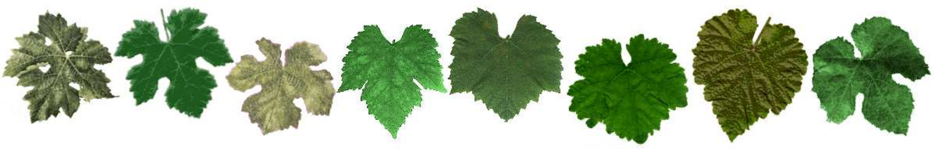
Water use efficiency of table and wine grapes in Western Cape, South Africa

The spatial and temporal variation of water use efficiency in grape cultivation using remote sensing technology



WaterWatch BV
Final report, 15 October 2008

Table of content

1 **INTRODUCTION 1**

1.1 Background 1
1.2 The study areas 2

2 **SATELLITE DATA AND LAND COVER MAPPING 5**

2.1 Satellite data 5
2.2 Brief description of the method 6
2.3 Land cover mapping 8
2.3.1 Field work 8
2.3.2 Land cover classification 9

3 **METEOROLOGICAL DATA 13**

3.1 Meteorological datasets 13
3.2 Weather conditions in the study areas 13
3.3 MeteoLook 17

4 **WATER BALANCE MEASUREMENTS IN VINEYARDS 21**

4.1 Rainfall measurements 21
4.2 Irrigation measurements 22
4.3 Soil moisture measurements 24
4.4 Evapotranspiration of table grapes as calculated with the water balance 25

5 **WATER CONSUMPTION FROM REMOTE SENSING 27**

5.1 Evapotranspiration (ET) of table and wine grape vineyards 27
5.1.1 Frequency distributions of grape water consumption 27
5.1.2 Water consumption trends over the different areas and years 29
5.2 Validation of table grape evapotranspiration in Hex River Valley 31
5.3 Conclusions on water consumption 34

6 **GRAPE PRODUCTION FROM REMOTE SENSING 37**

6.1 Biomass production 37
6.2 Wine grape production 38
6.3 Table grape production 40
6.4 Grape production statistics for sub-areas 44
6.5 Validation of grape production modelling 46
6.6 Conclusions on grape production 48

7 **WATER USE EFFICIENCY FROM REMOTE SENSING 51**

7.1 Biomass water use efficiency 51
7.2 Water use efficiencies of table and wine grapes 52
7.3 Water use efficiency in arbitrary divided areas 55
7.4 Some explanations for differences in water use efficiency 56
7.5 Conclusions on water use efficiency 60

8 **SUMMARY AND CONCLUSIONS 63**

REFERENCES 67

APPENDIX 1 A SHORT INTRODUCTION TO SEBAL 69

APPENDIX 2 MEASUREMENTS IN THE HEX RIVER VALLEY BLOCKS 73

Tables

Table 1 List of acquired Landsat images and the period for which they will be used in the SEBAL modelling 6
Table 2 Area covered by the different land cover and land use classes 11
Table 3 Error matrix resulting from classifying training set polygons (area in ha) 11
Table 4 Total annual rainfall (June-May) measured at for five meteorological stations (station name and number in brackets) in the different study areas.. 15
Table 5 Total rainfall in winter (June-August) measured at five meteorological stations in the different study areas.. 16
Table 6 Total rainfall in summer (October - February) measured at five meteorological stations in the different study areas 16
Table 7 Total rainfall as measured at De Vlei meteorological station 22
Table 8 Average monthly rainfall measured at various locations in the Hex River Valley (Source: ARC / Department of Agriculture), original data is shown in appendix 2 22
Table 9 Average irrigation water applied (mm) at the blocks in Hex River Valley (source: Department of Agriculture).. 23
Table 10 Monthly soil moisture change (mm) in the 5-95 cm soil profile from October 2004 until March 2005 . 24
Table 11 Evapotranspiration derived from the water balance in mm for 2005-6 25
Table 12 Average water consumption from September until April of table and wine grapes in arbitrary classes 31
Table 13 Evapotranspiration per block and per month calculated with the water balance (rain + irrigation – change in water storage in the 25-75 cm of soil profile) and with SEBAL for 2004-5 32
Table 14 Evapotranspiration per block and per month calculated with the water balance (rain + irrigation – change in water storage in the 25-75 cm of soil profile) and with SEBAL for 2005-6 33
Table 15 Evapotranspiration per block and per month calculated with the water balance (rain + irrigation – change in water storage in the 25-75 cm of soil profile) and with SEBAL for 2006-7 34
Table 16 Measured yield of table grapes in the Hex River Valley of all farmers that participated in the Department of Agriculture experiment 41
Table 17 Rainfall measured at Hex River Valley metereological station 42
Table 18 Average yield of table grapes and Colombar wine grapes in arbitrary classes (see Figure 23). Wine grapes in Stellenbosch, Somerset West, Franschhoek and Paarl were not included in this analysis. 45
Table 19 Average water use efficiency in arbitrary classes (see Figure 23) 55

Tables in Annex 2

Table a1 Rainfall in the Hex River Valley 2004-5 (Source: ARC / Department of Agriculture) 73
Table a2 Rainfall in the Hex River Valley 2005-6 (Source: ARC / Department of Agriculture) 73
Table a3 Rainfall in the Hex River Valley 2006-7 (Source: ARC / Department of Agriculture) 73
Table a4 Irrigation water applied (mm) in the season 2004-5, Hex River Valley 74
Table a5 Irrigation water applied (mm) in the season 2005-6, Hex River Valley 74
Table a6 Irrigation water applied (mm) in the season 2006-7, Hex River Valley 75
Table a7 Monthly soil moisture change (mm) in the 5-95 cm soil profile from October 2004 until March 2005 76
Table a8 Monthly soil moisture change (mm) in the 5-95 cm soil profile from October 2005 until March 2006 76
Table a9 Monthly soil moisture change (mm) in the 5-95 cm soil profile from October 2006 until March 2007 77
Table a10 Evapotranspiration derived from the water balance in mm for 2004-5 78
Table a11 Evapotranspiration derived from the water balance in mm for 2005-6 78
Table a12 Evapotranspiration derived from the water balance in mm for 2006-7 79
Table a13 Biomass production in the Hex River Valley blocks 80

Figures

Figure 1 The coverage of the satellite images used in this study (in grey) 1
Figure 2 Location of the study areas within the District and Local Municipalities 2
Figure 3 Topography in and around the study areas (based on the DEM and 2 Landsat images) 3
Figure 4 The location of path/row 175/83 and 175/84 5
Figure 5 Detail of the ground truth field polygon file created from the field survey in December 2007 8
Figure 6 Classification approach 9
Figure 7 Land cover map and grape map 10
Figure 8 Spatial distribution of meteorological stations 13
Figure 9 Monthly rainfall in 2004-5 (high rainfall in winter) from meteorological stations in Worcester (Nuy, 30216), Hex River Valley (De Vlei), Stellenbosch (Niet Voorbij, 30086), Somerset West (Vergelegenvrug, 30054), Paarl (Morewag, 30058) and Franschhoek (La Motte, 30453) 14
Figure 10 Monthly rainfall in 2005-6 from meteorological stations in Worcester (Nuy, 30216), Hex River Valley (De Vlei), Stellenbosch (Niet Voorbij, 30086), Somerset West (Vergelegenvrug, 30054), Paarl (Morewag, 30058) and Franschhoek (La Motte, 30453) 14
Figure 11 Monthly rainfall in 2006-7 from meteorological stations in Worcester (Nuy, 30216), Hex River Valley (De Vlei), Stellenbosch (Niet Voorbij, 30086), Somerset West (Vergelegenvrug, 30054), Paarl (Morewag, 30058) and Franschhoek (La Motte, 30453) 14
Figure 12 Average monthly wind speed as measured at the five representative meteorological stations 16
Figure 13 Average monthly relative humidity as measured at the five representative meteorological stations 17
Figure 14 MeteoLook 24h results for March 13, 2007 18
Figure 15 MSG transmissivity on March 13, 2007 showing clouds arising in the coastal region 1
Figure 16. Location of the irrigation blocks in the Hex River Valley on which the Department of Agriculture, Western Cape conducts field measurements 21
Figure 17 Mean irrigation application (lines) and rainfall (columns) in the experimental blocks of Hex River Valley 23
Figure 18 Average monthly temperature (average from daily $(T_{min}+T_{max})/2$) as measured at De Vlei station, Hex River Valley 23
Figure 19 The contribution of rainfall, irrigation supply and soil moisture change at the water balance ET 25
Figure 20 Average monthly evapotranspiration (based on the water balance estimations) in 2004-5, 2005-6 and 2006-7 26
Figure 21 The relationship between irrigation supply and the derived water balance evapotranspiration 26
Figure 22 Frequency distribution of water consumption in the grape season for all pixels in Hex River Valley, Worcester, Paarl, Franschhoek, Stellenbosch and Somerset West classified as table grape (left, n=76415) or wine grape (right, n=297424) 29
Figure 23 Arbitrary division of the study areas for the calculation of statistics in Table XII 30
Figure 24 Average period and accumulated evapotranspiration in the experimental blocks in Hex Valley during 2004-5 calculated with SEBAL and with the soil water balance based on field experiments 33
Figure 25 Average period and accumulated evapotranspiration in the experimental blocks in Hex River Valley during 2005-6 calculated with SEBAL and with the soil water balance based on field experiments 33
Figure 26 Average period and accumulated evapotranspiration in the experimental blocks in Hex River Valley during 2006-7 calculated with SEBAL and with the soil water balance based on field experiments 34
Figure 27 Frequency distribution of biomass production for all pixels classified as table grape (n=76415) or as wine grape (n=297424) in the study areas 38
Figure 29 Frequency distribution of modelled Colombar wine grape yield in Worcester (n=19889) in 2004-5 40
Figure 30 Frequency distribution of modelled Colombar wine grape yield in Worcester (n=19889) in 2005-6 40
Figure 31 Frequency distribution of modelled Colombar wine grape yield in Worcester (n=19889) in 2006-7 40
Figure 32 The relationship between biomass production and measured yield 42
Figure 33 Frequency distribution of modelled table grape yield in the season 2004-5 for all pixels (n = 76415) in Hex River Valley, Worcester, Paarl, Franschhoek, Stellenbosch and Somerset West areas classified as table grape 44
Figure 34 Frequency distribution of modelled table grape yield in the season 2005-6 for all pixels (n = 76415) in Hex River Valley, Worcester, Paarl, Franschhoek, Stellenbosch and Somerset West areas classified as table grape 44
Figure 35 Frequency distribution of modelled table grape yield in the season 2006-7 for all pixels (n = 76415) in Hex River Valley, Worcester, Paarl, Franschhoek, Stellenbosch and Somerset West areas classified as table grape 44

Figure 36 The relationship between grape water consumption and yield per arbitrary class (Table XII and Table XVIII) 46
Figure 37 Measured and predicted table grape yield in 2005 47
Figure 38 Measured and predicted table grape yield in 2006 47
Figure 39 Measured and predicted table grape yield in 2007 47
Figure 40 Frequency distribution of the biomass water use efficiency in table (left) and wine (right) grapes in the six study areas 52
Figure 41 Frequency distribution of water use efficiency of Colombar wine grapes in the season 2004-5 for all pixels (n = 19891) in Worcester 53
Figure 42 Frequency distribution of water use efficiency of Colombar wine grapes in the season 2005-6 for all pixels (n = 19891) in Worcester 53
Figure 43 Frequency distribution of water use efficiency of Colombar wine grapes in the season 2006-7 for all pixels (n = 19891) in Worcester 54
Figure 44 Frequency distribution of water use efficiency of table grapes in the season 2004-5 for all pixels (n = 76415) in Hex River Valley, Worcester, Paarl, Franschhoek, Stellenbosch and Somerset West areas 54
Figure 45 Frequency distribution of water use efficiency of table grapes in the season 2005-6 for all pixels (n = 76415) in Hex River Valley, Worcester, Paarl, Franschhoek, Stellenbosch and Somerset West areas 54
Figure 46 Frequency distribution of water use efficiency of table grapes in the season 2006-7 for all pixels (n = 76415) in Hex River Valley, Worcester, Paarl, Franschhoek, Stellenbosch and Somerset West areas 55
Figure 47 Water consumption (left), yield (center) and water use efficiency (right) of table grapes in Hex River Valley in 2004-5, 2005-6 and 2006-7 with the distribution of rainfall over summer (S) and winter (W) 57
Figure 48 Water consumption (left), biomass production (center) and biomass water use efficiency (right) of wine grapes in the Stellenbosch area in 2004-5, 2005-6 and 2006-7. The distribution of rainfall over winter (June-August) and summer (October-February) is also indicated, as well as the location of the town of Stellenbosch (red circle). 58
Figure 49 The effect of water logging (indicated with the white circle) on biomass production (left) and water consumption (right) in a wine grape vineyard in Stellenbosch 59
Figure 50 The effect of different cultivars on water consumption of a wine grape vineyard in Stellenbosch 59
Figure 51 The effect of management on water consumption in a wine grape farm in Worcester 60

1 Introduction

1.1 Background

In 2007 WaterWatch executed a study on the water use efficiency of winelands of the Western Cape, South Africa. This study was initiated by the Department of Agriculture, Western Cape, of South Africa, with the CSIR as an intermediate body between the client (Department of Agriculture, Western Cape) and the consultant (WaterWatch) for administrative reasons. The Surface Energy Balance Algorithm for Land (SEBAL) was applied in conjunction with Landsat satellite imagery to estimate water consumption and water use efficiencies of vineyards. The results of this study greatly improved the understanding of the spatial and temporal variation of water use efficiency in grape cultivation.

One of the conclusions was that irrigation management affects water use efficiency, and in turn, irrigation scheduling is strongly influenced by the water resources availability, especially the rainfall from the preceding winter season. The focus in the previous project was on two grape seasons, from September to April, in both 2004-5 and 2005-6. There was a big difference between the two hydrological years, and also in the way farmers irrigate their land. It was agreed that the temporal variation of water use efficiency was not yet properly understood by analyzing only two years, and that an extra year should be added before drawing general conclusions on the relationship between rainfall, irrigation, water consumption, yield, and water use efficiency.

Moreover, an important part of the winelands in the Western Cape was not included in the 2007 study. For the sake of obtaining a consistent and complete picture, it was desirable to expand the existing imagery of Hex Valley, Worcester, Paarl and Franschhoek to the Stellenbosch and Somerset West regions. Figure 1 shows the location of the satellite images used in this study.

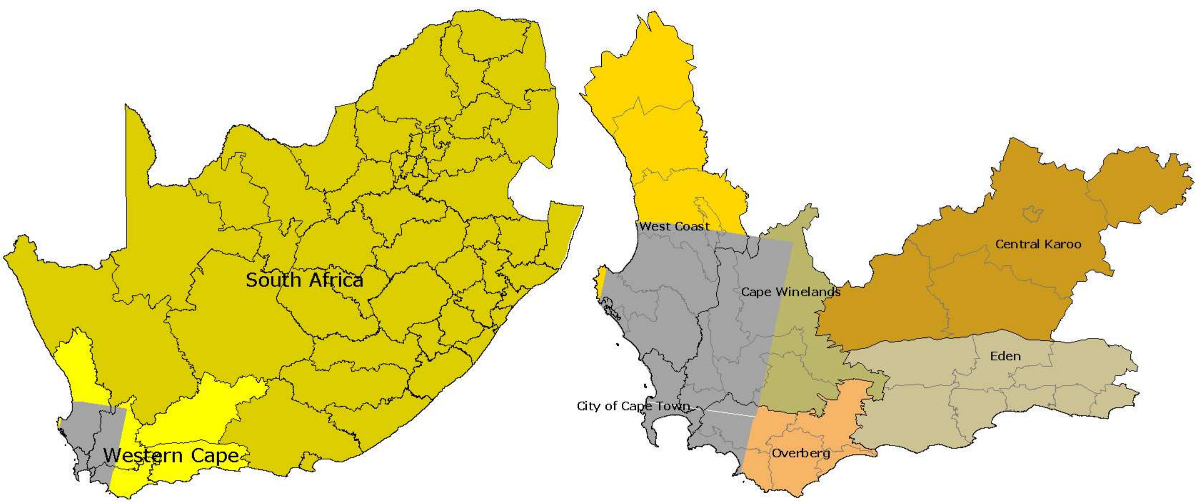


Figure 1 The coverage of the satellite images used in this study (in grey)

At the end of 2007 a new study was thus launched as a continuation of the prior work with improvements in:

- The spatial frame: besides the Hex Valley, Franschhoek, Worcester and Paarl area, also the Somerset West and Stellenbosch winelands have been analysed;
- The temporal frame: in addition to the grape growing seasons of 2004-5 and 2005-6 the season of 2006-7 has also been included;
- The fieldwork: A field work survey in Hex Valley, Franschhoek, Worcester and Paarl of two weeks was executed in 2006. In 2007 additional field work of four days was done in Stellenbosch and Somerset West; and
- The classification procedure: a field boundary file provided by the Department of Agriculture and additional Landsat images was included.

The same administrative arrangement as in the 2007 study was used, with CSIR as an intermediate body between WaterWatch and the Department of Agriculture, but now with a larger role for the CSIR in data analysis and reporting. This report summarizes the 2004-5 and 2005-6 results of the 2007 study, and includes the 2006-7 results as well as the new results of Somerset West and Stellenbosch of 2004-5 and 2005-6 for completion and consistency of a three year period.

1.2 The study areas

All study areas are located within the Cape Winelands District Municipality, formerly known as the Boland District Municipality (Figure 2).

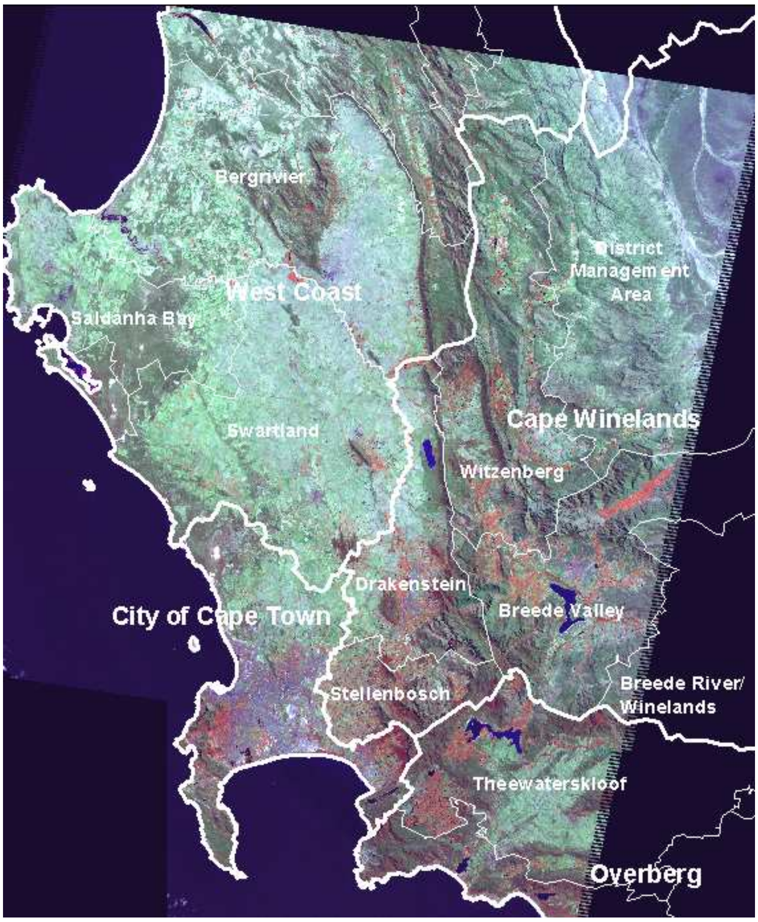


Figure 2 Location of the study areas within the District and Local Municipalities

The Cape Winelands District Municipality is divided into six local municipalities. The Worcester and Hex River Valley study areas fall within the Breede Valley Local Municipality (WC025). The Paarl area is part of the Drakenstein Local Municipality (WC023). The Stellenbosch and Somerset West study areas are part of the Stellenbosch Local Municipality (WC024). Hex River Valley and Worcester are part of the Breede River catchment. The Berg River catchment contains Paarl and Franschoek. The three rivers in the Stellenbosch and Somerset West area are called Eerste River, Kuils River and Lourens River, and all flow into False Bay.

The Cape Winelands District Municipality has a Mediterranean climate, with hot and dry summers, and cool and wet winters. The Wemmershoek Mountains divide the District Municipality in a typical Mediterranean zone at the west, highly influenced by the sea, and a more arid region at the east.

Figure 3 gives an impression of the topography in the study areas. Rainfall varies considerably in both time and space. Annual rainfall east of the mountain ranges is in general half of the amount of rainfall that falls in the west, but varies considerably from year to year.

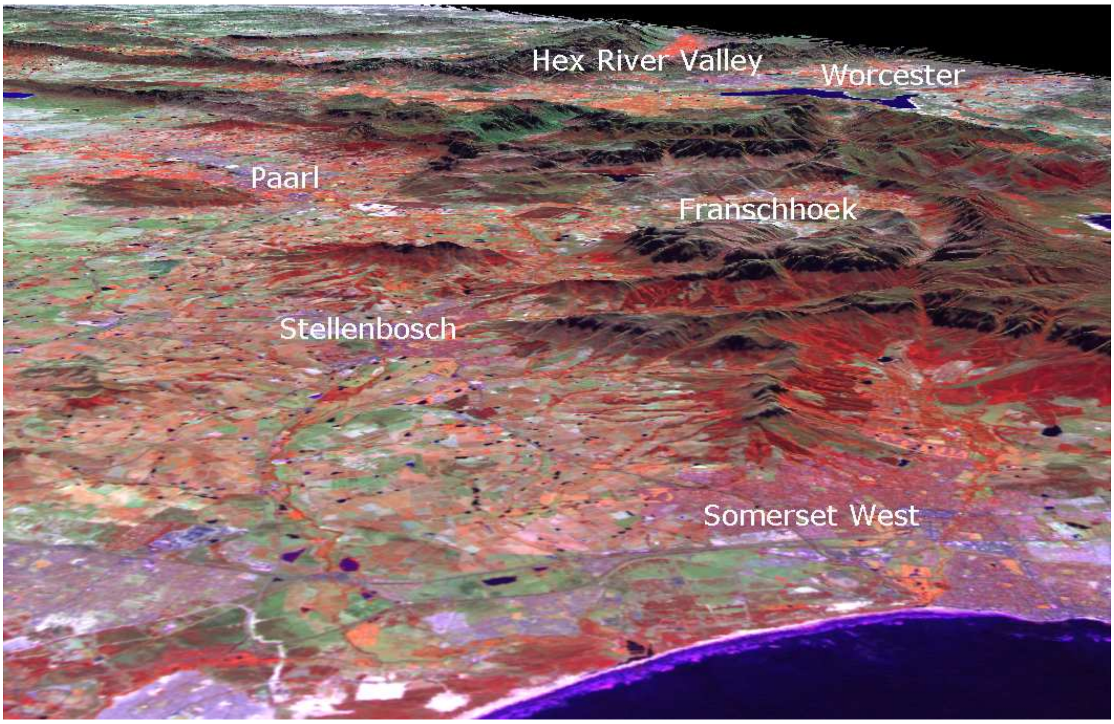


Figure 3 Topography in and around the study areas (based on the DEM and 2 Landsat images)

2 Satellite data and land cover mapping

2.1 Satellite data

For the expansion in time (adding 2006-7) and space (Stellenbosch and Somerset West winelands) additional satellite imagery has been acquired. The Stellenbosch and Somerset West winelands partly fall on a different Landsat scene (path/row 175/84), as is shown in Figure 4. As a result new Landsat images of path/row 175/84 for the two seasons of 2004-5 and 2005-6 needed to be acquired for the inclusion of the southern part of the study area. Fortunately these images were available for all dates, except one for October 30, 2004. To replace the image of October 30, 2004, an image of October 22, 2004 was purchased.

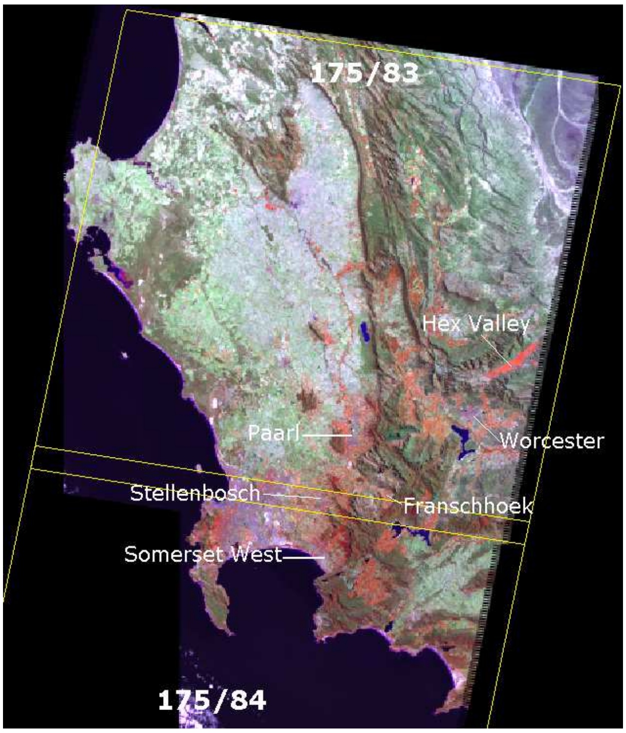


Figure 4 The location of path/row 175/83 and 175/84

For the season of 2006-7 Landsat images of both path/row 175/83 and 175/84 were acquired. Images of both rows were acquired for four dates. Unfortunately both rows were not always available for the same date, and only single images could be acquired for the three other dates.

Each individual Landsat image represents a certain period in the SEBAL modelling. The length of the period between consecutive images ranged between one to two months so it is not always identical. The study was limited to the grape season, so the focus was on the period September until April. In the previous study, the distinction between stone fruits and vineyards turned out to be difficult. For this reason, one earlier image acquired in August 25, 2006 was included to distinguish stone fruits (green in August) from grapes (no leaves in August). Vineyards however often have wheat as a cover crop in August (green). The images of

September appeared therefore to be more suitable to distinguish between stone fruits and grapes.

Table 1 shows the complete list of Landsat 5-TM and 7-ETM images acquired in the current as well as the prior study. Landsat images have a spatial resolution of 30-m in the visible, near infrared and mid infrared bands, which makes it possible to identify individual orchards. Six of the Landsat 5-TM images were largely cloud free and could be used in the classification process. Landsat 7-ETM images were Scan Line Corrected for missing pixels that affects the operating of Landsat 7-ETM since 2003. Landsat 7 ETM is suitable for SEBAL processing, but not for land cover and grape classification.

Table 1 List of acquired Landsat images and the period for which they will be used in the SEBAL modelling

Date	sensor	p175 r83	p175 r84	SEBAL period
20/09/04	5TM	•	•	September 2004
22/10/04	5TM	•	•	October 2004
30/10/04	7ETM	•	not available	October 2004
15/11/04	7ETM	•	•	November 2004
09/12/04	5TM	•	•	December 2004
18/01/05	7ETM	•	•	January 2005
27/02/05	5TM	•	•	February 2005
23/03/05	7ETM	•	•	March/April 2005
09/10/05	5TM	•	•	September/October 2005
04/12/05	7ETM	•	•	November 2005
20/12/05	7ETM	•	•	December 2005
06/02/06	7ETM	•	•	January/February 2006
10/03/06	7ETM	•	•	March/April 2006
25/08/06	5TM	•	•	For grape classification only
12/10/06	5TM	•	•	September/October 2006
28/10/06	5TM	•	•	November 2006
23/12/06	7ETM	•	•	December 2006
17/02/07	5TM	•	•	January/February 2007
13/03/07	7ETM	not available	•	March/April 2007
29/03/07	7ETM	•	not available	March/April 2007

Furthermore four ASTER images of March 16 and 23, 2005 encompass all the study areas, except for a small strip of the Stellenbosch area near Kuilsrivier. ASTER images have a spatial resolution of 15-m, and greatly improved the classification of vineyards.

All satellite images have been geo-referenced to the topographic maps of 1: 50,000 and 1: 100,000.

2.2 Brief description of the method

Landsat 5TM and 7ETM images provided several inputs to this project. First of all the satellite data was used to classify the land cover in the entire image, and to classify the pixels that are covered with table and wine grape vineyards. A distinction between the land cover classes was made based on their different reflectance properties in the visible light, near infrared, and mid infrared bands. Furthermore the Normalized Difference Vegetation Index (NDVI) was used. The NDVI is a measure of the fractional vegetation cover, and is based on the reflectance in the red and near infrared light. The final grape mapping was improved using ASTER images of the summer growing season, as ASTER has a higher spatial resolution as Landsat.

The Surface Energy Balance Algorithm for Land (SEBAL) was applied to calculate actual water consumption and biomass production. SEBAL needs satellite inputs, such as albedo (a measure of the reflectivity of the earth), NDVI and surface temperature. The land cover map created served to prepare a land surface roughness map that facilitated the computation, but was not used for any direct computation of ET because ET is based essentially on surface temperature. Other input for SEBAL was a digital elevation model (DEM) of 20 meter resolution provided by the Department of Agriculture, as well as weather data. Weather data consisted of air temperature, relative humidity, wind speed, and solar radiation used to calculate the transmissivity. The Agricultural Research Council and the South African Weather Service provided the necessary weather inputs. For the year 2006-7 satellite data on atmospheric shortwave transmissivity was available from the geostationary MSG satellite using the Land Surface Analysis Satellite Applications Facility (LANDSAF) product at http://landsaf.meteo.pt/.

SEBAL is based on the energy balance, and computes the radiation and heat fluxes at the land-atmosphere interface. It computes the energy associated to evapotranspiration in the form of latent heat flux. It is not based on the water balance, and therefore does not need hydrological information for local conditions such as soil type and crop type.

SEBAL distinguishes between actual evapotranspiration (ET_{act} or ET), potential evapotranspiration (ET_{pot}) and reference evapotranspiration (ET0). Actual evapotranspiration is used synonymously with water consumption in this report, and describes the real conditions encountered in the field. The reference evapotranspiration is the water consumption of a hypothetical grass surface that is defined according to the standard guidelines of the FAO (Allen et al., 1998). Potential evapotranspiration is based on the assumption that crop water stress does not exist, and that the stomatal conductance reaches the maximum possible value at a given Leaf Area Index. Actual water consumption is usually lower than potential evapotranspiration because of water stress that unavoidably arises.

The accumulated biomass production expresses the total above ground dry matter production of stems, leafs, grains, flowers etc. The biomass production in SEBAL is computed on the basis of intercepted photosynthetic active radiation and the stomatal aperture for the intake of carbon dioxide. A small fraction of the accumulated biomass production is a harvestable fraction, expressed as the harvest index. The harvest index is variable for each vineyard. A yield model, based on empirical relations between the harvest index and SEBAL outputs such as soil moisture and ET deficit, was developed for both table and wine grapes.

2.3 Land cover mapping

2.3.1 Field work

Two field surveys were carried out for the land cover and grape classification in this study. In December 2006 almost 3000 vineyards in Hex River Valley, Worcester, Paarl and Franschhoek were "ground truthed" (identified in the field and on the map) by two WaterWatch experts (Annemarie Klaasse MSc and Wouter Meijninger PhD). In December 2007 the same team visited the winelands of Stellenbosch and Somerset West to expand the field data set with an additional ground truth data sets of more than 1000 vineyards. In total 4000 vineyards had been visited to observe their exact location, the type of farming (table, wine or bush grapes) and the condition of the vineyards (e.g. recently planted).

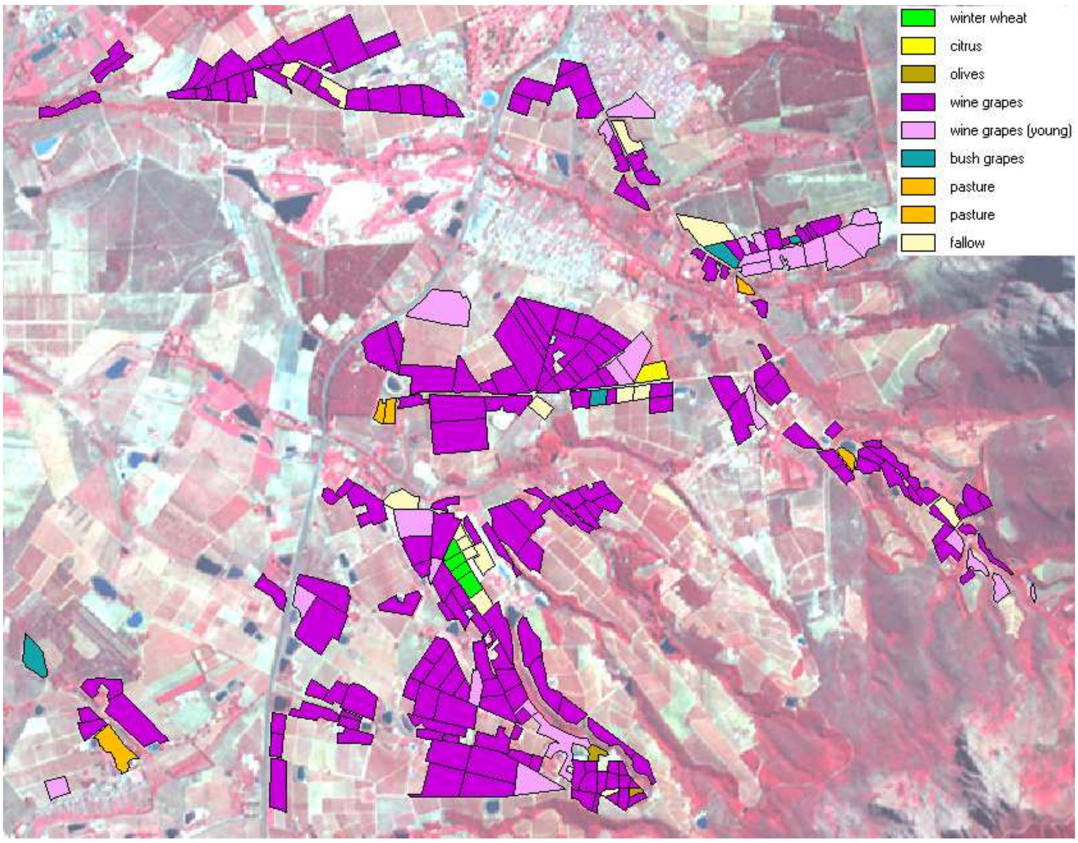


Figure 5 Detail of the ground truth field polygon file created from the field survey in December 2007

Some of the identified vineyards were recently planted. Most of the Landsat 5-TM images used for classification were acquired one to two years prior to the field data collection, and the recently planted vineyards are therefore not yet visible on the satellite imagery. For this reason these vineyards have been removed from the field data set. Finally 2789 vineyards in Paarl, Worcester, Hex River Valley and Franschhoek and 911 vineyards in Stellenbosch / Somerset West were found suitable for grape classification and validation. Of these ~3700 vineyards approximately 2000 plots are covered with table grapes. Most of the table grape vineyards were found in Hex Valley, the northern part of Worcester, and in the

Paarl area. In Franschhoek and Stellenbosch / Somerset West most vineyards contain wine grapes.

Two factors greatly improved the quality of the field survey in Stellenbosch / Somerset West. One factor is that the Department of Agriculture, Western Cape prepared a polygon dataset including all the agricultural fields in the Western Cape, although an attribute file was absent. These polygons show the exact areas of cropped land. The type of agriculture, (e.g. dryland farming or irrigated) and crop type cannot be derived from this dataset, but the polygon data was of great help for orientation and route planning. Another factor that greatly improved the field work quality was the application of Google Earth Pro, which allowed the WaterWatch team to orientate themselves on highly detailed aerial photography of Google Earth in combination with GPS in the field. The polygon dataset provided by the Department of Agriculture was projected on the Google Earth screen, thus allowing the field work team to delineate the orchards in very high detail. Figure 5 shows detail of the resulting polygon field data set.

2.3.2 Land cover classification

The cloud free Landsat 5-TM images of September 20, 2004, December 9, 2004, February 27, 2005, August 25, 2006, October 28, 2006 and February 17, 2007 were used for the land cover and grape classification. Furthermore, the land cover classification was based on the field polygon set provided by the Department of Agriculture and the ground truth data. Figure 6 shows the classification approach followed. Using the polygon dataset, a first division between agricultural and non-agricultural land could be made.

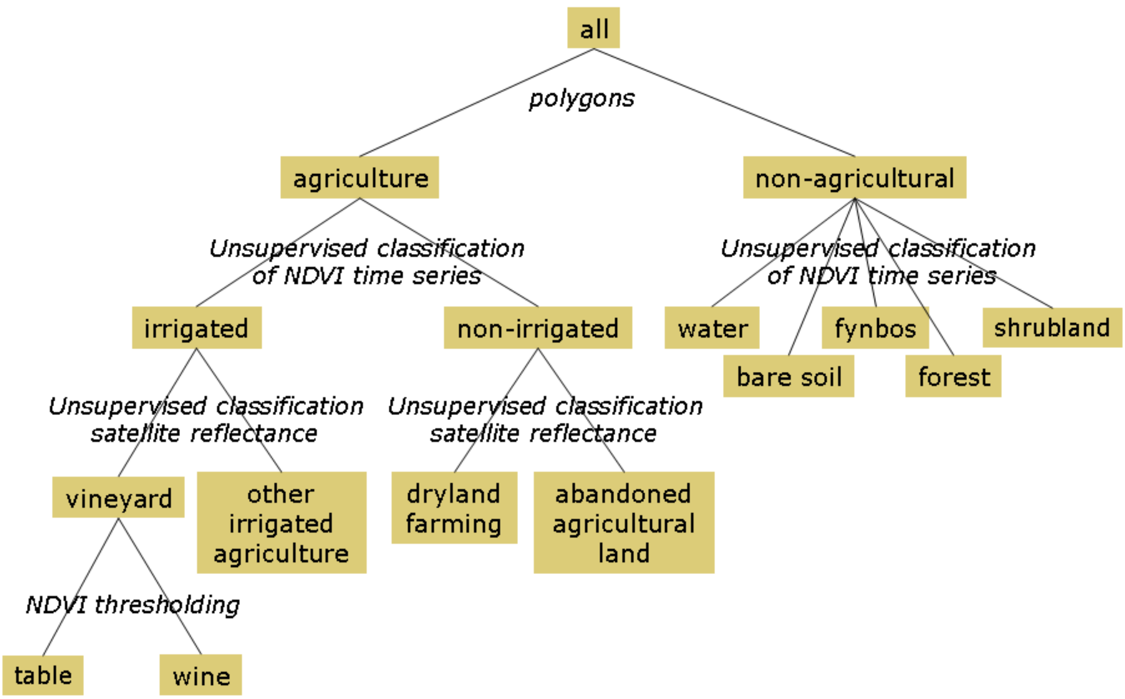


Figure 6 Classification approach

Subsequently a classification based on the NDVI trends in the six Landsat images had been applied. NDVI values distinguish non-agricultural classes such as forest (high NDVI values during both summer and winter), bare soil (very low NDVI values), water (negative NDVI values), shrubland (moderate NDVI values that slightly increase in winter) and fynbos (low NDVI values that slightly increase in winter). The class "bare soil" includes urban areas, as both bare soil and urban area have low NDVI values and similar reflectance. An unsupervised classification based on the reflectance values finally helped to further distinguish between the non-agricultural land cover classes.

Agricultural land could be divided easily into dryland and irrigated farming using the NDVI series. Dryland fields are fallow during the summer season, which results in very low NDVI values, while irrigated land is green in summer with corresponding high NDVI values. Some of the fields classified as agriculture by the Department of Agriculture did not show any agricultural activity in the period 2004-7, and were classified as abandoned agricultural land. Most likely these fields used to be irrigated, and were left fallow, resulting in regenerating vegetation that finally returned to fynbos.

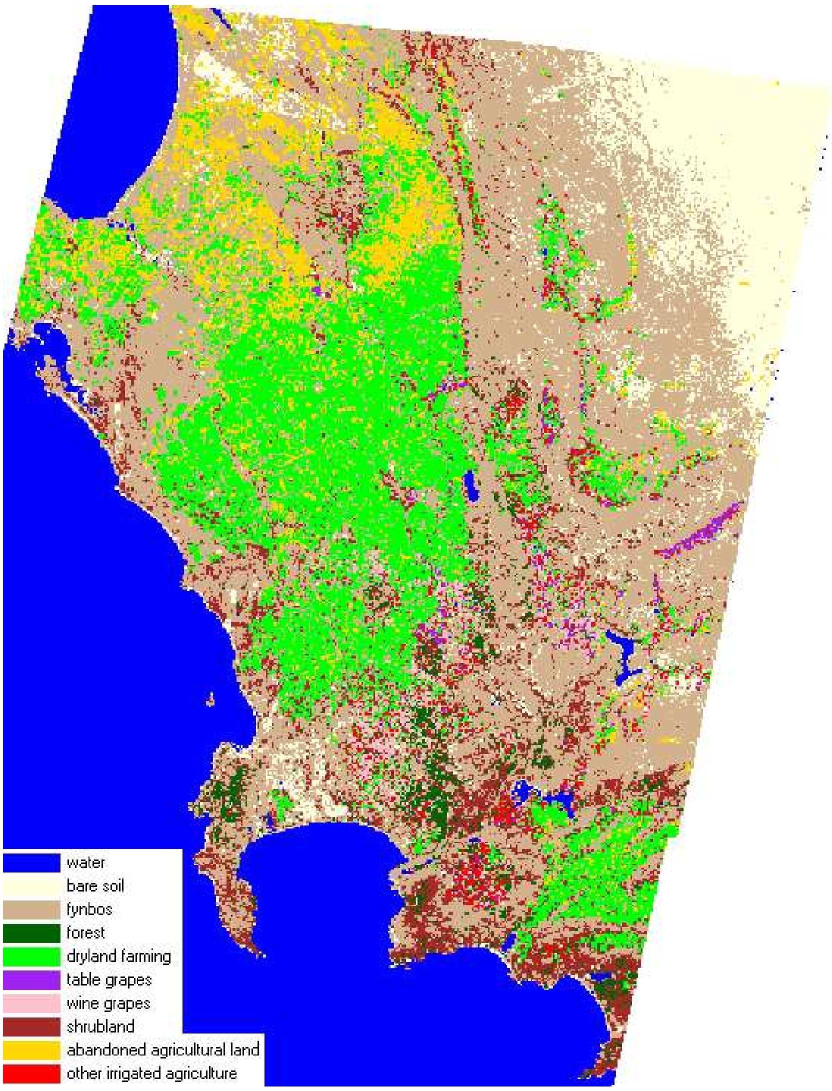


Figure 7 Land cover map and grape map

The irrigated agricultural fields were further classified into "vineyards" and "other irrigated agriculture" using unsupervised classification of the reflectance values of the Landsat 5-TM images as well as the NDVI values of the ASTER images of March

2005. Finally the table and wine grapes were classified using a threshold on the NDVI, which is mainly based on the fact that table grapes have higher biomass production and thus a higher NDVI than wine grapes. Young table grapes however also have low biomass production, and are therefore likely to be confused with wine grapes. Figure 7 shows the spatial distribution of the different land cover and land use classes.

Table 2 shows the area each land cover class encompasses on the two Landsat images. Almost half of the area is classified as fynbos, and 20% is dryland farming. Table and wine grapes only cover 2,4% of the total land surface, and wine grapes are at 1.8 % more common than table grapes at 0.6%.

Table 2 Area covered by the different land cover and land use classes

Land cover/use	Total area (103 ha)	% of total land surface
Water	1254	
Bare soil	367	12.6
Fynbos	1352	46.3
Forest	64	2.2
Dryland farming	559	19.2
Table grapes	18	0.6
Wine grapes	51	1.8
Shrubland	241	8.3
Abandoned agricultural land	219	7.5
Other irrigated agriculture	49	1.7
Total	**4175**	**100.0**

Landsat imagery of 30 m is technically speaking rather coarse for identification of orchards, but in combination with the field polygon set of the Department of Agriculture an overall accuracy of 82.3% could be achieved. Table 3 shows the error matrix that was prepared. Ninety one point one percent (91.1%) of all table grapes observed matched table grape classification. Of the table grapes classified, 94.6% was actually table grape. Accuracies of wine grape classification were slightly lower because of the confusion with other orchards, but still satisfactory. Ninety five point five percent (95.5 %) of the area classified as wine grape matched field observation of wine grapes. Some of the wine grapes observed in the field were not classified as wine grape, but still 78.5 % was. Accuracies of the class “other” were lowest, indicating that the total area of wine and table grapes was slightly underestimated in the classification. This might be the result of the time lag between field observations and image acquisition. In general however the classification results are very good.

Table 3 Error matrix resulting from classifying training set polygons (area in ha)

Observed	Classified as:			Total	
	Table grapes	**Wine grapes**	**Other**		
Table grapes	1800	38	138	1976	*91.1 %*
Wine grapes	102	3445	842	4389	*78.5 %*
Other	1	125	566	692	*81.8 %*
Total	1903	3609	1545	**7057**	
	94.6 %	*95.5 %*	*36.6 %*		***82.3 %***

3 Meteorological data

3.1 Meteorological datasets

Micro-meteorological data sets have been gathered from three different sources:

- The Agricultural Research Council manual weather stations (n=51);
- The Agricultural Research Council automatic weather stations (n=121); and
- The South African Weather Services (n=17).

The spatial distribution of the stations is depicted in Figure 8. Data of the stations was not always complete or correct, and for the final extrapolation only complete and correct data of ARC automatic weather stations was used.

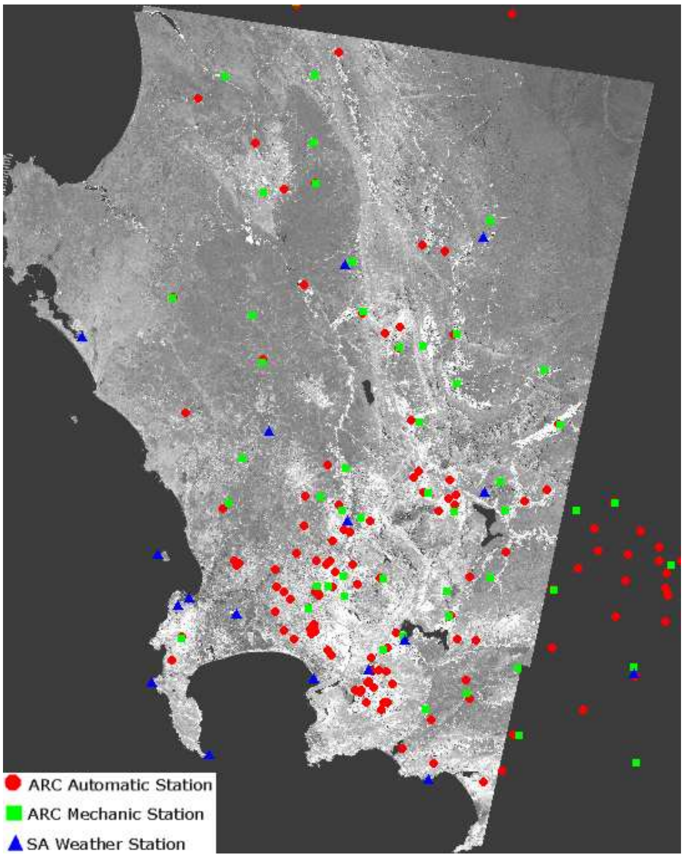


Figure 8 Spatial distribution of meteorological stations

3.2 Weather conditions in the study areas

The previous study showed that water use efficiency strongly varied between the two study years because of different weather conditions. In order to better understand the relationship between water use efficiency, rainfall and water availability, the year 2006-7 was included. In most areas 2004-5 had a dry winter and wet summer, while 2005-6 experienced a wet winter and dry summer. Concerning the distribution of rainfall, 2006-7 was a very standard year, similar to 2005-6 with most rainfall in winter, and a dry summer with little but well distributed rainfall. Figure 9, Figure 10, and Figure 11 show the monthly rainfall measured at different meteorological stations, each representing one of the six study areas.

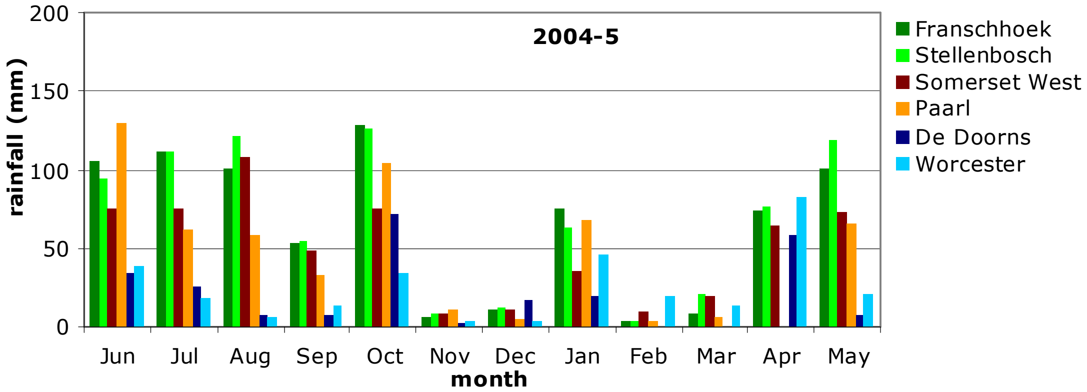


Figure 9 Monthly rainfall in 2004-5 (high rainfall in winter) from meteorological stations in Worcester (Nuy, 30216), Hex River Valley (De Vlei), Stellenbosch (Niet Voorbij, 30086), Somerset West (Vergelegenvrug, 30054), Paarl (Morewag, 30058) and Franschhoek (La Motte, 30453)

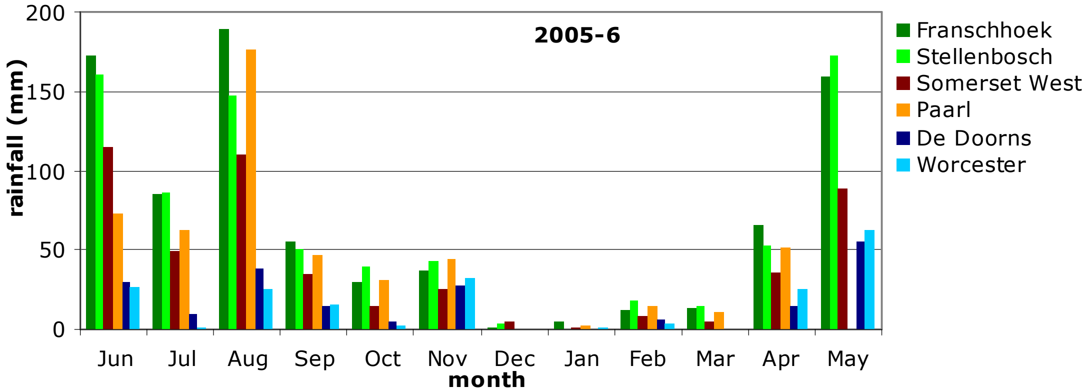


Figure 10 Monthly rainfall in 2005-6 from meteorological stations in Worcester (Nuy, 30216), Hex River Valley (De Vlei), Stellenbosch (Niet Voorbij, 30086), Somerset West (Vergelegenvrug, 30054), Paarl (Morewag, 30058) and Franschhoek (La Motte, 30453)

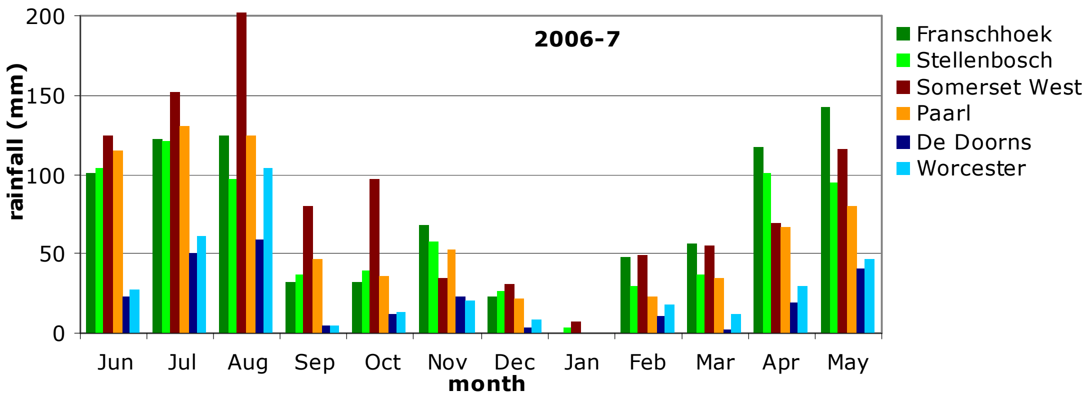


Figure 11 Monthly rainfall in 2006-7 from meteorological stations in Worcester (Nuy, 30216), Hex River Valley (De Vlei), Stellenbosch (Niet Voorbij, 30086), Somerset West (Vergelegenvrug, 30054), Paarl (Morewag, 30058) and Franschhoek (La Motte, 30453)

Rainfall in Franschhoek, Stellenbosch, Somerset West and Paarl is clearly higher than rainfall in Hex River Valley and Worcester. The monthly distribution of rainfall in 2004-5 is very distinct from 2005-6 and 2006-7. October 2004 and January 2005 especially received unusual high rainfall. In 2005-6 winter rainfall in the coastal areas was very high, with extremes in June and August 2005 and May 2006. In 2006-7 the rainfall was relatively equally distributed over the winter months.

Table 4 describes the total annual rainfall measured at the six representative stations. In the areas west of Wemmershoek Mountains (Paarl, Franschhoek, Stellenbosch and Somerset West) rainfall usually ranges between 700 and 850 mm. In 2004-5 annual rainfall was slightly lower in Paarl, a phenomenon that is also observed in other stations in the Paarl surroundings. Rainfall at the Vergelegen station (Somerset West), situated in the Lourens valley, showed a strong deviation from the other stations, with very low rainfall in 2005-6, and very high rainfall in 2006-7. Rainfall west of the Wemmershoek Mountains (Worcester and Hex Valley) varied between 250-450 mm. Total annual rainfall in Worcester was lower in 2005-6 because in this year both summer and winter were dry.

Table 4 Total annual rainfall (June-May) measured at for five meteorological stations (station name and number in brackets) in the different study areas

Total annual rainfall (mm)	**Worcester (Nuy 30216)**	**Hex Valley (De Vlei)**	**Stellenbosch (Niet Voorbij 30086)**	**Somerset West (Vergelegenvrug 30054)**	**Paarl (Morewag 30058)**	**Franschhoek (La Motte 30453)**
2004-5	300	388	810	603	545	780
2005-6	195	450	788	492*	795	824
2006-7	347	330	749	1032	730	869
Average	**281**	**389**	**782**	**818**	**690**	**824**

*Rainfall data of November 2005, February 2006 and March 2006 were missing, and patched with rainfall data from station 30689 (Vergelegen Bo)

Table 5 and Table 6 show the total rainfall in winter (June-August) and summer (October-February) respectively as measured at the six meteorological stations. Rainfall patterns in winter were not the same for the areas east and west of Wemmershoek Mountains. In the areas west of Wemmershoek Mountains rainfall in winter was not only much higher than in the eastern areas, but also distributed differently over the years. In the western study areas winter rainfall was slightly lower in 2004 for some of the stations but in general the total amount of rainfall in winter was relatively stable over the years. At the Vergelegen station rainfall was higher in the third year.

In the areas east of Wemmershoek Mountains considerable variation in the amount of winter rainfall was observed. In Worcester winter rainfall was low in 2004 and 2005, but very high in 2006. A completely different pattern is observed in Hex River Valley where rainfall in the winter of 2005 was much higher than the winter rainfall of 2004 and 2006.

Table 5 Total rainfall in winter (June-August) measured at five meteorological stations in the different study areas

Total winter rainfall (mm)	Worcester	Hex Valley	Stellenbosch	Somerset West	Paarl	Franschhoek
2004	64	163	328	259	249	317
2005	53	237	393	274	311	447
2006	193	171	322	491	370	348

The summer of 2004-5 was wet, with high rainfall measured at all stations. The summer of 2005-6 was the opposite, with very low rainfall at all stations. In 2006-7 summer rainfall was still low in Worcester and De Doorns, but moderate in the areas west of Wemmershoek Mountains.

Table 6 Total rainfall in summer (October - February) measured at five meteorological stations in the different study areas

Total summer rainfall (mm)	Worcester	Hex Valley	Stellenbosch	Somerset West	Paarl	Franschhoek
2004-5	106	110	213	140	192	225
2005-6	40	29	105	53	93	84
2006-7	60	69	157	220	132	173

In summary we can state that in the areas east of Wemmershoek Mountains (Worcester and De Doorns) the three years differed considerably. In 2004-5 the winter was dry and the summer wet, in 2005-6 both summer and winter were dry, and in 2006-7 the winter was wet and the summer dry in Worcester. In Hex Valley the first year rainfall in winter was moderate and rainfall in summer was high, the second year the winter was wet and the summer dry, and in the third year the winter was moderately wet again with a dry summer. In the areas west of Wemmershoek Mountains patterns were different with winter rainfall rates relatively similar in the three years, and high summer rainfall in 2004-5, low summer rainfall in 2005-6 and moderate summer rainfall in 2006-7.

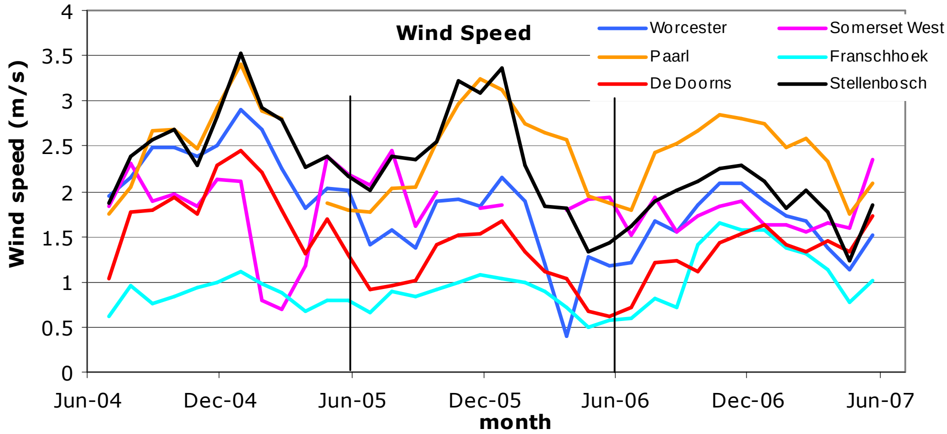


Figure 12 Average monthly wind speed as measured at the five representative meteorological stations

Evapotranspiration is highly influenced by wind speed and relative humidity. Well-watered plants evaporate more with high wind speeds and low relative humidities. Figure 12 shows the average monthly wind speed for the six meteorological stations. Wind speed in Franschhoek had a different pattern to the other stations;

wind speeds were lower (around 1 m/s) and there were only very small differences between winter and summer wind speed. In the third summer wind speed suddenly increased in summer to around 1.5 m/s. For all other stations the opposite happened; wind speed decreased in the second year, and even more in the third year. Moreover wind speed differed considerably between winter and summer for Stellenbosch, Paarl, Worcester and De Doorns, with high wind speeds in summer and low wind velocities in winter.

Figure 13 shows the changes of relative humidity over the three study years. Relative humidity was highest in Franschhoek, especially in the winter of 2004 and 2006. Relative humidity in summer decreased in 2005-6 and even more in 2006-7 in Stellenbosch and De Doorns. In Somerset West, Paarl and Worcester the relative humidity increased in the second and third year.

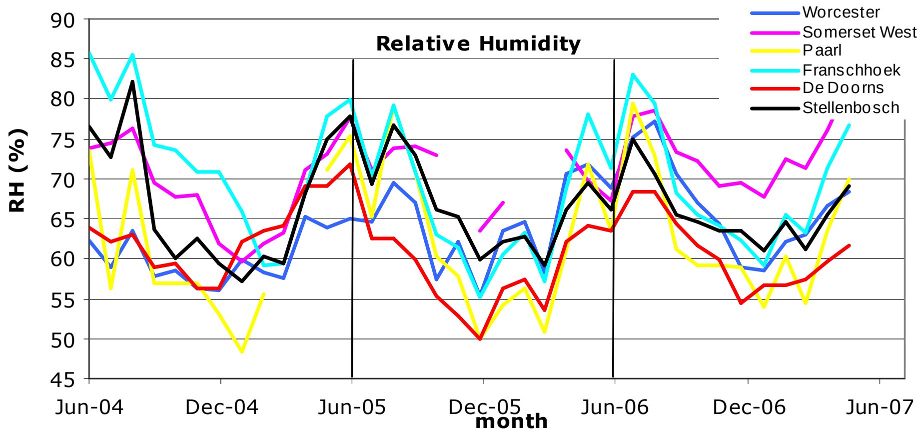


Figure 13 Average monthly relative humidity as measured at the five representative meteorological stations

3.3 MeteoLook

For spatially distributed computations of grape yield and grape ET, it is necessary to have an estimate of temperature, humidity, wind speed and solar radiation for every Landsat pixel. Hence, an interpolation and extrapolation technology needs to be applied. WaterWatch has developed the MeteoLook algorithm that interpolates point data on the basis of physio-graphical properties. The meteorological data of the automatic ARC stations in combination with several terrain characteristics such as a digital elevation model and a land cover map is are used to interpolate between weather stations.

In 2007 the data of the manual ARC stations and SA Weather stations was used for validation of the MeteoLook results. Through differences existed, the air temperature and relative humidity predicted with MeteoLook was within 1 C and 15% for air temperature and relative humidity. Some output products for a single day are demonstrated in Figure 14.

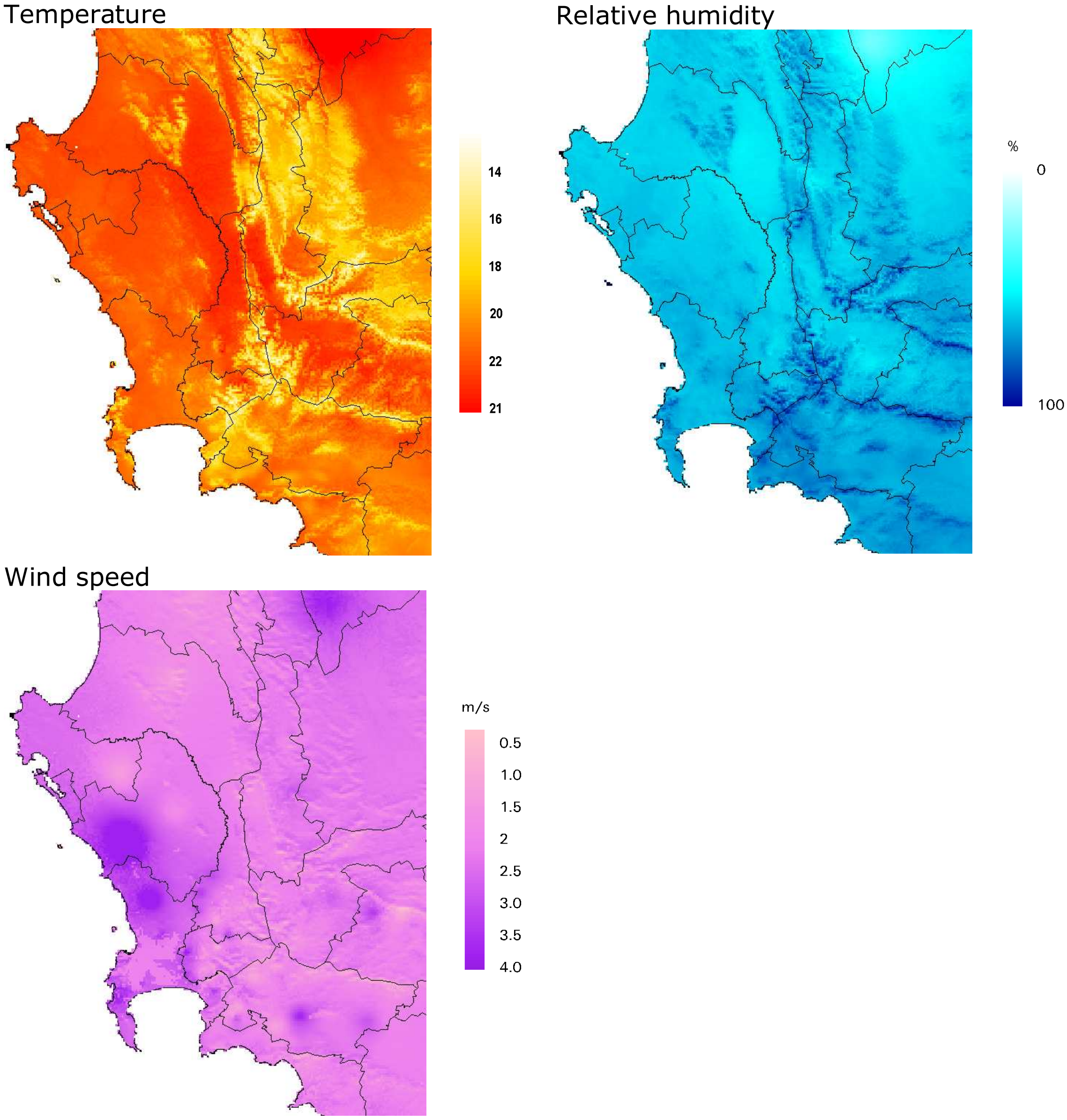


Figure 14 MeteoLook 24h results for March 13, 2007

Shortwave atmospheric transmissivity for the first two seasons were calculated from the station solar radiation measurements. The ARC automatic weather stations measure solar radiation (R_s) directly with pyranometers. The measured values of solar radiation were compared against the theoretical clear sky solar radiation: 0.75* R_a (extraterrestrial radiation). All stations with incomplete data, or periods with poor data (R_s higher or lower than expected) were removed from the station network.

For the season of 2006-7 no station data was used since atmospheric shortwave transmissivity maps of MSG (second generation MeteoSat) were available. The Land Surface Analysis Satellite Applications Facility (LSA SAF) generates downwelling surface short-wave radiation fluxes from the three short-wave MSG/SEVIRI channels (VIS, NIR, SWIR). Transmissivity is one of the products generated during this calculation. Figure 15 shows the 24-h transmissivity as generated from MSG.

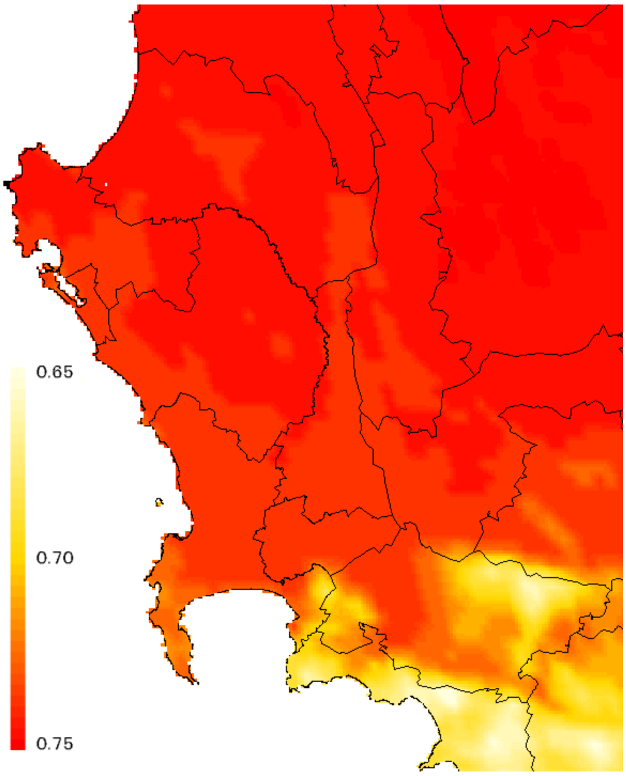


Figure 15 MSG transmissivity on March 13, 2007 showing clouds arising in the coastal region

4 Water balance measurements in vineyards

The Department of Agriculture, Western Cape, has been measuring rainfall, irrigation application and soil moisture in 27 to 32 blocks of table grapes in the Hex River Valley since 1999. Five table grape varieties are cultivated in the blocks, and grape production has been measured for each block. The water balance data has kindly been made available for an estimation of the water consumption of table grapes and thus calibration and validation of the remote sensing results.

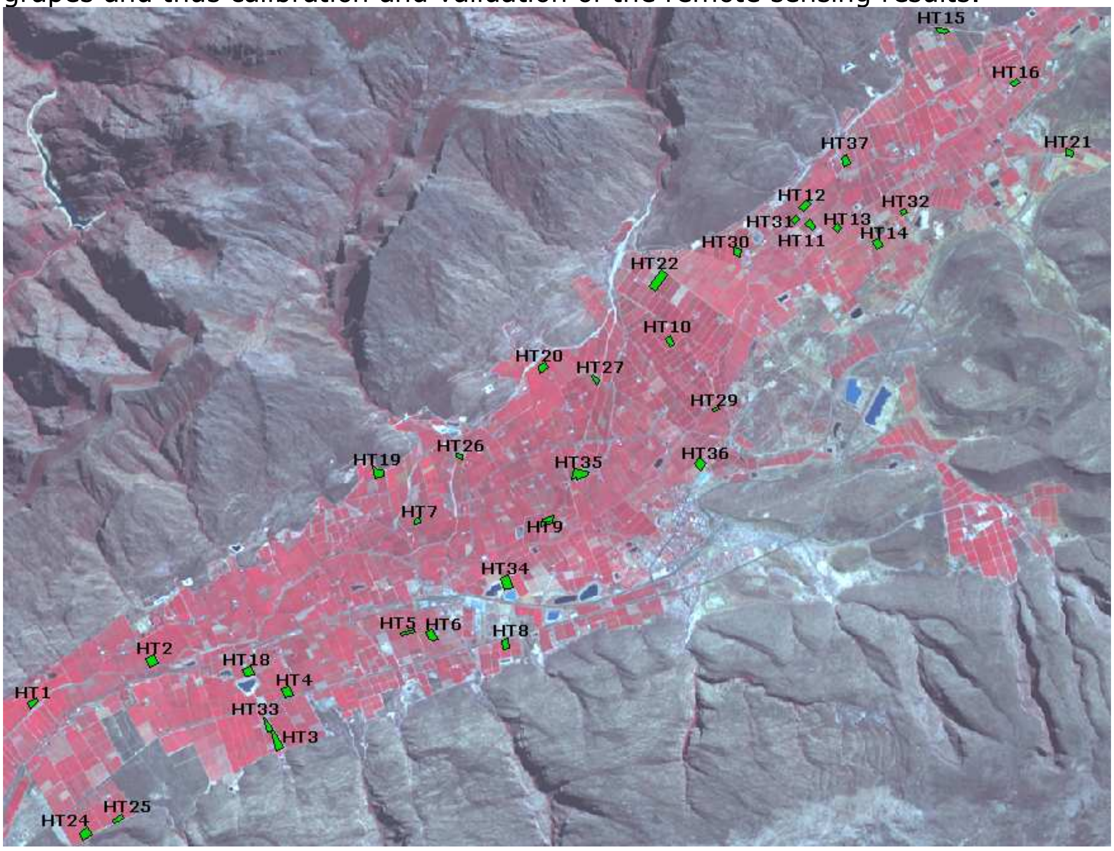


Figure 16 Location of the irrigation blocks in the Hex River Valley on which the Department of Agriculture, Western Cape conducts field measurements

In addition 10 blocks of wine grapes in the Worcester area were monitored from August 1999 until May 2005.

The validation and calibration of 2004-5 and 2005-6 using the field data of Hex River Valley and Worcester has been extensively discussed in the prior report (Klaasse et al., 2007) and will not be repeated here. For the sake of inclusion of the year 2006-7, the tabular information on rainfall, soil moisture and irrigation supply of 2004-5 and 2005-6 is presented again.

4.1 Rainfall measurements

As stated before in chapter 3, the three study years differed considerably in terms of the timing and amount of rainfall. Hex River Valley experienced a moderately wet winter with high summer rainfall in 2004-5, high winter rainfall and low summer rainfall in 2005-6, and again a moderately wet winter but with a dry summer in

2006-7. See Table 7. In 2004-5 irrigation supplies were cut with 40% because of water shortage.

Table 7 Total rainfall as measured at De Vlei meteorological station

Total rainfall (mm)	Annual (June – May)	Winter (June-August)	Summer (October – February)
2004-5	388	163	110
2005-6	450	237	29
2006-7	330	171	69

The computation of the water balance in the blocks requires rain gauges as near as possible to the block. Table 8 shows the average rainfall measured in the different rain gauges in Hex Valley in 2004-5, 2005-6 and 2006-7. Detailed information on rainfall in some of the individual blocks is available in Appendix 2. Although rainfall was highly variable across these blocks, some of the variations exceeded the expectations, suggesting that data quality is variable. For example measurements by the ARC Hex River Valley station in 2007 was suspect, as only at this station high rainfall was measured in April.

For some blocks no individual rain gauge measurements were available. Where possible data of nearby located rain gauges was used, for example blocks 1, 11, 12, 31 and 34 are all located near station De Vlei and it is assumed that they received the same amount of rainfall.

Table 8 Average monthly rainfall measured at various locations in the Hex River Valley (Source: ARC / Department of Agriculture), original data is shown in appendix 2

Month	2004-5	2005-6	2006-7	Average
Jun	47	50	59	52
Jul	50	44	52	49
Aug	20	74	60	51
Sep	8	18	12	13
Oct	48	0	14	21
Nov	7	22	29	19
Dec	12	0	7	6
Jan	22	1	3	9
Feb	1	0	5	2
Mar	1	0	4	2
Apr	75	39	21	45
May	18	85	45	49
Total	**310**	**334**	**311**	**318**

4.2 Irrigation measurements

Table 9 shows the monthly application of water on the experimental blocks in Hex River Valley. The average total irrigation water application was 559 mm in 2004-5, much lower than in 2005-6 (725 mm) and 2006-7 (729 mm). This difference can be explained by the amount of irrigation water available from the preceding winter (low in 2004-5) and the amount of rainfall in summer (dry in 2005-6 and 2006-7). Note that winter irrigation also takes place for keeping soil moisture at a minimum level and for keeping the vines dormant.

Table 9 Average irrigation water applied (mm) at the blocks in Hex River Valley (source: Department of Agriculture)

Month	2004-5	2005-6	2006-7	Average
Jun-Sep	42	30	25	32
Oct	39	60	58	53
Nov	91	116	107	105
Dec	124	132	144	133
Jan	89	147	143	126
Feb	77	116	111	101
Mar	64	78	80	74
Apr	21	38	49	36
May	11	7	13	10
Total	**559**	**725**	**729**	**681**

Irrigation supply in 2004-5 did not only deviate in annual total. The distribution of irrigation supply over the months also diverged in the experimental blocks. Figure 17 shows the distribution of irrigation application over the grape season for the three years and the average rainfall in the same months. In 2004-5 the amount of irrigation water applied in the months June to September was higher than for the other two years. Possible explanations for this extra irrigation between June and September may be: (1) replenishment of the water in soils that experience higher water deficits because of the dry preceding winter; and (2) cooling down of the vines to keep them dormant. Irrigation in May to July can prevent early budding by reducing temperature. Figure 18 shows that temperature in 2004-5 was different from the temperatures in 2005-6 and 2006-7.

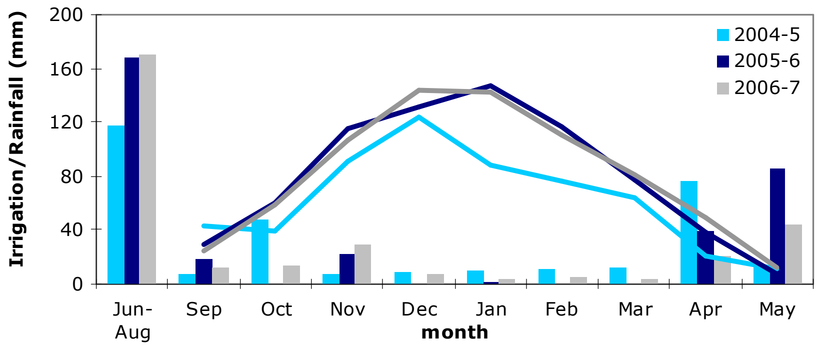


Figure 17 Mean irrigation application (lines) and rainfall (columns) in the experimental blocks of Hex River Valley

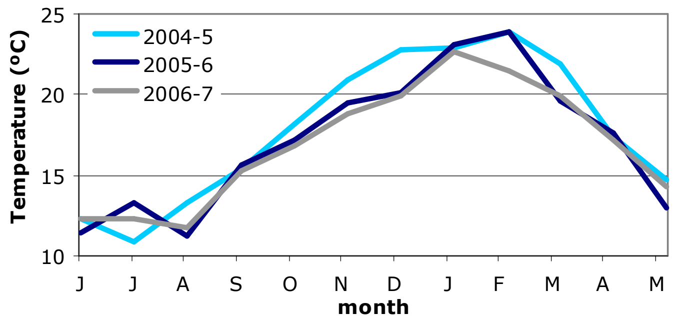


Figure 18 Average monthly temperature (average from daily (T_{min}+T_{max})/2) as measured at De Vlei station, Hex River Valley

In October 2004 a considerable amount of rainfall fell, resulting in reduced irrigation supply in the same month. Irrigation application was again strongly reduced in January and February 2005 in the absence of sufficient water, while in 2005-6 and 2006-7 enough irrigation water was available, and irrigation application still had to come to its peak.

4.3 Soil moisture measurements

The Department of Agriculture, Western Cape provided a dataset of soil moisture measurements in the 27-32 monitoring blocks in Hex River Valley. Soil moisture in irrigation blocks was measured at depth intervals of 10 cm starting at 10 cm up to 90 cm.

Analysis of the soil moisture profiles in the previous study (Klaasse et al, 2007) implied that an upward oriented gradient of soil water potential in the unsaturated soil matrix persisted, and that downward percolation was negligible.

According to the FAO the maximum rooting depth of table and wine grapes is between 1.0 and 2.0 meter (Allen et al., 1998). Grape vine rooting depth strongly depends on soil type and the irrigation system. Drip irrigation, which is commonly applied in the Hex River valley, is often associated with shallow rooting depths. It is however still possible that grape vines in some of the fields have deep rooting systems and are capable of subtracting water from the unsaturated zone, although this is not considered in the estimation of the evapotranspiration derived from the water balance (ET_{WB}).

The soil moisture content in general is very low in the Hex River Valley. Most of the Hex River vineyards are established on alluvial and terrace gravel deposits which in general have very low water-holding capacity. Considering all soil moisture measurements in the three years, soil moisture content in the 5-95 cm profile was on average 14.3 cm^3/cm^3, with a standard deviation of 6.0 cm^3/cm^3. Typically, soil moisture content starts at ±15.5 cm^3/cm^3 in October, and drops to ±11.0 cm^3/cm^3 in March. Hence soil moisture depletion is a source of influence for ET.

Table 10 Monthly soil moisture change (mm) in the 5-95 cm soil profile from October 2004 until March 2005

HT_Number	2004-5	2005-6	2006-7	Average
Oct	4.2	5.3	5.0	4.8
Nov	-4.2	7.4	16.0	6.4
Dec	-4.6	-8.6	-9.4	-7.5
Jan	-11.5	-7.4	-38.2	-19.0
Feb	-6.8	-24.9	-18.5	-16.7
Mar	-21.7	-13.9	6.9	-9.6
Total change	**-42.2**	**-37.8**	**-40.4**	**-40.1**

Table 10 shows the average monthly soil moisture change measured, and the total soil moisture change between October and March. Monthly soil moisture change per block is presented in Appendix 2. From October until March on average 40.1 mm of water was subtracted from the 5-95 cm soil profile. In all blocks soil moisture was replenished in October. In 2004-5 soil moisture content reduction started in November, while in 2005-6 and 2006-7 the first reductions started in December.

Most soil moisture was used in March 2004-5, February 2005-6 and January 2006-7 with 21.7, 24.9 and 38.2 mm respectively.

4.4 Evapotranspiration of table grapes as calculated with the water balance

The measurements of irrigation supply, rainfall and soil moisture depletion were used for an estimation of water consumption by table grape vineyards using the following equation:

$$ET_{WB} = I + P - \Delta\theta$$

Where ET_{WB} is the actual water consumption (or evapotranspiration) (mm), I is the irrigation supply (mm), P is the precipitation (mm) and $\Delta\theta$ is the change in soil moisture (mm). Deep percolation and runoff were not taken into account, as well as water subtraction from layers deeper than one meter.

Table 11 shows the average evapotranspiration derived from the water balance for 2004-5, 2005-6 and 2006-7 respectively. Evapotranspiration was lowest in 2004-5, at 536 mm in the period October until February. In 2005-6 and 2006-7 the average evapotranspiration was around 130 mm more, at 667 mm in 2005-6 and 663 mm in 2006-7 in the same months.

For individual blocks these annual differences are greater (see Appendix 2). Evapotranspiration in block 11 almost doubled in two years, increasing from 508 mm in 2004-5 to 748 mm in 2005-6 to 989 mm in 2006-7. In block 31 evapotranspiration was 377 mm in 2004-5, while in the preceding two years respectively 587 mm and 576 mm was consumed.

Table 11 Evapotranspiration derived from the water balance in mm for 2005-6

P+I-ΔS	**2004-5**	**2005-6**	**2006-7**	**Average**
Oct	81	50	71	67
Nov	117	129	124	124
Dec	124	129	151	135
Jan	131	154	185	157
Feb	78	135	146	120
Mar	74	97	93	88
Total Oct-Feb	**536**	**667**	**663**	**592**
Total Nov-Feb	**446**	**547**	**601**	**561**

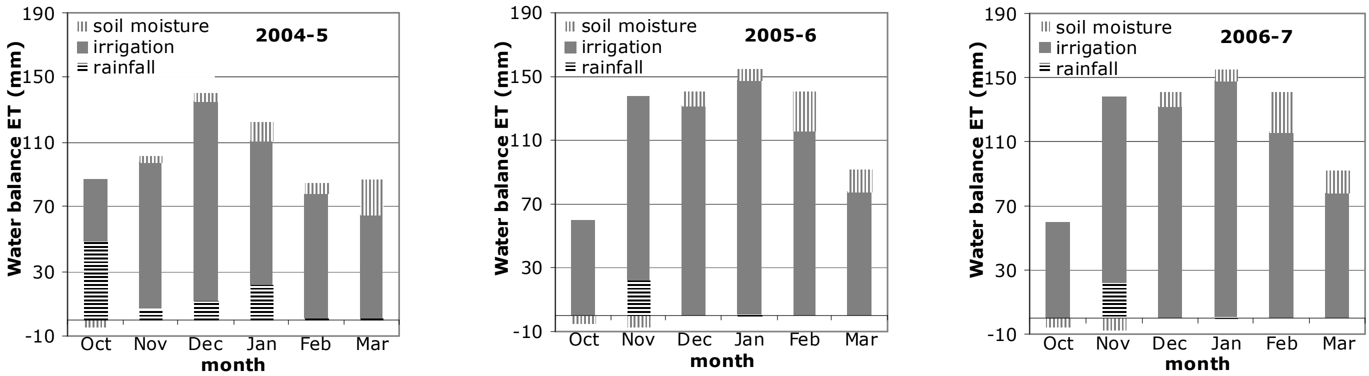


Figure 19 The contribution of rainfall, irrigation supply and soil moisture change at the water balance ET

Figure 19 shows the contribution of rainfall, irrigation and soil moisture change to the estimated water balance evapotranspiration. It shows that irrigation is the main contributor to the water balance evapotranspiration. Soil moisture change is mainly effective from December until March, and only has a small contribution to the total ET. Rainfall in 2004-5 is of importance from October until January, and only in November in 2005-6 and 2006-7.

Figure 20 shows the average monthly water consumption based on the water balance calculations. Evapotranspiration estimates were highest for January in 2005-6 and 2006-7. Water consumption in 2004-5 was very similar to the other two years from October until December, but was slightly reduced in January, and dropped considerably in February.

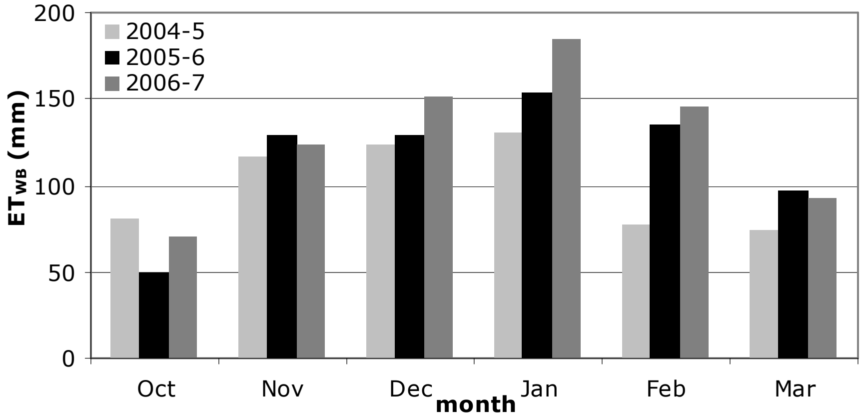


Figure 20 Average monthly evapotranspiration (based on the water balance estimations) in 2004-5, 2005-6 and 2006-7

Figure 21 shows that the water balance evapotranspiration is strongly influenced by the amount of irrigation supplied and that rainfall and soil moisture only have a minor effect. The relationship between irrigation supply and the water balance evapotranspiration is linear.

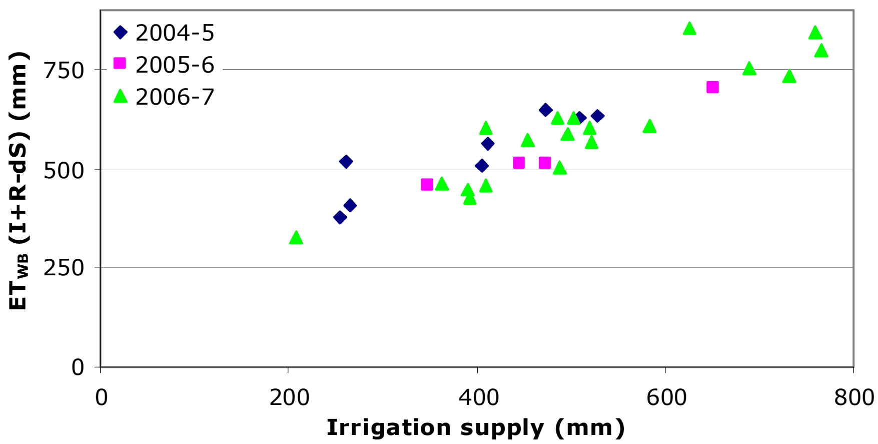


Figure 21 The relationship between irrigation supply and the derived water balance evapotranspiration

5 Water consumption from remote sensing

Actual evapotranspiration (ET_{act}) is used synonymously with water consumption in this report. The Surface Energy Balance Algorithm for Land (SEBAL) was applied to calculate actual evapotranspiration and biomass production in the two Landsat scenes for the grape growing seasons (Sep-Apr) of 2004-5, 2005-6 and 2006-7. SEBAL has been applied before in vineyards in Spain, Turkey and Brazil. In Appendix 1 a brief background of the underlying concepts and mechanisms of SEBAL is provided.

In this study SEBAL was applied on all the individual Landsat images listed in Table 1. SEBAL is executed without calibration or fine-tuning. No information on the properties of the soil, the cultivar and the irrigation system is used in SEBAL. The internal calibration of the range of ET values in SEBAL between minimum and maximum values was achieved by means of assigning wet and dry pixels in the study area. Wet pixels were selected over the reservoirs, and dry pixels were selected in the Karoo area.

SEBAL results were qualitatively evaluated by comparing the first estimates of ET against measured precipitation data in non irrigated landscapes. Rainfall should exceed ET in dryland areas. The wet and dry pixels were adjusted accordingly until the ET in the Karoo and lake areas was acceptable. No direct calibration with field measurements in the vineyards was applied, and the calibration procedure was entirely based on general hydrological principles and plausible ranges.

Irrigation water supply is often used as a measure of crop water use. ET is a better proxy for water use. ET is however not commonly used when estimating water use of crops as it is difficult to measure. As a result of the development in satellite imagery in the last 20 years and of SEBAL it is now possible to calculate the ET for large areas, and to evaluate water consumption at spatial and temporal scale.

The results of 2004-5 and 2005-6 of Hex River Valley, Worcester, Franschhoek and Paarl have been presented in the previous report (Klaasse et al., 2007). Statistics however have changed for all three years, because (1) the classification of all vineyards was improved using the field boundary file of the Department of Agriculture and additional satellite imagery, (2) the inclusion of two new areas: Stellenbosch and Somerset West, and (3) a redefinition of the exact location of the blocks in Hex River Valley. This report will provide a comprehensive overview of all years and areas.

5.1 Evapotranspiration (ET) of table and wine grape vineyards

5.1.1 Frequency distributions of grape water consumption

The calculations of SEBAL produced actual evapotranspiration of table and wine grape vineyards in three grape seasons in a 30-m grid. Figure 22 shows the frequency distributions of water consumption in table and wine grape vineyards in the three study seasons.

Table grapes consume more water than wine grapes. While the average table grape water consumption ranges from 690 to 866 mm, the average water consumption of wine grapes is around much lower ranging from 520 to 716 mm.

In addition water consumption of table grapes is in general more uniform than the water consumption of wine grapes. The standard deviation of wine grapes is 153, 199 and 181 mm, while the standard deviation of table grapes is 126, 210 and 156 mm in 2004-5, 2005-6 and 2006-7 respectively. So, the standard deviation of wine grape's seasonal water consumption is around 25 mm higher than of table grapes.

Water consumption of table grapes is higher and more uniform than water consumption of wine grapes because of:

- Water deficit management: Water deficits in table grape vineyards may negatively influence the export quality of table grapes, while wine grape quality sometimes improves after application of water stress at certain phenological stages (especially for the red cultivars);
- Irrigation type: Most table grape vineyards are under permanent drip irrigation, while irrigation in wine grape vineyards varies from rainfed or semi-rainfed (with only a small number of irrigation applications) in Stellenbosch and Somerset West to permanent drip and surface irrigation in Worcester; and
- Trellis system: Table grape vines are in general grown on horizontal trellises that completely cover the soil, resulting in very high and uniform leaf area indexes (LAI) in table grape vineyards. Wine grapevines are grown on a wide variety of vertical trellises, ranging in height, row distance, and plant distance, which results in a lower LAI.

Water consumption of table grapes was higher in 2005-6 and 2006-7, which might be related to higher cloud cover limiting evapotranspiration in 2004-5 and more available irrigation water in 2005-6 and 2006-7. The standard deviation of table grape water consumption was lower in 2004-5 in line with the lower water resource availability in 2004-5 and there was a tendency towards more uniform water stress.

Water consumption of wine grapes was very similar the first two years, but increased in 2006-7. The area of vineyards that consume low water volumes (less than 500 mm or 5000 m^3) is very similar for all three years, which indicates there are farms with very strict water conservation practices, and that by good management practices they are able to maintain that, despite the climatic variability.

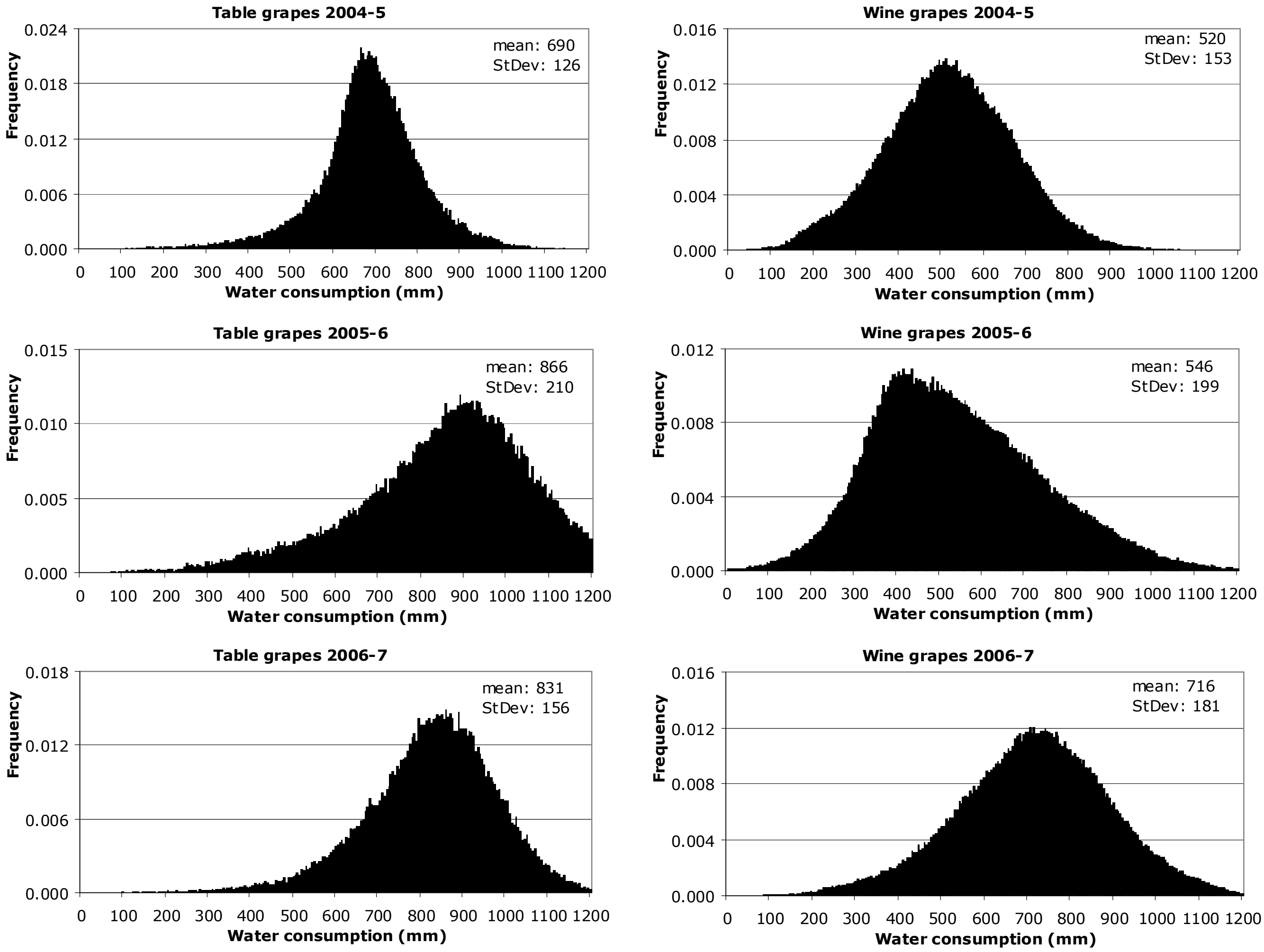


Figure 22 Frequency distribution of water consumption in the grape season for all pixels in Hex River Valley, Worcester, Paarl, Franschhoek, Stellenbosch and Somerset West classified as table grape (left, n=76415) or wine grape (right, n=297424)

5.1.2 Water consumption trends over the different areas and years

Figure 23 shows all the table and wine grape vineyards in the six study areas. An arbitrary subdivision has been made to group the vineyards that show a similar behaviour in water consumption and biomass production. Boundaries are placed arbitrarily, and the subdivision is only intended to describe the differences between areas better.

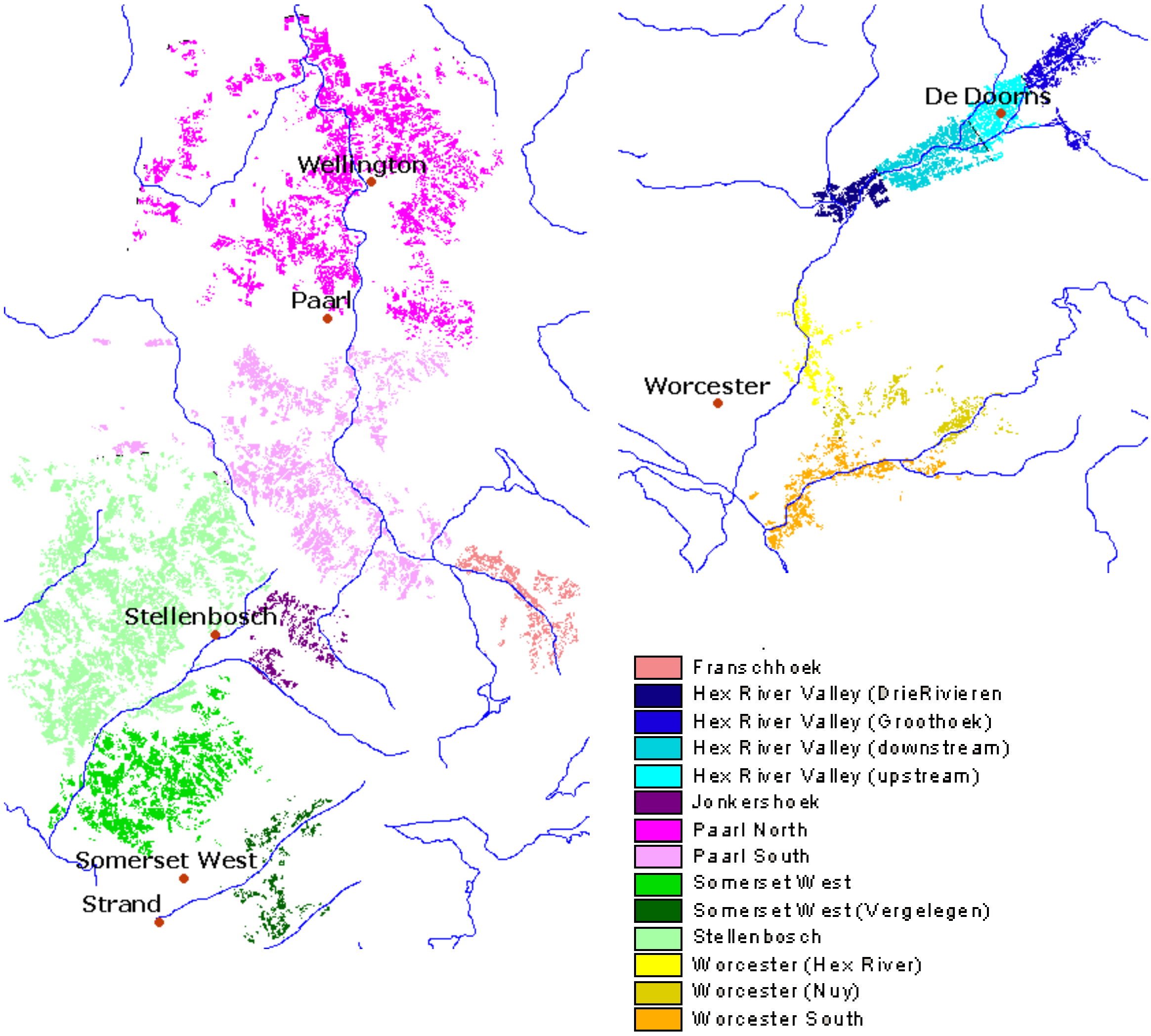


Figure 23 Arbitrary division of the study areas for the calculation of statistics in Table 12

Table shows the average water consumption in each arbitrary sub-area. Water consumption in table grape vineyards along the Hex River in Worcester area was at an average consumption of 979 mm remarkable higher than in all other table grape vineyards that used on average between 720 and 863 mm. Water consumption of table grapes in the neighbouring Nuy area was lower at 838 mm on average, but still 85 mm higher than in the Southern area of Worcester, where water availability often is a problem, as was confirmed by farmers.

In Hex River Valley two sub-areas had a clearly higher evapotranspiration: Groothoek and Drieriviere. These sub-areas consist of alluvium in the flood plains that have a high availability of ground water.

All table grape vineyards consumed considerable larger amount of water in 2005-6 and 2006-7 than in 2004-5. On average around 170 mm more water was consumed in 2005-6, which is an increase of 24%. Differences between 2005-6 and 2006-7 were smaller. Slightly more water was consumed in 2005-6, except for the table grape vineyards in Paarl South and Worcester South.

The wine grape vineyards in Hex River (Worcester) also consumed more water than other wine grape vineyards although differences between areas were not as great as between table grape areas. In two of the Worcester areas and in the valley of Vergelegen over 100 mm more water is consumed than in the other areas which is most probably related to the more arid climate of Worcester as compared to the coastal regions. Seasonal average ET in table grapes varied between areas from 720 to 979 mm, a factor 1.4 difference. The relative differences in wine grapes were from 540 to 802 mm even more profound.

Lowest water consumption in wine grapes occurred in the Stellenbosch and Paarl areas, where ET was well below 500 mm in the first year and only increased above 600 mm in the third year.

Water consumption was the lowest in 2004-5 in most areas, except in Stellenbosch and Somerset West where water consumption was low in both 2004-5 and 2005-6. In contrast with the table grapes, water consumption of wine grapes also increased in 2006-7, most likely because of a better temporal distribution of summer rainfall. The increase was especially remarkable in Somerset West, Jonkershoek/Banhoek and Stellenbosch where water consumption increased with more than 200 mm from 2004-5 to 2006-7. The increase in water consumption in Somerset West and Vergelegen can be contributed to the increased rainfall in 2006-7 (see Table 4). Stellenbosch however experienced similar rainfall and no clear explanation for the higher water consumption in 2006-7 could be found.

Table 12 Average water consumption from September until April of table and wine grapes in arbitrary classes

Name	Table grape water consumption September – April (mm)					Wine grape water consumption September – April (mm)				
	area (ha)	2004-5	2005-6	2006-7	Avg.	area (ha)	2004-5	2005-6	2006-7	Avg.
Somerset West (Vergelegen)						690	608	742	960	770
Somerset West						3625	607	566	855	676
Jonkershoek/Banhoek						696	535	644	822	667
Stellenbosch						9199	497	475	702	558
Paarl South	516	600	818	840	753	4687	434	520	705	553
Franschhoek						996	608	768	652	676
Paarl North	1657	662	883	830	792	6605	475	543	602	540
Worcester (Hex River)	293	861	1087	989	979	272	766	836	803	802
Worcester South	301	668	774	816	753	850	611	627	695	644
Worcester (Nuy)	210	767	903	845	838	504	721	726	746	731
Hex River Valley (Drieriviere)	637	764	945	879	863					
Hex River Valley (downstream)	1321	675	835	796	769					
Hex River Valley (Groothoek)	972	730	884	840	818					
Hex River Valley (upstream)	819	638	780	741	720					

5.2 Validation of table grape evapotranspiration in Hex River Valley

The previous chapter described the estimation of actual evapotranspiration using the water balance, based on field measurements of rainfall, irrigation supply and soil moisture in the Hex River Valley. The SEBAL ET results, based on the energy balance, were validated using the water balance ET results.

Table 13, Table 14 and Table 15 describe the water consumption per block and per month as estimated with the water balance and with SEBAL. In Figure 24, Figure 25 and Figure 26 the average (accumulated) monthly water balance ET and SEBAL ET are plotted.

In 2004-5 the water consumption from October until February could be compared. In 2005-6 and 2006-7 the water consumption from November until February was compared because for these years only one image was available for September and October. The water balance revealed 536, 547 and 601 mm in 2004-5, 2005-6 and 2006-7 respectively. The total average SEBAL ET for the same blocks and five/six months[1] was 603, 590 and 519 mm respectively.

SEBAL calculations of water consumption were on average 11% higher or lower than the estimates of the water balance, which is realistic. Water consumption calculated from the energy balance and water consumption calculated from the water balance will never be exactly the same because:

- Soil moisture is highly variable in time and space, resulting in variation in the water balance ET results;
- Runoff, deep percolation, and water uptake from deeper soil layers are ignored in the water balance and it is thus logical that SEBAL often has higher values;
- SEBAL ET results are an average of all 30 meter pixels in a block, while water balance results are for a block.

Table 13 Evapotranspiration per block and per month calculated with the water balance (rain + irrigation – change in water storage in the 25-75 cm of soil profile) and with SEBAL for 2004-5

2004-5	WB					SEBAL					WB	SEBAL
HT no	Oct	Nov	Dec	Jan	Feb	Oct	Nov	Dec	Jan	Feb	Total	Total
1	37		145	115		38		188	149			
3	99	118	92	220	121	11	98	137	143	102	651	492
4	65	190	129	139	107	44	132	165	149	111	630	601
5				123					125			
7	139	134	143	89		63	137	200	144			
8				155					161			
11	70	116	134	116	72	45	112	190	143	119	508	609
12	72	101	95	75	65	28	97	206	141	116	408	589
13	-21	152	61			28	116			122		
14	96	135	97			35	98			116		
18	47	123	174	154	133	20	111	158	162	106	632	556
20	86	109	147	129	94	32	125	236	176	176	565	745
27	215	104	76	98	25	26	122	188	158	133	518	627
29	40	105	159	138		5	110	193		131		
30	107	82		198	47	18	110		161	140		
31	62	97	92	86	41	38	115	195	144	111	377	603
32	98	79	190			40	95	172				
Avg	**81**	**117**	**124**	**131**	**78**	**31**	**113**	**186**	**151**	**124**	**536**	**603**

[1] October-February for 2004-5, November-February for 2005-6 and 2006-7.

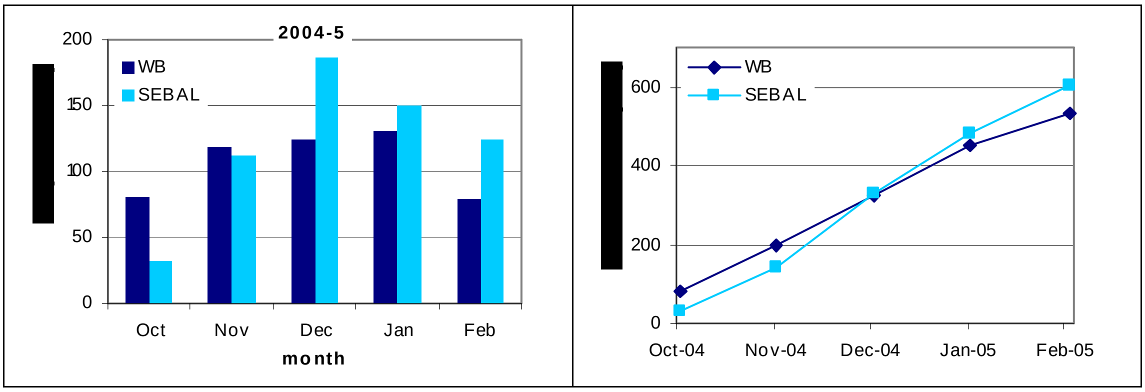


Figure 24 Average period and accumulated evapotranspiration in the experimental blocks in Hex Valley during 2004-5 calculated with SEBAL and with the soil water balance based on field experiments

Table 14 Evapotranspiration per block and per month calculated with the water balance (rain + irrigation – change in water storage in the 25-75 cm of soil profile) and with SEBAL for 2005-6

2005-6	**WB**			**SEBAL**			**WB**	**SEBAL**
HT no	**Nov**	**Dec**	**Jan/Feb**	**Nov**	**Dec**	**Jan/Feb**	**Total**	**Total**
3	76			79				
4	169			119				
5			280			182		
7	155			116				
8			239			230		
11	213	145	346	104	188	251	703	543
14	135			103				
18	182			112				
20	104	127	280	115	243	306	512	664
27	113	108	238	114	177	316	459	607
29	112			115				
30	100			118				
31	136	136	242	108	186	252	513	546
32	55			108				
Average	**129**	**129**	**271**	**109**	**199**	**256**	**547**	**590**

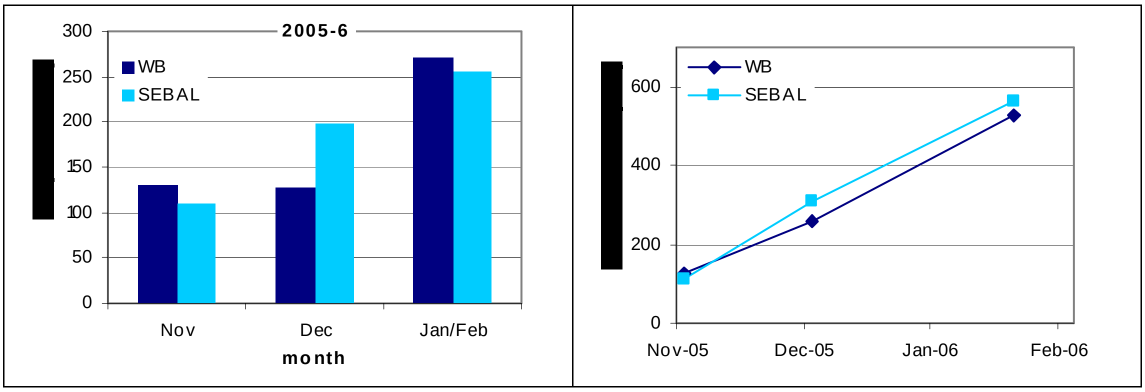


Figure 25 Average period and accumulated evapotranspiration in the experimental blocks in Hex River Valley during 2005-6 calculated with SEBAL and with the soil water balance based on field experiments

Table 15 Evapotranspiration per block and per month calculated with the water balance (rain + irrigation – change in water storage in the 25-75 cm of soil profile) and with SEBAL for 2006-7

2006-7	WB			SEBAL			WB	SEBAL
HT no	**Nov**	**Dec**	**Jan/Feb**	**Nov**	**Dec**	**Jan/Feb**	**Total**	**Total**
1	47	46	336	67	166	336	428	570
3	117	122	329	42	134	282	568	458
4	222	138	440	91	163	326	801	581
5	120	181	306	73	146	296	607	514
6	116			43				
7	171	229	355	76	117	250	756	443
8	110	53	340	94	112	195	503	401
9	169	209	469	93	150	336	846	579
11	319	184	350	92	143	295	853	530
12	95	163	372	72	148	313	629	533
13			381			315		
14			464			278		
16			410			340		
18	91	231	413	76	136	305	735	518
20	76	173	200	96	159	324	449	578
26	106	171	299	82	120	228	575	430
27	106	136	387	117	182	340	629	639
29	125	174	303	84	125	277	603	487
30	161	178	252	88	162	342	591	592
31	122	147	189	86	156	308	459	551
32			156			276		
34	62	88	313	108	145	299	463	553
35	15	168	145	68	149	304	329	521
36	136	76	392	45	110	223	604	378
Average	**124**	**151**	**330**	**80**	**143**	**295**	**601**	**519**

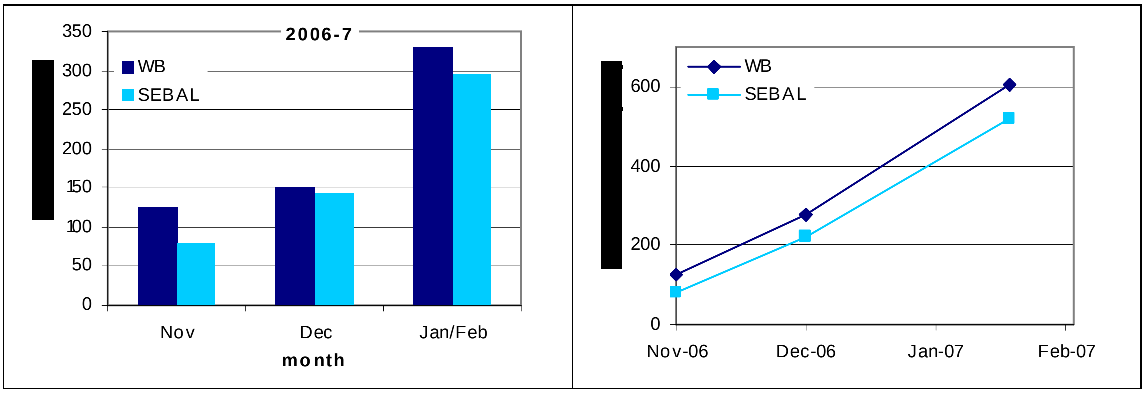


Figure 26 Average period and accumulated evapotranspiration in the experimental blocks in Hex River Valley during 2006-7 calculated with SEBAL and with the soil water balance based on field experiments

5.3 Conclusions on water consumption

- SEBAL estimates grape water consumption. SEBAL enables a spatial and temporal analysis of water consumption differences within the vineyard, between neighbouring vineyards and between different areas.
- According to the water balance the average total water consumption in the table grape blocks was 536, 547 and 601 mm. The total average SEBAL ET for the same blocks and periods was 603, 590 and 519 mm respectively. The difference is likely to be explained by root water uptake from deeper layers.

- Table grape vineyards consume more water than wine grape vineyards and water consumption of table grapes is less variable over areas than water consumption of wine grapes because of differences in trellis system, irrigation system and water deficit management.
- Water consumption differs considerably per year, but annual trends differ for wine and table grape vineyards. Water consumption of table grapes was very low in 2004-5 at 690 mm, but the increase in 2005-6 (866 mm) was not continued in 2006-7 (831 mm). Wine grapes consumed little water in both 2004-5 (520 mm) and 2005-6 (546 mm), and consumption only increased in 2006-7 (716 mm) because summer rainfall was more favourable in 2006-7. Hence wine grapes ET is susceptible to the amount of summer rainfall.
- Intra-seasonal variation in ET occurs. While the absolute differences are more distinct for table grapes the relative differences are greater for wine grapes.
- Wine grape vineyards in Worcester consume more water than wine grape vineyards in the coastal areas because in Worcester (1) permanent irrigation is usually applied and (2) weather conditions are more arid.
- Worcester showed highest variation between sub-areas concerning water consumption.
- Table grape water consumption in Hex Valley seems to have a relationship with soil type. Table grapes in areas with more sandy and gravelly soils consume more water (communication with farmers).
- Wine grapes in Stellenbosch and Paarl consume least water.

6 Grape production from remote sensing

SEBAL provides data on water consumption and biomass production. Biomass production is the total dry matter production of roots, stems, leaves and fruits. So SEBAL provides biomass production, and not total biomass stock. To produce more fruit with less water, information on the actual yield is essential. Farmers can use the SEBAL outputs on their individual fields to evaluate their water consumption with their own yield figures, but for a complete analysis of the relationship between water consumption and actual crop yield of a larger area, modelling of the grape yield is needed.

Grape yield modelling is complex because yield is not only determined by biomass production. Part of the berries is cut during the season to improve the quality of the total bunch, and also pruning is an important management strategy that strongly determines the vigour of the grape. From the satellite data it is impossible to monitor certain plagues and diseases such as fungus that reduce quality of the fruit while the plant remains green and healthy. Moreover the satellite images cannot distinguish cultivars, although the relationship between grape vigour and yield differs considerably between cultivars.

The yield model developed in this study is based on yield data provided by farmers in Hex River Valley and Worcester. Only a limited number of blocks were available for a limited number of cultivars. The yield model is based on empirical relationships with biomass production, soil moisture and water deficit during certain phenological stages (Klaasse et al., 2007). Because other yield determining factors such as management and cultivar type could not be included, the modelled yield will only provide an indication of the possible yield and will deviate from the actual yield achieved.

6.1 Biomass production

Figure 27 shows the biomass production of all table and wine grapes in the three study years. The irrigation water shortage in 2004-5 clearly had an effect on biomass production of table grapes. In the blocks of Hex River Valley, average biomass production increased from 22.4 tons/ha in 2004-5 on average, to 29.1 and 29.1 tons/ha in 2005-6 and 2006-7 (excluding blocks 33-37), as is shown in appendix 2. For all table grapes in the study areas, biomass production was 24.9 tons/ha in 2004-5 and increased to 27.5 tons/ha and 26.1 tons/ha in 2005-6 and 2006-7 (see Figure 27).

The biomass production of wine grapes is differently distributed over the years because wine grapes in general are less dependent on irrigation water but more on rainfall. In 2005-6 rainfall in summer was low, resulting in a low biomass production (12.3 tons/ha) of wine grapes. Biomass production in 2004-5 was higher at 16.4 tons/ha, and highest in 2006-7 at 19.0 tons/ha (see Figure 27).

Figure 27 also shows that biomass production of table grapes in 2004-5 was distributed more uniform, while in 2005-6 and 2006-7 the variation in biomass production between fields was much higher. So in years of water shortage the biomass production of table grapes becomes more similar between fields, farms and areas. For wine grapes the opposite effect was observed: the standard deviation was slightly higher in the low rainfall year 2005-6. The larger variation in wine grape biomass production in the dry summer of 2005-6 might be due to spatial variation in rainfall.

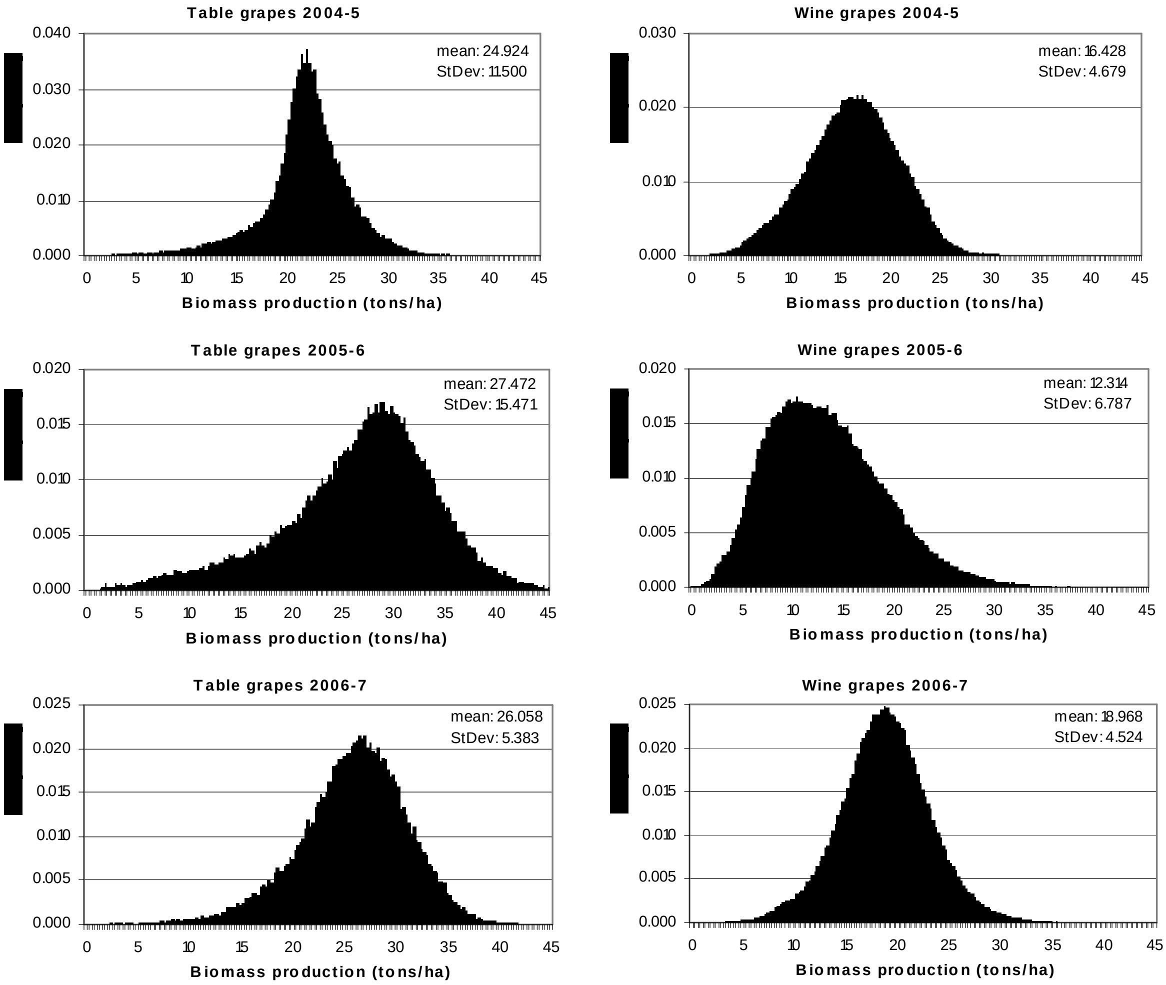


Figure 27 Frequency distribution of biomass production for all pixels classified as table grape (n=76415) or as wine grape (n=297424) in the study areas

6.2 Wine grape production

Data on wine grape yield were available for ten blocks of Colombar wine grapes in Worcester for the harvest of 2005. Colombar wine grapes have a long growing season, and have relatively high yields and high water consumption, thus making it suitable to implement water conservation practices.

The Colombar wine grape yield model has been extensively discussed in the previous study. Basically it is based on a Harvest Index (H_i) that indicates the proportion of the biomass production that is yield. Trial and error fitting showed wine grape yield is a function of accumulated biomass production in relation to water deficit in February and soil moisture content in November/December.

Water stress affects the growth and development of the shoots, leaves and fruits depending on its timing and level during the season. Generally, the most active growth process occurring in the vine during water stress will be most affected. Yield is most affected by high levels of water stress during flowering and fruit setting (Goodwin, 2002).

The amount of available soil moisture early in the season influences the vigour of the grapevine: when soil moisture is low, the vines will flower and produce berries as a survival strategy, while sufficient soil moisture causes an increased shoot growth. Van Zyl (1984) showed that water deficits during ripening reduced the berry size of Colombar. For other wine grape cultivars however the effects of water deficits on berry size development are greater when the deficit occurs early in the season compared with when the deficit occurs during ripening (Myburgh, 2005). For this reason the developed wine grape yield model is only valid for Colombar vines.

Final yield is a function of the biomass production and the Harvest Index in combination with the berry moisture content:

$$H_{i\,winegrape} = (0.16 + 0.03 \cdot \theta_{Dec}^{-1.1}) \cdot 0.91 \cdot ET_{defFeb}^{0.05} \quad (-)$$

$$\theta_{grape} = 4.483 \cdot \theta_{Mar}^{2} - 3.83 \cdot \theta_{Mar} + 1.5499 \quad (gr/gr)$$

$$Y_{winegrape} = (B_{io} \cdot H_i) / (1 - \theta_{Grape}) \quad (kg/ha)$$

where:

Hi	: Harvest index
ΘDec	: soil moisture in December (fraction of maximal saturation)
Θgrape	: moisture content of the berry (gr/gr)
ETdefFeb	: ET deficit in February (mm/month for 2005, mm/2months for 2006 and 2007)
ΘMar	: soil moisture in March/April (fraction of maximal saturation)
Bio	: total biomass production (kg/ha)
Y	: the actual marketable crop yield (kg/ha)

Figure 28, Figure 29 and Figure 30 show the normalized frequency distribution of modelled Colombar wine grape yield in 2004-5, 2005-6 and 2006-7 respectively. It shows the average yield is relatively low in 2004-5 at 22.7 tons/ha, and that yield is stable in the two other years at 27.6 tons/ha in 2005-6 and 26.9 tons/ha in 2006-7. Giddings (2005) observed the same for white wine grapes in Murray Valley, Australia. Colombar wine grapes had higher yields than other white varieties in his study, and produced very consistently, with little variation from season to season. The standard deviation of Colombar wine grapes in Worcester was slightly higher in 2005-6, indicating there was more variation in yield in this year.

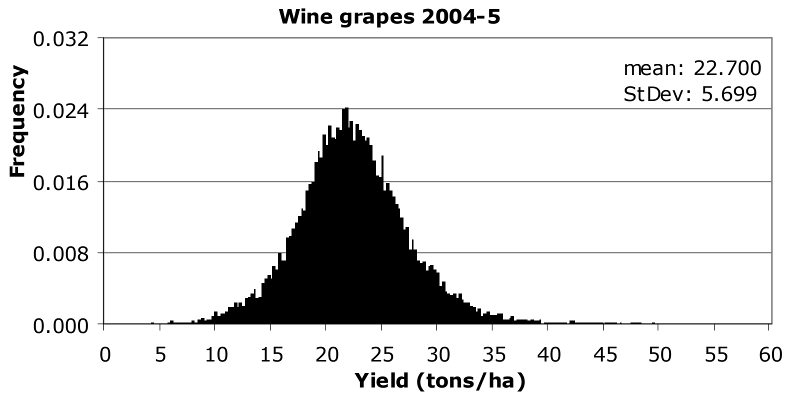


Figure 28 Frequency distribution of modelled Colombar wine grape yield in Worcester (n=19889) in 2004-5

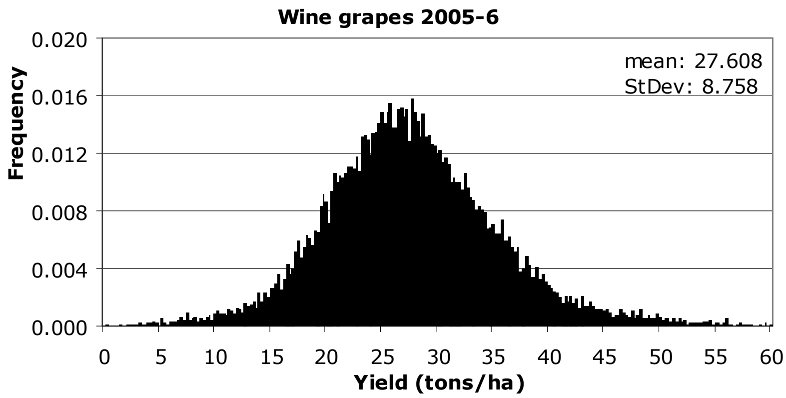


Figure 29 Frequency distribution of modelled Colombar wine grape yield in Worcester (n=19889) in 2005-6

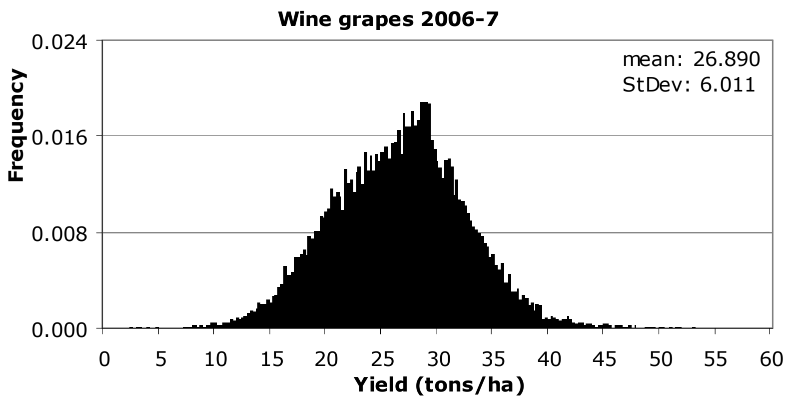


Figure 30 Frequency distribution of modelled Colombar wine grape yield in Worcester (n=19889) in 2006-7

Yield data of additional years and other cultivars in wine vineyards in Stellenbosch, Paarl and Somerset West were requested, but were not yet available during the preparation of this report.

6.3 Table grape production

The producers of Hex River Valley that participated in the water balance measurements in Hex River Valley also made their grape production data available.

Most yield data is from blocks with Dauphine, Sunred and Crimson cultivars. Table describes the yield data set. Yield varied considerably between blocks and between cultivars. Measured yields were on average around 6 tons/ha higher in the blocks with Sunred than in the blocks with Dauphine. Highest production for Dauphine was obtained in block 12, with an average yield above 40 tons/ha. The blocks with the Crimson cultivar were all recently planted (after 2000), which is reflected in the relatively low yields below 15 tons/ha of block 33 and 35.

Table 16 Measured yield of table grapes in the Hex River Valley of all farmers that participated in the Department of Agriculture experiment

Block	Cultivar	Area (ha)	Yield (kg/ha)			
			2005	2006	2007	average
HT1	Dauphine	1.14	30.6	28.1	24.5	27.7
HT2	Dauphine	2.15	28.3	18.3	20.6	22.4
HT3	Dauphine	2.42	33.2	25.1	22.1	26.8
HT4	Dauphine	1.78	22.1	25.2	24.5	23.9
HT5	Dauphine	0.93	28.8	32.1	39.7	33.6
HT6	Dauphine	1.70	16.7	18.2	28.7	21.2
HT7	Dauphine	0.67	27.8	26.1	32.3	28.7
HT8	Dauphine	1.35	28.8	29.3	28.0	28.7
HT9	Dauphine	1.70	27.2	19.7	32.0	26.3
HT10	Dauphine	1.09	29.5	29.1	27.9	28.8
HT11	Dauphine	1.43	21.4	24.0	28.8	24.7
HT12	Dauphine	1.41	44.3	31.4	46.5	40.7
HT13	Dauphine	1.02	26.0	19.8	24.6	23.5
HT14	Dauphine	1.59	16.6	17.2	27.6	20.5
HT15	Dauphine	1.11	24.8	14.8	28.0	22.5
HT16	Dauphine	1.02	17.0	29.0	37.7	27.9
HT18	Dauphine	1.67	21.8	34.1	20.9	25.6
HT20	Alphons	1.32	26.2	24.3	26.8	25.8
HT21	Red Globe	1.13	33.6	33.6	32.7	33.3
HT24	Sunred	1.98	28.2	28.2	35.9	30.8
HT25	Sunred	0.97	58.6	25.0	41.2	41.6
HT26	Sunred	0.59	30.7	40.4	37.5	36.2
HT27	Sunred	0.85	27.2	44.0	55.8	42.3
HT29	Sunred	0.34	31.6	47.2	38.7	39.2
HT30	Sunred	1.17	24.0	17.1	31.1	24.1
HT31	Sunred	0.76	21.8	20.2	15.7	19.2
HT32	Sunred	0.50	42.7	28.5	21.2	30.8
HT33	Crimson	1.20		11.0	12.5	11.8
HT34	Crimson	2.67		19.7	26.9	23.3
HT35	Crimson	2.70		16.6	12.0	14.3
HT36	Crimson	1.77		18.2	21.3	19.7
HT37	Crimson	0.65		22.3	16.4	19.4
Average			**28.5**	**27.0***	**30.8***	**28.8***

* The recently planted Crimson blocks 33-37 have been excluded in the calculation of the average

Average yield was slightly lower in 2006, and highest in 2007. On average the table grape yield in the blocks was 28.8 tons/ha. Table repeats the rainfall information of the Hex River Valley already described in Table 5, Table 6 and Table 7. In 2004-5 summer rainfall was higher than in the other years but irrigation water was cut down by 40% because of low rainfall in winter. Measured yield in 2005 is however not affected by the irrigation water shortages.

Table 17 Rainfall measured at Hex River Valley metereological station

	Rainfall in Hex Valley (mm)		
	Annual (June - May)	**Winter (June - August)**	**Summer (October - February)**
2004-5	388	163	110
2005-6	450	237	29
2006-7	330	171	69

Table 16 shows there was a considerable variation in production of table grapes between blocks, cultivars and growers. Prediction of table grape yield is of great importance for the water use efficiency analysis.

Figure 31 shows that the relationship between the biomass production derived from SEBAL and the measured yield in the same block is not linear, and that for this reason a variable harvest index is needed.

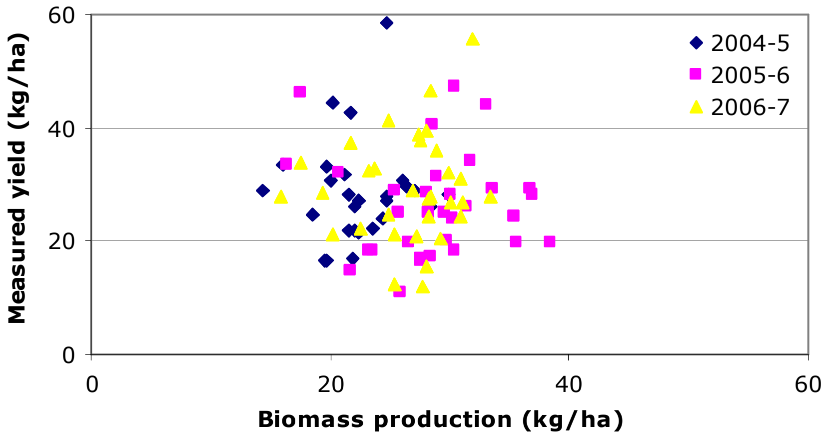


Figure 31 The relationship between biomass production and measured yield

The HI model developed in the previous project appeared to be a complex function of soil moisture in November/December and water deficit in February.

$$H_{i\,tablegrapes} = (0.1036 \cdot \theta_{Nov}^{-1.215}) \cdot a \cdot ETdef_{Feb}^{0.4}$$

where:

Hi	: harvest index
ΘNov	: soil moisture in November (fraction of maximal saturation)
ETdefFeb	: ET deficit in February (mm/month for 2005, mm/2months for 2006 and 2007), when ET deficit < 1.5 mm, it is assumed to be 1.5 mm
a	: constant, 0.20 in 2005, 0.14 in 2006 and 0.11 in 2008

Recently the data on position, shape and size of a small number of field work blocks was changed by the Department of Agriculture. For this reason the data on soil moisture, ET deficit and biomass production measured with SEBAL changed too. The function of soil moisture and water deficit slightly changed. Also additional corrections for the constant a were needed.

Vines show strong vegetative growth in spring and summer, and this vegetative growth can continue the whole season, although growing rate is reduced when berries start growing. Early in the season, vegetative growth is sensitive to available soil moisture. Strong vegetative growth before flowering may lead to weak fruit set (Burger and Deist, 2005). Vegetative growth can be significantly reduced by moderate levels of water stress early in the season (Goodwin, 2002). With low soil moisture levels during this period, the vines will flower and produce berries as a survival strategy and excessive shoot growth is reduced. In the HI model the maximum value of HI is controlled by soil moisture early in the season.

The ET deficit component is a result of data fitting procedures; the overall model performance improved if a crop water deficit parameter was included. The average biomass production in all blocks describes the inverse relationship between foliage development and HI, similar to the constant a in the previous model.

Since biomass production is the total dry matter production, and yield also includes the moisture in the fruits, the dry matter content of grapes needed to be estimated. In view of the fact that table grape berry moisture is not as variable as wine grape berry moisture, it was assumed to be constant at 25 %. Final fresh yield of table grapes was calculated at a pixel-by-pixel basis with the following equation:

$$Y_{tablegrape} = (B_{io} \cdot H_i)/(1-0.75) \qquad \text{[kg/ha]}$$

where:
Ytablegrape: fresh yield of table grapes (kg/ha)
Bio: total biomass production in a season (kg/ha)

Figure 32, Figure 33 and Figure 34 show the normalized frequency distribution of table grape yield in 2004-5, 2005-6 and 2006-7 respectively based on the HI model for table grapes developed in Klaasse et al. (2007). Table grape yield was calculated for all pixels classified as table grape in the study areas. In paragraph 2.3.2 it was pointed out that the land cover classification was greatly improved by the field polygon set of the Department of Agriculture that prevented confusion between agricultural and non-agricultural fields.

The average yield in 2004-5 and 2005-6 decreased slightly compared to results of the previous study, which might be related to the improved land cover classification used. The general patterns were still the same. Average yield was lowest in 2004-5, at 24.924 tons/ha. In the two following years the average yield was very similar, at respectively 27.472 tons/ha in 2005-6 and 27.712 tons/ha in 2006-7. The standard deviation of the table grape yield was remarkably different. During the dry 2004-5, the standard deviation was 11.5 tons/ha only. The latter variability increased to 16.8 tons/ha during 2006-7 (thus after the wet winter). Indeed yields went up to 60 tons/ha and it seems that more irrigation leads to more yield.

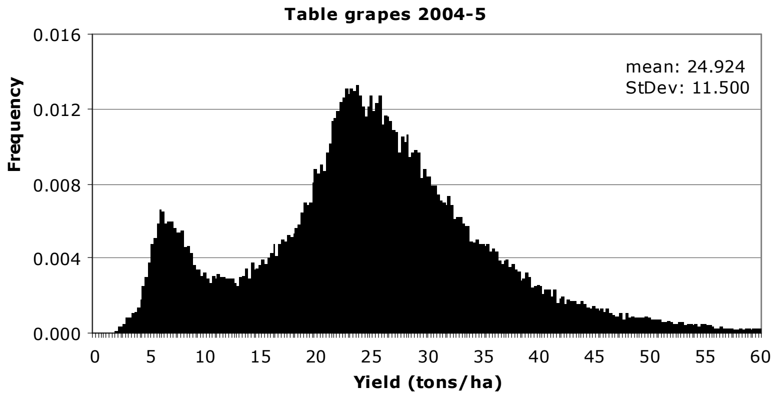


Figure 32 Frequency distribution of modelled table grape yield in the season 2004-5 for all pixels (n = 76415) in Hex River Valley, Worcester, Paarl, Franschhoek, Stellenbosch and Somerset West areas classified as table grape

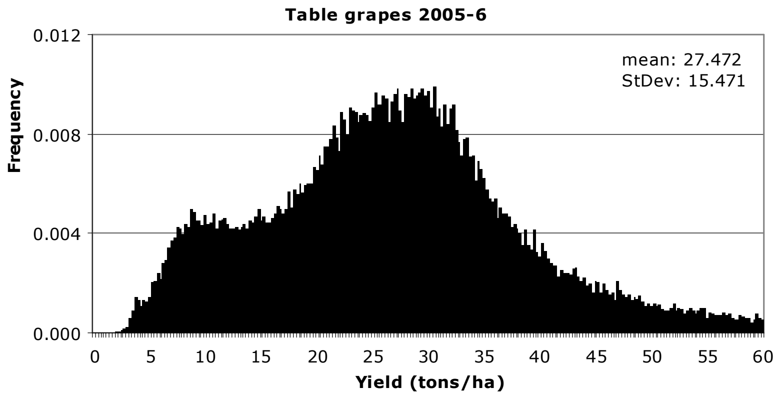


Figure 33 Frequency distribution of modelled table grape yield in the season 2005-6 for all pixels (n = 76415) in Hex River Valley, Worcester, Paarl, Franschhoek, Stellenbosch and Somerset West areas classified as table grape

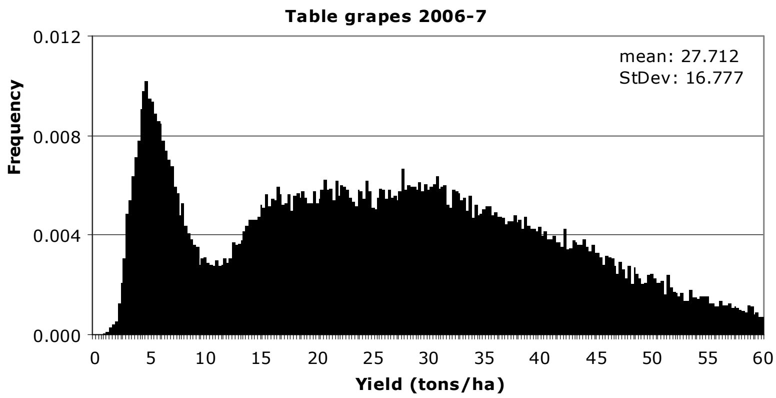


Figure 34 Frequency distribution of modelled table grape yield in the season 2006-7 for all pixels (n = 76415) in Hex River Valley, Worcester, Paarl, Franschhoek, Stellenbosch and Somerset West areas classified as table grape

6.4 Grape production statistics for sub-areas

Table 18 shows the average yield of table and Colombar wine grapes in the arbitrary classes of Figure 23 in the previous chapter. Wine yield data of Stellenbosch and Somerset West is not included in this table because no field measurements on the wine yield were made available for calibration of the yield model. Table grape yield was high, with yields above 30 tons/ha, in the southern part of Paarl, and in the downstream and upstream areas of Hex River Valley. Table grape yield was slightly lower in the northern part of Paarl, and in the Drieriviere and Groothoek area of Hex River Valley. The table grapes in Worcester had very low yields, ranging from 11.2 up to 26.4 tons/ha. The Colombar wine grapes in Worcester had very similar yields in Hex River, Nuy area and the Southern part.

Table grape yield varied considerable per year. In Worcester table grape yield was lowest in 2005-6. In Paarl table grape yield dropped considerable from over 30 tons/ha in 2005-6 to 20 tons/ha in 2006-7. In Hex River Valley the table grape yield was highest in 2006-7.

Wine grape yield was lowest in 2004-5 ranging from 21.8 to 24.1 tons/ha. In 2005-6 and 2006-7 wine grape yield varied between 26.0 and 29.6 tons/ha.

Table 18 Average yield of table grapes and Colombar wine grapes in arbitrary classes (see Figure 23). Wine grapes in Stellenbosch, Somerset West, Franschhoek and Paarl were not included in this analysis.

Name	**Table grape yield**				**Wine grape yield**			
	2004-5	**2005-6**	**2006-7**	**Avg**	**2004-5**	**2005-6**	**2006-7**	**Avg**
Paarl North	27.9	33.3	20.1	27.1				
Paarl South	33.0	39.6	20.4	31.0				
Worcester (Hex River)	19.8	14.7	16.2	16.9	22.1	29.6	27.1	26.3
Worcester South	24.3	16.6	26.4	22.4	24.1	29.1	27.2	26.8
Worcester (Nuy)	15.6	11.2	20.6	15.8	21.8	26.0	26.6	24.8
Hex River Valley (Drieriviere)	23.5	20.8	28.7	24.3				
Hex River Valley (downstream)	26.6	26.5	37.0	30.0				
Hex River Valley (Groothoek)	21.4	26.9	31.3	26.5				
Hex River Valley (upstream)	25.8	35.6	37.5	33.0				
Average	**24.2**	**25.0**	**26.5**	**25.2**	**22.7**	**28.2**	**27.0**	**25.9**

Figure 35 shows the relationship between average grape water consumption (Table 12) and grape yield (Table 18) in the arbitrary classes. The figure shows that there is a negative relationship between table grape water consumption and yield. Areas where table grapes consume less water, have higher yields than areas with high water consumption. For the areas with wine grapes no relationship could be established.

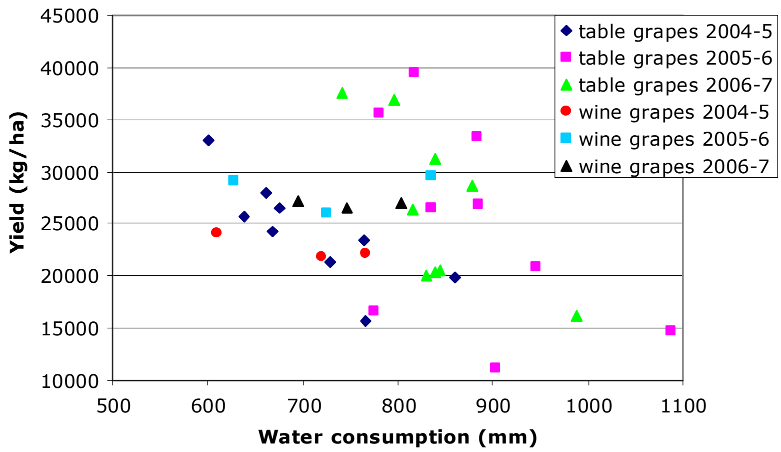


Figure 35 The relationship between grape water consumption and yield per arbitrary class (Table 12 and Table 18)

6.5 Validation of grape production modelling

The validation of the wine grape yield has been extensively discussed in the previous report. Average table grape yields measured in the Hex Valley field blocks (blocks 1-37) were 28.5, 27.0 and 30.8 tons/ha for 2005, 2006 and 2007 respectively. The modelled yields in the same experimental blocks were 27.6, 27.2 and 30.7 tons/ha for the same years. The predicted yields in the experimental blocks were thus three percent lower in the first year, less than one percent higher in the second year, and less than one percent lower in the third year.

The results for each individual block are shown in Figure 36, Figure 37 and Figure 38. Deviations on individual blocks can be attributed to management practices such as pruning and berry selection, and biological factors such as diseases and plagues.

The yield model was originally developed for 2005. A correction factor *a* was used to adjust the yield model to 2006 and 2007. As mentioned before, the application of the yield model on other years was difficult. The model's performance in the first year was very good, but only moderate in 2005-6 and poor in 2006-7.

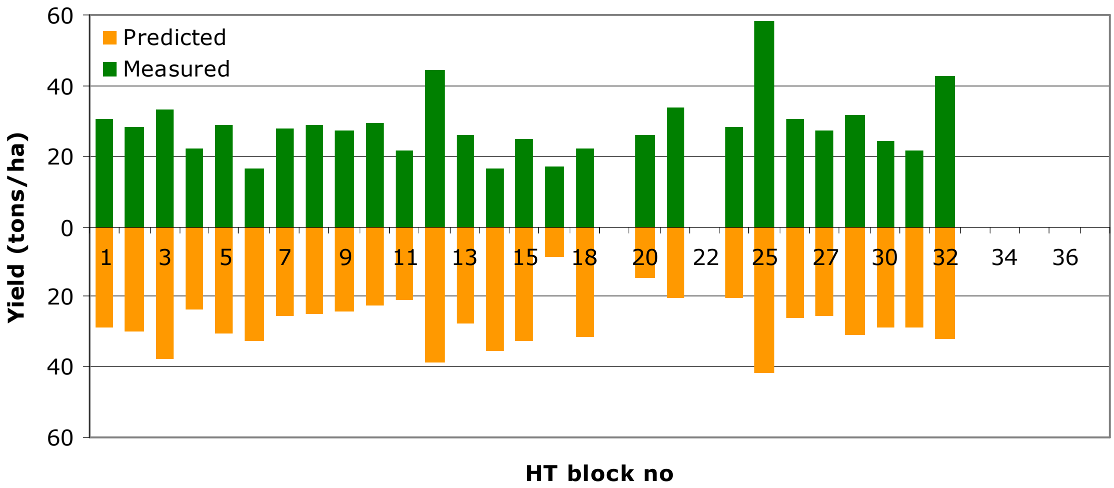


Figure 36 Measured and predicted table grape yield in 2005

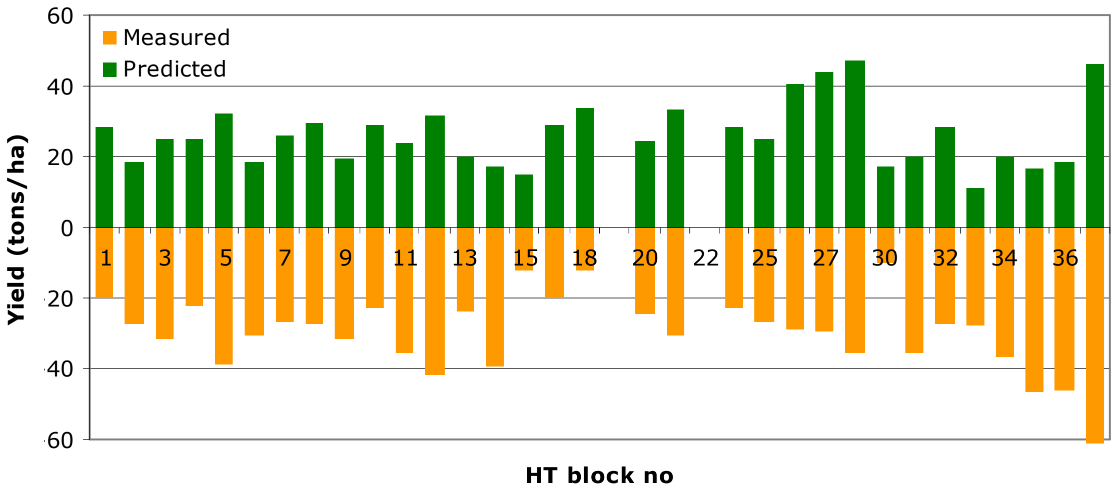


Figure 37 Measured and predicted table grape yield in 2006

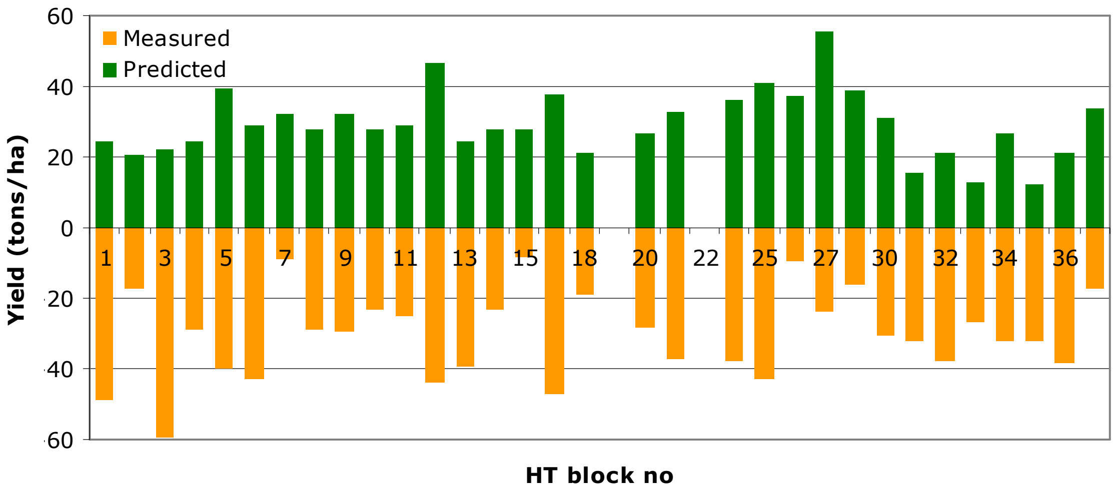


Figure 38 Measured and predicted table grape yield in 2007

One possible explanation is the different water availability between the first and the other two years. In 2004-5 irrigation supply from September until April was on average 560 mm, while in 2005-6 and 2006-7 respectively 725 and 729 mm of irrigation water was applied. Rainfall during summer was higher in 2004-5, ranging from 100 to 200 mm, than in 2005-6 and 2006-7, when rainfall was around 50 mm for the period September-April. The larger amount of available irrigation water had its effect on biomass production, which was lower in 2004-5. In other words, the final yield of 2005 was mainly determined by water stress, while the final yield of 2006 and 2007 was more determined by other factors, such as management and diseases.

Measured yield was fitted against a large number of parameters. Relationships were investigated with temperature, vegetation cover/NDVI and albedo. Also the relationships between yield and SEBAL outputs such as biomass production, soil moisture, ET deficit, actual evapotranspiration, potential evapotranspiration and KcKs were analysed. It seemed that soil moisture was the limiting factor in 2004-5, but that yields in 2005-6 and 2006-7 were also dependent of many other factors, such as pruning, diseases and management that could not be modelled. For this reason the modelling of the harvest index was not as successful as hoped for, and results on individual blocks showed relatively strong deviations, especially in 2005-6 and 2006-7.

The Census of Agricultural Provincial Statistics in 2002 (Statistics South Africa, 2006) estimated the total table grape production in 2002 on 332,214 tons on a total area of 11,107 ha. Average table grape yield in Western Cape should therefore be 29,910 tons/ha in 2002. In the yield estimations of this study the yields varied between 24.9 tons/ha in 2005 to 27.5 tons/ha in 2006 and 26.0 tons/ha in 2007. The census yield estimate is slightly higher than the yields estimated in 2005, 2006 and 2007. Most probably the data of the census does not include recently planted/crafted fields, while the yields estimated in this study also included these low producing fields, which may explain this difference.

6.6 Conclusions on grape production

- Table grape yield was measured in Hex River Valley on 27-32 blocks with mainly Dauphine, Sunred and Crimson cultivars. Sunred blocks produced on average 6 tons/ha more than Dauphine blocks. Crimson blocks were all recently planted, and therefore had very low yields.
- Measured table grape yield in Hex River Valley ranged from 11.0 tons/ha in a young Crimson block up to 58.6 tons/ha in a Sunred block. On average table grape yield was 28.5 tons/ha in 2004-5, decreased slightly to 27.0 tons/ha in 2005-6 and was highest in 2006-7 at 30.8 tons/ha.
- Grape yield modelling is complex because the final yield is not only determined by field characteristics that can be extracted from satellite data (e.g. biomass production, soil moisture, water deficit), but also determined by the applied management strategy (pruning, cutting of berries) and the presence of plagues and diseases that affect the fruit and not the crop.
- Available yield data was limited. Inclusion of more field data on table and wine grape yield of more areas (Stellenbosch, Paarl, Somerset West, and Franschhoek) and more cultivars will greatly improve the yield modelling.

- Both the table and wine grape model were a complex function of biomass production, soil moisture in November/December and water deficit in February.
- Modelled table grape yield was lowest in 2004-5 at 24.9 tons/ha, and very similar in 2005-6 and 2006-7 at 27.4 and 27.7 ton/ha. Water shortages in 2004-5 explained the lower yields and smaller variations in 2005 yield.
- Colombar wine grape yield was very constant over the three years (23-24 tons/ha), but variation was higher in 2005-6.
- Table grape yield was lowest in Worcester area and highest in Paarl and some parts of Hex River Valley. The areas with sandy and rocky soils in Hex River Valley (Groothoek and Drieriviere) had lower yields than the other areas in Hex River Valley.
- Average measured table grape yield was 28.5, 27.0 and 30.8 tons/ha in 2004-5, 2005-6 and 2006-7 respectively. Modelled table grape yield in the same years was 27.6, 27.2 and 30.7 tons/ha. Modelled yield was thus three percent lower, less than one percent higher, and less than one percent lower than measured yield.
- Biomass production in table and wine grapes seemed to be strongly related to the water availability. Biomass production in table grapes was mostly influenced by the availability of irrigation water. A shortage in irrigation water in 2004-5 caused high variation in biomass production of table grapes, while biomass production was very uniformly distributed in 2005-6 and 2006-7 when ample irrigation water was available. Summer rainfall determines the variation in biomass production of wine grapes. The summer of 2005-6 was dry, and biomass production of wine grapes was more variable in that year. Biomass production in 2004-5 and 2006-7 was more uniform distributed because enough summer rainfall fell.
- Average modelled table grape yield was slightly lower than the average yield estimated by the Census of Agricultural Provincial Statistics in 2002 (Statistics South Africa, 2006), most probably because new and recently planted fields are not included in these statistics.

7 Water use efficiency from remote sensing

The previous chapter discussed the biomass production and yield of wine and table grape vineyards. Yield is expressed in quantity of fruit per unit of land. In the Western Cape however water and not land is the limiting factor for a productive and sustainable agriculture. A focus on production per unit of water (kg/m^3) instead of crop production per unit of area (kg/ha) would therefore be more appropriate.

The spatial estimates of evapotranspiration and yield were used to calculate water use efficiency (WUE in kg/m^3). Water use efficiency (or water productivity) is defined as the marketable crop yield (Y in kg/ha) per unit of actual total evapotranspiration (ET in mm). Often the term water use efficiency becomes confounded when used in irrigated agriculture, because of the difference between actual water consumption (ET_{act}) and gross applied water. Part of the gross applied water is not consumed by the crop, but will remain in the system. Actual evapotranspiration as calculated by SEBAL is the real water consumption and will therefore be a more realistic input to calculate water use efficiency.

Information on the water use efficiency of different crops, farms and irrigation is required to suggest improvement in water utilization. The application of remote sensing technologies makes it possible to estimate and evaluate water use efficiencies spatially and temporally. The results of this study improve the understanding of the spatial and temporal variation of water use efficiency in grape cultivation in order to inform farmers how productively they are managing their available water resources.

7.1 Biomass water use efficiency

First of all the relationship between biomass production and water consumption is investigated by calculating the biomass water use efficiency:

$$WUE_{bio} = \frac{B_{io}}{10 \cdot ET} \qquad [kg/m^3]$$

Where:
WUEbio : Biomass water use efficiency (kg/m3)
Bio : Biomass production (kg/ha)
ET : Actual evapotranspiration (mm)

The biomass water use efficiency is a measure of the vigour of vine grapes per unit of water. Figure 39 shows the frequency distribution of the biomass water use efficiency of table and wine grapes in the six study areas.

Except for 2004-5 the biomass water use efficiency of table grapes was slightly higher than of wine grapes. Table grapes produced more biomass, but they are grown in horizontal trellises, which may create cooler conditions under the canopy, and thus might reduce water consumption compared to wine grapes which grow on vertical trellises. Biomass water use efficiency of table grapes was fairly constant at 3.2, 3.0 and 3.1 kg/m^3 in 2004-5, 2005-6 and 2006-7 respectively, indicating that the relationship between biomass production and water consumption is very constant in table grape vineyards.

The biomass water use efficiency of wine grapes was high in 2004-5 at 3.2 kg/m^3, and dropped to 2.2 kg/m^3 in 2005-6 and 2.7 kg/m^3 in 2006-7. In 2004-5 the water consumption was low (520 mm) while biomass production was moderate (16.4 tons/ha). In 2005-6 the water consumption remained at a similar level (546 mm) while biomass production dropped (12.3 tons/ha), thus causing a decrease in biomass water use efficiency. In 2006-7 the biomass production was high at 19 tons/ha, but as water consumption also increased considerably to 716 mm, biomass water use efficiency remained low. These results clearly show that to improve biomass water use efficiency either the water consumption should go down without lowering the biomass production, or the biomass production should increase without increasing the water consumption.

The standard deviation of biomass water use efficiency was higher in 2005-6 and similar in 2004-5 and 2006-7 for both table and wine grapes. This is because in 2005-6 both water consumption and biomass production showed more variation.

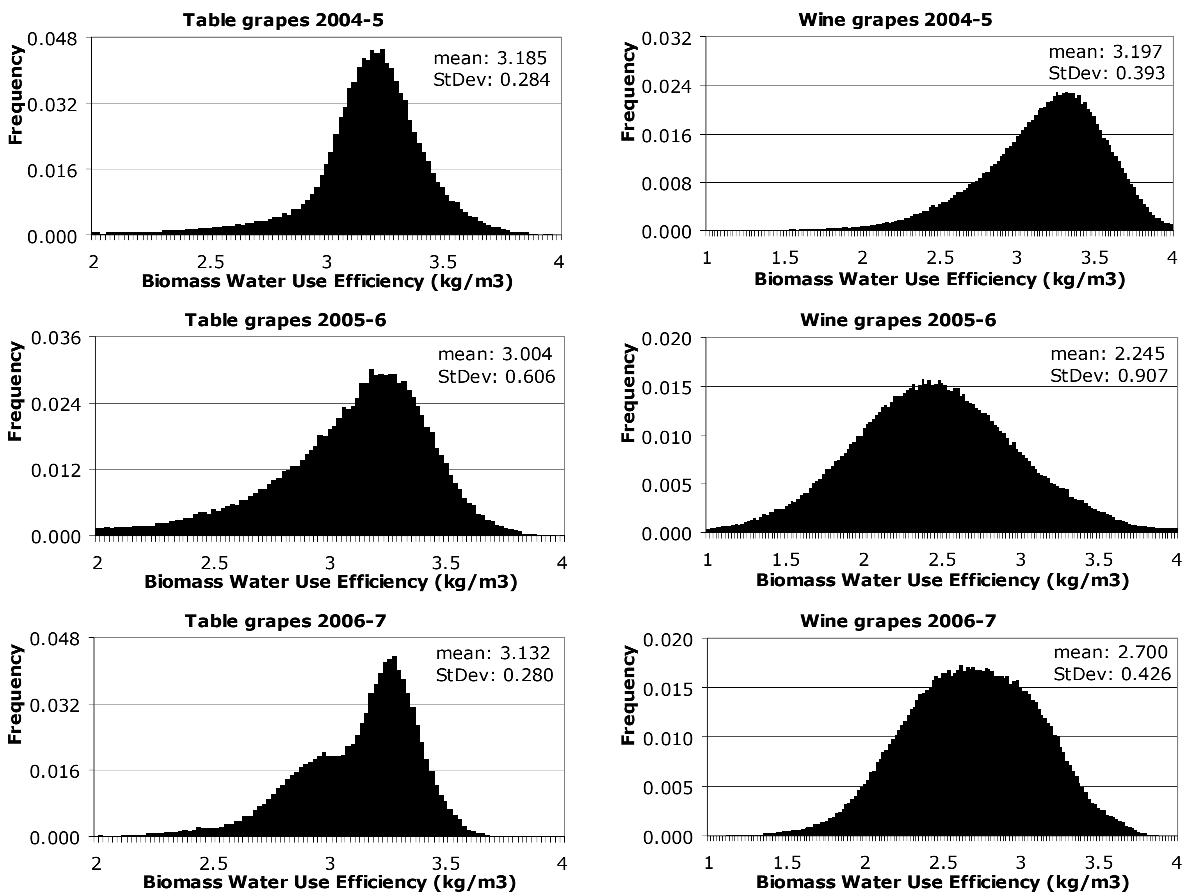


Figure 39 Frequency distribution of the biomass water use efficiency in table (left) and wine (right) grapes in the six study areas

7.2 Water use efficiencies of table and wine grapes

Water use efficiency of table grapes and Colombar wine grapes was calculated using the yield derived from the biomass production (as described in chapter 6) and the water consumption as calculated in SEBAL (chapter 5):

$$WUE_{grapes} = \frac{Y}{10 \cdot ET} \qquad [kg/m^3]$$

Where:

WUE_{grapes} : Water use efficiency of grapes (kg/m^3)

Y : Grape yield (kg/ha)

ET : Actual water consumption or evapotranspiration (mm)

Figure 40, Figure 41 and Figure 42 show the frequency distribution of water use efficiency of Colombar wine grapes in Worcester. Water use efficiencies of wine grapes in Stellenbosch, Somerset West, Franschhoek and Paarl were not calculated, as no yield data was available for these areas. Water use efficiency in 2004-5 and 2006-7 was almost similar at 3.6 kg/m^3 in the first year, and 3.9 kg/m^3 in the third year. Colombar water use efficiency in 2005-6 was significantly higher at 4.5 kg/m^3, as well as the standard deviation. This implies that in 2005-6 some farmers in Worcester achieved higher water use efficiencies, but that others remained at the same level as in 2004-5 and 2006-7.

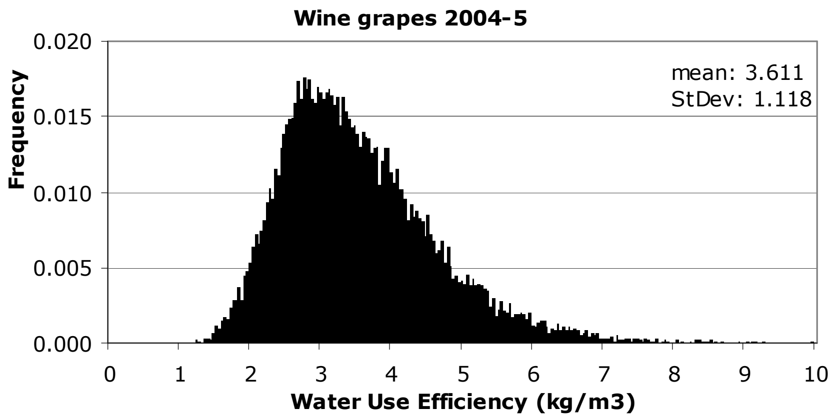


Figure 40 Frequency distribution of water use efficiency of Colombar wine grapes in the season 2004-5 for all pixels (n = 19891) in Worcester

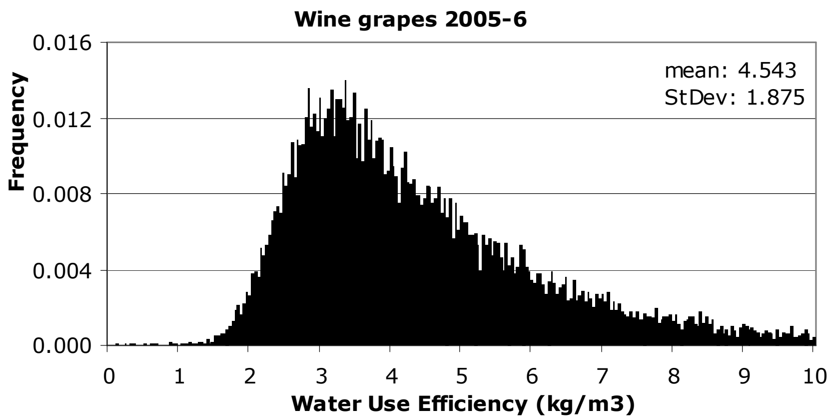


Figure 41 Frequency distribution of water use efficiency of Colombar wine grapes in the season 2005-6 for all pixels (n = 19891) in Worcester

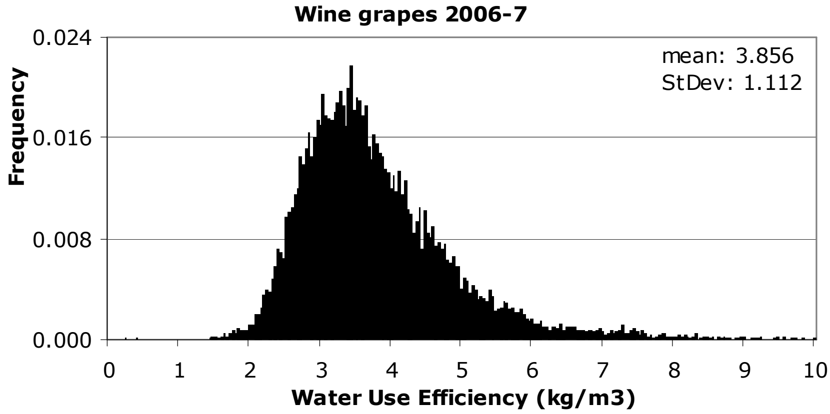


Figure 42 Frequency distribution of water use efficiency of Colombar wine grapes in the season 2006-7 for all pixels (n = 19891) in Worcester

The frequency distributions shown in Figure 43, Figure 44 and Figure 45 present the water use efficiency of table grapes. Water use efficiency of table grapes was highest in 2004-5 at 3.9 kg/m^3, and was slightly lower in 2005-6 (3.6 kg/m^3) and 2006-7 (3.7 kg/m^3). Similar to the water use efficiency of wine grapes, standard deviation was highest in the second year.

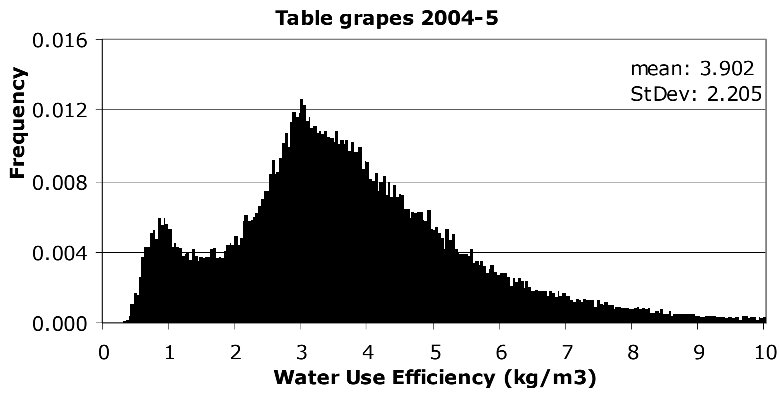


Figure 43 Frequency distribution of water use efficiency of table grapes in the season 2004-5 for all pixels (n = 76415) in Hex River Valley, Worcester, Paarl, Franschhoek, Stellenbosch and Somerset West areas

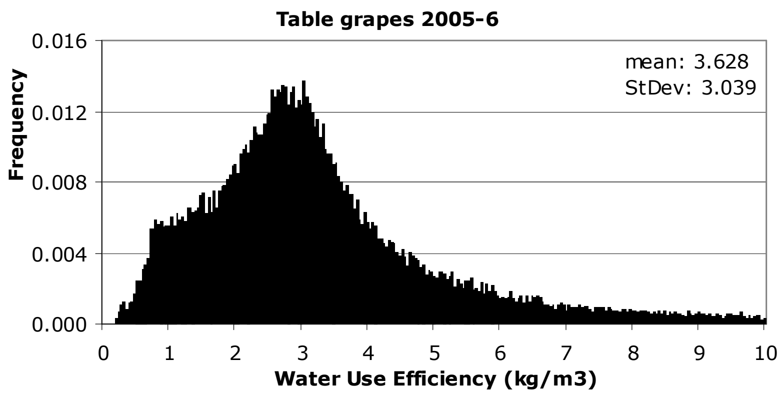


Figure 44 Frequency distribution of water use efficiency of table grapes in the season 2005-6 for all pixels (n = 76415) in Hex River Valley, Worcester, Paarl, Franschhoek, Stellenbosch and Somerset West areas

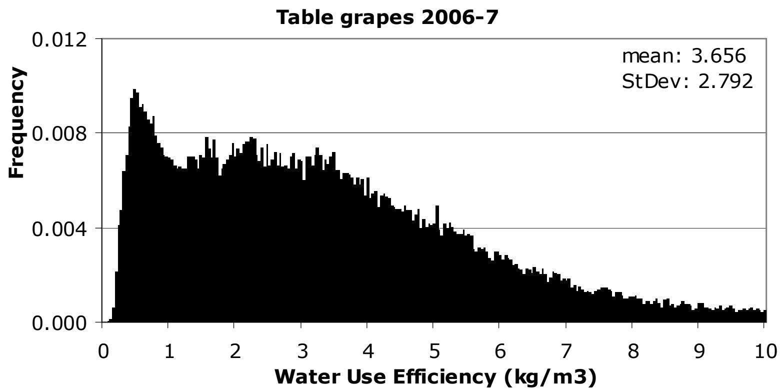


Figure 45 Frequency distribution of water use efficiency of table grapes in the season 2006-7 for all pixels (n = 76415) in Hex River Valley, Worcester, Paarl, Franschhoek, Stellenbosch and Somerset West areas

7.3 Water use efficiency in arbitrary divided areas

Table 19 shows the average water use efficiency of the classes resulting from the arbitrary area division in Figure 23. Water use efficiency of table grapes was on average above 4 kg/m^3 in Paarl South and the parts of Hex River Valley with good soils (downstream and upstream area). Grapes on sandy and rocky soils in Hex River Valley and Paarl North had slightly lower water use efficiencies, but still above 3 kg/m^3 on average. Average water use efficiency in Worcester was lower, from a reasonable 3.3 kg/m^3 in the south down to a low 1.8 kg/m^3 in the Hex River area of Worcester. Wine water use efficiency in Worcester was higher than table water use efficiency, and ranged from 3.5 to 4.4 kg/m^3 on average.

Water use efficiency was highly variable between years. In Paarl South water use efficiency ranged from 6.2 in the first year to only 2.7 kg/m^3 in the third year as a result of a strong decrease in table grape yield in 2007. In Worcester water use efficiency was lowest in 2005-6, and dropped even below 2 kg/m^3 for the Hex River and Nuy area because yield decreased while water consumption increased. In Hex River Valley water use efficiency in 2004-5 was higher than in 2005-6 in the downstream areas, while in the upstream areas the water use efficiency was higher in 2005-6 as compared to 2004-5. Water use efficiency was highest in 2006-7 for all Hex River Valley areas because of the high yields obtained in that year.

Table 19 Average water use efficiency in arbitrary classes (see Figure 23)

	Table grapes				Wine grapes			
Name	**2004-5**	**2005-6**	**2006-7**	**Avg**	**2004-5**	**2005-6**	**2006-7**	**Avg**
Paarl South	6.19	5.54	2.71	4.82				
Paarl North	4.43	4.28	2.60	3.77				
Worcester (Hex River)	2.37	1.40	1.72	1.83	2.99	3.85	3.56	3.46
Worcester South	3.81	2.54	3.57	3.31	4.10	5.07	4.08	4.42
Worcester (Nuy)	2.10	1.34	2.71	2.05	3.10	3.87	3.68	3.55
Hex River Valley (Drieriviere)	3.18	2.45	3.64	3.09				
Hex River Valley (downstream)	4.01	3.40	4.88	4.10				
Hex River Valley (upstream)	4.08	5.18	5.39	4.88				
Hex River Valley (Groothoek)	2.99	3.25	3.94	3.39				
Average	**3.69**	**3.26**	**3.46**	**3.47**	**3.40**	**4.26**	**3.77**	**3.81**

7.4 Some explanations for differences in water use efficiency

Water use efficiency reflects the amount of water consumed to produce fruit. Water use efficiency reflects how well farmers manage their land and water resources, but also reflects differences in rainfall, irrigation shortages, differences in soil type and differences between cultivars. In July 2008 the results were presented to, and discussed with farmers of Hex River Valley and Worcester. Philip Myburg, Eugene Lategan and Ansie Du Toit of the Agricultural Research Council provided some in-field knowledge on several vineyards in the Stellenbosch area. This section presents some of the outcomes of these meetings in the form of a few examples of why water use efficiency varied at region-scale and field-scale.

Figure 46 shows the effect of rainfall and irrigation water availability on water use efficiency. It presents the ET, yield and water use efficiency of Hex River Valley in 2004-5, 2005-6 and 2006-7. The distribution of rainfall over the preceding winter and summer is also indicated. Water consumption in 2004-5 was low, moderate in 2006-7 and very high in 2005-6. The yield however did not increase between 2004-5 and 2005-6, but did only increase in 2006-7. The result is that water use efficiency was high in 2004-5 (low water consumption, normal yield) and in 2006-7 (high water consumption, high yield). In 2005-6 water use efficiency was low because the water consumption increased without increasing yield.

In 2004-5 water was short in Hex River Valley because of the dry preceding winter, and farmers were cut by 40% in their irrigation supplies. The reduced amount of irrigation water resulted in a very low water consumption that however did not affect yield. This is an interesting conclusion and suggests that deficit ET and deficit irrigation do not necessarily result in lower production. In 2005-6 ample water was available, resulting in very high water consumption. Nevertheless yield did not increase. Some farmers suggested that water shortages in one year affect the yield in the following year which might indeed have happened. In 2006-7 water consumption was slightly lower than in 2005-6, but production improved considerably. Summer rainfall in Hex River Valley seems to be of minor importance as compared to irrigation water availability.

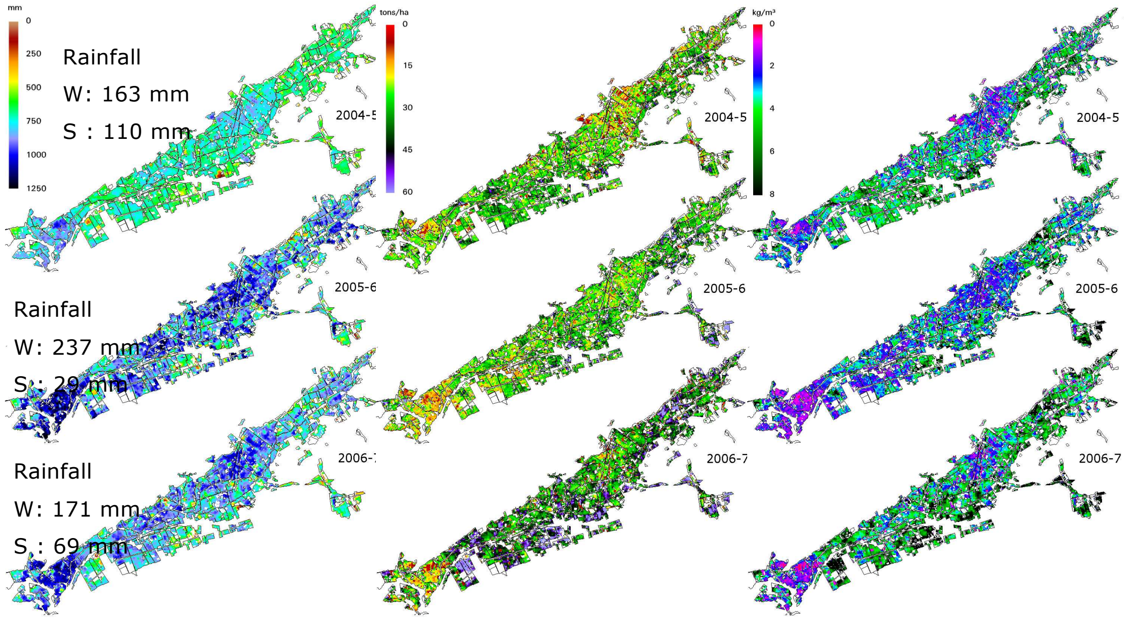


Figure 46 Water consumption (left), yield (center) and water use efficiency (right) of table grapes in Hex River Valley in 2004-5, 2005-6 and 2006-7 with the distribution of rainfall over summer (S) and winter (W)

Figure 47 shows the effect of rainfall on water consumption, biomass production and biomass water use efficiency of wine vineyards with no or only supplementary irrigation, in the Stellenbosch and Somerset West area. Water consumption dropped in the summer of 2005-6 because of low summer rainfall. This is especially clear in the northern and north-western part of the area. The low rainfall in the summer of 2005-6 was disastrous for the biomass production in that year dropped considerably. The result was that the biomass water use efficiency was very low in 2005-6.

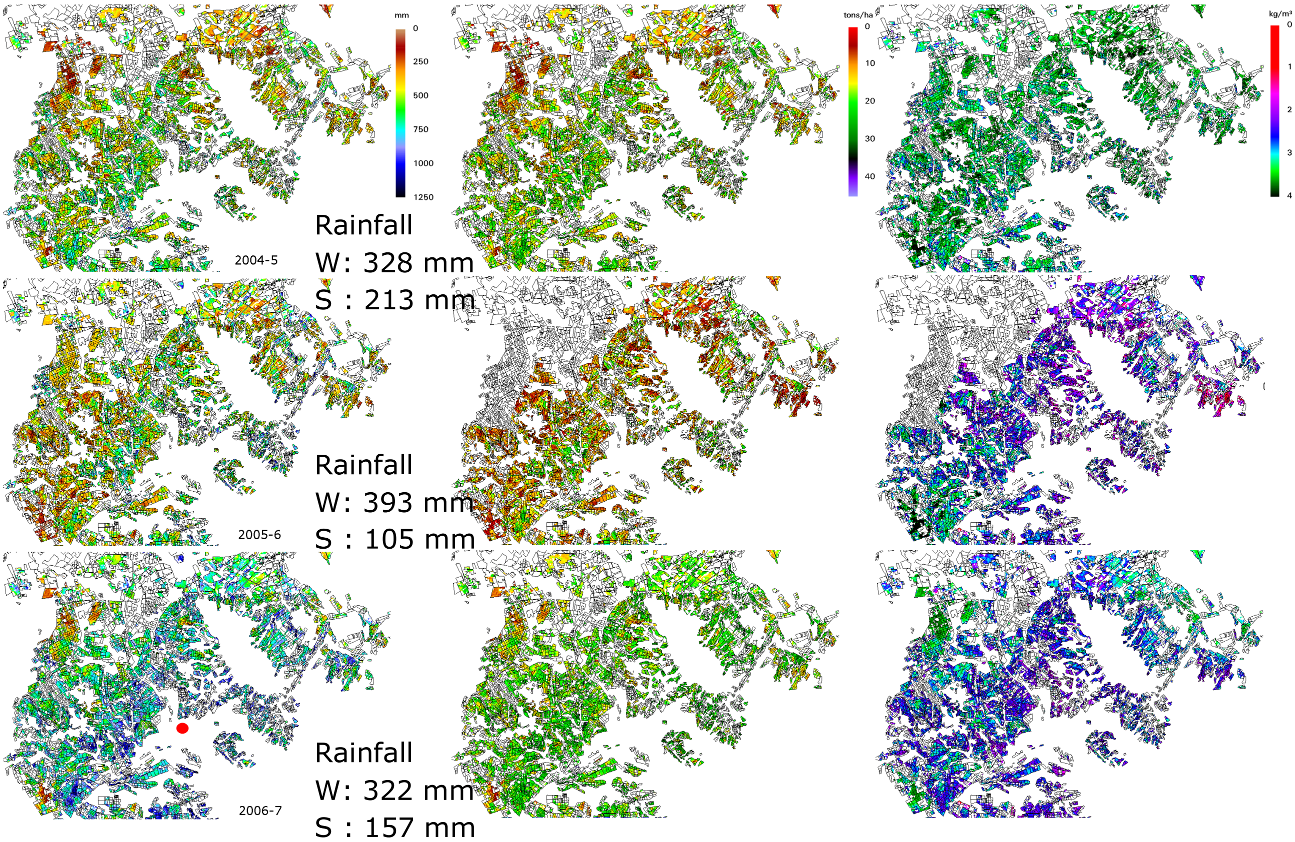


Figure 47 Water consumption (left), biomass production (center) and biomass water use efficiency (right) of wine grapes in the Stellenbosch area in 2004-5, 2005-6 and 2006-7. The distribution of rainfall over winter (June-August) and summer (October-February) is also indicated, as well as the location of the town of Stellenbosch (red circle).

Figure 48 shows a wine grape vineyard in the Stellenbosch region. The team of Philip Myburgh (ARC) has been performing field measurements in this vineyard, and monitored water logging in the white encircled part early in the season. For this reason plant growth lagged behind compared to the rest of the vineyard, which is clearly reflected in the lower biomass production estimated by SEBAL in the map on the left. A plant with a lower leaf area index consumes less water, as is shown by the SEBAL ET output on the right.

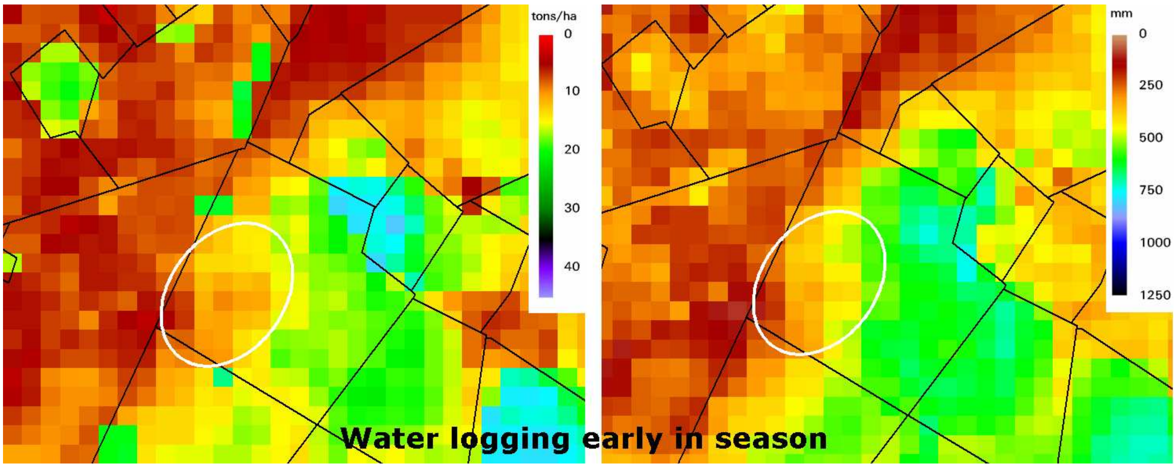


Figure 48 The effect of water logging (indicated with the white circle) on biomass production (left) and water consumption (right) in a wine grape vineyard in Stellenbosch

Figure 49 shows another wine grape vineyard in the Stellenbosch region. The team of Philip Myburg (ARC) is familiar with this vineyard, and provided the information that this vineyard consists of two cultivars, Cabernet Sauvignon in the western part and Pinotage in the eastern part. Water consumption of Cabernet Sauvignon was higher in this specific field. It is not known whether the difference in water consumption is characteristic for the two cultivars, or related to field properties that also influenced the choice for two cultivars. To understand the relationship between water consumption and cultivar, more data on the location of cultivars is needed.

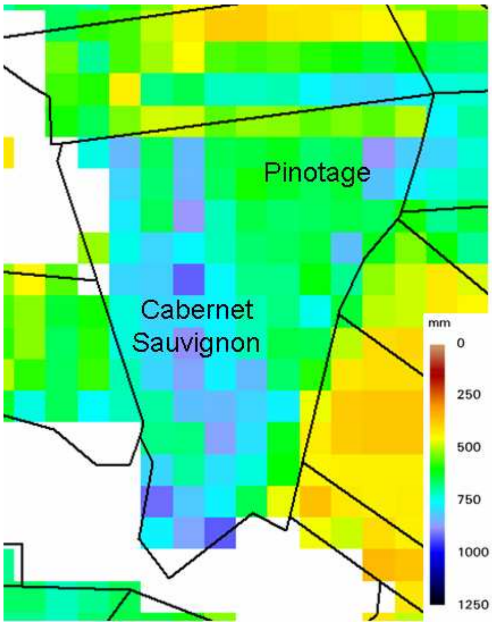


Figure 49 The effect of different cultivars on water consumption of a wine grape vineyard in Stellenbosch

Figure 50 shows a wine grape farm in Worcester. In 2004-5 water availability was a problem in Worcester, which is reflected in relatively low water consumption rates. In 2005-6 the farmer adapted a new management system that unfortunately did not provide the results hoped for. Vines biomass production was low, and water consumption dropped to even a lower level than in 2004-5, while ample water was available. In 2006-7 the farmer altered his management system again, resulting in high yields and a higher water consumption.

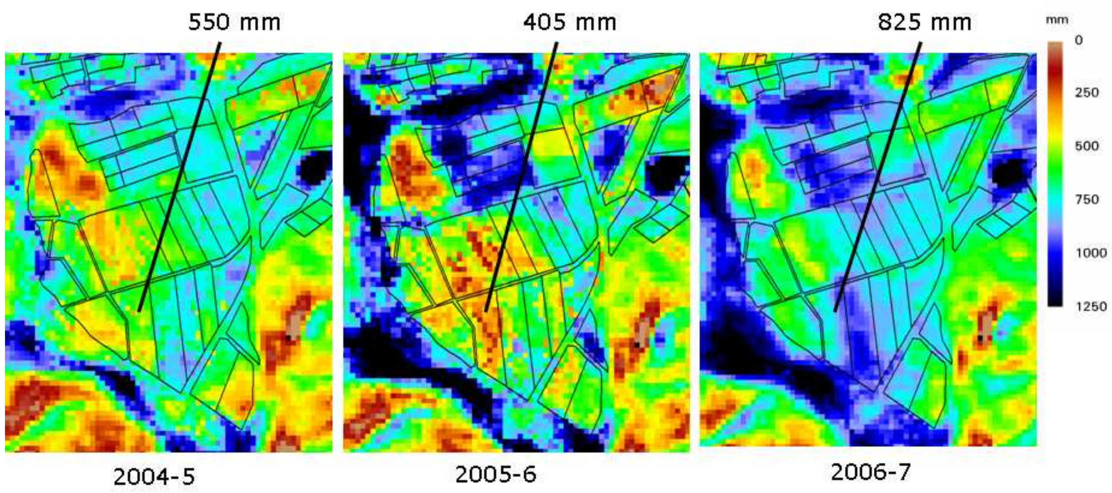


Figure 50 The effect of management on water consumption in a wine grape farm in Worcester

7.5 Conclusions on water use efficiency

- Water use efficiency in terms of yield of fruit or produce per unit water, (kg/m3) is a more appropriate measure of agricultural production than yield of produce per unit land (kg/ha) in water-short areas such as the Western Cape.
- Biomass water use efficiency (kg/m3) serves to quantify the vigour of a vine grape in relation to its water consumption. It can be used to replace yield (fruit) water use efficiency if the cultivar is not known.
- The biomass water use efficiency of table grapes (3.0-3.2 kg/m3) is slightly higher than biomass WUE of wine grapes (2.2-3.2 kg/m3).
- Table grapes biomass WUE is very uniform between years and areas because (1) water consumption is controlled by irrigation, and thus relatively stable; and (2) the horizontal trellis system results in uniform LAI and biomass production.
- Wine grapes biomass WUE is very variable both in time and space because (1) many vineyards receive no or limited irrigation, resulting in a strong relationship between rainfall distribution and water consumption; and (2) biomass production is very variable between vineyards because of differences in row height, distance, trellis system and cultivars.
- Water use efficiency of Colombar wine grapes in Worcester was significantly higher in the second year (4.5 kg/m3) as compared to 2004-5 (3.6 kg/m3) and 2006-7 (3.9 kg/m3). In 2005-6 the water consumption was low while yields were high. Both water consumption and yield were low in 2004-5, and high in 2006-7. Apparently water use efficiency of Colombar wine grapes is only reached by reducing water consumption and increasing yield at the same time. But, the standard deviation in 2005-6 was higher than in the other two years, suggesting that only some of the wine grape farmers in Worcester were able to improve their WUE in that year.
- For all three years, water use efficiencies were higher in the southern part of Worcester because these vineyards have almost similar yields if compared to the other vineyards in Worcester while consuming less water. The lower water consumption is a result of lower irrigation water availability, and suggests water consumption in Worcester can be reduced without affecting yields.

- Average water use efficiency of table grapes is very stable over time ranging from 3.6 to 3.9 kg/m3. WUE of table grapes however varied considerably between areas. Highest water use efficiency (> 4 kg/m3) was obtained in the better soils of Hex River Valley (the upstream and downstream area) and in Paarl South. The water use efficiency of Worcester table grapes was lowest, in one year even dropping below 2 kg/m3. In general, higher water consumption of table grapes did not lead to higher yields. WUE of table grapes is most affected by water consumption, which seems to be related to location, most probably the soil type.
- Water use efficiency variability is explained by (1) seasonal variables such as rainfall and irrigation water availability; (2) the management strategy applied; and (3) field characteristics such as soil type. SEBAL calculates water consumption, yield and water use efficiency independent of all these variables.

8 Summary and conclusions

Improvements of this study

- The inclusion of an additional hydrological year (2006-7) and the expansion of the study area to Somerset West and Stellenbosch, resulted in a more consistent and complete picture of water consumption, yield and water use efficiency of vineyards in the Western Cape. It greatly improved the spatial and temporal analysis of water use efficiencies.
- Shortwave atmospheric transmissivity maps are available from the MSG sensor since 2006, and were used for the SEBAL calculations of 2006-7. Spatial measurements of transmissivity are preferred above meteorological station measurements because no real spatial extrapolation of cloud cover can be done.

Area description

- The Wemmershoek Mountains divide the study areas in a typical coastal Mediterranean zone on the west (Somerset West, Stellenbosch, Franschhoek, and Paarl) and a more arid zone on the east (Hex River Valley, Worcester). Vineyards in the more arid zones usually have a permanent irrigation system while especially the wine vineyards in Stellenbosch and Somerset West often receive no or only a small number of irrigation applications. For this reason vineyards in the west are more susceptible to low rainfall, while vineyards in the east are more vulnerable to low irrigation supplies.
- Rainfall distribution over summer and winter is highly variable over years and between areas, as is shown in the following table (based on rainfall measurements at representative stations). In Worcester and Hex River Valley farmers were cut in their irrigation supplies in 2004-5 as a result of the preceding dry winter. The summer of 2005-6 was very dry, which mainly affected the vineyards without permanent irrigations system in Stellenbosch and Somerset West.

Total rainfall (mm)	Worcester		Hex Valley		Stellenbosch		Somerset West		Paarl		Franschhoek	
	W	S	W	S	W	S	W	S	W	S	W	S
2004	64	106	163	110	328	213	259	140	249	192	317	225
2005	53	40	237	29	393	105	274	53	311	93	447	84
2006	193	60	171	69	322	157	491	220	370	132	348	173

- More than 4000 vineyards were visited in 2006 and 2008 to validate the grape classification. According to the classification vineyards only occupy 68,683 ha, or 2.4 % of the total land on the Landsat images. The total accuracy of the grape classification was 82.3%, which is high.

Water consumption

- Irrigation supply in the table grape measurement blocks in Hex River Valley was only 559 mm in 2004-5 because the farmers were cut in their water supplies. In 2005-6 and 2006-7 the irrigation supply was comparable at 725 mm and 729 mm respectively. Irrigation supply in 2004-5 started to replenish soil moisture earlier than 2005-6 and 2006-7 after the dry winter of 2004.

- Typically, over 40 mm of soil moisture is subtracted from the 5-95 profile from October until March in the table grape measurement blocks in Hex River Valley. In all blocks soil moisture was replenished in October, and soil moisture was most reduced in January, February and March. Soil moisture extraction was similar in the three years, and did not increase when irrigation water was limited during the summer of 2004-5.
- The water consumption of table grapes in Hex River Valley was calculated with SEBAL and with the water balance equation. Measurements of rainfall, irrigation supply, and soil moisture may be used to estimate evapotranspiration, but the resulting water balance evapotranspiration does not incorporate deep percolation, water uptake from deeper soil layers, and spatial and temporal variation in the soil moisture within a field. The SEBAL calculations of water consumption were on average 11% higher or lower than the estimates of the water balance, which is realistic considering these limitations.
- SEBAL estimates of water consumption of all table grapes in Worcester, Paarl and Hex River Valley showed that water consumption was indeed very low (690 mm) when farmers were cut in their water supplies in 2004-5. In 2005-6 and 2006-7 sufficient irrigation water was available and as a result the table grape’s consumption increased to 866 and 831 mm respectively.
- Table grape vineyards consume more water than wine grape vineyards, and water consumption is less variable over different areas because (1) water deficit management is less common in table grape vineyards; (2) table grapes are more intensive irrigated and less dependent on rainfall; and (3) the trellis system of table grapes is less variable than that of wine grapes.
- In Worcester a large variation in water consumption was found between areas. This is most probably related to the variation in irrigation water resources in this area. Wine grape vineyards consumed more water in Worcester than in the coastal areas because of the climate and because of the irrigation system. Wine grapes in Stellenbosch and Paarl consumed least water as they are (semi) rainfed.
- Water consumption is a result of among others rainfall, irrigation supply, management and field characteristics (i.e. soil type, aspect, altitude).

Yield

- Measured table grape yield ranged from 11.0 tons/ha, in a young Crimson block, to 58.6 tons/ha in a Sunred block. Average table grape yield measured in the blocks was 28.5, 27.0 and 30.8 tons/ha for 2005, 2006 and 2007 respectively. These measurements showed that table grape yield did not decrease with decreased water consumption.
- Grape yield modelling is complex because yield is not linearly related to biomass production and because yield is strongly influenced by management, such as cutting of berries before harvest.
- The developed grape yield models are based on empirical relationships for a small number of fields only. Additional yield data of more areas and other cultivars will greatly improve the current yield model. The currently modelled table grape yield was three percent lower in 2004-5, less than one percent higher

in the second year, and less than one percent lower in 2006-7 as compared to the measured yield.

- Modelled table grape yield in all table grape fields was on average 24.9 tons/ha in 2005, and increased slightly in 2006 and 2007 to 27.4 and 27.7 tons/ha. A lower average yield in 2005 is ascribed to water shortages. The higher variation in table grape yield in 2005 however suggests that not all vineyards were affected by the water shortages.
- The wine grape model was only valid for Colombar wine grapes in Worcester as no other yield data was available for this report. Colombar wine grape yield in Worcester was lowest in 2005 at 22.7 tons/ha, and very similar in 2005 and 2006 at 27.6 tons/ha and 26.9 tons/ha respectively. Wine grape yield of other cultivars is expected to be considerably lower.

Water Use Efficiency

- Water use efficiency in terms of yield per unit water (kg/m3), is a more appropriate measure of agricultural production than yield per unit land (kg/ha) in water-short areas such as the Western Cape.
- Water use efficiency of Colombar wine grapes was significantly higher in 2005-6 (4.5 kg/m^3) because water consumption was low while yield was high. Both water consumption and yield were low in 2004-5 and high in 2005-6, resulting in lower WUE in both years (3.6 kg/m^3 and 3.9 kg/m^3 respectively). The standard deviation of WUE however was higher in 2005-6, indicating that only some farmers improved their WUE while others maintained the same level.
- WUE of Colombar wine grapes was highest in Worcester South in all three years due to low water consumption without affecting yield, which suggests a reduction of water consumption of Colombar wine grapes is possible without affecting yield.
- Water use efficiency of other wine grape cultivars could not be calculated as yield data was not yet available during the preparation of this report. Water consumption of wine grapes in Somerset West, Stellenbosch and Franschhoek was lower than in Worcester because of the less arid climate and lower irrigation supply. But, Colombar wine grapes in general have higher yields than other wine grape cultivars. It is suspected that water use efficiency of wine grapes in the coastal regions varies considerable between years as their performance strongly relies on rainfall. For example, the dry summer of 2005-6 strongly affected water consumption and biomass production of wine grapes in Stellenbosch and Somerset West. A low wine grape yield however may be of excellent quality and therefore of high value.
- Average water use efficiency of table grapes was relatively constant over the three study years at 3.9, 3.6 and 3.7 kg/m^3. WUE however varied considerable between the different areas. Water use efficiency of table grapes in Worcester was lowest of all areas, dropping below 2 kg/m^3 in one year. In Paarl South and on the better soils of Hex River Valley the highest WUE was obtained (>4 kg/m^3). In 2006-7 the table grape WUE in Paarl dropped to its lowest values because of a strong decline in yield, while in Hex River Valley the WUE improved to its highest values.
- Water use efficiency is highly variable between areas and years because of variations in rainfall, irrigation water availability, management strategies and field characteristics such as soil type. Water use efficiency of wine grapes in

Stellenbosch and Somerset West might improve by more irrigation during dry years, as the water shortage in the summer of 2005-6 seriously affected grape growth, although more information on wine yield is needed to draw final conclusions. Water use efficiency of table grapes however might improve by a reduction in the irrigation supply, as the irrigation cuts in 2004-5 did not affect table grape yield in all vineyards.

General

- SEBAL calculated water consumption, yield and thus water use efficiency without any knowledge on soil type, cultivar, irrigation system and supply and plant condition.

References

Allen, Richard G., Luis S. Pereira, Dirk Raes, and Martin Smith (1998) Crop evapotranspiration – Guidelines for computing crop water requirements. FAO Irrigation and Drainage Paper 56

Burger, Johan, and Jacob Deist (2005) Wingerdbou in Suid-Afrika. CTP Boekdrukkers, Kaapstad.

Goodwin, Ian (2002) Managing water stress in grape vines in Greater Victoria. Agriculture Notes, State of Victoria, Department of Primary Industries, AG1074, ISSN 1329-8062.

Giddings, Jeremy (2005) Winegrape irrigation benchmarking 1998-03. Report, Murray Valley Winegrowers, Australia.

Klaasse, Annemarie, Wim Bastiaanssen, Jan Bosch, Caren Jarmain and Martin de Wit (2007) Remote Sensing Tools for Water Use Efficiency of Table and Wine Grapes in the Winelands of Western Cape, South Africa. WaterWatch report for the Department of Agriculture of Western Cape. Wageningen.

Myburgh, P.A. (2005) Water status, vegetative growth and yield responses of Vitis vinifera L. cvs. Sauvignon blanc and Chenin blanc to timing of irrigation during berry ripening in the coastal region of South Africa. S. Afr. J. Enol. Vitic., Vol. 26, No. 2, 2005

Statistics South Africa (2006) Census of Agriculture Provincial Statistics 2002 – Western cape. Financial and production statistics. Statistics South Africa, Pretoria

Van Zyl, J.L. (1984) Interrelationships among soil water regime, irrigation and water stress in the grapevine (Vitis vinifera L.). Thesis, Stellenbosch University, Private Bag X1, 7602 Matieland (Stellenbosch), South Africa

Appendix 1 A short introduction to SEBAL

Evapotranspiration, the sum of evaporation and plant transpiration, is an important part of the hydrological cycle. Evaporation is the movement (vaporization) of water to the air from the soil, water bodies and canopy interception. Transpiration is the loss of water as vapour through stomata in the plants' leaves. Evapotranspiration is an indicator of how much water vegetation needs for healthy growth and productivity.

Evapotranspiration is not only an important part of the hydrological cycle; it is also a component of the energy balance. Evapotranspiration uses energy. Each water molecule that becomes water vapour takes a parcel of heat with it. The energy required for evapotranspiration is provided by the sun.

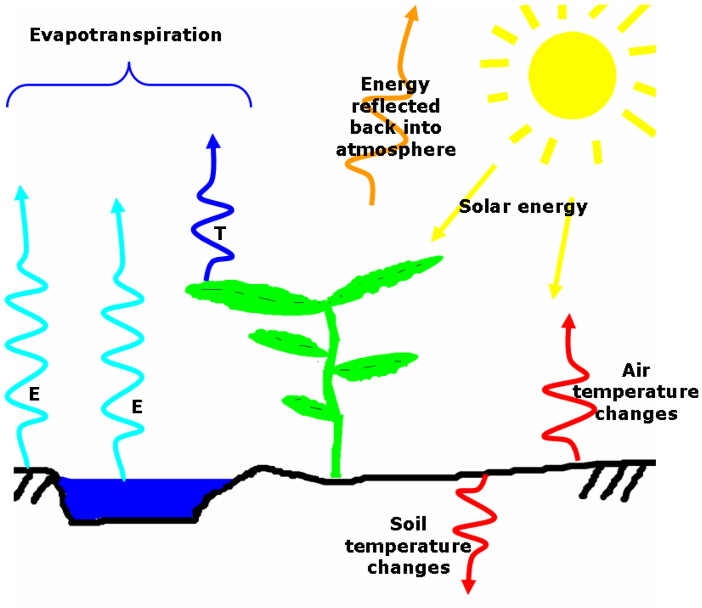


Figure a1 The energy balance

The earth is constantly exposed to energy from the sun. **Solar energy** drives many processes on the earth's surface. Figure a1 shows the different components of the earth's energy balance.

Most obviously solar energy causes **changes in temperature**, for example the heating up of **air** and **soil**. Hence, temperature differences produce winds.

A very small part of the sun's energy is used by plants for photosynthesis. However, this component is so small in comparison with the other components it is usually ignored in the calculation of the energy balance.

Part of the solar energy is absorbed in the hydrological cycle by driving **evapotranspiration**. The amount of solar energy used for evapotranspiration depends on the amount of water available and also on the meteorological conditions. The evapotranspiration process needs for example less energy when the relative humidity and wind speed are high.

Not all incoming energy is converted to other types of energy; a part is **reflected back into space**. How much energy is reflected back depends among others on the earth surface's reflectivity (albedo). Bright surfaces such as desert reflect more energy than dark surfaces (i.e. forest, water).

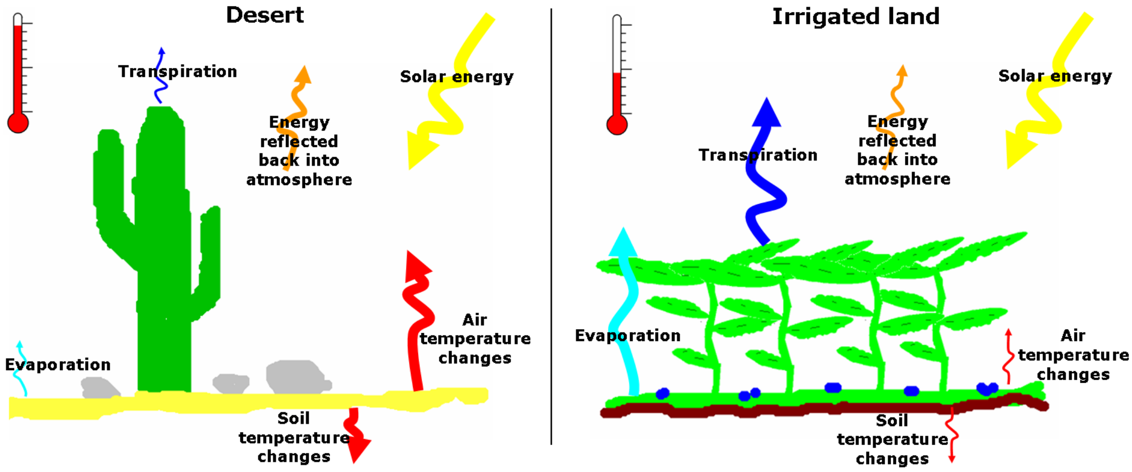


Figure a2 The energy balance for desert and irrigated land

Figure a2 shows the energy balance for two land use types: desert and irrigated land, with very distinct water availability conditions. In a desert little water is available, which means relatively little energy is used for the evapotranspiration of water. A large amount of the solar energy will therefore be used for the heating up of air and soil, resulting in a very high soil and air temperature.

When enough water is available, for example in irrigated land with a dense and healthy vegetation cover, the evapotranspiration process consumes a significant part of the solar energy. Little energy remains for the heating up of air and soil, and as a result soil and air temperature are lower.

The Surface Energy Balance Algorithm for Land (SEBAL) uses the energy balance to estimate some aspects of the hydrological cycle. SEBAL maps evapotranspiration, biomass growth, water deficit and soil moisture. The basis of SEBAL is the energy balance: the energy driving the hydrological cycle is equal to the incoming energy minus 1) the energy going to heating of the soil and air, and 2) the energy reflected back to space.

The energy balance can be quantified from satellite data. Land surface characteristics such as surface albedo, leaf area index, the vegetation index and surface temperature are derived from satellite imagery. In addition to satellite images, the SEBAL model requires some meteorological data, such as wind speed, humidity, solar radiation and air temperature. In this study MeteoLook was applied to extrapolate meteorological point measurements to spatial representations of wind speed, humidity and air temperature. Since the SEBAL model uses the energy balance, and not the water balance, no data on land cover, soil type or hydrological conditions is required.

The energy balance applies to all scales: from global level to river basin to region to farm and field. Satellite images come in a wide variety of spatial and temporal resolutions. Evapotranspiration and biomass production are key indicators for water management and irrigation performance. SEBAL applies the energy balance in combination with satellite imagery to map these key indicators in time and space for days, weeks or years.

Appendix 2 Measurements in the Hex River Valley blocks

Table a1 Rainfall in the Hex River Valley 2004-5 (Source: ARC / Department of Agriculture)

month	**ARC Hex Valley**	**De Vlei**	**HT blocks**										
			1	**4**	**7**	**9**	**14**	**16**	**21**	**27**	**29**	**30**	**34**
Jun-04	47	70	0	51	57	47	54	44	40	59	49	62	40
Jul-04	51	65	55	42	56	53	39	48	41	54	48	60	47
Aug-04	21	28	8	10	39	28	9	14	13	30	18	30	16
Sep-04	8	12	0	9	10	6	7	9	10	13	8	9	0
Oct-04	56	54	24	67	53	55	52	50	51	53	57	47	0
Nov-04	4	6	0	45	5	4	8	5	4	5	6	5	0
Dec-04	19	28	5	10	10	12	17	14	12	3	21	0	0
Jan-05	28	21	17	16	28	26	0	19	16	34	28	29	25
Feb-05	8	1	0	3	0	0	0	0	0	3	0	1	0
Mar-05	1	2	0	4	2	0	0	1	1	1	0	0	1
Apr-05	75	94	72	99	77	80	25	70	62	100	74	90	70
May-05	10	8	27	32	19	13	84	12	9	11	5	6	10
Total	**328**	**388**	**208**	**388**	**356**	**324**	**295**	**286**	**259**	**366**	**314**	**339**	**209**

Table a2 Rainfall in the Hex River Valley 2005-6 (Source: ARC / Department of Agriculture)

month	**ARC Hex Valley**	**De Vlei**	**HT blocks**										
			1	**4**	**7**	**9**	**14**	**16**	**21**	**27**	**29**	**30**	**34**
Jun-05	57	75	29	44	68	62	36	50	41	63	55	35	42
Jul-05	49	67	26	15	56	46	46	35	28	66	47	60	25
Aug-05	117	94	6	59	95	131	70	44	34	103	73	83	54
Sep-05	26	29	3	19	31	21	25	6	6	30	10	26	3
Oct-05	1	1	1	0	0	0	0	0	0	0	0	0	1
Nov-05	2	26	0	37	36	23	22	21	41	25	24	25	0
Dec-05		0	0	0	0	0	0	0	0	1	0	0	0
Jan-06	1	3	0	3	0	0		0	0	2	3	2	2
Feb-06	0	0	0	0	0	0		0	0	3	0	0	1
Mar-06	2	1	0	0	3	0		0	0	0	0	0	0
Apr-06	50	49	33	33	47	0		41	42	49	44	52	30
May-06	73	105	60	119	114	40		69	66	109	87	104	78
Total	**377**	**450**	**158**	**329**	**450**	**323**		**266**	**258**	**451**	**343**	**387**	**236**

Table a3 Rainfall in the Hex River Valley 2006-7 (Source: ARC / Department of Agriculture)

month	**ARC Hex Valley**	**De Vlei**	**HT blocks**										
			1	**4**	**7**	**9**	**14**	**16**	**21**	**27**	**29**	**30**	**34**
Jun-06	55	57	66	61	79	93		46	39	67	43	52	51
Jul-06	68	45	28	55	53	62		49	52	55	58	51	42
Aug-06	75	69	49	67	79	54		33	33	75	57	63	68
Sep-06	14	7	0	10	14	62		0	0	14	8	6	10
Oct-06		18	0	12	17	12		17	17	14	14	14	14
Nov-06	15	43	15	27	48	14		22	20	42	38	37	29
Dec-06	31	3	0	2	0	40		4	2	0	0	0	1
Jan-07	33	2	0	0	0	0	3	0	0	0	0	2	0
Feb-07	48	3	4	3	5	0	0	0	0	0	2	0	3
Mar-07	9	2	8	5	7	2	0	0	0	9	4	0	5
Apr-07	347	31	22	24	24	25	20	1	1	31	28	28	21
May-07	95	50	87	59	6	46	28	66	63	49	37	41	4
Total	**790**	**330**	**279**	**325**	**332**	**410**		**238**	**227**	**356**	**289**	**294**	**248**

Table a4 Irrigation water applied (mm) in the season 2004-5, Hex River Valley (source: Department of Agriculture)

HT no	Jun-Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Total
1	46	26	86	142	94	84	96	9	21	606
2	122	50	63	100	95	50	37	8	24	550
3	56	15	74	125	139	120	102	0	0	631
4	44	23	141	130	111	105	38	0	7	600
5	15	0	63	104	106	71	44	16	25	445
6	76	78	143	128	48	61	27	15	0	575
7	15	66	118	119	57	99	30	0	0	504
8	63	59	113	184	125	115	70	26	11	766
9	128	29	129	151	115	86	87	38	0	764
10	6	5	32	148	68	88	70	5	1	422
11	32	40	82	83	91	109	114	101	0	652
12	7	31	48	63	61	63	72	82	36	462
13	0	24	71	105	92	53	0	25	2	372
14	41	44	96	80	69	111	28	0	22	491
15	10	28	87	129	84	145	107	6	13	607
16	48	65	85	176	118	60	83	25	0	661
18	48	12	95	146	169	105	112	25	18	731
20	46	40	90	130	84	66	38	0	0	495
21	56	58	147	195	64	36	24	0	0	579
24	41	26	80	139	85	56	118	19	17	582
25	45	55	97	110	89	97	66	10	9	579
26	42	73	115	147	65	44	38	8	1	534
27	52	34	65	88	53	21	22	5	5	345
29	0	22	94	147	121	136	144	63	65	793
30	40	65	61	65	84	54	91	9	8	477
31	33	29	76	76	49	25	44	78	7	416
32	32	65	102	136	66	6	33	1	0	442
Avg.	**42**	**39**	**91**	**124**	**89**	**77**	**64**	**21**	**11**	**559**

Table a5 Irrigation water applied (mm) in the season 2005-6, Hex River Valley (source: Department of Agriculture)

HT no	Jun-Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Total
1	5	23	68	84	112	102	69	28	4	496
2	5	46	93	141	135	93	76	46	52	686
3	71	37	72	108	137	87	71	43	23	649
4	8	51	126	144	179	138	92	53	13	805
5	28	40	95	110	152	125	79	0	0	629
6	97	93	85	77	88	115	138	27	11	731
7	0	36	127	179	183	121	78	0	0	724
8	57	88	90	107	118	93	63	36	0	652
9	28	130	134	133	245	138	72	58	3	942
10	1	0	125	102	170	172	91	39	0	701
11	49	32	130	145	186	192	82	65	0	880
12	16	47	93	116	157	137	86	42	13	708
13	4	24	54	96	131	139	84	26	12	571
14	27	27	151	219	141	111	61	0	0	737
15	17	40	108	109	128	136	78	46	4	666
16	0	127	195	199	212	155	94	35	0	1017
18	27	97	164	168	218	130	110	32	9	954
20	31	54	72	137	159	77	35	20	0	584
21	111	124	253	160	173	122	67	53	9	1071
24	57	77	135	172	122	133	77	38	15	825
25	26	53	131	101	129	132	70	31	8	680
26	18	83	113	129	122	101	89	81	0	736
27	35	47	87	95	96	71	29	17	1	478
29	41	59	107	175	198	147	123	81	17	947
30	8	102	89	69	78	76	56	22	0	501
31	34	72	136	129	142	67	101	54	4	738
32	10	20	96	159	64	31	26	57	0	463
Avg.	**30**	**60**	**116**	**132**	**147**	**116**	**78**	**38**	**7**	**725**

Table a6 Irrigation water applied (mm) in the season 2006-7, Hex River Valley (source: Department of Agriculture)

HT no	Jun-Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Total
HT1	10	17	79	108	96	110	81	42	35	578
HT2	12	58	57	92	130	104	85	57	19	614
HT3	31	41	91	134	156	141	113	94	12	813
HT4	12	82	175	187	210	193	103	79	14	1057
HT5	27	58	95	186	141	163	87	47	14	816
HT6	14	52	77	78	108	64	108	59	23	584
HT7	0	95	123	209	199	159	137	47	0	969
HT8	24	72	115	133	111	128	75	26	10	695
HT9	2	114	144	204	221	191	118	70	34	1098
HT10	34	72	103	138	182	144	83	28	3	787
HT11	29	81	155	162	150	158	92	28	2	858
HT12	8	22	71	141	163	129	88	65	28	715
HT13	3	26	76	137	179	153	106	42	12	734
HT14	43	62	132	187	234	153	108	28	0	947
HT15	4	31	79	145	167	133	114	62	3	738
HT16	59	84	179	175	189	160	161	96	22	1125
HT18	20	65	115	213	224	179	104	27	0	948
HT19	35	87	153	215	199	136	122	102	36	1085
HT20	24	56	73	113	122	83	76	30	42	618
HT21	72	112	161	226	131	79	26	114	13	934
HT22	50	78	141	134	135	57	72	53	6	726
HT24	50	55	116	136	162	46	0	0	0	564
HT25	13	9	53	96	112	95	59	31	16	484
HT26	13	46	130	147	87	91	56	54	0	623
HT27	35	57	122	140	123	101	62	10	9	661
HT29	5	61	112	184	178	46	1	53	10	650
HT30	29	114	141	150	117	89	66	35	0	740
HT31	37	72	137	136	75	61	80	32	0	630
HT32	68	52	139	185	76	16	20	10	0	566
HT33	29	20	52	80	91	85	70	60	7	494
HT34	16	33	63	108	110	81	60	55	22	549
HT35	5	18	46	55	57	49	43	40	14	328
HT36	16	58	73	88	141	106	103	44	15	644
HT37	8	23	51	74	81	77	57	32	14	417
Avg.	**25**	**58**	**107**	**144**	**143**	**111**	**80**	**49**	**13**	**729**

Table a7 Monthly soil moisture change (mm) in the 5-95 cm soil profile from October 2004 until March 2005

HT no	Oct-04	Nov-04	Dec-04	Jan-05	Feb-05	Mar-05	Total change
1	13.4	4.9	2.6	-3.6	-2.0	-10.0	5.3
2	-56.0	1.0	-71.0	-15.8	-7.3	54.9	-94.
3	-17.4	1.7	42.8	-65.2	2.0		
4	25.0	-4.0	11.6	-12.1	0.9	-27.3	-6
5	8.6	30.4	-9.7	7.7	-43.0	11.4	5.3
7	-20.4	-10.9	-14.5	-3.4	16.8	-18.2	-50.5
8	15.5	8.8	-26.7	-4.6	-0.1	-38.2	-45.5
11	24.6	-28.4	-23.2	-4.7	38.5	-44.1	-37.2
12	13.1	-47.6	-4.0	6.4	-1.4	-18.7	-52.1
13	97.2	-73.3	60.4	-51.8	0.6	-19.0	14.1
14	0.7	-30.9	-0.9	67.2	12.5	-111.0	-62.4
15	33.1	49.1	-25.0	-14.0	-57.3	-22.2	-36.2
18	32.4	17.4	-18.1	30.5	-24.8		
20	7.1	-13.5	-14.0	-11.0	-24.4		
24	-48.8	51.5	-43.3	-27.4	-7.4		
27	-128.0	-34.1	14.9	-11.2	-1.2	-11.1	-170.6
29	38.7	-5.3	9.1	10.0	-17.9	-48.7	-14.0
30	4.8	-15.9	41.5	-84.9	7.9	-23.1	-69.6
31	21.0	-15.7	12.3	-15.9	-14.4	7.7	-4.9
32	18.9	31.4	-36.7	-26.4	-13.7	-30.1	-56.7
Average	**4.2**	**-4.2**	**-4.6**	**-11.5**	**-6.8**	**-21.7**	**-42.2**

Table a8 Monthly soil moisture change (mm) in the 5-95 cm soil profile from October 2005 until March 2006

HT no	Oct-05	Nov-05	Dec-05	Jan-06	Feb-06	Mar-06	Total change
1	-5.6	12.8	-3.1	20.0	-20.7	15.8	19.2
2	17.2	44.4	17.7	-107.0	6.2	15.8	-5.7
3	-18.5	33.2	-10.8	-13.4	8.7		
4	33.4	-5.6	-2.1	4.1	-10.5	-3.8	15.6
5	1.9	29.8	-7.5	20.4	-19.5	-57.5	-32.4
7	-15.4	7.4	-11.4	8.5	-16.7	-21.4	-49.1
8	27.1	-25.5	-9.0	-17.7	-5.6	-3.2	-33.7
11	-12.1	-57.1	-0.4	53.6	-18.7	-9.7	-44.3
12						-22.4	
13					-64.9	-40.9	
14	-22.2	38.1	-15.2	-34.0	-33.9	17.8	-49.4
15	4.4	-22.3	-28.4	42.7	-22.3	-24.0	-50.0
18	12.5	18.6	4.4	1.0	-35.8		
20	-4.1	-7.5	11.0	6.0	-45.4	-9.9	-49.8
24	26.2	-54.3	9.1	-17.4	-3.6		
27	-0.6	-0.4	-11.8	-43.1	-23.4	-13.9	-93.2
29	-7.7	18.6	0.2	-30.4	-27.5	39.1	-7.8
30	27.0	14.5	-28.9	-18.9	-12.0	-23.7	-42.1
31	0.0	25.4	-7.3	30.3	-60.4	17.2	5.2
32	31.1	62.6	-61.3	-37.1	-66.4	-78.5	-149.6
34						-46.4	
Average	**5.3**	**7.4**	**-8.6**	**-7.4**	**-24.9**	**-13.9**	**-37.8**

Table a9 Monthly soil moisture change (mm) in the 5-95 cm soil profile from October 2006 until March 2007

HT no	Oct-06	Nov-06	Dec-06	Jan-07	Feb-07	Mar-07	Total change
1	-5.9	47.1	62.0	-86.6	-39.3	50.6	27.8
2	-11.0	25.4	-8.1	-15.8	-33.9	-47.2	-90.5
3	17.7	0.7	13.2	-57.1	27.9	-11.5	-9.0
4		-20.0	51.4	-90.3	56.0	18.6	
5	5.8	4.2	6.0	-1.8	2.1	-31.2	-14.9
6	12.8	-10.4					
7	22.1	0.2	-20.2	-23.6	30.8	58.7	68.0
8	-37.8	34.5	80.1	-128.5	31.3	-17.4	-37.8
9	115.6	-11.1	35.3	-125.5	68.9	-11.6	71.7
11	-36.7	-121.3	-18.7	156.1	-192.9	6.2	-207.3
12		18.9	-19.1	0.7	-75.1	-38.5	
13	-20.8	36.6	-147.8	185.3	-230.7	30.2	-147.3
14	16.7			-31.2	-42.3	47.0	-147.5
15	55.2	-20.0	27.7	-107.1	-8.4	-3.5	-56
16				-63.2	2.4	-30.6	
18	-0.1	51.5	-16.5	-40.8	34.2	-40.3	-12.1
20		39.0	-60.0	89.1	-84.9	3.6	
21	-37.2						
24			-93.9	-47.0	123.1		
25	34.5	-15.1	-113.9				
26	-16.4	72.3	-23.7	-69.4	-46.9	12.3	-71.9
27	15.7	58.1	4.3	-43.7	-119.2	81.7	-3.0
29	6.8	24.6	10.0	-30.0	-46.9	-28.3	-63.9
30		17.6	-27.5	-128.2	83.3	55.9	
31	-26.7	57.5	-8.4	-41.6	-6.7	21.9	-4.0
32	-34.9	66.7	-65.8	-27.5	-32.5	30.5	-63.6
34	-26.7	30.3	21.2	-97.7	-21.6	33.3	-61.2
35	29.8	44.9	-72.6	-58.7	19.8	29.3	-7.4
36	35.6	-32.7	45.8	-109.2	21.0	-46.4	-85.9
Average	**5.0**	**16.0**	**-9.4**	**-38.2**	**-18.5**	**6.9**	**-45.8**

Table a10 Evapotranspiration derived from the water balance in mm for 2004-5

HT no	Oct-04	Nov-04	Dec-04	Jan-05	Feb-05	Mar-05	Total Oct-Feb	Total Nov-Feb
1	37		145	115				
3	99	118	92	220	121		651	551
4	65	190	129	139	107	69	630	565
5				123		35		
7	139	134	143	89		50		
8				155		111		
11	70	116	134	116	72	160	508	438
12	72	101	95	75	65	92	408	337
13	-21	152	61					
14	96	135	97					
18	47	123	174	154	133		632	585
20	86	109	147	129	94		565	479
27	215	104	76	98	25	34	518	303
29	40	105	159	138				
30	107	82		198	47			
31	62	97	92	86	41	37	377	315
32	98	79	190					
Average	**81**	**117**	**124**	**131**	**78**	**74**	**536**	**446**

Table a11 Evapotranspiration derived from the water balance in mm for 2005-6

HT no	Oct-05	Nov-05	Dec-05	Jan-06	Feb-06	Mar-06	Total Oct-Feb	Total Nov-Feb
1	30							
3		76		153				
4		169		178				
5	40			133	146			
7		155				102		
8	63			138	101			
11	45	213	145	135	210	93	748	703
12						109		
14		135						
18		182		220				
20		104	127	155	126			512
27		113	108	141	97			459
29		112		231				
30		100		99				
31	73	136	136	114	127	84	587	513
32		55						
Average	**50**	**129**	**129**	**154**	**135**	**97**	**667**	**547**

Table a12 Evapotranspiration derived from the water balance in mm for 2006-7

HT no	Oct-06	Nov-06	Dec-06	Jan-07	Feb-07	Mar-07	Total Oct-Feb	Total Nov-Feb
1	23	47	46	183	153	38	451	428
3	35	117	122	213	116	130	604	568
4		222	138	301	140	90		801
5	66	120	181	143	164	123	673	607
6	53	116						
7	89	171	229	222	133	86	845	756
8	124	110	53	240	100	98	627	503
9	10	169	209	347	122	132	856	846
11	136	319	184	-4	354	88	989	853
12		95	163	165	207	128		629
13				-3	384	75		
14				268	196	61		
16				252	158	192		
18	78	91	231	264	148	150	812	735
20		76	173	33	168	82		449
21	166							
26	80	106	171	156	142	51	655	575
27	55	106	136	167	220	-10	684	629
29	69	125	174	208	95	33	671	603
30		161	178	247	5	10		591
31	117	122	147	119	71	60	576	459
32				107	49	-11		
34	74	62	88	208	105	32	537	463
35	0	15	168	116	30	16	329	329
36	38	136	76	298	94	496	642	604
Average	**71**	**124**	**151**	**185**	**146**	**93**	**663**	**601**

Table a13 Biomass production in the Hex River Valley blocks

HT no	Biomass production from September until April (tons/ha)		
	2004-5	**2005-6**	**2006-7**
1	26.1	30.1	28.3
2	21.5	30.4	29.2
3	19.8	25.7	22.5
4	23.6	28.2	30.9
5	14.3	20.8	28.1
6	19.6	23.6	19.4
7	24.8	31.4	23.2
8	27.0	33.7	28.4
9	24.8	35.6	29.9
10	26.4	36.8	33.5
11	22.4	30.3	27.0
12	20.3	28.9	28.4
13	22.1	26.6	24.9
14	19.8	28.4	28.2
15	18.6	21.8	15.9
16	21.9	25.5	27.5
18	21.6	31.7	27.2
20	28.3	35.5	31.1
21	16.0	16.3	23.7
24	30.0	36.9	28.9
25	24.8	29.5	24.9
26	20.0	28.5	21.7
27	22.4	33.1	31.9
29	21.2	30.4	27.4
30	24.4	27.5	30.9
31	22.0	29.7	28.1
32	21.8	28.1	25.4
33		25.9	25.4
34		38.5	30.0
35		27.5	27.7
36		23.2	20.3
37		17.5	17.6
	22.4	**28.7**	**26.5**