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Cover Photograph: Tropical rainforest immersed in cloud at Bellenden Ker, north Queensland, Australia

Source: David McJannet

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Executive Summary

This technical report provides a detailed description of a method for estimating cloud interception inputs to tropical rainforests. The report includes two main sections; firstly a description of the field instrumentation required to measure water balance components, and secondly, a step by step description of the methodology used to calculate cloud interception from field measurements. The application of the method is demonstrated using field data from the Wet Tropics.
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1. Introduction

An understanding of the water balance of tropical rainforest is crucial for assessing the role that these forests play in regulating the delivery of water to rivers and streams. In order to understand the hydrology of rainforest systems it is essential to understand the processes controlling the amount of water delivered from the forest system (water yield). This can be achieved by determining the water balance of different forest types. The water balance of a forested system can be expressed by Equation 1:

\[ P_g = I + T + E_s + R + D + \delta S \]  

Equation 1

Where, \( P_g \) represents precipitation inputs to the forest system through rainfall, \( I \) is amount of precipitation intercepted by and evaporated from the canopy, \( T \) is transpiration of the forest, \( E_s \) is forest floor evaporation, \( R \) is runoff, \( D \) recharge and \( \delta S \) change in soil water storage.

Canopy interception is calculated as the difference between above canopy (gross) and below canopy (net) precipitation inputs. Net precipitation can be determined by measuring both the amount of water falling through the canopy, a process known as throughfall (\( T_f \)), and the amount of water running down stems and trunks of trees; a process known as stemflow (\( S_f \)).

In most hydrological studies gross precipitation is generally derived from rainfall alone, however, at higher altitude and exposure, rainforests can receive significant inputs of water in addition to that measured in a standard rain gauge. There are three main sources of this additional water, the first results from rain gauge wind-losses due to turbulence around the gauge (Førland et al. 1996), the second is due to wind blown (near horizontal) rain being intercepted on sloping land (e.g. de Lima 1990; Holwerda 2005; Sharon 1980), and the third results from cloud or fog droplets collecting on vegetation surfaces, a process commonly known as 'cloud interception' (e.g. Brujinzeel 2005; Clark et al. 1998; Holder 2003).

Theoretical methodologies based on wind characteristics and rainfall intensity (see Holwerda 2005) have been developed for correcting for the first two additional inputs, however, determining inputs from cloud interception remains 'notoriously difficult' (Brujinzeel 2005). Including rainfall adjusted for wind losses and slope effects (\( P_{ga} \)), and cloud interception inputs (\( P_c \)), results in a revised representation of the water balance as is demonstrated in Equation 2. Theoretical corrections to rainfall will be outlined below, however, estimation of the additional water input through cloud interception is the main subject of this report.

\[ (P_{ga} + P_c) = I + T + E_s + R + D + \delta S \]  

Equation 2

A number of hydrological studies in high altitude tropical rainforest from around the world report considerable contributions of additional water through cloud interception (see Brujinzeel 2005). The higher altitude rainforests (>1000 m) in the Wet Tropics are subject to frequent immersion in cloud and exposure to prevailing winds, therefore, to correctly estimate the water balance any cloud interception must be accounted for. Quantifying cloud interception is not only important for hydrological reasons, it is also believed to be an important process in ecological studies. The distribution of a number of plant and animal species in the Wet Tropics is believed to be party dependent on the availability of cool, moist conditions which typify forested environments subjected to frequent immersion in cloud (e.g. Williams et al. 2003).

Studies of cloud interception have generally relied on some form of a gauge for assessing precipitation inputs not collected in a standard rain gauge (e.g. Cavelier et al. 1996; Juvik et al. 1995; Schemenauer et al. 1994). A number of different 'calibration' techniques for these gauges which enable estimation of cloud interception have been reported in the literature (e.g. Cavelier et al. 1989; Hafkenscheid 2000; Holder 2003; Juvik et al. 1974), however, the ability of such gauges to mimic the capture of cloud interception in a real forest canopy under...
variable climatic conditions is questionable. Each forest site will also represent a distinct set of conditions (e.g. forest structure and climate) that will prohibit standardisation of cloud interception gauge measurements (Bruijnzeel 2001). The ‘direct’ use of gauges for estimating cloud interception is, therefore, fraught with difficulties and uncertainty. However, ‘indirect’ uses of cloud interception gauges in methodologies such as that employed by Hutley et al. (1997) or techniques based on comparison of the canopy water balance under conditions with and without cloud interception, such as those described by Harr (1982) and Sigmon et al. (1989), may provide a more reliable means of quantifying cloud interception. Bruijnzeel (2005) and Bruijnzeel et al. (2005) provide a comprehensive review of techniques for estimating cloud interception and the limitations and advantages of each.
2. Field measurement methodology

The field measurement methodologies described below are those employed in a number of water balance studies undertaken in the Wet Tropics of north Queensland. In some cases alternative measurement methodologies are available and those seeking to determine cloud interception should choose techniques best suited to their needs. The technique that we present here requires measurements of throughfall, stemflow, rainfall and the occurrence of cloud interception.

2.1. Rainfall

Measurements of rainfall for Wet Tropics forests were undertaken using tipping bucket rain gauges (Figure 1). Such gauges are commercially available in pre-calibrated tip increments (i.e. 0.2 mm, 0.5 mm) from suppliers such as Hydrological Services (Sydney, Australia). Rain gauges were installed in an opening adjacent to the forest at each site in order to obtain measurements equivalent to above canopy rainfall. Gauges were installed at a height of 2 m to avoid damage by rodents and sheltering by vegetation. As a rule of thumb rain gauges should be located at least three times the height of the forest canopy from the forest edge. Rainfall was recorded using a Hobo Event logger (Onset Corporation, Massachusetts).

![Tipping Bucket rain gauge](image)

Figure 1. Tipping Bucket rain gauge installed along side forest to measure ‘above’ canopy rainfall.

As several of the sites we studied were very windy, measurements were corrected for losses due to turbulence around the gauge using half hourly measurements of wind speed and rainfall intensity in the method described by Holwerda (2005). When rain falls during windy conditions on a sloping surface, there is a further additional input of water to the surface as ‘horizontal rain’ (Holwerda 2005; Sharon 1980). The amount of horizontal rainfall depends on the inclination and direction of incident rain and the slope and aspect of surface it impinges on. We used half hourly rainfall, wind speed and wind direction data in the trigonometric model described by Holwerda (2005) to derive horizontal rain our study sites. Adding wind-losses and horizontal rain to the measured rainfall \(P_g\), gives adjusted rainfall inputs, \(P_{ga}\).
2.2. Throughfall

The throughfall measurement system we employed collected water using a number of long troughs (Figure 2). Troughs were constructed from 6.0 m lengths of 100 mm diameter PVC pipe which were cut in half longitudinally. Each throughfall measurement system consisted of between 4 and 6 troughs which drained into a central reservoir with a capacity of 70 l. These throughfall systems had an overall collection area of between 2.4 to 3.6 m². From the central reservoir the water drained to a large custom built tipping bucket (Figure 3) via a 25 mm outlet. The reservoir and small outlet regulated the flow of water from the troughs so that large events could be measured by the tipping bucket. Calibration of tipping bucket volume for each throughfall system produced volumes ranging between 1.8 - 2.1 l per tip. The tipping bucket was housed in a plastic box (Figure 4) and the water from the reservoir drained through a tube positioned directly over the centre of the tipping mechanism. Tips of the bucket mechanism were recorded using a reed switch connected to a Hobo Event logger (Onset Corporation, Massachusetts). Throughfall systems were located randomly beneath the forest canopy at locations at least 50 m from the forest edge. Replication of this throughfall design (McJannet et al. 2006a) gives confidence in the ability of this technique to represent throughfall processes in rainforest. The event logger was stored in a water tight PVC container to protect it from rodents and water damage.

Figure 2. Throughfall troughs and collection reservoir positioned beneath the forest canopy.

Figure 3. Large tipping bucket gauge (~2 litre capacity) used for measuring the volume of water collected by either stemflow or throughfall systems.
Figure 4. Box enclosing tipping bucket gauge to prevent addition of rain.

Depending on site characteristics, some troughs were joined to create 12 m long troughs. The troughs and central reservoirs were fitted with fine wire 10 x 10 mm mesh covers to prevent collection of leaf litter or debris which could cause blockages at the reservoir outlet. Troughs were installed at angles greater than 10º to the horizontal to ensure efficient drainage. Draining water quickly reduces the potential for water in troughs to evaporate and also minimises the likelihood of losses from rain drop splash which is more severe when water ponds in the troughs. Horizontal collection area was calculated by accounting for installation angle of each trough. Troughs were mounted on brackets fixed to steel posts.

This automated technique enables the large volume of water collected during high intensity rainfall events to be measured without the need for water storage, thus greatly increasing the time between site visits. Throughfall measurements were scaled up to the plot level in the same way as a tipping bucket rain gauge. The volume of water collected was divided by the collection area to give a depth equivalent. This resulted in a throughfall measurement resolution of between 0.5-1.0 mm.

2.3. Stemflow

Sample tree selection for measuring stemflow involved surveying each site for the distribution of tree sizes and then choosing a representative sub-set (10 -15 trees) of these. Tree size was measured as the diameter at breast height (DBH). Each sample tree was fitted with a spiral collar made from CVT (Clear Vinyl Tubing) hose with an internal diameter of 32 mm. A length of tubing equivalent to 2.3 times the DBH of the tree plus an additional 30 cm was cut for each tree. All of the hose apart from the last 30cm was split longitudinally using a specially designed cutter. This cutter ensured that both split pieces of hose had the same dimensions. The un-split portion of the hose was then fixed to the tree using a galvanised saddle and nails. Each half of the remaining hose was then fixed onto the tree in an upward spiralling direction using galvanised nails. The two halves of the hose overlapped at the back of the tree and the excess hose was removed. The hose was then sealed to the bark of the tree using silicon sealant. The seal of the collar with the tree was maintained over time by regularly applying a coating of water proof grease.

Once collars were fixed to all selected trees, the entire system was connected together using 40 mm PVC tubing. The central line drained into a covered 70 l plastic storage reservoir. As with the throughfall design, an outlet fitted with 25mm PVC pipe regulated the flow of water to a tipping bucket measurement system (Figure 3). Most systems were also fitted with an
additional 70 l plastic storage reservoir which was used as an overflow if the main reservoir overtopped in large events. This additional reservoir was also connected to the tipping bucket.

Figure 5. Stemflow collar fitted to tree and connected to drainage network.

Tree basal area was used to scale from stemflow volume from the sample trees to stemflow depth (mm) for each site. The volume of water collected from the sample trees was expressed as an equivalent volume per m$^2$ of basal area. This value was then multiplied by the site basal area to determine stemflow for each site. This technique and scaling methodology has been tested through replication and has been shown to be reliable (McJannet et al. 2006a).

2.4. Cloud interception

The occurrence (not the amount) of cloud interception was measured using a gauge as shown in Figure 6. These cloud interception gauges were similar to that described by Juvik and Ekern (1978) and Juvik and Nullet (1995). The collecting surface is a louvred aluminium shade screen (Phifer Shadescreen, Alabama) with a diameter of 0.16 m and a height of 0.2 m. The cylindrical shape of the mesh ensures measurements are made irrespective of wind direction. The louvred shade screen cylinder is attached to the underside of a 0.8 by 0.8 m marine ply board. Rain falling at an angle less than 60º from vertical is not collected on the mesh. The instrument therefore collects steeply angled (near horizontal) rain and passing cloud droplets which blow through the cylinder and collect on the mesh. From the mesh, the collected water drains into a 0.5 mm tipping bucket rain gauge (TB3, Hydrological Services, Sydney, Australia). Cloud interception gauges were installed in exposed areas at each site at a height of 2.5 m. The occurrence of cloud interception was recorded using a Hobo Event logger (Onset Corporation, Massachusetts).
Figure 6. Cloud interception gauge illustrating the mesh collecting surface and hose for draining collected water to a covered tipping bucket rain gauge.
3. Estimating cloud interception

Using the measurement techniques described above it is possible to calculate the contribution of cloud interception to a forest site using the canopy water balance method. To illustrate the process, data from a forest site at Upper Barron will be used. Upper Barron is located on the Atherton Tablelands in the Longlands Gap State Forest (17°27.1 S 145°29.7 E). This site is located 30 km from the coast at an altitude of 1050 m and has an easterly aspect with a slope of 20° and is subject to frequent immersion in cloud.

In order to determine the cloud interception rate ($P_c$) on the canopy we prefer an 'indirect' use of the cloud interception gauge which is based on a combination of rainfall, throughfall and stemflow measurements. The technique used is similar to that used by Harr (1982), Sigmon et al. (1989) and Hutley et al. (1997) and relies on the comparison of the canopy water balance under conditions with and without cloud interception.

Using field data from the Upper Barron (Figure 7) it can be seen that the relationship between daily net precipitation ($S_f + T_f$) and rainfall ($P_{ga}$) shows a lot of scatter. The reason for this is because rainfall does not account for all of the water inputs to the forest.

![Figure 7. Relationship between daily net precipitation (stemflow plus throughfall) and daily precipitation.](image)

If we use the cloud interception gauge to group the measurements into days with and without cloud interception we can see two distinct groups of data (Figure 8). On days when no cloud interception was recorded (i.e. $P_{ga} =$ gross precipitation) a strong relationship exists between $P_{ga}$ and ($S_f + T_f$). It is possible to fit a linear regression to these data points giving the regression shown as follows:

$$P_{ga} = 1.14(S_f + T_f) + 3.58$$

Equation 3
Since $P_c$ rarely occurs in the absence of $P_{ga}$ ($<5\%$ of the time), it will be intercepted and evaporated in the same way as $P_{ga}$. Therefore, a plot of $(S_f + T_f)$ against $(P_{ga} + P_c)$ would fall on the same line as Equation 3. In other words, gross and net precipitation always show the same relationship regardless of the source of precipitation input. This means that when cloud interception occurs, $P_c$ can be estimated as the difference between that predicted by Equation 3 and total daily $P_{ga}$. This process is shown in Figure 9 where an example data point is used to illustrate the canopy water balance methodology. Rearranging Equation 3 it is possible to determine $P_c$ as follows:

$$P_c = \{1.14(S_f + T_f) + 3.58\} - P_{ga}$$

Equation 4

This method for estimating $P_c$ only applies to precipitation events that are large enough to saturate the canopy and small precipitation events ($P_{ga} + P_c < 5\, \text{mm}$) are therefore ignored in fitting Equation 3. On days where the input to the canopy is less than 5 mm, $(S_f + T_f)$ is assumed to be equal to the rain which falls directly to the forest floor without touching the canopy (the ‘free throughfall coefficient’, (Gash et al. 1995)) and is calculated as the product of $P_{ga}$ and the canopy gap fraction. A canopy gap fraction of 0.04 was determined for Upper Barron using digital analysis of hemispherical photographs (Frazer et al. 1999). When cloud interception contributes to these small precipitation events it can be calculated as follows:

$$P_c = \{(1/0.04)(S_f + T_f)\} - P_{ga}$$

Equation 5
Figure 9. Method by which linear regression line describing the relationship between net and gross precipitation is used to calculate cloud interception. The data points represent days where cloud interception gauge measurements were made. The methodology is illustrated using an example data point (shown in red).

In order to demonstrate the uncertainty involved in calculating cloud interception from direct ‘calibration’ of cloud interception gauges we compared estimates of $P_c$ derived from the canopy water balance methodology described in this report with the corresponding ‘catch’ of the cloud interception gauge at the Upper Barron site. The catch of the gauge was defined by the volume of water collected divided by the collection area of the aluminium mesh (1005cm$^2$). A comparison of the two methods is shown in Figure 10. From this figure we can see that there is a positive relationship between $P_c$ and gauge catch. Since the gauge catches a mixture of cloud droplets and wind blown rain, the relationship may be affected by wind speed and rainfall intensity (c.f. Clark et al. 1998; Hutley et al. 1997). There is some evidence for this in where the slope of the linear regression of gauge catch and $P_c$ increases with wind speed. This is consistent with the expectation that higher wind speeds increase the amount of rain that falls at steep angles from the vertical and would hence be caught by the cloud interception gauge.

Statistical analysis of the difference in the slopes of the linear regressions (Zar 1999) in Figure 10 indicates that all slopes are significantly different from each other ($p<0.05$). Although the slopes are statistically different there is still a large amount of scatter in the relationship between $P_c$ and gauge catch. The scatter in the relationship is likely to be the result of the inability of the cloud interception gauge to accurately mimic the capture of cloud droplets in real forest canopies under variable climatic conditions. The observed scatter may also be because the cloud interception gauge will also capture steeply angled rainfall in very windy conditions, thus resulting in overestimates of cloud interception inputs. A much stronger relationship between the two variables would be necessary for a higher level of confidence to be gained in developing a ‘calibration’ for the gauge. Further analyses of these types of data on a sub-daily and individual storm basis may reveal more meaningful relationships.
To illustrate the importance of cloud interception to water inputs to the forest at Upper Barron, monthly totals of $P_{ga}$ and $P_c$ are shown for a 20 month period in Figure 11. It can be seen from this figure that failure to account for $P_c$ would have lead to large under-estimates of actual forest water inputs. Addition of $P_c$ is particularly important during the dry season months where as much as 66% of gross precipitation was sourced from $P_c$. Over the entire 1309 day study cloud interception at this site contributed 30% of gross precipitation (McJannet et al. 2006b).
4. Summary

In this report we have described the measurement methodologies and analysis techniques used to quantify cloud interception inputs to forested systems. In contrast to alternative gauge calibration methodologies the canopy water balance methodology uses the cloud interception gauge only to define the occurrence of cloud interception. This indirect use of the cloud interception gauge overcomes any problems associated with how well the gauge mimics the cloud interception catching capacity of the forest.

This method requires measurement of the following parameters:

1. Total daily rainfall
2. Total daily throughfall
3. Total daily stemflow
4. Occurrence of cloud interception

The steps for estimating daily $P_c$ are:

1. Split net precipitation data into days with and without $P_c$ based on cloud interception gauge measurements.
2. Fit a linear regression to the days where precipitation input is from $P_{ga}$ alone and $P_{ga} > 5$ mm.
3. Estimate $P_c$ from the difference between daily $P_{ga}$ and that predicted by the linear regression.
4. On days where the input to the canopy is less than 5 mm, calculate $P_c$ using Equation 5 which requires measurements of $(S_f + T_f)$, $P_{ga}$ and canopy gap fraction.

The canopy water balance methodology works well when there are significant differences in $(S_f + T_f)$ between days with and without cloud interception, however, at locations where cloud interception is limited, regressions between $P_{ga}$ and $(S_f + T_f)$ may not be significantly different, thus rendering the approach meaningless from a statistical point of view (Bruijnzeel 2001).
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