EXECUTIVE SUMMARY

1. MOTIVATION

Expansion of agricultural and forestry activities in catchments west of the Kruger National Park are placing increasing demands on their limited water resources. One of the rivers that has been most affected is the ecologically important Sabie River. Reduced winter base-flows in the river have resulted in increased water stress levels amongst the natural river biota. Consequently, there is an urgent need to manage the water resources within the catchment effectively to ensure the viability of riverine ecosystems.

This report focuses mainly on one aspect of riverine hydrology - evapotranspiration. In many biological systems evapotranspiration is the most important output flux accounting for up to 100% of annual water losses in wetland systems (Linacre 1976). However, accurate estimates of evapotranspiration are notoriously difficult to obtain. Rivers running through semi-arid areas such as the Kruger National Park present a particularly difficult challenge for estimating evapotranspiration, because of the problems associated with advection from the surrounding dry (hotter) areas and the limited fetch within the generally narrow boundaries of the outer banks of the river. In addition, the riverine systems, range from open water or inundated areas, where evapotranspiration is not constrained by water availability, to those where the water table is frequently below the surface and water availability for evapotranspiration is controlled by vegetation factors. As a consequence the evapotranspiration results produced are often inconclusive or conflicting.

In a previous study conducted on the Sabie River (Birkhead *et al* 1997) preliminary estimates of the water use of the reeds and trees were established. Tree transpiration rates were found to be conservative ($\bar{x}$ = 2 mm day^{-1} in summer). By contrast the modelled rates for the reeds consistently averaged more than 15 mm day^{-1} and were considered unrealistically high. The results of the study require verification if water resources within the catchment are to be managed effectively. The aim of the present study was to verify the empirically based transpiration estimates of Birkhead *et. al.* (1997) by using the physically based Bowen ratio technique to estimate evapotranspiration from the Sabie river.

2. PROJECT OBJECTIVES

- To verify preliminary estimates of water use of the trees and reeds on the Sabie River in the Kruger National Park.
- To directly measure reliable, spatially averaged (10^3 to 10^4 m^2) evapotranspiration rates for the two major community types (reeds and forest) using micrometeorological techniques.
- To compare the magnitude of the fluxes both between sites and seasonally, their daily trends and controls and to assess the magnitude of the evaporative losses over a 50km riparian strip.
- To test simple, physically based evapotranspiration models with simple data requirements of value for longer term modelling of the water use of riparian vegetation along the Sabie River and other similar sites.

Although the absolute magnitudes of the results reported are directly relevant only to similar climatic and vegetation types, the processes and controls described may be representative of other major river systems within southern Africa.

3. BACKGROUND

The work for this project (phase II) arose as a direct recommendation from a previous project funded by the Water Research Commission (phase I), which investigated "Developing an Integrated approach to

Predicting the Water Use of Riparian Vegetation", by Birkhead AI, Olbrich BW, James CS & KH Rogers in 1997 (WRC Report No 474/1/97). These authors recommended that further measurements on the water use of reed beds be carried out as the original estimates were not satisfactory. Since reed beds are the dominant vegetation type in the Sabie River, over-estimation of evapotranspiration rates would result in unrealistic values when modelling water use in the Kruger Park. The present project was therefore initiated to determine independent estimates of evapotranspiration from a reed bed and forest community.

4. METHODS

The energy balance Bowen ratio technique was used to estimate evapotranspiration at the reed site. However, the technique could not be used in sites where the reed roots were permanently inundated with water because of insufficient fetch distance and difficulties in building towers.

Since the Bowen ratio technique also has limitations when used over tall tree canopies, the eddy covariance technique was used to measure the latent heat fluxes above the forest canopy.

The data collected from the sites were then substituted into the Penman Monteith equation to calculate actual total evapotranspiration (*ET*).

5. RESULTS

5.1 Reed evapotranspiration

Daily reed evapotranspiration rates (mm day^{-1}) measured during the study period included three summer seasons (1998, 1999 and 2000), two winter periods (1998 and 1999), and the spring of 1999. Strong seasonal trends were exhibited by these data, with mean monthly summer values varying between 4.5 and 7 mm day^{-1} during 1998 and 1999. Mean monthly values in January in 2000 were significantly lower as a result of the high incidence of rain during this year. Maximum evapotranspiration rates of 8-9 mm day^{-1} were often found between December and February. This contrasts with the 12 mm day^{-1} in February reported in the previous study using the dynagauge technique (WRC report 474/1/97).

Evapotranspiration rates from the reeds during the winter months of May and June were noticeably lower, but still averaged about 4 mm day^{-1} in 1999. Evapotranspiration from the reed beds in the Kruger National Park therefore ranged from 4 to 9 mm day^{-1} depending on the season.

As suspected in phase I (Birkhead et al. 1997), the modelled reed values of between 10 and 30 mm day^{-1} were unrealistic and not physically possible, since the values far exceeded the amount of available energy. The reed models developed in phase I should therefore not be used for calculating reed transpiration.

5.2 The use of infra red thermometry to estimate forest evapotranspiration

The use of the infrared technique to estimate evapotranspiration at the forest site was not satisfactory. The infrared data implied that all of the available energy was converted into sensible heat, a very unlikely result in this instance. The Bartholic-Namken-Wiegand method overestimated the equilibrium evaporation rate at all values above 300 Wm^{-2}. Because of the disappointing performance of this technique and the difficulty of routine measurements in the Kruger National Park, it was decided to investigate the technique at a site closer to Pietermaritzburg. The events of the flood, in which all the sensors and data loggers were lost, have prevented this.

5.3 Tree evapotranspiration using the eddy covariance technique

Diurnal evapotranspiration measured with the eddy covariance technique indicated that the tree canopy exhibited very low rates of transpiration during winter (approximately 0.6 mm day^{-1}). One of the problems with this technique is that approximately 200 W m^{-2} of energy are unaccounted for. This may be due to energy in tree trunk storage which was not measured in this study.

5.4 Tree evapotranspiration using the Bowen ratio technique

The results showed that trees transpire freely during winter (up to 2.57 mm day^{-1}), although the maximum rates are limited by the available energy. A striking feature of the summer evapotranspiration data was that the maximum daily rate seldom exceeded 4 mm day^{-1}. Unlike winter, most of the energy (500-700 Wm^{-2}) was utilized in the early morning to drive the evapotranspiration process. At mid-day this trend was reversed, when approximately 300-600 Wm^{-2} was partitioned into heating the air. The main differences between the summer and the winter energy balances were: (i) the magnitude of the fluxes and (ii) the time at which the partitioning between the latent and sensible flux changes from being predominantly latent heat to principally sensible heat.

There were no strong seasonal trends in the tree evapotranspiration data with winter values being similar to summer values. The mean daily evapotranspiration for the winter and summer was 2.62 and 2.23 mm respectively. The lower incidence of cloud cover and rain in winter resulted in the marginally higher evapotranspiration rate in winter. The results of this study were higher than those recorded in phase I (1 mm day^{-1} in winter).

Both studies have shown that the evapotranspiration from the tree community was surprisingly low, especially considering the high atmospheric demand experienced in the KNP and the freely available supply of water to the trees. A possible explanation is that the transpiration per unit leaf area declines in mature trees that have extensive flow paths from the roots through long branches to the leaves. The corollary, that young trees will have significantly higher water requirements, now has particular relevance, due to the removal of most of the mature forest during the February 2000 floods. The post flood succession of the riparian forest now offers a unique opportunity to investigate this hypothesis.

5.5 Comparison of trees and reeds

Comparisons of simultaneous evapotranspiration rates from the reeds and forest communities in the KNP showed that the daily water use of the reeds was consistently higher than in the forest community. During the study period the forest community used 36% less water that the reed community (2.5 mm day^{-1} versus 3.9 mm day^{-1} respectively).

6. MODELLING REED AND TREE EVAPOTRANSPIRATION

The estimates of actual evapotranspiration obtained in this study were used to develop canopy specific models of the Penman-Monteith equation that could be used for the reeds and trees. A very close agreement was found in the reed site between the measured (Bowen ratio evapotranspiration) and the simulated Penman-Monteith evapotranspiration in summer with totals of 176.7 mm and 178 mm respectively. Good relationships were also found between the autumn and spring Bowen ration evapotranspiration data and the Penman-Monteith estimates. However, a poor relationship was measured during winter, possibly due to the underestimation of the simulated net radiation and soil heat flux density.

7. LOW FLOW VERIFICATION STUDIES

The results of the vegetation cover analysis showed that the forests (38%) and reeds (22%) were the dominant vegetation types accounting for 60 % of the area. Open water, rock and sand accounted for a further 28%. These data were used to scale up the evapotranspiration data for a 55 km section of the Sabie between the Kruger and Lower Sabie weirs. Comparisons of the total evaporation losses during the low flow period attributed to vegetation (0.32 $m^3 s^{-1}$)

and gauging losses (0.35 $m^3 s^{-1}$) showed good agreement, and added validity to the evapotranspiration data.

8. CONCLUSIONS

The main objective of the verification of previous transpiration measurements from reeds and trees in the Sabie River was achieved using the Bowen ratio energy balance technique. The results have shown that the previously high evapotranspiration rates attributed to reeds were unfounded. These reed evapotranspiration models should therefore not be used to model consumptive water use of the vegetation.

Evapotranspiration from the tree site was consistent with the previous research where conservative tree transpiration rates were found. However, the absolute daily evapotranspiration rates were higher in this study (3.2 mm day^{-1}) when compared with the previous study (1.7 mm day^{-1}).

Canopy specific models for the reeds and trees have been developed through an understanding of the energy balance of each community and its relationship to the well-known Penman-Monteith approach, providing a more accurate calculation of the water requirements of similar riparian vegetation in southern Africa.

Verification of the evapotranspiration estimates of this study was achieved by comparing the Bowen ratio estimates with transmission losses estimated through gauging studies. The gauging data were consistent with the evapotranspiration data collected in this project, confirming the validity of the evapotranspiration data.

9. EXTENT TO WHICH CONTRACT OBJECTIVES HAVE BEEN MET

Project Objective:

- *To verify preliminary estimates of water use of the trees and reeds on the Sabie River in the Kruger National Park.*

Verification of previous transpiration measurements from reeds and trees in the Sabie River was successfully achieved using the Bowen ratio energy balance technique.

- *To directly measure reliable, spatially averaged (10^3 -10^4 m^2) evapotranspiration rates for the two major community types (reeds and forest) using micrometeorological techniques.*

Good seasonal data were obtained from the reed site. Tree data were obtained only for the winter and spring periods. High river levels and the February 2000 floods prevented the collection of summer tree data.

- *Compare the magnitude of the fluxes both between sites and seasonally, their daily trends and controls and to assess the magnitude of the evaporative losses over a 50 km riparian strip.*

Low flow verification studies confirmed the spatially averaged estimates of the consumptive water use of the riparian vegetation along a 55 km stretch of the Sabie River.

- *To test simple, physically based evapotranspiration models with simple data requirements of value for longer term modelling of the water use of riparian vegetation along the Sabie River and other similar sites.*

In terms of modelling the latent heat flux in the Sabie River and other similar environments, either the Priestley-Taylor or Penman-Monteith methods yield the best results. The use of canopy and seasonal specific surface resistances and modelled available energy from relationships determined in this study, provides a model that yields excellent results yet is simple to use.

10. RECOMMENDATIONS FOR FURTHER RESEARCH

1. Further research is required on the physiological and physical processes that underlie the conservative water use of the forests growing along the Sabie River. This research should determine the extent to

which these conservative rates are applicable to other indigenous riparian systems in South Africa, since some hydrological models, such as ACRU, depend on a crop factor approach to determine the water use of different plant communities. The data from this project are inconsistent with popular beliefs that indigenous riparian communities are high water users. For example, the future development of the BLINKS riparian vegetation model is to encourage links with the ACRU model, so that meaningful hydrological scenarios can be used to predict the response of the riparian vegetation (Mackenzie et al 1999). This will be dependent on accurate predictions of the consumptive water use of the vegetation.

2. Both the phase I and II projects have highlighted the difficulties in obtaining routine measurements of evapotranspiration from mixed tree canopies in riverine situations. There is an urgent need to find a technique that will overcome these problems if progress is to be made in the area of evaporative research in riparian communities. Recent investigations have demonstrated the potential use of scintillometry to measure spatially averaged sensible heat fluxes over path lengths that range from 50 m to several kilometres. A scintillometer measures the intensity fluctuations of visible or infrared radiation after propagation over the plant canopy of interest. In contrast to local measurements, scintillometers provide path-averaged results. The temporal resolution achievable is one order of magnitude higher than that of point measurements. Due to the spatial averaging, extended experimental areas can be representatively characterised with a single instrument. Future research should test the feasibility of using this technique in riverine areas.

3. For practical reasons the reed measurements of this project were carried out on communities growing on elevated sand banks. There is still a need to characterise the evapotranspiration of permanently inundated reeds, which represent a large proportion of vegetation growing along the banks of South African rivers. Scintillometry would provide an alternative solution to the problems faced when working with conventional techniques. The use of infrared thermometry should also be investigated as a cheaper solution.

4. A possible reason suggested for the low consumptive water use of the trees is that the transpiration rate per unit of leaf area declines as a result of the extensive pathways water must follow from the roots through long branches to the leaves. The corollary, that young actively growing trees will have significantly higher water requirements, now has particular relevance, due to the removal of most of the mature forest during the February 2000 floods. The post flood succession of the riparian forest now offers a unique opportunity to investigate this hypothesis.

5. A major threat to the Sabie river ecosystem is through the replacement of indigenous vegetation by alien invasives. The manner in which these invasives invade the river ecosystem following the floods needs to be researched. A key question must be the impact that these fast growing and hence highly water efficient plants, must have on the delicate balance between the indigenous riparian plants and the soil and ground water reserves.

6. Water resources development and management require an understanding of basic hydrologic processes and simulation at the catchment scale (thousands to tens of thousands of square kilometres). Recent advances in computer hardware and software and GIS/spatial analysis software have allowed large area simulation to become feasible. The information on the evapotranspiration of the dominant indigenous vegetation collected in this study will ultimately provide modellers with important inputs and data for the verification of these models. It is recommended that a workshop be held (outside the scope of this project), on how to further interpret the research in terms of the "ecological reserve", by bringing all the results on the impact of the water use of vegetation together, and by developing a link to the operational management of rivers.

11. CAPACITY BUILDING

The research field of micrometeorology is currently in a crisis with very few new researchers entering the discipline. Mrs Jarmain (nee Burger) is the only new young female researcher to be recruited into this field in recent years. As the use of the open path eddy covariance represented a new research approach not used in South Africa before, it is clear that new capacity was imparted to both the junior and senior researchers. It must be recognised that neither previously disadvantaged students, nor other students are entering this field. Capacity building in the future must focus on attracting promising young scientists into hydrology and micrometeorology and building the skills that are needed for the research and management of South Africa's scarce water resources.

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