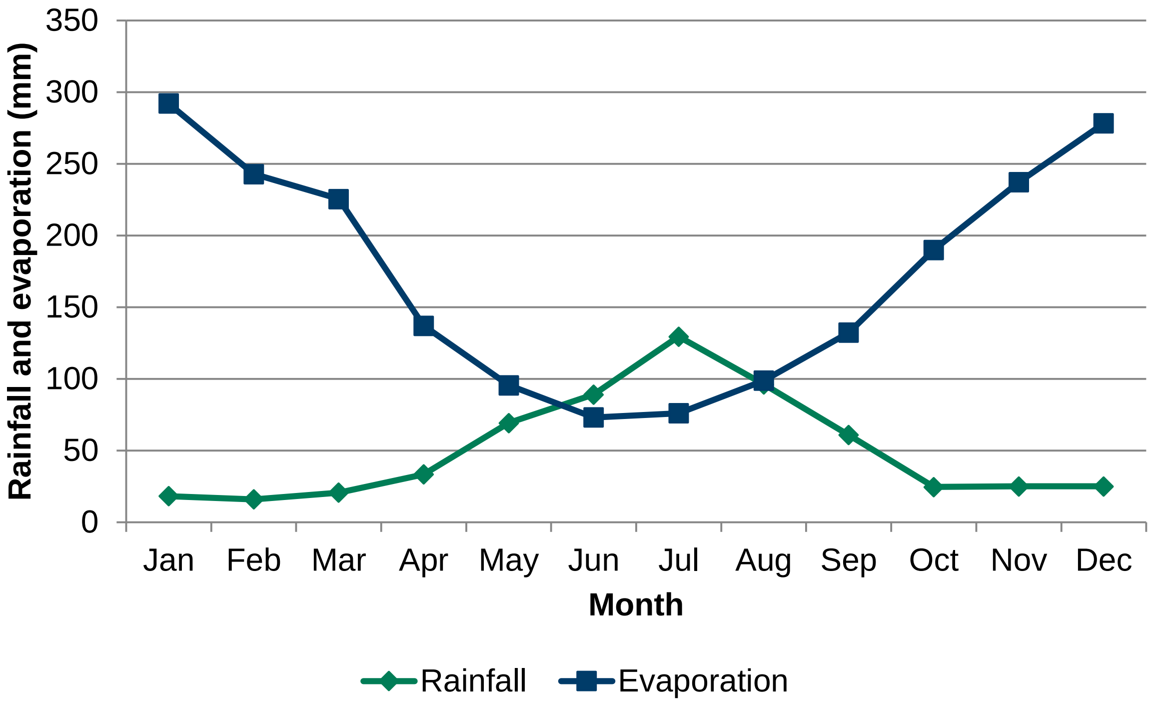


Figure 2.2 Monthly evaporation and rainfall for Lancelin East

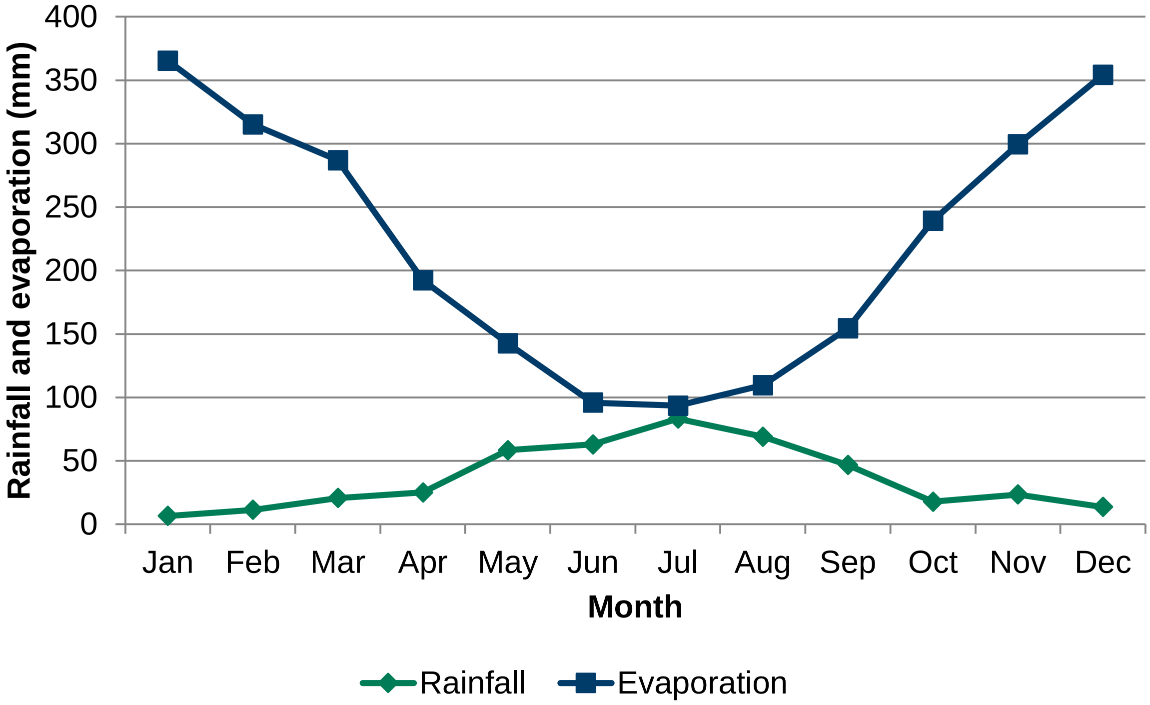


Figure 2.3 Monthly evaporation and rainfall for Mingenew

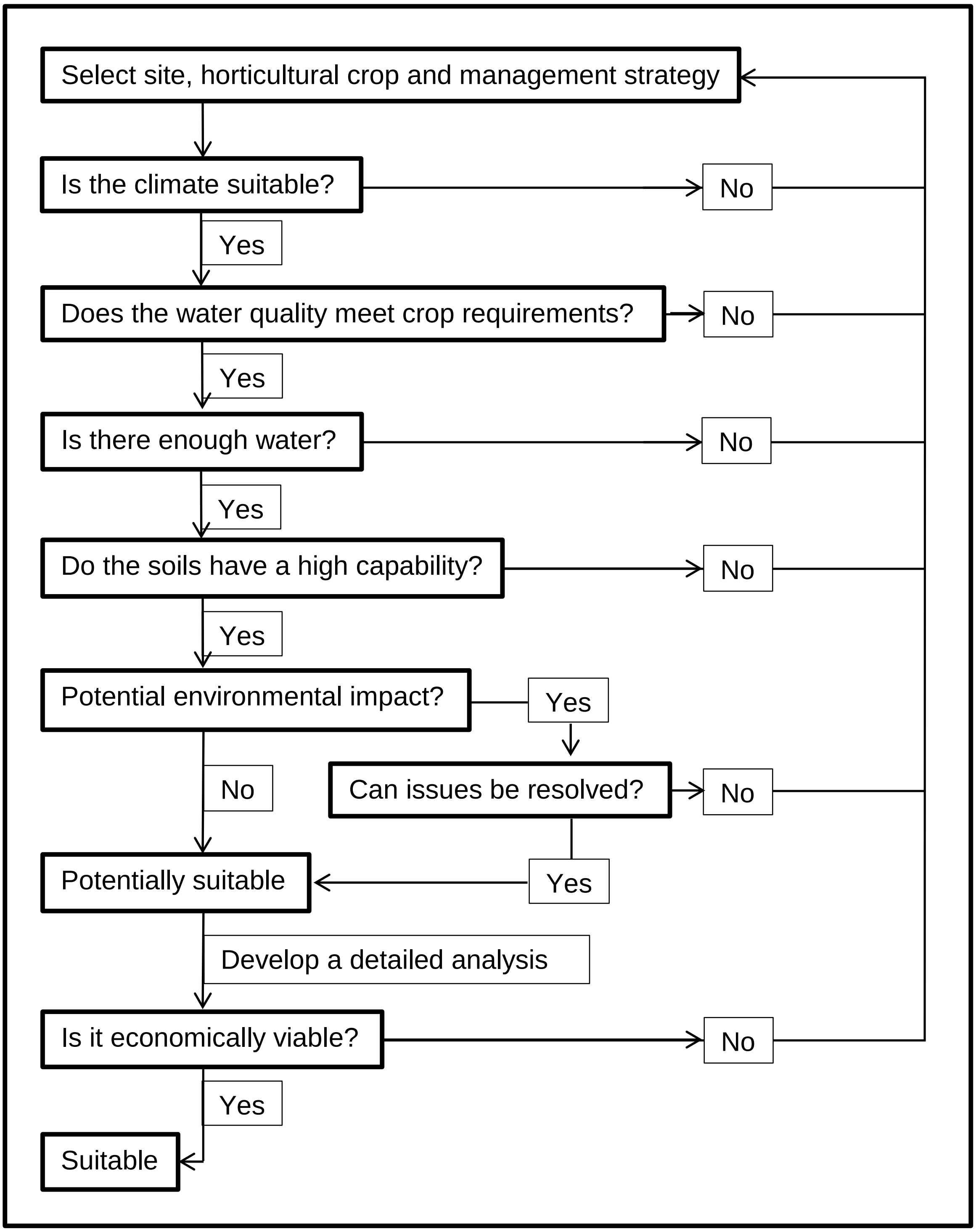
2.3 Microclimate

Microclimate is climate on a small scale, where weather variables like temperature, rainfall, wind or relative humidity may vary from surrounding larger climatic areas. A microclimate might be an irrigated crop, a valley or a city.

Frost risk in the study area is lower in the coastal plain than in the inland areas, and the risk also reduces from south to north. However, due to the effects of microclimate, some areas do have a higher frost risk. For example, during clear, winter nights with very little wind, the risk of frost in the lower reaches of valleys is much greater. This is because as the air cools during the night, it begins to flow downhill and gathers on the valley floor or in pockets where there are dips in the ground. These higher risk valleys should be avoided when considering frost-sensitive crops (Met Office 2011).

3 Crop suitability

Moore and Phillips (n.d.) recommended a specific sequence of steps to follow when determining the potential for a specific crop in a selected area (Figure 3.1). The following sections discuss these crop selection criteria.



Source: Moore & Phillips (n.d.)

Figure 3.1 Steps to follow to determine if a site is suitable for a specific crop or range of crops

3.1 Is the climate suitable?

Climate suitability for irrigated crops is initially determined using maximum and minimum temperatures, therefore an understanding of the optimum and tolerated temperature ranges for crops is important (Table 3.1).

Some crops require a complex relationship of climatic factors to generate good growth and stimulate flowering, fruit set and crop maturation. Maximum and minimum temperatures provide basic indications of climate suitability, but more details on when the temperature extremes occur and the accumulation of chill factors and heat units are required. For example, some crops require certain temperature regimes to coincide with changes in day length.

If the climate is not suitable for a specific crop, it is not always economically feasible to artificially modify climatic conditions (for example, using techniques such as covered cropping).

Temperature varies across the region, mainly due to the influence of the Indian Ocean and the latitude. During summer, the average maximum temperatures along the coast range from 30°C in the south to 32°C in the north, with the highest average maximum in February. Moving east, there is an increase in the average maximum summer temperatures, ranging from 35°C in the south to 37°C in the north. The coastal influence is also apparent in the winter minimum temperatures, with a 9°C average minimum in July and August at the coast and a 7°C average inland (Bureau of Meteorology 2017).

The northern part of the study area has warmer winters, which is a climatic advantage over the southern parts for vegetable crops that are harvested from June to September (Moore & Phillips n.d.). The Irwin focus area has milder winters than the Dinner Hill focus area and the risk of frost is also significantly lower.

Table 3.1 Temperature ranges for vegetable crops

Crop	Temperature (°C)			
	Minimum	Ideal lower	Ideal upper	Maximum
Artichoke	7	15	18	24
Babyleaf – chard	5	15	18	24
Babyleaf – rocket	5	16	24	32
Babyleaf – spinach	5	15	18	30
Bean	10	15	21	27
Beetroot	5	15	18	27
Broccoli	4	15	18	32
Brussels sprout	5	15	18	24
Cabbage	7	15	18	24
Capsicum	18	20	25	32
Carrot	7	15	18	30
Cauliflower	0	15	18	32
Celery	7	15	18	24
Chilli	18	21	30	35
Cucumber	15	18	24	32
Eggplant	18	21	30	35
Garlic	7	13	24	30
Herbs	7	15	18	24
Leek	7	13	24	30
Lettuce (Iceberg, Cos, babyleaf)	7	12	21	24
Parsnip	5	15	18	24
Pea	7	15	18	24
Potato	7	15	18	30
Pumpkin	10	18	24	32
Shallot	2	13	24	30
Silverbeet	5	15	18	24
Snow pea and sugar snap pea	7	15	18	24
Swede and turnip	5	15	18	24
Sweet corn	12	24	30	32
Tomato	18	18	24	29
Zucchini and butter squash	10	18	24	32

Source: Maynard & Hochmuth (2007) with modifications

3.2 Does the water quality meet crop requirements?

Successful crop irrigation requires an adequate supply of suitable-quality water. Irrigation water quality is dependent on the amount and type of dissolved salts present in the water, normally referred to as total dissolved salts.

Good quality water is not always available for irrigation, so sound planning and management is required when using water of less-than-optimal quality.

Problems caused by the use of low quality irrigation water can greatly vary in type as well as severity. The soil type, climate, crop and irrigation management influences these problems. Salts and other elements can accumulate in the soil (root zone) and the impact of this accumulation on crop yield determines the suitability of the water for irrigation use (Ayers & Westcot 1985).

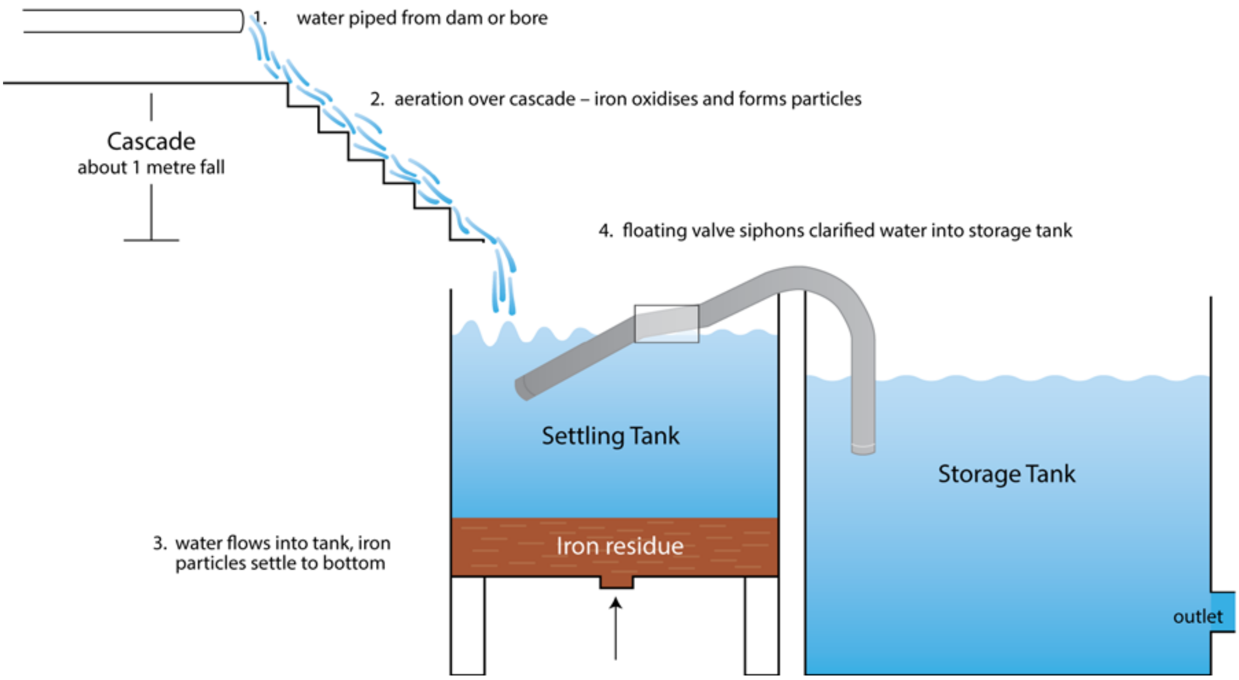
3.2.1 Soluble iron

Iron is soluble in water where oxygen is absent or at very low levels. Therefore, high iron levels are generally associated with water from deep bores. Soluble iron is an issue in the Midlands area because almost all of the irrigation water originates from deep bores.

Soluble iron is also associated with iron-loving bacteria that extract iron out of the water and convert it to sludge. This can cause blockages in pipes, drippers and sprinklers and can damage sensitive equipment such as pressure gauges. High iron levels in water can also stain crops, which can affect the value of the crop. Iron deposits can make pasture unpalatable to livestock and if eaten, can cause dairy cattle to scour and milk production to drop.

When using an irrigation system to fertigate, water with levels of dissolved iron higher than 1.5 milligrams per litre should be avoided. This is because the injection of unchelated phosphates or calcium salts into the irrigation system will accelerate the precipitation of iron and cause blockages.

When water that contains iron is oxidised, the iron will form solid particles that can then settle out or be filtered out of the solution. The simple cascade method — as illustrated in Figure 3.2 — can assist in removing iron from water.



Source: New South Wales Department of Primary Industries (2014)

Figure 3.2 Cascade method for removing iron from water

3.2.2 Salinity

Salinity is the accumulation of salts in the root zone to a point where it affects plant growth. In irrigated agriculture, salinity is mainly the result of applying marginal or saline irrigation water. Reductions in crop yield occur when the soil salinity reaches a level where the plants are no longer able to extract water from the salty soil-water solution. This will lead to water stress and plants can display the same symptoms as when experiencing drought.

Using marginal irrigation water can affect plant growth through salinity or toxicity. Salinity is a measure of the amount of total dissolved salts (TDS) present in water. It is often measured by electrical conductivity (EC) and then converted to TDS.

EC is measured in millisiemens per metre (mS/m) and this value can be converted to TDS in milligrams per litre (mg/L) by multiplying the EC by 5.5. This conversion figure gives an approximate value of the salt concentration in the water (Lantzke et al. 2007). The EC does not identify the types of salts present in the water, but it gives a reliable measure of salinity problems. Table 3.2 shows the general salinity classifications for water.

Table 3.2 General salinity classifications for water

EC (mS/m)	TDS (mg/L)	Classification status
0–80	0–440	Low
80–250	440–1375	Moderate
250–500	1375–2750	Saline
>500	>2750	Highly saline

EC = electrical conductivity; TDS = total dissolved solids

Source: Lantzke et al. (2007)

Not all plants are affected by salinity to the same extent, because the tolerance of crops varies (see Table 3.3 for fruit and tree crop tolerances and Table 3.4 for vegetable crop tolerances). The values in these tables should only be used as a guide because the extent of salinity damage depends on multiple factors. When the salinity of the irrigation water is close to the recommended upper limit, it is recommended to conduct trials to determine if crop damage will occur under these conditions.

Table 3.3 Tolerance of fruit and tree crops to saline irrigation water on loamy soil

Crop	No expected yield loss EC (mS/m)[a]	10% yield loss EC (mS/m)[a]	25% yield loss EC (mS/m)[a]
Almond	100	140	190
Apple	–	150	–
Apricot	110	130	180
Avocado	90[b]	–	–
Blackberry	100	130	180
Date palm	270	450	730
Fig	–	253	–
Grapefruit	120	160	220
Grape	100	170	270
Mulberry	90–270[b]	–	–
Nectarine	90[b]	–	–
Olive	–	250	–
Orange	110	160	220
Peach	110	130	180
Pear	–	150	–
Plum	100	140	190
Pomegranate	–	250	–
Raspberry	–	90	–
Strawberry	70	90	120

EC = electrical conductivity; – = not applicable

a EC values would be slightly higher for sandy soils and lower for clay soils.

b The maximum concentration or range of concentrations is provided because detailed data on yield loss is not available.

Source: Lantzke et al. (2007)

Table 3.4 Tolerance of vegetable crops to saline irrigation water on loamy soil

Crop	No expected yield loss EC (mS/m)[a]	10% yield loss EC (mS/m)[a]	25% yield loss EC (mS/m)[a]
Asparagus	270–635[b]	–	–
Bean	70	100	150
Beetroot	270	340	450
Broccoli	190	260	370
Cabbage	120	190	290
Capsicum	100	150	220
Carrot	70	110	190
Cauliflower	90–270[b]	–	–
Celery	120	230	390
Cucumber	170	220	290
Kale	270–635[b]	–	–
Lettuce	90	140	210
Onion	80	120	180
Parsnip	902	–	–
Pea	902	–	–
Potato	110	170	250
Pumpkin	90–270[b]	–	–
Radish	80	130	210
Rockmelon	90–270[b]	–	–
Spinach	130	220	350
Squash	210	260	320
Sweet corn	110	170	250
Sweet potato	100	160	250
Tomato	170	230	340
Watermelon	150	240	380

EC = electrical conductivity; – = not applicable

a EC values would be slightly higher for sandy soils and lower for clay soils.

b The maximum concentration or range of concentrations is provided because detailed data on yield loss is not available.

Source: Lantzke et al. (2007)

3.2.3 Toxicity

Toxicity occurs when plants take up certain ions in the soil solution and these accumulate to a concentration that is high enough to cause damage. The amount of damage depends upon the crop's sensitivity. In general, perennial tree crops are more sensitive. Toxicity is mainly caused by the accumulation of sodium, chloride and boron in the plant.

Griffin et al. (2019a) found boron at depth in the soils on the alluvial plain of the Irwin focus area. The soil pH of these soils is generally high and this can create toxicity problems for sensitive crops because of the increased solubility of boron at a high pH.

3.2.4 Soil types and irrigation

Understanding what constitutes suitable soil for horticulture is vital for a thriving crop. The type of soil strongly influences the approach to management, including irrigation. Griffin et al. (2019a, 2019b) describe the main soil types found in the two focus areas.

When using water of less-than-optimal quality, the key to successful irrigation is to move salts below the root zone through the process of leaching. Applying additional irrigation water can successfully leach salts from the root zone in well-drained soils like sands or loams, but this is not always successful in clay soils, which are poorly drained.

Clay soils consist of clay particles that are negatively charged and these particles repel each other when moved close together. These particles are held together in the presence of positively charged cations (such as calcium or sodium) in the space between the clay particles to enable the formation of aggregates. While aggregates exist, water and dissolved nutrients can move through the soil profile.

Because sodium ions have only half the positive charge of calcium ions, the bonds between clay particles will weaken if the spaces between the clay particles are dominated by sodium ions. Because of the large size of sodium ions, a larger amount of water molecules are attracted, and this pushes the clay particles apart. Too much sodium in the soil leads to excessive swelling, which can cause soil structural collapse known as dispersion. This is a risk factor for horticulture in the Irwin valley alluvial soils, which are described by Speed and Killen (2018) and Griffin et al. (2019a).

When irrigating a clay soil with water that has high sodium content, the calcium in the space between the clay particles is replaced by sodium, which pushes the clay particles apart and causes the structural collapse of the soil. A dispersive soil is very prone to waterlogging and this will adversely affect crop production (McKenzie 2003).

3.3 Is there enough water?

The amount of suitable-quality water that is available for irrigation will determine the area of crop or combination of crops that can be grown. It is therefore important to know how much water a specific crop or crop combination requires. This understanding enables the development of a water budget. DPIRD's irrigation calculator can assist with preparing a water budget because it provides guidance on the water requirements of commercially grown crops in Western Australia (DPIRD 2017b).

For this project, the Department of Water and Environmental Regulation compiled an analysis of groundwater characteristics for the Midlands area in its *Prospectivity map*

(Department of Water 2017b). More details about water licensing and availability are available from the department's Mid West regional office.

3.4 Do the soils have a high capability?

Land capability is the ability of land to support a specific use without degradation of the soil, land, air or water resources. When assessing land capability for horticultural use, soil requirements such as depth, soil water-holding capacity and the risk of degradation associated with the horticultural activity are taken into account. Once a soil has been assessed for a specific use, it is assigned a land capability class from very high to very low (Table 3.5).

Table 3.5 Land capability classes

Capability class	General description
1: Very high	Very few physical limitations are present and these are easily overcome. Risk of land degradation is negligible.
2: High	Minor physical limitations affecting productive land use or risk of degradation are present. Limitations can be overcome by careful planning.
3: Fair	Moderate physical limitations that significantly affect productive land use or risk of degradation are present. Careful planning and conservation measures are required.
4: Low	High degree of physical limitation is present and not easily overcome by standard development techniques or results in a high risk of degradation. Extensive conservation measures are required.
5: Very low	Severe limitations are present. The land use is usually prohibitive in terms of development costs or the associated risk of degradation.

The predominant irrigation methods in the study area are likely to be sprinklers, centre pivots or trickle type irrigation systems. Using these irrigation systems the general soil and land requirements for horticulture are:

- low risk of soil salinity
- low susceptibility to waterlogging — watertable more than 2m below surface
- favourable pH for the intended crop or ability to amend
- suitable plant rooting conditions
- moderate to good nutrient retention ability
- flat or gentle slopes.

The specific requirements of horticultural crops may vary, but these general requirements are essential to determine the initial suitability of land for horticultural production (ERM Mitchell McCotter 1994).

3.5 Is there potential for environmental impact?

Intensive horticulture requires large inputs of fertiliser and in some instances this can lead to leaching of nutrients into the environment. This can affect water quality and cause algal blooms and fish kills. It is therefore important to assess the potential environmental impact of a new horticultural development and determine if it will be possible to minimise the potential impacts.

The Department of Water and Environmental Regulation monitors groundwater trends and groundwater dependent ecosystems in the Midlands area to assess the impacts of water use on the environment, and to ensure abstraction for irrigation or other land uses is sustainable. This is summarised in the Department of Water and Environmental Regulation (2018) report.

3.6 Potentially suitable for horticultural crop production

If all the criteria from Figure 3.1 are satisfied, the area is potentially suitable for the planned crop. The next step is to obtain site-specific information about the soil and groundwater and to ground-proof the microclimate expectations. The final step is to conduct a detailed economic analysis to determine the viability of the project.

4 Potential crops

The climate and range of soils in the study area will suit a wide range of horticultural crops. The main constraint for widespread horticultural development is the availability of suitable water for irrigation. This report only provides information on current commercial horticultural crops.

4.1 Established crops (proven)

A range of tree (perennial) crops are currently in production in the study area. These are dominated by citrus (oranges and mandarins), with olives, almonds and mangos produced in smaller quantities. The only annual crop currently produced in significant quantities is potatoes, for the fresh market and seed for local and export markets.

4.2 Possible future crops

The climate of the Midlands area is suitable for producing a large range of perennial and annual horticultural crops and annual field crops.

4.2.1 Perennial crops

A range of tree (perennial) crops was evaluated for climatic suitability to the study area and the results are summarised in Table 4.1.

Table 4.1 Climate suitability of tree (perennial) crops

Crop	Suitability	Comment
Almond	Marginally suitable	Only low-chill varieties suited
Apple	Not suitable	Not enough chilling hours in this area
Apricot	Marginally suitable	Only low-chill varieties suited — no market-preferred varieties available
Avocado	Marginally suitable	High temperatures and dry conditions in summer will negatively affect yields; frost-free areas only
Blueberry	Marginally suitable	Only low-chill varieties suited
Cashew	Marginally suitable	No Australian processing facility
Cherry	Not suitable	Not enough chilling hours in this area
Citrus	Suitable	Wind protection may be needed
Fig	Suitable	Wind protection may be needed
Jujube (Chinese date)	Marginally suitable	Only low-chill varieties suited
Kiwifruit	Not suitable	Not enough chilling hours in this area
Macadamia	Suitable	Wind protection may be needed
Mango	Suitable	Protection required from cold winds during winter and spring; frost-free areas only
Nectarine/peach	Marginally suitable	Only low-chill varieties suited
Olive	Suitable	No comment

(continued)

Table 4.1 continued

Crop	Suitability	Comment
Pear	Not suitable	Not enough chilling hours in this area
Pecan nut	Marginally suitable	Only low-chill varieties suited
Pistachio	Suitable	Wind protection may be needed
Plum	Marginally suitable	Only low-chill varieties suited — no market-preferred varieties available
Pomegranate	Suitable	Wind protection may be needed
Table grape	Marginally suitable	Special production methods required to break dormancy
Walnut	Not suitable	Not enough chilling hours in this area
Wine grape	Not suitable	Not enough chilling hours in this area

Source: Moore and Phillips (n.d.) with modifications

4.2.2 Annual horticultural crops

The climatic suitability of a range of commercial annual horticultural crops was evaluated and the results are summarised in Table 4.2. We do not recommend growing most of these crops in summer because of the high temperatures and the general lack of competitive market advantage for this area during summer. However, in areas north and south of the Midlands area, these issues are managed by using covered cropping techniques.

Table 4.2 Climate suitability of annual horticultural crops

Crop	Growing season	Comment
Baby leaf lettuce	Winter & spring	Only suited to frost-free areas
Baby leaf spinach	Winter & spring	Only suited to frost-free areas
Bean	Spring & autumn	Only suited to frost-free areas; windbreaks recommended
Broccoli	Winter, spring & autumn	
Brussel sprout	Winter	
Cabbage	Winter, spring & autumn	
Capsicum	Spring & autumn	Only suited to frost-free areas; windbreaks recommended
Carrot	Winter & spring	
Cauliflower	Winter	
Celery	Winter & spring	
Chilli	Spring & autumn	Only suited to frost-free areas; windbreaks recommended

(continued)

Table 4.2 continued

Crop	Growing season	Comment
Chinese cabbage	Winter & autumn	
Cucumber	Spring & summer	Windbreaks recommended
Eggplant	Spring	Only suited to frost-free areas; windbreaks recommended
Lettuce	Winter and spring	Only suited to frost-free areas
Onion	Spring	Windbreaks recommended
Parsnip	Winter, spring & autumn	
Pea	Winter	
Potato	Winter & autumn	Frost damage can occur in some landscape positions
Pumpkin	Spring	
Radish	Winter, spring & autumn	
Rockmelon	Spring, summer & autumn	
Silverbeet	Winter	
Sweet corn	Spring & autumn	Only suited to frost-free areas
Sweet potato	Spring & summer	Only suited to frost-free areas
Strawberry	Winter & spring	Only suited to frost-free areas
Tomato	Early spring	Only suited to frost-free areas
Turnip	Winter, spring & autumn	
Watermelon	Spring, summer & autumn	Only suited to frost-free areas
Zucchini/squash	Winter, spring & autumn	Only suited to frost-free areas

Source: Moore & Phillips (n.d.) with modifications

4.2.3 Annual field crops

Annual field crops can be used as part of a crop rotation to assist with managing diseases and weeds while still giving an income to the producer. A range of annual field crops can be successfully grown in the study area, but choice will be based on the ease at which crops can be integrated into the production system and the potential income from the crop. Possible annual crops are listed in Table 4.3.

Table 4.3 Suitable annual field crops

Crop	Growing season	Comment
Bean (dry)	Summer	Avoid high temperatures when flowering
Cotton	Summer	No cotton mills occur in the area
Maize (grain or silage)	Summer	
Millet	Summer	
Peanut (groundnuts)	Summer	Special harvesting equipment and grain dryer required
Sorghum	Summer	
Soybean	Summer	No processing facility in the area
Sunflower	Summer	

4.3 Marketing and economic analysis

Coriolis (2016) identified target market opportunities in Asia for premium Western Australian products. Twenty high-growth, high-potential opportunities were identified and a range of other high-potential opportunities were also identified. These opportunities for the study area are listed in Table 4.4.

Table 4.4 Premium Western Australian products potentially suited to the study area with market opportunities in Asia

High potential (clear opportunity)	High potential (more investigation required)
Orange/mandarin	Blueberry
Carrot	Lucerne seed
Avocado	Durum wheat
Virgin olive oil	Fig
Rolled oats	Millet

Source: Coriolis (2016)

The Perth Market Authority analysed products sold at Western Australian (WA) fresh markets and identified the proportion of WA-produced fresh fruit and vegetables that contribute towards the consumption of fresh fruit and vegetables in WA (Freshlogic 2013). This helped to identify fruits and vegetables that are imported into WA to make up for the shortfall of local production. There is potential to increase production of these products to supply the local market. However, additional analysis is required to confirm this because the shortfall could simply be a result of seasonal shortages. Table 4.5 lists the products with a higher consumption rate than the amount produced in WA.

Table 4.5 Products suited to the study area with a higher consumption rate than WA production

Crop (product)	Amount imported (tons)	Comment
Onion	2469	
Lettuce	3906	Winter and spring only
Orange	3788	
Cauliflower	3446	Winter only
Broccoli	3862	Winter, spring and autumn only
Capsicum	4500	Spring and autumn only
Table grape	1866	
Celery	3231	Winter and spring only
Mandarin	2833	
Sweet potato	4799	

Source: Freshlogic (2013)

Lastly, once it has been determined if there are good marketing prospects for the chosen crop(s), a detailed economic analysis should be prepared. This analysis should take all conditions of the chosen site into consideration and must be completed prior to any investment in a new horticultural enterprise or expansion.

5 Conclusion

The climate in the study area is suited to a wide range of crops, but because of the high summer temperatures and a general lack of market advantage, most vegetables should be produced during the cooler months of the year. Frost-sensitive crops should be confined to areas with a low frost risk, which generally tends to be close to the coast. Wind is characteristic of the area and protection against prevailing winds will be required for many crops.

Irrigating with suboptimal (saline) water adversely affects plants, but not all plants are affected to the same extent. This will influence crop choice.

Saline water will also affect irrigation management because the accumulated salts must be regularly leached out of the root zone. This can be done fairly successfully on well-drained soils like sands and loams, but can be problematic on clay soils. It is therefore best to avoid using water with more than 500mg/L of salt on heavier soils, like those prominent in the Irwin valley.

The type of crop to be produced in the area will influence the choice of soil, but the decision will also be influenced by the property location, quality and availability of irrigation water sources. Because most of the soils in the study area are capable of producing horticultural crops, it is the availability of water for irrigation, not soil, which is the limiting factor.

Appendices

A Climate information

B Monthly evaporation and rainfall

Appendix A Climate information

Table A1 Climate summary for Badgingarra (49 years)

Climatic element	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Mean maximum temperature (°C)	34.7	34.7	31.9	27.1	22.4	18.7	17.6	18.3	20.5	24.5	28.4	32
Highest temperature (°C)	46.9	46	43.3	40.5	35.2	27.2	26	27.7	34.6	38.8	42.2	44.3
Mean number of days >= 30°C	20.8	19.5	17	6.8	0.7	0	0	0	0.4	3.8	10.3	16.2
Mean number of days >= 35°C	12.9	12.2	7.6	1.1	0	0	0	0	0	0.6	3.2	7.9
Mean number of days >= 40°C	4	3.3	1	0	0	0	0	0	0	0	0.2	1.8
Mean number of days <= 2°C	0	0	0	0	0	0.1	0.2	0.3	0.2	0.1	0	0
Mean number of days <= 0°C	0	0	0	0	0	0	0	0	0	0	0	0
Mean rainfall (mm)	10.5	15.1	16.6	28	70.2	99	101.5	82.7	49.9	27.7	19.4	9.1
Mean 9am humidity (%)	49	51	54	63	72	79	82	80	75	63	50	47
Mean 3pm humidity (%)	29	28	30	38	50	57	62	60	60	47	33	31

Source: Bureau of Meteorology (2017)

Table A2 Climate summary for Carnamah (73 years)

Climatic element	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Mean maximum temperature (°C)	36.1	35.6	32.8	27.6	22.6	19.1	17.9	19.2	22.1	26.2	30.2	33.5
Highest temperature (°C)	48.1	47.2	43.9	40	35.5	27.8	27.8	31.4	35.1	41.7	43.1	45.3
Mean number of days >= 30°C	25.7	23.8	20.8	8.5	0.9	0	0	0	1.2	6.4	14.2	21.9
Mean number of days >= 35°C	17.7	15.5	10.1	1.6	0	0	0	0	0	1.3	5.3	11.7
Mean number of days >= 40°C	6.2	5.2	1.5	0	0	0	0	0	0	0	0.6	2.7
Mean number of days <= 2°C	0	0	0	0	0	0.1	0.5	0.3	0.1	0	0	0
Mean number of days <= 0°C	0	0	0	0	0	0.1	0	0	0	0	0	0
Mean rainfall (mm)	12.6	16.2	20.6	23	50.8	74.7	67.2	52	28.1	16.3	10.6	8.9
Mean 9am humidity (%)	46	49	51	61	68	79	81	77	68	53	48	47
Mean 3pm humidity (%)	26	28	31	39	46	51	56	51	46	33	28	27

Source: Bureau of Meteorology (2017)

Table A3 Climate summary for Eneabba (43 years)

Climatic element	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Mean maximum temperature (°C)	36.4	36.5	33.7	29.3	24.3	20.9	19.7	20.8	23	26.8	30.2	33.6
Highest temperature (°C)	47.3	48.7	44.9	40	36.1	29	29.3	30.5	35.4	41	45.2	45.9
Mean number of days >= 30°C	22.5	21.5	19.6	10	1.9	0	0	0	1.3	6	12	17.4
Mean number of days >= 35°C	15.7	15.2	10.7	2.5	0	0	0	0	0	1.7	5.2	9.4
Mean number of days >= 40°C	6.7	5.9	2.4	0	0	0	0	0	0	0.1	0.8	3.1
Mean number of days <= 2°C	0	0	0	0	0	0	0.2	0	0	0	0	0
Mean number of days <= 0°C	0	0	0	0	0	0	0	0	0	0	0	0
Mean rainfall (mm)	7.5	13.5	13.9	27.6	69.3	99	93.6	75.2	45.9	22.8	14.8	8.9
Mean 9am humidity (%)	47	48	51	59	66	75	77	74	65	56	49	46
Mean 3pm humidity (%)	31	30	34	40	47	55	57	54	49	42	38	33

Source: Bureau of Meteorology (2017)

Table A4 Climate summary for Geraldton Airport (72 years)

Climatic element	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Mean maximum temperature (°C)	31.7	32.6	31	27.7	24.1	20.9	19.5	20.1	22.1	24.5	27.2	29.6
Highest temperature (°C)	47.7	47.3	45.2	39.7	36.6	29.5	29	31.6	36.1	40.7	43.8	46.8
Mean number of days >= 30°C	15.6	17	15.8	8	1.5	0	0	0	0.9	3.6	7.3	11.4
Mean number of days >= 35°C	8.6	9.9	7.1	1.8	0	0	0	0	0	0.9	2.8	5.6
Mean number of days >= 40°C	3.2	2.8	1.3	0	0	0	0	0	0	0	0.3	1.5
Mean number of days <= 2°C	0	0	0	0	0	0	0.2	0.1	0.1	0	0	0
Mean number of days <= 0°C	0	0	0	0	0	0	0	0	0	0	0	0
Mean rainfall (mm)	5.7	11.1	15.9	23.8	69.5	97.2	91.3	64.7	32	19.6	9.1	5.3
Daily evaporation (mm)	10.7	10.6	9.3	6.5	4.6	3.4	2.9	3.2	4.3	6.4	8.5	10.1
Mean 9am humidity (%)	51	51	53	59	66	75	78	76	67	55	49	49
Mean 3pm humidity (%)	46	44	44	46	49	55	58	58	53	50	47	47

Source: Bureau of Meteorology (2017)

Table A5 Climate summary for Jurien Bay (47 years)

Climatic element	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Mean maximum temperature (°C)	30	30.9	29.5	26.4	23.2	20.6	19.5	20	21.3	23.4	25.9	28.2
Highest temperature (°C)	45.2	44.7	44	37.3	32.1	27.8	26.2	28.2	34.2	38.2	40.5	44.7
Mean number of days >= 30°C	12.4	14.1	12.3	4.4	0.3	0	0	0	0.4	2	5.5	9.2
Mean number of days >= 35°C	6.2	6.4	3.7	0.3	0	0	0	0	0	0.3	1.2	3.9
Mean number of days >= 40°C	1.2	1.1	0.3	0	0	0	0	0	0	0	0.1	0.4
Mean number of days <= 2°C	0	0	0	0	0	0.4	0.5	0.1	0	0	0	0
Mean number of days <= 0°C	0	0	0	0	0	0.1	0	0	0	0	0	0
Mean rainfall (mm)	7.6	14.5	14.9	30.7	78.2	105.3	114.2	80	44.7	25.6	17.8	6.5
Mean 9am humidity (%)	56	57	59	64	70	75	77	73	68	61	58	56
Mean 3pm humidity (%)	59	58	58	59	61	63	65	62	62	60	59	59

Source: Bureau of Meteorology (2017)

Table A6 Climate summary for Lancelin (50 years)

Climatic element	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Mean maximum temperature (°C)	29.2	29.9	28.6	25.5	22.7	20.2	19.2	19.4	20.5	22.6	24.9	27.3
Highest temperature (°C)	46	45.3	43.6	37.5	32	29.4	27.7	29	32.5	39	40.7	43.2
Mean number of days >= 30°C	11.3	12.7	10.6	4	0.6	0	0	0	0.2	2	4.3	8.4
Mean number of days >= 35°C	5.5	5.7	3.9	0.5	0	0	0	0	0	0.3	1.1	3.6
Mean number of days >= 40°C	1.1	0.7	0.5	0	0	0	0	0	0	0	0.1	0.5
Mean number of days <= 2°C	0	0	0	0	0	0.1	0.1	0.1	0	0	0	0
Mean number of days <= 0°C	0	0	0	0	0	0	0	0	0	0	0	0
Mean rainfall (mm)	10.8	13.3	15.7	31.8	81.5	118.2	120	89.4	56.6	28.4	20.4	7.9
Mean 9am humidity (%)	55	56	59	67	70	75	76	74	69	63	59	56
Mean 3pm humidity (%)	61	60	60	62	61	63	65	64	64	62	62	61

Source: Bureau of Meteorology (2017)

Table A7 Climate summary for Morawa (20 years)

Climatic element	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Mean maximum temperature (°C)	37.4	36.8	33.2	28.8	23.9	20	18.6	20.3	23.1	28.3	32.1	35.2
Highest temperature (°C)	47.2	47.2	43	38.8	35	28.4	26.7	32.4	36.2	41.2	43.7	46.8
Mean number of days >= 30°C	27.6	24.8	22.1	11.6	1.8	0	0	0.2	2.1	11	18.7	25.6
Mean number of days >= 35°C	21.8	18.7	11.9	2.4	0.2	0	0	0	0.1	2.8	8.7	16.4
Mean number of days >= 40°C	9.2	6.4	2.3	0	0	0	0	0	0	0.1	1.1	5.8
Mean number of days <= 2°C	0	0	0	0	0	1.8	4.5	2.9	1	0	0	0
Mean number of days <= 0°C	0	0	0	0	0	0.2	1	0.1	0	0	0	0
Mean rainfall (mm)	23	17.7	18.9	18.8	38.8	39.6	44.2	32.1	24	8.9	10.4	16
Mean 9am humidity (%)	43	46	47	56	68	76	80	76	63	47	39	38
Mean 3pm humidity (%)	20	23	25	31	41	46	51	46	39	27	21	18

Source: Bureau of Meteorology (2017)

Appendix B Monthly evaporation and rainfall

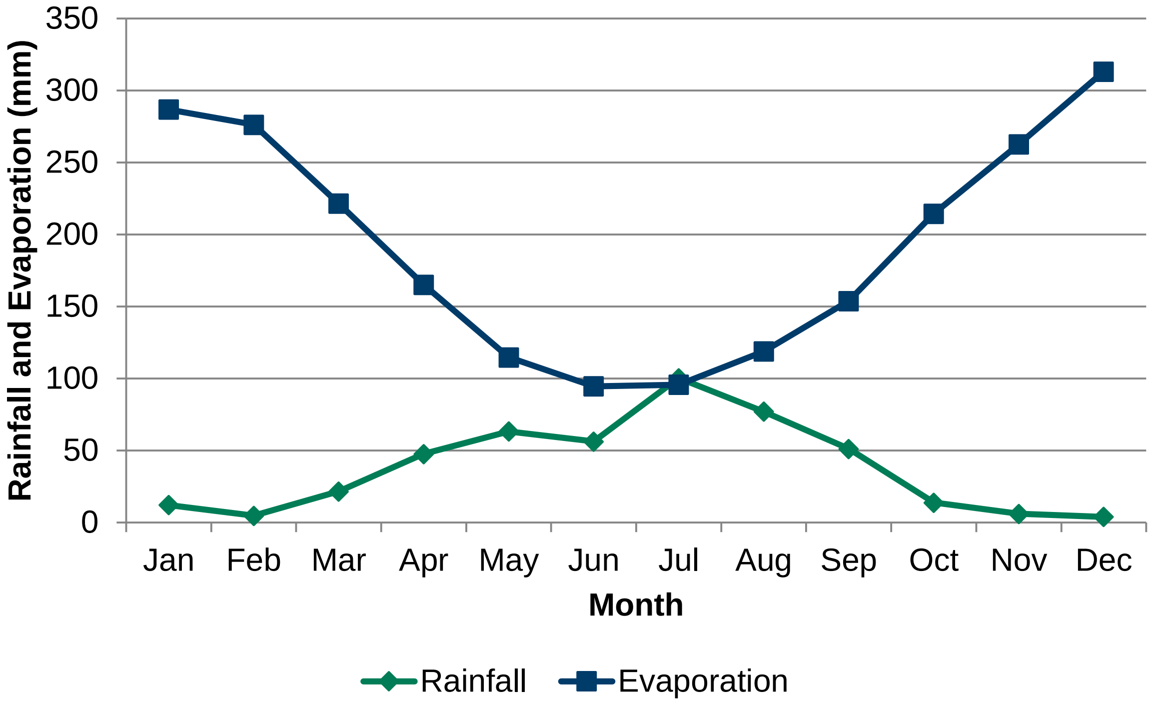


Figure B1 Allanooka monthly evaporation and rainfall

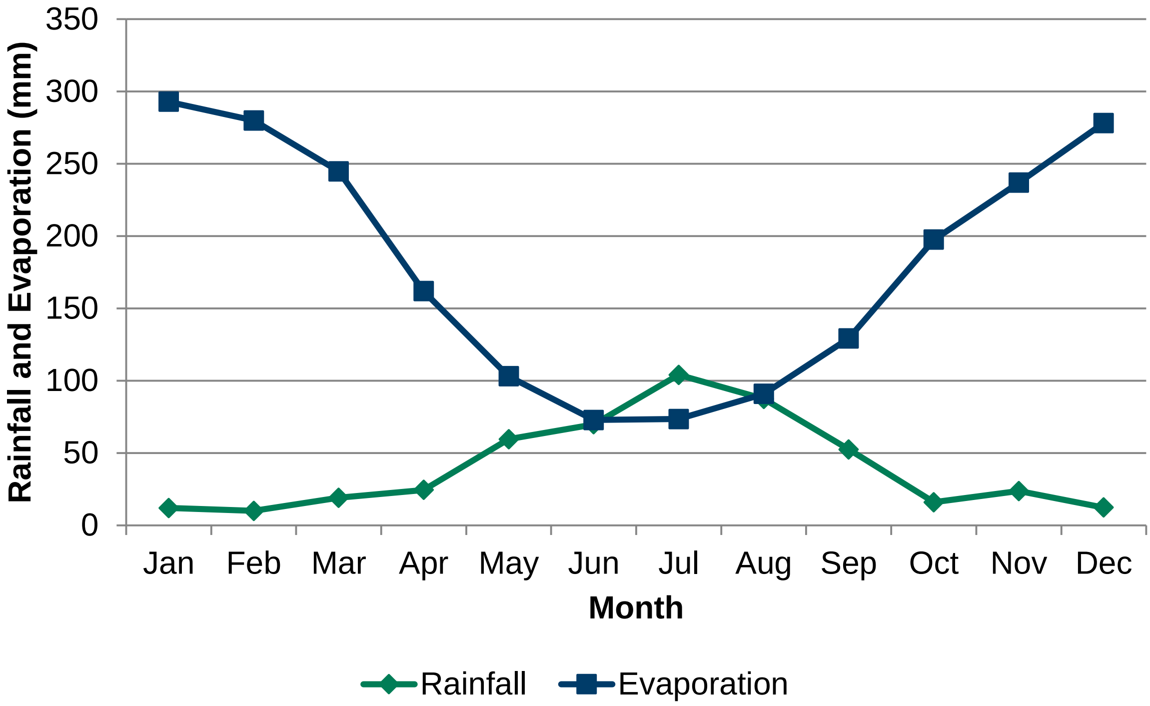


Figure B2 Badgingarra monthly evaporation and rainfall

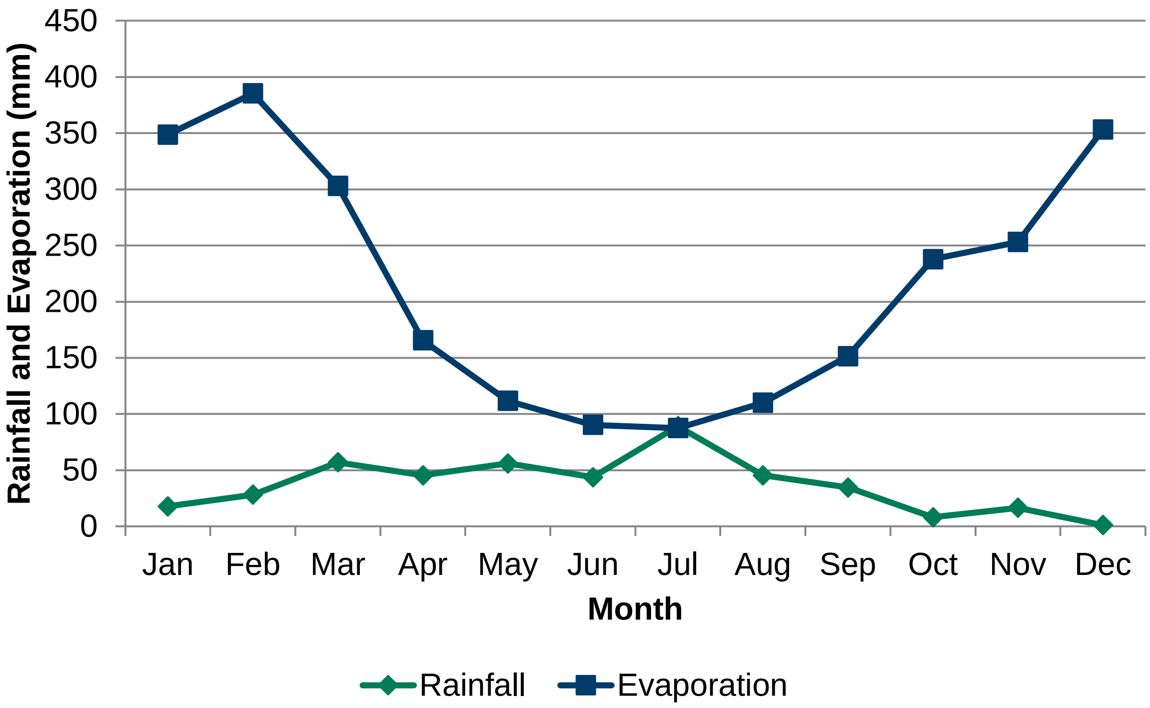


Figure B3 Coorow monthly evaporation and rainfall

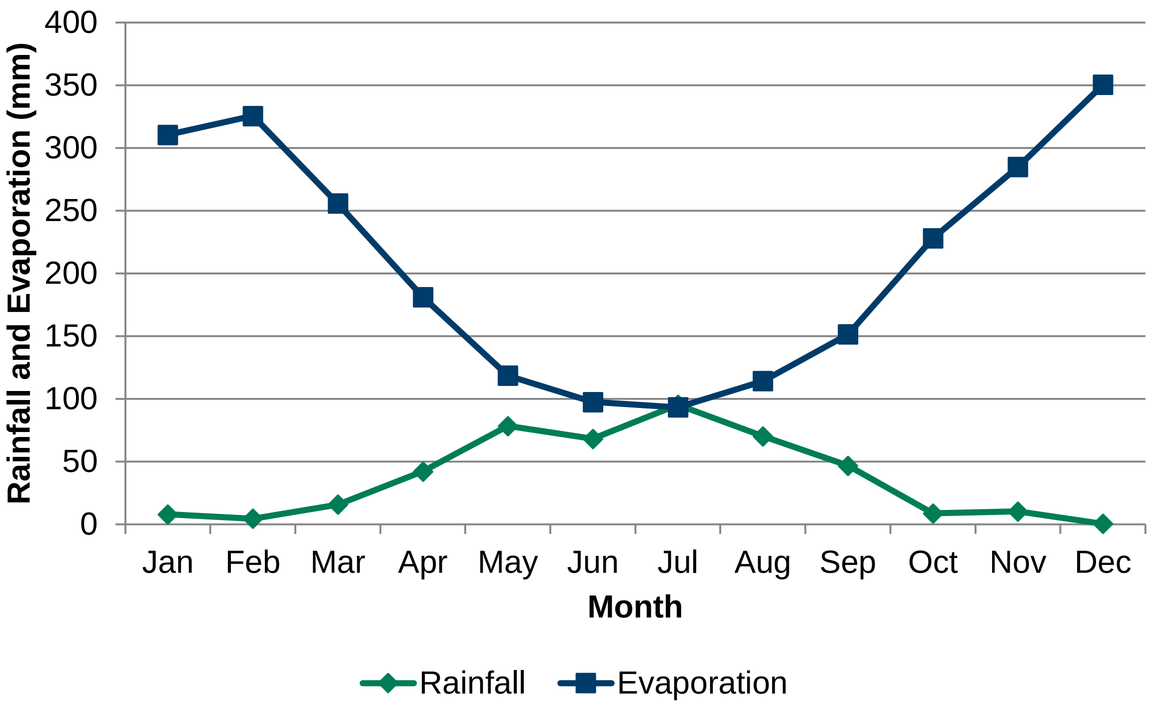


Figure B4 Eneabba monthly evaporation and rainfall

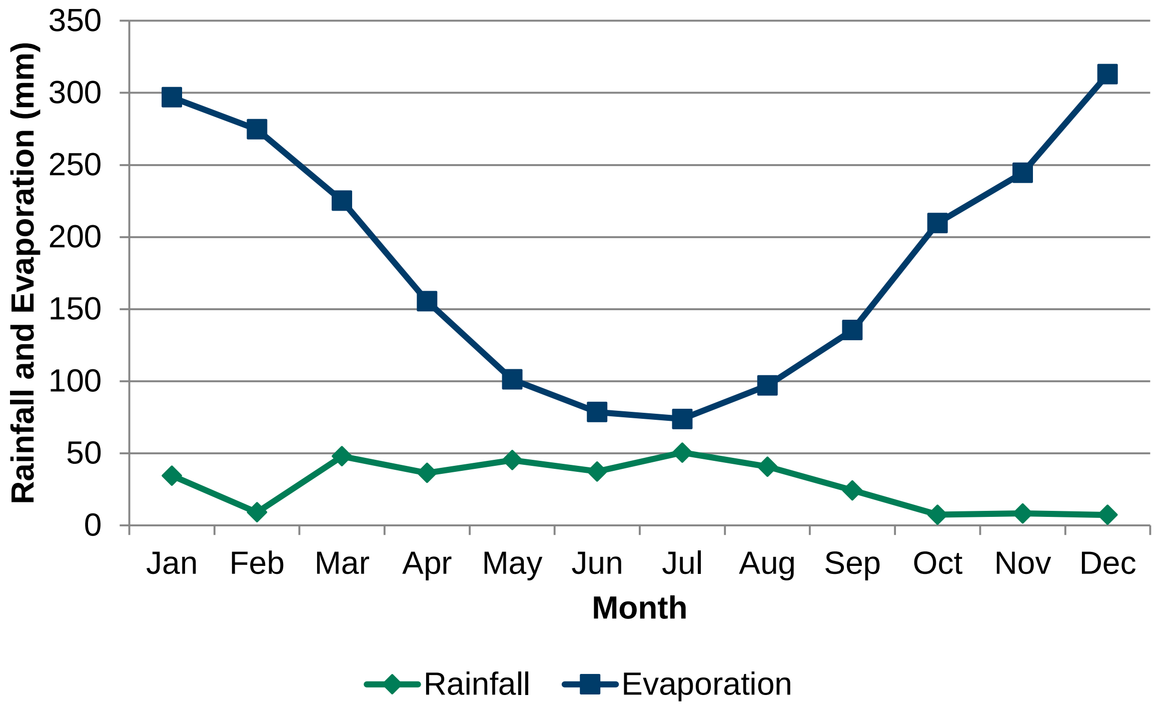


Figure B5 Gutha West monthly evaporation and rainfall

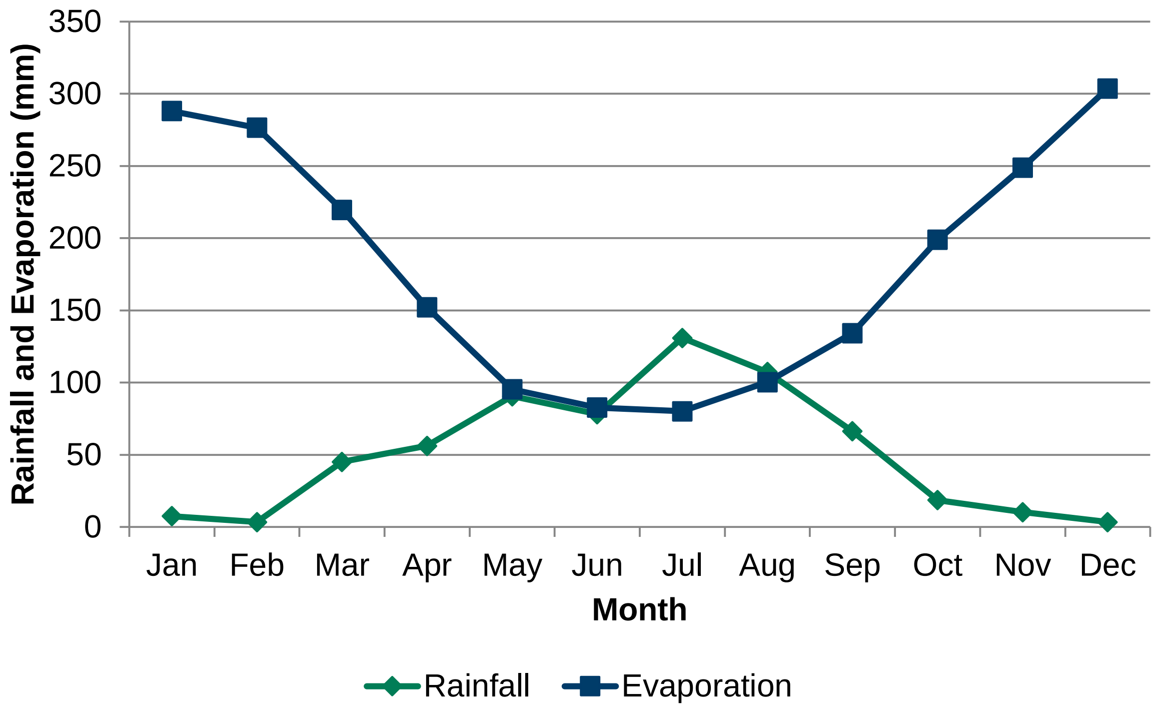


Figure B6 Jurien Bay monthly evaporation and rainfall

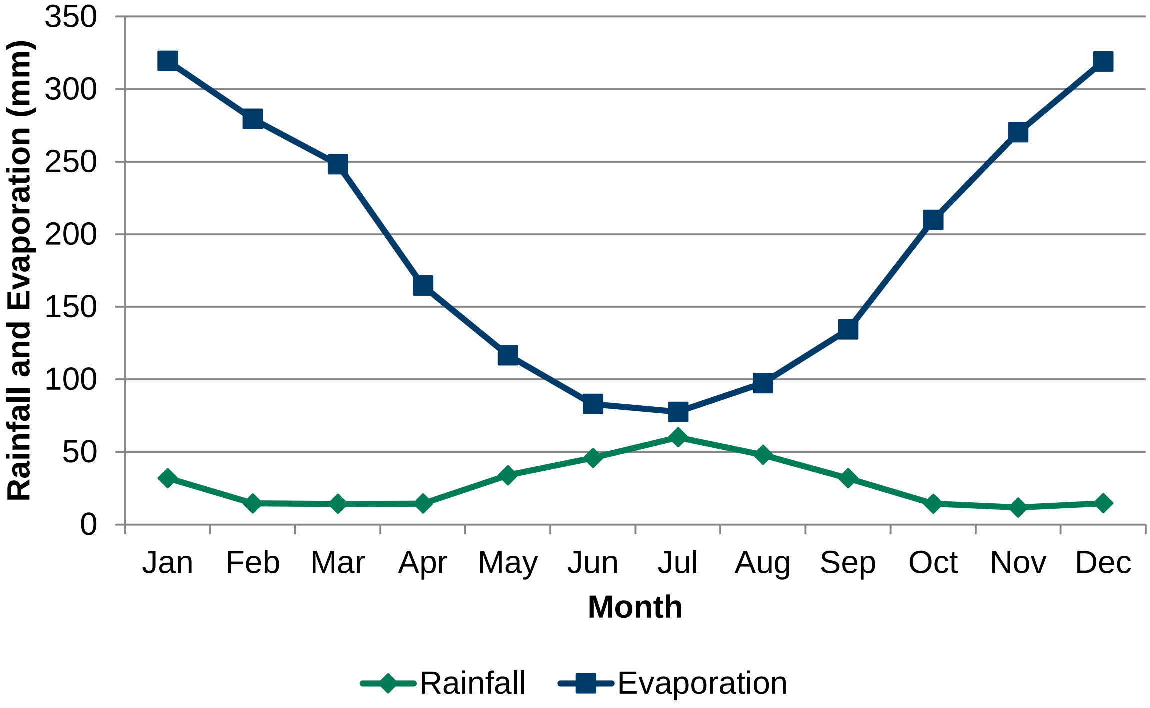


Figure B7 Moora monthly evaporation and rainfall

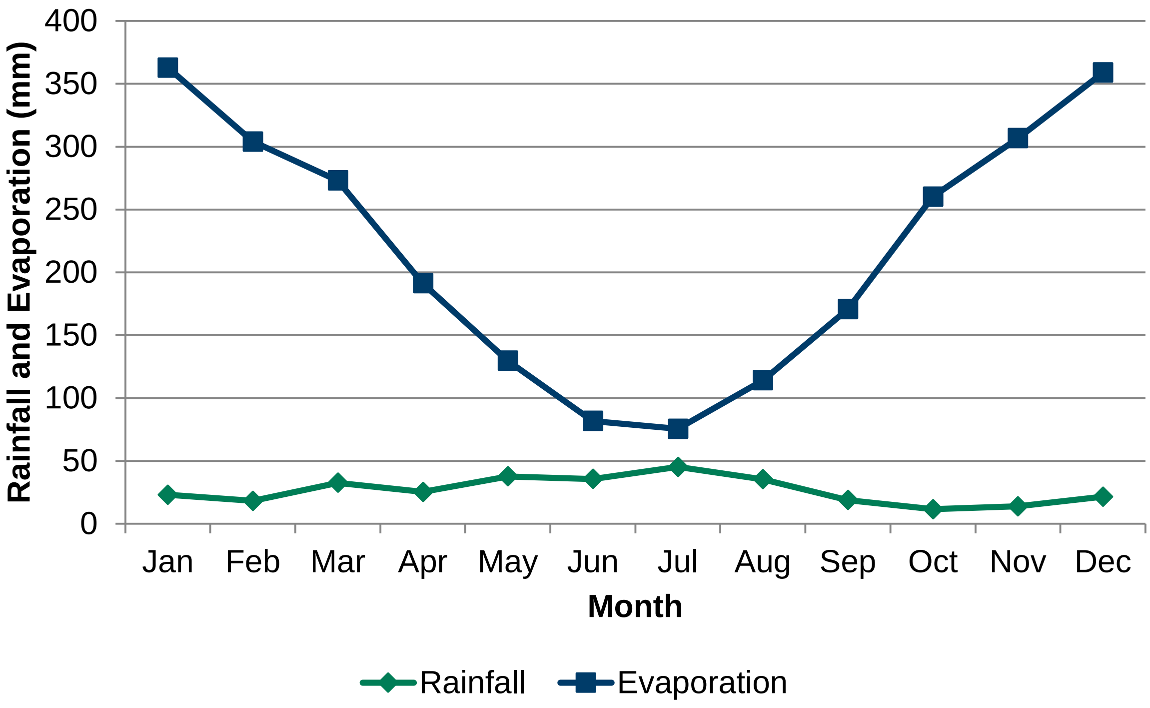


Figure B8 Morawa monthly evaporation and rainfall

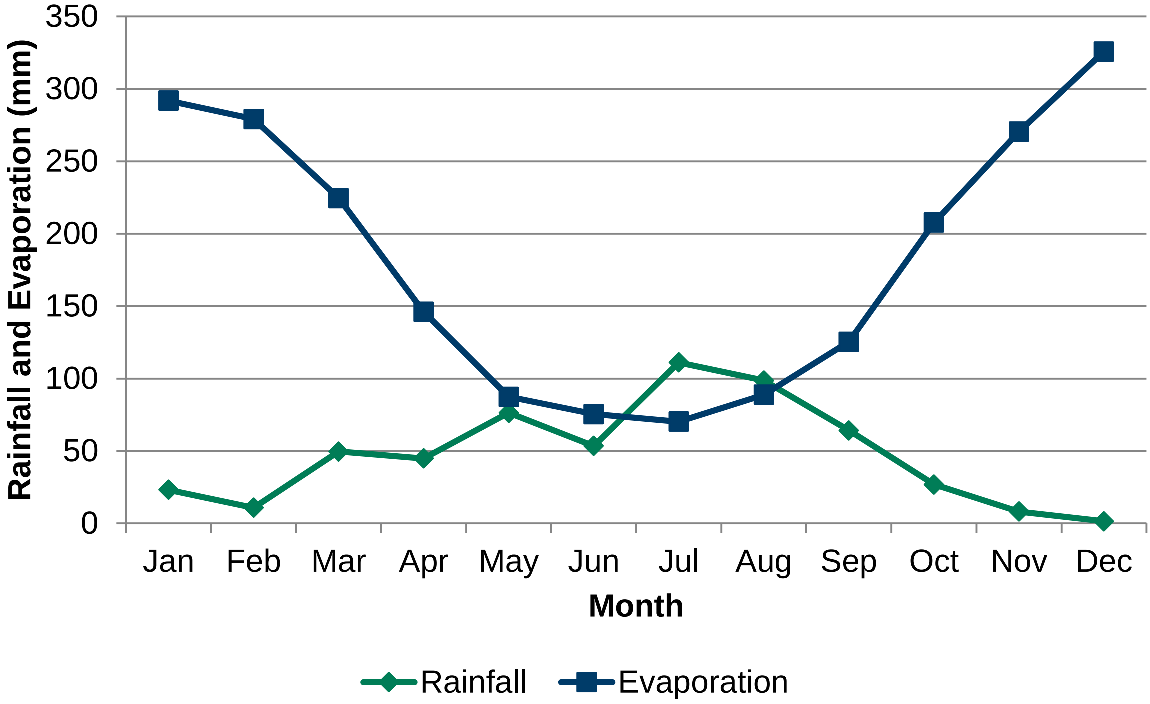


Figure B9 New Norcia monthly evaporation and rainfall

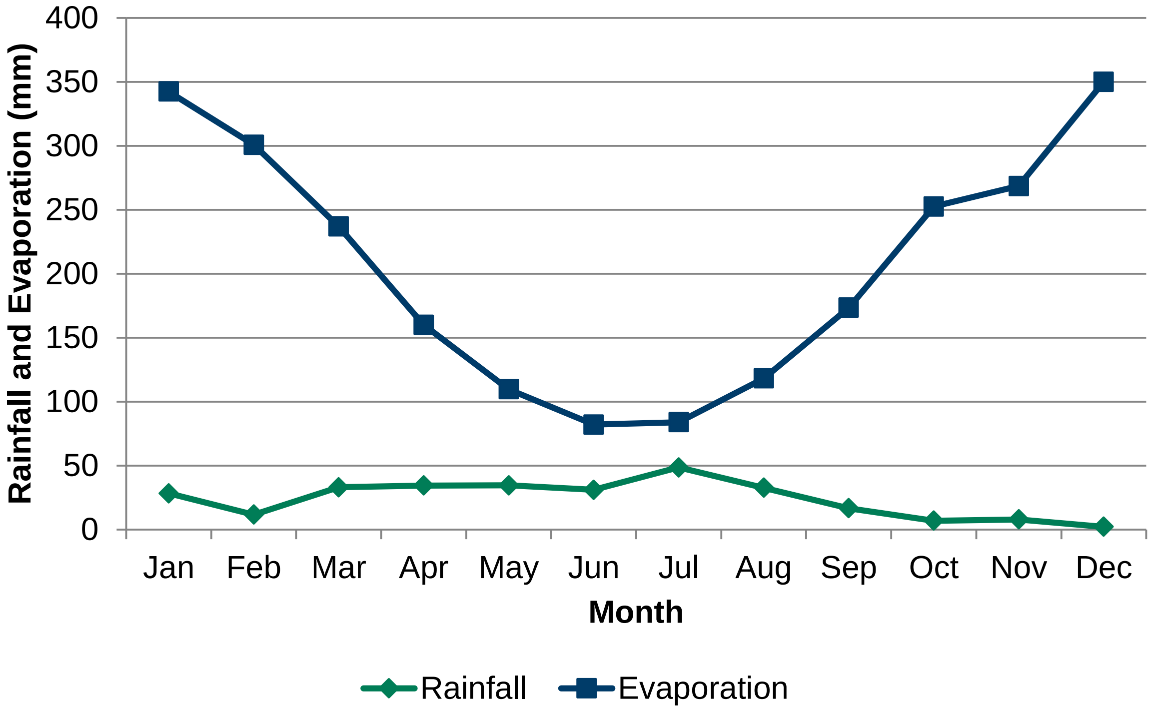


Figure B10 Perenjori monthly evaporation and rainfall

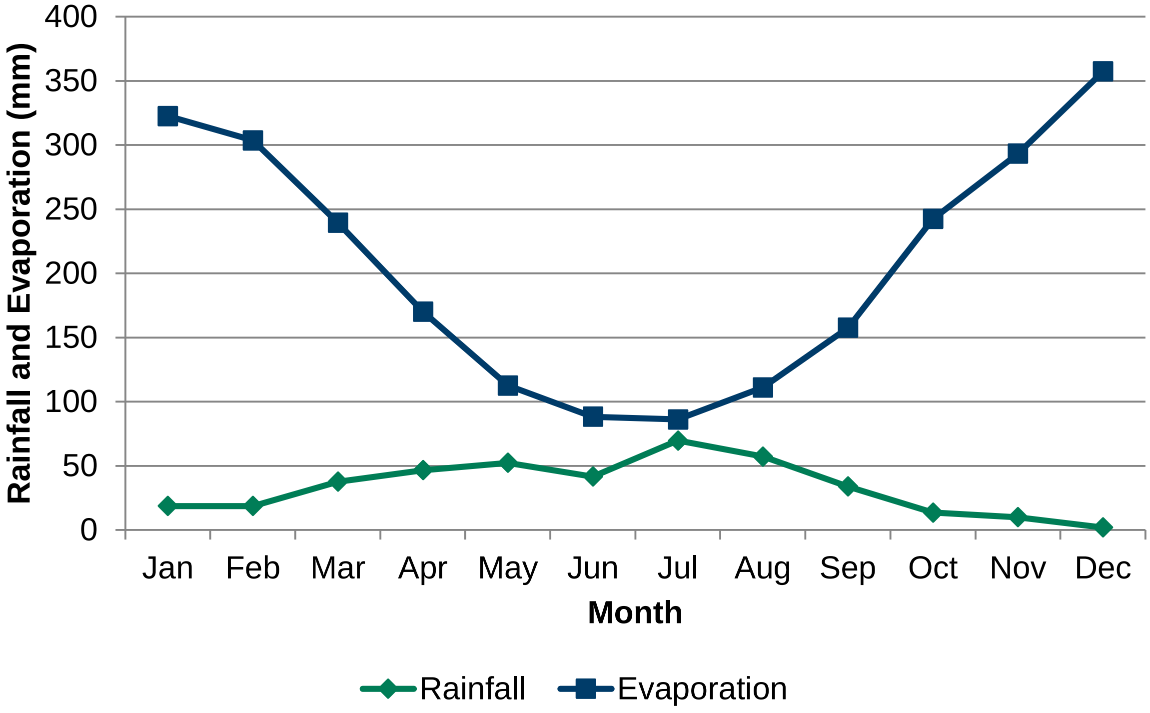


Figure B11 Three Springs monthly evaporation and rainfall

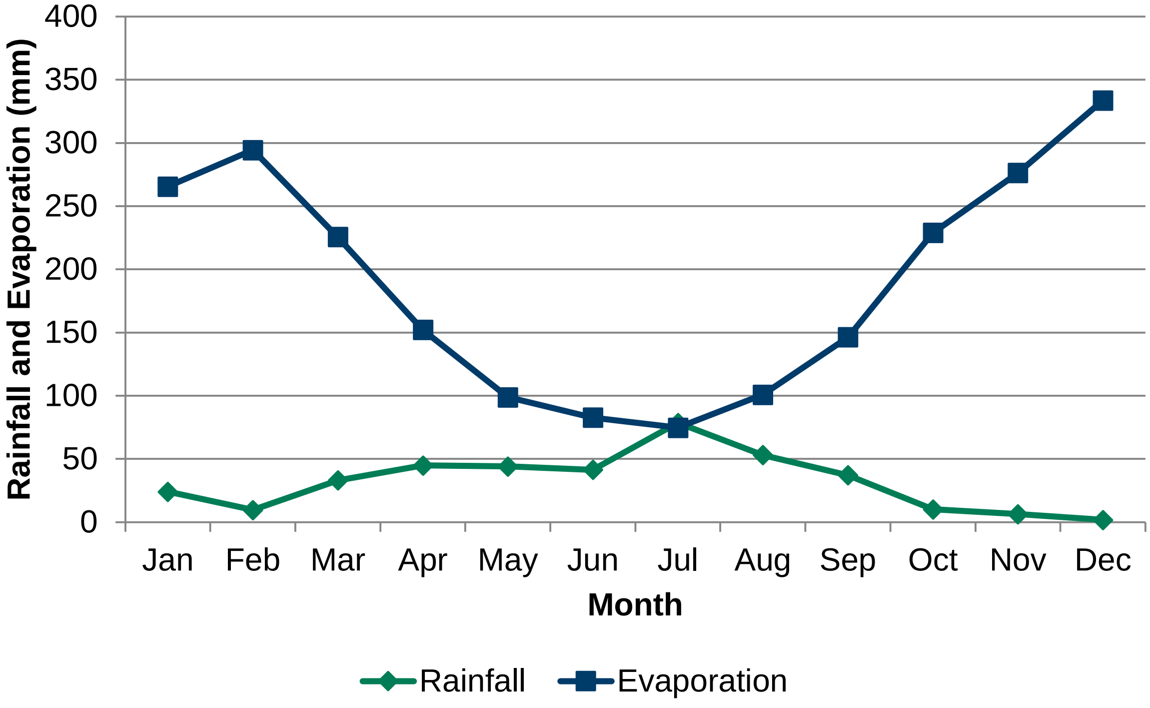


Figure B12 Watheroo monthly evaporation and rainfall

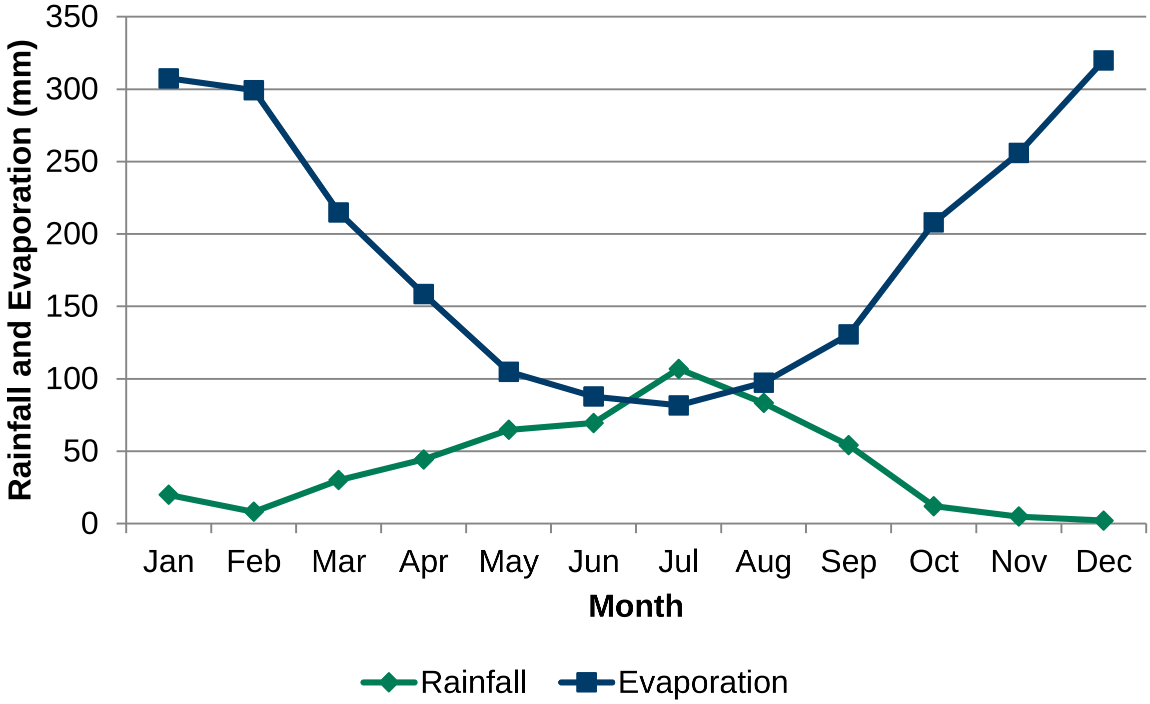


Figure B13 Warradarge East monthly evaporation and rainfall

References

Ayers, RS & Westcot, DW 1985, *Water quality for agriculture*, FAO Irrigation and Drainage paper 29, Food and Agriculture Organization of the United Nations, Rome.

Bureau of Meteorology 2017, *Weather and climate data*, viewed 15 March 2017, bom.gov.au/.

Coriolis 2016, *Target market opportunities in Asia for Western Australian premium products*, Western Australian Agriculture Authority, Perth.

Department of Agriculture and Food, Western Australia 2016, *Evaporation-based irrigation scheduling*, viewed March 2017, agric.wa.gov.au/water-management/evaporation-based-irrigation-scheduling.

Department of Primary Industries and Regional Development (DPIRD) 2017a, *Weather stations and radar*, viewed March 2017, agric.wa.gov.au/weather-stations-and-radar.

Department of Primary Industries and Regional Development 2017b, *Irrigation calculator*, viewed March 2017, agric.wa.gov.au/irrigation-calculator.

Department of Water 2017a, *Focus area selection report*, Government of Western Australia, Perth, unpublished draft.

Department of Water 2017b, *Groundwater prospectivity in Midlands area, Government of Western Australia*, draft report, Department of Water, Perth.

Department of Water and Environmental Regulation 2018, G*roundwater dependent environmental values relevant to the Irwin and Dinner Hill focus areas*, Environmental water series, Report no. 30, Government of Western Australia, Perth.

ERM Mitchell McCotter 1994, *Mid West horticulture strategy study*, Mid-West Labour Market Advisory Council, Geraldton.

Freshlogic 2013, *Perth Market Authority: Assess and define the Perth Market traders' share of the wholesale fruit and vegetable market*, Perth Market Authority, Perth.

Griffin, T, Stuart-Street, A & Tille, P 2019a, 'Soil capability assessment for expanding irrigated agriculture in the Irwin focus area and surrounding lands', *Resource management technical report 408,* Department of Primary Industries and Regional Development, Perth.

Griffin, T, Stuart-Street, A, van Wyk, L & Tille, P 2019b, 'Soil capability assessment for expanding irrigated agriculture in the Dinner Hill focus area', *Resource management technical report 406*, Department of Primary Industries and Regional Development, Perth.

Lantzke, N, Calder, T, Burt, J & Prince, R 2007, 'Water salinity and plant irrigation', *Farmnote 234*, Department of Agriculture and Food, Western Australia, Perth.

Maynard, DN & Hochmuth, GJ 2007, *Knott's handbook for vegetable growers*, 5th edn, John Wiley & Sons Inc., Hoboken, New Jersey.

McKenzie, D 2003, ‘Salinity and sodicity — what’s the difference?’, *The Australian Cottongrower*, vol. 24/1, pp. 28–29.

Met Office 2011, *Microclimates*, National Meteorological Library and Archive fact sheet 14, Met Office, Devon, United Kingdom.

Moore, GA & Phillips, DR (n.d.), Potential horticulture in the Dongara region, Western Australian Department of Agriculture, Perth, unpublished report.

New South Wales Department of Primary Industries 2014, 'Farm water quality and treatment', *Primefact 1337*, New South Wales Department of Primary Industries, Orange.

Speed, R & Killen, A 2018, Hydrological assessment for irrigated agriculture in the Irwin focus area of Western Australia, *Resource management technical report 407*, Department of Primary Industries and Regional Development, Perth.