The Method for Estimating Crop Irrigation Volumes for the Tindall Limestone Aquifer, Katherine, Water Allocation Plan

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SUMMARY

This report describes the method to estimate crop irrigation water volumes for the Tindall Limestone Aquifer, Katherine, Water Allocation Plan. Estimates of volumes are needed for water allocation planning. An assessment is also given of the method's usefulness in estimating crop irrigation volumes elsewhere for water allocation plans. Such information will be of interest to water allocation planners, water users and irrigators.

The method used to estimate crop irrigation volumes for the Tindall Limestone Aquifer, Katherine, Water Allocation Plan was pan evaporation based. Monthly rainfall (based on an annual decile 1 rainfall of 655 mm) was subtracted from the monthly pan evaporation rate multiplied by a crop factor. If rainfall exceeded the crop factor-adjusted pan evaporation, no irrigation volume was calculated. If the crop factor-adjusted pan evaporation exceeded rainfall, the volume of irrigation to make up the deficit (after correction for the area of foliage cover and the irrigation delivery efficiency value of the system being used) was calculated. Monthly values were summed to provide an estimate of annual crop irrigation volumes required. The method was flexible and was successfully used for a wide range of crops. The method selected data from a site with high evaporation levels (~10% higher annually than a current Bureau of Meteorology site in the region) in order to correct for perceived future increases in evaporative demand due to climate change.

A number of areas were identified where the method to estimate crop irrigation volume requirements could be improved. Internationally accepted standard methods require that pan coefficients be used to calculate reference evapotranspiration (ET_o) from pan evaporation data (Allen et al. 1998). A pan coefficient was not used in the Tindall method, which would lead to a minimum of 15% over-estimation of evaporative demand and possible over-allocation when crop factor-adjusted pan evaporation exceeded rainfall.

Where crop irrigation volume estimates are based on pan evaporation, the standard methods to calculate ET_o from pan evaporation data should be followed (Allen et al. 1998), which is common in other water planning jurisdictions, such as in South Australia (Skewes 2008). An upper pan evaporation limit may also be required to account for crops shutting down physiologically under high evaporative conditions.

The selection of sources of data for any method needs to be representative of the current range of environmental conditions. The inclusion of additional volumes to correct for perceived future increases in water requirements could be included, however, the amount of such additions and the level of correction intended should be explicitly stated.

If rainfall-based methods are used, a consideration to exclude non-effective rainfall and carry over in soil water levels between months after the wet season may improve the accuracy of estimates.

Methods that estimate crop-specific irrigation volumes require accurate crop factors or crop coefficients. Where accurate crop factors or crop coefficients are not available, non crop-based estimates could be more appropriate. The determination of the range in crop water requirements across a district would also be useful.

The literature on evaporative demand indicates that pan evaporation-based estimates can overestimate demand compared with evapotranspiration figures calculated from other meteorological measurements, such as Penman-Montheith (Allen et al. 1998) especially during the dry season. It is therefore recommended that evaluations of crop irrigation volume estimates be based on ET_o for future water allocation plans and be calculated from meteorological data using established methods. In addition, it is recommended that an independent review be undertaken of the methods and outcomes of estimating crop irrigation volumes as part of developing future water plans.

Specific recommendations from this review are:

1. Where meteorological data for different variables (rainfall or pan evaporation) is required for estimating crop irrigation volumes, variables should all be selected from one monitoring station and time period. An improved approach would be to compare the estimated crop irrigation volumes using data from different sites and time periods within a region.

2. Determine the variability in estimated evaporation across irrigation regions, including a comparison of known wet and dry periods in long-term data sets.

3. Make a comparison of reference evapotranspiration (ET_o) (Allen et al. 1998) and pan evaporation values, especially for the dry season when most irrigation occurs and compare these values with actual evapotranspiration (ET_{crop}) in a number of important crops in order to identify the level of accuracy for the estimated crop irrigation volumes between the two methods.

4. Evaluate the effect of excluding non-effective rains to improve the accuracy of crop irrigation volume requirements.

5. Measure the carry over of soil water in some months to improve the accuracy of irrigation estimates.

6. Conduct research on crop factors or coefficients for important crops in the NT.

7. When using pan evaporation data to estimate crop irrigation volumes, use pan coefficient (K_p) values.

8. When using a pan evaporation-based method to estimate crop irrigation volumes, select pan evaporation records that have a demonstrated relationship to calculated crop transpiration and soil evaporation.

9. When using a pan evaporation-based method to estimate crop irrigation volumes, conduct research to identify the need and application of an upper pan evaporation limit.

10. Estimate contemporary crop irrigation volumes on the basis of current needs, without allowance for future crop water requirements due to climate change. Increases in crop irrigation volume estimations on the basis of climate change require substantial justification and should be based on actual changes.

11. Ensure that any method used and results obtained for crop irrigation volume estimations are reviewed by an independent expert.

INTRODUCTION

The sustainable management and use of water resources for food production is an important issue in Australia (Pigram 2006; Khan et al. 2009). The National Water Initiative required that the development of water allocation plans was a central component to sustainable water resource management and that water plans had to be implemented to a prescribed schedule in Australian states and territories (Anon 2004). Agriculture accounts for a substantial amount of water use. For example, fruit trees are estimated to use ~9% of the water used nationally for irrigation (557 535 ML) per year (ABS 2009). Methods have been developed to estimate crop water use in order to calculate water allocations for irrigation in areas of Australia (Skewes 2008).

In the Northern Territory (NT), crops produced in the dry season depend on irrigation, almost exclusively from ground water (Williams et al. 1985; Anon 2009c). This report describes a method to estimate the volume of water required to irrigate a range of crops in Katherine. The results were used to make water allocations from the Tindall Limestone Aquifer, Katherine for irrigated crops (Anon 2009b).

The objectives of the report are to:

1. Make available to the public the method used to estimate crop irrigation volume for the Tindall Limestone Aquifer Water Allocation Plan, Katherine.

2. Identify areas where the method could be improved to imform future water plan allocations.

BACKGROUND

DEVELOPMENT OF THE METHOD

Spreadsheets have been available since the 1980s to aid in the scheduling of irrigation in relation to rainfall and evaporative demand and continue to be updated (Snyder 1990; Snyder et al. 2007). Yan Diczbalis from the then Department of Primary Industry and Fisheries developed a spreadsheet system in the 1990s for in-house research on crop irrigation scheduling (Diczbalis 1991). The system used meteorological data, crop cover and crop factors to estimate crop water requirements for maintenance and yield. This spreadsheet was later adapted and used by the Department of Natural Resources, Environment the Arts and Sport (NRETAS) from 2003 for allocating water in the Katherine region (Brown 2010 pers. comm.). In February 2007, the Katherine Water Advisory Committee was formed to assist in the development and review of a water allocation plan for the Tindall Limestone Aquifer in Katherine. The Department of Regional Development, Primary Industry, Fisheries and Resources revised the weather inputs in the spreadsheet before it was presented to the Katherine Plant Industry Advisory Forum in May 2007 (Anon 2007) (Appendix 2). The forum requested input from growers on actual crop irrigation requirements and practices. A crop irrigation workshop was conducted for growers in September 2007 at Katherine Research Station in addition to other consultation activities (Anon 2009a). Further industry consultations resulted in changes in figures used in the spreadsheet to reflect crop management, including modification of some crop factors.

ESTIMATES OF CROP WATER USE AND ENVIRONMENTAL MEASUREMENTS

This section briefly introduces fundamental concepts to plant water use and irrigation scheduling, some of which are important for estimating irrigation volumes.

Water used by crops is predominantly lost by transpiration (T) but there are also evaporative (E) losses from the soil and from plant surfaces. The amount of water used by plants together with water losses through evaporation is called evapotranspiration (ET). Other potential areas of water loss during irrigation include lateral run off, deep drainage and leaks in the delivery system. These are not directly accounted for in ET calculations, but can be measured and included in estimates of crop irrigation requirements.

ET is caused by an energy gradient between water in plants and soil and water in the atmosphere. This can be influenced by meteorological factors, such as wind speed, radiation and by the supply of water in the soil and on plant surfaces. There are various methods to calculate ET, such as:

1. Directly using lysimeters. Plant transpiration can also be measured with a number of other methods, including soil evaporation to provide ET estimates. Appendix 1 contains a more detailed outline of different methods available to calculate ET.

2. Indirectly from meteorological factors. Meteorological data (net radiation, soil heat flux, air temperature, wind speed, saturated and actual vapour pressure) can be used to calculate reference ET_o (also called potential ET) for a hypothetical reference crop (often grass) using a range of methods. A recommended method is the United Nations Food and Agriculture Organisation's (FAO) modified Penman Monteith procedure (Allen et al. 1998), which is recommended as it has been internationally tested and can be used in a wide variety of environments. In addition, other procedures exist that calculate evaporation or ET from meteorological data. It is therefore important to identify which procedure is being cited and if values from differing procedures are being compared. A superscript ^{X} label is used to identify the procedure used in studies. For example, the calculation of ET_o in the method described by Allen et al. (1998) ^{A} is the FAO 1998 modified Penman-Monteith method. Appendix 1 catalogues the range of procedures used by studies cited in this report.

   ET_o is used as a reference point from which crop ET (termed ET_{crop}) can be calculated by multiplying ET_o by a crop species-specific, and often cultivar-specific, value. The water requirements of a crop can be compared with the ET_o by using an experimentally-derived crop coefficient (K_c) as follows:

   $$ET_{crop} = K_c * ET_o$$

   For example, water melon ET_{crop} accounts for 0.44 – 0.98 (or 44 to 98%) of a reference crop's (ET_o) evapotranspiration (Table 1). Crop coefficients are specific to particular crops and growth stages of crops, and can differ between environments.

Table 1. Examples of crop coefficients (K_c) for three crops (Anon. 2010)

Crop	K_c
Watermelons	0.44 - 0.98
Maize	0.30 - 1.20
Citrus	0.65 - 0.70

3. Estimating crop water use with pan evaporation data. The calculation of ET_o requires specific meteorological data. Where such data is not available, an alternative approach is to estimate ET_o from pan evaporation data. Pan evaporation data is used as a last resort when the data required to calculate ET_o is not available (Chiew and McMahon 1992) ^{B} and only for estimating ET_o over periods longer than three days (Chiew et al. 1995) ^{C} (Allen et al. 1998). The use of pan evaporation data is less accurate than the Penman Monteith procedure for calculating ET_o (Allen et al. 1998).

   Pan evaporation (E_{pan}) measures water evaporated from a standardised pan of water (typically a Class A pan in Australia) (Figure 1). This method is useful as it provides an indication of evaporation due to radiation, temperature, humidity and wind; but differences between the surface of water and the surface of a crop produce significant differences in water loss between the two (Allen et al. 1998). Therefore, a pan coefficient (K_p) is used to correct for this difference. K_p values are specific to each pan due to surrounding conditions affecting evaporation. However, some general values have been recommended where a K_p value is lacking for a pan. For example, a pan in a dry fallow area with light winds (< 2 m/s) will have K_p values from 0.55 to 0.75, depending on humidity levels (Allen et al. 1998). The minimum K_p value reported for any Class A pan was 0.85 (Allen et al. 1998). Pan evaporation corrected by a K_p value allows ET_o to be estimated:

$$ET_{o\ pan} = K_p * E_{pan}$$

The label $ET_{o\ pan}$ will be used to discriminate between ET calculated using meteorological data (ET_o) and ET calculated from pan data ($ET_{o\ pan}$). A crop factor is then used to describe the proportion of water used by a crop or specific growth stage of a crop relative to $ET_{o\ pan}$, and allows a crops water requirement to be estimated by:

$$\text{Crop water requirements} = \text{Crop factor} * ET_{o\ pan}$$

Some examples of crop factors are provided in Table 2.

Table 2. Examples of evaporation based crop factors for three crops

Crop	Crop factor	Reference
Mango	0.7	(Diczbalis et al. 2006)
Maize	1.00 – 1.20	(Anon 1975)
Citrus	0.75 -0.85	(Anon 1975)

Figure 1. Example of a Class A pan in Australia

METHOD – ASSUMPTIONS AND BASIS

From here on, the method that provides estimates of irrigation volumes for water allocation plan for the Tindall Limestone Aquifer, Katherine will simply be referred to as ‘the Tindall method’. In brief, the Tindall method calculates total irrigation volume requirement then corrects this by the area of the crop and efficiency of the irrigation system. The method used to estimate crop irrigation volumes for the water allocation plan for the Tindall Limestone Aquifer (hereafter, the water plan) Katherine, was based on pan evaporation, but differed in some respects from the method described in the previous Section. Variables in the method were monthly pan evaporation values, crop factors for crop species, water requirements and growth stages.

A number of assumptions were made with respect to the crop and environmental factors. Crop assumptions were:

1. That there are no limitations to typical water use and production placed on crop growth by pests, diseases or low soil fertility (Assumption 1).

2. That sites are identical in terms of factors affecting water availability, such as the water-holding capacity of soils (Assumption 2).

Environmental assumptions were:

1. That pan evaporation levels across the Katherine area and among irrigation sites are the same as those at meteorological recording stations in the area (Assumption 3).

2. That the use of rainfall data similar to that of rainfall in a decile 1 (D1) year would enable the allocation of water volumes necessary to irrigate crops in drier than average years under current conditions (Assumption 4). D1 annual is the total annual rainfall value that is exceeded in 90% of years. D4 monthly rainfall values, when summed, were roughly equivalent to this D1 annual rainfall.

3. That the selection of weather data from sites with high evaporation levels can be used to make water allocations that will account for increased evaporation levels in the future (Assumption 5). Implicit in this assumption is that the effects of climate change will lead to future average climatic conditions with higher evaporation values than historic conditions.

METHOD –CALCULATIONS AND DATA SOURCES

Briefly, the Tindall method subtracts monthly rainfall from monthly pan evaporation levels corrected by a crop factor. If rainfall exceeds crop factor-adjusted pan evaporation, no irrigation is required. If adjusted pan evaporation exceeds rainfall, the deficit in volume of irrigation required is corrected for foliage projected cover and the irrigation-delivery efficiency value.

Calculations in the model are based on:

1. Calender month (Gregorian calendar) time units.
2. Annual rainfall of 655 mm per year.
3. An average monthly crop factor.
4. Average monthly pan evaporation.
5. For annual crops, it was assumed that the crop was sown on the first day of the sowing month and harvested on the last day of the harvest month.

EXAMPLE ESTIMATE FOR A MONTH'S ALLOCATION (OCTOBER) FOR MANGOES

An example of the workings of the method is provided for a single month (October) for a mango crop, with a crop factor of 0.7 in that month (Table 3). Monthly D4 rainfall for that month was 6.8 mm and average monthly E_{pan} was 292 mm. D4 monthly rainfall is defined as the monthly rainfall value that is exceeded in 60% of years. Total water use by the mango crop was estimated at 204.4 mm (from crop factor 0.7*monthly pan evaporation of 292 mm), which left 197.6 mm for irrigation after correcting for rainfall, and averaged 6.4 mm a day.

As seventy percent of the ground was covered by mature mango trees in this example (FPC value), the 198 mm of required irrigation was reduced by 30% to 138 mm. Units were converted from mm to ML/ha where (1 000 000 L = 1 ML and 100 mm/ha = 1 ML/ha); therefore the total irrigation requirement was 1.38 ML/ha.

Foliage projected cover values were used to represent both the effects of differing tree density and tree age. For example, lower values would be used on newly-established trees or trees at lower densities.

This value was finally adjusted upwards for the irrigation efficiency of the delivery system (mini-sprinklers were assumed to have 85%, as 15% was estimated to not reach tree roots) to provide a total of 1.63 ML/ha for the month of October. The complete spreadsheet for this example for all 12 months is presented in Appendix 2.

Table 3. Example of spreadsheet calculations for a mature (70% ground cover, 200 trees/ha) mango orchard for the month of October

Input	Equations and abbreviations	Values	Explanation of each step
Month		Oct.	
Number days per month		31	
Crop factor	CF	0.7	Crop factor of 0.7 for October
Rainfall[1] (mm/month)	Rain	6.8	October monthly D4 rainfall of 6.8 mm
Mean evap. (mm/month)	Epan	292.0	October Epan of 292 mm
Crop water req. (mm/month)	CFxEpan	204.4	0.7x292 = 204 mm
Crop irrig. req. (mm/month)	(CFxEpan)-Rain	197.6	204.4 - 6.8 = 197.6 mm
Crop irrig. req. (mm/day)	((CFxEpan) - rain)/number of days	6.4	197/31 = 6.4 mm/day
Water requirement/ha section			
Foliage projected cover (FPC[2]) (%)	70	70	Crop covers 70% of ground
Min. water req. (mm/month)	FPCxCrop Irrig. Req (0.7x197.6)	138.3	mm/month
Min. water req. (ML/ha/month)	((CFxEpan)-Rain)/(10000/1000000)xFPC	1.383	((197.6x10000)/(1000000))x0.7 = 1.383
Irrigation efficiency (%)	85	85	85% irrigation efficiency for sprinkler
Final water requirement (ML/ha/month)		1.63	(1.383)/(85/100) = 1.63

[1]monthly D4 rainfall, [2]FPC = foliage protected cover, the area of ground coverage of a crop by percentage; for example, 70% = 70% of ground covered by crop, 30% bare non-crop area.

EXAMPLE OF AN ESTIMATION FOR YEARLY ALLOCATION FOR MANGOES

Table 4 shows the monthly totals of irrigation requirements as calculated in Table 3. From December to March, no irrigation is required, but from April to November, irrigation is required. Adding these monthly values gives a total of 8.6 ML/ha, which is the value estimated for mature mango trees in the water plan (Anon 2009b) (Appendix 5).

Table 4. Monthly and yearly totals of irrigation volume (ML/ha) estimates from the methods used in Table 3

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
ML irrigation	0.00	0.00	0.00	0.60	0.59	0.97	1.05	1.22	1.55	1.63	0.96	0.00	8.6

BASIS FOR CALCULATIONS - SOURCES OF WEATHER DATA

A number of weather data sources were used in the method (Table 5).

D4 monthly rainfall data was collected at the Katherine Experimental Farm (1944-68, station no. 14904) (Table 5). The sum of all D4 months gave an annual rainfall of 655 mm. These D4 monthly values were selected for use in the method to estimate allocations for annual rainfall at a level similar to that of a D1 year for Katherine of 636 mm (Katherine Council, station no.14902, see Appendix 4 for further details) as the allocation method required monthly rainfall averages. D1 annual rainfall is defined as the total yearly rainfall value that is exceeded in 90% of years.

Average monthly values for pan evaporation were sourced from records collected by the CSIRO at the Katherine Research Station (1974-81) (Table 5). Pan evaporation levels were recorded at the Katherine Experimental Farm, but the records were not readily available.

Table 5. The D4 monthly rainfall (mm) and monthly average pan evaporation (mm) values used in the allocation method spreadsheet

Data	Jan	Feb	Mar	Apr	May	June	July	Aug	Sep	Oct	Nov	Dec	Total
D4 monthly rainfall[1]	170	167	109	1	0	0	0	0	0	7	74	128	655
Pan evaporation[2]	194	156	173	186	180	169	182	212	235	292	272	242	2496

[1] Source, BOM Katherine Experimental Farm (14904) 1944 to 1968, annual rainfall of 655 mm.

[2] Source, CSIRO Katherine Research Station records 1974-81 (Williams et al. 1985).

BASIS FOR CALCULATIONS - CROP FACTORS

Crop factors were from published literature and local industry representatives. The sources of crop factors used to calculate water allocation for the crops cited in the water plan (Anon 2009b) are provided in Appendix 5.

BASIS FOR CALCULATIONS - IRRIGATION EFFICIENCIES

The efficiency at which an irrigation system applies water to a soil varies with the type of system and can be influenced by the time of day the crop is irrigated, the presence or absence of mulch and weather conditions. Application efficiency is the measure of water received at the root zone in relation to the amount of water pumped by the irrigation system. The difference between the two amounts is made up of losses to evaporation, surface runoff, percolation beyond the root zone and leaks in the delivery system. Values for irrigation efficiency of common systems in Katherine are shown in Table 6.

Table 6. Irrigation efficiency values for four delivery systems used in the method

Type	System	Efficiency value (%)	Efficiency range (%)and source
Moving	Traveller or water cannon	75	65-75 (Solomon 1993)
	Centre pivot	85	75-90, (Solomon 1993)
Stationary	Sprinklers	85	Solid set 70-80, (Solomon 1993)
	Micro sprinklers	85	Source unknown
	Drippers or tape	90	75-90, (Solomon 1993)
	Buried tape or tape below mulch	95	Source unknown

The application efficiency values used for specific crops in the spreadsheet were selected on the basis of which application system was most commonly used in the Katherine region. The efficiency values used were for broad-acre crops in the Katherine region grown under centre pivots e.g. maize, 85%; crops irrigated by covered tape e.g. melons, 95%; and tree crops, such as mangoes, on micro sprinklers, 85%.

APPRAISAL OF THE METHOD

This Section comments on aspects of the Tindall method with the view to improve estimates of crop irrigation requirements for use in future water allocation planning.

A number of aspects of the Tindall method can be improved for use in other districts, particularly in the technical methods employed and the assumptions adopted.

TECHNICAL METHODS

A number of technical methods would affect the accuracy of crop irrigation volume estimations, including the following:

1. The Tindall method was evaporation-based and used specific pan evaporation records but did not include the use of a pan coefficient (K_p). Pan evaporation values are typically higher than ET_o values, but can be successfully corrected using a pan coefficient (K_p) (Allen et al. 1998). For example, the pan evaporation from June to August at Tennant Creek required a K_p value of 0.56 to provide similar values to meteorologically calculated ET_o (Chiew et al. 1995). When pan evaporation data was used to estimate crop irrigation volumes for water plans in South Australia (Skewes 2008), $ET_{o\ pan}$ was calculated using K_p values recommended by Allen et al. (1998). As the Tindall method used E_{pan} values directly, the results of the method cannot be described as being equivalent to $ET_{o\ pan}$.

   K_p values differ among individual pan locations due to the effects of local wind and advection levels (Rana and Katerji 2000). However, mean K_p levels have been reported for some relevant environments and include 0.7 for semi-arid environments (Jensen et al 1990) and values from ~0.8 at 60% RH to 0.55 at 20% RH for wet and dry seasons, respectively (Perrier and Hallaire 1979). Allen et al (1998) also provided default K_p values for use in estimations. The minimum K_p value for a Class A pan was 0.85. An evaluation of earlier FAO recommended K_p values (range 0.55-0.85) in a tropical environment found that these values were conservative as the recommended values often overestimated actual K_p by 10-15% (Pereira et al. 1995) [D], which indicated that they may be used without under-estimating ET_o. A prior summary of Katherine pan evaporation levels used a default K_p value of 0.75 for the estimation of ET_o pan across seven meteorological stations in northern Australia, including records for the Katherine Research Station (Cook and Russell 1983).

   The use of a K_p value would have reduced pan evaporation levels used in the method by a minimum of 15% on the basis of the examples provided here. This highlighted the need for K_p values to be used in pan evaporation-based calculations to prevent overestimation of water requirements.

2. A source of pan evaporation data with high values was used; however, it is unclear if these high values related to higher actual (crop and environment) evaporation levels. Weather data was sourced from two sites in Katherine, the Katherine Research Station (pan evaporation) and Katherine Experimental Farm (rainfall). The pan evaporation records from the Katherine Research Station had higher evaporation values than recorded at another Katherine site, the Katherine Aviation Museum (Table 7). The selection of pan evaporation data from the Research Station was deliberate in order to represent the potential effects of climate change leading to increased temperatures and evaporation and so irrigation requirements (pers. comm. M. Bennett). Values for the Katherine Research Station ranged from -2% to 26% (11.7% on average from June to November) higher than at the Katherine Aviation Museum for the months of June to November when the majority of dry season crop irrigation occurs.

Table 7. Pan evaporation values (mm) from the Katherine Aviation Museum and Katherine Research Station on monthly and annual average with the difference between the two records indicated

Katherine	Jan	Feb	Mar	Apr	May	June	July	Aug	Sep	Oct	Nov	Dec
Aviation Museum[1]	164.3	148.4	176.7	186.0	173.6	148.8	167.4	198.4	228.0	244.9	229.4	192.2
Research Station [2]	194	156	173	186	180	169	182	212	235	292	272	242
Difference (%)	18.1	5.1	-2.1	0.0	3.7	13.6	8.7	6.9	3.1	19.2	18.6	25.9

[1] Source, BOM Katherine Aviation Museum (14903) 1999 to 2010. [2]Source, CSIRO Katherine Research Station records 1974-1981 (Williams et al. 1985).

A comparison of differing pan evaporation data from three different sites (Jabiru, Manton Dam and Darwin) within the same region found that calculated evaporation levels were very similar for the three sites (Vardavas 1987) ^{E}. Solar radiation had the largest effect on evaporation levels and this did not differ greatly among the three sites. The distance between the three sites in that study (Jabiru, Manton dam and Darwin) was much greater than the distance between the two sites where pan evaporation was collected in Katherine, making it unlikely that local radiation levels were responsible for the differing pan evaporation levels. The differences indicate the need for a pan coefficient (K_p) due to the widely acknowledged effect of site condition and pan placement on pan evaporation readings (Allen et al. 1998), or else may suggest that actual evaporation was higher in the years 1974 to1981 than in 1999 to 2010.

The use of the Katherine Research Station pan evaporation record would have resulted in pan evaporation levels that were 12% higher for most of the dry season irrigation period than that observed at the Katherine Aviation Museum over a slightly longer period of years. It is unclear if the Katherine Research Station data represented a period of higher evaporation. An improvement for future water allocation methods, if they are pan evaporation-based, would be to use pan evaporation data records that have a consistent relationship to calculated evaporation levels as described by Vardavas (1987) or to choose pan evaporation records that cover documented dry and wet decades to limit potential bias from the use of selected periods of records.

3. Corrected pan evaporation can relate well to ET_o, but not at high pan evaporation values, as the relationship is not linear in the upper ranges of the relationship (Chiew et al. 2002). Average daily pan evaporation values for October and November of 9.4 and 8.8 mm/day, respectively were used in the model, but the relationship between pan evaporation and actual ET_o was probably inaccurate at these pan evaporation levels, due to physiological adaptations by plants, reducing water use under very high evaporative demand. The relationship is expected to be curvilinear.

   An investigation should be made of the relationship between E_{pan} and ET_o at high evaporation levels.

4. Assessment of ‘effective’ rainfall. Effective rainfall is defined as rainfall which is useful directly and/or indirectly for crop production (Dastane 1978). Small amounts of rain are not effective in irrigating crops, particularity when falling on dry soil. The method included some months with less than 10 mm and 74 mm for the month of November, following the dry season. A proportion of the initial wet season rains is likely to be ineffective (Table 5).

   An evaluation of the effect of excluding non-effective rains to improve the accuracy of irrigation volume estimations may be useful.

5. Calculation of crop available water. Each month was treated independently in the Tindall method. Water in the soil may be available to plants in the month after the cessation of the wet (especially for established deep rooted crops). An assessment of the carry over of soil water in some months could be used to improve the accuracy of irrigation volume estimates.

6. Improved accuracy of crop factors. In some cases, there was no information on crop factors for some crops. In such cases, extrapolations from other similar crops had to be made. The accuracy of crop factors developed for crops in other regions remains unclear. It is acknowledged by many workers that determining accurate crop factors or coefficients is difficult (Rana and Katerji 2000). Crop factors vary with different growth stages, varieties, seasons and sites (Stanghellini et al. 1990). There is a need to determine crop factors for crop growth stages and population densities. For some crops, such as mahogany, no crop factors were available and estimates were made. Unknown crop factors or coefficients for crops present particular difficulties for water allocation methods (Skewes 2008). In addition, with a few exceptions, there is an absence of crop factors or coefficients that have

been determined through structured experiments in the NT. This is despite the dry season in the NT placing crops under high levels of evaporative demand that may differ from more temperate areas where crop factors were determined.

The determination of crop factors or coefficients for important crops in the NT would improve estimation of crop irrigation requirements. Alternatively, if accurate crop water requirement information is not available, a reasonable approach may be the consideration of non-crop-based allocations, such as using conservative area- based allocations, such as 4 ML/ha.

ASSUMPTIONS

The method included a number of stated and un-stated assumptions that could be validated or justified. They are summarised below:

1. Pan evaporation data from a site with high evaporation levels was included in the Tindall method so that anticipated increases in evaporation due to climate change could be incorporated to provide water allocations suitable for those future conditions. Hence, it was assumed that the level of evaporation from the Katherine Research Station site (10% higher annually than another site) would represent future evaporation levels.

   A study of potential climate effects on Australian rangelands, including areas of the NT, concluded there was not enough information on wind run and solar radiation to establish if a warmer drier climate would increase evaporative demand (McKeon et al. 2009) [F]. In other work, simulations were based on the assumption that ET_o increases would range from little to 6% by 2030 in the north and east of Australia, with the best estimate being a 2% increase (Pearce et al. 2007) [G]. Conversely, recent work comparing ET calculated using five methods for data from 1981 to 2006 in Australia, found that air temperature did increase, but changes in other key variables (net radiation, vapour pressure and wind speed) over the period, each reduced evaporation, resulted in an overall negative trend in potential evaporation (Donohue et al. 2010) [H]. Johnson and Sharma (2010) [I] also concluded from a study of pan evaporation trends in Australia that assumptions of increasing potential evaporation because of rising temperatures will need to be assessed in relation to the effects of changes in vapour pressure deficit and wind speed. Indeed, large studies have concluded that pan evaporation levels are declining in many areas, including north-west Australia, due to increasing cloudiness decreasing radiation (Roderick and Farquhar 2002; Roderick and Farquhar 2004; Jovanovic et al. 2008).

   Climate change and climate change predictions are complex and contentious issues. If future allocation methods include an assumption of increasing evaporative demand, it would be useful to quantify the level of increase which the allocation is meeting. This should include explicit statements on whether allocation estimates for contemporary production require a future proofing allocation. Alternatively, allocations could be adjusted in the future on the basis of actual changes.

2. Data was sourced from two different sites (Katherine Research Station and Katherine Experimental Farm) for use in the Katherine method. In one case, data was selected on the basis of comparative results from a third site (Katherine Council), which in effect created a ‘hybrid’ Katherine climate for use in the allocation method. For example, the annual D1 rainfall from one site was similar to the D4 monthly rainfall at another site. Implicit was the assumption that this hybrid climate represents the behaviour of the future climate on which crop irrigation water use was based.

   If data comes from different sites, an examination of the representative value of this combination would be important for assessing the accuracy of irrigation volume estimations.

3. The method assumed that evaporation across the allocation district would be similar to that calculated for the sites where weather data was collected. Due to the importance of radiation level on evaporation, other work in the NT has shown that this approach has some basis (Vardavas 1987)[F]. Other work in Australia also agreed with this finding (Humphreys et al. 1994).

   Some work may be required to investigate the level of variation in evaporation or ET_o across regions where there is evidence factors affecting evaporation or ET_o differ significantly. The level of rainfall, for example, has large effects on pan evaporation values (Jovanovic et al. 2008). However, this area will be challenging as rainfall is variable in this environment. Rainfall can vary by 36% each month in the Darwin area during the wet season and variability is particularly high at the beginning and end of the wet season in the region (Williams et al. 1985; Mollah 1986; Mollah and Cook 1996). In addition, there is a high degree of variability in the spatial distribution of rainfall in the Australian tropics (Cook and Heerdegen 2001).

   Should an accuracy of plus or minus 10% in evaporation across a region, for example, be required for use in calculating irrigation volumes, actual year to year variability may be higher than 10%. Thus chosen levels of accuracy will need to account for large annual variability and so should be based on long-term data.

ADVANTAGES

The Tindall method discussed here has a number of limitations, but also has a number of strong advantages, including:

1. It is flexible and was successfully used on a wide range of crops and plant population densities.

2. The use of an evaporation approach in the method was advantageous as pan evaporation can be well related to ET_o levels, especially over longer periods (three to 10-day intervals) when appropriate pan coefficients are used (Chiew and McMahon 1992; Chiew et al. 1995).

3. Using farmer-generated crop factors kept the participants engaged with the allocation process.

FUTURE WATER PLANNING

Lessons learnt from the Tindall method could be used to develop improved methods for allocation planning in water plans in other areas of the NT. Pan evaporation was used as surrogate for crop ET_o levels, but the use of pan evaporation levels to represent crop water use presented a number of technical issues due to lack of a pan coefficient and selection of data from different sites and periods. If pan evaporation methods are being considered for use in water allocation planning, it may be necessary to compare ET_o calculated from meteorological data (Allen et al. 1998) with that calculated from pan data.

This study highlighted the need for ET_o or ET_{crop} studies on crops in the NT environment. In addition, where information is required for water allocations, it would be useful information on:

1. Calculated[A] ET_{crop} values for the dry season when the majority of irrigation occurs.

2. The use of weather station data to calculate ET_o to assess estimated requirements within an allocation area (between farms) and the variability in ET_o or to validate region-wide modelled in $ET_{o.}$

Regardless of the method used to calculate crop water requirements, the identification of error terms or confidence intervals for predicted crop water requirements would also be useful.

It would also be appropriate to recommend that an independent review of any future crop irrigation volume estimation method be made prior to implementation to ensure that the appropriate methods and data sources have been used.

CONCLUSIONS

The Tindall method used for the Water Allocation Plan for the Tindall Limestone Aquifer, Katherine was successful in calculating irrigation volumes for a wide variety of crops and the allocation enabled producers to ascertain water supplies for continued production, which was important.

There were a number of areas where the Tindall method appeared to have contributed to the calculation of higher than required allocations. In particular, the use of selected pan evaporation data on the basis of climate change and lack of a pan coefficient would lead to larger than required allocations. As the Tindall Limestone Aquifer is fully allocated, over-allocation could restrict industry expansion.

There is a need to further develop methods for establishing crop irrigation requirements in the NT that are accurate in order to enable the optimal use of water resources in future water planning processes.

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LIST OF SOURCES AND PROCEDURES USED TO CALCULATE EVAPORATION OR ET_O

[A] FAO 1998 Penman-Monteith method from Allen et al. (1998)

[B] Modified Penman (1948) with wind function of Watts and Hancock (1985).

[C] FAO 1992 Penman-Monteith, Smith et al. (1992).

[D] Modified Penman equation with values from Doorenbos and Pruitt (1975) as described in Pereira et al. (1995).

[E] Modified from Penman (1948) as described in Vardavas (1987).

[F] Evaporation as a function of solar radiation and VPD and as described in Hall et al. (1998)

[G] ET calculated using the Complementary Relationship Areal Evaporation model from Morton (1983).

[H] Compared five methods modified Penman, Priestly-Taylor, Morton point, Morton Areal and Thornwaite formulations; see Donahue et al. (2010) for details.

[I] PenPan model of Rotstayen et al. (2006) with modified wind functions, see Johnson and Sharma (2010).

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APPENDICES

APPENDIX 1. CALCULATION OF EVAPOTRANSPIRATION

The following terminology and abbreviations are sourced primarily from Allen et al. (1998), there are also many alternative methods to describe ET (see Rana and Katerji 2000; Shuttleworth and Wallace 2009) but the methods described by Allen et al. (1998) are the accepted standard for estimations based on meteorological data only.

A range of methods is used to estimate ET for a crop (Allen et al. 1998; Rana and Katerji 2000). Some of the commonly used methods for crops to calculate or estimate ET are:

1. The direct measurement and calculation of a crop ET (ET_{crop}) (which is also termed actual ET in some cases) can be made using weighing lysimeters (see Rana and Katerji 2000).

2. The calculation of ET_{crop} is also determined with the use of energy balance, Bowen ratio, Eddy covariance, sap-flow and chamber measurement methods (Rana and Katerji 2000). These require specialised equipment, expertise and may require the definition of unique evaporation parameters for each crop species and stage of growth (Allen et al. 1998; Rana and Katerji 2000).

3. The estimation of ET by using meteorological data only can be made by first calculating ET for a hypothetical reference crop (ET_o), (often grass), from weather data (net radiation, soil heat flux, air temperature, wind speed, saturated and actual vapour pressure) (Allen et al. 1998), then multiplying this by a crop coefficient to estimate ET_{crop}. Methods to calculate ET_o using limited weather sources are also available (Allen et al. 1998). The calculation of ET_o uses established formulas[A] as described by Allen et al (1998). This approach is also termed the estimation of potential ET (abbreviated as PET). This approach allows crops to be compared with the reference level of ET thereby avoiding the need to separately calculate ET_{crop} values for each crop and growth stage, with the main requirement being the appropriate meteorological data.

APPENDIX 2. DEVELOPMENT OF THE IRRIGATION VOLUME ESTIMATION METHOD

Table 1. A schedule of versions (Ver.) of the estimation method using mango cv. Kensington Pride (KP) as an example crop with developing versions, changing crop factor, rainfall and pan evaporation values

						Crop factor																	
Date	Ver.	Author	cv.	Tree space (m)	Age (years)	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Rain (mm)	Pan evap (mm)	Irri. effi. (%)	FPC (%)	Ann. all. ML/ ha	Changes mapped
1991	1	Y. Diczbalis	KP	10 X 5	7+																		Original spreadsheet
2003	NR*	C. Wicks	KP	10 X 5	7+	0.5	0.5	0.5	0	0	0	0	0.7	0.7	0.7	0.7	0.5	1012	2493	85	65	4.43	
2007	2	M. Bennett (MB)	KP	10 X 5	7+	0	0	0	0	0	0	0.7	0.7	0.7	0.7	0	0	960	2173	85	70	4.32	Agnote D14, long term weather, machine pruning
2007	3	MB	KP	10 X 5	7+	0	0	0	0	0	0	0.7	0.7	0.7	0.7	0	0	655	2493	85	70	5.25	D1 rainfall, hotter temp. and increased evaporation
	3	presented to KPIAF*																					
2007	3i	Industry	KP	10 X 5	7+	0	0	0	0	0	0.7	0.7	0.7	0.7	0.7	0.7	0	655	2493	85	70	7.19	Length of flowering to fruiting season
2007	3i	Industry	KP	10 X 5	7+	0	0	0	0	0	0.7	0.7	0.7	0.8	0.7	0.7	0	655	2493	85	70	7.38	Peak cell expansion
2007	3i	Industry	KP	10 X 5	7+	0.4	0.4	0.4	0.4	0.4	0.7	0.7	0.7	0.8	0.7	0.7	0.4	655	2493	85	70	8.58	Wet season supplementary, pre-flowering
2007	NR	MB/Industry	KP	10 X 5	7+	0.4	0.4	0.4	0.4	0.4	0.7	0.7	0.7	0.8	0.7	0.7	0.4	655	2493	85	70	8.58	

Expected KP yield = 7 t/ha changes highlighted

KPIAF (Katherine Plant Industry Advisory Forum); NR (NRETAS)

Industry input into allocation planning process

A KIPAF meeting on 29 May 2007 discussed changes to the method used by NRETAS. Minutes of this meeting are on the NTG website (Anon 2007). A crop water use method workshop was held in September 2007, where growers of peanuts, maize, hay, pasture, melons, pumpkins, mung beans, bananas, mangoes, onions, avocados, citrus, forage sorghum and leucaena had an input in management and water use figures.

APPENDIX 3. AN EXAMPLE OF A CROP WATER USE SPREADSHEET

Table 1. Worksheet examples for seven-year-old mango trees (10*5 m spacing, 200 trees/ha), management to account for paclobutrazol treatment and supplementary irrigation during dry breaks in the wet season, crop yield 7 t/ha

Location:	**KT region**					**(200 trees/ha)**								
Crop:	Mango (10 x 5 m spacing)					Depends on whether trees are paclobutrazol treated or not								
Worksheet:	MB 2008													
		Jan	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**	**Total**
Days per month		31	28	31	30	31	31	31	31	30	31	31	31	
Crop Factor		0.4	0.4	0.4	0.4	0.4	0.7	0.7	0.7	0.8	0.7	0.7	0.4	
D1 rainfall (mm/month)	KT	170	167	109	1	0	0	0	0	0	7	74	128	655
Mean evaporation (mm/month)		194	156	173	186	180	169	182	212	235	292	272	242	2493
Crop water requirement (mm/month)		78	62	69	74	72	118	127	148	188	204	190	97	1429
Crop irrigation requirement (mm/month)		0	0	0	73	72	118	127	148	188	198	117	0	1042
Crop irrigation requirement (mm/day)		0.0	0.0	0.0	2.4	2.3	3.8	4.1	4.8	6.3	6.4	3.8	0.0	
Water requirement/ha														
Irrigation efficiency (%)	85													
		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	
Cover (%)		70	70	70	70	70	70	70	70	70	70	70	70	mature orchard
Minimum water requirement (ML/ha/month)		0.00	0.00	0.00	0.51	0.50	0.83	0.89	1.04	1.32	1.38	0.82	0.00	7.3
at (85%) irrigation efficiency		0.00	0.00	0.00	0.60	0.59	0.97	1.05	1.22	1.55	1.63	0.96	0.00	8.6

APPENDIX 4. RAINFALL RECORDS USED IN THE VOLUME ESTIMATION METHOD

The method used an annual rainfall value of 655 mm based on the sum of values for decile four months from the Katherine Experimental Farm (Table 2 below). This source was used as it provided monthly values for use in calculations that are similar to an annual D1 year for Katherine (Table 1 below).

Table 1. Long term mean monthly rainfall (mm) records for Katherine Council[1]

	Jan[2]	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
Lowest record	50.9	10.1	0	0	0	0	0	0	0	0	1.3	35.3	439.5
1st decile	103.3[2]	78.0	23.9	0.0	0.0	0.0	0.0	0.0	0.0	0.7	25.9	83.9	636.0[3]
2nd decile	134.0	123.5	45.5	0.0	0.0	0.0	0.0	0.0	0.0	3.2	44.8	109.8	745.1
3rd decile	169.5	146.0	79.5	0.0	0.0	0.0	0.0	0.0	0.0	5.1	56.1	125.7	828.3
4th decile	190.6	187.3	103.1	4.7	0.0	0.0	0.0	0.0	0.0	9.7	66.0	155.4	893.5
5th decile	207.9	204.4	131.0	8.9	0.0	0.0	0.0	0.0	0.0	15.9	74.2	176.8	968.8
6th decile	233.8	238.3	158.2	20.4	0.0	0.0	0.0	0.0	0.5	22.4	86.8	199.9	1022.9
7th decile	267.5	268.0	209.8	36.8	0.8	0.0	0.0	0.0	3.1	34.0	107.3	240.8	1115.3
8th decile	329.2	307.7	239.4	57.5	5.6	0.2	0.0	0.0	6.3	56.3	133.6	280.9	1177.1
9th decile	390.2	352.5	317.9	96.7	20.2	3.5	0.0	0.0	21.0	76.8	166.3	335.3	1289.3
Highest record	704.6	492.7	647.2	212.9	85.6	54.1	48.0	19.3	90.9	148.8	355.6	752.1	1575.4
Average record	234.3	215.1	159.9	32.7	5.6	2.0	1.0	0.5	5.9	29.0	88.6	197.0	968.9
Number of years of data	127	125	127	127	127	127	126	125	125	127	129	127	

[1] Source BOM (station number 14902) for records between 1873 and 2005

[2] Monthly D1rainfall values; D1 monthly rainfall is defined as the total monthly rainfall value that is exceeded in 90% of years

[3] Annual D1 rainfall values; D1 annual rainfall is defined as the total annual rainfall value that is exceeded in 90% of years

Table 2. Long term mean monthly decile four rainfall (mm) records for the Katherine Experiment Farm[1]

Statistic description	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual	Sum of monthly values
Lowest	67.6	27	16.2	0	0	0	0	0	0	0	10	48.5	406.9	169.3
1st decile	115.6	67.4	27.7	0	0	0	0	0	0	0.6	21.5	64.3	611.2	297.1
2nd decile	141.2	110.9	66.6	0	0	0	0	0	0	1.8	29.1	87.1	705.6	436.7
3rd decile	150.7	138.6	93.3	0	0	0	0	0	0	3.2	46.3	113.6	742.1	545.7
4th decile	169.8	166.7	109.1	1.4	0	0	0	0	0	6.8	73.6	127.6	814.4	655
5th decile	184.9	182.1	134.8	7.9	0	0	0	0	0	14.9	75.5	158.8	866.8	758.9
6th decile	220.4	204.4	145.4	20.2	0	0	0	0	0	19.9	91.4	170	900.6	871.7
7th decile	246.4	232.7	190.4	50.5	1	0	0	0	0.4	31.8	98.2	179.5	925.3	1030.9
8th decile	263.3	264.3	216	99.1	14.1	0	0.1	0	1.8	41.4	118.9	233.8	1033.9	1252.8
9th decile	337.7	271.7	230.6	138.8	17.7	0	1.7	0.4	7.2	79.8	146.3	284.5	1213.7	1516.4
Highest	411	320.6	477.7	194.3	35.3	8.4	42.4	26.7	53.9	158.4	168.2	398.8	1302.3	2295.7
Average	207.8	178.8	152.9	43.6	5.6	0.4	2.1	1.2	3.9	28.2	79.8	165.9	866.1	870.2
Number	25	23	24	24	24	24	24	24	24	24	23	25	22	

[1] Source BOM (14904) for available data between 1944 and 1968

[2] Monthly rainfall D4 values D4 monthly rainfall is defined as the total monthly rainfall value that is exceeded 60% of years.

APPENDIX 5. SOURCE OF CROP FACTORS USED IN THE TINDALL METHOD (ANON 2009B)

Table 1. Perennial crops, some values were used from Anon (2010) [1] or from local sources

Crop type	Stage of growth	ML/ha/year	Crop factor	Reference or source
Avocados	Mature	9.6	0.4 -0.8	Adapted from discussions PM and BS (CF 0.6 - 0.85)1 (K_c 0.6 – 0.85)[2]
Bananas	Mature	19.6	1.0	Adapted from 2003 model (CF 1.0 – 1.1) (K_c 1.0 – 1.20)
Citrus	1 year	0.3	0.8	Adapted from discussions BD and BS, 2003 model and Dept trials (CF 0.65 – 0.70) (K_c 0.65 – 0.70)
	2 years	1.6	0.8	
	3 years	3.6	0.8	
	4 years	5.7	0.8	
	Mature	9.0	0.8	
Leucaena	1 year	2.1	0.8	Adapted from discussions MP (2.2 Ml/ha per 4 months QLD)
	2 years	4.1	0.8	
	3 years	6.7	0.8	
Mahogany	1 year	1.3	0.4 - 0.7	Adapted from discussions DR
	2 years	2.6	0.3 - 0.4	
	3 years	2.8	0.0 - 0.2	
	4 years	0	0.0	
Mangoes	1 year	0.3	0.7 - 0.8	Adapted from discussions PM, BD, DH, BS, 2003 model
	2 years	0.9	0.7 - 0.8	
	3 years	2.0	0.7 - 0.8	
	4 years	3.1	0.4, 0.7 - 0.8	
	5 years	4.8	0.4, 0.7 - 0.8	
	6 years	7.4	0.4, 0.7 - 0.8	
	Mature (7+ years)	8.6	0.4, 0.7 - 0.8	(7 t/ha)
Pawpaws	Mature	18.5	1.0	MB (was changed to 11.5 ML and CF 0.8)

Abbreviations for sources: PM = Peter Marks, MB = Mal Bennett, BS = Bob Sandrey BD = Bill Davy MP = Mick Pierce DR = Don Reilly DH = David Higgins

[1] K_c values taken from FAO56 (Allen *et al.* 1998) and fitted to Southern Hemisphere crop calendars

Table 2. Annual crops, some values were used from Anon (2010) [1] or from local sources

Crop Type	Growing period	ML/ha/year	Crop factor	Reference or source
Rhodes grass	March-Dec.	12.3	0.7	MB (K_c 0.75 low inputs)
Forage sorghum/millet	April-Nov	10.5	0.8	MB, adapted from discussions AS and 2003 model (K_c 0.85 medium inputs)
	May-Dec	10.7		
Lawn	March-Nov	3.9 (0.5 ha)	0.4 - 0.6	MB (CF 0.4 – 0.6 Improving Irrigation Efficiency – principles and practices)
Lucerne	March-Nov	10.3	0.8	MB (K_c 0.85 medium inputs)
Maize	April-Aug	5.8	0.6 - 0.8	Adapted from discussions AS, 2003 model and Dept trials (10 t/ha)
Melons	March-May	2.9	1.0	Adapted from 2003 model (CF 0.75 – 1.0) (K_c 0.44, 0.87 – 0.98)
	April-June	2.9	1.0	
	May-July	3.0	1.0	
	June-Aug	3.4	1.0	
	July-Sept	3.8	1.0	
	Aug.-Nov	4.5	1.0	
	Sept-Nov	3.8	1.0	
Nursery shade house		1.74 (0.1 ha)	1.0	MB
Onions	Apr.-Aug	5.4	0.7	Adapted from discussions JS (K_c 0.7 May -1.05 Sep)
	May-Sept	5.9	0.7	
Peanuts	Mar.-Aug	7.2	0.7	Adapted from discussions AS (5 t/ha)
	April-Sept	7.9	0.7	
	May-Oct	8.8	0.7	
	May-Nov	10.1	0.7	
Potatoes	16 weeks	4.7	0.9	MB (CF 0.8 - 1.0)
	18 weeks	5.8	0.9	MB (K_c 0.5 - 1.15)

Abbreviations for sources: JS = John Shaw AS = Andrew Simon

[1] K_c values taken from FAO56 (Allen et al. 1998) and fitted to southern hemisphere crop calendars