SAPWAT CHANGE OF CUSTODIANSHIP AND CLIMATE DATABASE UPGRADE

Report to the

WATER RESEARCH COMMISSION

By

B Grové[1], JH Barnard[2], AS Steyn[2] P van Heerden[3]

[1] Department of Agricultural Economics, University of the Free State
[2] Department of Soil, Crop and Climate Sciences, University of the Free State
[3] PICWAT consulting

WRC Report No. 3249/1/26
ISBN 978-0-6392-0780-3

May 2026

Obtainable from:

Water Research Commission
Private Bag X03
Gezina, 0031

orders@wrc.org.za or download from www.wrc.org.za

DISCLAIMER

This report has been reviewed by the Water Research Commission (WRC) and approved for publication. Approval does not signify that the contents necessarily reflect the views and policies of the WRC, nor does mention of trade names or commercial products constitute endorsement or recommendation for use.

Published in the Republic of South Africa

EXECUTIVE SUMMARY

BACKGROUND AND MOTIVATION

South Africa faces increasing climate variability, rapid population growth, and rising competition for limited water resources. Irrigated agriculture, the country's largest water user, is under pressure to improve efficiency, making accurate estimates of crop water requirements essential. For more than two decades, the SAPWAT software has been the national standard for irrigation planning, widely used by farmers, advisors, researchers, and the government.

However, the continued use of SAPWAT now faces critical challenges. The custodian can no longer sustain its maintenance and provide decision support. Consequently, the continued use of SAPWAT in new computer operating environments is infeasible without proper maintenance. SAPWAT uses a dated quaternary catchment dataset that does not cover the last 25 years of climate change, casting doubt on the validity of crop water-use estimates under current climate conditions. The implementation of the FAO 56 dual crop coefficient methodology to estimate crop water requirements in SAPWAT is not well documented, and it is unclear to what extent SAPWAT incorporates the recent methodological improvements in crop water estimation. Without the transfer of custodianship and technical evaluation, the relevance, reliability, and future use of SAPWAT are at risk, directly impacting water allocation and irrigation water management in South Africa.

PROBLEM STATEMENT

The current custodian can no longer sustain the development and maintenance of SAPWAT, resulting in an outdated system that struggles to remain relevant in a rapidly advancing technological environment. At the same time, shifting climate conditions are increasing the uncertainty of crop water requirement estimations, further undermining confidence in the software for irrigation water management in South Africa.

OBJECTIVES

The project's overall objective is to transfer custodianship of SAPWAT to the University of the Free State.

The following specific objectives were set to achieve the general objective of this research:

- Capacitate researchers at the University of the Free State to provide support with respect to the use of SAPWAT software.
- Improve the applicability of SAPWAT through a new climate database to determine reference evapotranspiration for South Africa.

APPROACH AND METHODS

The research commenced with installing the SAPWAT software on the research team members' computers. Installing the software was initially problematic since the version distributed by the Water Research Commission as part of the project on "Upgrading SAPWAT3 as a Management Tool to Estimate the Irrigation Water Use of Crops: Revised Edition SAPWAT4" does not work on Windows 11. The research team acquired SAPWAT4-2 and its source code using a DropBox shared link from Dr Van Heerden. After installing the software, the project team members from the University of the Free State received training in its use from Dr Van Heerden. Dr Van Heerden's eyesight has deteriorated to such an extent that one of the project team members navigated the screens while Dr Van Heerden provided the necessary content.

The next step was to review the implementation of SAPWAT4-2's FAO 56 dual coefficient methodology for calculating irrigation water requirements. The research team began by conducting a literature review of the proposed improvements to the FAO 56 methodology and procedures, published in a special issue of the Agricultural Water Management journal in 2021 entitled "Updates and advances to the FAO 56 crop water requirements method." The FAO 56 methodologies were thereafter compared with those of SAPWAT. The developers of SAPWAT did not document the details of the calculation procedures well. Consequently, the research team relied on the source code to evaluate the implementation. SAPWAT4-2 is programmed in dBASE®. Unfortunately, the University of the Free State does not support dBASE®. The research team accessed the source code using Notepad.

An explicit objective of the research was to update SAPWAT's climate database. The new climate database was developed using AgERA5, a global reanalysis dataset tailored for agricultural and environmental applications. The database includes daily time series for key near-surface climate variables – maximum and minimum temperature (Tmax, Tmin), relative humidity (RHmax, RHmin), vapour pressure (VP), wind speed (WS), solar radiation (SR), precipitation (Pr), and reference evapotranspiration (ETo) – from 1979 to 2024, at a spatial resolution of 0.1° (~9 km), covering all land-based grid points between 20–35°S and 15–35°E. Custom Python scripts were developed to automate data downloads from the Copernicus Climate Data Store, extract variables, assign elevation using a digital elevation model, and calculate evapotranspiration using the FAO 56 Penman-Monteith method. Processing was performed on the University of the Free State High-Performance Computing Cluster to manage the computational load. Outputs were written as structured CSV files compatible with SAPWAT's fixed column format. The climate database can be updated regularly, typically every six months or as required.

The researchers' inability to directly import the newly developed climate database into SAPWAT4-2 significantly impacted the envisaged technology transfer activities. The technology transfer activities consisted of individual discussions with key SAPWAT users. During the sessions, the researchers assessed the users' experience using the SAPWAT4-2 software and informed them about the climate database.

SUMMARY OF RESULTS AND CONCLUSIONS

A new climate database was successfully developed to replace the outdated quaternary catchment dataset previously used in SAPWAT. Evaluation against eight stations showed strong agreement for maximum and minimum temperatures at daily and monthly scales, with R^2 up to 0.97 and Root Mean Square Error generally below 2°C, though biases varied by site. Wind speed correspondence was mixed, with limited improvement at the monthly scale and a general smoothing of calm and strong events. Solar radiation compared well, with modest monthly bias and lower monthly errors than daily. Precipitation agreement was weak at the daily scale but improved after monthly aggregation, with R^2 reaching 0.73 at some sites; the magnitude and sign of bias depended on location. ETo from AgERA5 inputs agreed well with station estimates, and the relationship tightened on monthly aggregation, though small positive biases appeared at several stations.

The development of the reanalysis-based database represents a substantial step forward from the outdated quaternary catchment dataset, providing a much richer and more up-to-date climate resource for irrigation planning. The validation exercises confirmed that the database is fit for purpose across key variables, particularly temperature and reference evapotranspiration, making the effort worthwhile. Technology transfer was achieved as far as possible within the constraints of the legacy SAPWAT environment, and the project has created a strong foundation for full integration once reprogramming into a modern platform is undertaken.

SHORTCOMING

The research team successfully developed a new climate database. However, the research team identified programming errors during the import of the climate database into SAPWAT4-2, resulting in a non-functional system. The unavailability of a functional SAPWAT version with the climate database hampered the envisioned technology activities.

RECOMMENDATIONS

SAPWAT

- Reprogram SAPWAT in a modern language to enhance functionality.
- The SAPWAT crop coefficient database must be standardised to conform to the FAO 56 standard climate. Region-specific parameters derived from measurements should be transformed to the standard climate before inclusion.
- Develop documentation for the calculation procedures embedded in SAPWAT and software use.
- Integrate irrigation cost estimation procedures with SAPWAT to enhance energy management planning.
- Develop a business plan to ensure sustainable maintenance and software development.

FURTHER RESEARCH

- Future research should prioritise evaluating existing regional studies on crop water use and systematically incorporate these results into the SAPWAT database.

- Although AgERA5 products are bias-corrected at source, regional refinements remain important. Incorporating local ground-based observations and targeted adjustments can help address site-specific discrepancies, especially for variables such as rainfall and wind speed, which are subject to greater uncertainty in reanalysis products. This would further enhance the value of the climate database for irrigation decision-making in South Africa.
- Research should also explore the use of remote sensing and spatially explicit data to derive dynamic crop coefficients that reflect real field conditions.
- ETo remains a critical input for estimating crop water requirements. Further local work is needed to address challenges in estimating ETo in arid, data-scarce environments.
- Research is needed to test the feasibility of adapting SIMS (Satellite Irrigation Management Support) to South African conditions. SIMS was developed in California to provide near real-time irrigation scheduling support by combining satellite-derived canopy cover, FAO 56-based crop coefficients, and weather-based ETo. It has been successfully applied in California irrigation districts, where dense weather networks (CIMIS) provide the required ETo input. The research can specifically focus on:
    - Calibration of fractional cover–Kc relationships for local crops and management systems.
    - Validation of SIMS-derived ETc against lysimeter and field water balance measurements.
    - Integration with ERA5-based ETo and regional weather data, given South Africa’s sparser ground station network.
    - If successfully adapted, SIMS could complement or be integrated into a re-programmed SAPWAT, offering irrigation boards and farmers high-resolution, operational irrigation scheduling support tailored to local conditions.

ACKNOWLEDGEMENTS

The following reference group members supervised the project:

Prof NS Mpandeli	Water Research Commission (Chairperson)
Dr L Nhamo	Water Research Commission
Dr SN Hlophe-Ginindza	Water Research Commission
Prof JG Annandale	University of Pretoria
Prof N Jovanovic	University of the Western Cape
Dr R Mottram	Mottram Associates
Mr H Schoeman	HNS Consulting
Mr G Smith	South African Association For Water User Associations
Mr E Mametja	Department of Water and Sanitation
Mr S Mkhaliphi	Department of Water and Sanitation
Ms A Nefale	Department of Water and Sanitation
Mr SS Mbuyane	Department of Water and Sanitation
Mr T Masike	Department of Water and Sanitation
Prof N Matthews	Minute Secretary

The research team would like to sincerely thank the reference group members, especially the project chairman, for their guidance, valuable input, and for always being available to provide guidance and support when required.

Special thanks to Dr Van Heerden and his wife for sharing their intellectual property on the SAPWAT software. Without your contribution, the project would not have succeeded.

Thanks to the SAPWAT users for sharing their experiences with using the software with us.

TABLE OF CONTENTS

EXECUTIVE SUMMARY iii

ACKNOWLEDGEMENTS viii

TABLE OF CONTENTS ix

LIST OF TABLES xii

LIST OF FIGURES xiii

LIST OF SUPPLEMENTAL MATERIALS xv

LIST OF ACRONYMS xvii

LIST OF SYMBOLS xix

CHAPTER 1: INTRODUCTION 1

1.1 BACKGROUND AND MOTIVATION 1

1.2 PROBLEM STATEMENT 2

1.3 OBJECTIVES 2

1.4 STRUCTURE OF THE REPORT 3

CHAPTER 2: ESTIMATING CROP WATER REQUIREMENTS: A REVIEW OF SAPWAT AND FAO 56 4

2.1 INTRODUCTION 4

2.2 SYNTHESIS OF UPDATES AND ADVANCES TO THE FAO 56 METHOD 5

2.2.1 COMPUTING REFERENCE EVAPOTRANSPIRATION (ETO) 5

2.2.2 SINGLE AND DUAL CROP COEFFICIENTS 7

2.2.3 GROUND AND REMOTE SENSING DATA 10

2.2.4 MANAGEMENT PRACTICES 11

2.3 SAPWAT IMPLEMENTATION OF THE FAO 56 METHOD 13

2.3.1 REFERENCE EVAPOTRANSPIRATION 14

2.3.2 BASAL CROP COEFFICIENT CURVES 14

2.3.2.1 FAO 56 14

2.3.2.2 SAPWAT 15

2.3.3 SOIL EVAPORATION 16

2.3.3.1 FAO 56 16

2.3.3.2 SAPWAT 18

2.3.4 TRANSPIRATION 19

2.3.4.1 FAO 56 19

2.3.4.2 SAPWAT ... 20
2.3.5 GROSS IRRIGATION REQUIREMENTS ... 21
2.4 DISCUSSION ... 21
CHAPTER 3: CLIMATE DATABASE ... 24
3.1 INTRODUCTION ... 24
3.2 CLIMATE DATA ... 24
3.2.1 SAPWAT REQUIREMENTS ... 24
3.2.2 REANALYSIS DATA ... 25
3.3 SAPWAT REANALYSIS CLIMATE DATABASE DEVELOPMENT ... 26
3.3.1 DATA ACCESS AND EXTRACTION ... 27
3.3.2 DERIVED CLIMATE VARIABLES ... 28
3.3.3 SET UP ON A HIGH-PERFORMANCE CLUSTER ... 30
3.4 SAPWAT REANALYSIS CLIMATE DATABASE VALIDATION ... 30
3.4.1 STATION-SCALE (POINT) VALIDATION ... 30
3.4.1.1 Data and methods ... 30
3.4.1.2 Results ... 31
3.4.2 SPATIAL PATTERN VALIDATION ... 46
3.4.2.1 Case study description ... 46
3.4.2.2 Results ... 46
3.4.3 DISCUSSION ... 48
3.5 ACCESSING THE REANALYSIS CLIMATE DATABASE IN SAPWAT ... 49
3.5.1 AGERA5 WEATHER DATA IMPORT ... 49
3.5.2 SOFTWARE PROBLEMS AND CHALLENGES ... 53
3.5.3 DISCUSSION ... 54
CHAPTER 4: SAPWAT TECHNOLOGY TRANSFER AND RECOMMENDATIONS ... 55
4.1 INTRODUCTION ... 55
4.2 SAPWAT USER FEEDBACK ... 55
4.2.1 SOUTH AFRICAN IRRIGATION INSTITUTE (SAII) ... 55
4.2.2 BANKING SECTOR ... 55
4.2.3 ZZ2 ... 55
4.2.4 GENERAL ... 56
4.2.5 SYNTHESIS ... 56
4.3 RECOMMENDATIONS ... 56
REFERENCES ... 57

APPENDIX A: STUDENT CAPACITY BUILDING **62**
APPENDIX B: KNOWLEDGE DISSEMINATION **65**
APPENDIX C: DATA ARCHIVING **66**
APPENDIX D: SUPPLEMENTAL MATERIAL FOR CHAPTER 2 .... **67**

LIST OF TABLES

Table 2.1: Title and DOI related to each paper of the special issue on the FAO 56 method for calculating crop water requirements (Pereira et al., 2021)........ 6

Table 3.1: Required format of SAPWAT climate data 25

Table 3.2: Climate variables available in AgERA5 for direct download from CDS (D) or to be obtained from subsequent calculations (C) 28

Table 3.3: Prepared data structure for AgERA5 weather data imported into SAPWAT4 as a .csv file 49

LIST OF FIGURES

Figure 2.1: Example of basal crop coefficient curve 15

Figure 2.2: Crop characteristics of maize, short grower, planted in the middle of October, showing the different stage lengths for warmer and colder areas. Source: Van Heerden and Walker (2016)........ 16

Figure 3.1: Geographical area included in the SAPWAT Climate Database........ 28

Figure 3.2: Plot of DEM-derived elevations on AgERA5 grid resolution. 29

Figure 3.3: Scatterplots of daily comparisons between station and reanalysis maximum temperature. 33

Figure 3.4: Scatterplots of monthly comparisons between station and reanalysis maximum temperature. 34

Figure 3.5: Scatterplots of daily comparisons between station and reanalysis minimum temperature. 35

Figure 3.6: Scatterplots of monthly comparisons between station and reanalysis minimum temperature. 36

Figure 3.7: Scatterplots of daily comparisons between station and reanalysis wind speed. 37

Figure 3.8: Scatterplots of monthly comparisons between station and reanalysis wind speed. 38

Figure 3.9: Scatterplots of daily comparisons between station and reanalysis solar radiation. 40

Figure 3.10: Scatterplots of monthly comparisons between station and reanalysis solar radiation. 41

Figure 3.11: Scatterplots of daily comparisons between station and reanalysis precipitation. 42

Figure 3.12: Scatterplots of monthly comparisons between station and reanalysis precipitation. 43

Figure 3.13: Scatterplots of daily comparisons between station and reanalysis reference evapotranspiration. 44

Figure 3.14: Scatterplots of monthly comparisons between station and reanalysis reference evapotranspiration. 45

Figure 3.15: Airmass RGB at 12:00 UTC (left) and TRMM daily rainfall field (right) for 19 January 2013. 46

Figure 3.16: AgERA5 reanalysis for southern Africa on 19 January 2013 for a) mean temperature, b) mean vapour pressure, c) mean wind speed, d) total solar radiation, e) total precipitation, and f) reference evapotranspiration. 47

Figure 3.17: Screenshot example of data structure for AgERA5 weather data imported into SAPWAT4 as a .csv file. 50

Figure 3.18: Screenshot 1 of the procedure to import AgERA5 weather data into SAPWAT4. 51

Figure 3.19: Screenshot 2 of the procedure to import AgERA5 weather data into SAPWAT4. 51

Figure 3.20: Screenshot 3 of the procedure to import AgERA5 weather data into SAPWAT4. 52

Figure 3.21: Screenshot 4 of the procedure to import AgERA5 weather data into SAPWAT4. 52

Figure 3.22: Screenshot 5 of the procedure to import AgERA5 weather data into SAPWAT4 53

LIST OF SUPPLEMENTAL MATERIALS

Appendix D.1: Screenshot of Figure 4 in Allen et al. (2020), showing vapour, air temperature and wind speed profiles. 67

Appendix D.2: Screenshot of Figure 5 in Allen et al. (2020), showing the author's method to condition gridded weather data by extrapolating air temperature, vapour pressure, and wind speed profiles using standard surface energy balance equations and flux-profile relationships 68

Appendix D.3: Screenshot of Figure 1 in Paredes et al. (2020) showing a flow-chart of the FAO Penman-Monteith temperature approach to compute ETo. 69

Appendix D.4: Screenshot of Figure 7 in Paredes et al. (2020) showing a flux diagram of the Hargeaves-Samani compute ETo. 70

Appendix D.5: Updated and FAO 56 tabulated Kc values for vegetables (Table 9 and in Pereira et al. 2021a).................... 71

Appendix D.6: Updated and FAO 56 tabulated Kcb values for vegetables (Table 10 in Pereira et al. 2021a).................... 72

Appendix D.7: Updated standard indicative parameters for vegetables (Table 11 in Pereira et al. 2021a) 73

Appendix D.8: Updated and FAO 56 tabulated Kc and Kcb values for legumes (Table 11 in Pereira et al. 2021b).................... 74

Appendix D.9: Updated and FAO 56 tabulated Kc and Kcb values for fiber crops, oil crops and sugar crops (Table 12 in Pereira et al. 2021b).................... 75

Appendix D.10: Updated and FAO 56 tabulated Kc and Kcb values for cereals (Table 13 in Pereira et al. 2021b).................... 76

Appendix D.11: Updated and FAO 56 tabulated Kc and Kcb values for rice (Table 14 in Pereira et al. 2021b).................... 77

Appendix D.12: Updated standard indicative parameters for grain legumes, fiber crops, oil crops, sugar crops and cereals (Tables 15 in Pereira et al. 2021a) 78

Appendix D.13: Updated standard indicative parameters for rice (Tables 16 in Pereira et al. 2021a).................... 79

Appendix D.14: Updated indicative standard values of Kc and Kcb for vine, fruit crops, berries and hops (Tables 5 in Rallo et al. 2021) 80

Appendix D.15: Updated indicative standard values of Kc and Kcb for evergreen fruit tree crops (Tables 6 in Rallo et al. 2021) 81

Appendix D.16: Updated indicative standard values of Kc and Kcb for deciduous fruit tree crops (Tables 7 in Rallo et al. 2021) 82

Appendix D.17: Updated indicative standard values of Kc and Kcb for tropical and subtropical fruit tree crops (Tables 8 in Rallo et al. 2021) 84

Appendix D.18: Crop evapotranspiration, crop water requirements, irrigation requirements and FAO 56 soil water balance calculations (Pereira et al. 2020b) 85

Appendix D.19: Updated salt tolerance of common agricultural crops (Table 1 in Minhas et al. 2020) 87

LIST OF ACRONYMS

AgERA5	Agricultural ERA5 database (see ERA5)
A&P	Allan and Pereira's approach for predicting Kc and Kcb values using observed ground cover and crop height.
ARC	Agricultural Research Council
CDS	Climate Data Store
CFSR	Climate Forecast System Reanalysis database
CSV	Comma-Separated Values
DEM	Digital Elevation Model
ECMWF	European Centre for Medium-Range Weather Forecasts
ET	Evapotranspiration
ETo	Reference evapotranspiration
ERA5	ECMWF Reanalysis 5th Generation database (see ECMWF)
FAO	Food and Agriculture Organisation
fc	Ground cover
Fr	Stomatal adjustment
h	Crop height
GUI	Graphical User Interface
JRA-55	Japanese 55-year Reanalysis database
Kc	Crop coefficient
Kcb	Basal crop coefficients
LST	Local Standard Time
MAE	Mean Absolute Error
MERRA-2	Modern-Era Retrospective Analysis for Research and Applications, Version 2
ML	Canopy transparency
n	Population size
NASA	National Aeronautics and Space Administration
NCAR	National Center for Atmospheric Research
NCEP	National Centers for Environmental Prediction
NDVI	Normalised Difference Vegetation Index
NetCDF	Network Common Data Form
Pr	Precipitation
R^2	Coefficient of determination
RHmax	Maximum Relative Humidity
RHmin	Minimum Relative Humidity
RMSE	Root Mean Square Error
SAII	South African Irrigation Institute
SAPWAT	Southern African Procedure for estimating crop WATer requirements

SIMDualKc	Simulation of Dual crop coefficients (Kc)
SIMS	Satellite Irrigation Management Support
SR	Solar Radiation
SRTM	Shuttle Radar Topographic Mission
Tmax	Maximum Temperature
Tmean	Mean Temperature
Tmin	Minimum Temperature
TRMM	Tropical Rainfall Measuring Mission
UFS	University of the Free State
VP	Vapour Pressure
VI	Spectral vegetation indices
VPmean	Mean Vapour Pressure
WRC	Water Research Commission
WS	Wind Speed

LIST OF SYMBOLS

Kr_t	dimensionless evaporation reduction coefficient dependent on the soil water content of the evaporative layer on day *t* (fraction)
EWC_t	water content of the evaporative layer at the end of day *t* (mm)
P_t	infiltrated precipitation on day *t* (mm)
I_t	infiltrated irrigation depth on day *t* (mm)
fw	portion of soil wetted by an irrigation event on day *t* (fraction)
TEW	total evaporable water in the evaporative layer (mm)
REW	readily evaporable water in the evaporative layer (mm)
E_t	evaporation on day *t* (mm)
$Kc\ max_t$	maximum value of Kc following rain or irrigation (fraction)
Kcb_t	basal crop coefficient on day *t* (fraction)
ETo_t	reference evapotranspiration on day t (mm)
few_t	portion of soil that is both exposed and wetted on day *t* (fraction)
u_t^{2m}	wind speed on day *t* at 2m height (m s^{-1})
RH_t^{min}	relative minimum humidity on day *t* (%)
h_t	crop height on day *t* (m)
RZD_t	root zone depletion below total available water at the end of day *t* (mm)
TAW_t	difference between water content at field capacity and permanent wilting point in the root zone (mm)
RAW_t	readily available soil water in the root zone (mm)
T_t	transpiration on day *t* (mm)
R_t	increase in total available water on day *t* due to root growth (mm)
p_t	proportion of total available water that is readily available on day *t* (fraction)
L_t^{rain}	amount of rainfall that is lost through percolation (mm)
L_t^{irri}	amount of irrigation that is lost through percolation (mm)
GI_t	gross irrigation application on day *t* (mm)
SE	irrigation system efficiency (fraction)
DU	distribution uniformity (fraction)

CHAPTER 1: INTRODUCTION

1.1 BACKGROUND AND MOTIVATION

The South African climate is highly variable, and global and regional climate changes may influence intra- and inter-seasonal variability. Unprecedented population growth and the increasing transformation of natural ecosystems further strain water resources. The agricultural sector is experiencing increasing competition from industrial and domestic use, while agricultural production and water management are intrinsically linked to climate variability. Increasing pressure is mounting on irrigated agriculture to improve water-use efficiency, as it is the largest water user in South Africa, and small improvements are perceived to have a large impact on water availability. The key to improving water-use efficiency in irrigated agriculture is accurate estimates of crop water requirements.

The Water Research Commission (WRC) has financed the development of SAPWAT software for more than two decades to improve the planning of irrigation water use for various crops at various spatial scales. Since then, SAPWAT has become the standard procedure for estimating crop water requirements in South Africa. Consequently, SAPWAT has a large user base comprising individual farmers, irrigation advisors, irrigation system designers, and water managers responsible for water distribution at the water user association level. Some tertiary institutions use it as a training aid in undergraduate modules, while researchers use it to investigate various environmental and management factors on crop water use. Furthermore, the South African government uses SAPWAT as a reference for establishing the lawful use of irrigation water. In 2011, the developers of SAPWAT received the prestigious WatSave Technology Award from the International Commission on Irrigation and Drainage.

The current custodian of SAPWAT, Dr Pieter van Heerden, is 75 years old and has deteriorating eyesight, making it difficult for him to maintain the SAPWAT software. There is a need to transfer the custodianship of SAPWAT to the University of the Free State (UFS) to ensure the upkeep of the software and its user base. The process entails transferring the software and programming code to the UFS and the knowledge of Dr Van Heerden embedded in the code to the research team. SAPWAT uses the methods described in FAO Irrigation and Drainage Paper 56 (Allen et al., 1998) to calculate crop water requirements. Unfortunately, the specific procedures used to implement the methods are not documented. Since the publication of FAO 56, several researchers have proposed improvements to the FAO 56 methodology and procedures, published in a special issue of Agricultural Water Management entitled "Updates and advances to the FAO 56 crop water requirements method" during 2021. It is unclear which of these developments has already been implemented in SAPWAT. Knowing which developments of the FAO 56 methodology are embedded in SAPWAT is key to ensuring sustainable upkeep of SAPWAT.

A known shortcoming of SAPWAT, expressed by several users in recent years, is the dated climate database used to calculate crop water requirements. SAPWAT includes the quaternary catchment database of daily minimum and maximum temperature values, relative humidity, rainfall, average wind speed, and solar radiation, derived statistically from 1 925 points across South Africa (Schulze and Maharaj, 2006). The climate database comprehensively covers South Africa from 1950 to 1999. The quaternary catchment database is outdated, and its usefulness is increasingly questioned in light of a changing climate. There is a clear need to update SAPWAT's climate database to reflect the current production environment.

1.2 PROBLEM STATEMENT

The current custodian can no longer sustain the development and maintenance of SAPWAT, resulting in an outdated system that struggles to remain relevant in a rapidly advancing technological environment. At the same time, shifting climate conditions are increasing the uncertainty of crop water requirement estimations, further undermining confidence in the software for irrigation water management in South Africa.

1.3 OBJECTIVES

The project's overall objective is to transfer custodianship of SAPWAT to the University of the Free State.

The following specific objectives were set to achieve the general objective of this research:

- Capacitate researchers at the University of the Free State to provide support with respect to the use of SAPWAT software.
- Improve the applicability of SAPWAT through a new climate database to determine reference evapotranspiration for South Africa.

1.4 STRUCTURE OF THE REPORT

Chapter 1 provides the background and motivation for the research, as well as the problem statement and objectives.

Chapter 2 evaluates how SAPWAT implements the FAO 56 dual crop coefficient methodology for estimating crop water requirements. The chapter commences with a review of the papers in the special issue of Agricultural Water Management entitled "Updates and advances to the FAO 56 crop water requirements method". Next, a comparison is made between the calculation procedures of FAO 56 and SAPWAT.

Chapter 3 reports the development and validation of the reanalysis database. The final section of the chapter covers integrating the climate database with SAPWAT.

The last chapter, Chapter 4, provides an overview of the technology transfer activities and makes some recommendations for the way forward.

CHAPTER 2: ESTIMATING CROP WATER REQUIREMENTS: A REVIEW OF SAPWAT AND FAO 56

2.1 INTRODUCTION

This chapter reviews the FAO 56 method for estimating crop water requirements (Allen et al., 1998) and how it is implemented in SAPWAT4. Accurate estimation of crop water requirement and irrigation scheduling is central to SAPWAT's purpose as a decision-support tool for irrigation planning and water-use assessment. Because SAPWAT4's calculation engine is built entirely around the FAO 56 dual coefficient framework, a careful, chapter-length review must (a) document the theoretical basis behind the model's calculations and (b) assess whether the software implementation reflects the accepted method and recent advances.

Transferring custodianship to the University of the Free State entails moving files and responsibilities and ensuring technical stewardship, including ensuring that custodians understand the calculation logic, assumptions, and limits of SAPWAT's outputs. Therefore, a transparent, documented comparison between the FAO 56 reference calculations and SAPWAT4's embedded procedures is a prerequisite for trustworthy future maintenance, updates, and user support.

This chapter has two complementary aims. First, it synthesises updates and advances to the FAO 56 method, based on the 2020-2021 special issue of 19 papers published in Agricultural Water Management. Second, it documents and evaluates the SAPWAT4 implementation of FAO 56, identifying where SAPWAT faithfully reproduces FAO 56 procedures, where assumptions or shortcuts are used, and where updates from the literature could improve SAPWAT's applicability to South African conditions. The evaluation concentrates on the calculation procedures (the "black-box" algorithms) and how SAPWAT4 transforms inputs (weather, crop, soil, management) into outputs (ETo, Kc/Kcb, effective rainfall, net/gross irrigation requirement, soil water balance). It does not attempt a comprehensive software audit (e.g., graphical user interface, GUI, behaviour, database schemas, or binary dependencies) or replace empirical validation with field measurements. The lack of a dBASE execution environment meant that testing relied on static code inspection and reproduction of FAO 56 spreadsheets.

2.2 SYNTHESIS OF UPDATES AND ADVANCES TO THE FAO 56 METHOD

The Agricultural Water Management special issue on FAO 56 addressed four broad categories, which are individually discussed below. Table 2.1 provides the authors, titles, and DOIs for each paper (Pereira et al., 2021).

2.2.1 COMPUTING REFERENCE EVAPOTRANSPIRATION (ETO)

Two papers discuss research efforts to address challenges in estimating reference evapotranspiration (FAO Penman-Monteith ETo) in arid and data-scarce environments. FAO 56 and the American Society of Civil Engineers assume well-watered surfaces for ETo calculations. However, meteorological data are often collected in arid regions where the lack of evapotranspiration from surfaces where they are collected can affect the data.

- Allen et al. (2020) studied biases in weather data due to aridity and developed a conditioning process to adjust the data to reflect the characteristics of well-watered vegetated surfaces. Using standard surface energy balance equations and flux-profile relationships, the authors proposed a method (Appendix D.1 and Appendix D.2) to condition gridded weather data by extrapolating air temperature, vapour pressure, and wind speed profiles. The process was robust and transferable, resulting in more accurate ETo estimates.

- With the second paper, Blankenau et al. (2020) assessed six gridded weather datasets to calculate ETo and compared them with data from well-watered weather stations across the United States. The gridded datasets generally overestimated standardised ETo due to biases in temperature, radiation, and wind speed, and an understatement of air humidity. The authors recommended careful evaluation and bias correction of gridded data before using them to replace observed weather station data. The study identified the best-performing gridded dataset and concluded that spatial resolution is not the primary factor affecting correspondence with station data.

The remaining two papers explored alternative methods for estimating ETo due to reduced availability of weather data, particularly temperature-based approaches, reanalysis, and geostationary satellite products.

- Paredes et al. (2020) introduced a consolidated method to parameterise simplified temperature methods, i.e., the FAO Penman-Monteith temperature approach (Appendix D.3) and Hargreaves-Samani equation (Appendix D.4), which estimate shortwave solar radiation using air temperature differences and regression equations based on local or nearby weather station data.

Table 2.1: Title and DOI related to each paper of the special issue on the FAO 56 method for calculating crop water requirements (Pereira et al., 2021)

Authors	Title	DOI
Pereira, L.S. et al. (2021)	Updates and advances to the FAO56 crop water requirements method	https://doi.org/10.1016/j.agwat.2020.106697
Allen, R.G. et al. (2020)	Conditioning point and gridded weather data under aridity conditions for calculation of reference evapotranspiration	https://doi.org/10.1016/j.agwat.2020.106531
Blankenau, P.A. et al. (2020)	An evaluation of gridded weather data sets for estimating reference evapotranspiration in the United States	https://doi.org/10.1016/j.agwat.2020.106376
Paredes, P. et al. (2020)	Reference grass evapotranspiration with reduced data sets: Parameterization of the FAO Penman-Monteith temperature approach and the Hargeaves-Samani equation using local climatic variables.	https://doi.org/10.1016/j.agwat.2020.106210
Paredes, P. et al. (2021a)	Daily grass reference evapotranspiration with Meteosat Second Generation shortwave radiation and reference ET products	https://doi.org/10.1016/j.agwat.2020.106543
Pereira, L.S. et al. (2021b)	Standard single and basal crop coefficients for vegetable crops, an update of FAO56 crop water requirements approach.	https://doi.org/10.1016/j.agwat.2020.106196
Pereira, L.S. et al. (2021)	Standard single and basal crop coefficients for field crops. Updates and advances to the FAO56 crop water requirements method	https://doi.org/10.1016/j.agwat.2020.106466
Rallo, G. et al. (2021)	Updated single and dual crop coefficients for trees and vine crops	https://doi.org/10.1016/j.agwat.2020.106645
Pereira, L.S. et al. (2020a)	Prediction of crop coefficients from fraction of ground cover and height. Background and validation using ground and remote sensing data.	https://doi.org/10.1016/j.agwat.2020.106197
Pereira, L.S. et al. (2021c)	Prediction of crop coefficients from fraction of ground cover and height. Practical application to vegetable, field and fruit crops with focus on parameterization.	https://doi.org/10.1016/j.agwat.2020.106663
López-Urrea, R. et al. (2020)	Evapotranspiration and crop coefficients from lysimeter measurements for sprinkler-irrigated canola	https://doi.org/10.1016/j.agwat.2020.106260
Pôças, I. et al. (2020)	Remote sensing for estimating and mapping crop coefficients: a review	https://doi.org/10.1016/j.agwat.2020.106081
French, A.N. et al. (2020)	Satellite-based NDVI crop coefficients and evapotranspiration with eddy covariance validation for multiple durum wheat fields in the US Southwest	https://doi.org/10.1016/j.agwat.2020.106266
Wang, T. et al. (2021)	Evaluation of crop coefficient and evapotranspiration data for sugar beets from Landsat surface reflectances using micrometeorological measurements and weighing lysimetry	https://doi.org/10.1016/j.agwat.2020.106533
Pereira, L.S. et al. (2020b)	Soil water balance models for determining crop water and irrigation requirements and irrigation scheduling focusing on the FAO56 method and the dual Kc approach	https://doi.org/10.1016/j.agwat.2020.106357
Garrido-Rubio, J. et al. (2020)	Remote sensing–based soil water balance for irrigation water accounting at plot and water user association management scale	https://doi.org/10.1016/j.agwat.2020.106236
Jovanovic, N. et al. (2020)	A review of strategies, methods and technologies to reduce non-beneficial consumptive water use on farms considering the FAO56 methods	https://doi.org/10.1016/j.agwat.2020.106267
Minhas, P.S. et al. (2020)	Coping with salinity in irrigated agriculture: Crop evapotranspiration and water management issues	https://doi.org/10.1016/j.agwat.2019.105832

- Paredes et al. (2021) assessed the accuracy of two shortwave radiation products from the Satellite Application Facility on Land Surface Analysis and ERA5 reanalysis for estimating ETo when combined with observed weather variables. The products showed promise for estimating ETo in limited-data situations, with good results in continental climates and innovation in oceanic islands.

2.2.2 SINGLE AND DUAL CROP COEFFICIENTS

Pereira et al. (2021a), Pereira et al. (2021b), and Rallo et al. (2021) reviewed crop coefficient (Kc) and basal crop coefficient (Kcb) literature for vegetables, field crops and tree and vines, respectively. Tables with updated standard Kc and standard Kcb values were developed. Standard refers to a sub-humid climate with a minimum relative humidity of 45% and a wind speed of 2 m s^{-1}. Tables with updated indicative ancillary crop parameters were also developed as part of these reviews, for example, maximum rooting depth, crop height, maximum fraction of ground cover, soil water depletion fraction for no stress, etc.

- Vegetables (Appendix D.5 to Appendix D.7) are grouped according to edible parts, namely i) roots, tubers, bulbs, and stem vegetables, ii) leaves and flowers vegetables, and iii) fruits and pod vegetables. Kc data for new vegetable crops are provided, i.e., iv) herbs, spices, and special crops.

- Field crops (Appendix D.8 to Appendix D.13) are grouped into i) grain legumes, ii) fibre crops, iii) oil crops, iv) sugar crops, v) small grain cereals, vi) maize and sorghum and vii) rice. New crops include camelina, linseed, mustard, amaranth grain, quinoa, rye, teff, durum wheat, silage maize and silage sorghum. Rice is also in these updated tables and described according to diverse irrigation management systems.

- Vine and tree crops (Appendix D.14 to Appendix D.17) are grouped according to i) vine fruit crops, berries and hops, ii) temperate climate evergreen fruit trees, iii) deciduous fruit trees, and iv) tropical and sub-tropical fruit crops. New crops include pomegranate, hazelnut, pecan, pistachio, fig, persimmon, avocado, cherimoya, guava, mango, and papaya. Moreover, Kc and Kcb values for each crop are generally provided, allowing differentiation by orchard density, ground cover fraction, and vine training system.

The authors mentioned above considered only studies published after the first FAO 56 publication, whose results permitted the identification of standard Kc and Kcb values.

Particular attention was paid to the constraints imposed by energy availability and, hence, the upper limits of ET. There's an upper limit on ET, even under extreme advection conditions, due to limitations on aerodynamic transport and equilibrium forces above a vegetation canopy. Tall, dense crops in windy arid and semi-arid conditions can have Kc values approaching 1.3 due to the dominance of aerodynamics. In humid climates, where net radiation is more dominant, Kc values are generally lower. Regional advection effects can impact Kc values. In arid and semi-arid climates with strong advection, Kc might reach 1.2 or higher, even exceeding 1.4 for specific vegetation types. When measuring ET from small patches of vegetation, the internal boundary layer above the vegetation might not be in equilibrium with the surface. This can lead to discrepancies between small patches and large fields' ET estimates. Kc values above certain thresholds, e.g., 1.2 in sub-humid regions or 1.2 to 1.4 in the arid areas, should prompt scrutiny of ET measurements, weather data used for ETo calculations, or data collection procedures.

All three papers mentioned above also address experimental and reporting inefficiencies that limit the transferability of Kc. This includes deviating from the standard segmented FAO Kc curve, which can result in approximate Kc estimates across different growth stages. Hence, the use of non-standard curves can affect the accuracy and transferability of Kc values. Practices such as plastic mulch or intercropping alter crop evapotranspiration and soil evaporation, thereby influencing Kc. While these practices are beneficial, documenting their impact on Kc is crucial for accurate estimations and transferability. When crop conditions deviate from pristine conditions, due to reduced crop development caused by plant density, crop management, soil fertility and fertilisation, plant diseases, soil salinity, and/or water deficits, the actual Kc may be reduced. Unlike the standard Kc, the actual Kc is not transferable between sites. In addition, several measurement approaches can lead to problems in obtaining accurate crop ET values and usable data for Kc determination, as summarised below.

- Inadequate characterisation of soil hydraulic properties, incomplete consideration of root zone depth, inaccuracies in measuring soil water content, irrigation, and rainfall, and poor estimation of deep percolation and capillary rise lead to inaccurate soil water balance calculations. These inaccuracies affect the Kc values.

- Using lysimeters improperly can affect accuracy. Differences in lysimeter conditions compared to field conditions, incorrect positioning, and inadequate surroundings can affect Kc measurements.

- Methods like Bowen ratio energy balance, and eddy covariance require proper instrumentation and correction procedures. Inaccurate measurements of net radiation and ground heat flux affect Kc estimations.

- Remote sensing using vegetation indices like the normalised difference vegetation index or SAVI can estimate Kc, but proper calibration and pixel correspondence to pristine conditions are crucial. Energy balance methods in remote sensing for Kc estimation face similar challenges.

- Missing or incomplete data on crop characteristics, growth stages, cultivation practices, and weather variables during experiments hinder accurate Kc assessments.

FAO 56 assumes that the reported Kc values refer to a standard semi-humid climate. In the reviewed literature, assessing whether reported values were for standard conditions was often difficult. To adjust Kc to standard conditions, minimum relative humidity and wind speed at a height of 2 m (u^{2m}) are required and were sometimes undocumented. Equations 2.1 and 2.2 are used to adjust Kc to the assumed standard condition, which refers to irrigation management and precipitation frequencies typical of a sub-humid climate where minimum relative humidity (RHmin) is 45% and u_2 = 2 m s^{-1}.

$$K_{c\ mid(std)} = K_{c\ mid(obs)} - \left[0.04\left(u_2^{mid} - 2\right) - 0.004\left(RH_{min}^{mid} - 45\right)\right]\left(\frac{h}{3}\right)^{0.3} \quad (2.1)$$

$$K_{c\ end(std)} = K_{c\ end(obs)} - \left[0.04(u_2^{late} - 2) - 0.004\left(RH_{min}^{late} - 45\right)\right]\left(\frac{h}{3}\right)^{0.3} \quad (2.2)$$

The superscripts mid and late refer to average values for the mid and late seasons, respectively. Pereira et al. (2021b) highlight that "when crops senesce and dry out in the field (Kc end < 0.45), no adjustment is necessary for Kc end". Crop height should be observed in the field, and tabulated h values often deviate from reality and should not replace field observations. Similar adjustments apply to Kcb (Equations 2.3 and 2.4).

$$K_{cb\ mid(std)} = K_{cb\ mid(obs)} - \left[0.04\left(u_2^{mid} - 2\right) - 0.004\left(RH_{min}^{mid} - 45\right)\right]\left(\frac{h}{3}\right)^{0.3} \quad (2.3)$$

$$K_{cb\ end(std)} = K_{cb\ end(obs)} - \left[0.04(u_2^{late} - 2) - 0.004\left(RH_{min}^{late} - 45\right)\right]\left(\frac{h}{3}\right)^{0.3} \quad (2.4)$$

Unlike vegetables and field crops, the adjustment to standard climate conditions proposed in FAO 56 was not implemented for vine and tree crops (Rallo et al., 2021). Tree and vine crops have different aerodynamic behaviours that do not align with the climate adjustment equations in FAO 56 (Equations 2.3 and 2.4).

The last two papers in this section focused on predicting Kc and Kcb values utilising observed ground cover (fc) and crop height (h).

- Pereira et al. (2020c) obtained outstanding results regarding the efficacy of the Allen and Pereira (2009) approach (A&P), tested across various crops, including trees, vines, vegetables, field crops, grasslands, and Bermudagrass pastures. With the approach, a crop density coefficient is established using fc and h data, which is then used to directly compute Kc and Kcb values. The authors also obtained accurate daily crop ET estimates by combining satellite-derived fc and Kcb from the approach with ETo data. The SIMS framework was used, and ETo data were obtained from Spatial SIMS for California.

- Pereira et al. (2021c) optimised values of non-observed parameters, namely canopy transparency (ML) and stomatal adjustment (Fr), through a numerical search. This search was used to find ML and Fr values that minimise discrepancies between Kcb from A&P and standard Kcb values listed in Pereira et al. (2021a), Pereira et al. (2021b) and Rallo et al. (2021). The study produced tabulated parameter values and estimated Kcb and Kc values for different crop growth stages. Cross-validation using independent field observations demonstrated excellent agreement between observed and estimated Kcb values, with estimation errors below 10% of the standard tabulated Kcb. The tabulated Fr and ML values are suggested as default values to support practical A&P applications when combined with observed fc and h values.

2.2.3 GROUND AND REMOTE SENSING DATA

Four papers in this section of the special issue collectively underscore, through various case studies, the significance of remote sensing and lysimeter-based approaches in accurately estimating crop evapotranspiration and refining crop coefficient values.

- The study by López-Urrea et al. (2020) demonstrated three crucial aspects regarding the successful use of weighing lysimeters to determine Kc and Kcb values for canola, namely:

  - Details on calibration and maintenance procedures for accurate ET measurements.
  - Ancillary crop data like maximum root depth, crop height, and depletion fraction for no stress.
  - Positive agreement between Kcb and ground cover fraction and remotely sensed vegetation indices.

- Poças et al. (2020) conducted a review covering the past 20 years of research on using remote sensing data, specifically spectral vegetation indices (VIs), to provide spatially distributed information on actual single- and basal-crop coefficients. The review presents a set of best practices for analysing the diverse range of Kc-VI and Kcb-VI relationships established for various crops.

- The study by French et al. (2020) applies the Kcb-VI approach within the FAO 56 guidelines to estimate durum wheat crop evapotranspiration using NDVI data from Sentinel 2 and the Venus microsatellite. This study demonstrated the potential of remote sensing to estimate crop ET and refine crop coefficients, providing insights for water management and irrigation scheduling.

- Wang et al. (2021) present a case study of the use of the SIMS framework for drip-irrigated sugar beets in California. Satellite data, the A&P approach and ETo data were combined to estimate actual crop ET. Strong agreement between observed actual ET and daily estimates from SIMS was observed.

2.2.4 MANAGEMENT PRACTICES

The evolution of tools, models, and strategies to improve irrigation management, enhance water-use efficiency, and address challenges such as salinity in agricultural practices was the focus of the papers in this section of the review.

- Pereira et al. (2020b) reviewed a wide range of computational tools developed after FAO 56 to support the determination of crop water requirements and irrigation scheduling. The review emphasises that while the theoretical foundations of FAO 56 remain valid, practical applications rely heavily on software tools that implement and extend the method. The authors highlight the key reference concepts underpinning these tools, including ET, crop and irrigation water requirements, and the soil water balance equations of FAO 56, which are central to the present project (summarised in

Figure D.18). Several soil water balance models have adopted the FAO 56 time-averaged Kc and dual Kc approaches. These include ISAREG, CROPWAT, AquaCrop, DSSAT-CSM, and the widely used SIMDualKc model. Applications of these models demonstrate their versatility in tasks such as evaluating alternative sowing dates, differentiating beneficial from non-beneficial water use, and analysing groundwater contributions in rainfed or partially irrigated systems. Among these tools, SIMDualKc is particularly significant. It is a daily soil water balance model that explicitly adopts the FAO 56 dual Kc methodology to partition crop evapotranspiration into crop transpiration and soil evaporation. The model has several advanced features:

- It incorporates effects of mulches, no-till planting, active ground cover, intercropping, and salinity on crop water use.
- It can estimate deep percolation, runoff, and groundwater contributions when relevant data are available.
- It supports rigorous calibration and validation using observed soil water content, ET, or sap flow data, ensuring reliable performance across diverse conditions.
- It has been applied to complex systems such as relay intercropping, orchards, vineyards, and forage crops under multiple cuttings, demonstrating flexibility across crop and management practices.

Other FAO 56-based models are also worth noting:

- ISAREG, an earlier FAO 56-based model, later formed the basis for SIMDualKc.
- AquaCrop, FAO's official crop growth model, is widely used for water productivity studies, although its ET partitioning differs somewhat from FAO 56.
- DSSAT-CSM, a crop growth simulation framework that recently incorporated FAO 56's ETo–Kcb methodology to improve irrigation scheduling applications.

- The paper by Garrido-Rubio et al. (2020) focused on developing a Remote Sensing-Based Soil Water Balance model using remote sensing time-series data, combined with ancillary data such as agro-meteorological information, soil types, and crop characteristics. The model provides pixel-based maps of net irrigation requirements at field and water user association scales. Using time series of FAO 56 Kcb and NDVI-derived fractional vegetation cover, the model offers accurate irrigation water accounting for irrigation management. Validated against measured irrigation water volumes, the model showed average errors of 12% and 15% at the field and water user association scales, respectively. The model's success in vineyards under deficit irrigation practices is noted, providing valuable insights for water managers.

- The review by Jovanovic et al. (2020) explores strategies, methods, and technologies to reduce consumptive water use at the farm level, particularly under conditions of water scarcity and climate change. The FAO 56 crop coefficient approach is a foundational component of these strategies. The review covers diverse water-saving practices related to irrigation methods, management, remote sensing, mulching, and soil management. The impact of these water-saving practices on soil evaporation, total water use, yield and evapotranspiration water productivity is discussed. The review notes that much of the existing research using the FAO 56 approach has diverse objectives and often doesn't specifically focus on the impact of various techniques and practices on crop evapotranspiration or crop coefficients. To improve water management, it's crucial to conduct research that explicitly addresses these aspects. The authors also highlight that some water-saving practices require optimisation algorithms due to the complexity of factors involved. For example, optimising micro-irrigation practices may involve considering wetted area, row spacing, plant density, and mulching. Optimisation is also needed for strategies like deficit irrigation. In addition, research findings claiming substantial water savings alongside substantial increases in yield and water productivity should be approached cautiously. Such outcomes may not align with physical and physiological crop responses and could result from poorly designed experiments.

- Minhas et al. (2020) reviewed approaches to assess the effects of salinity on crop yields and ET within the FAO 56 framework. Under salinity conditions, a daily soil water balance is required, with actual crop ET computed using the Kc-ETo approach and a stress coefficient to account for water and salt stresses. Stress coefficients were updated and tabulated (Figure D19), and the article delves into soil-crop-water management practices for coping with salinity conditions, including leaching fraction computation and appropriate irrigation methods.

2.3 SAPWAT IMPLEMENTATION OF THE FAO 56 METHOD

The FAO 56 dual crop coefficient method estimates crop water requirements by separating evapotranspiration into two components: crop transpiration and soil evaporation. The method applies a four-stage basal crop coefficient curve to represent plant transpiration under non-stressed conditions over the growing season and a soil evaporation coefficient (Ke) to account for evaporation from the exposed soil surface. A reference evapotranspiration is multiplied by the sum of Kcb and Ke to obtain crop evapotranspiration. The approach allows dynamic adjustment of soil evaporation following rainfall or irrigation events and as canopy cover develops, making it more accurate than the single Kc method, especially under partial canopy cover and variable wetting conditions. By explicitly tracking soil water balance in the topsoil layer and root zone, the dual Kc method improves irrigation scheduling and water requirement estimates across different growth stages.

2.3.1 REFERENCE EVAPOTRANSPIRATION

SAPWAT4 uses the Penman-Monteith equation to calculate the grass reference to estimate the crop water requirements. Inspection of the SAPWAT4 source code revealed no discrepancies in the ETo calculation. The reader is referred to Chapter 3 for a detailed discussion on ETo.

2.3.2 BASAL CROP COEFFICIENT CURVES

2.3.2.1 FAO 56

FAO 56 (Allen et al., 1998) uses a basal crop coefficient curve to calculate changes in crop transpiration over a crop's growing season under no water stress conditions. Four growth stages (i.e. initial, crop development, midseason and late-season) characterise the basal crop coefficient curve. Constructing the basal crop coefficient curve requires specifying the lengths of the growth stages and the initial, midseason, and end-of-season basal crop coefficients. FAO 56 uses linear interpolation to construct a daily basal crop coefficient curve. Figure 2.1 provides an example of a basal crop coefficient curve.

Allen et al. (1998) tabulate the initial, midseason, and end-of-season values for Kcb to construct the Kcb-curve for a sub-humid climate with moderate wind speed. Consequently, the Kcb values for the midseason and end-of-season need adjustment for environments where relative minimum humidity and wind speed differ from 45% and 2 ms^{-1}, respectively, before constructing the Kcb-curve. Equations 2.5 and 2.6 show the procedure for adjusting the tabulated Kcb values for the midseason and end-of-season.

$$K_{cb\ mid} = K_{cb\ mid(std)} + \left[0.04\left(u_2^{mid} - 2\right) - 0.004\left(RH_{min}^{mid} - 45\right)\right]\left(\frac{h}{3}\right)^{0.3} \quad (2.5)$$

$$K_{cb\ end} = K_{cb\ end(std)} + \left[0.04(u_2^{late} - 2) - 0.004\left(RH_{min}^{late} - 45\right)\right]\left(\frac{h}{3}\right)^{0.3} \quad (2.6)$$

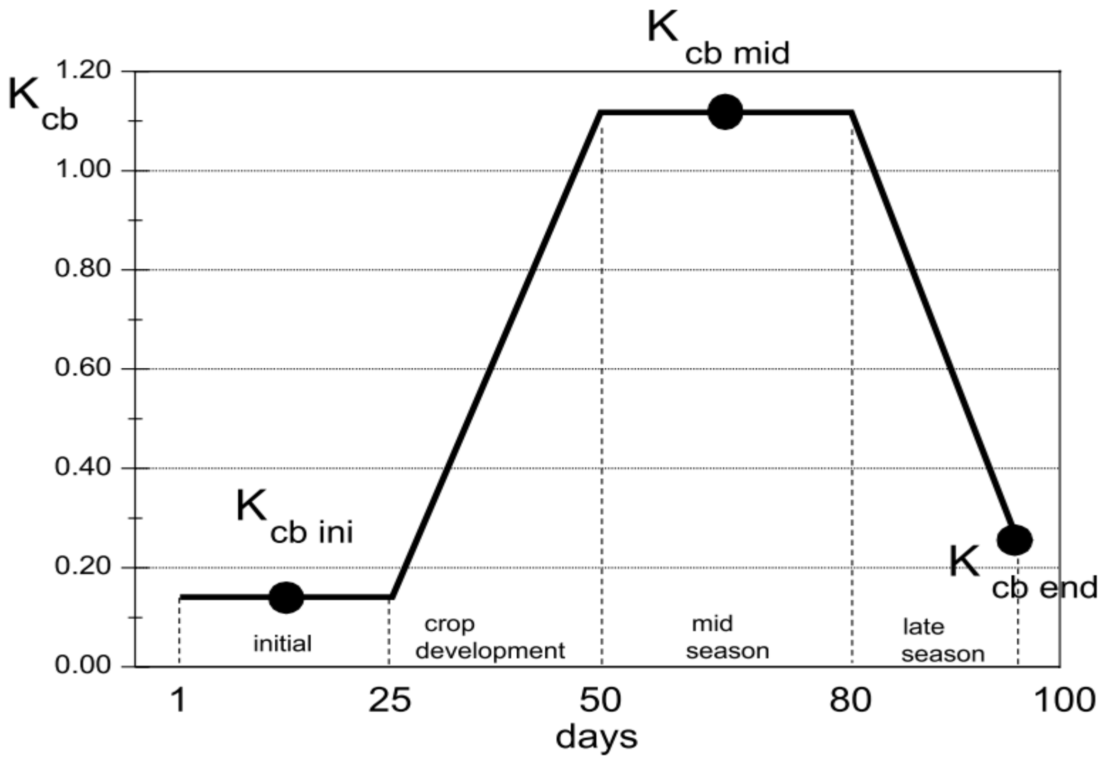

Figure 2.1: Example of basal crop coefficient curve

2.3.2.2 SAPWAT

SAPWAT4 comprises two databases containing the weather variables required to calculate ETo. The FAO CLIMWAT database comprises 3262 weather stations from 144 countries and contains long-term monthly average weather data. A cosine curve is used in SAPWAT4's source code to estimate daily values of monthly weather variables statistically. The second database was developed by the School of Bioresources Engineering and Environmental Hydrology at the University of KwaZulu-Natal from the South African Atlas of Climatology and Agrohydrology. Long-term daily weather variables (1950-1999) were derived for each quaternary catchment of South Africa. The source code also allows for an option to import daily or monthly weather data. SAPWAT4 classifies each weather station location according to the Köppen-Geiger climate system (Strahler and Strahler, 2002) based on temperature-rainfall combinations from temperature and rainfall data (Figure 2.2).

In South Africa, the number of possible climatic regions amounts to five, namely i) tropical, ii) dry, hot, iii) dry, cold, iv) mild, humid, hot summers and v) mild, humid, warm summers. The number of days describing the four-stage development curve for a specific crop is linked to the five Köppen climates in a crop data table. This classification differs from FAO 56, which is for single area-crop linkages. Hence, SAPWAT4 allows approximating the effects of climate, planting data, management strategies, and crop variety on individual development stages. SAPWAT4 uses Equations 2.5 and 2.6 to correctly adjust the tabulated Kcb values when estimating crop water requirements. The implication is that all the Kcb values contained in the SAPWAT4 database are assumed to correspond to a sub-humid climate with moderate wind speed. However, the length of the growth stages is specified for each climatic region.

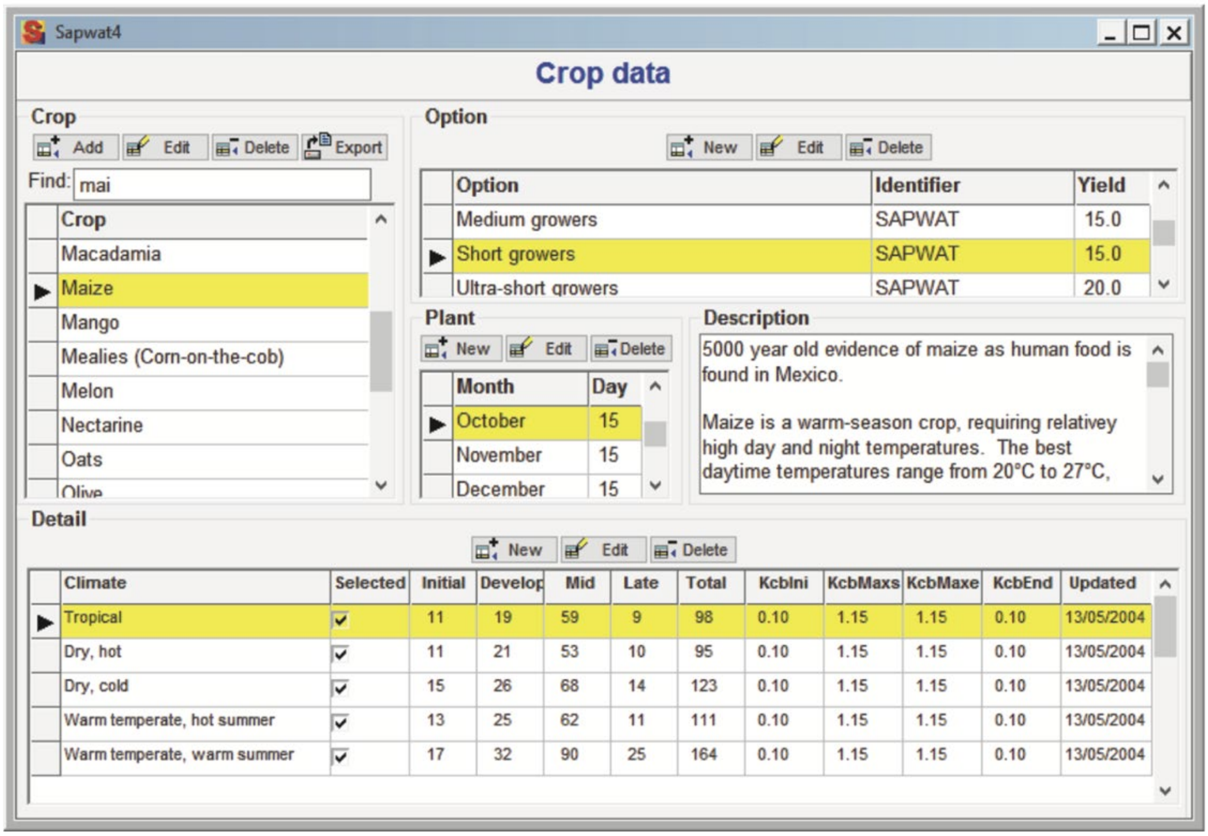

Figure 2.2: Crop characteristics of maize, short grower, planted in the middle of October, showing the different stage lengths for warmer and colder areas. Source: Van Heerden and Walker (2016).

2.3.3 SOIL EVAPORATION

2.3.3.1 FAO 56

In the original FAO 56 method, soil evaporation is assumed to occur from the upper 10-15 cm (Allen et al., 1998). Furthermore, the assumption is that transpiration from the top 10 cm is minimal. Therefore, the calculations for the evaporative layer do not include transpiration. Equations 2.7 to 2.9 show the water budget calculations necessary to compute soil evaporation:

$$Kr_t = MIN \left| \begin{matrix} (EWC_{t-1} + P_t + I_t/fw)/(TEW - REW) \\ 1 \end{matrix} \right. \tag{2.7}$$

$$E_t = MIN \left| \begin{matrix} Kr_t \times (Kc\ max_t - Kcb_t) \times ET0_t \\ Kc\ max_t \times ET0_t \times few_t \end{matrix} \right. \tag{2.8}$$

$$EWC_t = MIN \left| \begin{matrix} EWC_{t-1} + P_t + I_t/fw \\ TEW \end{matrix} \right. - E_t/few_t \tag{2.9}$$

where

Kr_t	dimensionless evaporation reduction coefficient dependent on the soil water content of the evaporative layer on day *t* (fraction)
EWC_t	water content of the evaporative layer at the end of day *t* (mm)
P_t	infiltrated precipitation on day *t* (mm)
I_t	infiltrated irrigation depth on day *t* (mm)
fw	portion of soil wetted by an irrigation event on day *t* (fraction)
TEW	total evaporable water in the evaporative layer (mm)
REW	readily evaporable water in the evaporative layer (mm)
E_t	evaporation on day *t* (mm)
$Kc\ max_t$	maximum value of Kc following rain or irrigation (fraction)
Kcb_t	basal crop coefficient on day *t* (fraction)
ETo_t	reference evapotranspiration on day t (mm)
few_t	portion of soil that is both exposed and wetted on day *t* (fraction)

The first step in calculating soil evaporation is determining whether the energy-limiting (evaporation occurs at the maximum rate, limited only by the available energy at the soil surface) or soil-limiting (evaporation is constrained by the ability of water to move through the drying soil profile) phase applies by assessing the value of Kr_t. Equation (2.7) shows that the soil-limiting stage applies if the water content of the evaporative layer, after accounting for precipitation and rainfall, is below a threshold $(TEW - REW)$ water content. Consequently, $Kr_t < 1$, which indicates that soil evaporation will reduce proportionally to the amount of water in the evaporative layer. The energy-limiting stage applies if the water content is above the threshold water content, resulting in a $Kr_t = 1$, which implies maximum soil evaporation rates.

Equation (2.8) calculates soil evaporation while constraining maximum soil evaporation rates to two upper bounds. The first bound (i.e. $Kr_t \leq 1$) restricts soil evaporation to be less than the maximum soil evaporation rate, where the maximum soil evaporation rate is the difference between the maximum evapotranspiration rate ($Kc\ max_t \times ET_{0_t}$) and crop transpiration rate

($Kcb_t \times ET_{0t}$). $Kc\,max_t$ defines the upper limit on soil evaporation and transpiration from any cropped area as constrained by natural energy availability (Allen et al., 1998). The second bound acknowledges that soil evaporation predominantly occurs from the wetted soil fraction exposed to sunlight. few_t is calculated as the minimum value of the fraction of the soil not covered by the crop's canopy and the area wetted.

Key to the application of the bounds is the correct specification of Kcb_t and $Kc\,max_t$. Kcb_t is already adjusted for the climate effects. However, $Kc\,max_t$ also needs to be adjusted for climate effects. Equation 2.10 defines the upper limit on $Kc\,max_t$ as follows:

$$Kc\,max_t = MAX \begin{vmatrix} 1.2 + \left[0.04 \times \left(u_{2t} - 2\right) - 0.004 \times \left(RH_t^{min} - 45\right)\right] \times \left(\frac{h_t}{3}\right)^{0.3} \\ Kcb_t + 0.05 \end{vmatrix} \tag{2.10}$$

where

u_{2t}	wind speed on day *t* at 2m height (m s^{-1})
RH_t^{min}	relative minimum humidity on day *t* (%)
h_t	crop height on day *t* (m)

Equation 2.10 ensures that wet soil will always increase the value of $Kc\,max_t$ by 0.05 following a complete wetting of the soil by irrigation or rain, even under full canopy cover (Allen et al., 1998).

Equation 2.9 calculates the evaporative layer's water content at the day's end. The MIN function ensures that the addition of irrigation and precipitation does not exceed the capacity of the evaporative layer to store water (TEW). Consequently, Equation 2.9 calculates percolation before subtracting soil evaporation to determine EWC_t.

2.3.3.2 SAPWAT

SAPWAT4 does not track water content in the evaporative layer. The model uses the daily root zone depletion level to calculate Kr_t as follows:

$$Kr_t = MAX \begin{vmatrix} MIN \begin{vmatrix} (TEW - RZD_{t-1})/(TEW - REW) \\ 1 \end{vmatrix} \\ 0 \end{vmatrix} \tag{2.11}$$

where

RZD_t root zone depletion below total available water at the end of day t (mm)

The calculation of RZD_t will be covered in Section 2.3.4, since the calculation depends on transpiration, which is covered in that section. The first argument of the MAX function uses the MIN function to ensure that the value of Kr_t will not exceed one if the root zone depletion level is less than REW. The MAX function ensures that $Kr_t = 0$ if the root zone depletion level is more than TEW. SAPWAT4 uses Equation 2.8 to calculate soil evaporation using the Kr_t value calculated with Equation 2.11. The implication is that soil evaporation will be low on the day of irrigation or rainfall and high the day after.

2.3.4 TRANSPIRATION

2.3.4.1 FAO 56

Allen et al. (1998) calculate transpiration as a function of root water content using the following two equations:

$$T_t = MIN \left| \begin{array}{l} [(RWC_{t-1} - E_t - Kcb_t \times ET0_t + P_t + I_t + R_t)/(TAW_t - RAW_t)] \times Kcb_t \times ET0_t \\ Kcb_t \times ET0_t \end{array} \right. \quad (2.12)$$

$$RWC_t = MIN \left| \begin{array}{l} RWC_{t-1} - E_t - T_t + P_t + I_t + R_t \\ TAW_t \end{array} \right. \quad (2.13)$$

where

TAW_t difference between water content at field capacity and permanent wilting point in the root zone (mm)

RAW_t readily available soil water in the root zone (mm)

T_t transpiration on day t (mm)

R_t increase in total available water on day t due to root growth (mm)

The first argument of the MIN function in Equation 2.12 calculates crop transpiration as a function of root water content. Important to note is that the calculation of root water content includes maximum crop transpiration ($Kcb_t \times ET_{0_t}$). The soil-limiting stage commences when the estimated root water content falls below a threshold water content ($TAW_t - RAW_t$), resulting in reduced crop transpiration proportional to the water remaining in the layer. Consequently, crop transpiration rates will be less than the maximum transpiration rate. The second argument of the MIN function ensures that crop transpiration does not exceed the maximum transpiration rate when the estimated root water content exceeds the threshold (i.e., the energy-limiting stage).

Equation 2.13 calculates the root water content at the end of the day using the calculated soil evaporation and transpiration. The second argument of the MIN function ensures that the calculated RWC_t cannot exceed TAW_t. Consequently, the calculation assumes instantaneous drainage losses. Both TAW_t and RAW_t are defined for each day, as these values depend on root growth throughout the season.

2.3.4.2 SAPWAT

SAPWAT4 calculates transpiration as a function of root water depletion using the following four equations:

$$T_t = MIN \left| \begin{matrix} [(TAW - RZD_{t-1})/(1 - p_t) \times TAW] \times Kcb_t \times ET0_t \\ Kcb_t \times ET0_t \end{matrix} \right. \quad (2.14)$$

$$RZD_t = RZD_{t-1} - \left(P_t - L_t^{rain}\right) - \left(I_t - L_t^{irri}\right) + E_t + T_t \quad (2.15)$$

$$L_t^{rain} = MAX \left| \begin{matrix} P_t - RZD_{t-1} \\ 0 \end{matrix} \right. \quad (2.16)$$

$$L_t^{irri} = MAX \left| \begin{matrix} I_t - RZD_{t-1} - P_t + L_t^{rain} \\ 0 \end{matrix} \right. \quad (2.17)$$

where

TAW	total available water (mm)
p_t	proportion of total available water that is readily available on day *t* (fraction)
L_t^{rain}	amount of rainfall that is lost through percolation (mm)
L_t^{irri}	amount of irrigation that is lost through percolation (mm)

The calculation in square brackets in Equation 2.14 estimates the transpiration reduction coefficient using the root-zone depletion level from the previous day, without accounting for rainfall or irrigation on that day. We found no evidence in the source code that the level TAW changes with root growth.

Equation 2.15 shows that the RZD_t calculation explicitly accounts for losses from rainfall and irrigation through percolation. Percolation losses from rainfall are calculated first, followed by those from irrigation.

2.3.5 GROSS IRRIGATION REQUIREMENTS

Both FAO 56 and SAPWAT4 derive an irrigation schedule using the following condition:

$$I_t = RZD_{t-1} \quad \text{if} \quad RZD_{t-1} \geq RAW_{t-1} \tag{2.18}$$

Equation 2.18 shows that an irrigation requirement is calculated using the previous day's depletion level and that irrigation is applied the following day.

SAPWAT4 calculates the gross irrigation requirement based on the irrigation system efficiency and the distribution uniformity of irrigation water application. The following equation shows the calculation:

$$GI_t = I_t / SE \times DU \tag{2.19}$$

where

GI_t	gross irrigation application on day t (mm)
SE	irrigation system efficiency (fraction)
DU	distribution uniformity (fraction)

2.4 DISCUSSION

The review of the Agricultural Water Management special issue on "Updating FAO 56 methods" confirms that the fundamental equations for calculating crop water requirements (summarised in Appendix D.18) remain unchanged since Allen et al. (1998). However, the special issue strongly emphasises that the published crop coefficients (Kc and Kcb) are based on a standard climate, i.e., sub-humid, with a minimum relative humidity of 45% and a wind speed of 2 ms^{-1}. When conditions deviate from this standard, coefficients must be adjusted using the FAO 56 climate correction equations. It is important to note that the adjustment to standard climate conditions was not applied to vine and tree crops.

Our comparison of SAPWAT4 with FAO 56 revealed that SAPWAT4 correctly implements the FAO 56 equations for adjusting Kcb values for climate. However, uncertainty exists on the treatment of observed Kcb coefficients as the database may contain a mixture of coefficients derived directly from lysimeter studies under local conditions (i.e., actual coefficients that already incorporate climate effects) alongside standard coefficients intended for use with

FAO 56's adjustment equations. Users risk applying Kcb coefficients that are adjusted twice when using observed coefficients, potentially leading to inaccurate estimates of irrigation requirements.

The review further highlights that most of the methodological advances since FAO 56 focus on improving the estimation of ETo and crop coefficients. These advances include bias correction of gridded weather data, alternative temperature- and satellite-based ETo approaches, integration of remote sensing for estimating Kc/Kcb, and refined experimental protocols for lysimeters and soil water balance studies. Collectively, these improvements yield more accurate and transferable estimates of crop water requirements, thereby enhancing irrigation scheduling and water productivity. At present, SAPWAT does not adjust crop coefficients based on dynamic canopy descriptors, such as Leaf Area Index. Future redevelopment of SAPWAT could incorporate density-based approaches, such as those proposed by Allen and Pereira (2009), to allow dynamic adjustment of Kcb when canopy observations or remote-sensing products are available.

From this WRC-funded project perspective, these insights are particularly relevant. SAPWAT4 is built on FAO 56 but coded in dBASE, a now obsolete programming environment. As the custodianship moves to the University of the Free State, the opportunity arises to reprogram SAPWAT in a modern programming language and to consider integrating selected functionalities from models such as SIMDualKc. Doing so could:

- Enhance SAPWAT's flexibility and accuracy in partitioning ET and simulating diverse management practices.
- Provide a more rigorous platform for calibration and validation against local data.
- Facilitate integration with modern climate databases (e.g., ERA5, see Chapter 3), sensors, and remote sensing technologies.

In addition, international developments show how remote sensing can operationalise FAO 56 methods at scale. The SIMS framework (Satellite Irrigation Management Support), developed in California, integrates satellite-derived canopy cover, FAO 56-based coefficients, and weather-based ETo to provide field-scale, near real-time irrigation scheduling support. While SIMS relies on the dense weather network in California, its principles could be adapted in South Africa by combining Sentinel-2 imagery with ERA5 or regional weather data. Therefore, exploring the adaptation of SIMS-like approaches represents an important avenue for future SAPWAT development, especially if the tool is reprogrammed into a modern coding environment.

FAO 56 remains the foundation, but models such as SIMDualKc and frameworks such as SIMS illustrate how methodological refinements and computational advances can make crop water requirement estimation more robust and versatile. Incorporating such features into a future reprogrammed SAPWAT would position the tool at the forefront of irrigation decision support in South Africa and beyond.

Key takeaways from Chapter 2 linked to the project objectives include:

- Objective 1: Transfer custodianship to UFS
    - A transparent and standardised crop coefficient database is essential for the UFS to assume full technical stewardship of SAPWAT.
    - Clear documentation will ensure future custodians and users trust SAPWAT outputs.
- Objective 2: Capacitate researchers at UFS
    - Researchers must be trained not only in the FAO 56 dual crop coefficient method but also in recent advances in ETo estimation and Kc/Kcb derivation (e.g., lysimeters, remote sensing, and bias correction of gridded data).
    - Re-programming SAPWAT in a modern language, potentially integrating SIMDualKc functionalities, would provide a stronger platform for training and applied research.
- Objective 3: Improve applicability through a new climate database
    - Advances in gridded weather data and reanalysis (e.g., ERA5) directly support the creation of a new climate database for South Africa, as described in Chapter 3.
    - Integrating ERA5 with FAO 56-based methods and future SAPWAT developments will enhance the reliability of irrigation requirement estimates across diverse climatic regions.

CHAPTER 3: CLIMATE DATABASE

3.1 INTRODUCTION

Efficient irrigation management under changing climatic conditions requires access to reliable and spatially comprehensive climate data. SAPWAT is a widely used decision-support tool for estimating crop water requirements, supporting a broad range of stakeholders across multiple spatial scales, from individual farms to Water User Associations and Water Management Areas. Developed with WRC funding, SAPWAT enables irrigation engineers, planners, and agriculturalists to make informed water-use decisions (Van Heerden & Walker, 2016).

A key limitation of SAPWAT lies in its climate database. The current database, which provides daily temperature, humidity, rainfall, wind speed, and solar radiation values for South African quaternary catchments, was statistically derived from station observations (Schulze, 2007). However, it covers only the period 1950–1999 and has not been updated since 2000. This restricts the relevance of SAPWAT under contemporary climatic conditions, especially given the increasing variability and extremes observed in recent decades.

To address this, a methodologically sound alternative is required that can provide long-term, high-resolution, and spatially consistent climate inputs. This study presents the development of a new SAPWAT climate database based on AgERA5, a global reanalysis dataset specifically tailored for agricultural applications (Boogaard et al., 2020). Derived from ERA5, AgERA5 provides daily meteorological data at ~9 km spatial resolution from 1979 to the present, with bias adjustments to improve accuracy for agricultural use. Integrating AgERA5 into SAPWAT enhances the tool to better support irrigation planning across southern Africa under current and future climatic conditions.

3.2 CLIMATE DATA

3.2.1 SAPWAT REQUIREMENTS

The performance of SAPWAT depends on access to accurate climate data that represent the variables governing evapotranspiration and rainfall. For daily ETo calculations, SAPWAT applies the FAO 56 Penman–Monteith method (Allen et al., 1998), which requires:

- Maximum and minimum air temperature (Tmax, Tmin);

- Relative humidity (RHmax, RHmin) or mean vapour pressure (VPmean);
- Solar radiation (SR) or sunshine duration, and
- Wind speed (WS).

These measurements should be taken at a height of 2 m over a uniform surface of actively growing, well-watered grass that fully shades the soil surface, ensuring consistency with the assumptions of the reference crop model. In addition, SAPWAT requires daily precipitation totals (Pr) to determine effective rainfall and crop water requirements.

To ensure a standardised and user-friendly data management approach, SAPWAT requires input in text or CSV format. Each row corresponds to a specific date, with climatic variables arranged in columns following a fixed sequence (Table 3.1). This prescribed structure enhances the efficiency of the system in processing and analysing long-term climate data for irrigation planning.

Table 3.1: Required format of SAPWAT climate data

Longitude	Latitude	Elevation	Date	T_{max}	T_{min}	RH_{max}	RH_{min}	Wind Speed	Solar Radiation	Precipitation	ETo
decimal degrees	decimal degrees	m	dd/mm/yyyy	°C	°C	%	%	km d^{-1}	MJ m^{-2} d^{-1}	mm	mm

3.2.2 REANALYSIS DATA

Reanalysis datasets are a cornerstone of modern climate science, providing spatially and temporally consistent reconstructions of past atmospheric states. They are produced by assimilating a wide range of observations from weather stations, radiosondes, ships, aircraft, satellites, and other remote-sensing systems into numerical weather prediction models. Through iterative assimilation processes, these datasets combine the strengths of observations and model physics to produce coherent, gap-free descriptions of the climate system (Hersbach et al., 2020).

The modern reanalysis era began in 1979 with the advent of globally comprehensive satellite data, which significantly improved the quality of assimilation systems (Bromwich et al., 2007; Dee et al., 2011). Since then, several global reanalysis products have been developed, including NCEP/NCAR (Kalnay et al., 1996), CFSR (Saha et al., 2010), JRA-55 (Kobayashi et al., 2015), MERRA-2 (Gelaro et al., 2017), and ERA5 (Hersbach et al., 2020). ERA5 is widely used among these due to its high temporal resolution, modern assimilation methods, and relatively fine grid (~31 km). Hersbach et al. (2020) describe its design and applications.

No reanalysis product is perfect. Despite their value for climate monitoring, the relatively coarse spatial resolution of these datasets (often >30 km) limits their direct use in agricultural modelling (Muñoz-Sabater et al., 2021). ERA5 generally improves over earlier reanalyses, but retains biases, especially in precipitation over complex terrain (Steinkopf & Engelbrecht, 2022). In South Africa, district-level rainfall errors indicate that local station data remain essential for calibration (Terblanche et al., 2022). Solar radiation fields from reanalysis correlate well with observations, but systematic offsets (overestimation) occur (Mabasa et al., 2021). To overcome some of these limitations, the Joint Research Centre of the European Commission developed AgERA5, a high-resolution dataset derived from ERA5 and tailored to agricultural applications (Boogaard et al., 2020). AgERA5 provides daily values of agroclimatic variables, including Tmax, Tmin, RHmax, RHmin, VP, SR, WS, and Pr at 0.1° (~9 km) spatial resolution, spanning 1979 to the present (CDS, 2024). Its bias-adjusted fields and agricultural relevance make it particularly suitable for irrigation planning, drought analysis, and crop modelling across data-sparse regions such as southern Africa.

3.3 SAPWAT REANALYSIS CLIMATE DATABASE DEVELOPMENT

Covering a wide range of global variables, ERA5 reanalysis data have emerged as an indispensable resource for researchers and modellers worldwide during the last decade (Decker et al., 2012; Hoffmann et al., 2018; Tarek et al., 2020; Baker et al., 2021). A comprehensive overview of the ERA5 reanalysis is provided by Hersbach et al. (2018; 2020), detailing its development, data assimilation techniques and a broad range of applications. ERA5 is continuously updated from 1950 to the present, making it valuable for historical and contemporary climate and agrohydrological studies (Hersbach et al., 2020). Various studies successfully used such reanalysis data to estimate ETo or as input for hydrometeorological models (Liu et al., 2016; Muñoz-Sabater et al., 2021), leveraging its global scope and detailed variables to bridge the gap between atmospheric conditions and land surface processes (Baker et al., 2021).

For this project, AgERA5 reanalysis data, derived from ERA5, were used for the near-surface climatic variables required by SAPWAT. AgERA5 (Boogaard et al., 2020) offers several advantages that make it particularly useful for agricultural applications:

- Comprehensive agrometeorological variables: These include essential variables for agriculture, such as near-surface temperature, relative humidity, wind speed, solar radiation, and precipitation.
- High spatial and temporal resolution: Whereas the original ERA5 data described in Deliverable 5 has a spatial resolution of 0.25° arc degrees, the recently developed AgERA5 provides daily meteorological data at a resolution of 0.1° × 0.1° (about 9 km), which is crucial for capturing localised weather conditions that directly impact agricultural productivity.
- Long-term consistency and global coverage: Since it is derived from the ERA5 reanalysis, the dataset offers consistent, high-quality data spanning 1979 to the present. This long-term data is invaluable for studying climate trends, assessing the impact of climate change on agriculture, and developing adaptation and resilience strategies for agricultural systems. The global coverage makes it a valuable tool for agricultural research, facilitating comparative studies across diverse geographic regions.
- Tailored for agricultural applications: AgERA5 is tuned to local day definitions, while a location-, variable-, and season-specific bias correction was applied, adapting it to finer topography, land-use patterns, and land-sea delineation. The dataset is processed to be directly applicable for crop modelling, drought monitoring, and other agrometeorological applications, reducing the need for users to process additional data.

3.3.1 DATA ACCESS AND EXTRACTION

AgERA5 data were downloaded from CDS (2024) for the domain 20–35°S and 15–35°E to cover southern Africa (Figure 3.1) and will be updated annually. A dedicated Python script, "AgERA5_download_All.py", was developed to request and directly download monthly compressed files for each climatic variable listed in Table 3.2 from January 1979 onwards. The compressed files were downloaded to their respective directories on the UFS Cluster. Since daily RHmax and RHmin were unavailable in AgERA5, the 3-hourly values (06:00, 09:00, 12:00, 15:00 and 18:00 local time) were downloaded. The download files were subsequently uncompressed to extract the daily NetCDF-4 (.nc) files. These daily files ranged from 40 to 100 KB in size (depending on the climate variable) and comprised data at 150 × 200 (i.e., 30 000) grid points, of which 22 795 were land-based. A dedicated script was used to verify the integrity of the NetCDF files and to detect and correct issues such as mislabelled metadata or corrupted records that may have occurred during file transfer.

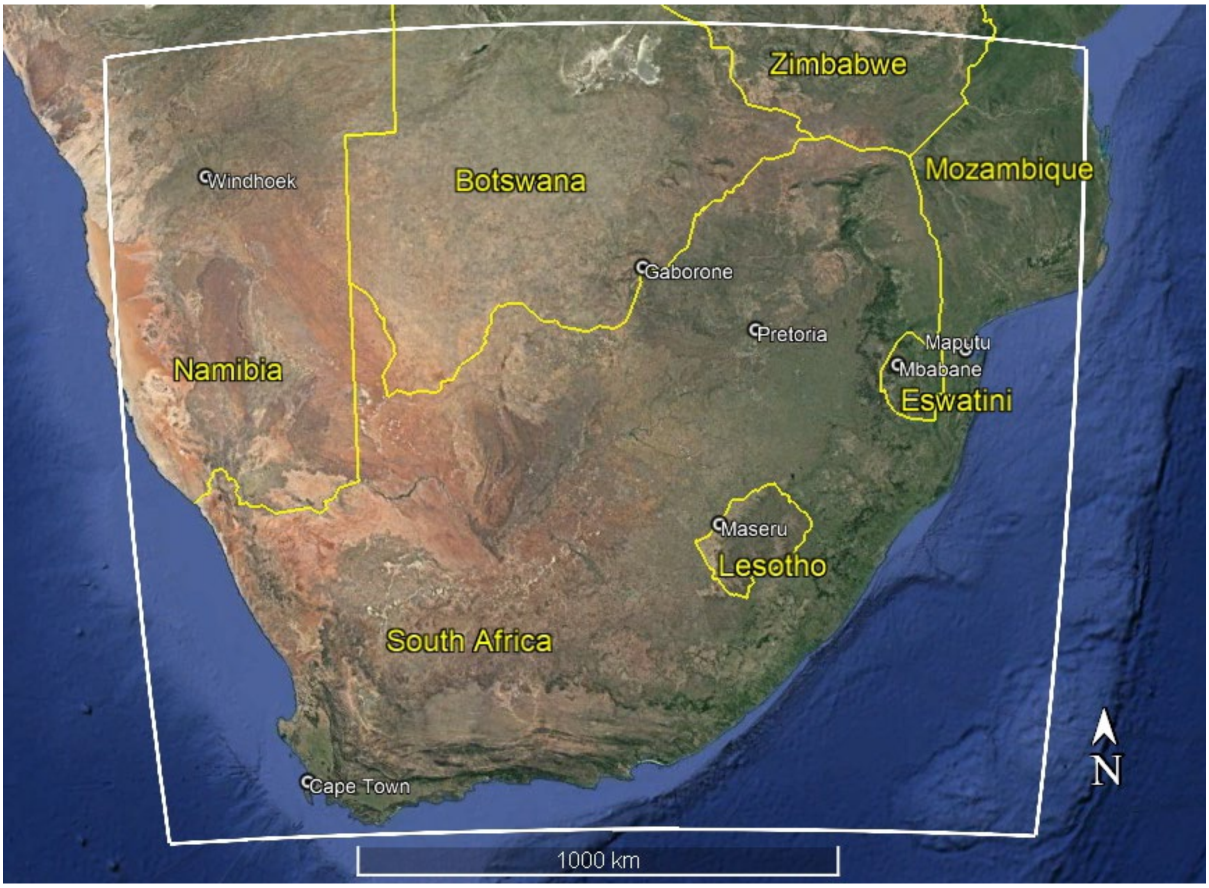

Figure 3.1: Geographical area included in the SAPWAT Climate Database.

Table 3.2: Climate variables available in AgERA5 for direct download from CDS (D) or to be obtained from subsequent calculations (C)

Source	Variable	Level	Units	Time	Interval	Abbreviation
D	Maximum temperature	2 m	K	00:00 – 24:00 LST	Daily	Tmax
	Minimum temperature	2 m	K	00:00 – 24:00 LST	Daily	Tmin
	Mean vapour pressure	2 m	hPa	00:00 – 24:00 LST	Daily	VP
	Total solar radiation	Surface	J m^{-2}	00:00 – 24:00 LST	Daily	SR
	Mean wind speed	10 m	ms^{-1}	00:00 – 24:00 LST	Daily	WS
	Total precipitation	Surface	Mm	00:00 – 24:00 LST	Daily	Pr
	Relative humidity	2 m	%	06:00, 09:00, 12:00, 15:00, 18:00 LST	Daily	RH
C	Mean wind speed	2 m	ms^{-1}	00:00 – 24:00 LST	Daily	U2
	Maximum relative humidity	2 m	%	00:00 – 24:00 LST	Daily	RHmax
	Minimum relative humidity	2 m	%	00:00 – 24:00 LST	Daily	RHmin
	Reference evapotranspiration	Surface	Mm	00:00 – 24:00 LST	Daily	ETo

3.3.2 DERIVED CLIMATE VARIABLES

Unfortunately, there is no option on the CDS site to retrieve the elevations of the AgERA5 grid points. However, these elevations are required as input to SAPWAT (Table 3.1) and to calculate the daily ETo at each grid point. The NASA Shuttle Radar Topographic Mission (SRTM) has provided digital elevation data for over 80% of the globe. The SRTM digital elevation model (DEM) is available at a horizontal resolution of 3 arc seconds (approximately

90 m) and a vertical error reported to be less than 16 m. Jarvis et al. (2008) further processed the original DEM to fill any no-data voids, producing SRTM V4. The DEM was downloaded for 22 5° × 5° tiles from the Consultative Group on International Agricultural Research – Consortium for Spatial Information GeoPortal. A Python script called "MergeSTRM.py" was developed to merge the tiles into a single DEM. A Python script called "writeAgERA5_GridPoints.py" was developed and used to read the coordinates from one of the downloaded NetCDF files and write them out to a CSV file, while another script named "AgERA5_GridPoint_DEMelevations.py" was used to map and assign elevations to the listed AgERA5 grid points. Figure 3.2 is not the 90 m DEM, but rather the reinterpreted elevations of the AgERA5 grid at a resolution of 0.1° × 0.1° (about 9 km).

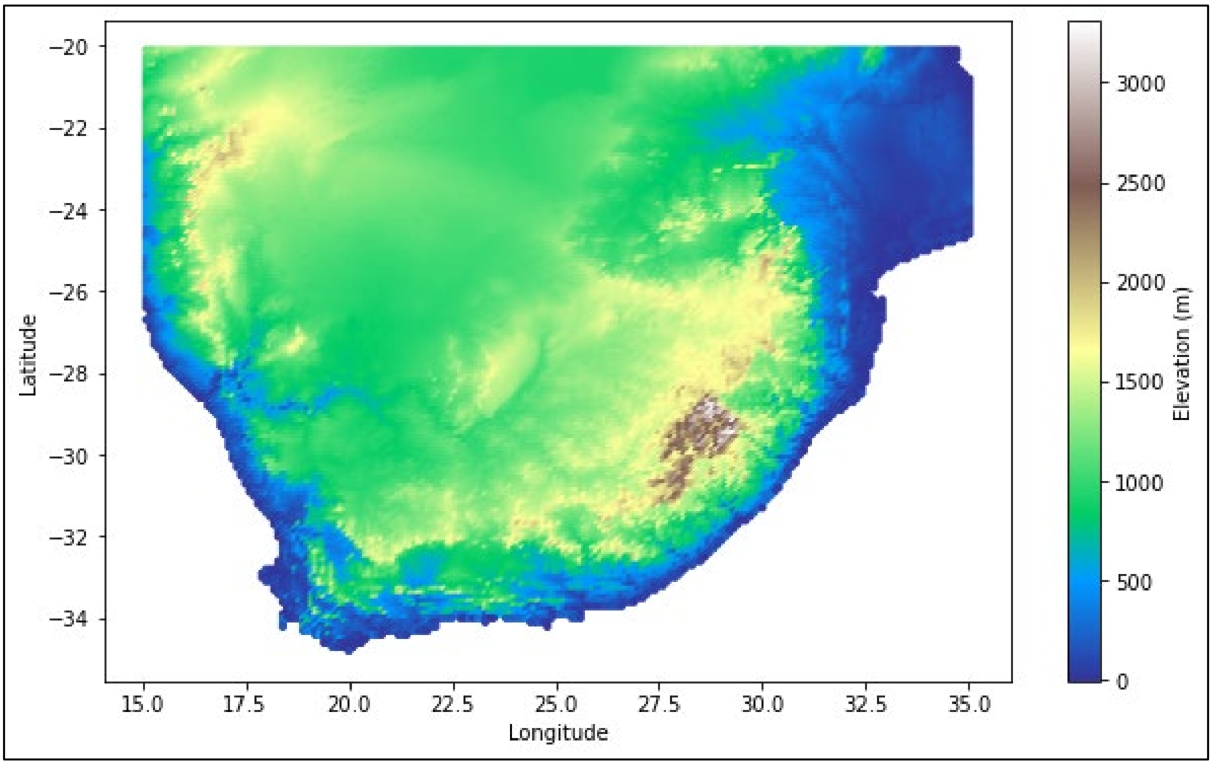

Figure 3.2: Plot of DEM-derived elevations on AgERA5 grid resolution.

A major step in developing the climate database involved calculating the derived climate variables (listed in the bottom half of Table 3.2) required by SAPWAT (Table 3.1). A Python script called "CalculateDailyETo_cluster.py" was developed and used to:

a) Read the gridded NetCDF files for RH at 06:00, 09:00, 12:00, 15:00 and 18:00 LST, determine the daily RHmax and RHmin and write these out as gridded NetCDF files.
b) Read the gridded NetCDF files for Tmax and Tmin, calculate the mean temperature (Tmean) and convert these from K to °C.
c) Read the gridded NetCDF files for SR and convert these from $Jm^{-2}d^{-1}$ to $MJm^{-2}d^{-1}$.

d) Read the gridded NetCDF files for WS at 10 m and reduce these logarithmically to 2 m.
e) Read the gridded NetCDF files for VP and Pr.
f) Use the FAO 56 Penman-Monteith method to calculate daily ETo and write the results to gridded NetCDF files.

It should be noted that even though daily RHmax and RHmin were calculated, these were not used in estimating ETo. Instead, VP was used as it was downloaded directly and deemed more accurate.

3.3.3 SET UP ON A HIGH-PERFORMANCE CLUSTER

The processing of AgERA5 data at the regional scale was conducted using a high-performance computing environment at the UFS. Batch processing with parallel computation enabled the extraction and processing of long-term daily climate time series across all land-based grid points. A Python script (multiprocess_GridPoints_cluster_updater.py) was used for this, with the final outputs stored as structured .csv files and compiled into a comprehensive Climate Database. Another script, "Interface4ClimDataBase.py", was developed as a more user-friendly interface for exploring and selecting points of interest via an interactive map or manually entering coordinates. This script will then identify the nearest AgERA5 grid point for extraction and provide a quick summary of the climate variables at this location.

3.4 SAPWAT REANALYSIS CLIMATE DATABASE VALIDATION

3.4.1 STATION-SCALE (POINT) VALIDATION

A comprehensive comparison was conducted using meteorological variables that influence hydroclimatic variability. This process involved several key stages: data quality control, spatial pairing of datasets, temporal aggregation, and statistical comparisons of modelled versus observed values.

3.4.1.1 Data and methods

Station data was requested from 1979 onwards from the South African Weather Service and the Agricultural Research Council (ARC). Eventually, eight ARC stations were selected based on completeness, accessibility, agricultural relevance, and geographical spread across different homogeneous rainfall regions of South Africa (Landman et al., 2005). The selected stations were (in order from north to south): Polokwane (1985–2024), Mbombela (1985–2024), Potchefstroom (1979–2024), Glen College Bloemfontein (1984–2024), Richards Bay (2003–

2024), East London (1985–2024), Gqeberha (1984–2024), and Oudtshoorn (1979–2023). The FAO Penman-Monteith method was used to calculate daily ETo.

Station datasets frequently exhibit inconsistencies such as outliers, duplicate records, and prolonged periods of missing or suspiciously constant values. In addition to correcting logical inconsistencies (e.g., when Tmax is less than Tmin) and standardising the handling of missing values, a Python script was developed to conduct tolerance checks and flag records outside physically realistic bounds. These included Tmax > 50.9°C, RH < 0%, RH > 100%, ETo > 15 mm d^{-1}. However, values that remained constant over several consecutive days, potentially indicating sensor malfunctions, were not removed. No attempt was made to fill gaps in the station records.

AgERA5 data were extracted from the grid point nearest to each station. The selected variables included Tmax and Tmin, RHmax and RHmin, SR, WS, Pr, and ETo. These variables correspond to those used at the ARC stations and serve as key inputs for ETo and drought monitoring applications.

Daily values from the station and AgERA5 reanalysis data were aggregated into monthly time series to allow for seasonal comparisons. A completeness threshold of 60% was applied, and months that did not meet this criterion were omitted from the analysis. This approach ensured that only periods with sufficient valid observations for both station and reanalysis data were retained, maintaining the reliability of long-term summaries while maximising the volume of usable data.

Statistical comparisons were conducted to quantify the agreement between observed and modelled values. Standard goodness-of-fit metrics were applied, including the Pearson correlation coefficient (r), the coefficient of determination (R^2), the mean absolute error (MAE), and the root mean square error (RMSE). These metrics were used to assess both the strength of linear association and the magnitude of discrepancies across temporal scales. Scatterplots were generated for visual inspection at daily, monthly, and annual timescales, while cumulative distribution functions of annual aggregates were used to assess differences in distributional properties.

3.4.1.2 Results

Maximum temperature (Tmax) comparisons between reanalysis and stations were consistent across sites, with strong agreement at daily (R^2 ranging from 0.72 at Mbombela to 0.93 at

Oudtshoorn) and monthly scales (R^2 up to 0.97 at Oudtshoorn) (Figures 3.3 and 3.4). Inland stations such as Bloemfontein, Polokwane, Mbombela, and Potchefstroom showed systematic underestimation, with average biases ranging from about −1.0°C to −1.6°C. In contrast, East London and Richards Bay coastal stations displayed minimal bias (+0.14°C and −0.26°C, respectively). Across stations, RMSE values were generally below 2°C, indicating that Tmax was represented consistently across diverse environments at higher temporal resolution.

Reanalysis and station minimum temperature (Tmin) compared well at daily and monthly scales, as shown by the scatterplots in Figures 3.5 and 3.6. Agreement was strongest at Bloemfontein and Potchefstroom, where daily R^2 reached 0.93, and monthly R^2 reached 0.98, respectively. Agreement was weakest at Richards Bay (daily R^2 = 0.77; monthly R^2 = 0.84), probably due to the smaller population (n = 6589 days) compared to other stations (e.g. n = 16 249 at Potchefstroom). Bias patterns were consistent across most stations, with Tmin generally higher in the reanalysis than in observations. The largest warm bias occurred at Polokwane (+1.88°C, daily and monthly), with smaller biases at Bloemfontein (+1.58°C), Potchefstroom (+0.74°C), East London (+0.55°C), and Richards Bay (+1.37°C). Mbombela was the exception, where Tmin was cooler in the reanalysis by about −0.86°C. It should be noted that colder Tmin values were generally overestimated in the reanalysis data at all locations.

Wind speed (WS) showed mixed correspondence across stations. Daily R^2 ranged from 0.16 at Mbombela to about 0.64 at Bloemfontein (Figure 3.7). Monthly aggregation did not increase the coefficient of variation. Monthly R^2 was low at Mbombela (0.10), Gqeberha (0.04), East London (0.11) and Oudtshoorn (0.34). Values were moderate at Richards Bay (0.53) and Potchefstroom (0.40), and higher at Bloemfontein (0.64) and Polokwane (0.76) (Figure 3.8). Bias direction was mostly positive. Polokwane had the largest mean difference, about +1.20 ms^{-1} on both scales (roughly 85% of the station mean). Positive differences also appeared at Mbombela (+0.33 ms^{-1}), Potchefstroom (+0.41 ms^{-1}), Richards Bay (+0.40 ms^{-1}), and Bloemfontein (+0.11 ms^{-1}). East London was an exception, with a small negative difference of −0.20 ms^{-1}. The general impression was that reanalysis data yielded mean wind speeds, failing to capture calm and strong events. Local dynamics, including sea breeze and terrain effects, likely influenced skill, especially at coastal or complex-terrain locations.

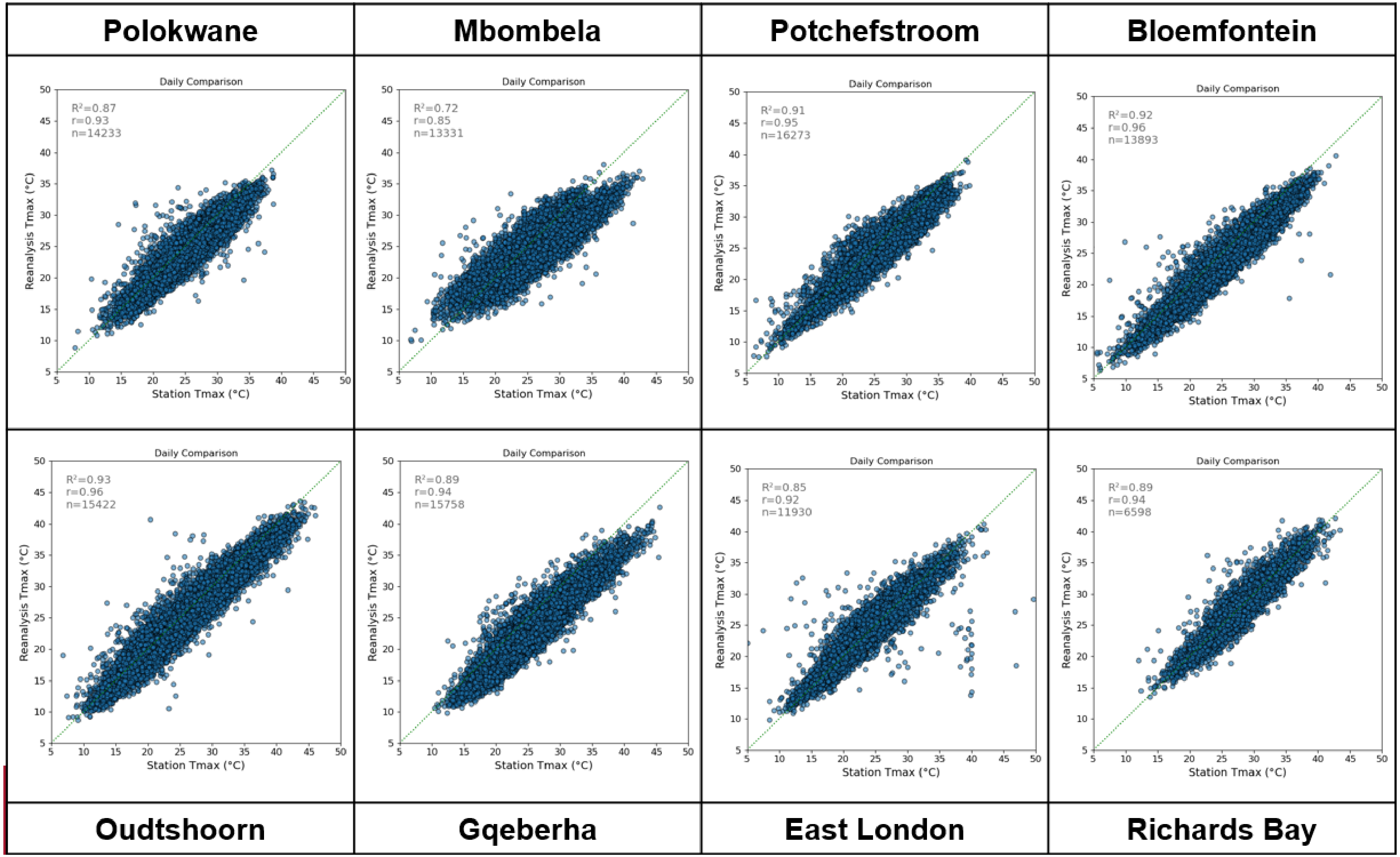

Figure 3.3: Scatterplots of daily comparisons between station and reanalysis maximum temperature.

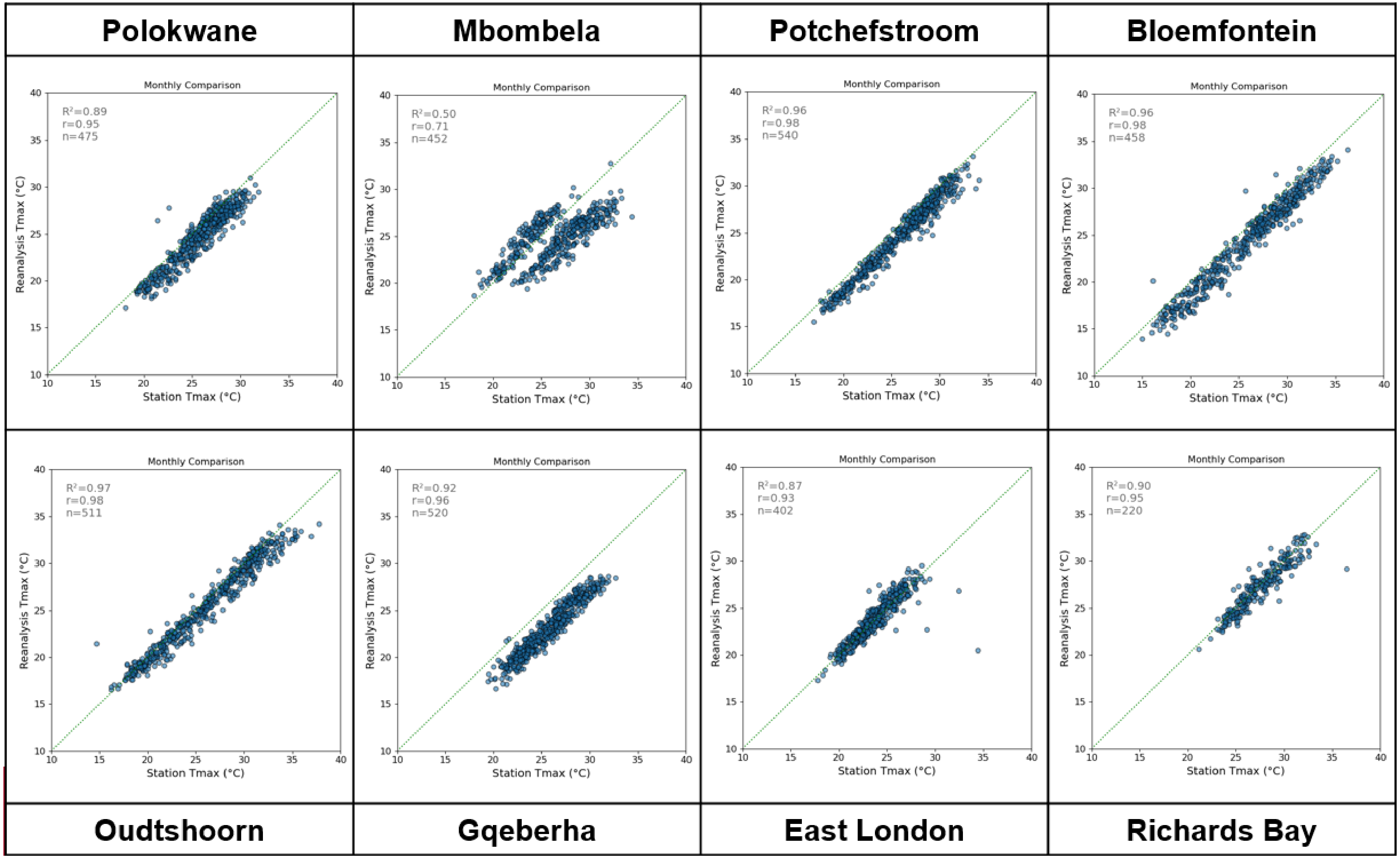

Figure 3.4: Scatterplots of monthly comparisons between station and reanalysis maximum temperature.

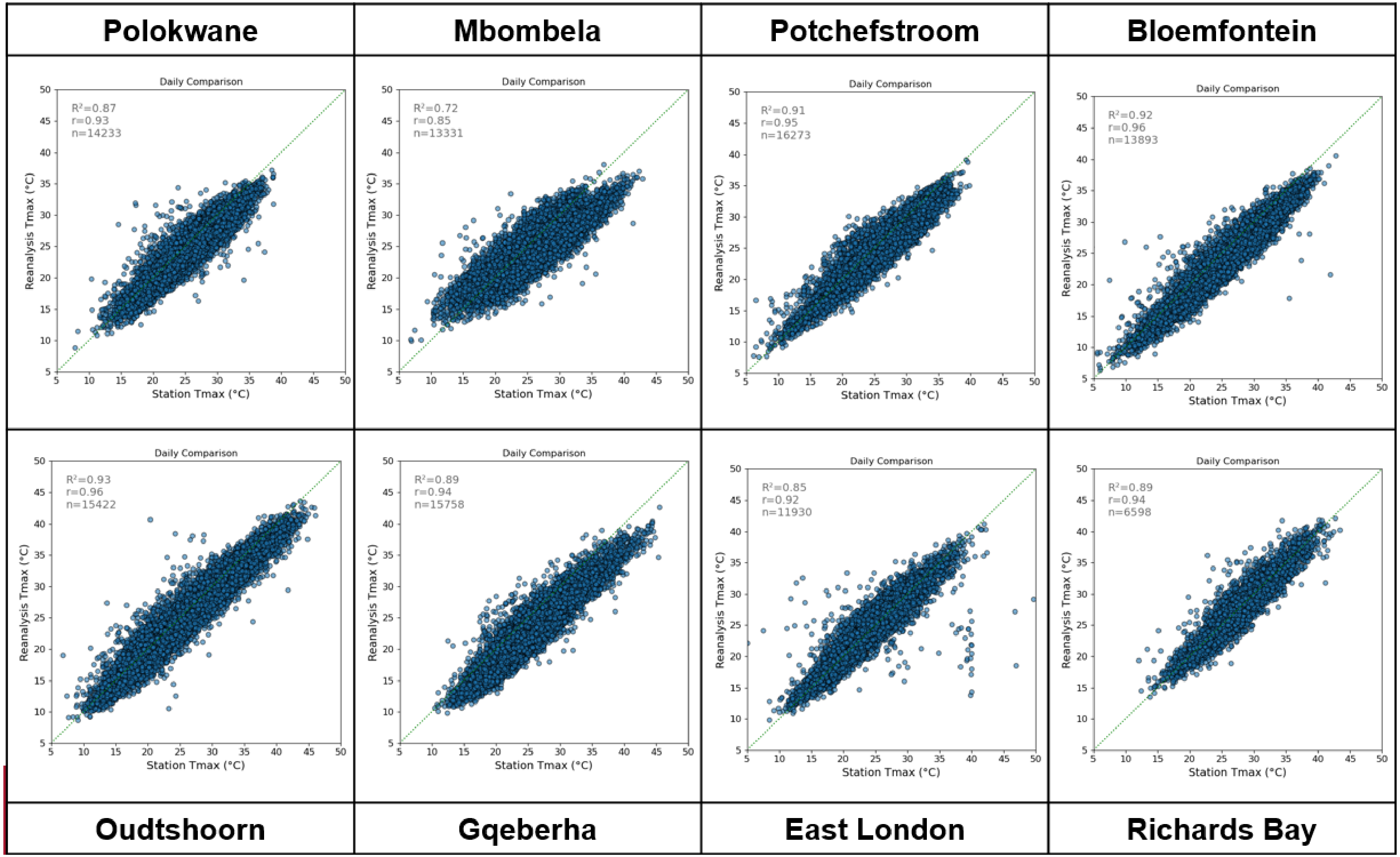

Figure 3.5: Scatterplots of daily comparisons between station and reanalysis minimum temperature.

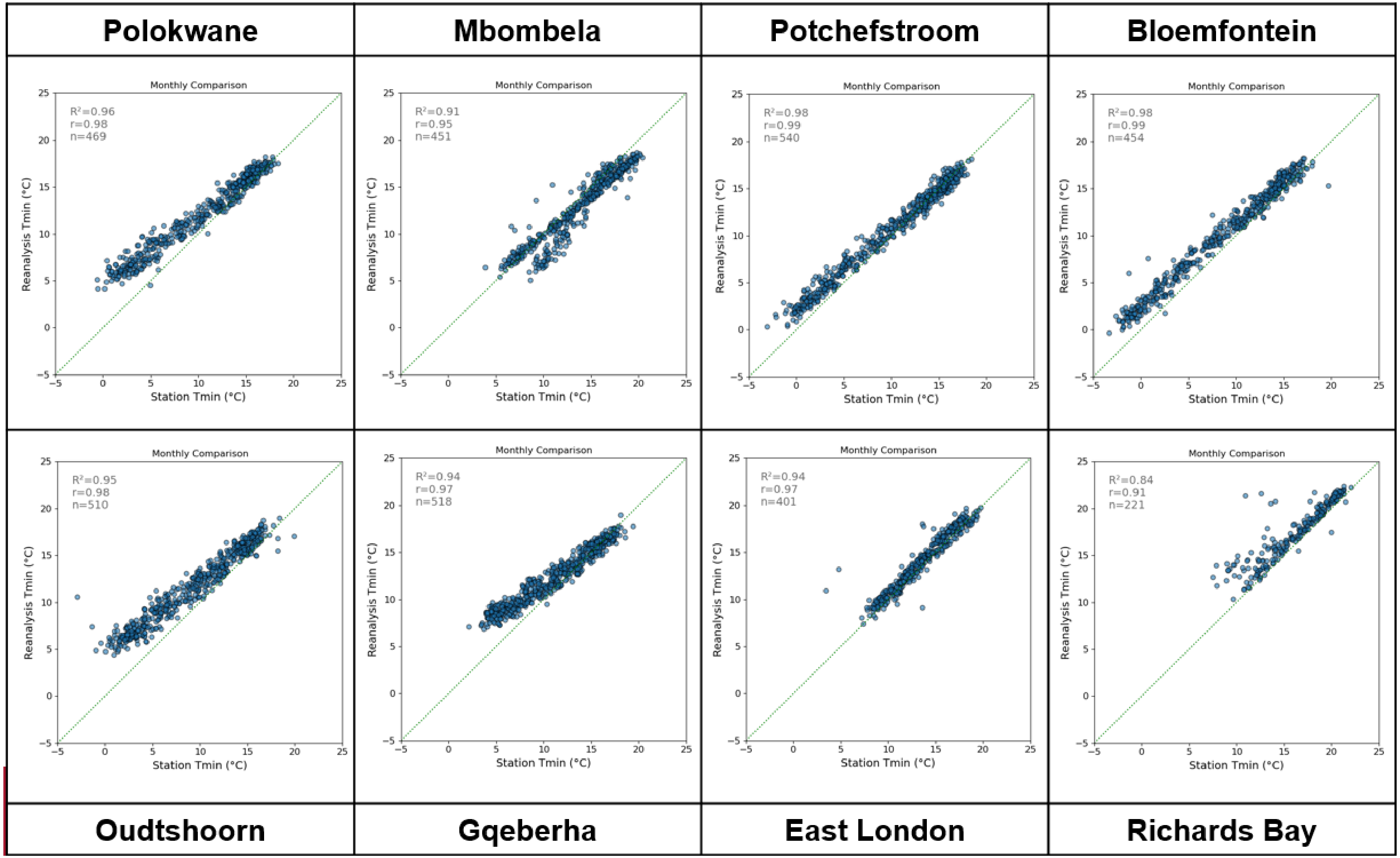

Figure 3.6: Scatterplots of monthly comparisons between station and reanalysis minimum temperature.

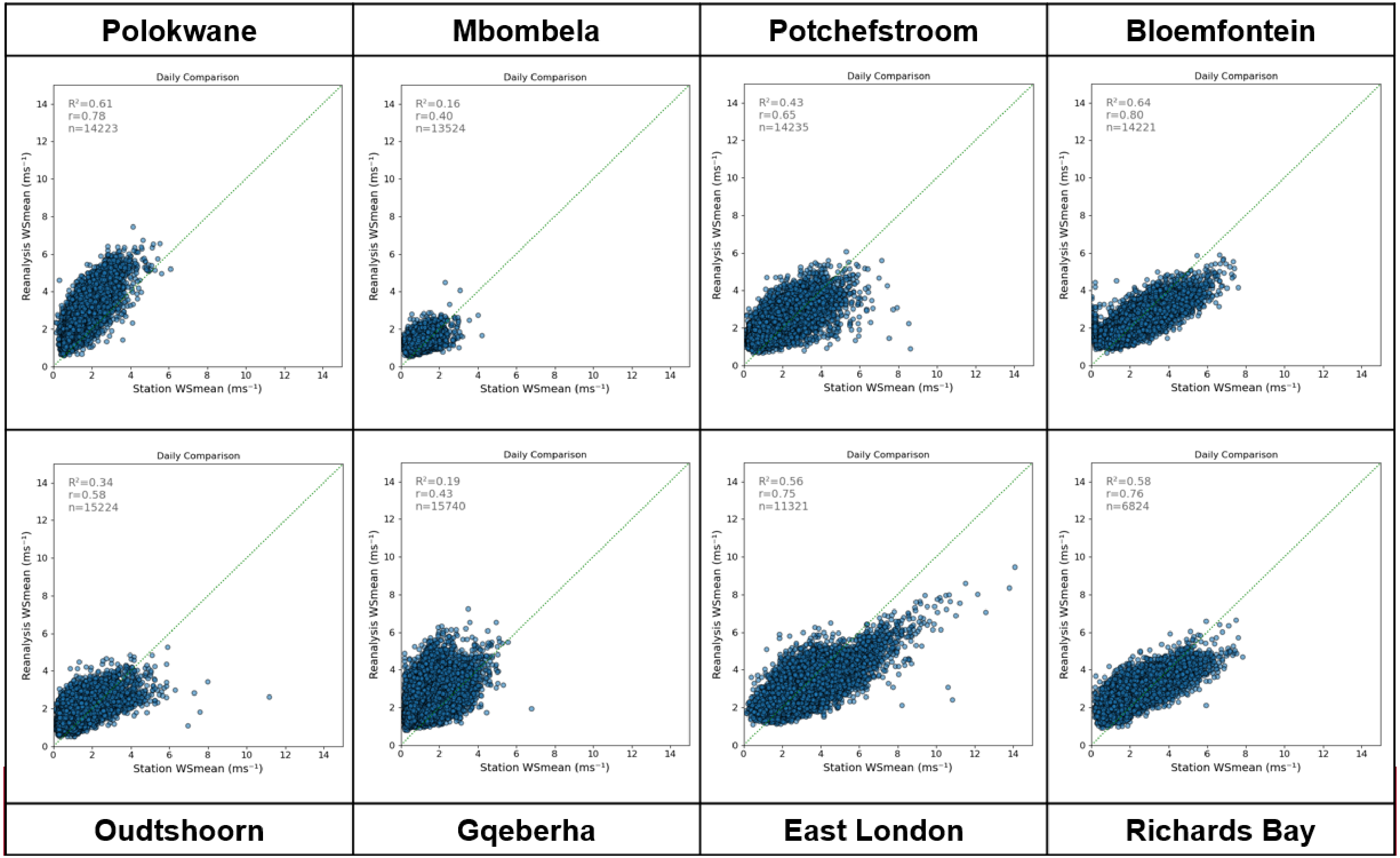

Figure 3.7: Scatterplots of daily comparisons between station and reanalysis wind speed.

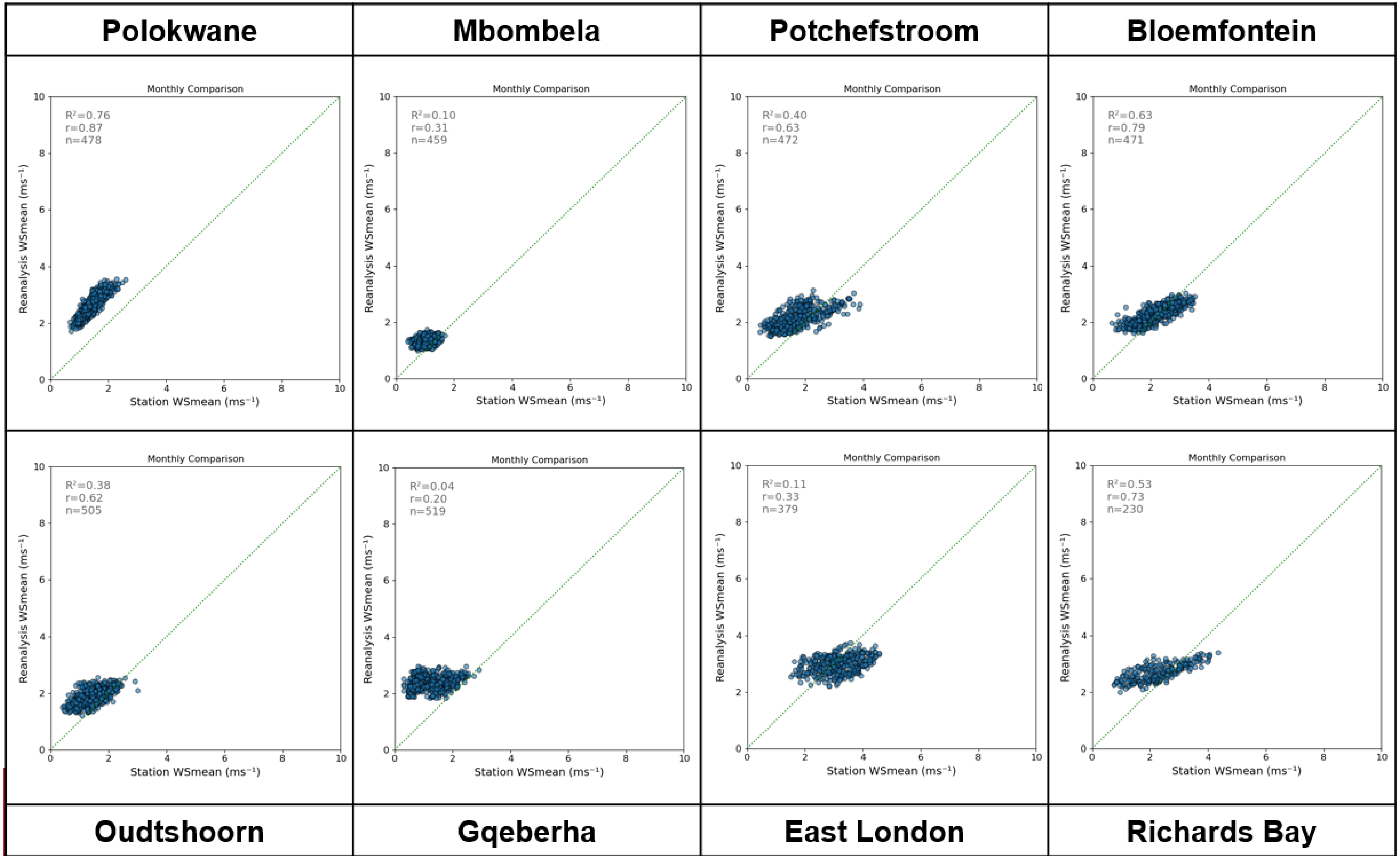

Figure 3.8: Scatterplots of monthly comparisons between station and reanalysis wind speed.

Solar radiation (SR) showed broadly consistent station–reanalysis agreement, with stronger relationships at the monthly scale than at the daily scale (scatterplots in Figures 3.9 and 3.10). Daily R^2 sat near two-thirds at most inland sites and peaked at Richards Bay and Oudtshoorn (R^2 = 0.77). Monthly correspondence improved further. R^2 values ranged from 0.693 at Mbombela to 0.881 at Polokwane. Bias patterns were consistent. Reanalysis exceeded station totals on average at both scales. Typical daily bias lies near 1 MJ m^{-2} (e.g., 1.046 at Richards Bay and 1.366 at Bloemfontein). In contrast, monthly bias commonly ranged from about 25 to 50 MJ m^{-2} (e.g., 25.424 at East London and 49.787 at Polokwane). Absolute bias percentages were modest on the monthly scale across stations, generally ranging from 4 to 9 per cent. East London sat at 4.09 per cent, while Polokwane reached 8.87 per cent. Errors remained moderate. Daily RMSE typically ranged from roughly 3 to 4.5 MJ m^{-2}, and monthly RMSE from about 38 to 77 MJ m^{-2}, with examples at East London (3.078 daily; 38.281 monthly) and Potchefstroom (3.777 daily; 77.402 monthly). Overall, the reanalysis and station SR agreed well on monthly aggregates. At the same time, a small but systematic positive bias suggested the need for a simple bias adjustment before applications sensitive to radiation magnitude.

Precipitation (Pr) posed the greatest challenge. Daily agreement was weak, with R^2 ranging from 0.13 at Polokwane to 0.39 at Oudtshoorn (Figure 3.11). Absolute bias at this scale varied widely; Potchefstroom recorded 6.32%, whereas Bloemfontein reached 15.39%. Aggregation to months improved correspondence (Figure 3.12), with the lowest R^2 of 0.48 at Polokwane and the highest (0.73) at Mbombela and Bloemfontein. For example, at Potchefstroom R^2 increased from 0.18 (daily) to 0.64 (monthly). Bias sign and magnitude at the monthly scale differed by setting; East London showed +11.443 mm $month^{-1}$ with an ABIAS of 21.60%, compared with Potchefstroom, which showed +3.422 mm $month^{-1}$ and an ABIAS of 6.43%. These tendencies reflected unresolved convective structure and event intermittency, which reduced agreement at the single-gauge level. Monthly aggregation smoothed these spatial and timing errors, so correspondence improved.

Across sites, ETo from reanalysis and stations compared well. The daily scatterplots in Figure 3.13 showed close agreement at low to moderate values, with larger scatter at the upper end. Monthly aggregation in Figure 3.14 tightened the relationship and reduced errors. A slight positive bias was observed at several stations, indicating slightly higher ETo from the reanalysis on average. At very high daily and monthly ETo, some inland stations showed underestimation. This pattern is consistent with known issues in the reanalysis inputs for solar radiation, wind, and humidity. Overall, agreement improved with temporal aggregation, and the joint use of both datasets supported a coherent picture of ETo behaviour across stations.

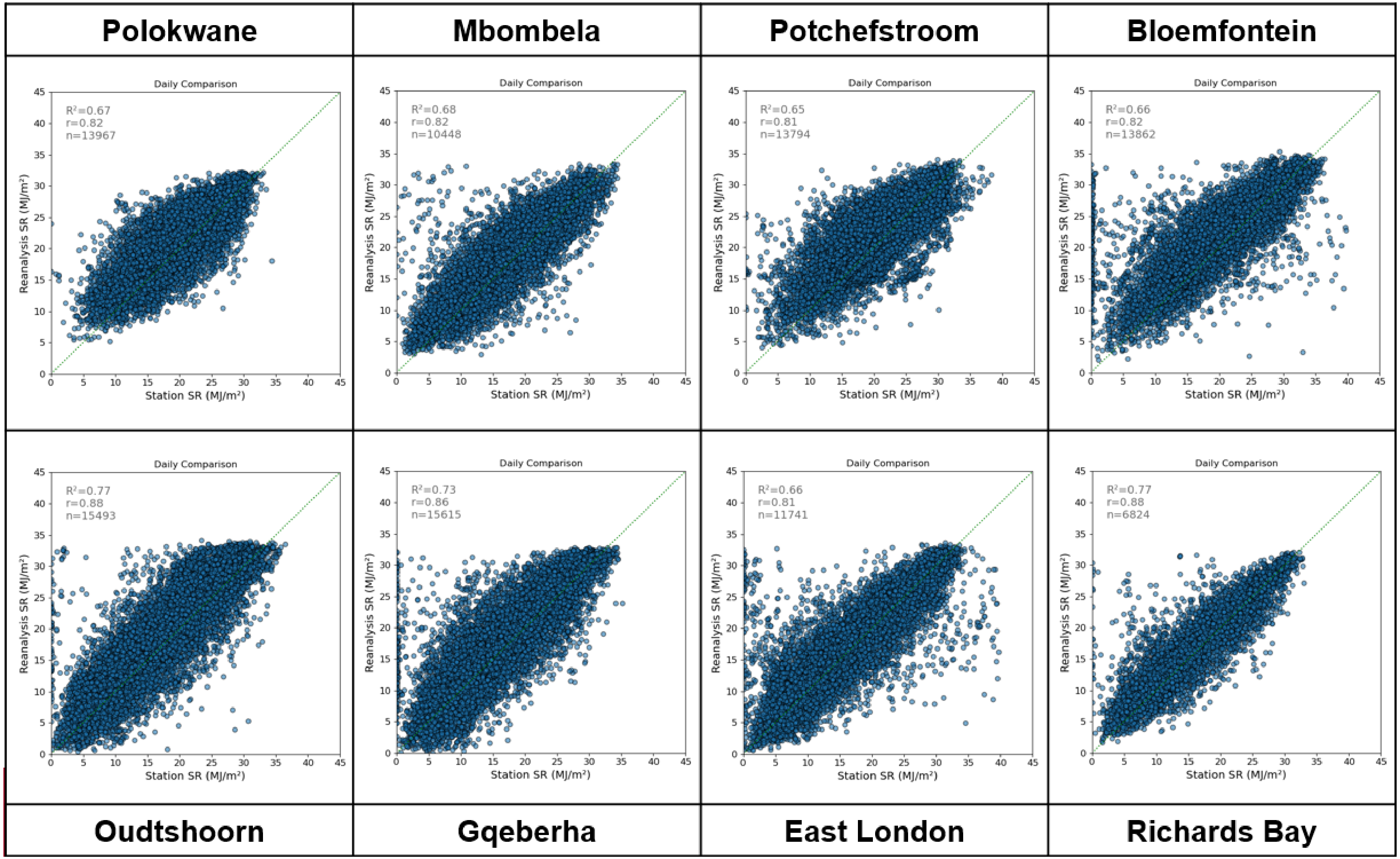

Figure 3.9: Scatterplots of daily comparisons between station and reanalysis solar radiation.

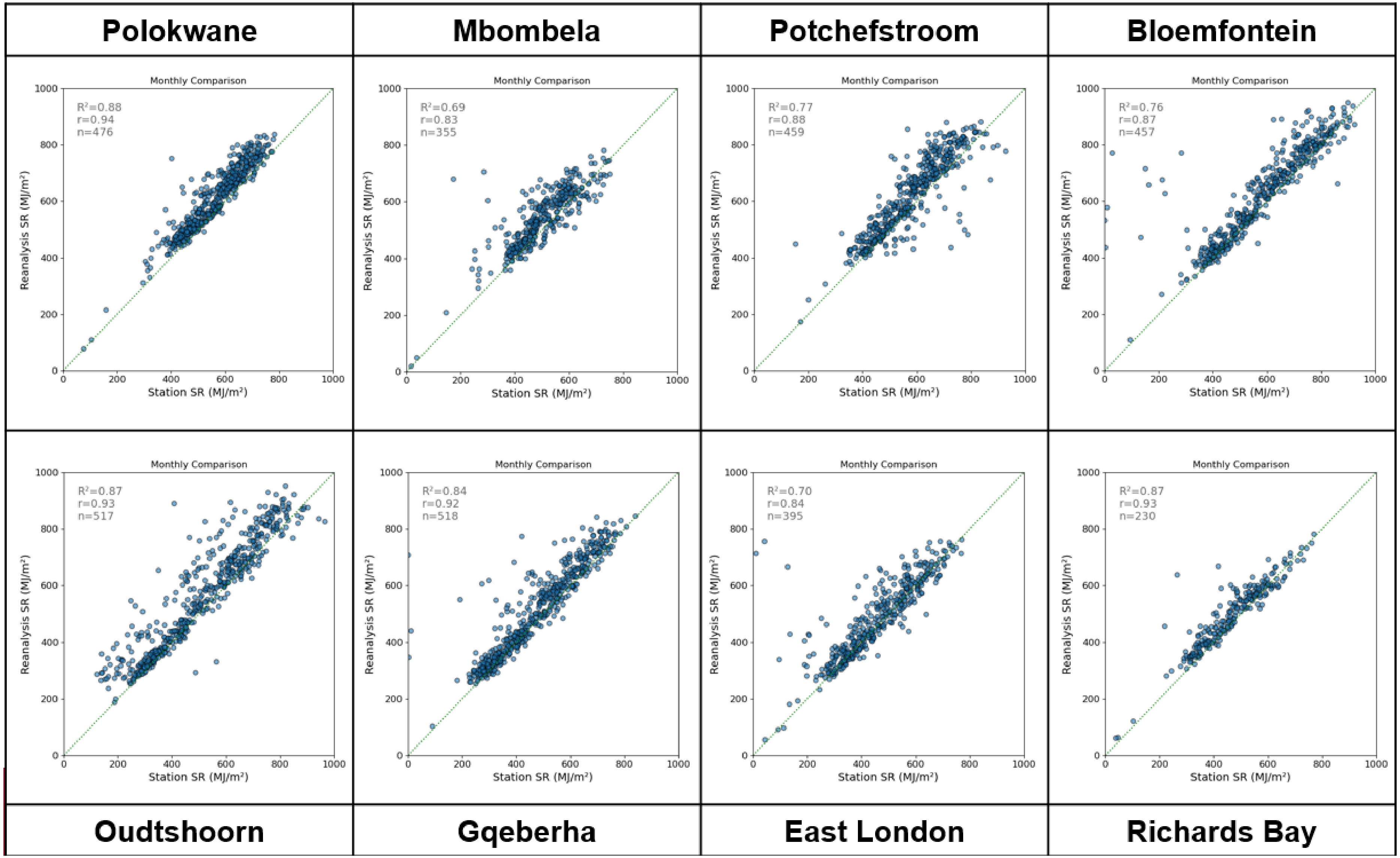

Figure 3.10: Scatterplots of monthly comparisons between station and reanalysis solar radiation.

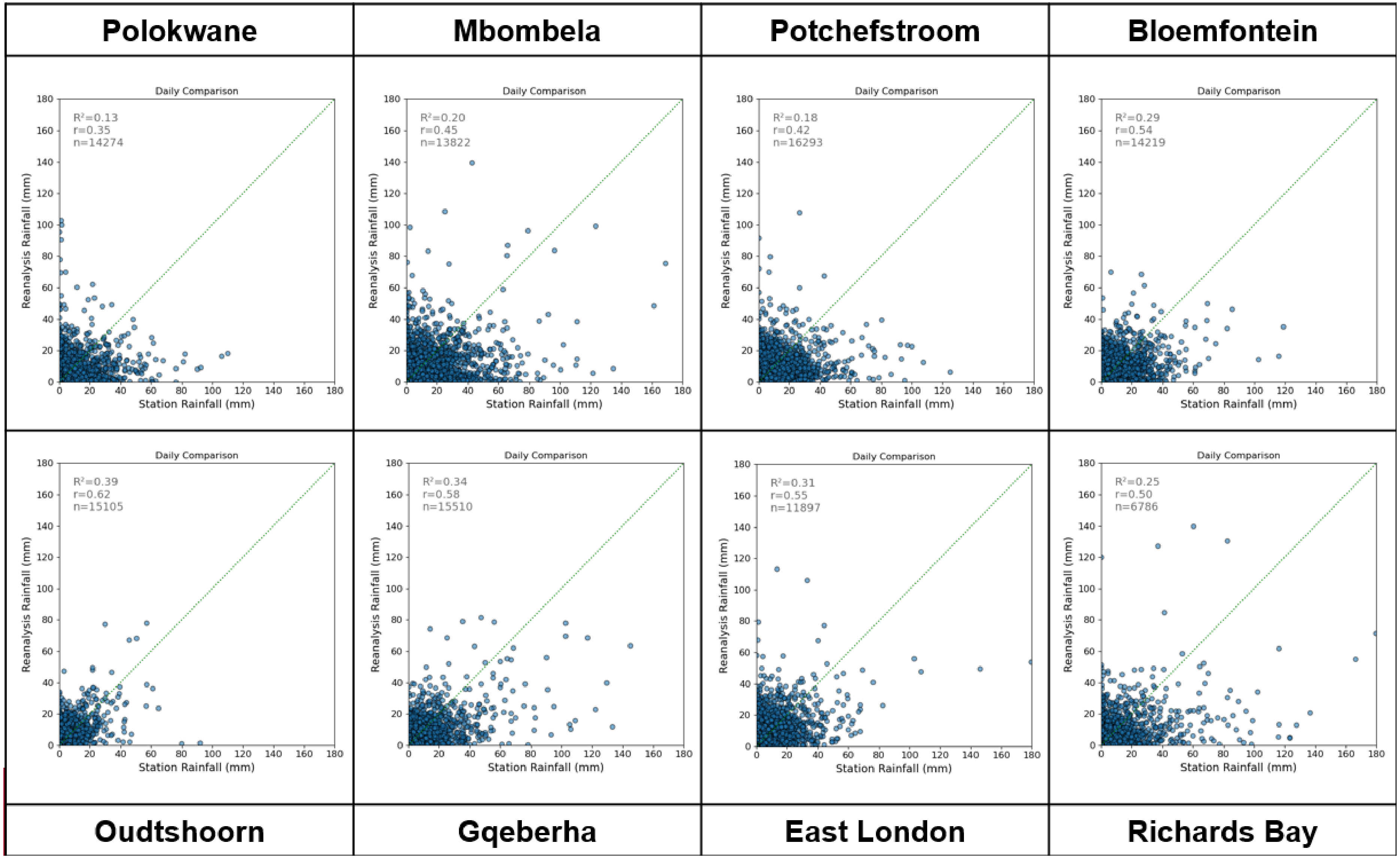

Figure 3.11:Scatterplots of daily comparisons between station and reanalysis precipitation.

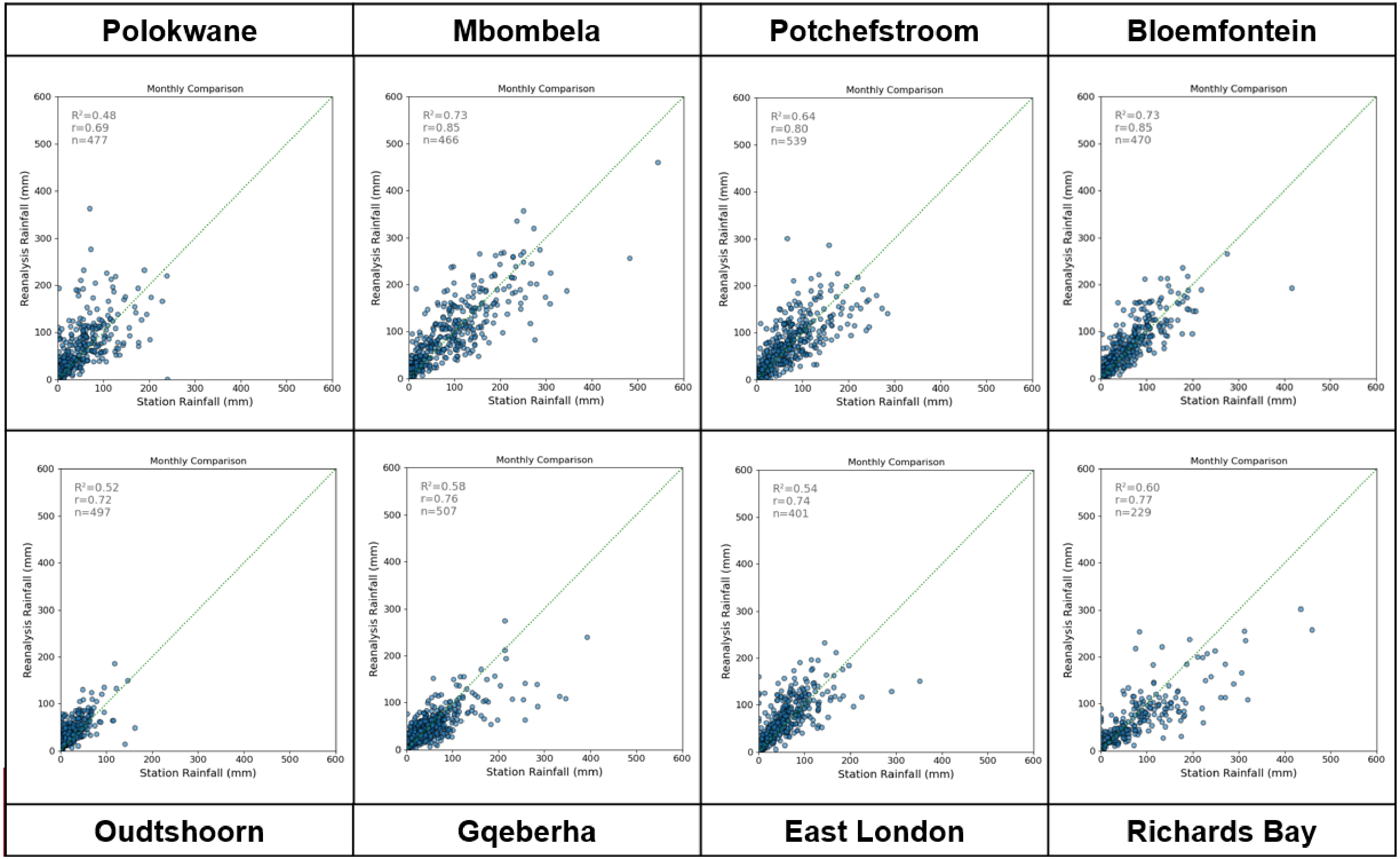

Figure 3.12: Scatterplots of monthly comparisons between station and reanalysis precipitation.

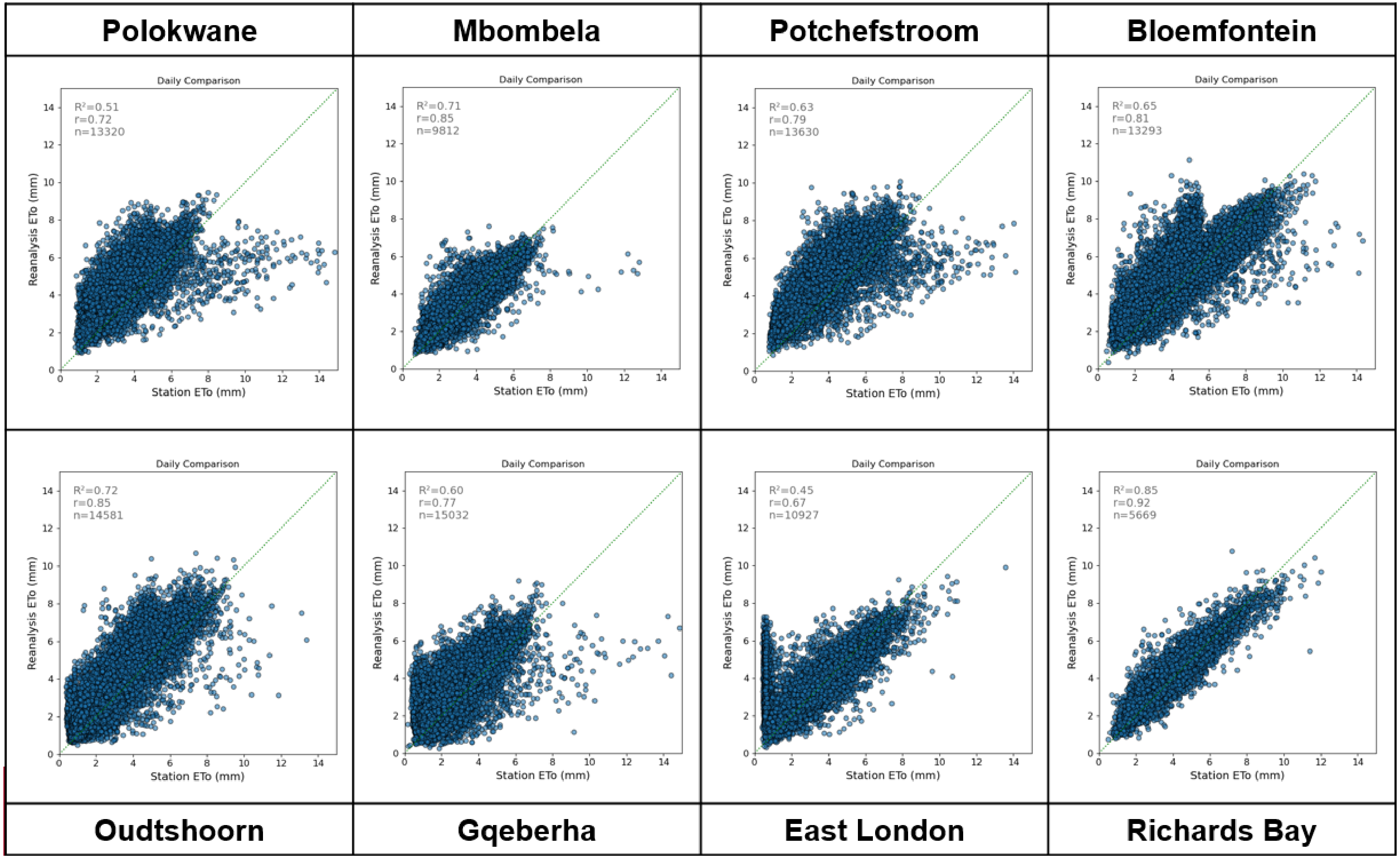

Figure 3.13: Scatterplots of daily comparisons between station and reanalysis reference evapotranspiration.

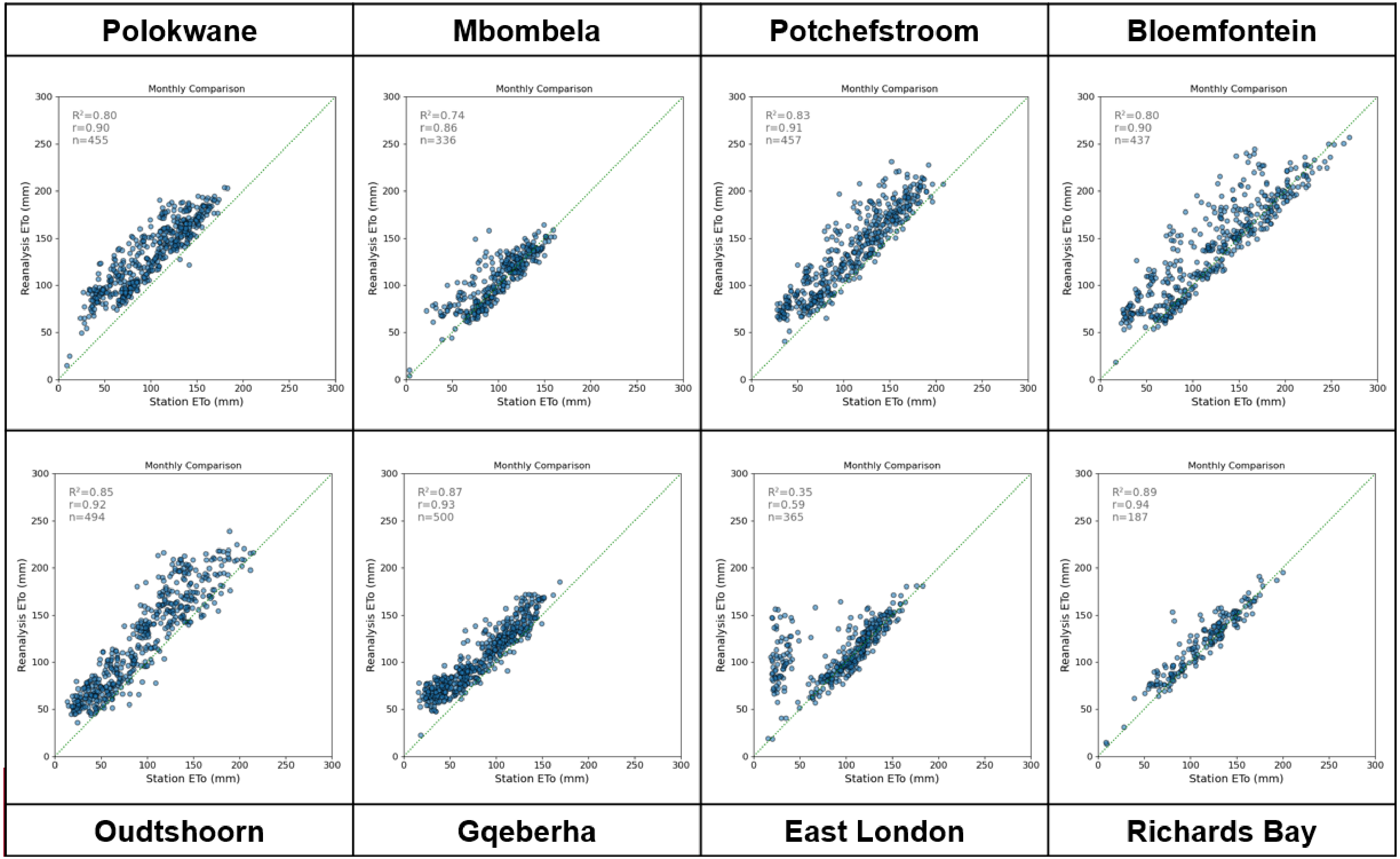

Figure 3.14: Scatterplots of monthly comparisons between station and reanalysis reference evapotranspiration.

3.4.2 SPATIAL PATTERN VALIDATION

Station-based checks addressed accuracy at points but not spatial structure. Because reanalysis is used to map fields and drive spatial models, pattern realism must also be assessed. A dataset can match a gauge while misplacing gradients, centres, and mesoscale features. Event case studies offer a practical, qualitative way to judge feature placement and field coherence across variables.

3.4.2.1 Case study description

An easterly low (Africane) was positioned over Botswana on 19 January 2013. Figure 3.15 shows extensive cloud cover over southern Africa, with deep convection over the northeastern parts, where heavy rainfall occurred. The satellite image in Figure 3.15 (left) provided a synoptic context. Extensive cloud cover occurred over southern Africa, with deep convection evident in the tropical moisture transported southwards to the east of the low-pressure system. Low clouds were also observed in the moist onshore flow along the southeast coast and adjacent interior. The Tropical Rainfall Measuring Mission (TRMM) product (Figure 3.15, right) mapped the spatial pattern of rainfall for the day. Widespread rain occurred over the central and eastern parts of the subcontinent, while heavy falls affected the north-eastern sector. These products served as independent references for a qualitative spatial check of the reanalysis fields of temperature, precipitation, vapour pressure, and solar radiation.

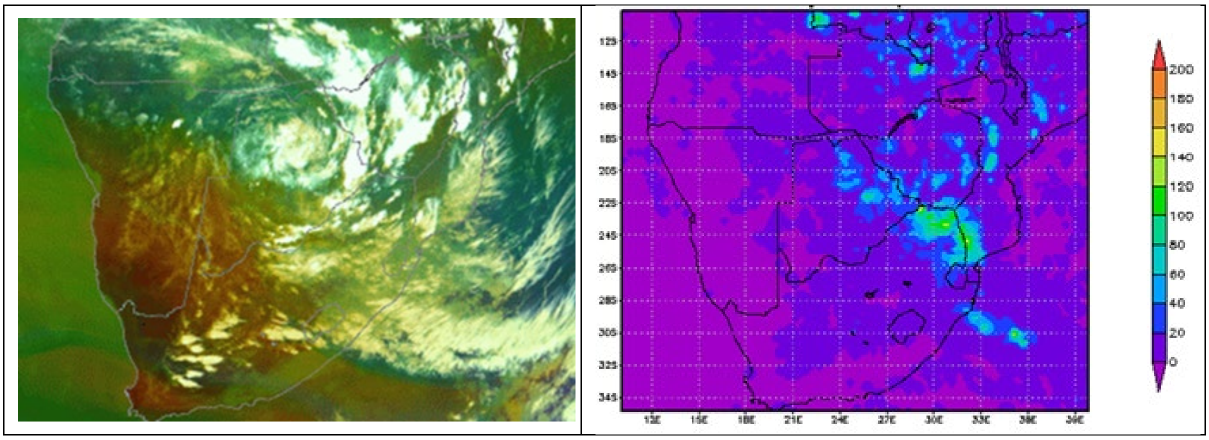

Figure 3.15: Airmass RGB at 12:00 UTC (left) and TRMM daily rainfall field (right) for 19 January 2013.

3.4.2.2 Results

The AgERA5 fields (direct download and derived) for 19 January 2013 for southern Africa are presented in Figure 3.16. Lower mean temperatures (Tmean) were observed over the central parts, consistent with cooling driven by extensive cloud cover and widespread rainfall. Topographical influences were also evident with cooler Tmean over the Highveld and escarpment (Fig. 3.16a). Tmean over the central Kalahari exceeded 30°C due to dry, sunny conditions. Mean vapour pressures (VP) concur with dry conditions over the western parts and elevated moisture in the north and east (Fig. 3.16b). Wind speeds were moderate over most parts (Fig. 3.16c) but stronger in the vicinity of the low-pressure system. Cloudy conditions must have resulted in reduced solar radiation (SR) over the northeastern parts of the subcontinent, particularly in the vicinity of the low-pressure system over Botswana and in the moist onshore flow in the southeast (Fig. 3.16d). High SR occurred over the drier western interior.

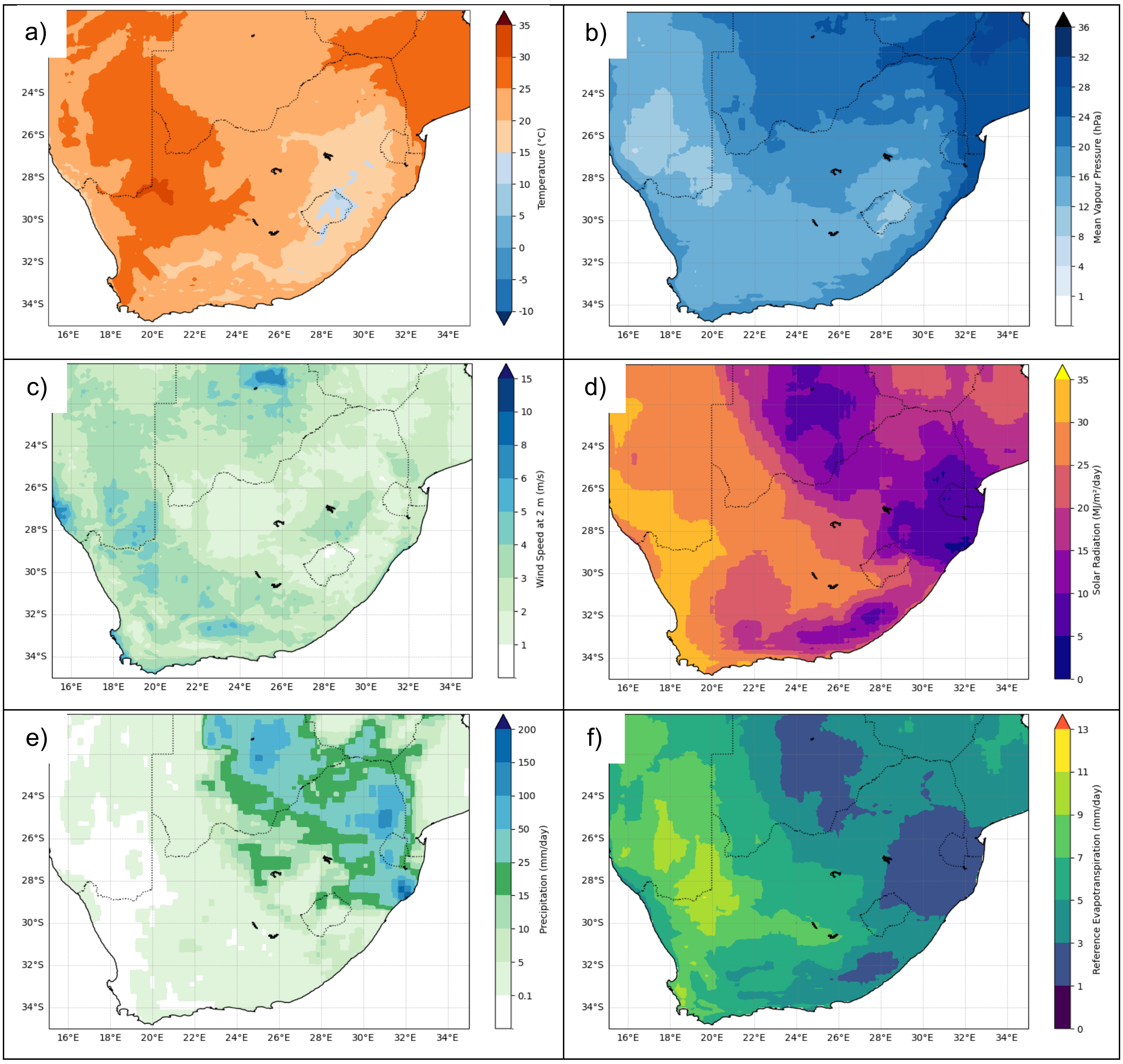

Figure 3.16: AgERA5 reanalysis for southern Africa on 19 January 2013 for a) mean temperature, b) mean vapour pressure, c) mean wind speed, d) total solar radiation, e) total precipitation, and f) reference evapotranspiration.

The precipitation field was consistent with the TRMM rainfall, indicating a large area of showers and thundershowers over the central parts, becoming more severe (i.e. heavy falls) in a band stretching north-westwards from Richards Bay, across the eastern escarpment to northern Botswana (Fig. 3.16e). Daily ETo depicted higher values over the warmer, drier western interior, exceeding 10 mm d^{-1} over the central Kalahari (Fig. 3.16f), and falling below 3 mm d^{-1} in the cloudy areas where heavy rains were indicated.

3.4.3 Discussion

Comparison with daily station observations from eight locations spanning diverse climatic settings indicates that AgERA5 reproduces Tmax, Tmin, solar radiation (SR), and reference evapotranspiration (ETo) with high consistency at both daily and aggregated timescales. In contrast, weaker agreement was evident for wind speed (WS) and precipitation (Pr) at the daily resolution. These discrepancies are consistent with known limitations in point representativeness, measurement uncertainty, and the treatment of highly variable processes in reanalysis systems. Daily Pr should thus be treated as a low-confidence variable, with preference given to monthly totals for water-balance studies. There was a tendency for reanalysis data to underestimate higher Tmax and WS, and to overestimate lower Tmin and WS. Extreme conditions were thus harder to reproduce. Lower skill near complex terrain and coastal zones was consistent with station representativeness and convective variability.

The spatial validation exercise based on an easterly low-pressure system affecting Botswana on 19 January 2013 further supports the dataset's regional applicability. Spatial patterns derived from AgERA5 showed close correspondence with satellite-based observations for mean temperature, vapour pressure, solar radiation, precipitation, and ETo. Agreement in the spatial placement of maxima and minima, together with internally consistent cross-variable behaviour, provides complementary evidence beyond point-based statistics and strengthens confidence in regional-scale applications.

Despite their dependence on the quality and density of assimilated observations, reanalysis products remain a valuable source of climate information in regions where long-term, homogeneous station records are limited or unavailable. The evaluated dataset provides spatially continuous, regularly updateable, and methodologically consistent climate time series, making it suitable for a wide range of agricultural and hydrological analyses across southern Africa.

3.5 ACCESSING THE REANALYSIS CLIMATE DATABASE IN SAPWAT

3.5.1 AGERA5 WEATHER DATA IMPORT

The following steps were followed to import the AgERA5 reanalysis weather data into SAPWAT4.

1. Data preparation

- The AgERA5 dataset was formatted according to SAPWAT4's required input format, i.e., CSV or text file.
- Each row should correspond to a specific date, while the various climatic variables should be organised in columns following the sequence outlined in SAPWAT4's data input structure (Table 3.3).

Table 3.3: Prepared data structure for AgERA5 weather data imported into SAPWAT4 as a .csv file

Column	Description	Data type
WSFilename	Unique File Name	Character
Wstation	Station Name	Character
Longitude	Decimal Degrees (negative for west)	Numeric
Latitude	Decimal Degrees (negative for south)	Numeric
Elevation	Meters	Numeric
Yearsdata	Years of Records	Numeric
rDate	Date or (Year & DOY)	Numeric
rYear	Year	Date
DOY	Day of year	Numeric
rTime	24-hour format	Numeric
Tmax	Maximum temperature (°C)	Numeric
Tmin	Minimum temperature (°C)	Numeric
RHmax	Maximum humidity (%)	Numeric
RHmin	Minimum humidity (%)	Numeric
RHavg	Average humidity (%)	Numeric
Wind	Wind speed (ms^{-1})	Numeric
Windrun	Wind distance (km)	Numeric
Sunshine	Sunshine (hrs)	Numeric
Radiation	Radiation ($MJm^{-2}day^{-1}$)	Numeric
RadWatt	Radiation (Wm^{-2})	Numeric
Rain	Rainfall (mm)	Numeric

- The first row of the CSV file should not contain column headings, and the last row should contain data; i.e., the last row cannot be left blank. To test whether the last row in the CSV file contained data, the project team opened the CSV file as a text file and scrolled down to the last row (line). The last row was deleted if it contained no data.

- All the column names in Table 3.3 were included in the CSV file. If a weather variable was unavailable, that column's values were left blank. Hence, the rows in that column were empty, as shown in Figure 3.17.

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U
1	AgERA5	TestT	26.2	-29.1	1417	1	01/01/2023	2023	1		25.3	14	90.7	37.8		1.6			50		50
2	AgERA6	TestT	26.2	-29.1	1417	1	01/02/2023	2023	2		27.7	14.4	95.6	35.9		2.2			29.6		0.8
3	AgERA7	TestT	26.2	-29.1	1417	1	01/03/2023	2023	3		27.8	14.5	92.5	32.4		2.3			25.6		0.9
4	AgERA8	TestT	26.2	-29.1	1417	1	01/04/2023	2023	4		29	16	81.9	39.7		2.2			26.8		4.3
5	AgERA9	TestT	26.2	-29.1	1417	1	01/05/2023	2023	5		27.9	15.7	96.3	22.4		2.8			26.5		1.5
6	AgERA10	TestT	26.2	-29.1	1417	1	01/06/2023	2023	6		23.8	13.1	91.9	38.6		2.7			24.7		2.8
7	AgERA11	TestT	26.2	-29.1	1417	1	01/07/2023	2023	7		24.6	11.9	86.5	29.4		1.8			24.7		0
8	AgERA12	TestT	26.2	-29.1	1417	1	01/08/2023	2023	8		26.9	12.4	82.1	33.2		2.5			29.2		0.1
9	AgERA13	TestT	26.2	-29.1	1417	1	01/09/2023	2023	9		30.6	15.8	79.8	18		2.6			28		0
10	AgERA14	TestT	26.2	-29.1	1417	1	01/10/2023	2023	10		32.2	15.7	76.4	16.6		1.9			29.9		0
11	AgERA15	TestT	26.2	-29.1	1417	1	01/11/2023	2023	11		32.9	17	72.2	18.2		2			27.9		0
12	AgERA16	TestT	26.2	-29.1	1417	1	01/12/2023	2023	12		32.9	17.4	67.4	17.9		2.2			28.9		0
13	AgERA17	TestT	26.2	-29.1	1417	1	01/13/2023	2023	13		32.8	17.7	55.4	18		2.2			32.5		0
14	AgERA18	TestT	26.2	-29.1	1417	1	01/14/2023	2023	14		34.3	18.6	59.6	15.6		1.9			32.2		0
15	AgERA19	TestT	26.2	-29.1	1417	1	01/15/2023	2023	15		33.5	19	56.7	19.6		3			30.7		0
16	AgERA20	TestT	26.2	-29.1	1417	1	01/16/2023	2023	16		33.7	18.8	54.8	23.6		2.8			31.4		0
17	AgERA21	TestT	26.2	-29.1	1417	1	01/17/2023	2023	17		33.1	18.4	63.6	18.7		2			31.9		0
18	AgERA22	TestT	26.2	-29.1	1417	1	01/18/2023	2023	18		32.8	18.2	61.7	23.3		1.9			28.7		0
19	AgERA23	TestT	26.2	-29.1	1417	1	01/19/2023	2023	19		30.7	19.9	61.6	29		1.8			23.1		2.1
20	AgERA24	TestT	26.2	-29.1	1417	1	01/20/2023	2023	20		31.3	18.6	75.7	32.9		2.1			28.4		2.5
21	AgERA25	TestT	26.2	-29.1	1417	1	01/21/2023	2023	21		30.6	17.7	82	31.5		1.3			27.3		2.1
22	AgERA26	TestT	26.2	-29.1	1417	1	01/22/2023	2023	22		27.1	17.4	91.4	38.6		1.5			23		2.6
23	AgERA27	TestT	26.2	-29.1	1417	1	01/23/2023	2023	23		29.1	17.4	82	25.9		3			29.1		3.1
24	AgERA28	TestT	26.2	-29.1	1417	1	01/24/2023	2023	24		30.9	17.2	56.8	32.4		2.6			28.1		0.8
25	AgERA29	TestT	26.2	-29.1	1417	1	01/25/2023	2023	25		29.9	17.1	84.6	32.9		2.6			22.4		7.9
26	AgERA30	TestT	26.2	-29.1	1417	1	01/26/2023	2023	26		26.5	15.7	86.2	42.1		2.6			26.1		2.4
27	AgERA31	TestT	26.2	-29.1	1417	1	01/27/2023	2023	27		28.9	15.9	89	29.2		1.8			27.7		0.1
28	AgERA32	TestT	26.2	-29.1	1417	1	01/28/2023	2023	28		31.8	16.1	81.5	21.3		2.5			28.3		0.1
29	AgERA33	TestT	26.2	-29.1	1417	1	01/29/2023	2023	29		30.9	14.4	87	25.9		2.8			28.6		0
30	AgERA34	TestT	26.2	-29.1	1417	1	01/30/2023	2023	30		30.8	17.1	88.4	31.2		3.7			22.4		3.3

Figure 3.17: Screenshot example of data structure for AgERA5 weather data imported into SAPWAT4 as a .csv file.

2. Import procedure

A structured process was followed to import AgERA5 weather data into SAPWAT4. The *Sapwat4 Startup* form was closed because it is not required to import weather data. In the top left corner, under *File, Weather Stations was selected* (Figure 3.18). Below the world map, South Africa was selected under the Filter by country and station type heading (Figure 3.19). Next, for South Africa, the option Own was selected, after which the Station record tab at the bottom of the table was selected. New was chosen at the top of the newly opened form (Figure 3.20). Next, out of the six available options, *Manual weather stations and Daily data were selected, but the latter could be presented as a longer time-span average* (Figure 3.21), which opened a new form where the path to the .csv file was entered (Figure 3.22).

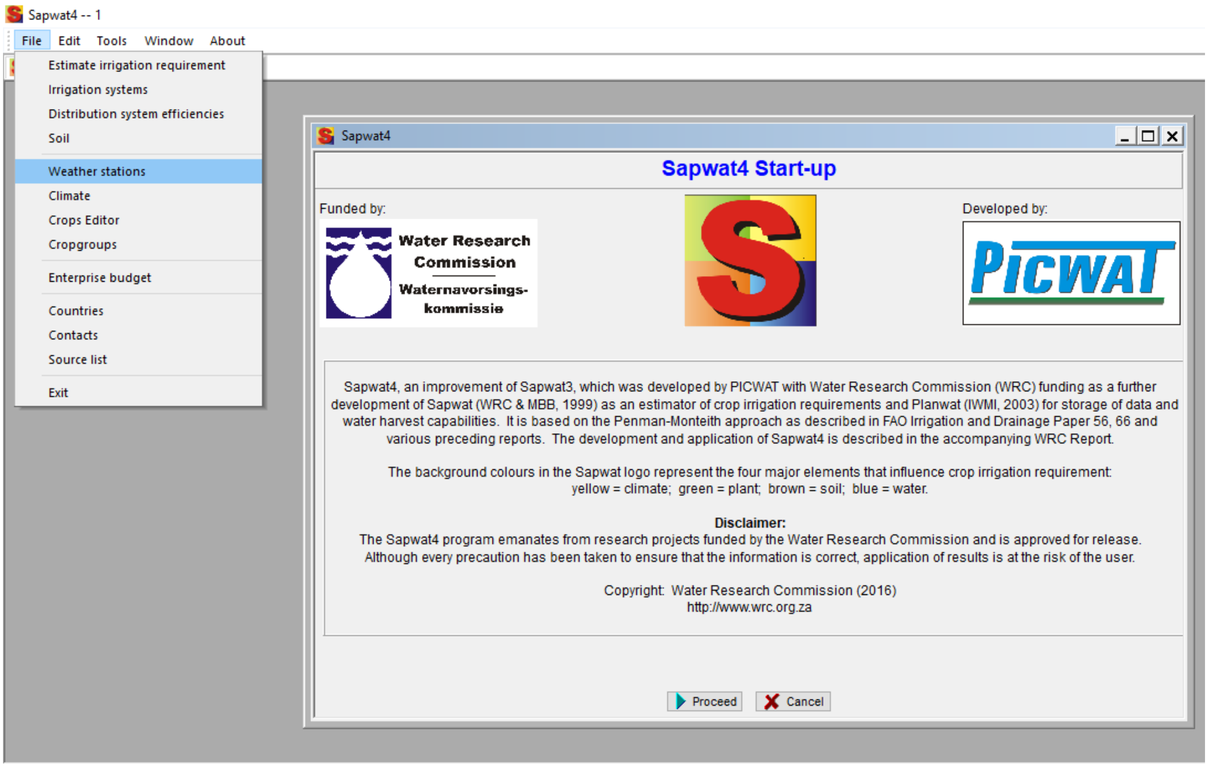

Figure 3.18: Screenshot 1 of the procedure to import AgERA5 weather data into SAPWAT4.

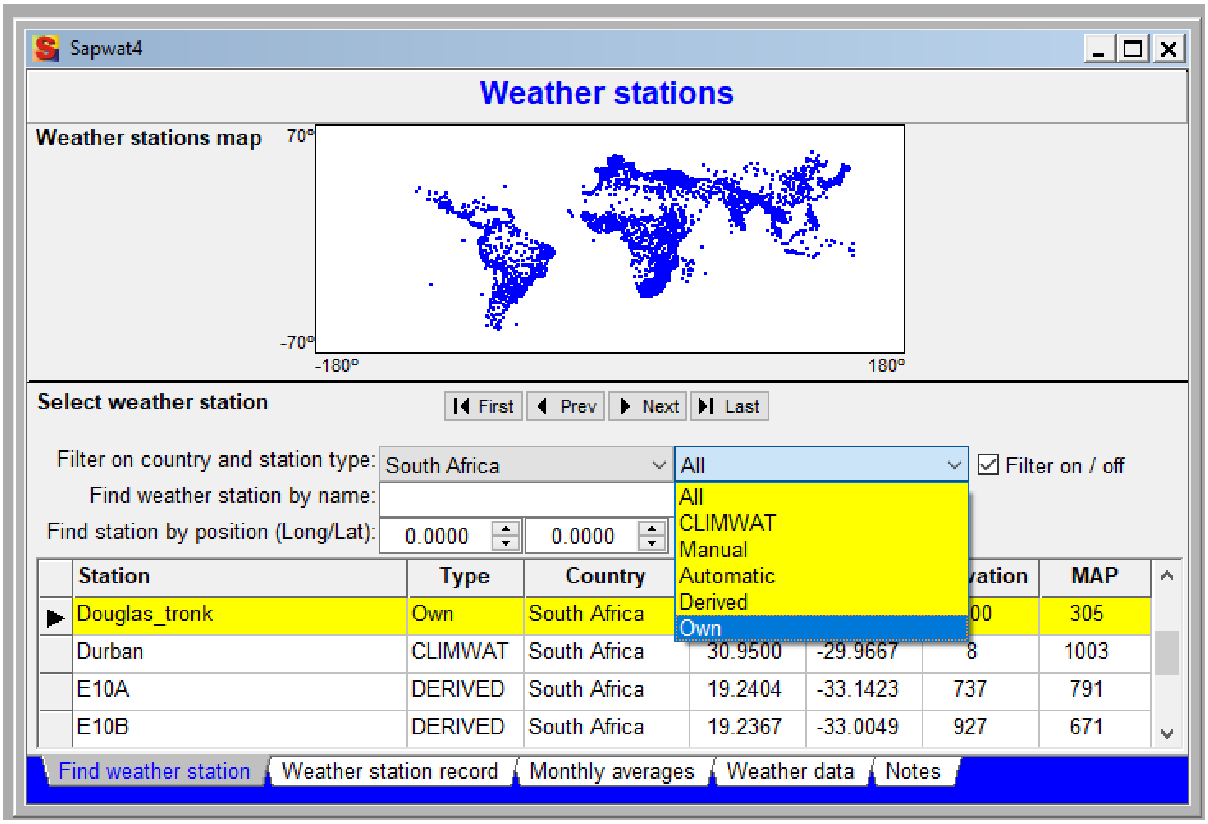

Figure 3.19: Screenshot 2 of the procedure to import AgERA5 weather data into SAPWAT4.

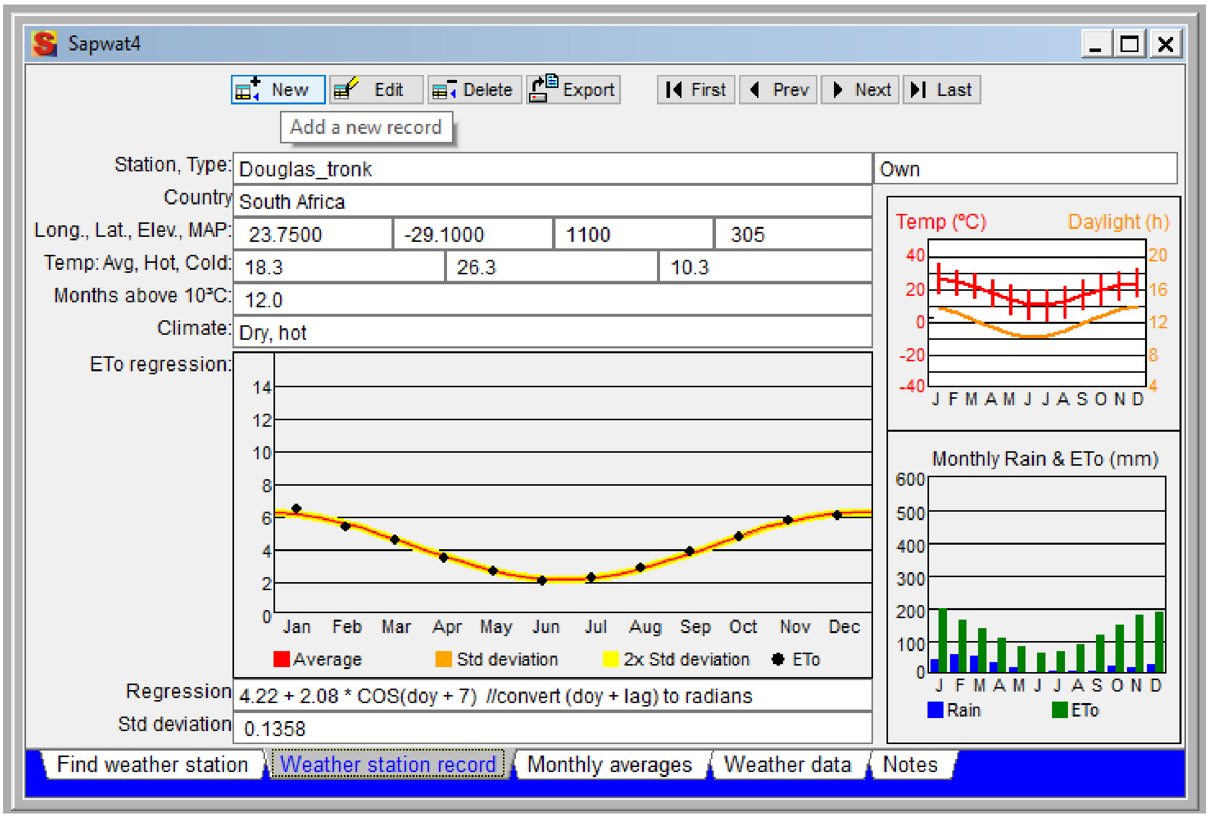

Figure 3.20: Screenshot 3 of the procedure to import AgERA5 weather data into SAPWAT4.

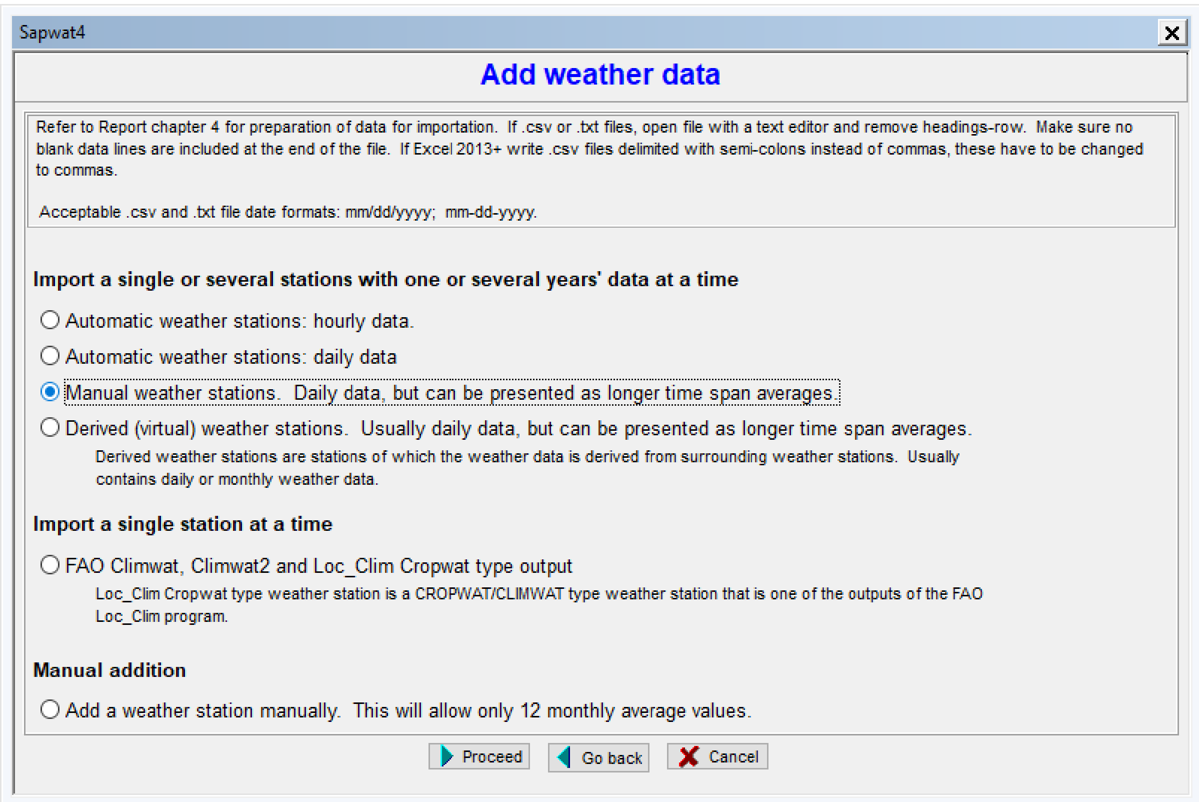

Figure 3.21: Screenshot 4 of the procedure to import AgERA5 weather data into SAPWAT4.

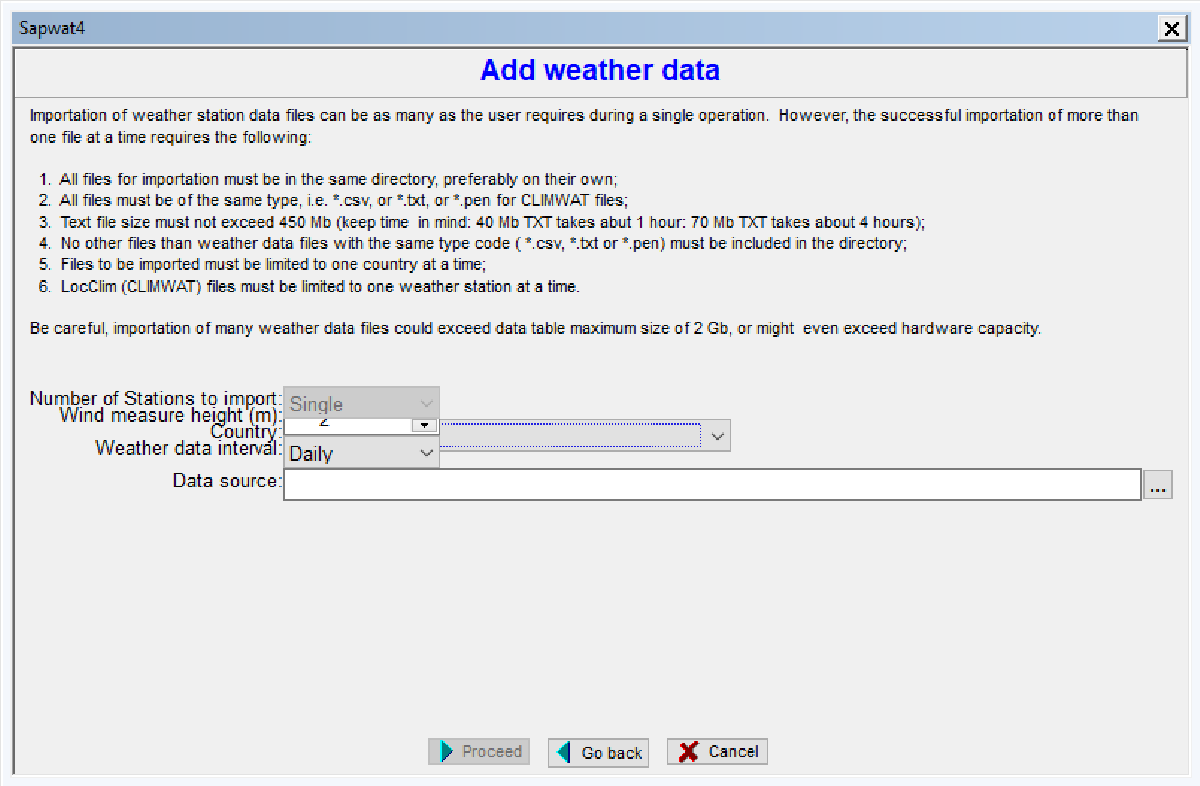

Figure 3.22: Screenshot 5 of the procedure to import AgERA5 weather data into SAPWAT4

3.5.2 SOFTWARE PROBLEMS AND CHALLENGES

Dr Van Heerden developed SAPWAT4 using DBASE. No researchers at the UFS are proficient in DBASE programming. The installation of SAPWAT4 was distributed with the WRC report entitled, “Upgrading SAPWAT3 as a Management Tool to Estimate the Irrigation Water Use of Crops: Revised Edition SAPWAT4”. The distributed version accompanying the report does not install on Windows 11. The UFS has migrated to Windows 11, which is troublesome. However, the research team accessed the software on an old personal computer.

At first, installing SAPWAT4 was troublesome since the anti-virus software detected malicious code (i.e., Trojan[Spy]/Win32.Nivdort), resulting in software installation failure. Dr Van Heerden provided a new installation that the research team could install on the computer if the anti-virus program were deactivated. The University of Pretoria experienced similar problems.

The research team requested the SAPWAT software from Dr Van Heerden and successfully installed it on a Windows 11 computer. However, it appears the software differs from the software distributed with the WRC Report, as the startup screen shows “SAPWAT 4 Version 2”.

Despite the successful import of AgERA5 reanalysis weather data using SAPWAT4 and SAPWAT4 Version 2, several challenges have been encountered, as listed below.

- In addition to the imported data, for example, 2023 and 2024, SAPWAT4 includes 19 years of data from 2000 to 2019. The project team does not know which region the 2000-2019 data are from.
- If data from before 2000 is imported, the previously imported data will remain, including the 19-year data.
- SAPWAT4 does not allow for the import of ETo values. These values are calculated from the imported weather variables.
- The fact that data are included in the imported file without any indication of their source complicates the estimation of irrigation requirements. The user must specify the start and end dates for the imported data for each growing season.

3.5.3 DISCUSSION

The research successfully developed an updated weather database using reanalysis data. During the project's inception, it was anticipated that the weather database could be seamlessly imported into SAPWAT4 to compare crop water requirements from the SAPWAT weather databases with those estimated from the reanalysis database. Inherent programming flaws in the data-indexing procedures prevented such comparisons. Using the updated reanalysis weather database will require updating SAPWAT's source code to a modern programming language.

CHAPTER 4: SAPWAT TECHNOLOGY TRANSFER AND RECOMMENDATIONS

4.1 INTRODUCTION

The problems encountered when importing AgERA5 data into SAPWAT affect the technology transfer of SAPWAT4 with the new weather database to users. This chapter reports on the interaction the team members had with significant users.

4.2 SAPWAT USER FEEDBACK

4.2.1 SOUTH AFRICAN IRRIGATION INSTITUTE (SAII)

SAII expressed their gratitude towards the project. However, they feel the Kc values may be outdated, especially when comparing them across regions for the same crop. SAII members use irrigation requirement estimations when designing irrigation systems. The irrigation system design manual has been updated and is nearly complete. The design manual uses SAPWAT data to estimate crop water requirements. SAII emphasised the importance of credible databases for Kc values and weather data.

4.2.2 BANKING SECTOR

ABSA enquired about SAPWAT. They use the software to verify crop water requirements against water entitlements when providing loans. Like the SAII members, they emphasised the importance of a credible method for estimating crop water requirements. Due to the software's outdated operating environment, they expressed a willingness to support its updating financially.

4.2.3 ZZ2

Discussions with ZZ2 revealed that they see SAPWAT as necessary, primarily because the Department of Water and Sanitation uses the software in its water-use verification studies. Again, they highlighted the importance of accreditation in the discussions. Furthermore, they indicated they want to collaborate to improve the software in future research.

4.2.4 GENERAL

Dr Van Heerden and his wife presented a day course on using SAPWAT for environmentalists wanting to use the software in environmental impact assessments.

4.2.5 SYNTHESIS

SAPWAT users agree that SAPWAT's value lies in its weather database covering South Africa. Weather data is available for remote locations, making it easy to estimate crop water requirements for these areas. The same applies to the crop database, which covers many crops. Some users assume that the estimations are credible, while others question the validity of the Kc values. The research team found many misconceptions about crop Kc values, mainly because the Kc values reported in FAO 56 are for a standard climate with an average wind speed of 2 ms^{-1} and a relative humidity of 45%. Future use of the software will require reprogramming and updating.

4.3 RECOMMENDATIONS

- Reprogram SAPWAT in a modern language to enhance functionality.
- The SAPWAT crop coefficient database must be standardised to conform to the FAO 56 standard climate. Region-specific parameters derived from measurements should be transformed to the standard climate before inclusion.
- The exception handling of region-specific parameters derived from measurements
- Develop documentation for the calculation procedures embedded in SAPWAT and software use.
- Integrate irrigation cost estimation procedures with SAPWAT to enhance energy management planning.
- Develop a business plan to ensure sustainable maintenance and software development.

REFERENCES

Allen, R.G., Pereira, L.S., 2009. Estimating crop coefficients from fraction of ground cover and height. Irrig. Sci. 28, 17–34. https://doi.org/10.1007/s00271-009-0182-z

Allen, R.G., Dhungel, R., Dhungana, B., Huntington, J., Kilic, A., Morton, C. (2020) Conditioning point and gridded weather data under aridity conditions for calculation of reference evapotranspiration. Agricultural Water Management 245, 106531. https://doi.org/10.1016/j.agwat.2020.106531

Baker, J., Souza, D., Kubota, P., Buermann, W., Coelho, C., Andrews, M., Gloor, M., Garcia-Carreras, L., Figueroa, S.N., Spracklen, D.V. (2021) An Assessment of Land–Atmosphere Interactions over South America Using Satellites, Reanalysis, and Two Global Climate Models. Journal of Hydrometeorology 22, 905-922. https://doi.org/10.1175/JHM-D-20-0132.1

Blankenau, PA., Kilic, A., Allen, R.G. (2020) An evaluation of gridded weather data sets for the purpose of estimating reference evapotranspiration in the United States. Agricultural Water Management 242, 106376. https://doi.org/10.1016/j.agwat.2020.106376

Boogaard, H., Schubert, J., De Wit, A., Lazebnik, J., Hutjes, R., Van der Grijn, G., (2020) Agrometeorological indicators from 1979 to present derived from reanalysis. Copernicus Climate Change Service (C3S) Climate Data Store (CDS). https://doi.org/10.24381/cds.6c68c9bb

Bromwich, D. H., Fogt, R. L., Hodges, K. I., Walsh, J. E. (2007) A tropospheric assessment of the ERA-40, NCEP, and JRA-25 global reanalyses in the polar regions. Journal of Geophysical Research: Atmospheres, 112(D10). https://doi.org/10.1029/2006JD007859

Copernicus Climate Data Store (CDS). (2024) AgERA5 documentation. Available at: https://cds.climate.copernicus.eu

Decker, M., Brunke, M., Wang, Z., Sakaguchi, K., Zeng, X., Bosilovich, M. (2012) Evaluation of the Reanalysis Products from GSFC, NCEP, and ECMWF Using Flux Tower Observations. Journal of Climate 25, 1916-1944. https://doi.org/10.1175/JCLI-D-11-00004.1

Dee, D. P., Uppala, S. M., Simmons, A. J., Berrisford, P., Poli, P., Kobayashi, S., Andrae, U., Balmaseda, M. A., Balsamo, G., Bauer, P., Bechtold, P., Beljaars, A. C. M., van de Berg, L., Bidlot, J., Bormann, N., Delsol, C., Dragani, R., Fuentes, M., Geer, A. J., Haimberger, L., Healy, S. B., Hersbach, H., Hólm, E. V., Isaksen, L., Kållberg, P., Köhler, M., Matricardi, M., McNally, A. P., Monge-Sanz, B. M., Morcrette, J. J., Park, B. K., Peubey, C., de Rosnay, P., Tavolato, C., Thépaut, J. N., Vitart, F. (2011) The ERA-Interim reanalysis: configuration and performance of the data assimilation system. Quarterly Journal of the Royal Meteorological Society, 137(656), 553–597. https://doi.org/10.1002/qj.828

French, A.N., Hunsaker, D.J., Sanchez, C.A., Saber, M., Gonzalez, J.R., Anderson, R. (2020) Satellite-based NDVI crop coefficients and evapotranspiration with eddy covariance validation for multiple durum wheat fields in the US Southwest. Agricultural Water Management 239, 106266. https://doi.org/10.1016/j.agwat.2020.106266

Garrido-Rubio, J., González-Piqueras, J., Campos, I., Osann, A., González-Gómez, L., Calera, A. (2020) Remote sensing–based soil water balance for irrigation water accounting at plot and water user association management scale. Agricultural Water Management 238, 106236. https://doi.org/10.1016/j.agwat.2020.106236

Gelaro, R., McCarty, W., Suárez, M.J., Todling, R., Molod, A., Takacs, L., Randles, C.A., Darmenov, A., Bosilovich, M.G., Reichle, R., Wargan, K., Coy, L., Cullather, R., Draper, C., Akella, S., Buchard, V., Conaty, A., da Silva, A.M., Gu, W., Kim, G.-K., Koster, R., Lucchesi, R., Merkova, D., Nielsen, J.E., Partyka, G., Pawson, S., Putman, W., Rienecker, M., Schubert, S.D., Sienkiewicz, M., Zhao, B. (2017) The Modern-Era Retrospective Analysis for Research and Applications, Version 2 (MERRA-2). Journal of Climate, 30(14), 5419–5454. https://doi.org/10.1175/JCLI-D-16-0758.1

Hersbach, H., Bell, B., Berrisford, P., Hirahara, S., Horányi, A., Muñoz-Sabater, J., Nicolas, J., Peubey, C., Radu, R., Schepers, D., Simmons, A., Soci, C., Abdalla, S., Abellan, X., Balsamo, G., Bechtold, P., Biavati, G., Bidlot, J., Bonavita, M., de Chiara, G., Dahlgren, P., Dee, D., Diamantakis, M., Dragani, R., Flemming, J., Forbes, R., Fuentes, M., Geer, A., Haimberger, L., Healy, S., Hogan, R. J., Hólm, E. A., Janisková, M., Keeley, S., Laloyaux, P., Lopez, P., Radnoti, G., Rosnay, P. d'., Rozum, I., Vamborg, F., Villaume, S., Thépaut, J.-N. (2020) The ERA5 global reanalysis. Quarterly Journal of the Royal Meteorological Society, 146, 1999–2049. https://doi.org/10.1002/qj.3803

Hoffmann, L., Günther, G., Li, D., Stein, O., Wu, X., Griessbach, S., Heng, Y., Konopka, P., Müller, R., Vogel, B., Wright, J. (2018) From ERA-Interim to ERA5: considerable impact of ECMWF's next-generation reanalysis on Lagrangian transport simulations. Atmospheric Chemistry and Physics 19, 3097-3124. https://doi.org/10.5194/ACP-19-3097-2019

Jarvis A., Reuter, H.I., Nelson, A., Guevara, E. (2008) Hole-filled seamless SRTM data V4, International Centre for Tropical Agriculture (CIAT). Available from http://srtm.csi.cgiar.org (Accessed 15/05/2024).

Jovanovic, N., Pereira, L.S., Paredes, P., Pôças, I., Cantore, V., Torodovic, M. (2020) A review of strategies, methods and technologies to reduce non-beneficial consumptive water use on farms considering the FAO 56 methods. Agricultural Water Management 239, 106267. https://doi.org/10.1016/j.agwat.2020.106267

Kalnay, E., Kanamitsu, M., Kistler, R., Collins, W., Deaven, D., Gandin, L., Iredell, M., Saha, S., White, G., Woollen, J., Zhu, Y., Chelliah, M., Ebisuzaki, W., Higgins, W., Janowiak, J., Mo, K. C., Ropelewski, C., Wang, J., Leetmaa, A., Reynolds, R., Jenne, R., Joseph, D. (1996) The NCEP/NCAR 40-Year Reanalysis Project. Bulletin of the American Meteorological Society, 77, 437–471. https://doi.org/10.1175/1520-0477(1996)077

Kobayashi, S., Ota, Y., Harada, Y., Ebita, A., Moriya, M., Onoda, H., Onogi, K., Kamahori, H., Kobayashi, C., Endo, H., Miyaoka, K., Takahashi, K. (2015) The JRA-55 Reanalysis: General specifications and basic characteristics. Journal of the Meteorological Society of Japan, 93(1), 5–48. https://doi.org/10.2151/jmsj.2015-001

Landman, W.A., Botes, S., Goddard, L., Shongwe, M. (2005) Assessing the predictability of extreme rainfall seasons over southern Africa. Geophysical research letters, 32(23). https://doi.org/10.1029/2005GL023965

Liu, W., Wang, L., Zhou, J., Li, Y., Sun, F., Fu, G., Li, X., Sang, Y. (2016) A worldwide evaluation of basin-scale evapotranspiration estimates against the water balance method. Journal of Hydrology 538, 82-95. https://doi.org/10.1016/J.JHYDROL.2016.04.006

López-Urrea, R., Sánchez, J.M., de la Cruz, F., González- Piqueras, J., Chávez, J.L. (2020) Evapotranspiration and crop coefficients from lysimeter measurements for sprinkler-irrigated canola. Agricultural Water Management 239, 106260. https://doi.org/10.1016/j.agwat.2020.106260

Mabasa, B., Lysko, M. D., Moloi, S. J. (2021) Validating Hourly Satellite Based and Reanalysis Based Global Horizontal Irradiance Datasets over South Africa. Geomatics, 1(4), 429-449. https://doi.org/10.3390/geomatics1040025

Minhas, P.S., Ramos, T., Ben-Gal, A, Pereira, L.S. (2020) Coping with salinity in irrigated agriculture: Crop evapotranspiration and water management issues. Agricultural Water Management 227, 105832. https://doi.org/10.1016/j.agwat.2019.105832

Muñoz-Sabater, J., Dutra, E., Agustí-Panareda, A., Albergel, C., Arduini, G., Balsamo, G., Boussetta, S., Choulga, M., Harrigan, S., Hersbach, H., Martens, B., Miralles, D.G., Piles, M., Rodríguez-Fernández, N.J., Zsóter, E., Buontempo, C., Thépaut, J.-N. (2021) ERA5-Land: A state-of-the-art global reanalysis dataset for land applications. Earth System Science Data, 13(9), 4349–4383. https://doi.org/10.5194/essd-13-4349-2021

Paredes, P., Pereira, L.S., Almorox, J., Darouich, H. (2020) Reference grass evapotranspiration with reduced data sets: Parameterization of the FAO Penman-Monteith temperature approach and the Hargeaves-Samani equation using local climatic variables. Agricultural Water Management 240, 106210. https://doi.org/10.1016/j.agwat.2020.106210

Paredes, P., Trigo, I., de Bruin, H., Simões, N., Pereira, L.S. (2021) Daily grass reference evapotranspiration with Meteosat Second Generation shortwave radiation and reference ET products. Agricultural Water Management 248, 106543. https://doi.org/10.1016/j.agwat.2020.106543

Pereira, L.S., Paredes, P., Melton, F., Johnson, L., Wang, T., Mota, M., López-Urrea, R., Cancela, J.J., Allen, R.G. (2020a) Prediction of crop coefficients from fraction of ground cover and height. Background and validation using ground and remote sensing data. Agricultural Water Management 241, 106197. https://doi.org/10.1016/j.agwat.2020.106197

Pereira, L.S., Paredes, P., Jovanovic, N. (2020b) Soil water balance models for determining crop water and irrigation requirements and irrigation scheduling focusing on the FAO 56 method and the dual Kc approach. Agricultural Water Management 241, 106357. https://doi.org/10.1016/j.agwat.2020.106357

Pereira, L.S., Paredes, P., López-Urrea, R., Hunsaker, D.J., Mota, M., Mohammadi Shad, Z. (2021a) Standard single and basal crop coefficients for vegetable crops, an update of FAO 56 crop water requirements approach. Agricultural Water Management 243, 106196. https://doi.org/10.1016/j.agwat.2020.106196

Pereira, L.S., Paredes, P., Hunsaker, D.J, López-Urrea, R., Mohammadi Shad, Z. (2021b) Standard single and basal crop coefficients for field crops. Updates and advances to the FAO 56 crop water requirements method. Agricultural Water Management 243, 106466. https://doi.org/10.1016/j.agwat.2020.106466

Pereira, L.S., Paredes, P., Melton, F., Johnson, L., Mota, M., Wang, T. (2021c) Prediction of crop coefficients from fraction of ground cover and height. Practical application to vegetable, field and fruit crops with focus on parameterization. Agricultural Water Management 252, 106663. https://doi.org/10.1016/j.agwat.2020.106663

Pereira, LS, Paredes, P., Hunsaker, D.J., López-Urrea, R., Jovanovic, N. (2021d) Updates and advances to the FAO 56 crop water requirements method. Agricultural Water Management 248, 106697. https://doi.org/10.1016/j.agwat.2020.106697

Pôças, I., Calera, A., Campos, I., Cunha, M. (2020) Remote sensing for estimating and mapping single and basal crop coefficients: a review on spectral vegetation indices approaches. Agricultural Water Management 233, 106081. https://doi.org/10.1016/j.agwat.2020.106081

Rallo, G., Paço, T., Paredes, P., Puig, A., Provenzano, G., Massai, R., Pereira, L.S. (2021) Updated single and dual crop coefficients for trees and vine crops. Agricultural Water Management 250, 106645. https://doi.org/10.1016/j.agwat.2020.106645

Saha, S., Moorthi, S., Pan, H.-L., Wu, X., Wang, J., Nadiga, S., Tripp, P., Behringer, D., Hou, Y.-T., Chuang, H.-Y., Iredell, M., Ek, M., Meng, J., Yang, R., Mendez, M.P., van den Dool, H., Zhang, Q., Wang, W., Chen, M., Becker, E. (2010) The NCEP Climate Forecast System Reanalysis. Bulletin of the American Meteorological Society, 91(8), 1015–1057. https://doi.org/10.1175/2010BAMS3001.1

Steinkopf, J., Engelbrecht, F. (2022) Verification of ERA5 and ERA-Interim precipitation over Africa at intra-annual and interannual timescales. Atmospheric Research 280. 106427. https://doi.org/10.1016/j.atmosres.2022.106427

Tarek, M., Brissette, F.P., Arsenault, R., Martel, J.L. (2020) Evaluation of the ERA5 reanalysis as a potential reference dataset for hydrological modelling over North America. Hydrology and Earth System Sciences, 24(5), 2527-2544. https://doi.org/10.5194/hess-24-2527-2020

Terblanche, D., Lynch, A., Chen, Z., Sinclair, S. (2022) ERA5-Derived Precipitation: Insights from Historical Rainfall Networks in Southern Africa. J. Appl. Meteor. Climatol., 61, 1473–1484, https://doi.org/10.1175/JAMC-D-21-0096.1

Wang, T., Melton, F.S., Pôças, I., Johnson, L.F., Thao, T., Post, K., Cassel-Sharma, F. (2021) Evaluation of crop coefficient and evapotranspiration data for sugar beets from Landsat surface reflectances using micrometeorological measurements and weighing lysimetry. Agricultural Water Management 244, 106533. https://doi.org/10.1016/j.agwat.2020.106533

APPENDIX A: STUDENT CAPACITY BUILDING

INTRODUCTION

From the start of the project, the project team envisaged that Mr Nhlanhla Sithole would actively conduct research as part of his Master's thesis. However, Mr Sithole took a position at the South African Weather Service and did not continue with his studies. Dr Steyn identified another student, Mrs Tshedza Matladi, who successfully completed her studies on the project. Two other students, Ms Anfal Fatima and Mr Omphile Sehoole, are using the data in their postgraduate studies.

COMPLETED MASTERS

Matladi, T. (2025 Cum Laude).
Assessing the Influence of the El Niño - Southern Oscillation (ENSO) Phase on Hydrological Indicators in the Summer Rainfall Region of South Africa. M.Sc. (Climate Change) dissertation, Department of Soil, Crop and Climate Sciences, University of the Free State.

ABSTRACT
The El Niño-Southern Oscillation (ENSO) influences hydroclimatic variability in South Africa's Summer Rainfall Region (SRR). This study evaluates the suitability of the AgERA5 reanalysis dataset as a replacement for station-based observations, focusing on its ability to replicate key hydroclimatic variables at six locations: Bloemfontein and Potchefstroom (central interior), Polokwane (northeastern interior), Mbombela (Lowveld), East London (southeast coast), and Richards Bay (east coast). Climatic variables considered include precipitation, temperature, reference evapotranspiration (ETo), relative humidity, wind speed, and solar radiation, all of which are critical for drought monitoring and agricultural risk assessments. The study also investigates the relationship between ENSO phases and hydroclimatic extremes, specifically their influence on drought severity. To assess AgERA5's performance, non-exceedance probability distributions were used to evaluate the dataset's representation of low, moderate, and extreme climatic conditions. Correlations were calculated for daily, monthly, and annual values across the variables. The results show that AgERA5 aligns well with station observations under moderate conditions but tends to underestimate extreme values, particularly precipitation exceeding 750 mm, ETo exceeding 1500 mm, Tmax exceeding 27°C, and solar radiation exceeding 7000 MJm^{-2}. These discrepancies were most evident at inland

stations (e.g., Bloemfontein, Polokwane, and Mbombela), where AgERA5 struggled to capture the spatial variability of extreme conditions. Strong correlations were observed between AgERA5 data and temperature minima. However, the dataset's performance was weaker for more dynamic variables, such as rainfall and wind speed, particularly on an annual scale. Additionally, ENSO phases exhibited a significant correlation with drought conditions at inland stations, such as Bloemfontein and Mbombela, especially during the summer months (DJF/DJFMAM). These relationships were weaker in spring, autumn, and annually, emphasising the temporal specificity of ENSO's impact on hydroclimatic extremes. When combined with station data, AgERA5 proves to be a valuable resource for improving drought monitoring, enhancing seasonal predictions, and supporting adaptive decision-making in water and agricultural resource management within South Africa's SRR.

MASTER’S STUDENTS USING THE CLIMATE DATABASE

Anphal, T.
Optimising irrigation scheduling of maize under El Niño-Southern Oscillation conditions in central South Africa. M.Agric dissertation in Irrigation Management, Department of Soil, Crop and Climate Sciences, University of the Free State.
She is still developing her research proposal.

Sehoole, O.
Analysis of climate variability and implications for maize production in the North West province, South Africa. M.Sc. dissertation, Department of Soil, Crop and Climate Sciences, University of the Free State.

COURSES AT THE UNIVERSITY OF THE FREE STATE

SAPWAT is part of the learning material for the following modules.

- SANR7906, Advanced Assessment and Management of Natural Resources. The module outcomes and objectives are: Sustainable management of natural resources, such as water, soil, climate, and plants, requires a holistic understanding of the interactions between environmental factors and human activity. One of the requirements of sustainable agriculture is that the quality of the natural agricultural resources must be maintained and, if possible, even improved. Basic principles of soil, climate, water resources and crop production are needed to complete this module. Emphasis in this advanced module will be on the promotion of integrated assessment of natural resources such as water and soil quality, and the utilisation of climate data, to contribute to a sustainable crop production system on a viable basis.

SAPWAT are specifically covered in Learning Unit 2, namely Soil physical properties and water resources assessment for crop production, where the outcomes are: Define the moisture requirements of crops under rain-fed and irrigation production systems, assess the influence of various soil physical properties on the yield potential of rainfed and irrigated production systems, the sustainability of various water management practices in rainfed and irrigated production systems, and the sustainability of various practices for managing the salt load associated with irrigation.
In 2025 and 2024, student numbers were 71 and 116, respectively.

- IRRI6816, Evaluation of soil and water for irrigation suitability. On successful completion of the module, students will be able to:
    1. Utilise instruments to quantify soil water content.
    2. Apply knowledge of soil water instrumentation, soil physical and hydraulic properties, crop water requirements and irrigation water quality to past and possible future real-world scenarios.
    3. Gain proficiency in using pedotransfer functions and mathematical models (software) to assess soil and water suitability for irrigation.
    4. Present and communicate irrigation-related problems and solutions academically and professionally.
    5. Make traditional and mechanised irrigation decisions to control the soil water and salt balance.

  In 2025 and 2024, student numbers were 7 and 5, respectively.

- Course: Climate Change and Variability
  Outcome: Students are expected to use climate data to analyse trends in maximum and minimum temperatures and precipitation, and to test these for significance.
  Students: 11

APPENDIX B: KNOWLEDGE DISSEMINATION

ORAL PRESENTATIONS

Steyn, A.S. and Matladi, T. (2025). Development and Validation of a Reanalysis-Based Climate Database for Southern Africa. Proceedings of the 60th annual congress of the Grassland Society of Southern Africa (GSSA), 21-24 July 2025, Hilton, South Africa.

Matladi, T. and Steyn, A.S. (2025). Seasonal Drought Variability Associated with El Niño-Southern Oscillation (ENSO) Phases in South Africa's Summer Rainfall Region. Proceedings of the 60th annual congress of the Grassland Society of Southern Africa (GSSA), 21-24 July 2025, Hilton, South Africa.

Steyn, A.S. and Matladi., T. (2025). Upgrading SAPWAT'S climate database using AgERA5 to support climate-smart irrigation decisions in Southern Africa. Symposium presentation. South African National Commission on Irrigation and Drainage Symposium (SANCID), Bloemfontein, 6-8 May 2025.

PUBLISHED PAPERS

Steyn, A.S. and Matladi, T. (2023). Assessing the influence of the El Niño – Southern Oscillation phase on rainfall variability in the Gauteng province of South Africa. *South African Journal of Plant and Soil*, 40(3), 1–9. https://doi.org/10.1080/02571862.2023.2240736.

APPENDIX C: DATA ARCHIVING

Prof Bennie Grové
Department of Agricultural Economics
University of the Free State
Bloemfontein
9300
Tel: 051 401-3359
Cell: 0833841987
Email: groveb@ufs.ac.za

APPENDIX D: SUPPLEMENTAL MATERIAL FOR CHAPTER 2

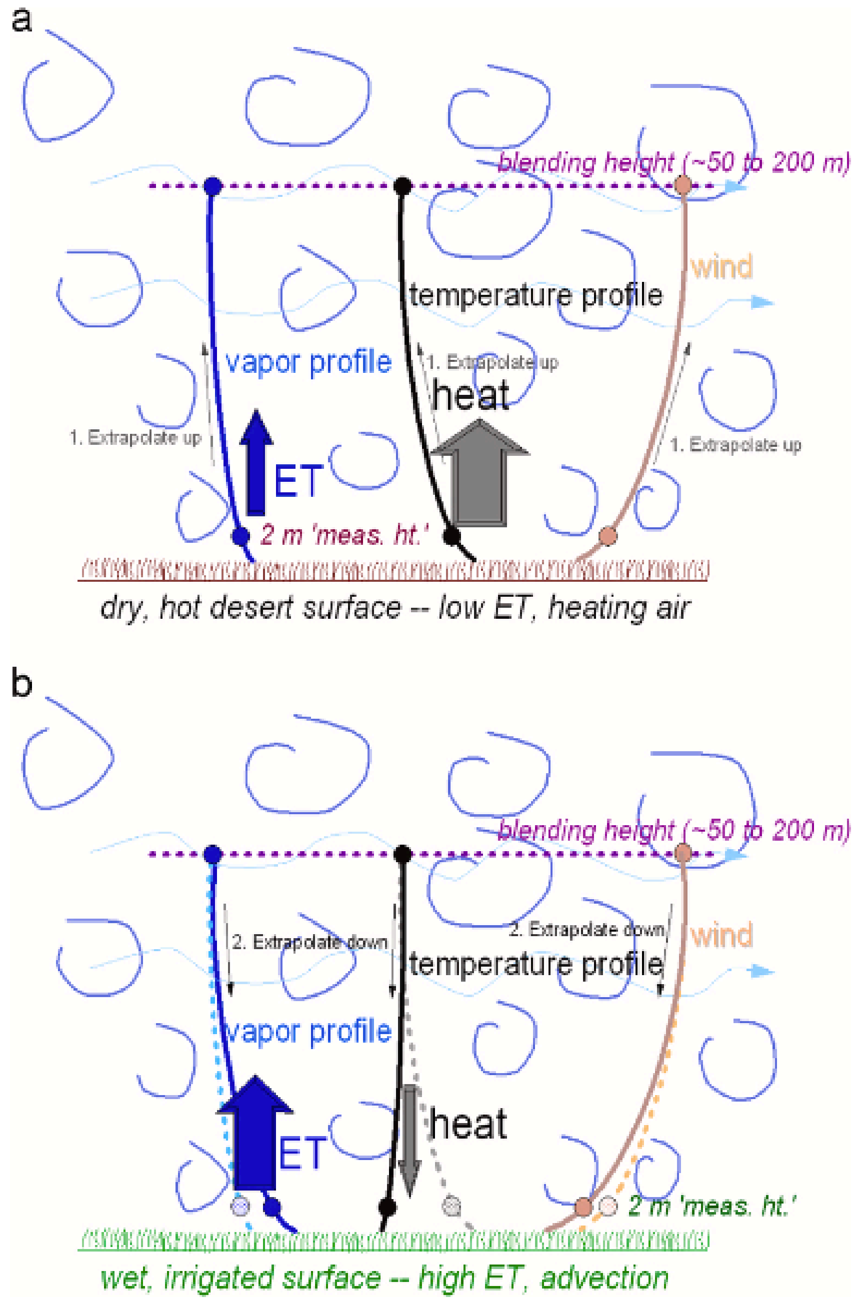

Fig. 4. (a) Vapor, air temperature and wind speed profiles over a hot, dry surface where precipitation is the only water input, where a blending height is shown. (b) Vapor, air temperature and wind speed profiles over an evaporating (vegetated) surface (solid lines) where soil water is not limited, and where the profiles are tied to the same regional blending height shown in Fig. 4a. The original ambient-based profiles are shown as dashed lines.

Appendix D.1: **Screenshot of Figure 4 in Allen et al. (2020), showing vapour, air temperature and wind speed profiles.**

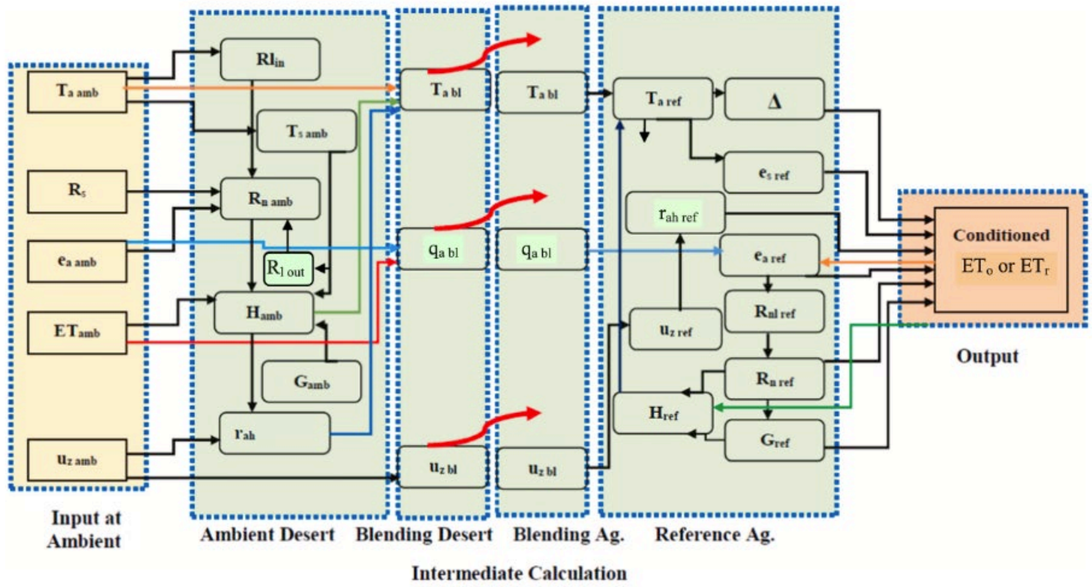

Fig. 5. Flowchart showing primary components of the conditioning process divided into input, intermediate-internal calculations, and final conditioned (reference) weather data and reference ET output.

Appendix D.2: **Screenshot of Figure 5 in Allen et al. (2020), showing the author's method to condition gridded weather data by extrapolating air temperature, vapour pressure, and wind speed profiles using standard surface energy balance equations and flux-profile relationships**

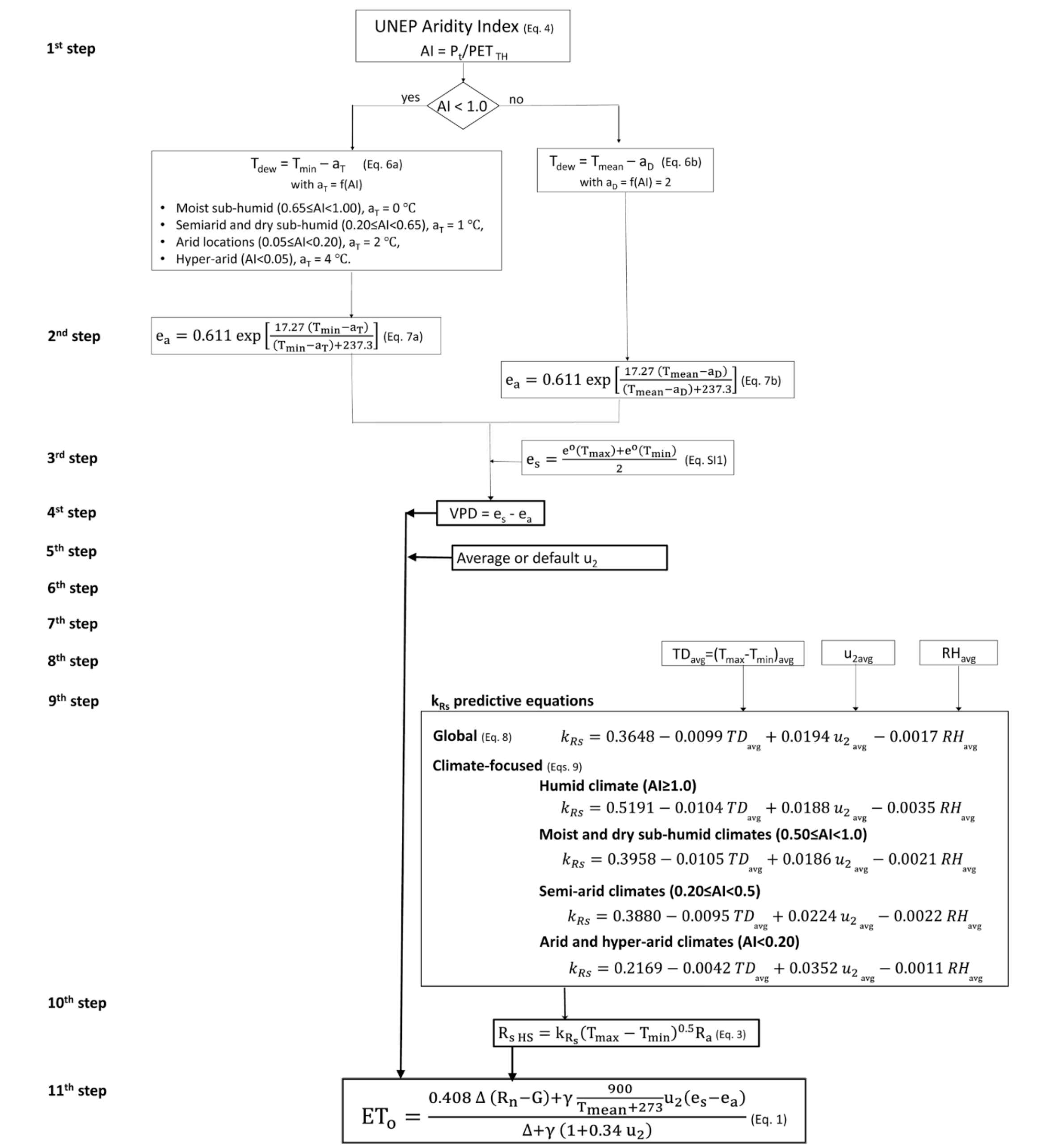

Fig. 1. Flow-chart of the PMT approach to compute ET_o with reduced data sets when k_{Rs} is estimated with a global or climate focused predictive equation as a function of locally observed or estimated average climatic variables TD_{avg}, RH_{avg} and $u_{2\ avg}$, with climates defined according to the UNEP Aridity Index (AI) (adapted from Paredes and Pereira, 2019).

Appendix D.3: Screenshot of Figure 1 in Paredes et al. (2020) showing a flow-chart of the FAO Penman-Monteith temperature approach to compute ETo.

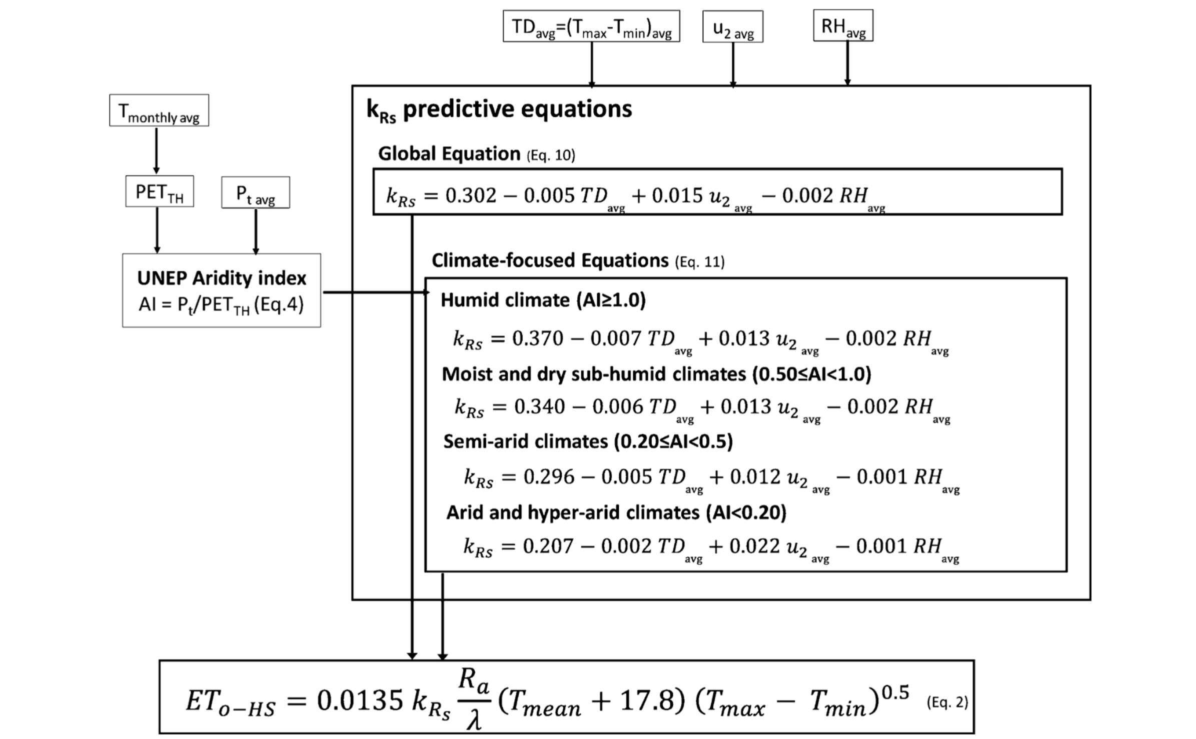

Fig. 7. Flux diagram for the calculation of $ET_{o\text{-}HS}$ when k_{Rs} is estimated with a global or climate focused predictive equation as a function of locally observed or estimated average climatic variables TD_{avg}, RH_{avg} and $u_{2\ avg}$, with climates defined according to the UNEP Aridity Index (AI).

Appendix D.4: Screenshot of Figure 7 in Paredes et al. (2020) showing a flux diagram of the Hargeaves-Samani compute ETo.

Table 9
Updated standard single crop coefficients $K_{c\ mid}$ and $K_{c\ end}$ for vegetable crops.

Crop	Observed, standard K_c		FAO56 tabulated K_c		Updated standard K_c	
	$K_{c\ mid\ (std)}$	$K_{c\ end\ (std)}$	$K_{c\ mid}$	$K_{c\ end}$	$K_{c\ mid}$	$K_{c\ end}$
Roots, tubers, bulbs and stem vegetable crops						
Asparagus (*Asparagus officinalis*)	n/r	n/r	0.95	0.30	**0.95**	**0.30**
Carrots (*Daucus carota*)	1.01–1.04	0.84–0.98	1.05	0.95	**1.05**	**0.95**
Cassava (*Manihot esculenta*)						
Year 1	0.95–1.19	0.63–0.80	0.80	0.30	**1.00**	**0.60**
Year 2	n/r	n/r	1.10	0.50	**1.10**	**0.60**
Celery (*Apium graveolens*)	n/r	n/r	1.05	1.00	**1.05**	**1.00**
Garlic (*Allium sativum*)	0.88–1.18	0.15–0.80	1.00	0.70	**1.05**	**0.70**
Onions (*Allium cepa*)						
Dry	0.84–1.13	0.42–0.68	1.05	0.75	**1.05**	**0.65**
Green	1.02	0.81	1.00	1.00	**1.05**	**0.90**
Seed	n/r	n/r	1.05	0.80	**1.05**	**0.80**
Parsnip (*Pastinaca sativa*)	n/r	n/r	1.05	0.95	**1.05**	**1.00**
Potato (*Solanum tuberosum*)						
Long season	1.10–1.14	0.10–0.45	1.15	0.40	**1.15**	**0.40**
Short season	1.08	n/r	1.15	0.75	**1.15**	**0.75**
Radish (*Raphanus sativus*)	n/r	n/r	0.90	0.85	**0.90**	**0.85**
Rutabaga (*Brassica napobrassica*)	n/r	n/r	1.10	0.95	**1.10**	**1.00**
Sweet potato (*Ipomoea batatas*)	0.93–1.21	0.44–0.81	1.15	0.65	**1.10**	**0.60**
Table beets (*Beta vulgaris*)	n/r	n/r	1.05	0.95	**1.05**	**1.00**
Taro (*Colocasia esculenta*)	1.15	1.10	n/r	n/r	**1.10**	**1.05**
Turnip (*Brassica rapa var. rapa*)	n/r	n/r	1.10	0.95	**1.10**	**1.00**
Leaves and flowers vegetable crops						
Artichoke (*Cynara scolymus*)	0.77	n/r	1.00	0.95	**1.00**	**0.95**
Broccoli (*B. oleracea* v. *italica*)	1.09–1.11	1.09–1.11	1.05	0.95	**1.10**	**1.10**
Brussel sprouts (*B. oleracea* v. *gemmifera*)	n/r	n/r	1.05	0.95	**1.05**	**1.05**
Cabbage (*B. oleracea* v. *capitata*)	1.05–1.10	1.00–1.05	1.05	0.95	**1.05**	**1.00**
Cauliflower (*B. oleracea* v. *botrytis*)	n/r	n/r	1.05	0.95	**1.05**	**1.00**
Lettuce (*Lactuca sativa*)	0.92 – 1.08	0.92–1.08	1.00	0.95	**1.00**	**1.00**
Spinach (*Spinacia oleracea*)	0.98	0.98	1.00	0.95	**1.00**	**1.00**
Fruit and pod vegetable crops						
Bell pepper (*Capsicum annuum*)	0.90–1.25	0.83–1.25	1.05	0.90	**1.10**	**1.05**
Chili pepper (*Capsicum annuum*)	1.13	0.76	n/r	n/r	**1.10**	**0.80**
Chili, tabasco pepper (*Capsicum frutescens*)						
First harvest	1.32	0.73	n/r	n/r	**1.10**	**0.70**
Second harvest	1.16	0.62	n/r	n/r	**1.05**	**0.60**
Cucumber (*Cucumis sativus*)						
For processing	n/r	n/r	1.00	0.90	**1.05**	**0.90**
Fresh market	1.08	0.65	1.00	0.75	**1.05**	**0.80**
Eggplant (*Solanum melongena*)	0.99–1.19	0.96–1.06	1.05	0.90	**1.05**	**1.00**
Melon (*Cucumis melo*)	0.96–1.20	0.64–0.97	1.05	0.75	**1.05**	**0.85**
Melon, cantaloupe (*Cucumis melo*)	1.04	0.81	0.85	0.60	**1.00**	**0.80**
Okra (*Abelmoschus esculentus*)	0.93–1.00	0.63–0.90	n/r	n/r	**0.95**	**0.90**
Pumpkin, winter squash (*C. pepo*)	0.91	0.60	1.00	0.80	**1.00**	**0.80**
Squash, Zucchini (*Cucurbita pepo*)	1.01–1.07	0.65–0.70	0.95	0.75	**1.00**	**0.75**
Strawberries (*Fragaria × ananassa*)	0.73–0.78	n/r	0.85	0.75	**0.80**	**0.75**
Tomato (*Solanum lycopersicum*)						
For processing	1.08–1.09	0.75	1.15	0.70–0.90	**1.10**	**0.90**
Fresh market	1.08–1.11	0.63-1.07	1.20	n/r	**1.10**	**1.00**
Watermelon (*Citrullus lanatus*)	1.01–1.17	0.41–0.73	1.00	0.75	**1.05**	**0.70**
Herbs, spices and special vegetable crops						
Basil (*Ocimum basilicum*)						
Single harvest	1.05	1.05	n/r	n/r	**1.00**	**0.95**
Multiple harvest	1.00–1.05	0.32-0.53	n/r	n/r	**1.00**	**0.50**
Black cumin (*Nigella sativa*)	1.11	0.60	n/r	n/r	**1.05**	**0.60**
Coriander (*Coriandrum sativum*)	1.12–1.25	0.55-0.81	n/r	n/r	**1.10**	**0.75**
Lemon balm (*Melissa officinalis*)						
Single harvest	1.03	0.96	n/r	n/r	**1.05**	**1.00**
Multiple harvest	0.89	0.66	n/r	n/r	**0.90**	**0.65**
Mint (*Mentha spicata*)	n/r	n/r	1.15	1.10	**1.15**	**1.10**
Parsley (*Petroselinum crispum*)	1.00	n/r	n/r	n/r	**1.00**	**0.90**
Pineapple (*Ananas comosus*)	0.94	0.93	0.30–0.50	0.30-0.50	**0.90**	**0.90**
Saffron (*Crocus sativus*)	0.95	0.35	n/r	n/r	**0.95**	**0.35**

n/r – not reported.

Appendix D.5: Updated and FAO 56 tabulated Kc values for vegetables (Table 9 and in Pereira et al. 2021a)

Table 10
Updated standard basal crop coefficients $K_{cb\ mid}$ and $K_{cb\ end}$ for vegetable crops.

Crop	Observed, standard K_{cb}		FAO56 tabulated K_{cb}		Updated standard K_{cb}	
	$K_{cb\ mid\ (std)}$	$K_{cb\ end\ (std)}$	$K_{cb\ mid}$	$K_{cb\ end}$	$K_{cb\ mid}$	$K_{cb\ end}$
Roots, tubers, bulbs and stems vegetable crops						
Asparagus (*Asparagus officinalis*)	n/r	n/r	0.90	0.20	**0.90**	**0.20**
Carrots (*Daucus carota*)	n/r	n/r	0.95	0.85	**0.95**	**0.85**
Cassava (*Manihot esculenta*)						
Year 1	n/r	n/r	0.70	0.20	**0.90**	**0.45**
Year 2	n/r	n/r	1.00	0.45	**1.00**	**0.45**
Celery (*Apium graveolens*)	n/r	n/r	0.95	0.90	**0.95**	**0.90**
Garlic (*Allium sativum*)	0.95–1.00	0.15–0.35	0.90	0.60	**0.95**	**0.60**
Onions (*Allium cepa*)						
Dry	1.03	0.58	0.95	0.65	**0.95**	**0.55**
Green	n/r	n/r	0.90	0.90	**0.95**	**0.80**
Seed	n/r	n/r	0.95	0.70	**0.95**	**0.70**
Parsnip (*Pastinaca sativa*)	n/r	n/r	0.95	0.85	**0.95**	**0.90**
Potato (*Solanum tuberosum*)						
Long season	1.10	0.35	1.10	0.35	**1.10**	**0.35**
Short season	n/r	n/r	n/r	n/r	**1.10**	**0.65**
Radish (*Raphanus sativus*)	n/r	n/r	0.85	0.75	**0.85**	**0.75**
Rutabaga (*Brassica napus*)	n/r	n/r	1.00	0.85	**1.00**	**0.90**
Sweet potato (*Ipomoea batatas*)	n/r	n/r	1.10	0.55	**1.05**	**0.50**
Table beets (*Beta vulgaris*)	n/r	n/r	0.95	0.85	**0.95**	**0.90**
Taro (*Colocasia esculenta*)	n/r	n/r	n/r	n/r	**1.05**	**1.00**
Turnip (*Brassica rapa*)	n/r	n/r	1.00	0.85	**1.00**	**0.90**
Leaves and flowers vegetable crops						
Artichoke (*Cynara scolymus*)	n/r	n/r	0.95	0.90	**0.95**	**0.90**
Broccoli (*B. oleracea* var. *italica*)	0.94 – 1.01	0.94–1.01	0.95	0.85	**1.00**	**1.00**
Brussel sprouts (*B. oleracea* v. *gemmifera*)	n/r	n/r	0.95	0.85	**0.95**	**0.95**
Cabbage (*B. oleracea* v. *capitata*)	0.96	0.90	0.95	0.85	**0.95**	**0.90**
Cauliflower (*B. oleracea* v. *botrytis*)	n/r	n/r	0.95	0.85	**0.95**	**0.90**
Lettuce (*Lactuca sativa*)	0.84–0.97	0.80–0.97	0.90	0.90	**0.95**	**0.95**
Spinach (*Spinacia oleracea*)	n/r	n/r	0.90	0.85	**0.90**	**0.90**
Fruit and pod vegetable crops						
Bell pepper (*Capsicum annuum*)	1.01–1.06	0.95–1.03	1.00–1.10	0.80	**1.05**	**1.00**
Chili pepper (*Capsicum annuum*)	0.90–1.00	0.87–1.00	n/r	n/r	**1.00**	**0.75**
Chili, tabasco pepper (*Capsicum frutescens*)						
First harvest	n/r	n/r	n/r	n/r	**1.05**	**0.65**
Second harvest	n/r	n/r	n/r	n/r	**1.00**	**0.55**
Cucumber (*Cucumis sativus*)						
For processing	n/r	n/r	0.95	0.80	**1.00**	**0.80**
Fresh market	n/r	n/r	0.95–1.10	0.70	**1.00**	**0.70**
Eggplant (*Solanum melongena*)	n/r	n/r	1.00	0.80	**1.00**	**0.90**
Melon (*Cucumis melo*)	n/r	n/r	0.75	0.50	**0.95**	**0.75**
Melon, cantaloupe (*Cucumis melo*)	n/r	n/r	0.95	0.70	**0.95**	**0.70**
Okra (*Abelmoschus esculentus*)	0.83	n/r	n/r	n/r	**0.85**	**0.80**
Pumpkin, winter squash (*C. pepo*)	n/r	n/r	0.90	0.70	**0.95**	**0.70**
Squash, Zucchini (*Cucurbita pepo*)	0.96	0.67	0.95	0.70	**0.95**	**0.65**
Strawberries (*Fragaria* × *ananassa*)	n/r	n/r	0.80	0.70	**0.75**	**0.65**
Tomato (*Solanum lycopersicum*)						
For processing	1.12	n/r	1.10	0.60–0.80	**1.05**	**0.85**
Fresh market	n/r	n/r	1.15	0.60–0.80	**1.05**	**0.90**
Watermelon (*Citrus lanatus*)	n/r	n/r	0.95	0.70	**0.95**	**0.60**
Herbs, spices and special vegetable crops						
Basil (*Ocimum basilicum*)						
Single harvest	n/r	n/r	n/r	n/r	**0.95**	**0.90**
Multiple harvest	n/r	n/r	n/r	n/r	**0.95**	**0.45**
Black cumin (*Nigella sativa*)	1.02	0.48	n/r	n/r	**1.00**	**0.50**
Coriander (*Coriandrum sativum*)	1.02–1.04	0.68	n/r	n/r	**1.05**	**0.70**
Lemon balm (*Melissa officinalis*)						
Single harvest	1.00	1.00	n/r	n/r	**1.00**	**0.95**
Multiple harvest	n/r	n/r	n/r	n/r	**0.85**	**0.60**
Mint (*Mentha spicata*)	n/r	n/r	1.10	1.05	**1.10**	**1.05**
Parsley (*Petroselinum crispum*)	n/r	n/r	n/r	n/r	**0.95**	**0.85**
Pineapple (*Ananas comosus*)	n/r	n/r	0.25–0.45	0.25–0.45	**0.80**	**0.80**
Saffron (*Crocus sativus*)	0.65	0.15	n/r	n/r	**0.85**	**0.30**

n/r – not reported.

Appendix D.6: Updated and FAO 56 tabulated Kcb values for vegetables (Table 10 in Pereira et al. 2021a)

Table 11
Updated standard crop parameters for vegetable crops: maximum root depth ($Z_{r\ max}$), maximum crop height (h_{max}) maximum fraction of ground cover ($f_{c\ max}$) and soil water depletion fraction for no-stress (p) when ET_c is of 5 mm d^{-1}.

Crop	Observed				FAO56 tabulated			Updated standard		
	$Z_{r\ max}$ (m)	h_{max} (m)	$f_{c\ max}$	p	$Z_{r\ max}$ (m)	h_{max} (m)	p	$Z_{r\ max}$ (m)	h_{max} (m)	p
Roots, tubers, bulbs and steams vegetable crops										
Asparagus (*Asparagus officinalis*)	n/r	n/r	n/r	n/r	1.20–1.80	0.80	0.45	1.20–1.80	0.80	0.45
Carrots (*Daucus carota*)	0.30	0.30	n/r	0.30	0.50–1.00	0.30	0.35	0.30–0.50	0.30	0.30
Cassava (*Manihot esculenta*)										
Year 1	n/r	n/r	n/r	n/r	0.50–0.80	1.00	0.35	0.50–0.80	1.00	0.50
Year 2	n/r	n/r	n/r	n/r	0.70–1.00	1.50	0.40	0.70–1.00	1.50	0.50
Celery (*Apium graveolens*)	n/r	n/r	n/r	n/r	0.30–0.50	0.60	0.20	0.30–0.50	0.60	0.20
Garlic (*Allium sativum*)	0.30	0.65	0.85	0.30	0.30–0.50	0.30	0.30	0.30–0.50	0.50	0.30
Onions (*Allium cepa*)	0.40	n/r	0.72	0.30	0.30–0.60	0.40	0.30	0.30–0.60	0.45	0.30
Parsnip (*Pastinaca sativa*)	n/r	n/r	n/r	n/r	0.50–1.00	0.40	0.40	0.50–1.00	0.40	0.40
Potato (*Solanum tuberosum*)	0.50	0.60	0.88	0.40	0.40–0.60	0.60	0.35	0.40–0.60	0.60	0.40
Radish (*Raphanus sativus*)	n/r	n/r	n/r	n/r	0.30–0.50	0.30	0.30	0.30–0.50	0.30	0.30
Rutabaga (*Brassica napus*)	n/r	n/r	n/r	n/r	0.50–1.00	0.60	0.50	0.50–1.00	0.60	0.50
Sweet potato (*Ipomoea batatas*)	1.00	0.50	0.98	0.45	1.00–1.50	0.40	0.65	1.00–1.20	0.50	0.40
Table beets (*Beta vulgaris*)	n/r	n/r	n/r	n/r	0.60–1.00	0.40	0.50	0.60–1.00	0.40	0.45
Taro (*Colocasia esculenta*)	0.30	1.20	n/r	n/r	n/r	n/r	n/r	0.30–0.40	1.20	0.40
Turnip (*Brassica rapa*)	n/r	n/r	n/r	n/r	0.50–1.00	0.60	0.50	0.50–1.00	0.60	0.50
Leaves and flowers vegetable crops										
Artichoke (*Cynara scolymus*)	n/r	n/r	0.60	n/r	0.60–0.90	0.70	0.45	0.60–0.90	0.80	0.45
Broccoli (*B. oleracea* var. *italica*)	0.40	0.60	0.95	0.45	0.40–0.60	0.30	0.45	0.40–0.60	0.60	0.40
Brussel sprouts (*B. oleracea* var. *gemmifera*)	n/r	n/r	n/r	n/r	0.40–0.60	0.40	0.45	0.40–0.60	0.75	0.40
Cabbage (*B. oleracea*)	0.30	n/r	n/r	0.40	0.50–0.80	0.40	0.45	0.30–0.50	0.40	0.40
Cauliflower (*B. oleracea* var. *botrytis*)	n/r	n/r	n/r	n/r	0.40–0.70	0.40	0.45	0.40–0.60	0.40	0.40
Lettuce (*Lactuca sativa*)	0.30	0.37	0.70	n/r	0.30–0.50	0.30	0.30	0.30–0.50	0.35	0.30
Spinach (*Spinacia oleracea*)	n/r	n/r	n/r	n/r	0.30–0.50	0.30	0.20	0.30–0.50	0.35	0.20
Fruit and pod vegetable crops										
Bell pepper (*Capsicum annuum*)	0.60	0.60	0.90	n/r	0.50–1.00	0.70	0.30	0.50–1.00	0.70	0.30
Chili pepper (*Capsicum annuum*)	0.60	0.76	0.82	0.20	n/r	n/r	n/r	0.50–1.00	0.75	0.30
Chili, tabasco pepper (*Capsicum frutescens*)	0.60	0.80	0.55	n/r	n/r	n/r	n/r	0.50–1.00	0.80	0.30
Cucumber (*Cucumis sativus*)	0.60	n/r	n/r	n/r	0.70–1.20	0.30	0.50	0.60–1.20	0.30	0.40
Eggplant (*Solanum melongena*)	0.40	n/r	n/r	n/r	0.70–1.20	0.80	0.45	0.40–1.00	0.80	0.45
Melon (*Cucumis melo*)	0.60	0.30	0.95	n/r	0.80–1.50	0.40	0.40	0.60–1.20	0.30	0.40
Melon, cantaloupe (*Cucumis melo*)	n/r	n/r	n/r	n/r	0.90–1.50	0.30	0.45	0.60–1.20	0.30	0.40
Okra (*Abelmoschus esculentus*)	0.60	0.90	n/r	0.40	n/r	n/r	n/r	0.60–0.80	0.90	0.40
Pumpkin, winter squash (*C. pepo*)	0.90	n/r	n/r	n/r	1.00–1.50	0.40	0.35	0.90–1.50	0.40	0.40
Squash, Zucchini (*Cucurbita pepo*)	0.50	0.55	0.99	0.50	0.60–1.10	0.30	0.50	0.60–1.10	0.50	0.50
Strawberries (*Fragaria × ananassa*)	n/r	n/r	0.80	n/r	0.20–0.30	0.20	0.20	0.30–0.50	0.20	0.25
Tomato (*Solanum lycopersicum*)										
Processing	1.00	0.70	0.95	0.30	0.70–1.50	0.60	0.40	0.60–1.20	0.70	0.40
Fresh market	0.60	1.25	0.85	0.30	0.70–0.50	2.00	0.40	0.60–1.20	0.70*	0.40
Watermelon (*Citrullus lanatus*)	n/r	n/r	0.80	n/r	0.80–1.50	0.40	0.40	0.80–1.50	0.40	0.40
Herbs, spices and special vegetable crops										
Basil (*Ocimum basilicum*)	0.30	0.40	1.00	0.10	n/r	n/r	n/r	0.30–0.60	0.40	0.30
Black cumin (*Nigella sativa*)	0.60	n/r	n/r	0.30	n/r	n/r	n/r	0.50–0.80	0.40	0.40
Coriander (*Coriandrum sativum*)	0.60	0.13	n/r	0.10	n/r	n/r	n/r	0.30–0.50	0.30	0.30
Lemon balm (*Melissa officinalis*)	n/r	0.15	0.80	n/r	n/r	n/r	n/r	0.30–0.50	0.50	0.40
Mint (*Mentha spicata*)	n/r	n/r	n/r	n/r	0.40–0.80	0.60–0.80	0.40	0.40–0.80	0.40	0.40
Oregano (*Origanum vulgare*)	n/r	n/r	n/r	n/r	n/r	n/r	n/r	0.30–0.50	0.30	0.35
Parsley (*Petroselinum crispum*)	n/r	n/r	n/r	n/r	n/r	n/r	n/r	0.30–0.50	0.30	0.30
Pineapple (*Ananas comosus*)	n/r	1.15	n/r	n/r	0.30–0.60	0.60–1.20	0.50	0.30–0.60	1.20	0.50
Saffron (*Crocus sativus*)	0.60	n/r	n/r	n/r	n/r	n/r	n/r	0.50–0.80	0.20	0.30

*h_{max} = 1.50 m when cultivated with a trellis system.
$Z_{r\ max}$ – maximum root depth; h_{max} – maximum crop height; LAI_{max} – maximum leaf area index; $f_{c\ max}$ – maximum fraction of ground cover; p_{ini}, p_{mid}, p_{end} – soil water depletion fraction for no stress for the initial, mid- and end-season stages, respectively; n/r – not reported.

Appendix D.7: Updated standard indicative parameters for vegetables (Table 11 in Pereira et al. 2021a)

Table 11
Updated standard K_c and K_{cb} for grain legumes.

Crop	Observed, standard K_c and K_{cb}		FAO56 tabulated K_c and K_{cb}		Updated standard K_c and K_{cb}	
	$K_{c\ mid\ (std)}$	$K_{c\ end\ (std)}$	$K_{c\ mid}$	$K_{c\ end}$	$K_{c\ mid}$	$K_{c\ end}$
Single crop coefficient						
Bean (*Phaseolus vulgaris*)						
Green	n/r	n/r	1.05	0.90	**1.05**	**0.95**
Dry	0.98–1.12	0.47–0.49	1.15	0.35	**1.05**	**0.40**
Black and green gram (*Vigna mungo*)						
Black gram (dry)	1.22	0.39	1.05	0.35	**1.15**	**0.35**
Green gram	0.88–0.94	0.29–0.40	1.05	0.60	**1.15**	**0.65**
Chickpea (garbanzo) (*Cicer arietinum*)	0.95–1.03	0.29–0.47	1.00	0.35	**1.10**	**0.35**
Cowpea (*Vigna unguiculata*)						
Green	n/r	n/r	1.05	0.60	**1.10**	**0.60**
Dry	1.11–1.23	0.49–0.55	1.05	0.35	**1.10**	**0.45**
Fababean (*Vicia faba*)						
Fresh	n/r	n/r	1.15	1.10	**1.10**	**1.05**
Dry	1.03–1.16	0.54	1.15	0.30	**1.10**	**0.40**
Groundnut (peanut) (*Arachis hypogaea*)	0.88–1.18	0.61–0.63	1.15	0.60	**1.10**	**0.60**
Lentil (*Lens culinaris*)	n/r	n/r	1.10	0.30	**1.05**	**0.30**
Pea (*Pisum sativum*)						
Fresh	1.21	1.16	1.15	1.10	**1.15**	**1.10**
Dry	n/r	n/r	1.15	0.30	**1.10**	**0.30**
Soybean (*Glycine max*)	0.99–1.16	0.18–0.45	1.15	0.50	**1.15**	**0.35**
Basal crop coefficient	$K_{cb\ mid\ (std)}$	$K_{cb\ end\ (std)}$	$K_{cb\ mid}$	$K_{cb\ end}$	$K_{cb\ mid}$	$K_{cb\ end}$
Bean (*Phaseolus vulgaris*)						
Green	n/r	n/r	1.00	0.80	**1.00**	**0.85**
Dry	n/r	n/r	1.10	0.25	**1.10**	**0.30**
Black and green gram (*Vigna mungo*)						
Black gram (dry)	1.14	0.33	1.00	0.25	**1.10**	**0.30**
Green gram	n/r	n/r	1.00	0.55	**1.10**	**0.55**
Chickpea (*Cicer arietinum*)	0.92	0.25	0.95	0.25	**1.05**	**0.25**
Cowpea (*Vigna unguiculata*)						
Green	n/r	n/r	1.00	0.55	**1.05**	**0.50**
Dry	n/r	n/r	1.00	0.25	**1.05**	**0.35**
Fababean (*Vicia faba*)						
Fresh	n/r	n/r	1.10	1.05	**1.05**	**0.95**
Dry	n/r	n/r	1.10	0.20	**1.05**	**0.30**
Groundnut (peanut) (*Arachis hypogaea*)	n/r	n/r	1.10	0.50	**1.05**	**0.50**
Lentil (*Lens culinaris*)	n/r	n/r	1.05	0.20	**1.00**	**0.20**
Pea (*Pisum sativum*)						
Fresh	1.16	1.13	1.10	1.05	**1.10**	**1.05**
Dry	n/r	n/r	1.10	0.20	**1.05**	**0.25**
Soybean (*Glycine max*)	1.05–1.13	0.15–0.35	1.10	0.30	**1.10**	**0.25**

Appendix D.8: Updated and FAO 56 tabulated Kc and Kcb values for legumes (Table 11 in Pereira et al. 2021b)

Table 12
Updated standard K_c and K_{cb} for fiber crops, oil crops and sugar crops.

Crop	Observed, standard K_c and K_{cb}		FAO56 tabulated K_c and K_{cb}		Updated standard K_c and K_{cb}	
	$K_{c\ mid\ (std)}$	$K_{c\ end\ (std)}$	$K_{c\ mid}$	$K_{c\ end}$	$K_{c\ mid}$	$K_{c\ end}$
Single crop coefficient						
Fiber crops						
Cotton (*Gossypium hirsutum*)	0.88–1.22	0.20–0.75	1.15–1.20	0.70–0.50	**1.10**	**0.50**
Flax (Linseed) (*Linum usitatissimum*)	n/r	n/r	1.10	0.25	**1.05**	**0.25**
Sisal (*Agave sisalana*)	n/r	n/r	0.40–0.70	0.40–0.70	**0.55**	**0.55**
Oil crops						
Camelina (*Camelina sativa*)	1.12	0.47	n/r	n/r	**1.10**	**0.45**
Canola (*Brassica napus*)	1.15	0.35	1.00–1.15	0.35	**1.10**	**0.35**
Castorbean (*Ricinus communis*)	1.09	0.82	1.15	0.55	**1.10**	**0.55**
Linseed (Flax) (*Linum usitatissimum*)	0.95–0.97	0.20–0.26	n/r	n/r	**0.95**	**0.25**
Mustard (*Brassica juncea*)	1.00–1.17	0.35–0.45	n/r	n/r	**1.15**	**0.40**
Safflower (*Carthamus tinctorius*)	1.04–1.22	0.22–0.30	1.00–1.15	0.25	**1.10**	**0.25**
Sesame (*Sesamum indicum*)	1.00	n/r	1.10	0.25	**1.05**	**0.25**
Sunflower (*Helianthus annuus*)	1.07–1.20	0.10–0.36	1.00–1.15	0.35	**1.20**	**0.30**
Sugar crops						
Sugar beet (*Beta vulgaris*)	0.96–1.11	0.82–0.83	1.20	0.70	**1.05**	**0.75**
Sugar cane (*Saccharum officinarum*)	1.03–1.23	0.56–0.83	1.25	0.75	**1.20**	**0.80**
Basal crop coefficient	$K_{cb\ mid\ (std)}$	$K_{cb\ end\ (std)}$	$K_{cb\ mid}$	$K_{cb\ end}$	$K_{cb\ mid}$	$K_{cb\ end}$
Fiber crops						
Cotton (*Gossypium hirsutum*)	1.02–1.21	0.15–0.56	1.10–1.15	0.50–0.40	**1.05**	**0.40**
Flax (Linseed) (*Linum usitatissimum*)	n/r	n/r	1.05	0.20	**1.00**	**0.20**
Sisal (*Agave sisalana*)	n/r	n/r	0.40–0.70	0.40–0.70	**0.50**	**0.50**
Oil crops						
Camelina (*Camelina sativa*)	1.09–1.10	0.37–0.47	n/r	n/r	**1.05**	**0.40**
Canola (*Brassica napus*)	0.94–1.11	0.20	0.95–1.10	0.25	**1.05**	**0.25**
Castorbean (*Ricinus communis*)	n/r	n/r	1.10	0.45	**1.05**	**0.45**
Linseed (Flax) (*Linum usitatissimum*)	0.92	0.18	n/r	n/r	**0.90**	**0.20**
Mustard (*Brassica juncea*)	n/r	n/r	n/r	n/r	**1.10**	**0.35**
Safflower (*Carthamus tinctorius*)	n/r	n/r	0.95–1.10	0.20	**1.05**	**0.20**
Sesame (*Sesamum indicum*)	n/r	n/r	1.05	0.20	**1.00**	**0.20**
Sunflower (*Helianthus annuus*)	1.10–1.16	0.20–0.25	0.95–1.10	0.25	**1.15**	**0.25**
Sugar crops						
Sugar beet (*Beta vulgaris*)	1.11	n/r	1.15	0.50	**1.00**	**0.65**
Sugar cane (*Saccharum officinarum*)	n/r	n/r	1.20	0.70	**1.15**	**0.70**

Appendix D.9: Updated and FAO 56 tabulated Kc and Kcb values for fiber crops, oil crops and sugar crops (Table 12 in Pereira et al. 2021b)

Table 13
Updated standard K_c and K_{cb} for cereals.

Crop	Observed, standard K_c and K_{cb}		FAO56 tabulated K_c and K_{cb}		Updated standard K_c and K_{cb}	
	$K_{c\ mid\ (std)}$	$K_{c\ end\ (std)}$	$K_{c\ mid}$	$K_{c\ end}$	$K_{c\ mid}$	$K_{c\ end}$
Single crop coefficient						
Amaranth grain (*Amaranthus* sp.)	1.15	0.20	n/r	n/r	**1.10**	**0.25**
Barley (*Hordeum vulgare*)	0.98–1.07	0.20–0.30	1.15	0.25	**1.05**	**0.25**
Oats (*Avena sativa*)	n/r	n/r	1.15	0.25	**1.05**	**0.25**
Pearl Millet (*Pennisetum glaucum*)	n/r	n/r	1.00	0.30	**1.10**	**0.35**
Quinoa (*Chenopodium quinoa*)	1.01–1.15	0.40–0.67	n/r	n/r	**1.10**	**0.50**
Rye (*Secale cereale*)	n/r	n/r	n/r	n/r	**1.00**	**0.35**
Teff (*Eragrotis tef*)	1.09	0.25	n/r	n/r	**1.05**	**0.25**
Wheat, common (*Triticum aestivum*)						
Winter, low grain moisture	1.02–1.28	0.10–0.42	1.15	0.25	**1.15**	**0.25**
Winter, high grain moisture	1.06–1.26	0.45–0.64	1.15	0.40	**1.15**	**0.55**
Spring, low grain moisture	1.11–1.17	0.20–0.32	1.15	0.25	**1.15**	**0.25**
Spring, high grain moisture	n/r	n/r	1.15	0.40	**1.15**	**0.45**
Wheat, durum (*Triticum durum*)						
Winter, low grain moisture	1.03	0.25	n/r	n/r	**1.05**	**0.25**
Winter, high grain moisture	n/r	n/r	n/r	n/r	**1.05**	**0.55**
Maize (*Zea mays*)						
Low grain moisture	1.04–1.28	0.15–0.56	1.20	0.35	**1.20**	**0.30**
High grain moisture	1.03–1.30	0.55–0.80	1.20	0.60	**1.20**	**0.65**
Silage	1.01–1.21	0.54–1.01	n/r	n/r	**1.20**	**0.95**
Sweet	n/r	n/r	1.15	1.05	**1.15**	**1.05**
Sorghum (*Sorghum bicolor*)						
Grain	0.91–1.25	0.40–0.76	1.00–1.10	0.55	**1.10**	**0.45**
Silage	0.90	0.90	n/r	n/r	**1.10**	**0.90**
Sweet	0.90–1.10	0.55	1.20	1.05	**1.15**	**0.95**
Basal crop coefficient	$K_{cb\ mid\ (std)}$	$K_{cb\ end\ (std)}$	$K_{cb\ mid}$	$K_{cb\ end}$	$K_{cb\ mid}$	$K_{cb\ end}$
Amaranth grain (*Amaranthus* sp.)	1.05	0.13	n/r	n/r	**1.05**	**0.20**
Barley (*Hordeum vulgare*)	1.00–1.04	0.10	1.10	0.15	**1.00**	**0.20**
Oats (*Avena sativa*)	n/r	n/r	1.10	0.15	**1.00**	**0.20**
Pearl Millet (*Pennisetum glaucum*)	n/r	n/r	0.95	0.20	**1.05**	**0.25**
Quinoa (*Chenopodium quinoa*)	1.00	0.20	n/r	n/r	**1.05**	**0.45**
Rye (*Secale cereale*)	n/r	n/r	n/r	n/r	**0.95**	**0.30**
Teff (*Eragrostis tef*)	0.90	n/r	n/r	n/r	**1.00**	**0.20**
Wheat, common (*Triticum aestivum*)						
Winter, low grain moisture	0.99–1.12	0.25–0.30	1.10	0.15	**1.10**	**0.20**
Winter, high grain moisture	1.14	0.30–0.59	1.10	0.30	**1.10**	**0.45**
Spring, low grain moisture	1.05–1.15	0.15–0.25	1.10	0.15	**1.10**	**0.20**
Spring, high grain moisture	1.12	0.35	1.10	0.30	**1.10**	**0.40**
Wheat, durum (*Triticum durum*)						
Winter, low grain moisture	0.91	0.23	n/r	n/r	**1.00**	**0.20**
Winter, high grain moisture	n/r	n/r	n/r	n/r	**1.00**	**0.45**
Maize (*Zea mays*)						
Low grain moisture	1.02–1.17	0.20–0.30	1.15	0.15	**1.15**	**0.25**
High grain moisture	0.93–1.23	0.45–0.77	1.15	0.50	**1.15**	**0.60**
Silage	1.09–1.18	0.54–0.87	n/r	n/r	**1.15**	**0.85**
Sweet	n/r	n/r	1.10	1.00	**1.10**	**1.05**
Sorghum (*Sorghum bicolor*)						
Grain	0.87–0.99	0.39–0.55	0.95–1.05	0.35	**1.05**	**0.35**
Silage	n/r	n/r	n/r	n/r	**1.05**	**0.85**
Sweet	0.90–1.08	0.35	1.15	1.00	**1.10**	**0.90**

Appendix D.10: Updated and FAO 56 tabulated Kc and Kcb values for cereals (Table 13 in Pereira et al. 2021b)

Table 14
Updated standard K_c and K_{cb} values for rice (*Oryza sativa* L.) compared with reported observed data adjusted to the standard sub-humid climate and the FAO56 tabulated values for flooded paddies *(italics, in brackets)*.

Irrigation method	Observed K_c adjusted to climate			Updated crop coefficients		
Single crop coefficient	$K_{c\ ini\ (std)}$	$K_{c\ mid\ (std)}$	$K_{c\ end\ (std)}$	K_{cini}	$K_{c\ mid}$	$K_{c\ end}$
Flooded	0.97–1.16	1.01–1.29	0.73–1.14	**1.05** *(1.05)*	**1.20** *(1.20)*	**1.05** ***(0.90–0.60)***
Flooded, dry seeding	0.67–1.10	1.00–1.26	0.96–1.19	**0.85**	**1.20**	**1.05**
Flooded, anticipated cut-off	n/r	n/r	n/r	**1.05**	**1.20**	**0.80**
Intermittent	0.70–1.05	1.21–1.32	0.73–1.23	**0.95**	**1.20**	**1.00**
Aerobic, sprinkler irrigation	0.91–0.92	1.03–1.07	0.96–1.01	**0.90**	**1.10**	**0.95**
Aerobic, surface irrigation	0.60–0.95	1.04–1.17	0.51–0.98	**0.90**	**1.10**	**0.95**
Rainfed	0.75	1.23	0.82	**0.80**	**1.10**	**0.80**
Basal crop coefficient				$K_{cb\ ini}$	$K_{cb\ mid}$	$K_{cb\ end}$
Flooded	n/r	n/r	n/r	**0.15** *(1.00)*	**1.15** *(1.15)*	**0.90** ***(0.70–0.45)***
Flooded, dry seeding	0.07	0.96	0.72	**0.15**	**1.15**	**0.90**
Flooded, dry late season	n/r	n/r	n/r	**0.15**	**1.15**	**0.70**
Intermittent	n/r	n/r	n/r	**0.15**	**1.15**	**0.85**
Aerobic, sprinkler irrigation	0.20	1.21	0.58	**0.15**	**1.05**	**0.85**
Aerobic, surface irrigation	n/r	n/r	n/r	**0.15**	**1.05**	**0.85**
Rainfed	n/r	n/r	n/r	**0.15**	**1.05**	**0.70**

Appendix D.11: Updated and FAO 56 tabulated Kc and Kcb values for rice (Table 14 in Pereira et al. 2021b)

Table 15
Updated indicative ancillary crop parameters for grain legumes, fiber, oil and sugar crops and cereals.

Crop	Observed				FAO56 tabulated			Updated standard		
	$Z_{r\,max}$ (m)	h_{max} (m)	$f_{c\,max}$	p	$Z_{r\,max}$ (m)	h_{max} (m)	p	$Z_{r\,max}$[b] (m)	h_{max} (m)	p
Grain legumes										
Bean (*P. vulgaris*)	0.60–0.90	0.66	n/r	0.30	0.60–0.90	0.40	0.45	0.50–0.90	0.50–0.70	0.45
Black & green gram (*V. mungo*)										
Black gram (dry)	0.60	0.40	0.94	0.50	0.60–1.00	0.40	0.45	0.60–1.00	0.50–0.70	0.45
Green gram	0.40	n/r	n/r	n/r	n/r	n/r	n/r	0.40–1.00	0.60–0.90	0.45
Chickpea (*C. arietinum*)	0.80–0.90	0.41	0.80–0.97	n/r	0.60–1.00	0.40–0.80	0.45	0.70–1.00	0.50–0.70	0.45
Cowpea (*V. unguiculata*)	1.50	n/r	0.80	0.20	0.600–1.0	0.40	0.45	0.60–1.30	0.60–0.80	0.45
Fababean (*V. faba*)	n/r	n/r	0.85	n/r	0.5–0.7	0.80	0.45	0.50–0.70	0.80	0.45
Groundnut (*A. hypogaea*)	0.60–1.00		0.90	0.55	0.50–1.0	0.40	0.50	0.50–1.00	0.50	0.50
Lentil (*L. culinaris*)	n/r	n/r	n/r	n/r	0.60–0.8	0.50	0.50	0.60–0.80	0.50	0.50
Pea (*P. sativum*)										
Fresh	0.80	0.50	0.98	0.40	0.60–1.0	0.50	0.35	0.60–1.00	0.60	0.35
Dry	n/r	n/r	n/r	n/r	0.60–1.0	0.50	0.40	0.60–1.00	0.80	0.45
Soybean (*G. max*)	1.00–1.40	0.75–1.05	0.98–1.00	0.50	0.60–1.3	0.50–1.00	0.50	0.60–1.40	0.80	0.50
Fiber crops										
Cotton (*G. hirsutum*)	1.10–1.70	0.86–1.86	0.81–0.90	0.55–0.70	1.00–1.70	1.20–1.50	0.65	1.00–1.70	1.20	0.60
Flax (*L. usitatissimum*)	n/r	n/r	n/r	n/r	1.00–1.50	1.20	0.50	1.00–1.50	1.00	0.50
Sisal (*A. sisalana*)	n/r	n/r	n/r	n/r	0.50–1.00	1.50	0.80	0.50–1.00	1.50	0.80
Oil crops										
Camelina (*C. sativa*)	1.50–1.70	0.65–0.83	0.96–0.97	0.60–0.65	n/r	n/r	n/r	1.00–1.50	0.80	0.60
Canola (*B. napus*)	0.40–1.20	1.00	0.80–0.97	0.45	1.00–1.50	0.60	0.60	0.80–1.30	1.00–1.50	0.50
Castorbean (*R. communis*)	0.60	n/r	n/r	n/r	1.00–1.50	0.30	0.60	0.80–1.30	1.00–1.50	0.60
Linseed (*L. usitatissimum*)	0.67	n/r	n/r	n/r	n/r	n/r	n/r	1.00–1.50	0.90	0.60
Mustard (*B. juncea*)	0.40–1.17	0.95–1.60	n/r	0.50	n/r	n/r	n/r	0.50–1.10	1.50–2.00	0.55
Safflower (*C. tinctorius*)	1.66	1.09	n/r	n/r	1.00–2.00	0.80	0.60	1.00–2.00	1.10	0.60
Sesame (*S. indicum*)	n/r	n/r	n/r	n/r	1.00–1.50	1.00	0.60	1.00–1.50	1.30	0.60
Sunflower (*H. annuus*)	0.90–2.00	1.20–2.00	0.85–0.88	0.25–0.80	0.80–1.50	2.00	0.45	0.80–2.00	2.00	0.45
Sugar crops										
Sugar beet (*B. vulgaris*)	1.00	0.50	0.80	0.55	0.70–1.20	0.50	0.55	0.70–1.20	0.50	0.55
Sugar cane (*S. officinarum*)	0.60–0.75	2.54–4.00	0.97–0.98	0.65–0.80	1.20–2.00	3.00	0.65	1.00–1.50	3.00–4.00	0.60
Cereal crops										
Amaranth grain (*Amaranthus*)	0.60	1.70	0.90	n/r	n/r	n/r	n/r	0.50–1.50	2.00	0.55
Barley (*H. vulgare*)	0.60–0.90	0.80	0.80–0.88	0.55–0.60	1.00–1.50	1.00	0.55	0.60–1.20	0.70–0.90	0.55
Oats (*A. sativa*)	n/r	n/r	n/r	n/r	1.00–1.50	1.00	0.55	1.00–1.50	0.80–1.10	0.55
Pearl Millet (*P. glaucum*)	n/r	n/r	n/r	n/r	1.00–2.00	1.50	0.55	1.00–2.00	2.00	0.55
Quinoa (*C. quinoa*)	0.55	1.00	0.60	n/r	n/r	n/r	n/r	0.60–1.20	1.00–1.20	0.55
Rye (*S. cereale*)	n/r	n/r	n/r	n/r	n/r	n/r	n/r	0.60–1.20	0.90	0.55
Teff (*E. tef*)	0.30–1.00	n/r	0.80	n/r	n/r	n/r	n/r	0.60–1.20	1.10	0.55
Wheat, common (*T. aestivum*)										
Winter	0.55–1.50	0.60–1.12	0.80–0.98	0.50–0.70	1.50–1.80	1.00	0.55	1.00–1.50	0.70–1.10	0.55
Spring	1.00–1.30	0.68–1.30	0.87–0.97	0.45–0.80	1.00–1.50	1.00	0.55	1.00–1.50	0.70–1.10	0.55
Wheat, durum (*T. durum*)	0.55	1.05	0.94	n/r	n/r	n/r	n/r	1.00–1.50	0.70–1.10	0.55
Maize (*Z. mays*)										
Grain	0.60–1.50	1.60–3.40	0.80–0.99	0.40–0.66	1.00–1.70	2.00	0.50	0.60–1.50	2.50–3.50	0.50
Silage	0.60–1.40	2.00–3.00	0.80–0.90	0.50–0.65	n/r	n/r	n/r	0.60–1.50	2.50–3.20	0.50
Sweet	n/r	n/r	n/r	n/r	0.80–1.20	1.50	0.50	0.60–1.50	1.50–2.50	0.50
Sorghum (*S. bicolor*)										
Grain	1.00–1.40	1.48–1.89	n/r	0.55	1.00–2.00	1.00–2.00	0.55	1.00–1.50	1.50–2.00	0.55
Silage	1.40	3.00	n/r	n/r	n/r	n/r	n/r	1.00–1.50	2.00–3.00	0.55
Sweet	0.65–1.80	2.46–4.60	0.87–1.00	0.50	1.00–2.00	2.00–4.00	0.50	0.60–1.50	3.00–4.00	0.55

$Z_{r\,max}$ – maximum root depth; h_{max} – maximum crop height; LAI_{max} – maximum leaf area index; $f_{c\,max}$ – maximum fraction of ground cover; p – soil water depletion fraction for no stress at mid-season growth stage.
[a]All crop data depends on the crop variety and its adaptation to actual environmental conditions and cropping practices.
[b]Root depths depend on soil texture and structure. The first figure refers to heavy soils and the second to light soils.

Appendix D.12: Updated standard indicative parameters for grain legumes, fiber crops, oil crops, sugar crops and cereals (Tables 15 in Pereira et al. 2021a)

Table 16
Updated indicative ancillary parameters of the rice crop (*Oryza sativa L.*) compared with reported observed values and, in brackets and italics, the tabulated FAO56 values.

Irrigation method	Observed					Updated standard		
	$Z_{r\,max}$ (m)	h_{max} (m)	LAI_{max}	$f_{c\,max}$	p	$Z_{r\,max}$ (m)	h_{max} (m)	p
Flooded paddies	0.30-0.70 *(0.50–1.00)*	0.55–1.36 *(1.00)*	3.3–4.2 n/r	0.95 n/r	0.10 θ_{sat} (*0.20* θ_{sat})	0.50	1.00	0.20 θ_{sat}
Intermittent irrigation	0.30–0.45	0.70–1.00	n/r	n/r	0.10–0.20 θ_{sat}	0.70	1.00	0.20 θ_{sat}
Aerobic rice	0.40	0.70–0.83	4.0–5.2	0.95	n/r	1.00	0.80	0.35 ASW

$Z_{r\,max}$ — maximum root depth; h_{max} — maximum crop height; LAI_{max} — maximum leaf area index; $f_{c\,max}$ — maximum fraction of ground cover; p — soil water depletion fraction for no stress; Θ_{sat} — soil water at saturation; ASW — available soil water.

Appendix D.13: Updated standard indicative parameters for rice (Tables 16 in Pereira et al. 2021a)

Table 5
Updated indicative standard values for single and basal crop coefficients relative to the mid- and end-season for vine fruit crops, berries and hops, including reviewed literature and previous tabulated values.

Crop	Plant density and training system	f_c[a]	Plant height[a]	Literature reported K_c and K_{cb}				Previous tabulated standard K_c and K_{cb}				Indicative standard values (±10%) of K_c and K_{cb}			
				$K_{c\ mid}$	$K_{cb\ mid}$	$K_{c\ end}$	$K_{cb\ end}$	$K_{c\ mid}$	$K_{cb\ mid}$	$K_{c\ end}$	$K_{cb\ end}$	$K_{c\ mid}$	$K_{cb\ mid}$	$K_{c\ end}$	$K_{cb\ end}$
Table grapes	Young	0.20–0.35	1.0–1.8	0.91	–	0.80	–	0.60[c]	0.55[c]	0.50[c]	0.45[c]	0.60	0.55	0.55	0.45
	Overhead trellis	0.90–0.95	2.0	1.05	0.65	0.70–0.80	–	0.85[d]–1.10[c]	0.80[d]–1.05[c]	0.45[d]–0.90[c]	0.40[d]–0.80[c]	0.95	0.90	0.70	0.65
	Horizontal trellis	0.60–0.70	1.7–1.8	1.00	0.77	0.80	0.62	–	–	–	–	0.90	0.85	0.80	0.70
	T trellis	0.40–0.50	2.0	0.84	–	–	–	0.95[c]	0.90[c]	0.75[c]	0.70[c]	0.80	0.75	0.60	0.55
	Y shape*	0.60–0.90	2.2	0.55–0.80	0.65	–	–	–	–	–	–	0.70	0.65	0.55	0.50
Wine grapes	Young	0.15–0.30	1.0–1.5	–	–	–	–	0.45[c]	0.40[c]	0.40[c]	0.30[c]	0.45	0.40	0.40	0.30
	Pergola	0.50–0.60	2.0	–	0.60	–	0.46	0.75[c]	0.70[c]	0.60[c]	0.55[c]	0.65	0.60	0.50	0.45
	VSP+	0.25–0.45	1.5–2.0	0.56–0.80	0.46–0.80	–	0.20–0.60	0.70[d]	0.65[d]	0.45[d]	0.40[d]	0.70	0.65	0.45	0.40
	Guyot	0.15–0.50	1.5–2.0	0.50		–		–	–	–		0.50	0.45	0.40	0.35
Kiwi	Pergola	0.80-0.90[b]	2.0[b]	–	0.70	–	–	1.05[d]	1.00[d]	1.05[d]	1.00[d]	0.95	0.90	0.90	0.80
Highbush blueberries	Young	0.20–0.30	<1.0	–	–	–	–	–	–	–	–	0.40	0.35	0.30	0.20
	Low	0.30–0.50	1.5–1.8	0.49–0.52	–	–	–	–	–	–	–	0.50	0.45	0.35	0.25
	Medium	0.50–0.70	1.5–1.8	0.84	–	–	–	–	–	–	–	0.80	0.75	0.35	0.30
	High	>0.70	1.8–2.0	1.00	–	–	–	1.05[d]	1.00[d]	0.50[d]	0.40[d]	0.95	0.90	0.40	0.35
Hop	V trellis	0.10–0.20	5.0–6.0	1.02	0.97	0.85	0.83	1.05[d]	1.00[d]	0.85[d]	0.80[d]	1.00	0.95	0.85	0.80

*- includes Y shape gable & Y trellis training systems. +VSP - Vertical shoot positioned trellis. [a]Observed f_c and plant height values from Table 1. [b]Indicative values from McAneney et al. (1984) and Xue et al. (2019). [c]Ranges of values from Allen and Pereira (2009) and Jensen and Allen (2016). [d]Values for common crop system management from Allen et al. (1998).

Appendix D.14: Updated indicative standard values of Kc and Kcb for vine, fruit crops, berries and hops (Tables 5 in Rallo et al. 2021)

Table 6
Updated indicative standard values for single and basal crop coefficients relative to the mid- and end-season, under temperate climate, for evergreen fruit tree crops including reviewed literature and previous tabulated values.

Crop	Plant density	f_c[a]	Plant height[a] (m)	Ranges of literature reported K_c and K_{cb}				Previous tabulated standard K_c and K_{cb}				Indicative standard values (±10%) of K_c and K_{cb}			
				$K_{c\ mid}$	$K_{cb\ mid}$	$K_{c\ end}$	$K_{cb\ end}$	$K_{c\ mid}$	$K_{cb\ mid}$	$K_{c\ end}$	$K_{cb\ end}$	$K_{c\ mid}$	$K_{cb\ mid}$	$K_{c\ end}$	$K_{cb\ end}$
Citrus	Young	<0.25	1.0–1.5	–	–	–	–	0.50[b]	0.45[b]	0.50[b]	0.45[b]	0.40	0.35	0.60	0.35
	Low density	0.25–0.40	2.3–4.5	0.55	0.40–0.56	–	0.40–0.61	0.45[c]–0.50[b]	0.40[c]–0.45[b]	0.55[c]–0.50[b]	0.45[c]–0.50[b]	0.55	0.50	0.65	0.50
	Medium density, short	0.40–0.65	<3.5	0.51–0.55	–		–	0.60[c]–0.75[b]	0.55[c]–0.70[b]	0.65[c]–0.75[b]	0.50[c]–0.70[b]	0.60	0.55	0.70	0.55
	Medium density, tall	0.40–0.65	>3.5	0.71	–	–	–	–	–	–	–	0.65	0.60	0.75	0.60
	High density, short	>0.65	2.5–3.5	0.60–0.78	0.55–0.80	0.50–0.80	0.35–0.63	–	0.60–0.85	–	0.65–0.85	0.70	0.65	0.80	0.65
	High density, tall	>0.65	4.0–4.5	1.00	–	–	–	0.65[c]–0.90[b]	0.60[c]–0.85[b]	0.70[c]–0.90[b]	0.65[c]–0.85[b]	0.90	0.85	0.95	0.85
Olive	Young	0.15–0.30	1.5–2.0	–	–	–	–	0.25[b]	0.20[b]	0.25[b]	0.20[b]	0.25	0.20	0.60	0.15
	Traditional, low density	0.15–0.20	2.5–3.0	0.35	–	–	–	–				0.30	0.25	0.60	0.20
	Traditional, medium density	0.20–0.30	3.0–3.5	0.65	0.59	–	–	0.40[b]	0.35[b]	0.35[b]	0.30[b]	0.45	0.40	0.65	0.30
	Intensive (hedge prune)	0.30–0.40	2.5–3.5	0.48	0.25–0.40	0.97	0.15–0.22	0.60[b]–0.70[c]	0.55[b]–0.65[c]	0.55[b]–0.70[c]	0.50[b]–0.65[c]	0.45	0.40	0.70	0.35
	Super-Intensive, medium density	0.25–0.35	3.0–3.5	0.56	0.35	0.45	0.25	–	–	–	–	0.40	0.35	0.70	0.30
	Super-intensive high density*	0.35–0.45	3.0–4.0	0.71	0.48	0.84	0.43	–	–	–	–	0.50	0.45	0.75	0.40

*- typically hedgerow orchards. [a]Observed f_c and tree height values from Table 2. [b]Ranges of values from Allen and Pereira (2009) and Jensen and Allen (2016). [c]Values for common crop system management from Allen et al. (1998).

Appendix D.15: Updated indicative standard values of Kc and Kcb for evergreen fruit tree crops (Tables 6 in Rallo et al. 2021)

Table 7
Updated indicative standard values for single and basal crop coefficients relative to the mid- and end-season, under temperate climate, for deciduous fruit tree crops including reviewed literature and previous tabulated values.

Crop	Density	f_c [a,b,c,d,e,f]	Plant height[a,b,c,d,e,f] (m)	Literature reported K_c and K_{cb}				Previous tabulated standard K_c and K_{cb}				Indicative standard values (±10%) of K_c and K_{cb}			
				$K_{c\ mid}$	$K_{cb\ mid}$	$K_{c\ end}$	$K_{cb\ end}$	$K_{c\ mid}$	$K_{cb\ mid}$	$K_{c\ end}$	$K_{cb\ end}$	$K_{c\ mid}$	$K_{cb\ mid}$	$K_{c\ end}$	$K_{cb\ end}$
Stone fruit trees															
Apricot[a], Cherry[b] & Plum[a]	Young	0.15–0.30	1.5–2.0	–	–	–	–	0.60[h]–0.70[h]	0.55[h]–0.65[h]	0.45[h]–0.55[h]	0.40[h]–0.50[h]	0.55	0.50	0.40	0.30
	Low	0.30–0.40	2.0–3.0	–	–	–	–	0.60[h]–0.70[h]	0.55[h]–0.65[h]	0.45[h]–0.55[h]	0.40–0.50	0.60	0.55	0.45	0.35
	Medium	0.40–0.50	2.5–3.5	–	–	–	–	0.90[i]	0.85[i]	0.65[i]	0.60[i]	0.80	0.75	0.55	0.50
	High	0.50–0.60	2.5–4.0	–	0.80–0.85	–	–	1.00[h]–1.05[h]	0.95[h]–1.00[h]	0.70[h]–0.75[h]	0.65[h]–0.70[h]	0.90	0.85	0.60	0.55
	Very high	>0.60	2.5–5.0	0.95–1.20	1.05–1.10	–	–	1.15[h]–1.20[h]	1.10[h]–1.15[h]	0.80[h]–0.85[h]	0.75[h]–0.80[h]	1.05	1.00	0.70	0.65
Peach[a]	Young	0.15–0.25	1.5–2.5	0.90–0.95	0.60–0.70	–	0.16–0.20	0.60[h]	0.55[h]	0.45[h]	0.40[h]	0.55	0.50	0.45	0.35
	Low	0.25–0.40	2.5–3.0	–	0.44	–	–	0.60[h]	0.55[h]	0.45[h]	0.40[h]	0.65	0.60	0.50	0.40
	Medium	0.40–0.60	2.5–3.5	–	1.00	–	–	0.90[i]–1.00[h]	0.85[i]–0.95[h]	0.65[i]–0.70[h]	0.60[i]–0.65[h]	0.90	0.85	0.65	0.60
	High	>0.60	4.0–5.0	1.10	1.05–1.10	0.75	–	1.15[h]–1.20[h]	1.10[h]–1.15[h]	0.80[h]–0.85[h]	0.75[h]–0.80[h]	1.05	1.00	0.70	0.65
Pome fruit trees															
Apple[a]	Young	<0.25	1.0–1.8	–	–	–	–	0.70[h]	0.65[h]	0.55[h]	0.50[h]	0.40	0.35	0.35	0.25
	Low	0.25–0.30	3.0–3.6	0.48		–	–	0.70[h]	0.65[h]	0.55[h]	0.50[h]	0.50	0.45	0.40	0.30
	Medium	0.30–0.40	3.0–3.6	0.55–0.65	–	–	–	0.95[i]	0.90[i]	0.75[i]	0.70[i]	0.70	0.65	0.55	0.45
	High	0.40–0.50	3.0–3.6	0.76–1.04	0.60	0.17	0.10	1.05[h]	1.00[h]	0.75[h]	0.70[h]	0.90	0.85	0.65	0.45
	Very high	>0.50	3.0–4.5	0.85–1.01	0.80–1.00	0.40–0.84	0.10	1.15[h]	1.10[h]	0.80[h]	0.75[h]	1.00	0.95	0.65	0.60
Pear[a]	Young	<0.25	1.0–1.5	–		–		0.70[h]	0.65[h]	0.55[h]	0.50[h]	0.40	0.35	0.30	0.20
	Low	0.25–0.35	2.0–3.0	0.87–1.05	–	–	–	0.70[h]	0.65[h]	0.55[h]	0.50[h]	0.55	0.50	0.45	0.35
	Medium	0.35–0.40	2.0–3.0	1.00	–	–	–	0.95[i]	0.90[i]	0.75[i]	0.70[i]	0.85	0.80	0.65	0.60
	High	0.40–0.50	2.0–3.0	–	0.85–0.90	–	–	1.05[h]	1.00[h]	0.75[h]	0.70[h]	1.00	0.95	0.75	0.70
	Very high	>0.50	3.3–3.6	–	–	–	–	1.15[h]	1.10[h]	0.80[h]	0.75[h]	1.10	1.05	0.85	0.80
Nut trees															
Almond[a]	Young	0.15–0.30	1.0–2.0	–	–	–	–	0.50[h]	0.45[h]	0.40[h]	0.35[h]	0.40	0.35	0.35	0.25
	Low	0.30–0.40	4.0–5.0	–	0.45	–	0.40	0.50[h]	0.45[h]	0.40[h]	0.35[h]	0.45	0.40	0.40	0.30
	Medium	0.40–0.50	4.0–5.0	–	0.60	–	0.40	–	–	–	–	0.65	0.60	0.50	0.40
	High	0.50–0.60	4.0–5.0	–	0.75–1.00	–	0.50–0.65	0.85[h]–0.95[i]	0.80[h]–0.85[i]	0.60[h]–0.75[i]	0.55[h]–0.60[i]	0.90	0.85	0.65	0.60
	Very high	>0.60	4.0–5.5	1.12–1.20	0.95	–	0.60	1.00[h]	0.95[h]	0.70[h]	0.65[h]	1.05	1.00	0.75	0.70
Hazelnut[c]	Young	0.15–0.30	1.0–2.0		–		–	–	–	–	–	0.45	0.40	0.40	0.20
	Low	0.30–0.45	4.0–5.0	0.80	–	–	–	–	–	–	–	0.75	0.70	0.55	0.45
	High	0.45–0.60	1.5–2.0	0.93	–	0.80	–	–	–	–	–	0.95	0.90	0.65	0.55
Pecan[a]	Young	0.25–0.30	1.0–5.0	–	–	–	–	–	–	–	–	0.55	0.50	0.50	0.35
	Low	0.30–0.60	5.0–10.0	0.78	–	0.50	–	–	–	–	–	0.75	0.70	0.55	0.45
	Medium	0.60–0.70	7.0–11.5	0.85	–	0.63	–	–	–	–	–	0.85	0.80	0.60	0.55
	High	>0.70	10.0–13.5	0.90–1.14	–	0.39–0.70	–	–	–	–	–	1.00	0.95	0.65	0.60

Appendix D.16: Updated indicative standard values of Kc and Kcb for deciduous fruit tree crops (Tables 7 in Rallo et al. 2021)

Table 7 (*continued*).

Crop	Density	f_c[a,b,c,d,e,f]	Plant height[a,b,c,d,e,f] (m)	Literature reported K_c and K_{cb}				Previous tabulated standard K_c and K_{cb}				Indicative standard values (±10%) of K_c and K_{cb}			
				$K_{c\ mid}$	$K_{cb\ mid}$	$K_{c\ end}$	$K_{cb\ end}$	$K_{c\ mid}$	$K_{cb\ mid}$	$K_{c\ end}$	$K_{cb\ end}$	$K_{c\ mid}$	$K_{cb\ mid}$	$K_{c\ end}$	$K_{cb\ end}$
Pistachio[d]	Young, low	0.15–0.30	1.5–2.0	–	–	–	–	0.50[h]	0.45[h]	0.40[h]	0.35[h]	0.45	0.40	0.35	0.25
	Medium	0.30–0.50		–	–	–	–	0.85[h]	0.80[h]	0.60[h]	0.55[h]	0.80	0.75	0.55	0.50
	High	>0.50	2.0–3.0	1.00	0.90	0.50	0.45	1.00[h]–1.10[h]	0.95[h]–1.05[h]	0.45[h]–0.70[h]	0.40[h]–0.65[h]	0.95	0.90	0.65	0.60
Walnut[e]	Young, low	<0.30	1.0–2.0	–	–	–	–	0.55[h]	0.50[h]	0.40[h]	0.35[h]	0.50	0.45	0.45	0.25
	Medium	0.45–0.75	3.5–7.0	–	1.05	–	–	0.90[h]	0.85[h]	0.60[h]	0.55[h]	0.85	0.80	0.50	0.40
	High	0.75–0.85	3.5–7.0	1.00	–	0.37	–	1.10[i]	1.05[i]	0.65[i]	0.60[i]	0.95	0.90	0.55	0.50
	Very high	>0.85	3.5–7.0	1.07	–	0.58	–	–	–	–	–	1.05	1.00	0.60	0.55
Other fruit trees					–		–								
Fig tree[f]	Young, low	<0.30	1.0–1.5	0.49	–	–	–	–	–	–	–	0.45	0.40	0.35	0.25
	Medium	0.30–0.50	2.0–3.0	0.60	–	–	–	–	–	–	–	0.65	0.60	0.45	0.40
Persimmon[g]	Young, low	0.15–0.25	1.0–2.0	–	–		–	–	–	–	–	0.50	0.45	0.40	0.30
	Medium	0.30–0.50	2.5–3.5	0.95	0.56	–	–	–	–	–	–	0.95	0.90	0.75	0.70
Pomegranate[a]	Young	0.15–0.25	1.0–2.0	0.36	–	–	–	–	–	–	–	0.35	0.30	0.30	0.20
	Low	0.25–0.35	2.5–3.5	0.44	–	–	–	–	–	–	–	0.50	0.45	0.40	0.30
	Medium	0.35–0.45	2.5–3.5	0.46–0.56	–	–	–	–	–	–	–	0.60	0.55	0.45	0.40
	High	>0.45	2.5–3.5	0.71–1.00	–	0.40–0.64	–	–	–	–	–	0.85	0.80	0.60	0.55

[a]Observed f_c and plant height values from Table 3. [b]Indicative f_c and plant height values from Li et al. (2010) and Steiner et al. (2015). [c]Indicative f_c and plant height values from Me et al. (2004), Olsen (2013) and Fischbach (2017). [d]Indicative f_c and plant height values from Kallsen and Fanucchi (2008). [e]Indicative f_c and plant height values from Lampinen (2014). [f]Indicative f_c and plant height values from Kumar et al. (2014) and Hendricks et al. (1994). [g]Indicative f_c and plant height values from Ballester et al. (2013). [h]Ranges of values from Allen and Pereira (2009) and Jensen and Allen (2016). [i]Values for common crop system management from Allen et al. (1998).

Appendix D.16 Continues

Table 8
Updated indicative standard values for single and basal crop coefficients relative to the mid- and end-season for tropical and sub-tropical fruit crops including reviewed literature and previous tabulated values.

Crop	Density	f_c[a,b,c,d,e,f]	Plant height[a,b,c,d,e,f] (m)	Literature reported K_c and K_{cb}				Previous tabulated standard K_c and K_{cb}				Indicative standard values (±10%) of K_c and K_{cb}			
				$K_{c\ mid}$	$K_{cb\ mid}$	$K_{c\ end}$	$K_{cb\ end}$	$K_{c\ mid}$	$K_{cb\ mid}$	$K_{c\ end}$	$K_{cb\ end}$	$K_{c\ mid}$	$K_{cb\ mid}$	$K_{c\ end}$	$K_{cb\ end}$
Avocado[a]	Young, low	0.10–0.20	1.0–2.0	–	–	–	–	0.65[g]	0.60[g]	0.60[g]	0.50[g]	0.65	0.55	0.60	0.45
	Medium	0.30–0.50	2.0–3.0	0.75	–	0.50	–	0.85–0.90	0.80[h]–0.85[g]	0.75[h]–0.80[g]	0.70[h]–0.80[g]	0.80	0.75	0.70	0.60
	High	>0.50	3.0–4.0	1.10	–	0.80	–	1.00[g]	0.95[g]	0.90[g]	0.85[g]	1.00	0.95	0.85	0.80
Banana[b]															
1st cycle	High	0.80–0.95	2.0–2.5	1.00	–	–	–	1.10[h]	1.05[h]	1.00[h]	0.90[h]	1.05	1.00	0.95	0.90
2nd cycle	High	0.75–0.85	2.0–2.5	1.00–1.05	–	–	–	1.20[h]	1.10[h]	1.10[h]	1.05[h]	1.15	1.05	1.10	1.00
Cherimoya[c]	Medium	0.50–0.65	2.5–4.0	0.65		0.25		–	–	–	–	0.65	0.60	0.55	0.45
Coconut[d]	High	0.70–0.80	7.0–15.0	1.00	–	–	–	0.95[g]–1.00[h]	0.85[g]–0.90[h]	0.95[g]–1.00[h]	0.85[g]–0.90[h]	0.95	0.90	0.90	0.85
Coffee[e]	Young, low	0.15–0.25	1.0–2.0	0.79	–	0.31	–	–	–	–	–	0.75	0.70	0.70	0.65
	High	0.40–0.60	2.5–3.5	1.12	0.78	–	–	0.95[h]	0.90[h]	0.95[h]	0.90[h]	0.95	0.90	0.95	0.90
	Very High	>0.60	2.0–3.0	1.00	–	0.68	–		–		–	1.00	0.95	1.00	0.95
Date palm[a]	Young, low	0.15–0.25	8.0–10.0	–	–	–	–	0.55[g]	0.45[g]	0.55[g]	0.45[g]	0.50	0.45	0.55	0.45
	Medium	0.30–0.60	8.0–10.0	0.65		0.60		0.80[g]–0.95[h]	0.70[g]–0.85[h]	0.80[g]–0.95[h]	0.70[g]–0.85[h]	0.70	0.65	0.65	0.60
	High	>0.60	10.0–15.0	0.84	–	0.65	–	0.95[g]	0.85[g]	0.95[g]	0.85[g]	0.85	0.80	0.75	0.70
Guava[f]	High	>0.70	1.8–3.0	0.72–0.87	–	0.55	–	–	–	–	–	0.80	0.75	0.60	0.55
Mango[a]	Young, low	0.10–0.20	1.0–2.0	–	–	–	–	0.45[g]	0.40[g]	0.40[g]	0.35[g]	0.40	0.35	0.35	0.25
	Medium	0.30–0.70	2.5–3.0	0.70–0.82	–	0.15–0.25	–	0.75[g]	0.70[g]	0.60[g]	0.55[g]	0.75	0.70	0.60	0.55
	High	>0.70	5.0–5.5	0.72–0.95	–	0.20	–	0.90[g]	0.85[g]	0.75[g]	0.70[g]	0.90	0.85	0.70	0.65
Papaya[a]	High	>0.70	1.5–3.0	1.10	1.00	0.90	0.60	–	–	–	–	1.00	0.95	0.75	0.70

[a]Observed f_c and plant height values from Table 4. [b]Indicative f_c and plant height values from Turner et al. (2007) and Stevens et al. (2020). [c]Indicative f_c and plant height values from Pinto et al. (2005), González et al. (2010). [d]Indicative f_c and plant height values from Palaniswami et al. (2006) and Mohan et al. (2019). [e]Indicative f_c and plant height values from Philpott et al. (2008) and Chemura et al. (2017). [f]Indicative f_c and plant height values from Singh et al. (2007b) and Mushtaq et al. (2019). [g]Ranges of values from Allen and Pereira (2009) and Jensen and Allen (2016). [h]Values for common crop system management from Allen et al. (1998).

Appendix D.17: Updated indicative standard values of Kc and Kcb for tropical and subtropical fruit tree crops (Tables 8 in Rallo et al. 2021)

Equation	Variable description		
$\text{NIR} = \text{CWR} - (\text{P} + \text{SW}_{\text{var}} + \text{CR}) + \text{DP} + \text{RO}$	NIR	net irrigation requirement (mm)	-
	CWR	potential evapotranspiration (mm)	-
	P	precipitation (mm)	-
	SW_{var}	soil water storage variation (mm)	-
	CR	capillary rise (mm)	-
	DP	deep percolation (mm)	-
	RO	runoff (mm)	-
$\text{GIR}= \frac{\text{NIR}+ \text{LR}}{\text{BWUF}}$	GIR	gross irrigation requirements (mm)	-
	LR	leaching requirement (mm)	-
	BWUF	beneficial water use fraction of applied irrigation	A
$D_{r,i} = D_{r,i-1} - (P_i - RO_i) - I_i - CR_i + ET_{c\,act,i} + DP_i$	i	Day	-
	D_r	root zone depletion (mm)	-
	I	net irrigation depth that infiltrates (mm)	-
	ETc_{act}	actual crop evapotranspiration (mm)	B
$\text{ET}_{\text{c act}}=\text{K}_\text{s}\,\text{K}_\text{c}\,\text{ET}_\text{o} = (\text{K}_\text{s}\,\text{K}_{\text{cb}} + \text{K}_\text{e})\,\text{ET}_\text{o}$	Kc	standard crop coefficient values	C
	Kcb	standard basal crop coefficient values	C
	Ke	evaporation coefficient	-
	Ks	stress coefficient	-
$\text{K}_\text{s} = \frac{\text{TAW}-\text{D}_\text{r}}{\text{TAW} - \text{RAW}} = \frac{\text{TAW}-\text{D}_\text{r}}{(1 - \text{p})\text{TAW}}$ for $\text{D}_\text{r} > \text{RAW}$, $\text{K}_\text{s} = 1$ for $\text{D}_\text{r} \leq \text{RAW}$	TAW	total available water = $1000(\theta_{FC} - \theta_{WP})z_r$ (mm)	-
	θ_{FC}	volumetric soil moisture at field capacity ($m^3\ m^{-3}$)	-
	θ_{FC}	volumetric soil moisture at wilting point ($m^3\ m^{-3}$)	-
	z_r	root zone depth (m)	-
	RAW	readily available water (mm)	-
	p	soil water depletion fraction for no stress	D
$\theta_\text{p} = (1 - \text{p})\,(\theta_{\text{FC}} - \theta_{\text{WP}})$	θ_p	volumetric soil moisture threshold for no stress or full irrigation	-
$\theta_{\text{MAD}} = (1\text{-MAD})(\theta_{\text{FC}} - \theta_{\text{WP}})$	MAD	management allowed depletion larger then p for deficit irrigation	E

A = application efficiency or combined conveyance, distribution and application efficiency; B = both optimal and suboptimal crop and irrigation conditions under full or deficit irrigation and/or cropping practices; C = adjustment to climate of standard Kc_{mid}, Kc_{end}, Kcb_{mid} and Kcb_{end} values using Equations 62 and 65 of FAO 56, also Kc_{ini} and Kcb_{ini} values have to be determined as recommended by Allen et al. (1998, 2005a, 2005b); D = influence of salinity on Ks is discussed in Minhas et al. (2020); E = when depletion fraction exceeds p

Appendix D.18: Crop evapotranspiration, crop water requirements, irrigation requirements and FAO 56 soil water balance calculations (Pereira et al. 2020b)

Equation	Variable description		
$K_e = K_r\,(K_{c\ \max} - K_{cb}) \leq f_{ew}\ K_{c\ \max}$	K_r	evaporation reduction coefficient (0-1)	F
	f_{ew}	fraction of soil surface wetted and exposed to solar radiation	
	Kc_{max}	maximum value for Kc following rain or irrigation	
$K_{c\,max} = \max\left\langle \left\{1.2 + 0.04\,(u_2 - 2) - 0.004\,(RH_{min} - 45)\left(\frac{h}{3}\right)^{0.3}\right\},\ K_{cb} + 0.05\right\rangle$	U_2	wind speed (m s^{-1})	-
	RH_{min}	minimum relative humidity (%)	-
$D_{e\ i} = D_{e\ i-1} - (P_i - RO_i) - \frac{I_{n\ i}}{f_w} + \left(\frac{K_e\ ET_o}{f_{ew}}\right)_i + T_{s\ i}$	D_e	depth of water depleted from the f_{ew} fraction of soil wetted and exposed	G
	f_w	wetted fraction where net irrigation infiltrates the soil	-
	T_s	transpiration from the f_w fraction of the evaporating soil layer (mm)	-
$K_r = 1$ for $D_e \leq REW$ $K_r = \frac{TEW - D_e}{TEW - REW}$ for $D_e > REW$	REW	readily evaporable water in soil evaporation layer of depth	H
	TEW	total evaporable water in the soil evaporation layer of depth	
	z_e	depth of soil evaporation layer (m)	-
$f_{ew\ p} = 1 - f_c$	$f_{ew\ p}$	fraction of soil surface wetted by precipitation	-
	f_c	average fraction covered by vegetation (0-1)	-
$f_{ew\ i} = \min(1 - f_c, f_w)$	$f_{ew\ i}$	fraction of soil surface wetted by irrigation	-
$f_c = \left(\frac{K_{cb} - K_{c\ \min}}{K_{c\ \max} - K_{c\ \min}}\right)^{1+0.5h}$	Kc_{min}	minimum Kc for dry, bare soil, generally = 0.15	I

F = For the dual Kc approach two soil water balances are required, i.e., Ke is for the top evaporation layer; G = Computed from the daily water balance of the upper 0.10 to 0.15 m of soil; H = REW and TEW are for the evaporation layer with depth z_e; I = Ideally f_c should be observed in the field, the exponent "1+0.5h" represents the effect of plant height on shading the soil and increasing the Kcb given a specific value for f_c.

Appendix D.18: Continues

Table 1
Salt tolerance of common agricultural crops.
Source: Adapted from Allen et al. (1998); Ayers and Westcot (1985) and Grieve et al. (2012).

Crop		$EC_{e\ threshold}$ (dS m^{-1})	$EC_{e\ 50}$ (dS m^{-1})	b (% / dS m^{-1})	Rating
a. Small vegetables					
Broccoli	*Brassica oleracea* L. (Botrytis group)	1.3-2.8	8.2	9.2-15.8	MS
Brussels sprouts	*Brassica oleracea* L. (Gemmifera group)	1.8	–	9.7	MS
Cabbage	*Brassica oleracea* L. (Capitata group)	1.0-1.8	7.0	9.8-14.0	MS
Cauliflower	*Brassica oleracea* L. (Botrytis group)	1.5-1.8	–	6.2-14.4	MS
Celery	*Apium graveolens* L.	1.8-2.5	9.9	6.2-13.0	MS
Lettuce	*Lactuca sativa* L.	1.3-1.7	5.1	12.0-13.0	MS
Onion	*Allium cepa* L.	1.2	4.3	16.0	S
Purslane	*Portulaca oleracea* L.	6.3	–	9.6	MT
Spinach	*Spinacia oleracea* L.	2.0-3.2	8.6	7.6-16.0	MS
Swiss chard	*Beta vulgaris* L. (Cicla group)	7.0	–	5.7	T
Radish	*Raphanus sativus* L.	1.2-2.0	5.0	7.6-13.0	MS
b. Vegetables - Solanum Family (*Solanaceae*)					
Egg Plant	*Solanum melongena* L.	1.1	–	6.9	MS
Pepper	*Capsicum annuum* L.	1.5-1.7	5.1	12.0-14.0	MS
Tomato	*Lycopersicon esculentum* L.	0.9-2.5	7.6	9.0-9.9	MS
c. Vegetables Cucumber Family (*Cucurbitaceae*)					
Cucumber	*Cucumis sativus* L.	1.1-2.5	6.3	7.0-13.0	MS
Melon	*Cucumis melo* L.	1.0	–	8.4	MS
Pumpkin, winter squash	*Cucurbita moschata* Poir	1.2	–	13.0	MS
Squash, Zucchini	*Cucurbita pepo* L.var *melopepo* (L.) Alef.	4.7-4.9	10.0	10.0-10.5	MT
Squash (scallop)	*Cucurbita pepo* L.var *melopepo* (L.) Alef.	3.2	6.3	16.0	MS
Watermelon	*Citrullus lanatus* (Thunb.) Matsum. & Nakai	–	–	–	MS
d. Roots and Tubers					
Artichoke, Jerusalem	*Helianthus tuberosus* L.	0.4	–	9.6	MS
Beetroot	*Beta vulgaris* L. (Conditiva group)	4.0	–	9.0	MT
Carrot	*Daucus carota* L.	1.0	4.6	14.0	S
Garlic	*Allium sativum* L.	3.9	–	14.3	MS
Parsnip	*Pastinaca sativa* L.	–	–	–	S
Potato	*Solanum tuberosum* L.	1.7	5.9	12.0	MS
Sweet potato	*Ipomoea batatas* (L.) Lam.	1.5-2.5	6.0	10.0-11.0	MS
Turnip	*Brassica rapa* L.	0.9	6.5	9.0	MS
Sugarbeet	*Beta vulgaris* L. (Altissima group)	7.0	15.0	5.9	T
e. Legumes (*Leguminosae*)					
Bean	*Phaseolus vulgaris* L.	1.0	3.6	19.0	S
Bean, mung	*Vigna radiata* (L.) R. Wilcz.	1.8	–	20.7	S
Broadbean (faba bean)	*Vicia faba* L.	1.5-1.6	6.8	9.6	MS
Cowpea	*Vigna unguiculata* (L.) Walp.	4.9	9.1	12.0	MT
Groundnut (Peanut)	*Arachis hypogaea* L.	3.2	4.9	29.0	MS
Pea	*Pisum sativum* L.	1.5-3.4	–	10.6-14.0	S/MS
Soybean	*Glycine max* (L.) Merrill	5.0	7.5	20.0	MT
f. Perennial Vegetables (with winter dormancy and initially bare or mulched soil)					
Artichokes	*Cynara scolymus* L.	6.1	–	11.5	MT
Asparagus	*Asparagus officinalis* L.	4.1	–	2.0	T
Mint	*Mentha spicata* L.	–	–	–	–
Strawberry	*Fragaria sp.* L.	0.75-1.5	2.5	11.0-33.0	S
g. Fibre crops					
Cotton	*Gossypium hirsutum* L.	7.7	17.0	5.2	T
Flax	*Linum usitatissimum* L.	1.7	5.9	12.0	MS
Kenaf	*Hibiscus cannabinus* L.	8.1	–	11.6	T
h. Oil crops					
Castorbean	*Ricinus communis*L.	–	–	–	MS
Crambe	*Crambe abyssinica* Hochst. ex R.E. Fries	2.0	–	6.5	MS
Lesquerella	*Lesquerella fenderli* (Gray) S. Wats.	6.1	–	19	MT
Rapeseed	*Brassica sp.*L.	9.7-11.0	–	13-14	T
Safflower	*Carthamus tinctorius* L.	–	–	–	MT
Sunflower	*Helianthus annuus* L.	4.8	–	5.0	MT
i. Cereals					
Barley	*Hordeum vulgare* L.	8.0	18.0	5.0	T
Oats	*Avena sativa* L.	–	–	–	MT
Maize	*Zea mays* L.	1.7	5.9	12.0	MS
Maize, sweet	*Zea mays* L.	1.7	5.9	12.0	MS
Millet	*Setaria italica* (L.) Beauvois	–	–	–	MS
Rice	*Oryza sativa* L.	3.0	7.2	12.0	S
Rye	*Secale cereale* L.	11.4	–	10.8	T
Sorghum	*Sorghum bicolor* (L.) Moench	6.8	9.9	16.0	MT
Triticale	*X Triticosecale* Wittmack	6.1	–	2.5	T
Wheat	*Triticum aestivum* L.	6.0	13.0	7.1	MT
Wheat, semidwarf	*Triticum aestivum* L.	8.6	–	3.0	T
Wheat, durum	*Triticum turgidum L. var. durum Desf.*	5.7-5.9	15.0	3.8-5.5	T
j. Forages					
Alfalfa	*Medicago sativa* L.	2.0	8.8	7.3	MS
Barley (forage)	*Hordeum vulgare* L.	6.0	13.0	7.1	MT

Appendix D.19: Updated salt tolerance of common agricultural crops (Table 1 in Minhas et al. 2020)

Table 1 (*continued*)

Crop		$EC_{e\ threshold}$ (dS m^{-1})	$EC_{e\ 50}$ (dS m^{-1})	b (% / dS m^{-1})	Rating
Bermuda	*Cynodon dactylon* (L.) Pers.	6.9	15.0	6.4	T
Clover, Berseem	*Trifolium alexandrinum* L.	1.5	10.0	5.7	MS
Clover	*Trifolium sp.* L.	1.5	5.7	12.0	MS
Cowpea (forage)	*Vigna unguiculata* (L.) Walp.	2.5	7.1	11.0	MS
Fescue, tall	*Festuca elatior* L.	3.9	12.0	5.3-6.2	MT
Foxtail	*Alopecurus pratensis* L.	1.5	6.7	9.6	MS
Hardinggrass	*Phalaris tuberosa* L. var. *stenoptera* (Hack) A. S. Hitchc.	4.6	11.0	7.6	MT
Lovegrass	*Eragrostissp.* N. M. Wolf	2.0	8.0	8.4	MS
Maize (forage)	*Zea mays* L.	1.8	8.6	7.4	MS
Orchardgrass	*Dactylis glomerata* L.	1.5	9.6	6.2	MS
Rye (forage)	*Secale cereale* L.	7.6	–	4.9	T
Rye-grass (perennial)	*Lolium perenne* L.	5.6	12.0	7.6	MT
Sesbania	*Sesbania exaltata* (Raf.) V.L. Cory	2.3	9.4	7.0	MS
Sphaerophysa	*Sphaerophysa salsula* (Pall.) DC	2.2	9.3	7.0	MS
Sudangrass	*Sorghum sudanense* (Piper) Stapf	2.8	14.0	4.3	MT
Trefoil, narrow leaf birdsfoot	*Lotus corniculatus* var tenuifolium L.	5.0	10.0	10.0	MT
Trefoil, big	*Lotus pedunculatus* Cav.	2.3	–	19.0	MS
Vetch, common	*Vicia angustifolia* L.	3.0	7.6	11.0	MS
Wheat (forage)	*Triticum aestivum* L.	4.5	–	2.6	MT
Wheat, Durum (forage)	*Triticum turgidum L. var. durum Desf.*	2.1	–	2.5	MT
Wheatgrass, tall	*Agropyronelongatum* (Hort) Beauvois	7.5	19.0	4.2	T
Wheatgrass, fairway crested	*Agropyroncristatum* (L.) Gaertn.	7.5	15.0	6.9	T
Wheatgrass, standard crested	*Agropyronsibiricum* (Willd.) Beauvois	3.5	16.0	4.0	MT
Wildrye, beardless	*Elymus triticoides* Buckl.	2.7	11.0	6.0	MT
k. Sugar cane	*Saccharum officinarum* L.	1.7	10.0	5.9	MS
l. Tropical Fruits and Trees					
Banana	*Musa acuminata* Colla	–	–	–	MS
Coconut	*Cocos nucifera* L.	–	–	–	MT
Coffee	*Coffea sp.*L.	–	–	–	–
Date Palm	*Phoenix dactylifera* L.	4.0	18.0	3.6	T
Pineapple	*Ananas comosus* (L.) Merrill	–	–	–	MT
Tea	*Camellia sinensis* (L.) Kuntze	–	–	–	–
m. Grapes and berries					
Blackberry	*Rubus macropetalus* Doug. ex Hook	1.5	3.8	22.0	S
Boysenberry	*Rubus ursinus* Cham. and Schlechtend	1.5	3.8	22.0	S
Grape	*Vitis vinifera* L	1.5	6.7	9.6	MS
Hops	*Humulus lupulus*L.	–		–	–
n. Fruit trees					
Almond	*Prunus duclis* (Mill.) D.A. Webb	1.5	4.1	19.0	S
Avocado	*Persea americana* Mill.	–	–	–	S
Citrus (Grapefruit)	*Citrus x paradisi* Macfady	1.2-1.8	4.9	13.5-16.0	S
Citrus (Orange)	*Citrus sinensis* (L.) Osbeck	1.3-1.7	4.8	13.1-16.0	S
Citrus (Lemon)	*Citrus limon* (L.) Burm. f.	1.5	–	12.8	S
Citrus (Lime)	*Citrus aurantiifolia* (Christm.) Swingle	–	–	–	S
Citrus (Pummelo)	*Citrus maxima* (Burm.)	–	–	–	S
Citrus (Tangerine)	*Citrus reticulata* Blanco	–	–	–	S
Deciduous orchard					
Apple	*Malus sylvestris* Mill.	–	–	–	S
Peach	*Prunus persica* (L.) Batsch	1.7	4.1	21.0	S
Cherries	*Prunus spp.*	–	–	–	S
Pear	*Pyrus communis* L.	–	–	–	S
Apricot	*Prunus armeniaca* L.	1.6	–	24.0	S
Plum, prune	*Prunus domestica* L.	1.5-2.6	4.3	18.0-31.0	S/MS
Pomegranate	*Punica granatum* L.	–	–	–	MT
Guava	*Psidium guajava* L.	4.7	–	9.8	MT
Olive	*Olea europaea* L.	–	–	–	MT

$EC_{e\ threshold}$, EC_e value above which yield begins to decrease; $EC_{e\ 50}$, EC_e value at which crop yield is reduced by 50%; b, rate of reduction is yield per unit increase in EC_e;S, sensitive; MS, moderately sensitive; T, tolerant; MT, moderately tolerant.

Appendix D.19: Continues