EXECUTIVE SUMMARY

1. Motivation

Good estimates of tree water-use and the impacts thereof are critical to the forestry industry and equitable water supply to all South Africans. In this study, state-of-the-art technology was applied to quantify the water-use of trees and assess whether there was a potential long-term impact on water resources.

2. Project objectives

The specific objectives of the project were to:

- quantify the long-term effects of commercial forestry species on deep soil water profiles, streamflow and evaporation;
- describe the controlling environmental and soil water processes which allow for total evaporation to exceed the annual rainfall;
  provide a modelling framework for the catchment water balance to improve stream flow predictions and specifically low flows; and
- extend the hydrological record of the Two Streams catchment experiment to provide a long-term database of the catchment hydrological variables for future modelling studies.

3. Background

The Two Streams catchment experiments have been used over the last nine years to study the impact of trees on hydrological processes. Burger (1999), for example, estimated total evaporation using the Bowen ratio energy balance method and showed that annual total evaporation exceeded annual rainfall when measured over *Acacia mearnsii* at Two Streams during the exponential growth phase. This suggested that either the instruments used were providing incorrect results, or that tree roots were accessing groundwater and depleting soil water reserves from within the deep soil profile. Everson *et al*. (2008) showed the significant impact that riparian zone management can have on the hydrology of the catchment.

Currently the regulation of water-use by forestry is based on estimates of plantation water-use over entire rotations at quaternary catchment scale (Gush *et al*., 2002), which are average values that are not site or age specific. In addition the model used, Agricultural Research Catchment Unit (ACRU), did not account for soil water depletion at depths greater than 1.2 m. Gush *et al*. (2002) concluded that our understanding of the hydrological processes with regard to the water-use of trees from deep soil profiles was inadequate.

These experiments provided a good opportunity for studies to extend our understanding of some of the hydrological processes associated with afforestation such as low flows and deeper soil water dynamics.

4. Methods

The research catchment was situated at the Mistley-Canema Estate (Mondi Forests) approximately 70 km from Pietermaritzburg. The catchment had been fallow for two years since 2004 and was planted to a new rotation of *Acacia mearnsii* trees in 2006. This provided an opportunity to monitor the water balance of the catchment during the establishment of the trees and the initial growth phases of the plantation crop for a two and a half year period.

4.1 Tree growth

Tree heights were measured along the path of the scintillometer at 30 points through the plantation. To accurately monitor the high growth rate of the trees, heights were measured at monthly intervals.

Leaf area index (LAI) of the tress was measured using a LiCor LAI-2000 leaf area meter. When the trees reached two metres, a second LAI-2000 leaf area meter was run in combination with the first to capture above and below canopy radiation simultaneously and combined with the first to calculate LAI.

Root growth was assessed by hand auguring to depths of 4.8 m. Samples were collected and sieved in order to extract the root material.

4.2 General climatic variables

Campbell Scientific weather stations were used to monitor solar radiation, air temperature, relative humidity, rainfall, wind speed and wind direction. One station, historically used at Two Streams over Sugarcane, was maintained at the site for the long-term record. A new station was sited to conform specifically to the requirements of a short grass reference standard evaporation. A third station was mounted above the trees and, in addition to the standard weather station measurements, sensors for measurements of the soil heat flux and net radiation were included.

Rainfall was monitored at an additional two sites in the catchment using tipping bucket raingauges connected to event Onset Hobo dataloggers.

4.3 Evaporation

The shortened energy balance equation was used to estimate the daily total evaporation in the catchment from August 2006 to December 2008. Net radiation and soil heat flux were measured directly. Sensible heat flux was estimated using a Kipp and Zonen large aperture scintillometer (LAS) transmitter and receiver. The transmitter and receiver were mounted on towers that were extended as the tree height changed. The effective height of the LAS above the tree canopy was calculated at two-weekly intervals due to the fast growth rate of the trees.

4.4 Streamflow

- Streamflow was monitored continuously in the main catchment; initially using a 457.2 mm, 90° V-notch weir with a Belfort Streamflow recorder modified with an MCS 250-01 streamflow encoder. This was later replaced with an Ott Streamflow recorder and pressure transducer. A sieve was installed to prevent debris blocking the V-notch.

4.5 Soil water dynamics

Intensive soil water measurements were performed using various methods. Initially CS616 Water Content Reflectometer probes were used to capture the soil water changes while modified deep time domain reflectometer (TDR) probes were being developed. The CS616's were installed by digging a pit to a depth of 2.5 m and inserting the sensors at 0.4 m intervals to a depth of 2.4 m.

Time domain reflectometry probes operated with a Campbell Scientific TDR100 were designed for installation at depths in excess of 2.0 m. They were cylindrical in shape, had three short wave-guides and the head of the probe was moulded with a strong resin so that the probes could be hammered into the ground. They were installed at 0.4 m intervals to a depth of 4.8 m using a hand-auger.

- During the course of the project, in order to confirm volumetric water content results, watermark sensors manufactured by Irritol Corporation were installed near the cylindrical

TDR probes also to a depth of 4.8 m.

4.6 Water balance

A monthly water balance for the catchment was calculated based on rainfall, streamflow, evaporation and actual change in soil water storage to a depth of 2.4 m. The overall change in soil water storage was calculated as the residual of the water balance equation.

4.7 Hydrological modelling

The Water, Vegetation, Energy, Solute (WAVES) and revised Intermediate-Zone ACRU models were used to predict the soil profile water contents. The Intermediate-Zone ACRU model was also used to predict the streamflow in the catchment. The modelled results of soil profile water content and streamflow were compared to the measured values.

5. Results and discussion

Tree growth was consistent and did not fluctuate seasonally indicating that the trees were not stressed during drier months. Tree height growth over 30 months averaged 0.37 m month^{-1} or 4.5 m year^{-1} from planting to a height of approximately 11.2 m. Canopy leaf area measurements initially included a large contribution from tall weeds in summer 2006 to 2007. The weeds died off in winter 2007 and the LAI showed a steep rise to 2.5 in December 2007 when canopy closure was reached. Root samples were taken using a hand auger to a depth of 4.8 m in February 2008 and February 2009. There was a noticeable increase in the root mass (g kg^{-1} of soil) in 2009 at a depth of 3.2 m and roots were found at depths of 4.8 m.

The nine year average annual rainfall from 1999 to 2008 was 920 mm. The annual rainfall at the study site was highly variable with a range of 570 mm between the lowest and highest years (minimum = 659 mm and maximum = 1170 mm).

- Mean annual runoff (MAR) between 2001 and 2008 was 48 mm with an annual maximum of 91 mm in 2005 (when the mean annual precipitation (MAP) was 1139 mm) and an annual minimum

of 6.7 mm in 2003 (when the MAP was 659 mm). Streamflow was a relatively small fraction of the rainfall although this relationship changed in 2005 after clear-felling of the catchment. In 2001 to 2004 the average ratio was 0.03. After the catchment was clear-felled in 2004, the average ratio changed to 0.08.

The results from all the soil water methods were typical of a deep soil profile with high variability at the surface and less variability at depth. The soil profile was however driest at 1.6 m according to the cylindrical TDR probes and the Watermark sensors. Water content from 2.4 m to 4.8 m increased with depth. There was however, little or no recharge during the wet seasons which resulted in a steady reduction in volumetric water content to December 2008. The water content at 4.8 m was close to field capacity (45%).

The LAS estimates of daily total evaporation (ET_{LAS}) values ranged from 0 mm on rainy days to 6 mm on cloudless days for the first summer and 7 mm and 9 mm for the second and third summers respectively. On clear winter days the maximum total evaporation was 2.2 mm day^{-1} in 2007 and 2.4 mm day^{-1} in 2008. Monthly totals of total evaporation (*ET)* showed clear seasonal trends. Over the three-year period from 2006 to 2008 there was an exponential increase in the *ET* totals in the main growing period (October to December) from 305 mm, 334 mm and 417 mm for years 2006, 2007 and 2008 respectively. The 25% increase from 2006 to 2008 is ascribed to the high LAI (canopy closure) recorded in 2008.

The LAS estimates of total evaporation were verified using the Priestley-Taylor (1972) estimates of latent energy flux with an α (which represents the advective term) of 1.26. There was a significant (R^2 = 0.94) linear relationship between the daily ET_{LAS} and ET_{P-T} indicating that the trees at Two Streams were seldom stressed or subjected to advection. The Priestley-Taylor method therefore represented a simple and realistic descriptor of *A. mearnsii* water-use for trees up to three years old. This relationship may not be valid in other climatic areas where trees may experience water-stress.

Regression analysis between reference evaporation (ET_{sz}) and ET_{LAS} showed close agreement with a coefficient of determination of 0.85 and a slope of 1.04. Thus using a crop factor approach will explain approximately 85 % of the variation in daily tree evaporation. The daily crop factor from March 2007 to December 2008 showed large daily variations; however applying a 30 day moving average reduced this variation to average values of 0.8 in winter and 1.3 in summer.

The groundwater levels monitored at four boreholes in the catchment responded to low winter rainfall by dropping approximately 5 m. There was a noticeable difference in the recharge with distance from the stream with those boreholes closer to the stream responding first to the wet season. The delay between the start of the recharge in the centre borehole and the western borehole (most delayed) was approximately one month in 2008. Based on the south borehole with the longest record, the dry season water level dropped from 35 m below surface in 2007 to 36 m in 2008. This was interpreted to be a result of the impact of the trees on groundwater recharge.

An accumulated ET_{LAS} versus accumulated rainfall graph showed that from August 2006 to December 2008 the total evaporation exceeded the rainfall by 46%. Deviations from the 1:1 line (step changes) were evident during the winters of 2007 and 2008. These significant changes in slope of the rainfall – ET_{LAS} curve were a direct result of the continued high transpiration rates from the trees combined with the low rainfall at these times.

The monthly water balance for the catchment was used to calculate the change in soil water storage. Measurements of volumetric water content to a depth of 2.4 m were compared with water balance estimates of changes in soil water storage. Losses unaccounted for were -671 mm over 17 months or approximately -40 mm month^{-1}. These deficits in the water balance could only be supplied from the deep soil water stores beyond 2.4 m. These data were evidence that the wattle trees (whose roots went deeper than 4.8 m) were able to access the deep groundwater reserves.

- Both the WAVES- and ACRU-simulated soil water results were compared against measured values of soil profile water content to a depth of 2.4 m. The WAVES water content (561 mm) was very similar to the actual total profile water content (547 mm) whereas ACRU was noticeably different at 400 mm. During the simulation period, it was noticeable that the ACRU model values remained fairly constant throughout the year with only small responses to large rainfall events. By contrast, the WAVES model showed good agreement to the trends in the actual total profile water content. Generally the WAVES model tended to overestimate the response to summer rainfall events. Particularly good agreement was found between the measured and WAVES-simulated model values in the recession of the water content curves following large rainfall events. These data revealed that the WAVES values

were within 20% of the actual values for 95% of the time while the ACRU model values were within the 20% range for only 5% of the time.

The streamflow simulations using ACRU showed that the accumulated streamflow over time was underestimated. During the period of measurement from January 2000 to December 2008 the measured accumulated streamflow was 400 mm. The simulated total streamflow using the "old" and the "new" ACRU versions were 300 mm and 275 mm respectively. The simulation followed the measured data closely until the end of 2004 when the catchment was clear-felled. From January 2005 to December 2008 the simulations appeared to consistently underestimate the streamflow and the Intermediate Zone ACRU more so than ACRU 3.31. This apparent divergence between simulated and observed data together with a change in the conditions of the catchment provided an excellent opportunity to verify model performance. It also showed that ACRU was not able to effectively simulate changes in streamflow from an afforested scenario to a fallow catchment.

6. Conclusions

In this study the impact of *A. mearnsii* on soil hydrological processes was extended with additional detailed measurements of evaporation and soil water processes to improve our understanding of processes such as low flows and deeper soil water dynamics. The ever-growing demand for water makes it imperative that water resource management procedures and policies be wisely implemented and improved. Recent studies have raised concerns over the impact of deep-rooted trees "mining" the soil water and groundwater reserves. The effect of excess evaporation over rainfall is ultimately transmitted into reductions in streamflow. Therefore, a better understanding of the hydrological processes of deep rooted trees is needed to improve the granting of licenses to water-users and for water allocation.

In this study we described the processes of supply (rainfall) and demand (climate and land-cover) for water and how they influenced the evaporation process. From a biophysical standpoint, a forest or plantation cannot in the long-term use more water through evaporation than is available from the input of rainfall minus runoff and infiltration of water below the root zone. To balance the water supply, plants can use a number of adaptive mechanisms (Baldocchi, 2007). On a short time scale plants can limit transpirational losses by closing stomata. In this study evidence of the *A. mearnsii* trees closing stomata on hot dry windy days was found. These extreme events are rare however, and not likely to influence the water balance on an annual basis. On a longer time scale (millennia) plants can develop morphological and ecological adaptations that can lead to reduced transpiration, such as leaf drop or developing smaller leaves to convect heat more efficiently. When considering an exotic plant like *A. mearnsii*, imported from Australia in the last century, then this is clearly not a consideration. In addition, this study has shown that the *A. mearnsii* trees at Two Streams transpire at rates that are close to the Priestley-Taylor potential rate of evaporation (i.e. there was no evidence of reduced transpiration). The most plausible adaptation of the *A. mearnsii* trees is the development of deep roots that can access alternative sources of water. The Two Streams catchment received a nine year average rainfall of 920 mm, with a range of 570 mm between the lowest and highest years (minimum = 659 mm and maximum = 1170 mm). The upper range may appear adequate, but not all will be available to the trees as there will be losses due to interception, surface runoff and deep percolation past the root system. In dry years the trees will have to resort to an alternative source of previously stored soil water. In this study the annual *ET* of the actively growing *A. mearnsii* was 1156 mm and 1171 mm and the rainfall 689 mm and 819 mm for 2007 and 2008 respectively.

Evaporation from the developing wattle plantation measured using a large aperture scintillometer was shown to exceed the rainfall by 46%, confirming the previous Bowen ratio measurements (Jarmain and Everson, 2002). Potential evaporation rates estimated using the Priestley-Taylor equation were on average only 5% lower than to the ET_{LAS}. The implication of these results is that the wattle trees were using water at rates higher than the equilibrium rate throughout the year and that there was always some component of advective energy that increases the actual evapotranspiration. This means that true equilibrium potential evapotranspiration rarely occurred at the study site. Clearly, water was not a limiting factor to the wattle growth during its first three years of development.

Internationally, long-term catchment studies including actual measurements of all the water balance components are scarce; while locally this represents a unique study on the impact of an exotic tree plantation on catchment hydrological processes. The only other long-term data set to include actual measurements of *ET* was collected from the Cathedral Peak CVI in *Themeda triandra* dominated grassland in the KwaZulu-Natal Drakensberg (Everson *et al.*, 1998). This study provided a baseline against which the impacts of commercial forestry and other land-uses could be assessed. The daily total evaporation (ET_{LAS}) values for the *A. mearnsii* trees on cloudless summer days averaged 7 mm. On clear winter days the maximum total evaporation was approximately 2.4 mm day^{-1}. This contrasts with the *Themeda triandra* grassland evaporation rates measured in the Drakensberg of 7 mm in summer and < 1 mm in winter (Everson *et al*., 1998). It is, therefore, the difference in the winter *ET* between grasses and evergreen trees that has the biggest impact on changing the catchment water balance. This will be particularly noticeable during the critical low flow (winter) periods.

The rainfall:runoff relationship (*Rr*) was 0.02 prior to clear-felling of the catchment in 2004. Following clear-felling the *Rr* increased to 0.08. This indicated increased runoff during the two-year fallow period and the first two years of wattle tree development. Forest management practices, therefore, have significant impacts on catchment water yields. The impact of clearing the riparian vegetation followed by clear-felling the entire catchment in 2004, a replanting in June 2006 and regrowth to January 2009, resulted in a total gain in streamflow of 235 mm.

In this study it was shown that the total input by precipitation was +1308 mm while the combined losses of *ET* and *Q* were -2120 mm. The measured change in soil water storage in the upper 2.4 m soil profile was -141 mm. Unaccounted for losses were therefore -671 mm or approximately -40 mm per month. These deficits in the water balance could only be supplied from soil water stores deeper than 2.4 m. These data are evidence that the wattle trees, whose roots went deeper than 4.8 m were able to access the deep groundwater reserves. Other evidence for supporting this conclusion included the following:

- The electrical resistivity survey and borehole logs confirmed the presence of deep clays with high water contents to depths of 25 m. This represents a significant soil water storage reserve for access by deep rooted trees.

- Dry season borehole data showed a drop in water level of 1000 mm between 2007 and 2008, despite more rainfall in 2008. This drop in level was ascribed to the impact of the trees on the recharge rate.

- The *A. mearnsii* roots were found at depths > 4.8 m.

- The measurements of soil water and soil water potential showed a consistent drying out of the deeper soil profile as the trees developed.

7. Extent to which contract objectives have been met

The objectives of the original project contract have been met as described below:

a. The first objective was to quantify the long-term effects of commercial forestry species on deep soil water profiles, streamflow and evaporation. Through detailed water balance studies this objective was achieved and the hydrological record for Two Streams extended by a further three years (objective four).

b. Objective two was to describe the controlling environmental and soil water processes which allow for total evaporation to exceed the annual rainfall. This was achieved by actual measurements of the catchment water balance which have contributed to a better understanding of these processes.

Objective three was to provide a modelling framework for the catchment water balance to improve stream flow predictions and specifically low flows. Nine years of detailed hydrological data provides an excellent data source for verification and development of hydrological models.

8. Capacity building and technology exchange

The Two Streams catchment is well recognised in forestry research in South Africa and has initiated collaboration between a number of research institutions. The University of KwaZulu-Natal use the catchment for student field trips and hydrological modelling and verification. University of the Free State pedology students gained experience in soil classification and mapping in the Two Streams catchment.

An Institute for Commercial Forestry Research field day used the Two Streams catchment as a showcase of forestry research in South Africa. In April 2008, The Department of Water Affairs and Forestry held a workshop titled, 'International

Workshop on Forest Governance and Decentralisation in Africa'. During the workshop approximately 60 national and international delegates attended a field trip to the study site.

A number of individuals benefited from this research:

- Alistair Clulow was awarded his Masters degree (Agrometeorology) in 2008 based on the evaporation measurements performed during this project. He has worked extensively on the scintillometry component of this project and was exposed to other new techniques such as reference evaporation and TDR theory. He has also been involved in both workshops held in February and September 2006.

- Dumisani Shezi from Zululand University participated in the installation of the instrumentation while studying a Masters degree (Agrometeorology) at the University of KwaZulu-Natal. He has subsequently accepted a post with The Department of Water Affairs and Forestry.
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- Lucas Ngidi, Lelethu Sinuka and Vivek Naiken from the CSIR have all been involved as technicians on the project. They have been exposed to new technologies and the complexities of instrumentation and site management.

9. Recommendations

The data collected and research infrastructure established in the catchment over the last nine years provides an excellent platform to extend the studies in the catchment and in particular to observe the changes in water-use and growth of the trees towards maturity.

The role of interception in the water balance is not well understood. This includes rainfall interception and mist interception which may be significant in this catchment as it is in a mist-belt area. Whether it is accounted for in the scintillometer measurements needs further investigation. A method of quantifying the mist and establishing its frequency requires further research.

Surface energy balance models using remote sensing techniques can provide estimates of plant water-use over wide areas but require validation for South African conditions. The state-of-the-art total evaporation measurements recorded at the site provide an excellent opportunity for testing these techniques in afforested catchments. These will, in the future, provide water resource managers with catchment-wide water-use estimates and assist researchers in monitoring the impacts and changes associated with global climate change.

Cylindrical TDR probes were designed for installation in deep soils and were installed to 4.8 m. Although the practical aspects of installing probes at deep depths were overcome, the data were noisy and could be improved by extending the wave guides. Soil water content measurements over the deep profile would help to quantify the unaccounted deficits estimated from the water balance equation. More detailed information on root growth, root distribution and root turnover would also benefit the understanding of the water-use of the trees.

Peak flows of 10 mm were recorded in January 2005 which coincided with the clear-felling of the catchment. Due to the exposed soil surface and impact of heavy machinery on the soil structure, significant amounts of topsoil were washed into the river and weir at this time. Based on the damage caused during these events, it is strongly recommended that tree harvesting in wet seasons in areas susceptible to erosion be evaluated with further research.

Over the past nine years, the impacts of different treatments to the riparian zone and upslope areas have been assessed. The interaction of the hydrological processes between these two areas (i.e. the interface) is still not well understood. In the catchment, the two zones are distinct from a vegetation, slope, soils and groundwater perspective and yet they interact within the hydrological cycle. For hydrological models to capture this interaction, further research into the transfer functions at the interface are required.

10. Data

All processed data have been stored at NRE, CSIR, Faculty of Agriculture, University of KwaZulu-Natal, Carbis Road, Pietermaritzburg, South Africa.
Contact persons: Mr. AD Clulow and Prof. CS Everson.

The data are backed up on tape by Metrofile and can be supplied as requested on CD-R diskettes.

11. Publications

Clulow A D, 2008. The long-term measurement of total evaporation over *Acacia mearnsii* using large aperture scintillometry, MSc. thesis, University of KwaZulu-Natal, South Africa.

Clulow A D, Everson C S, Gush M B, 2009. The estimation of total evaporation over acacia mearnsii using large aperture scintillometry. Poster presentation at 14th SANCIAHS Symposium, Pietermaritzburg, 21-23 September, 2009.

Everson C S, Clulow A D, Gush MB, 2009. The Long Term Impact of Acacia Mearnsii Trees on Total Evaporation, Streamflow and Soil Water Storage. 14th SANCIAHS Symposium. Pietermaritzburg, South Africa, 21-23 September 2009, pp 18.