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Evaluation of the hydrologic Impact of Rehabilitation - A Review of Forests Department work in the Northern Jarrah Forest.

1. Introduction.

Large areas of the Northern Jarrah Forest either have been or may be exposed to some form of degradation. Since this region's dominant use is water catchment, the major objective of rehabilitation must be to satisfy water supply objectives.

In the non-saline western zone of the forest, where degradation due to disease and mining is already extensive, rehabilitation provides an opportunity to restrict the evapotranspiration component of water balance and favour streamflow. This means that less intensive rehabilitation treatments, giving rise to less dense, less vigorous plant communities are appropriate. This makes rehabilitation a less challenging task than it might otherwise be.

In the saline eastern zone of the forest the chosen rehabilitation strategy must prevent stream salinity. This will probably have to be accomplished by re-establishment of a water balance identical to the native forest i.e. virtual total consumption of rainfall by evapotranspiration. This may be very difficult to achieve (appendix 1). In this zone some rehabilitation of land previously cleared for agriculture is underway using unproven treatments. The potential introduction of bauxite mining and disease adds urgency to the need to identify rehabilitation strategies assured of success.

Rehabilitation involves a choice of treatments, the suitability of which may vary with site. The range of treatments and sites is very broad and can be outlined as follows:-

Treatments
- physical works (drainage, ripping)
- nutrition (fertilizer, legume understorey)
- revegetation (species, provenances, establishment/management methods).

Sites
- type of degradation (bauxite mining, dieback, agriculture).
- natural environment (salinity, rainfall, soil, topography).

There are numerous potential combinations of treatments and sites. Some could be rejected intuitively or by cursory testing. Others may require elaborate testing since it appears that quite small changes in water balance may affect stream salinity (appendix 1).

It is therefore essential that a sensitive and practical evaluation method be developed so rehabilitation strategies which will work can be positively identified. Since 1976 the Forests Department has commited considerable resources to this end. This report reviews the progress made.

2. Methods and Parameters for Evaluation.

Two broad evaluation methodologies could be followed. Firstly, the empirical approach would involve the setting up of treated plots or catchments over the full range of sites and ranking them with respect to an appropriate parameter . Secondly the predictive approach would involve developing an understanding of the processes in rehabilitation and water balance, and integrating them into a model to predict the outcome of any combination of treatment and site.

We initially took the empirical approach on the presumption that it would more rapidly and economically provide a result. Three parameters, appropriate to different scales were considered for evaluation:

(i) Streamflow on the sub-catchment scale: this is the standard technique for testing hydrologic impacts. However, the scale is too large and the responses too slow to screen all treatments and sites. Also it could not give any resolution of within-catchment effects such as the interaction between treated area and surrounding untreated forest.

(ii) Groundwater on the hillslope scale: this could be done on an intermediate area and time scale but we were discouraged from this course by uncertainty amongst groundwater hydrologists due to the problems of spatial heterogeneity.

(iii) Evapotranspiration on the small plot scale: this could be done on a convenient area scale and provide the earliest possible indication of what the water balance would be. In this respect it looked most suited for broad screening of treatments and sites and was adopted. Our understanding of the jarrah forest ecosystem (see section 3) suggested that the major variation in evapotranspiration is likely to occur in the transpiration component and so the measurement could be limited to transpiration only. There was one apparent disadvantage in using this parameter, the importance of which we were initially not able to determine. It was clear that quite small decreases in transpiration, accumulated over time, could cause a large increase in stream salinity. A high order or resolution would therefore be required in the measurement of transpiration. We were subsequently able to quantify the size of the transpiration differences that were relevant (see section 5).

3. Early Work 1976 - 78.

We initially explored methods by which we could infer transpirative potential, the rationale being that some of the factors upon which transpiration is dependent might be more readily measured than transpiration itself. This work of Grieve (1957), Doley (1967), and Kimber (1974) had suggested that jarrah has some outstanding water relations adaptations. Its transpiration appears insensitive to the dry summer climate in spite of high vapour pressure deficit and lack of available water in upper soil horizons. This is apparently due to its capacity to tap deep soil layers and to maintain plant water potentials above the level that triggers stomatal closure. In addition jarrah appears not to have a strong direct stomatal response to vapour pressure deficit.

Two key parameters in this water relations model appear to be root depth and stomatal conductance. We suggested these features of the jarrah model could be used to provide standards of performance by which the likely transpiration of rehabilitation treatments could be inferred (Bartle and Shea, 1978). We felt that this method of evaluation might be especially useful for identifying suitable replacement species for jarrah which may be excluded from rehabilitation areas by *Phytophthora cinnamomi*.

Excavation was explored as a means of assessing root depth. Some of this work has recently been prepared for publication (Dell, Bartle and Tacey, in prep). This method was not found to be practical due to the great depths (40m or more) and variability involved. An attempt was made to map root profiles using a radioactive tracer (P^{32}). This work was done on a pair of jarrah poles in December 1977. Tracer injected into the trunk was widely dispersed through the canopy but none could be detected in roots. This surprising result suggested very tight control of phosphate transport in jarrah, with all mobile reserves being directed to the canopy for the leaf flush period. The method was considered worthy of further development.

During 1977 some 40 species were screened for stomatal conductance (gs). This was done in old arboreta using a hand-held porometer. The objective was to define daily and seasonal patterns of gs and to compare all species with jarrah. Though considerable differences between species were apparent their value in inferring transpiration was doubtful because:-

(i) large variation in gs from leaf to leaf within the canopy and between leaves over time were observed. The samples taken were too small to be confident that the differences observed were real. Given the nature of the instrument and the difficulty of gaining access to tree canopies it was concluded that very few trees could be sampled with sufficient intensity to be confident of differences (Jarvis, 1980).

(ii) transpiration is dependent on leaf area as well as mean gs. Hence mean leaf gs as an index of transpiration can only be directly compared where leaf areas are similar. Where they are not, as was commonly the case in our work, the canopy conductance (gc) (the product of leaf area index and gs) can be used as the index of transpiration. However, this only sometimes facilitates comparisons, for example, when gc of species is consistently lower than jarrah then it could be concluded to be inferior in transpiration. But when a species has part of the year with a higher gc and part lower (eg. E.saligna) then no simple comparison with the jarrah model is possible.

Thus we were obliged to discard the conductance standard set by jarrah as a simple evaluation criterion. There was no alternative but to directly measure transpiration itself.

4. <u>The Ventilated Chamber.</u>

At about this time Dr.Eric Greenwood (CSIRO) announced that his scaling up of the ventilated chamber technique to allow direct transpiration measurement of whole trees was ready for general application We were invited to join in some of the final development work (Greenwood et al 1981, 82) in order to become familiar with the technique. Though large in scale (Greenwood had operated a 16m chamber for more than 1 year) the method was simple in concept. Being a whole tree method within-tree variation cannot cause problems. Integrating from individual trees up to the plot scale appeared readily within reach since it would be practical to have several chambers per plot or, alternatively, to use the chamber to calibrate the heat pulse method (yet to be developed) to obtain the necessary areal sample.

The technique appeared ideally suited to our need for a small plot measurement of transpiration.

The Project 5 working group organized meetings in June and August 1978 to seek comment from all possible sources. There was general support for the proposal that the ventilated chamber technique be applied to testing rehabilitation strategies. A joint CSIRO, Forests Department, Alcoa committee was formed to initiate this work. A preliminary joint project was conceived (Bartle 1979, Greenwood 1979). The project aim was to compare total transpiration of an area of healthy jarrah forest with that of an area of bauxite pit plantation. CSIRO was to be responsible for the forest understorey, Forests Department, for the forest overstorey and Alcoa for the bauxite pit plantation. Integration of transpiration over time was to be done by interpolation of daily rates between measurement dates. Various options to improve this integration were available if required. Integration over area could be crudely carried out from the small samples proposed but it was planned that CSIRO would develop the heat pulse method to improve the sample size. The project was scheduled to be operational by December 1979 and to be of 1 - 2 years duration. It was understood that some further development work might be required on the chamber structures to scale them up to take jarrah poles up to 25m.

In the Forests Department area of the joint project eight trees were selected to be measured. They were three each of jarrah and marri and two banksia. It soon became apparent that we had been too ambitious, that the problems of scaling up to 25m had been underestimated and that the system had other unforeseen flaws. We failed to meet the December 1979 deadline and in fact only got five trees operational before deciding in mid winter 1980 that a complete redesign of the chamber system was required.

5. Redesign of the Chambers.

Major upgrading of the system was required because both the durability of the structures and the accuracy of the measurements were unsatisfactory.

The durability problem was especially apparent in the larger chambers. They were too prone to wind damage and excessive time and expense were being incurred in repair.

Two measurements are taken in the system to calculate total transpiration. They are the wind speed through the chamber and the change in water vapour concentration as the air stream passes over the tree. The wind speed measurement, done with a small hand held anemometer at the exit and of the chamber, gave very variable results. Discussion with experts suggested that quantification of wind speed by this method was not possible. The water vapour determinations gave results obscurred by the noise of the system and prone to erratic and unexplicable behaviour. Possible causes of these problems included the smallness of the signal against a sharply fluctuating background, incomplete understanding of the operation of the instrument used for water vapour measurement, poor homogenization of air within the system leading to difficulty in collecting a representative sample, smallness of the sample and contamination of the sample lines with water vapour condensation.

The 15 months from winter 1980 were spent on redesign and the building and testing of upgraded prototypes. The Alcoa workers who were also anxious to improve their chambers, retained the services of an engineering consultant to advise the project partners on the aerodynamic aspects of redesign. The most notable advances in design were the incorporation of a windspeed measuring station, slight pressurization of the chamber and big improvement in robustness. These and other de-bugging measures gave us confidence that the precision of our measurement of transpiration for a whole tree was ± 3%. The major aspects of redesign are set out in appendix 2. A description of the whole system is in appendix 3.

6. Use of the new chambers.

We had placed an overriding priority for the redesign on getting the best precision practically possible. The objective of this was to be able to detect small differences between vegetation types or treatments. A consequence of striving for precision was that the chambers became complex and costly requiring up to 8 man months each to build. With such elaborate structures there was no question of being able to build enough to get a sufficiently large sample for a direct areal estimate of transpiration. We were therefore dependent on the heat pulse (or other) method of scaling up over area. However, we were not hopeful that the heat-pulse method would be successfully developed. Preliminary work on wound response in jarrah and some other eucalypts suggested potentially large effects on the transmission of heat-pulses and consequent difficulties in standardizing the method (J.Tippett pers.comm.). It was apparent that all we had achieved was the development of a system able to give good measurements of transpiration for single trees. Our objective of getting a plot scale measurement was still a long way off. We therefore decided that for the present project we should focus on the processes of transpiration within the tree with a view to exploring predictive methods of evaluation.

This conclusion coincided with the first hard data to become available from which we could quantify the size of differences in transpiration that we were trying to detect (Peck et al, 1979; Loh & Stokes 1981). The CSIRO/PWD Collie catchments were designed to demonstrate catchment scale effects of various vegetation treatments. The catchments were also equipped with groundwater observation wells. From these wells the rate of groundwater accumulation after conversion from native forest to annual pasture, which is equivalent to the decrease in evapotranspiration, was found to be only several percent of total rainfall (Table 1).

TABLE I.

Change in Et with conversion to Pasture.

Catchment	Rainfall	Rate of GW rise	Et decrease.
	mm	mm yr^{-1}	% rainfall
Wights	1150	90	7.8
Lemon	750	36	4.8

(Adapted from Loh & Stokes 1981).

To base an evaluation method on a parameter that shows so little variation, even across its full range represented by the extremes of pasture and native forest, is somewhat optimistic. That the parameter is, in addition, difficult to accurately measure makes it quite unsound. The problems of measuring transpiration and the use of transpiration as an evaluation criterion were discussed at the recent Evapotranspiration Workshop at Bunbury. It was generally agreed that no method of measurement of transpiration had sufficient sensitivity for the task. Stewart (1982) suggested the limit of resolution with current technology was about 20%.

Thus our original objective of developing a small plot measurement of transpiration for direct empirical evaluation of rehabilitation treatments was revealed to be unattainable. Our switch to process oriented research was the only option open to make full use of our considerable investment in the chambers. This is tantamount to rejecting empirical methods and adopting predictive methods of evaluation. Since data on transpiration processes would not stand alone it also means a commitment to some form of water balance model to predict the outcome of rehabilitation treatments.

There remains some potential applications for direct plot scale measurement of transpiration with the chamber. In any situation where substantial differences are expected direct measurements could be useful. For example:-

(i) What peak transpiration rates are possible when water is not limiting as may occur when trees are being used to dewater a largely saturated profile.

(ii) What is the proportion of available water used by understorey Vs overstorey.

(iii) Are there large variations in the topographic distribution to total transpiration.

7. Water Balance Model.

Following the Evapotranspiration Workshop the Forests Department and Alcoa organized a meeting with four key researchers to critically review our approach to the problem of identifying suitable rehabilitation practices. These researchers were Dr. J.J. Landsberg, Chief of Division, Forest Research, CSIRO, Dr. P.Jarvis, Head, Department of Forestry and Natural Resources, University of Edinburgh; Dr. J.B. Stewart, Institute of Hydrology Wallingford; Dr. J.M. Roberts Institute of Hydrology Wallingford.

They were very critical of what they saw as a fragmented and inadequate attack on a very complex problem. They could see no merit in the bias we had set in research priorities based on the poorly documented jarrah model. For example, they felt our focus on the transpiration component of evapotranspiration was unbalanced since they could see scope to manipulate interception to favour a desirable water balance. They could see no alternative to the predictive/ modelling approach and advocated the development of a flexible water balance model. During its development it would serve to allocate, co-ordinate and integrate research across boundaries between the Departments and Institutions working on the problem, and to indicate the relative importance of various parts of the problem so that research input could be apportioned rationally. Eventually the model could be refined to the point where it would predict the water balance of any combination of treatment and site.

The outline of a water balance model was discussed. It was felt that the model should incorporate a range of time scales from 15 min (appropriate to interception/runoff processes) to daily (soil moisture accounting) to yearly (ground water recharge/discharge). Area scale should range from domains (within catchment units - say a bauxite pit) to be summed to a whole catchment. The model should aim to solve the water balance equation:-

$$P = I + E\ soil + T + \Delta S + R.O.$$

where P: rainfall
I: interception
E soil: evaporation from bare soil
T: transpiration
ΔS: change in soil water storage
R.O.: streamflow

Sub-models and tests for each parameter would need to be developed.

Landsberg offered CSIRO Division of Forest Research assistance in developing this model. This offer was subsequently formalized.

8. Use of the Chamber for the Transpiration Sub-model.

The ventilated chamber can be used as a large continuous flow porometer. In this mode it could be used to specify canopy conductance (gc) as a function of the major forces controlling transpiration i.e. radiation, vapour pressure deficit and leaf water potential. This can be done for any stage of the seasonal wetting/ drying cycle. The system is well adapted to specifying these relationships for any species within a mixed stand or for any layer within a multi layered stand.

9. Conclusion.

The proposed model provides a rational basis for maximizing the value of the process oriented data which can be produced by the ventilated chamber. Our present objective is to produce such data for one dominant and one co-dominant jarrah and possibly for one dominant marri as well.

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Appendix 1: The problem of species selection.

Some observers have assumed that the native forest water balance will be automatically restored by the replanting of introduced species during rehabilitation of disturbed jarrah forest (Peck 1979). There are two grounds for rejection of this assumption. Firstly, salinity is such a sensitive issue politically that there is little margin for error in prescribing rehabilitation practices. No substantial area of risk or doubt should be tolerated. Secondly, it is unsound in an ecologic sense to discount the likely importance of particular plant adaptations to the specific environmental characteristics of the jarrah forest region.

A summary of some of the environmental characteristics likely to require particular plant adaptations follows:-

(i) Infiltration into jarrah forest profiles is variable with some water penetrating rapidly to considerable depth (20m or more). Such deep infiltration occurs because water can bypass much of the soil mass by percolation down macropores, also known as preferred paths, conductive channels or root channels (Johnston et al in press, Sharma 1982, Dell et al in prep). Though the amount of water penetrating to depth is quite small (Loh and Stokes, 1981) and may be able to be minimized (eg. by maximizing interception), it appears that an ability to tap the full depth of the wetted profile will be an essential attribute of the major species to be used in rehabilitation. This depth may be substantial and must be tapped by way of the macropores (one per m^2) which imposes a root form constraint.

The macropores or root channels, though abundantly occupied by native forest roots, present a rather unattractive range of micro-environmental conditions. They are of low pH, high in available aluminium and salt, low in nutrients and possibly oxygen (Dell et al in prep).

Roots appear confined to the channels (except in profiles formed over dolerite parent rock) due to the high density of the surrounding matrix (Dell et al op cit). Thus roots in the channels cannot directly tap soil water in the adjacent matrix.

This is apparently done by development of a potential gradient and unsaturated flow from the matrix to channel. This suggests long water flow paths and small flux.

The efficient exploitation of the deep root channel environment may require specific adaptations in fine root systems.

(ii) Recent work on the mode of action of *Phytophthora cinnamomi* in the rapid death syndrome in jarrah indicates that shallow subsurface perched water can favour intense activity (Shea et al 1982). This can focus disease in descending roots at the points where they enter depressions/channels in the perching layer. This phenomenon may be general with rapid death being its most extreme expression. Even species considered tolerant of the disease could suffer damage to descending roots under some conditions, and long term impairment of their transpiration capacity.

This new information suggests that in rehabilitation all possible measures to reduce *P.cinnamomi* activity should be taken, and rehabilitation species should possess a better level of resistance than has previously been thought necessary.

To fully exploit this environment the chosen species must have good *P.cinnamomi* resistance, and be able to penetrate many meters into an inhospitable subsoil along numerous vertical channels in order to obtain a quite small benefit in water availability. There appears to be no cause for optimism in locating the ideal species.

Appendix II. Major aspects of redesign of the ventilated chamber

There were four major objectives in the redesign:-

(i) To make a more robust and durable chamber.
(ii) To internally pressurize the chamber.
(iii) To establish a satisfactory wind speed measurement station.
(iv) To be able to direct the air entering the chamber.

The rationale and method of meeting each one of these objectives will be discussed in turn:-

i) A more robust and durable chamber was required as it was apparent from the original chambers, especially the larger ones, that they would not last the life of the project. They were too prone to wind damage, and excessive time and expense was being incurred in repair. The new chamber has been reduced in size, both in height by enclosing only the canopy, and in circumference by tailoring the perimeter to match the cross sectional shape of the tree. No single face of plastic is now wider than 1.8m which appears to be the limit for the strength of the material. In addition to the contraction in size the chamber itself has been increased in strength by triple rather than single welded vertical seams along the lines of attachment to the slide wires. The only disadvantage of these alterations is that pumps must now be located above the ground which reduces their accessibility.

ii) The objective of operating the chamber with a positive internal pressure was to make the internal wind speed less prone to fluctuation caused by external winds. This would confer the additional advantage of making the operating chamber more resistant to wind damage. Pressurization was achieved by constructing a partial cover (lid) over the top of the chamber to reduce the opening to about 40% of the diameter. Since the lid could not be attached to the chamber, which has to be capable of being raised for operation and lowered when not in use, it was necessary to design a seal between the chamber and the fixed lid which would close automatically as the chamber was winched up into position by a ground operator.

This aspect of the redesign was a fundamental change. The previous chamber was not pressurized and could be serviced with simple, propellor fans. These fans cannot operate against a pressure head and are therefore of no further use. Axial flow fans with considerably larger power demands are required. This in turn means a switch to three phase power, the purchase of a new large alternator set and substantial upgrading to the electrical distribution system.

iii) Perhaps the major design deficiency in the original system was the lack of any provision for accurate wind speed measurement. Not only was this measurement subject to fluctuation due to external winds but the location and method of measurement were not satisfactory. Accurate measurements require a specific wind speed measurement station/s to be constructed. It is desirable to have only a single station with all air passing through it so that a single measurement point serves a whole chamber. Other necessary features are:-

- Relatively small diameter duct to lift wind speed to a level within the optimum range for measurement by suitable precision instruments.
- Sufficient duct length and/or flow modifying apparatus to generate very near lamina flow.
- Choice of an appropriate location and instrument for measurement.

Both intake and outlet ends of the chamber were considered for location of the wind speed measurement station. It was decided to equip the prototype new chamber with both so that their respective merits could be evaluated.

An intake end module was developed to incorporate a single large fan, a single length of duct with measurement station which then branched into four outlets to enter the chamber. This module meets all the criteria for satisfactory measurement as well as being economical on pumps and ductwork, easily installed and is standard for a wide range of chamber diameters. Very large chambers may require two modules.

The outlet end measurement station provided a greater challenge in design. It had the potential advantage of more available space for a greater duct length and therefore for more ideal wind speed measurement conditions. This could be achieved by turning outlet air from the lid exit through 180° and attaching the measurement duct to the scaffolding tower. This method of measurement also had obvious disadvantages. i.e. it would require more efficient sealing of the chamber to prevent loss due to leakage of air, it would contribute to greater resistance to wind flow through the system which would take extra fan power and exacerbate leakage, and it would also involve more elaborate construction. A conscientious attempt was made to construct an outlet measuring station but it proved impractical.

iv) A weakness in the previous system was that air was moved passively through the chamber. This allowed the air stream to follow the path of least resistance and to partially bypass the canopy. Wind directing grills have been built into the air entry boxes in the new chamber. Air is blown into the chamber and the air stream can be directed to actively ventilate the canopy. Though this may not be any improvement in simulating air movement under natural conditions it is expected to give better homogenization of air thus simplifying the collection of a representative sample for water vapour analysis.

Appendix III. A Ventilated Chamber for Tall Trees

ABSTRACT

A ventilated chamber design for trees up to 25m in height and 5m in crown diameter is described. An objective in the design was to produce a system capable of good precision in the determination of transpiration. This makes it suitable for calibration of heat pulse devices and for quantitative analysis of the water relations of whole trees. The precision is also appropriate for application to Western Australian hydrologic problems where minor changes in current evapotranspiration can be of major long term importance.

The design described in detail consists of a scaffolding support structure; a robust, telescoping, transparent plastic chamber enclosing only the canopy bearing portion of the trunk; and a ventilation system capable of slightly pressurizing the chamber as well as pushing ambient air through in volumes comparable to that naturally ventilating the canopy.

The parameters measured to derive total transpiration are air volume throughput and water vapour pressure increment. A long intake duct length provides a stable wind profile for measurement of volume throughput. Water vapour pressure increment is continuously recorded with an infra-red gas analyzer from homogenized air samples. Difficulty with the selection of a representative air sample on the exit side is overcome with a multiple point sampler whose intakes are distributed across the exit orifice in proportion to flow.

Costs of materials and construction of a large chamber are given.

1. INTRODUCTION

The ventilated chamber method is being widely used to gather information on evapotranspiration from plant communities in the South-West of Western Australia (Greenwood, 1982). In one major project the communities being investigated include jarrah (Eucalyptus marginata Sm) forest trees up to 25m in height and with a crown diameter of 5m.

The development of chamber design for these trees has extended over two years. Initially it was attempted to develop a relatively simple chamber appropriate to measuring a large enough sample of trees to obtain an areal estimate of transpiration. However, satisfactory standards of durability and sensitivity could not be attained with a 'simple' design. The project was reconsidered and it was decided to proceed with the development of a more sophisticated design. Fewer such chambers could be built due to their complexity and cost which meant that the objective of direct areal estimation had to be abandoned. However , the more precise measurement possible with the improved design and the smaller number of chambers to be operated opened other options:-

(i) The improved chamber could be used for accurate calibration of the heat pulse method which, when developed, could provide the required sample for areal estimation of transpiration.

(ii) The meteorological and physiological factors influencing transpiration could be more intensively monitored enabling quantitative analysis of the water relations of individual trees.

(iii) Future application of the ventilated chamber method is likely to be dependent on the resolution attainable. Peck and Hurle (1973) have shown that serious stream salinity problems in Western Australia can develop from a small (5 - 6% of rainfall) decrement in current evapotranspiration. To detect differences of this order calls for exceptional precision.

In this paper the design and operation of these large chambers is described.

2. CHAMBER DESIGN

2.1 The Scaffolding Support Structure

A free-standing symmetrical octagonal scaffolding tower is built around the tree extending some 3m above canopy top. The tower is of sufficient diameter to avoid damage to the tree swaying in high winds.

The structure consists of four equally spaced prefabricated frame scaffold columns joined on the internal and external perimeters by horizontal scaffold tube. Guy wires are attached to each column at two heights. Design and erection was done by a local firm. An objective in the design was to have a minimum of materials in the structure and to minimize disturbance to roots with footings. Slight deformation in the taller towers placed doubt on the soundness of the design and extra vertical and horizontal diagonal bracing was subsequently added.

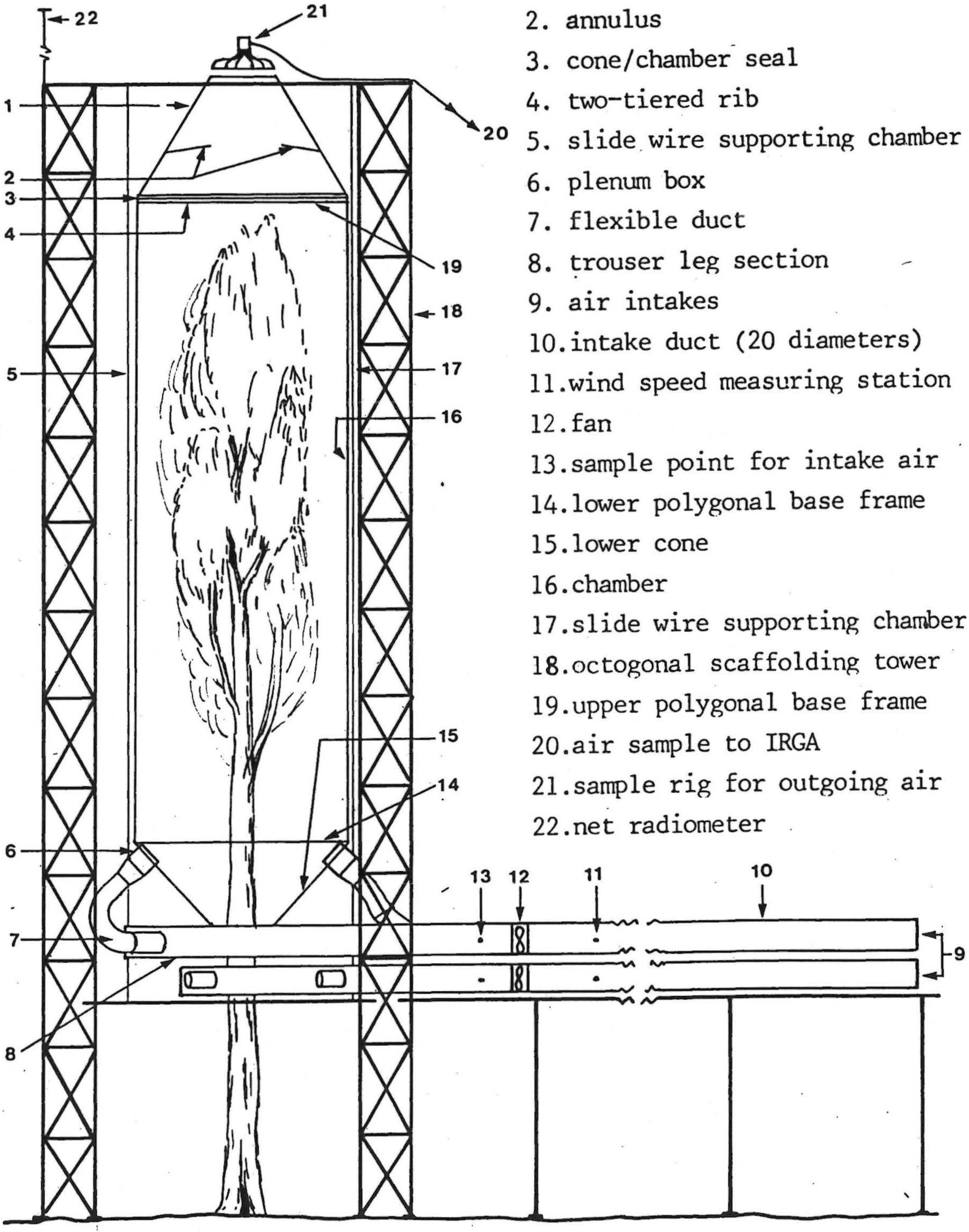
2.2 Chamber construction

The scaffolding tower is used to mount a tubular UV stablized, transparent polythene (I.C.I. 'Visqueen') chamber to enclose the canopy which extends over the upper half of the tree (Fig. I). The chamber is polygonal in cross-section and is tailored to closely match the canopy shape. No side exceeds 1.8m which is the limit for the strength of the material. Each corner is triple welded to produce a flap running the full height of the chamber, into which eyelets are inserted. The welds are arranged so that any pressure on the chamber exerts tension in the same plane as the welds. The eyelets are linked to taut vertical wires mounted within the tower. The chamber can be readily raised and lowered along these wires with a hand winch operated from ground level. Thus the tree need only be enclosed during measuring intervals and any cumulative bias due to enclosure can be minimized.

Immediately below the lowest branch the plastic chamber is sealed to a steel polygonal base of the same cross-sectional shape as the chamber. An inverted cone of reinforced plastic is sealed to the underside of this base and tied to the tree trunk with cord. Plenum boxes with direction grills are mounted and sealed into this cone to distribute a forced air stream up into the chamber.

At the top a permanent upright 'visqueen' plastic cone is mounted and sealed on a steel polygonal base. This reduces the top opening to about 0.4 diameters to pressurize the chamber during operation. Being at canopy top, the cone is exposed to high winds. It is reinforced with aluminium ribbing but may not withstand extreme storms. It has therefore been designed with a view to ease of replacement. Inside the cone at about mid height a flat plastic annulus is attached to flatten the velocity profile of the exit air stream to facilitate the collection of a representative air sample for measurement of water content.

FIG. I VENTILATED CHAMBER FOR LARGE TREES.



1. upper cone
2. annulus
3. cone/chamber seal
4. two-tiered rib
5. slide wire supporting chamber
6. plenum box
7. flexible duct
8. trouser leg section
9. air intakes
10. intake duct (20 diameters)
11. wind speed measuring station
12. fan
13. sample point for intake air
14. lower polygonal base frame
15. lower cone
16. chamber
17. slide wire supporting chamber
18. octogonal scaffolding tower
19. upper polygonal base frame
20. air sample to IRGA
21. sample rig for outgoing air
22. net radiometer

When the chamber is raised it must automatically seal onto the steel base of the top cone. To achieve this the upper perimeter of the plastic chamber is made rigid by, and sealed to, a two-tiered aluminium tubing rib some 20cm high. The lower level carries the wires by which the chamber is winched up and down. The upper level, shorter in perimeter and free of any obstruction around its circumference, seals into a rubber lined inverted channel mounted under the steel base of the cone.

2.3 Ventilation

The chamber has an open ventilation system i.e. ambient air is passed over the canopy then discharged to waste. The chamber air speed used (approximately $1 m\ sec^{-1}$) is of the same order as that naturally ventilating the canopy (Greenwood et al 1981).

Ventilation is carried out with a 7kW 760 mm diameter axial flow fan (Woods S type model 30J) mounted below the lower cone in a standard module with the following components in sequence:

(i) 15m (i.e. 20 diameters) of plain intake duct to provide a wind profile amenable to accurate measurement.

(ii) a wind speed measuring station 1.5m from the fan.

(iii) the fan

(iv) a trouser leg section with two outlets per leg to divide the air into four streams.

(v) flexible ducting to join the four outlets to four plenum boxes mounted in the lower cone.

The system is designed to give a duct air speed of approximately $20m\ sec^{-1}$ which is within the range suitable for accurate measurement with a Pitot tube and to give an average chamber air speed of approximately $1m\ sec^{-1}$ with a chamber static pressure of 50 Pa. Chambers with a cross-sectional area greater than $10m^2$ require two modules. Flexibility in adjusting wind speeds and pressures is available by regulation of top cone exit diameter and pitch of the fan blades. The slight pressurization of the chamber is designed to make the internal wind speed largely independent of external turbulence and to make the chamber robust enough to resist wind damage while, at the same time, not exceeding the structural limits of the plastic.

3. PARAMETERS MEASURED

Total transpiration is obtained from the product of air volume throughput and the increase in mass of water vapour in that air.

3.1 Air throughput

Air volume pumped through the system is determined from wind velocity and cross-sectional area of the intake duct(s) at the measuring station 1.5m upstream from the fan. Wind velocity is derived from air density and velocity pressure as specified by Daly (1978). Both air density and velocity pressure vary and must be regularly monitored. Air density is readily measured but velocity pressure can only be conveniently monitored by way of its relationship with duct static pressure. One of the main sources of variation in velocity pressure is the external wind speed and direction. Damping down this source of variation was one of the main objectives of slightly pressurizing the chamber.

3.2 Water mass increment

The increase in mass of water vapour in the air is derived from measurements of water vapour pressure increment made with an Analytical Development Corporation infra-red gas analyzer. Being an open system normal ambient fluctuations are observed in the intake air and these may considerably exceed the signal which is normally less than 0.2 mb. Precision in this measurement is improved by damping out these fluctuations by feeding the sample air volume (10 l min $^{-1}$) into a 20 l homogenizing chamber before subsampling for measurement.

A representative sample of intake air is readily collected downstream from the fan in the intake duct(s) where air is turbulently mixed.

Getting a representative sample of outgoing air is more difficult due to the formation of concentric layers of differing humidity and velocity in the exit cone reflecting the obstruction to flow by the canopy. This problem is solved by flattening the exit profile, as already described in section 2.2 and by collecting the sample from 64 intake points distributed across 16 concentric annuli in proportion to the volume throughput of each annulus.

4. COSTS

Approximate costs in 1982 Australian dollars for a chamber to equip a 25m x 5m tree are as follows:

scaffolding materials	8000
erection of scaffolding on contract	2000
plastic chamber mountings and cones	2000
duct work and fan (two modules)	6000
proportion of power generation cost	6000
TOTAL	$ 24000

Construction time is 8 man months.

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