

Water relations of the vegetation along the Kuiseb River, Namibia.

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ABSTRACT

The rate of evaporation and transpiration along the Kuiseb River bed was measured. Maximal transpiration rates (at noon) of *Acacia albida* Del., *A. erioloba* E. Mey., *Euclea pseudebenus* E. Mey. ex A. DC. and *Tamarix usneoides* E. Mey. ex Bunge X *Ramosissima* Ledeb. were respectively found to be 1,50; 1,03; 0,54 and 1,07 g H₂O g⁻¹ hr⁻¹. Total transpirational loss by all the vegetation was estimated to be about 2,02 x 10⁵ m³ km⁻¹ annually.

A model was constructed to account for the annual water loss from the river bed, as well as the depth of dry sand which would result from such losses. The accounting model was run with an iteration time of one week, for a period of 51 weeks.

The model estimated that the total volume of water in the aquifer comprises 10,7 x 10⁵ m³ water km⁻¹ immediately after flooding, with 2,59 x 10⁵ m³ km⁻¹ (24%) being lost due to evapotranspiration. 2,02 x 10⁵ m³ km⁻¹ (78% of the loss) is due to transpiration with 0,57 x 10⁵ m³ km⁻¹ (22%) due to evaporative losses from the sand. This amount would result in a 'dry depth' of 2,92 m by the end of 51 weeks. If the capillary fringe was taken into account the observed 'dry depth' would be greater than 2,92 m.

INTRODUCTION

The Kuiseb River rises in the Khomas Hochland of Namibia, south of the capital city, Windhoek. Its many initiating tributaries join as they flow west to the escarpment, from where the river then flows across the Namib Desert to its present estuary at the southern edge of Walvis Bay (Fig. 1).

Although it is basically a "dry" river, it floods in most years to below Gobabeb, the Namib Desert Research Station. Surface water, however, last reached the sea in 1963 (Braune 1991). The Khomas Hochland is

topographically highly dissected and rugged. It is ranching country and a myriad of small farm dams, for stock-watering purposes, have now reduced the run-off into the Kuiseb by a considerable amount.

Below the escarpment, the river runs through a steep gorge (the Kuiseb canyon) and eventually emerges to flow across the desert for some kilometres, dividing the desert into the gravel plains to the north and sand dunes to the south. The dunes end abruptly at the river's edge and, although there is some controversy regarding the cause-and-effect nature of the position of the edge of the dunes and the river, it is an observed fact that sand from several dunes which move into the river each year, is scoured out and washed away during floods (Bush 1991).

Surface water in the river lasts for only a few days a year but flows in large quantities in the sand aquifer of the river bed and, for example, the annual recharge to the Swartbank A-area is estimated to be 1,2 x 10⁶ m³ yr⁻¹ (Department of Water Affairs and Forestry 1991). This water gives rise to a riverine fringe of woodland, consisting of four main species, viz. *Acacia albida*, *A. erioloba*, *Euclea pseudebenus* and *Tamarix usneoides*, decreasing in size and in proximity to the river bank in approximately that order. These trees supply vital forage to many desert animals during times of extended drought.

Water in the area served by the Kuiseb River is in short supply and increased utilization by industry (e.g. mines) and human consumption (Swakopmund and Walvis Bay) is producing an increased demand for water from the sand

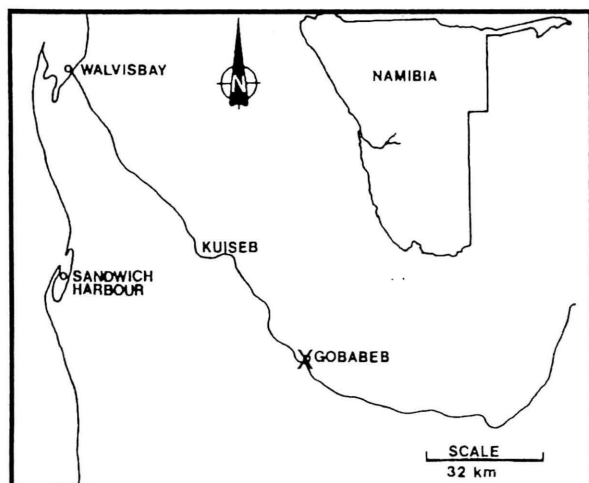


FIGURE 1. Map of the Kuiseb River and the study site (X) in relation to Namibia.

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reservoir of the Kuiseb River. There was, at one time, a proposal to remove all the trees along the Kuiseb in order to save water and the South African Council of Scientific and Industrial Research initiated a research programme in the late 1970's to determine the effects of the vegetation along the Kuiseb River.

The transpirational water loss by *Acacia albida*, *A. erioloba*, *Euclea pseudebenus* and *Tamarix usneoides* was determined since these four species make up approximately 80% of the vegetative biomass along the Kuiseb River and, therefore, account for the bulk of transpirational water use. These transpiration values, together with leaf dry mass, were used to determine the water loss per unit area of land on an annual basis. In order to arrive at a realistic assessment of water loss from the aquifer, all available data were included into an accounting model designed to incorporate such features as temperature changes, relative humidity and radiation level. To reduce the length of this report, much detail has been omitted; full details of the methods and the accounting model are described in Bate and Walker (1980).

GENERAL METHODOLOGY

Our approach was to develop a water budget model. We used a standard 1 km stretch of the river in the vicinity of Gobabeb and modelled the dynamics of water through this section. The parameters of the model constituted our research programme. The information required to meet our objectives consisted of estimates of i) the size of the aquifer, ii) the inflow of water i.e. the rate and frequency of recharge of the aquifer, iii) evaporation loss from the surface of the sand and, iv) transpirational loss from the vegetation.

Very briefly, we obtained these estimates as follows:-

i) The size of the aquifer. The average width was obtained from several measured transects of the vegetation across the river, and was found to average 307 m, thus 1 km of river length represented an area of 30.7 ha. The depth was estimated to average 10 m. This value was accepted after discussions with several other workers familiar with the Kuiseb and from knowledge of a few extraction boreholes. Thus the volume of sand storage included in the model was $3.07 \times 10^6 \text{ m}^3$.

ii) Aquifer recharge. The presence of silt and clay lenses in the river bed prevents rapid recharge when the river floods. Indeed, it takes several days of flooding to achieve complete recharge. In most years the river floods at least once (Seely *et al.* 1981) and we have assumed that recharge takes place. It is important to note, though, that this is by no means always the case and that the vegetation occasionally has to utilize deeper resources.

The flooding period was taken to be one week in the middle of summer. At the end of a one week flood, the aquifer was assumed to be filled to its water holding capacity. This involved the assumption that the annual flood volume was greater than the annual removal of

water and also, that it continued for a sufficiently long period to completely recharge the sand and that percolation was not restricted in any way by impermeable layers. We assumed, furthermore, that the basin was 'water-tight' and that there was, thus, no loss from the aquifer by percolation vertically down or laterally.

The water holding capacity of the soil was measured to be 34.7% by volume or 21% by mass. In this way the amount of water in the aquifer was determined and the water loss expressed as a proportion of the total volume.

iii) The water budget was based on inputs which included the flood and sub-surface lateral outflow. Evaporation was based on an evaporation factor under conditions similar to those in the Kuiseb River. Seely & Stuart (1976) reported standard class A pan evaporation rates for Gobabeb to be 3.5 m. This value, expressed on an hourly basis for a 12-hour average day was the maximal evaporation factor.

Evaporation was measured in the laboratory under simulated field conditions as well as directly in the field. Soil lysimeters were employed in the laboratory, either as columns of different lengths or as pots filled with sand. The lysimeter surfaces were subjected to various temperatures and wind conditions using atmospheric humidity and air temperature values measured in the field.

Maximum evaporation rates from a saturated soil were determined by maintaining the water level in the columns at the surface. Evaporation rates at different soil dry-depths were measured by adjusting the saturation water level with respect to the surface.

In the field, different sites were chosen to represent shaded, semi-shaded and exposed conditions. The soil was thoroughly soaked with water to ensure field capacity to a depth of 250 cm. After a period of 4 days the moisture content of the soil was measured gravimetrically. No roots were present in these surface layers of the soil, thus the water loss was presumed to be the result of evaporation.

iv) Transpirational water loss was estimated in four stages. First, transpiration rates were obtained for each of the four species per unit leaf mass. Secondly, leaf mass was related to stem area by allometry. Density, by size class, of each of the four species for the 1 km stretch of river and the proportion of the canopy in each size class which consisted of dead branches were also determined for each species.

DETERMINATION OF TRANSPIRATIONAL WATER LOSS:

Two methods were used for obtaining individual transpiration rates; the Cut-Shoot-Mass-Loss method (CSML) and lysimetry, the latter being considered the absolute value. A balance accurate to 10 mg was used. Transpiration rates were measured in the field using the CSML method over the first three minutes (Powrie 1979).

Transpirational water loss per hectare was calculated for each species as follows:

$$Tr = t_s \cdot b_s \cdot n \cdot 365 \cdot c$$

where Tr is the transpirational water loss ($m^3 ha^{-1} annum^{-1}$)

t_s is the mean daily transpiration rate ($g g^{-1} hr^{-1}$)

b_s is the dry leaf mass ($g ha^{-1}$)

n is the mean number of hours sunshine per day

365 is a constant to convert days to a year and

c is a constant to convert $g H_2O ha^{-1}$ to $m^3 ha^{-1}$

Information so obtained was synthesized by means of a simulation model, iterating on a daily basis, using recorded values for climatic variables (Seely & Stuart 1976) and deterministic flooding events.

DETERMINATION OF LEAF BIOMASS:

The technique involved the determination of a relationship between stem basal area and the leaf dry biomass subtended by a given stem diameter. The data were obtained by destructively sampling numerous medium-sized trees (up to 3 - 4 m) until a clear relationship between stem size and leaf biomass subtended by a given stem diameter was obtained. These data were used to estimate the leaf dry biomass per unit area in the river bed. Total stem basal area at ground level was estimated using 28 separate belt transects chosen at random within a two kilometre stretch of river at Gobabeb. Each belt transect was 10 m wide and ran the width of the vegetation which averaged 307 m.

The destructive technique produced data from the smallest twig of each tree, progressively getting larger until all the leaves on the tree from the trunk upwards were included. The data are, therefore, an extrapolation of smaller tree values but, since they also include branches and twigs, we believe the data set are reasonable.

RESULTS

To determine whether the CSML method was suitable for use in the field, transpiration rates from whole potted saplings were determined by lysimetry. These rates were

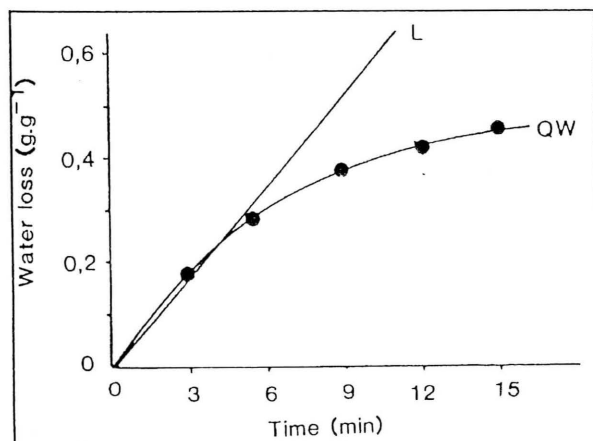


Figure 2. Water loss from the excised shoots (QW) of *Acacia albida* compared to actual transpiration (L) for the same species.

Table 1. Comparison of transpiration rates by the CSML method and the lysimeter method as determined in the laboratory under high light and saturated soil conditions.

Mean transpiration rates and standard errors ($g g^{-1} hr^{-1}$)

Species	Lysimeter	Cut-off-mass-loss using the first interval (3 min)	Cut-off-mass-loss using the maximum rate in any 3 min time interval
<i>A. albida</i>	2,21+/-0,122	2,36+/-0,12	2,45+/-0,13
<i>A. erioloba</i>	3,52+/-0,32	3,60+/-0,31	3,70+/-0,29

then compared with transpiration rates from the same plants by removing twigs and employing the Cut-Shoot-Mass-Loss (CSML) method. The most acceptable method determined from these experiments was later used in the field to determine the rates of transpiration from trees in the Kuiseb River.

Transpiration rates determined for the first three-minute interval after cutting (Slavik 1974) using the Cut-Shoot-Mass-Loss method (CSML) showed the best correlation to the rate determined by lysimetry (Drews 1979). The mean transpiration rates for the lysimeter method and the CSML method are given in Table 1. Plants between 4 and 8 months old which were grown in a greenhouse were used in these trials. The rates obtained in these trials were higher than the rates obtained for field-grown *Acacia* plants as might be expected.

Transpiration rates of detached plant parts decreased with time after excision (Figs. 2 & 3). The Ivanov effect (Ivanov 1928) was not observed, this is probably due to the woody nature of the material (Slavik 1974). The decrease in measured transpiration with time was because the material was drying out. All subsequent field work employed mass loss over the first three minutes after excision, to prevent errors due to this feature.

Transpiration rates varied with light, temperature, relative humidity and wind conditions, which generally are functions of the time of day. Thus transpiration rates are

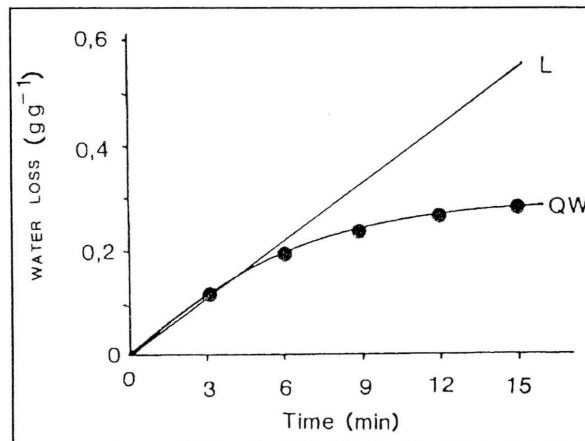


Figure 3. Water loss from the excised shoots (QW) of *A. erioloba* compared to the actual transpiration (L) for the same species.

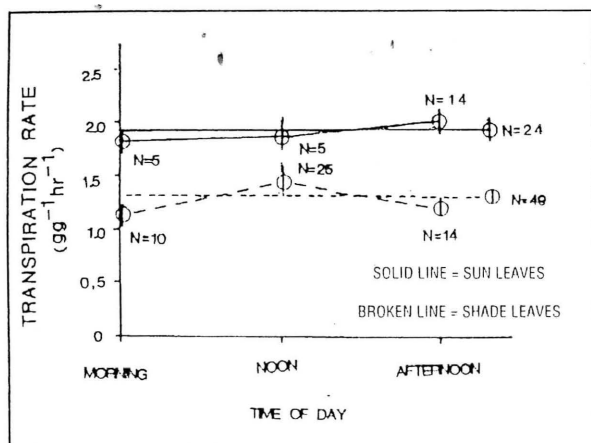


Figure 4. Transpiration rates for the sun and shade leaves of *A. albida* at different times of the day, showing the mean rate in each case and the number of trials constituting the sample (n). (Morning refers to the times between 09h00 and 11h30, noon refers to the times between 12h00 and 14h00, and afternoon refers to times between 14h30 and 17h30). Vertical lines represent 2.S.E.

given as functions of the time of day in Figs. 4 and 5. Mean transpiration rates of leaves of all four species in the sun were higher than those of leaves in the shade, but the extent of the difference varied with each species (Table 2).

In the field, using the CSML method, sun leaves of *A. erioloba* showed a decrease in the rate of transpiration with time over a day. This may be the result of a decrease in the water potential of the leaves due to the resistances to uptake and flow of water in the xylem. Despite this latter suggestion, the plants were not water stressed since leaf water potential was never less than -500 kPa for any of the species. The daily time-course of leaf water potential was not measured but random measurements were taken over several months and covered morning, noon and afternoon readings. However, shade leaves of *A. erioloba* showed the same general characteristics as those of *A. albida*.

For *E. pseudebenus*, sun leaves showed a depression at noon while the shade leaves had the highest transpiration at noon. At high radiation levels, it seems that these leaves control their rates of transpiration biologically, probably by decreasing stomatal aperture (Fig. 6).

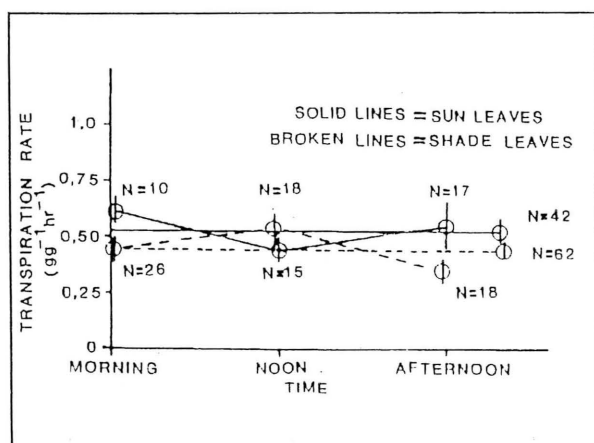


Figure 6. Transpiration rates for the sun and shade leaves of *E. pseudebenus* at different times of the day, showing the mean rate in each case and the number of trials constituting the sample (n). (Morning, noon and afternoon refer to the times given in fig. 3).

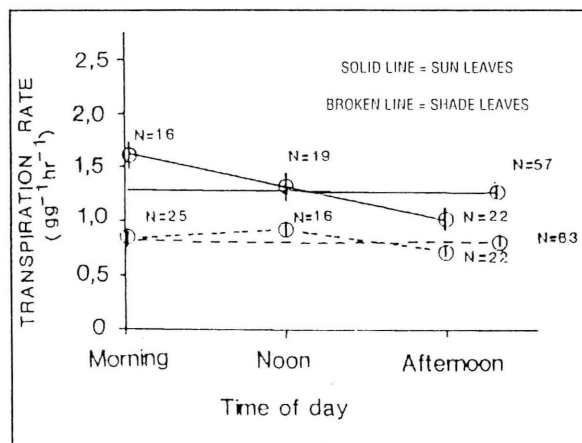


Figure 5. Transpiration rates for the sun and shade leaves of *A. erioloba* at different times of the day, showing the mean rate in each case and the number of trials constituting the sample (n). (Morning, noon and afternoon refer to the times given in fig. 3).

Table 2. Transpiration rates, standard errors and sample sizes used in the determination of transpiration rates for the four main species in the Kuiseb River aquifer.

Species	Transpiration rate ($\text{g g}^{-1} \text{hr}^{-1}$)	SE ($\text{g g}^{-1} \text{hr}^{-1}$)	n (sample)
<i>A. albida</i>	1.50	0.05	145
<i>A. erioloba</i>	1.03	0.03	226
<i>E. pseudebenus</i>	0.54	0.04	202
<i>T. usneoides</i>	1.07	0.03	234

T. usneoides showed the same pattern as *A. albida*, but with lower absolute rates of transpiration (Fig. 7).

In the determination of the relationship between the stem basal area and leaf dry biomass, values for a and b, in the regression formula:

$$\text{LDB} = a + b(\text{SBA})$$

where a = a constant and b = the slope of the relationship, together with the correlation coefficients for each species were calculated. The values of a and b for each of the four main species and the regression coefficients for the leaf biomass on the stem basal area are given in Table 3.

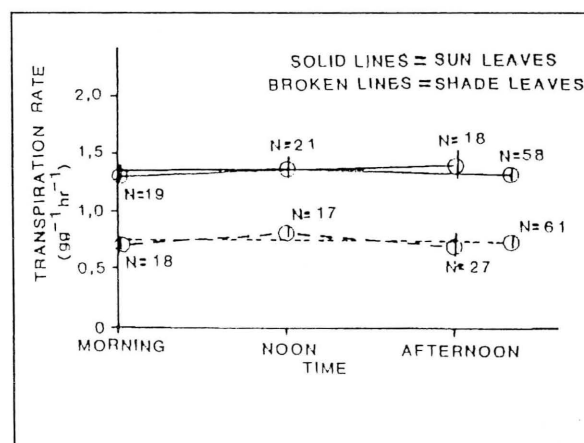


Figure 7. Transpiration rates for the sun and shade leaves of *T. usneoides* at different times of the day, showing the mean rate in each case and the number of trials constituting the sample (n). (Morning, noon and afternoon refer to the times given in fig. 3).

Table 3. Regression coefficients and (r^2) correlations for the leaf dry mass on stem basal area for the four major tree species in the Kuiseb River.

Species	a	b	r^2
<i>A. albida</i>	1,1	0,94	0,89
<i>A. erioloba</i>	1,59	0,99	0,94
<i>E. pseudebenus</i>	1,33	0,81	0,52
<i>T. usneoides</i>	1,64	0,88	0,96

The relationship between the stem basal area and leaf mass changes seasonally due to leaf fall. This is particularly the case with *A. albida*. An estimate of the seasonal variation of this species (min to max) was therefore made, by assessing percentage of maximum canopy density at the different times. The estimated leaf biomasses incorporating all these features are presented in Table 4.

Table 4. Basal areas and leaf dry mass biomass per hectare for the four major tree species in the Kuiseb River.

Species	Basal area ($m^2 ha^{-1}$)	Leaf mass (tonnes ha^{-1})	SE (tonnes ha^{-1})
<i>A. albida</i>	4,541	0,36-1,02	0,05
<i>A. erioloba</i>	2,069	0,71	0,10
<i>E. pseudebenus</i>	0,521	0,11	0,08
<i>T. usneoides</i>	0,986	0,23	0,05
Total		1,41-2,07	

The annual mean day length used in the calculations was 10,3 hours (Seely & Stuart 1976). This gave a transpirational water use of $1,61 \times 10^5 m^3 km^{-1}$ annually, using a biomass value of 2,07 tonnes ha^{-1} for the four species. All other species were considered to constitute 20% of the total biomass with transpiration rates equal to the mean rate of the other four species measured. On this basis, the total estimated transpirational water usage for all the vegetation was a maximum of $2,02 \times 10^5 m^3 km^{-1}$ annually.

Evaporation rate from a saturated sand surface was estimated at around 7 m per year, based on a 12 hour day. If the sand was not kept saturated, there was a distinct break in the rate of evaporation when the water content reached 8,5% v/v. Presumably this was the point when capillary action ceased to ensure an unbroken supply of water to the surface. When the dry depth of the sand reached about 120 cm, no further water loss occurs by evaporation. Total evaporative water loss from the Kuiseb was estimated to be $5,7 \times 10^4 m^3 km^{-1} yr^{-1}$.

DISCUSSION

Mean maximum transpiration rates for the four species, in $g g^{-1} hr$, were around 1,5 for *A. albida*, 1,0 for *T. usneoides* and *A. erioloba* and 0,5 for *E. pseudebenus*.

Standard errors of the means in each case were of the order of 0,04. *A. albida* and *A. erioloba* had more than five times the leaf biomass of the other two species. Corrected for the amount of dead material in the canopy, the total leaf biomass was somewhere between 1,0 and 1,5 $t ha^{-1}$.

The simulation output indicated that the total dry-depth accounted for by evaporation and transpiration was in the region of 2,92 m per annum. Observations of the depth of the water table at Natab (south-east of Gobabeb) showed it to be at a depth of almost 3 m one year after the previous flood. Furthermore, due to the capillary fringe above the water table, the table itself should be slightly deeper than calculated by our dry-depth.

Of the total dry-depth, 2,27 m was contributed by transpiratory losses and 0,62 m by evaporation. This transpirational and evaporative water loss was equal to a water volume of $2,59 \times 10^5 m^3 km^{-1} yr^{-1}$. The total volume of the water in the aquifer was estimated to be $10,7 \times 10^5 m^3 km^{-1} yr^{-1}$. Hence, the proportion lost by evapotranspiration in one year was in the region of 24%.

The total water loss calculated by the model is considered an overestimate for one or more of the following reasons:

A) The depth to which evaporation occurs was taken as the depth to which it was measured in a uniform column of sand with a surface temperature of about 60 °C. Clay and other irregularities due to bedding may reduce this depth.

B) The evaporative loss assumed a uniform bed without shade.

C) The evaporative loss excluded the input of water along a temperature gradient into the soil on nights when there was a precipitating fog.

D) The water holding capacity was based on values for compacted sand layers only. The degree of compaction by comparison with the natural condition is not known. Also, the clay layers, which have a greater water holding capacity, have been ignored due to their limited presence.

E) Transpiration rates, due to the method employed in their determination, may be slightly high, particularly the value for "other species".

F) The estimates of biomass are variable with the time of the year and the particular locality, so that apart from shortcomings of the technique, it becomes a complex entity to estimate. Comparison with other published data (Rutherford 1979) indicates that the total biomass estimate may be an overestimate of about 10-15%.

G) Day length has been taken as the annual mean day length for the month and is based on the number of hours of sunshine. On mornings after precipitating fogs, the vegetation remains wet for as long as 30 minutes after the fog has lifted. This may significantly alter transpirational water loss for such days.

A more realistic estimate of the water lost annually is probably somewhere between 15-20%, rather than the 24% indicated by the model. Apart from these features above, and to refine estimates, there are two other factors included in the model which need investigation:

a) The width of the aquifer was taken to be the mean vegetation width. It is, however, possible that the aquifer is either narrower or wider than that. Studies of rooting indicate that the water is abstracted from vertically below the plants, suggesting that the aquifer is either the same width as the area that the vegetation occupies, or wider. It is possible that the aquifer extends beneath the sand dunes on the south side but we still did not have the means to investigate this aspect.

b) The mean depth of the aquifer needs to be determined accurately over the whole length of the river affected by pumping.

From the estimates made in this study the aquifer, after a flood of several days, theoretically holds sufficient water to maintain normal tree growth for about five years. This estimate makes three important assumptions:

i) that the aquifer has a mean depth of 10 m and is square section, ii) that the tree roots reach all parts of the aquifer, and iii) that the trees take up water at a constant (maximum) rate until it is all depleted.

Pumping can only remove "free" water and it reduces the water content until the water potential of the soil is around 0 kPa. The total volume of water in the full aquifer is $10.7 \times 10^5 \text{ m}^3 \text{ km}^{-1}$ and, based on the difference between the saturated water volume and field capacity, pumping can reduce the water in the aquifer to $5.22 \times 10^5 \text{ m}^3 \text{ km}^{-1}$, leaving the sand at field capacity. Transpiration and evaporation annually account for something less than 50% of this amount and we therefore conclude that, in a

section of the river which is being pumped, the vegetation could survive for two years without recharge. A third year would likely prove fatal with long term effects on the ecosystem.

Pumping also results in an increased rate of dry-depth development, which effects seedling survival. *A. albida*, with a root growth rate of 10 cm week⁻¹ can easily keep up with the rate of decline in both unpumped and pumped aquifers. *A. erioloba*, however, grows much more slowly and appears to establish only in years of above average flooding (Bate *et al.* in prep.). It is therefore likely that its establishment will be reduced if an exhausting pumping programme is permitted.

If the level of the water table is dropped rapidly by pumping, the total volume of the water available to the trees is reduced. Normally, the volume is such that removal of water from the capillary fringe causes a gradual decline in the water table such that there is always water left by the time the next floods take place. A rapid removal of free (< 0 MPa) water after a flood could lead

to the trees continuing to remove water but depleting it in the event of a season without floods (as, for example, in 1980). The trees will then begin to die and a new (lower) long-term equilibrium density will then be established. The probability exists that, if more than two years were to elapse between floods, the new density could be zero. Thus pumping less water than enters the system could still lead to a decline in, and possible collapse of the Kuiseb riverine vegetation.

In 1991 a meeting in Walvis Bay (Department of Water Affairs and Forestry, 1991) reached the consensus that excessive pumping of the Kuiseb aquifer would have detrimental effects on the woody vegetation which, in turn, would cause the ecology of the Namib Desert to suffer. The meeting further identified that certain critical issues regarding the vegetation still needed to be solved before sustained and environmentally acceptable pumping rates can be determined.

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