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A flexible and easily constructed heat pulse system for monitoring sapflow in trees

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Cover Photograph:

Description: The heat pulse system installed in the trunk of a tree

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Executive Summary

The heat pulse technique is, essentially, a tracing technique, whereby, the rate of water flow through the trunk of a tree is inferred by tracking the rate of movement of a pulse of heat injected into the conducting tissue. The movement of the pulse of heat is measured using temperature sensing probes inserted into the tree in locations above and below a heating probe. This monitoring arrangement compensates for the process of heat diffusion and allows heat convection to be isolated and measured. Using a series of well established corrections, the velocity of the pulse of heat can be converted to a sap flow velocity and, hence, tree water use.

Our extensive use of commercially available heat pulse systems, and continual frustration at the limitations of these systems, lead us to the development of the technique that we describe in this report. For those with a reasonable level of technical competency and a good understanding of heat pulse theory, we believe that our system will provide a flexible, robust, user serviceable, means by which to measure tree water use.

In this report we present the background theory behind heat pulse measurements and outline the procedures undertaken to determine sap flow rates from heat pulse measurements. We detail the hardware and software requirements for the system that we have developed and provide useful information for programming data loggers, installing equipment in the field and collecting high quality data.

The heat pulse system that we describe in this report has the following strengths:

- All system components are readily available, easily sourced, and have a proven track record of field performance.
- The entire system is controlled by a single commonly used data logger.
- The wiring configuration is designed to minimise electronic interference.
- Multiple concurrent measurements are made possible through the use of a multiplexer.
- System power consumption is low.
- System errors can be diagnosed and fixed in the field.
- Measurement resolution is very good.
- Probes and heaters are made from corrosion resistant stainless steel.
- Probe spacings can be changed for different applications.
- System is highly flexible allowing a modem and numerous additional sensors to be added.

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Introduction

Researchers and resource managers in a wide range of disciplines are interested in the rate at which trees use water. The water use of trees, or transpiration, is linked to their survival and growth, and transpiration is a critical component of the hydrologic cycle. The most common way to directly measure the transpiration rate of trees is to measure the amount of water passing through the trunk. Automated methods for doing this are limited and usually require application of heat to detect rates of water movement through the sapwood of trees. Two such methods are the ‘heat balance’ and ‘heat pulse’ techniques. Heat balance techniques are based around measurements of the conservation of applied heat (e.g. Baker and van Bavel 1987, Sakuratani 1981, Steinberg *et al.* 1989), while heat pulse techniques use heat as a tracer (e.g. Doley and Grieve 1966, Edwards and Warwick 1984,). In this report we describe a system that uses heat pulse methodology.

The heat pulse methodology was first developed in 1937 by Huber and Schmidt and has undergone improvement and refinement since this time. The heat pulse technique has had application in studies of forest hydrology (e.g. Becker *et al*. 1996, Vertessy *et al.* 1995), plantation water use (e.g. Hatton and Vertessy 1990, Morris *et al.* 1998, David *et al.* 1997), horticulture (Green and Clothier 1988, Sdoodee and Wongwongaree 2002) and tree physiology (Burgess *et al.* 2001, Scholz *et al.* 2002). The heat pulse method uses a heating probe, inserted into the trunk of a tree, to inject of a short (usually <2 sec) pulse of heat into the conducting tissue of the tree (sapwood). This pulse of heat can then be used to infer the rate of movement of water up the trunk of the tree by the use of temperature sensing probes inserted into the tree in locations above and below the heating probe. This monitoring arrangement compensates for the process of heat diffusion and allows heat convection to be isolated and measured. It is for this reason that the technique is sometimes referred to as the ‘compensation method’.

Commercially produced heat pulse measurement systems are available from Greenspan Technology, Australia (Sapflow Sensors) and Edwards Industries, New Zealand (Heat Pulser System). We have used both of these systems extensively in field situations but the limitations of these commercial systems lead us to develop the alternative technique that we describe in this report. To overcome commercial system limitations, our system is designed to be:

- Cheaper and based around commonly used, easily obtainable components
- Serviceable in the field by the user
- Capable of withstanding harsh environmental conditions
- Controlled by software regularly updated to meet new operating system requirements
- Capable of cancelling electronic noise
- Able to be accessed and controlled using telemetry
- Capable of measuring additional electronic sensors

We acknowledge that the methodology and instrumentation we describe in this report is by no means new, it is simply a variation on existing designs that we believe to be more flexible and robust than existing heat pulse measurement systems.

The system that we describe requires a reasonable degree of technical competency for assembly, installation and data collection and analysis, therefore, we recommend that those not confident in their ability should consider off-the-shelf commercially available systems which include pre-made sensors and data analysis software.

In this report we use the unified nomenclature and symbols for sap flow measurements proposed by Edwards *et al.* 1996.

1 Heat pulse methodology

The heat pulse technique is essentially a tracing technique, whereby, the rate of water movement through the trunk of a tree is inferred by tracking the rate of movement of a pulse of heat injected into the conducting tissue of a tree (Figure 1). The process of calculating heat pulse velocity and the subsequent steps involved in calculating tree water use are outlined in the following sections.

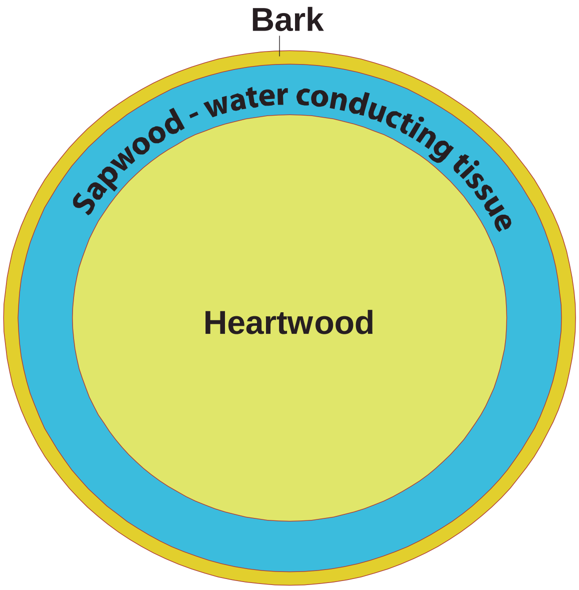


Figure 1. Cross section through the trunk of a tree showing the bark, sapwood and heartwood zones.

The configuration of the three probe measurement system we use and the way in which it is installed into the sapwood of a tree is shown in Figure 2.

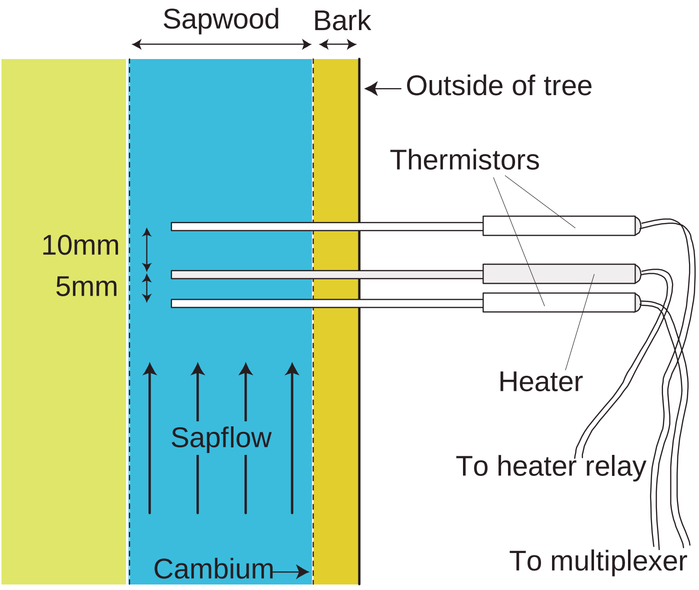


Figure 2. Heat pulse thermistors and heater installed in sapwood of a tree.

1.1 Calculating heat pulse velocity

Heat pulse velocity (v_h) is calculated by injecting a short pulse of heat (usually <2 sec) through the heater probe into the sapwood. The upstream sensor (ie. lowest) is the first to detect the heat change. Immediately after the heat pulse is injected into the tree (*T1*) there is an initial steep rise in the difference between upstream and downstream sensors as heat in the sapwood spreads through diffusion and sapflow (Figure 3). The downstream (upper) sensor then warms relative to the upstream sensor and the curve falls back to a baseline equilibrium of equal temperature (*T2*). The important value in the sequence is *T2*. The distance (*D*) travelled by the heat pulse at this time is the displacement, which is equal to the distance from the heater to the midpoint between the two sensors (2.5 mm in Figure 2). The heat pulse velocity (v_h) is then calculated using Equation 1.

$$v_h = D/T2$$

Equation 1

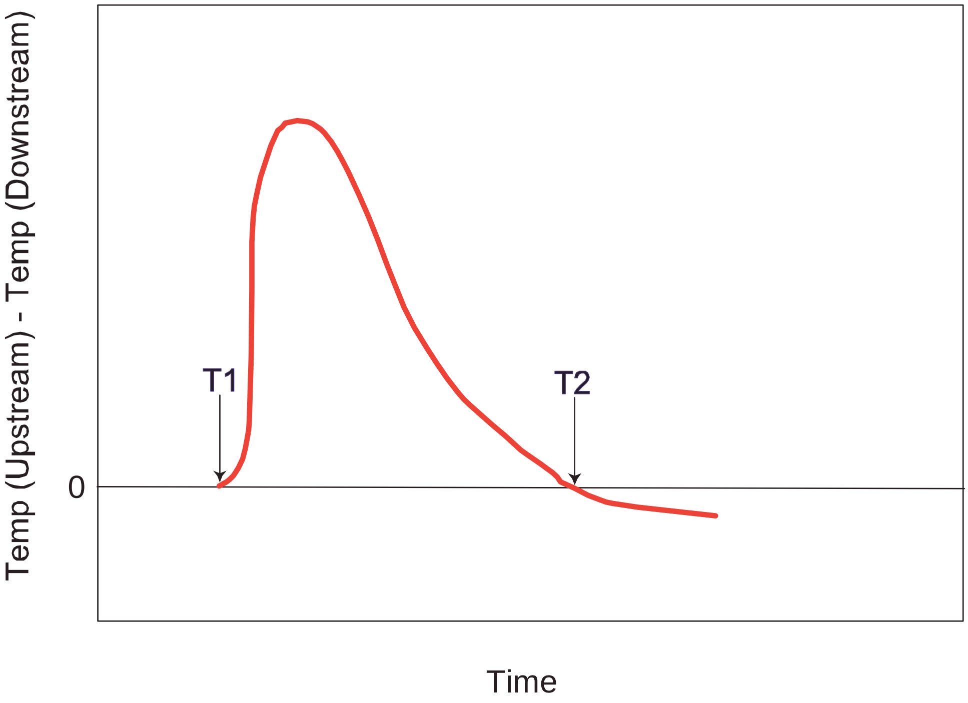


Figure 3. Response of sensors to heat pulse.

1.2 Correcting heat pulse velocity for wounding effects

Drilling holes and inserting probes into the tree disturbs the sapwood capillaries in the local region around the probe, therefore, sap velocity also needs to be adjusted to account for wounding effects, v_h. Hatton and Wu (1995) and Marshall (1992) found that the size of wounds stabilise over time. Appropriate corrections need to be made based on measured wound diameters (*w*) and the numerical solutions created by Swanson and Whitfield (1981). Techniques for measuring wound diameters and typical wound values are given in Hatton and Wu (1995) and Marshall (1992).

$$v_c = b1 + b2v_h + b3(v_h)^2$$

Equation 2

If v_h is **greater** than 3 cm/h then the coefficients *b*1, *b*2 and *b*3 can be calculated from the following quadratic equations based on the measurements of Swanson and Whitfield (1981).

$$b1 = -0.1175w^2 + 1.46w - 1.6432$$ **Equation 3**

$$b2 = 0.0721w^2 - 0.6441w + 2.2024$$ **Equation 4**

$$b3 = 0.0239w^2 - 0.0319w + 0.0259$$ **Equation 5**

N.B. *w* in equations 3 to 5 is mm. Original Swanson and Whitfield (1981) calculations are in cm.

If v_h is **less** than 3cm/h then the coefficients *b*1, *b*2 and *b*3 can be calculated from the following quadratic equations also based on the measurements of Swanson and Whitfield (1981).

$$b1 = 0.0259w^2 - 0.0397w - 0.4409$$ **Equation 6**

$$b2 = 0.0811w^2 - 0.1298w + 1.3316$$ **Equation 7**

$$b3 = 0.051w^2 - 0.0003w + 0.0166$$ **Equation 8**

N.B. *w* in equations 6 to 8 is mm. Original Swanson and Whitfield (1981) calculations are in cm.

1.3 Converting heat pulse velocity to sap velocity

The v_c is not equal to sap velocity , therefore, we need to apply the algorithm of Edwards and Warwick (1984) to correct our measurements for the actual sap velocity within lumens, v_l (Equation 9). This algorithm is based on volume fractions of wood (V_{wood}) and water (V_{water}) determined from samples of sapwood obtained using an increment corer.

$$v_l = v_c(k \cdot V_{wood} + V_{water})$$ **Equation 9**

The value *k* is a coefficient related to the heat capacities of wood and water at a given temperature (*t*). It is calculated using Equation 10.

$$k = 0.4 + 0.00214t - 0.000006t^2$$ **Equation 10**

1.4 Converting corrected sap velocity to tree water use

Multiple sets of heat pulse sensors, placed at varying depths within the sapwood, are used to account for variation in sap velocity with sapwood depth in any given tree. These simultaneous measurements of sap velocity are usually converted to sapflow using one of two techniques from the literature.

The first technique is that of Edwards and Warwick (1984). This technique uses a fitted polynomial of depth vs. velocity integrated around the annulus of sapwood. The second technique is that of Hatton *et al.* (1990). This technique is based on mean velocity weighted by the area of the sapwood annuli sampled by each sensor. The user of the heat pulse system should use the technique best suited to their needs. We use the technique of Hatton *et al.* (1990) for tree water use calculations as we also employ techniques from this paper to specify sensor depths for representing equal areas of sapwood. Alternatively, Benyon (1999) suggests dividing the sapwood area into concentric rings of equal area, then a probe is assigned to each ring. The implant depth of each sensor within its allocated ring is determined randomly

1.5 Scaling tree water use to stand water use

In many studies, particularly hydrological investigations, it is desirable to express the water use of a forest stand in hydrological depth units (e.g. mm/d). It is usually not practical to monitor the water use of every tree in a given area, therefore, sample trees need to be selected and measured and a scalar of water use (usually based on a measure of tree size) needs to be applied to all trees in a stand of known area. Hatton et al. (1995) provide a review of potential techniques. Leaf area, diameter, and sapwood area have all been used as scalars of water use (e.g. Hatton and Wu 1995, Vertessy *et al.* 1996, Benyon 1999, McJannet *et al*. 2000, Morris *et al.* 2004).

In our research in rainforest we find that tree diameter at breast height (DBH =1.3m) is a powerful scalar that can be easily measured. An example of the types of relationships we get between daily tree water use and DBH is shown in Figure 4. Other studies have found much simpler relationships which substantially reduce the number of calculations required. For example, Benyon (1999), working in a plantation where tree size is reasonably uniform, found that daily stand transpiration could be calculated as the product of the mean sap velocity of the sample trees and stand sapwood area. Numerous other techniques are reported throughout the literature.

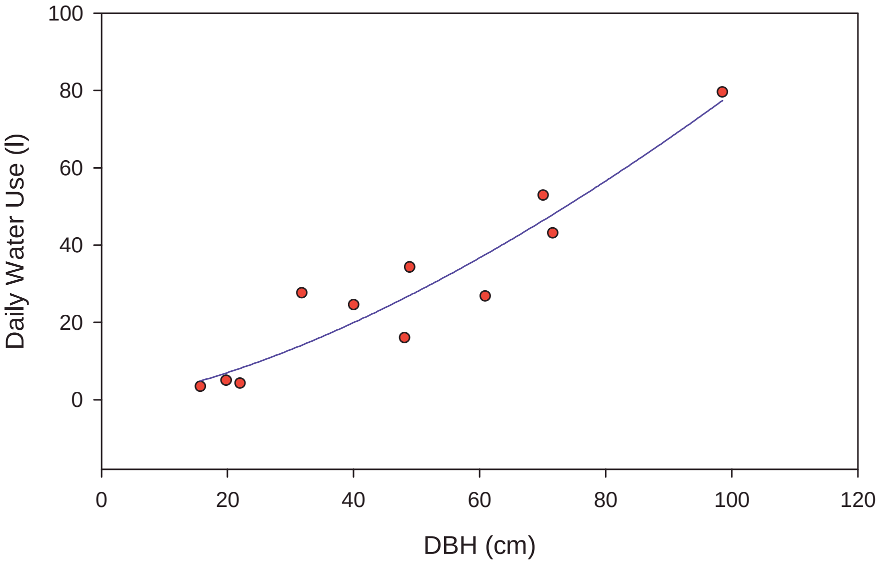


Figure 4. Relationship between DBH and daily water use showing the strength of tree size as a scalar.

2 System Design

2.1 Hardware configuration

The heat pulse sapflow system that we describe here is controlled by a Campbell Scientific CR10X data logger. The CR10X data logger has the capability to control the full heat pulse system plus a large number of additional sensors. The logger can also be easily accessed and controlled remotely by attaching a separately available modem.

The system that we describe here is powered by a single 100Ah deep cycle battery which can be replaced periodically or, preferably, charged by a solar array. Although power consumption is not large, the periodic heat pulsing of the system puts a large current drain on the batteries for a short period. For our applications in north Queensland, we use a 60W solar panel to keep the battery charged.

The system described in this report can make 16 concurrent measurements of heat pulse velocity and it does this through the use of a Campbell Scientific AM16/32 multiplexer set to 16 x 4 wire differential measurements. The multiplexer is controlled by the Campbell Scientific CR10X data logger through the wiring configuration shown in Table 1. Two wires are for the measurement of the differential signal and the other two provide excitation from one of the CR10X excitation channels.

The AM16/32 is a relay multiplexer which has the advantage of good isolation between channels and 4 wire switching, however, there are disadvantages in using such mechanical devices. With a mechanical relay, one of the manufacturers specifications is the Mean Time Between failure (MTBF) for the mechanical switching. It was calculated that for a mean measurement time of 300 seconds, cycled at 20ms per probe for 16 probes, run every 30 minutes, that the lifetime of the relays and would be 3 years. Should a relay fail, it is possible to get it replaced by Campbell Scientific.

Table 1. Campbell Scientific CR10X to Campbell Scientific AM16/32 wiring.

CR10 X		AM 16/32
E1	→	Com Even H
AG	→	Com Even L
Diff 1L	→	Com Odd L
Diff 1H	→	Com Odd H
G	→	Shield
(SDM) 12V	→	12V
G	→	GND
C1	→	Res
C2	→	CLK

Each of the 16 channels of the Campbell Scientific AM16/32 is used to measure one pair of thermistors probes (eg. upper and lower sensors of a heat pulse set). The 10KOhm stainless steel thermistor probes are constructed and supplied by OneTemp Pty Ltd, Australia (Product Code - 22THR316-65-150PTFE-10K). The construction details for the 10KOhm thermistors used is shown in Figure 5. The probes are made from 316 stainless steel which provides very high corrosion resistance.

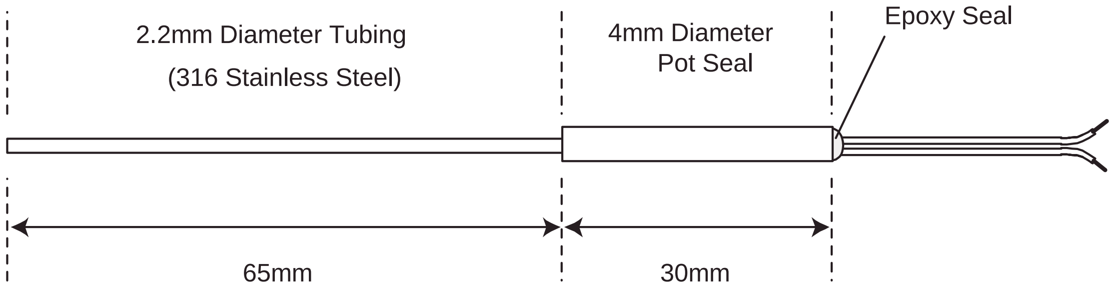


Figure 5. Thermistor dimensions, and materials.

Thermistors are connected to the multiplexer using twin twisted pair individually shielded cable (Belden Pty Ltd, Part No. 8732). The cable is more expensive than other products available but it has a higher quality and greater ability to shield out interference.

The thermistors are arranged in a conventional full bridge arrangement, as shown in Figure 6. This arrangement was found to work well in noisy environments as the common mode noise was cancelled by use of the differential measurement. We had tried a half bridge with a pseudo differential measurement, but the full bridge was found to be far superior.

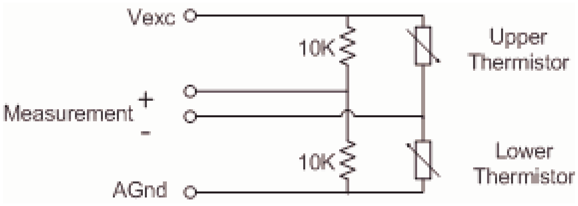


Figure 6. Full bridge measurement arrangement.

The thermistors are connected to the cable using the configuration shown in Figure 7.

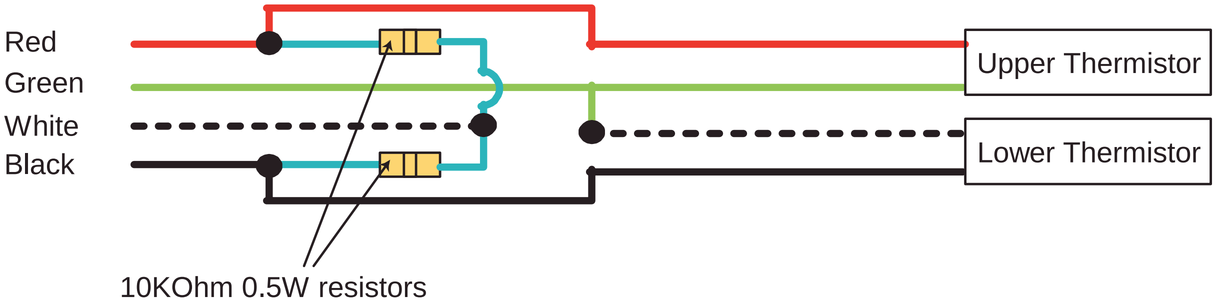


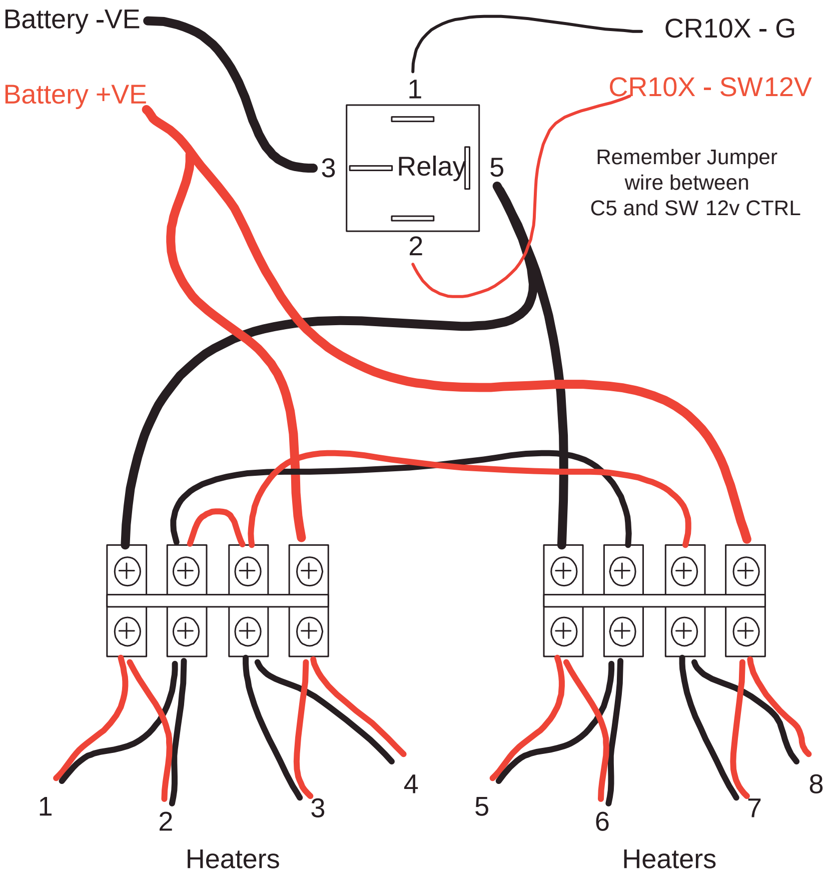
Figure 7. Connection of thermistor pairs to thermistor cable.

Each thermistor cable (which measures a thermistor pair) is wired to a single channel on the multiplexer. An example of the wiring of a thermistor pair for channel 1 of the multiplexer is given in Table 2. It should be noted that signals from thermistors will degrade as cable length increases, however, we have used cable lengths of 15m with no apparent effect on signal quality.

Table 2. Thermistor cable to multiplexer wiring for thermistor pair on Channel 1

Thermistor Cable		AM16/32
Green	→	1H
White	→	1L
Exposed Wire	→	Shield
Red	→	2H
Black	→	2L

The Campbell Scientific CR10X data logger is also used to control the timing and duration of the heat pulse delivered through the heater probes. The heaters are activated by the CR10X logger through the use of 12V relay (Omron Pty Ltd - Part No. G8JR-1A7T-R 12 DC). The CR10X data logger activates the relay which in turn closes the circuit allowing power to reach the heater probes. The heaters are de-activated when the CR10X turns the relay system off (0.8 sec later). The wiring of the heater system is shown in both Figure 7 and Table 3. The relay is activated when the control port (in our case C5) turns on the switched 12V control port (SW 12V CTRL) which sends power through the switched 12 V (SW 12V) port activating the relay, thereby, 'firing' the heaters. The wiring configuration for the screw blocks in Figure 7 provides 6V of power to each heater. This configuration also reduces the burden put on remaining heaters following the failure of one or more of the other heaters in the configuration.



(X 2 for full Heat Pulse Setup i.e. 16 Heaters)

Figure 7. Heater to relay wiring for 8 heaters.

Table 3. CR10X to heater relay wiring

CR10X		Relay
G	→	Relay1
SW 12V	→	Relay2
C5 → SW 12V CTRL		

The stainless steel heater probes are constructed and supplied by OneTemp Pty Ltd, Australia (Product Code - 22K310-65-150 PTFE/CU). The probes are made from 310 stainless steel and are the same dimensions as the thermistor probes. The mineral insulated metal sheathed probe has an internal conductor with a diameter of 0.36mm^2.

2.2 Data logger programming

The data logger program not only enables the heat pulse system to controls the firing of heaters and measurements of thermistors, but also instructs the system to perform a number of error checks to detect system failure and notify the user as to the source of any problems. The error checks are very useful for finding and fixing the source of measurement failure in the field. The programming routine uses the same principles used by Edwards Industries Pty Ltd for measuring heat pulse velocity and detecting errors for the Heat Pulser system.

A flow chart showing the ways in which the data logger program takes measurements and records errors is shown in Figure 8. The data logger program is written using the Campbell Scientific programming software ‘LoggerNet’. The user is able to specify the interval at which measurements will be made. We use a measurement interval of 20 or 30 minutes and find that this gives a good balance between power consumption and memory usage for our monthly field site visits.

Following the initial error checks for the battery and each thermistor pair and heater (32 thermistors and 16 heaters in a full setup), the program cycles through each thermistor pair determining the difference between the voltage of the lower and upper sensors. If the voltage difference is greater than zero the system continues to cycle through measurements until either the difference equals zero, or the time limit of 600 seconds for measurements is exceeded. Once the difference between lower and upper thermistor voltages equals zero the data logger records the time (*T2*). After 600 seconds (10 min) we make the assumption that the ability of the thermistors to detect sapflow has been exceeded and, hence, that there is no flow taking place. The fact that in our rainforest tree measurements we rarely record *T2* times between 500 and 600 secs, strengthens this assumption and suggests that zero flow probably occurs after 500 seconds. Other authors, such as Benyon (1999), present methods for defining zero flow based on measurements during conditions when sap flow is unlikely (i.e. night-time and humidity close to 100%).

The data logger program stores time and date of measurement and then the measurement time or error code for each thermistor pair and heater. Sample code is available upon request from the authors.

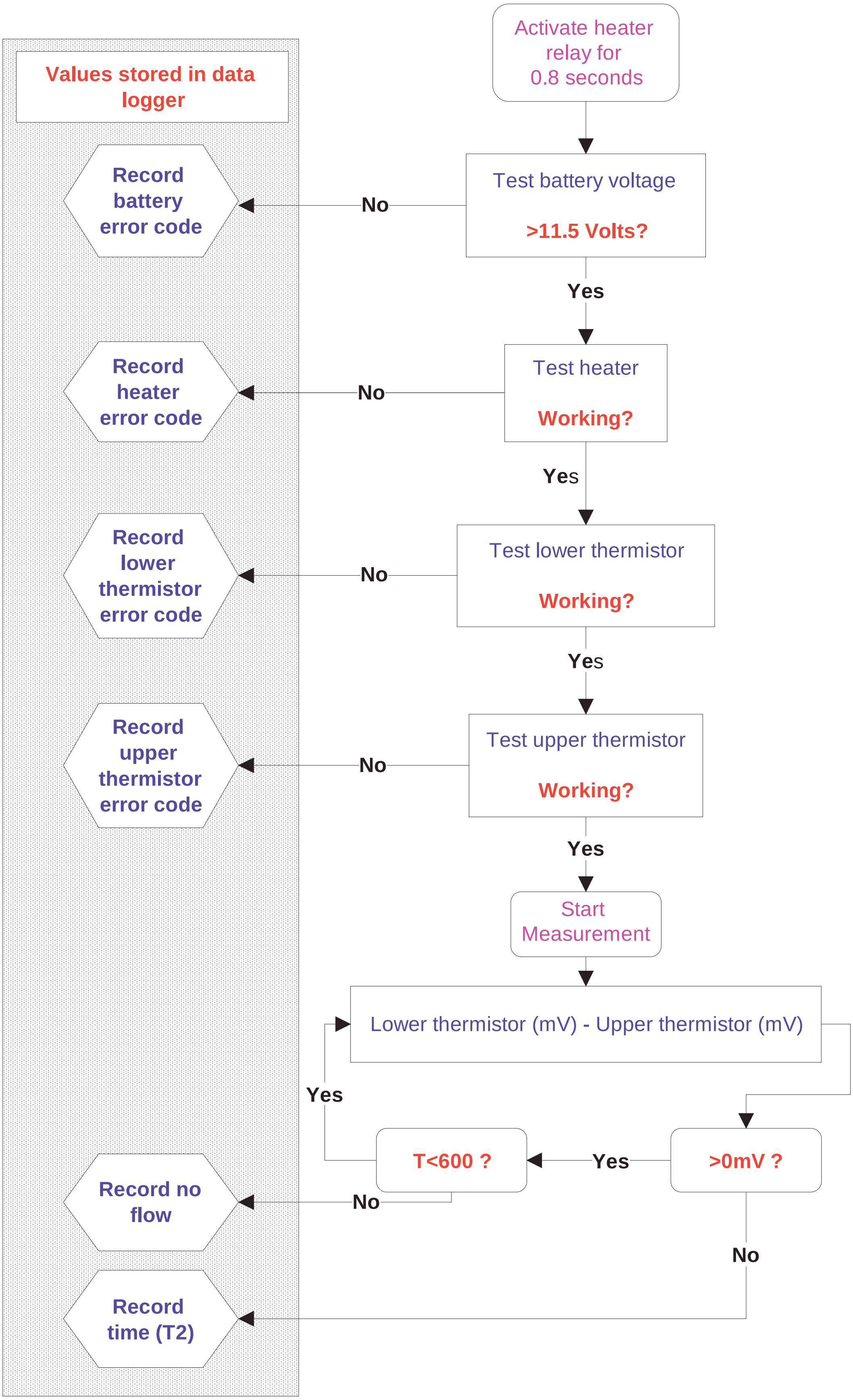


Figure 8. Flow chart of procedures for determining HPV and documenting system errors.

2.3 Measurement resolution

A number of studies have shown that the commercially available Greenspan Technology sapflow system is unsuitable for making heat pulse velocity measurements during low sapflow conditions (i.e. night, shade, rainfall) unless significant additional tests and adjustments to measurements are made (Becker 1998, Benyon 1999). The reason for this is the sensitivity of the thermistor measurements.

The thermistor arrangements for the system we describe in this report and the Greenspan Technology and Edwards Industries systems all have bridge arrangements relying on non equilibrium conditions to generate a voltage change. We expect that the thermistor properties for all systems are similar, although we cannot confirm this.

Both our system and the Edwards Industries Heat Pulser system use a Campbell Scientific CR10X data logger to make differential measurements. The specified resolution of the differential measurement is 0.00033mV(1). The resolution of the Greenspan system is not specified in the documentation, therefore, we performed our own tests to determine this.

The Greenspan system uses a half bridge arrangement which is excited by 5V. The voltage is only applied prior to measurement to minimise self heating of the thermistors. The measurement is made with a frequency to voltage converter which converts the input voltage sensed by the system to a frequency which is then in turn converted to ‘counts’ by a microprocessor.

To determine the resolution of the Greenspan data logger we connected it to a variable voltage source and measured the corresponding number of data logger counts. The results of this test and resulting line of best fit for the data can be seen in Figure 9. The equation of the line of best fit indicates a sensitivity of -0.46mV per count. Since the minimum resolution of the microprocessor is one count, the minimum resolution of the Greenspan system is 0.46mV. The resolution of the Campbell Scientific data logger (0.00033mV) is, therefore, more than 1000 times better than that of the Greenspan data logger.

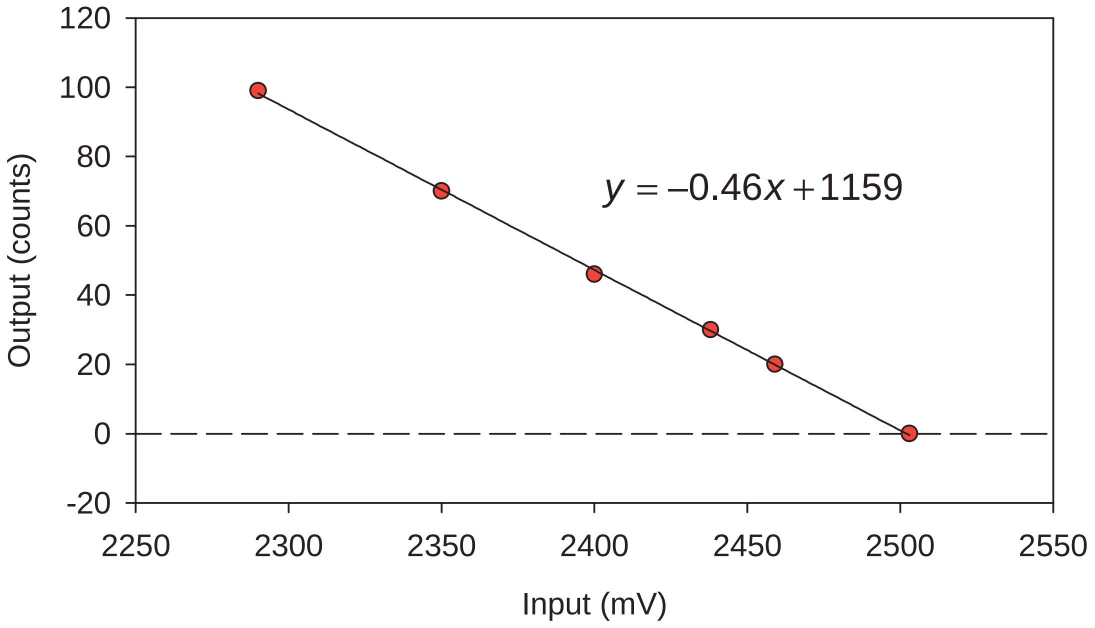


Figure 9. Sensitivity of Greenspan sapflow logger.

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[1] Campbell Scientific CR10X Logger manual, pOV-23.

The implication of the lower resolution of the Greenspan system is that the time T2, which is used to calculate heat pulse velocity, has a larger error associated with it. This error is further exacerbated at low flows as is demonstrated in Figure 10. This figure shows that during high sapflow the gradient of temperature difference with time is much steeper than at low sapflow. The red error bars in this figure show how the gradient of the temperature difference combines with the resolution of the measurement (dashed lines) to produce a much bigger error at low sapflow. The Campbell Scientific data logger has a resolution more than 1000 times better than the Greenspan data logger, therefore, the error in the estimate of T2 is correspondingly reduced and the ability to measure at much lower sapflow velocities is greatly enhanced.

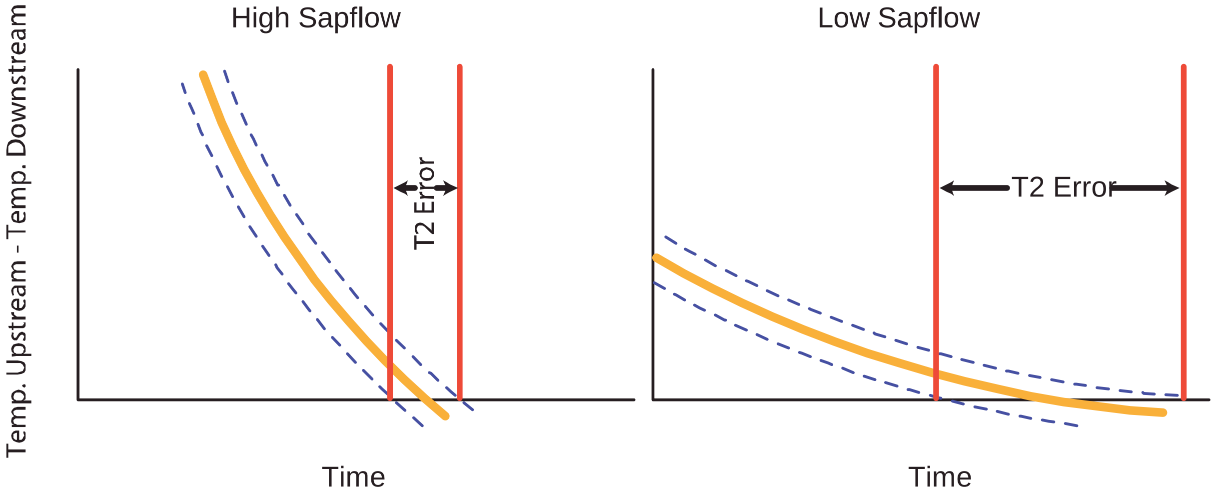

Figure 10. Error in T2 measurements in high and low sapflow conditions. Solid line shows logger measurement, dashed lines are the resolution of the measurement.

3 Heat pulse system installation

3.1 Sample tree selection

Selection of sample trees is a fundamental step in any study of tree water use where stand level estimates of water consumption are required. The sample trees need to be representative of the trees found in the stand. Often the best ways of selecting sample trees is to perform a census of tree diameters at breast height (DBH = 1.3m) for the stand of trees in question. Once the range and variation in trees sizes is known, sample trees can be selected to span this range. This process is demonstrated in Figure 11 which shows the diameters of all trees on a plot of known area and the way in which sample trees have been selected to represent the range of tree sizes found on the plot.

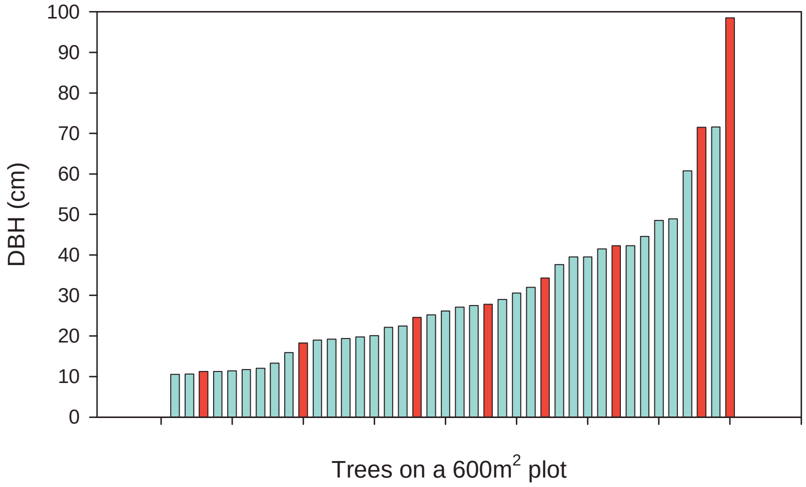

Figure 11. Tree diameters from a 600m^2 plot (blue) and selected samples trees (red)

The number of trees to be selected will be limited by the budget of the project and the capacity of the system (one data logger can take 16 measurements of v_h). Sample tree selection will also be controlled by the distance of trees from the point where the data logger will be housed. The number of trees that can be measured will also be controlled by the number of sensor pairs to be used for each tree. Working in rainforests, which have huge ranges in tree sizes, we use two measurement depths for trees less than 50 cm DBH and four measurement depths for trees greater than 50cm DBH. Our reasoning for this is that the larger trees are usually the taller emergent canopy trees and we find that these trees dominate the total water use of the plot (e.g. for the plot shown in Figure 11 the four trees larger than 50cm DBH account for ~50% of the total plot water use.) We believe it is much more desirable to get a more accurate tree water use estimate for these trees than the smaller ones which are far less significant in terms of total plot water use.

Tree selection techniques will vary depending on the study aims but as a general rule trees with obvious wounds and scars should not be selected for sample trees.

3.2 Field installation

Best results from the heat pulse system are achieved through careful installation of sensors and protection of equipment from the elements. Investment of time and a little extra money at the installation stage of the experiment is highly recommended.

We find that it is best to base the entire system around a central box in which the data logger, multiplexer and power supply are stored. We use locking galvanised tradesman style tool boxes which are made water proof from the inside using silicon sealant. A good seal between the lid and the box is achieved using self adhesive draft excluder strips which are normally used to ensure a good seal around windows and doors. The box is fixed to four posts to keep it off the soil and away from any surface water. Mounting the box on posts also makes access to cabling easier.

Condensation accumulates in the box over time so we like to drill some drainage/ventilation holes in the bottom of the box. We put fly wire over these holes to prevent insects entering the box. Cables and conduit enter the underside of the box through holes made using a 32mm hole saw. An example of an installed heat pulse system is shown in Figure 12.

All cables are run along the ground from the central box to the sample trees through 32mm PVC conduit. We use a separate run of conduit for each tree being measured as this helps minimise confusion about cable origin. Use of an electricians wiring ‘snake’ is highly recommended for feeding cables through the conduit as it saves much time and frustration.

32mm flexible conduit is ideal for running cables up into the central box and up the trunk of the tree. Labelling cables at both ends is highly recommended.

Figure 12. Heat pulse system showing locking storage box mounted on posts and conduits carrying cables entering through the underside of the box.

Conduit is fixed to each tree using nails and a 25mm galvanised saddle. Conduit entering the underside of the central box is fastened to the supporting star pickets using cable ties and a water proof seal with the underside of the box is achieved using silicon sealant. Once cables are run through the conduit and the system is functioning, each join should be sealed with PVC glue to prevent water intrusion and damage by animals to exposed cable. The ends of conduit should be sealed with silicon sealant to keep water and insects out of the central box. It is also a good idea to bend the end of the flexible conduit and fix it to the tree so that the opening faces downwards, this prevents water intrusion.

The ends of heater and thermistor cables at the trees should also be sealed with silicon sealant as we have found that water can travel through the cable beneath the protective casing and into the data logger or multiplexer box causing expensive damage and system malfunction.

Inside the central box, the data logger and multiplexer should be stored in separate water proof containers. Wires enter the sides of the containers through small drilled holes which are then made water proof through the use of Mastic Compound (also known as plumbers putty). Each box should be filled with about 20 silica gel sachets to keep the environment around the control system as dry as possible. Silica gel sachets are replaced on a monthly basis. The outer protective casing of the end of each thermistor cable should also removed for to a length of about 100mm outside of the waterproof box housing the multiplexer. This ensures that any water that may have travelled down the length of the cable from the tree does not drain into the multiplexer box.

The data logger and multiplexer are protected from lightening using the procedures recommended by the equipment manufacturer. A lightening rod is used to minimise damage to the system by providing a low resistance path around the system to a point of low potential.

If using a solar panel and regulator to maintain battery power, the solar panel regulator should be housed in a separate storage box at least 5m from the multiplexer and data logger. We have found that some regulators, particularly new ones that use ‘smart’ current control technology, produce a lot of localised interference which inhibit measurements.

3.3 Sensor installation and maintenance

The first step in the installation of the heat pulse sensors is to determine the thickness of the sapwood annulus of the tree. Sapwood can be determined through a variety of methods:

1) by taking one or more wood samples using an increment corer and determining sapwood depths by visual detection of colour change at the sapwood heart wood boundary or by the use of one or more of a number of available sapwood indicator solutions (see Kutscha and Sachs 1962)
2) by drilling a hole into the side of a tree and fitting the hole with a small hose which is filled with food dye from a reservoir above the hole. The dye is drawn through the sapwood by the tree and the region of the tree which is transporting dye is determined by taking an increment core slightly above the drilled hole a couple of hours after installation. The sapwood is easily identified by the colouration from the food dye.
3) by installing heat pulse probes at ever increasing depths until the zone of no flow is detected from successive measurements

Once sapwood depth has been obtained, installation depths can be assigned based on the technique of Hatton et al. (1990). Thermistor probes then need to be marked for correct installation depth. A permanent marker or correction fluid is ideal for marking the probes. For most trees, the bark can be left on the trunk and the bark thickness is simply taken into account during calculation of sensor depths. Some trees have very thick or uneven bark which needs to be stripped back before installation proceeds.

The next crucial step for making accurate measurements of sap flow is correct alignment of the heater and thermistor probes. A small error in probe alignment results in large sap velocity errors. In order to minimise errors related to probe alignment we suggest the use of a drilling jig such as that shown in Figure 13. This type of jig can be easily constructed by a metal working business. We use a 2.25mm drill bit (Sutton Tools, Item No. 008448) for the 2.2mm probes as this drill size ensures a good tight fit for the probes, thereby, maximising contact with the sapwood.

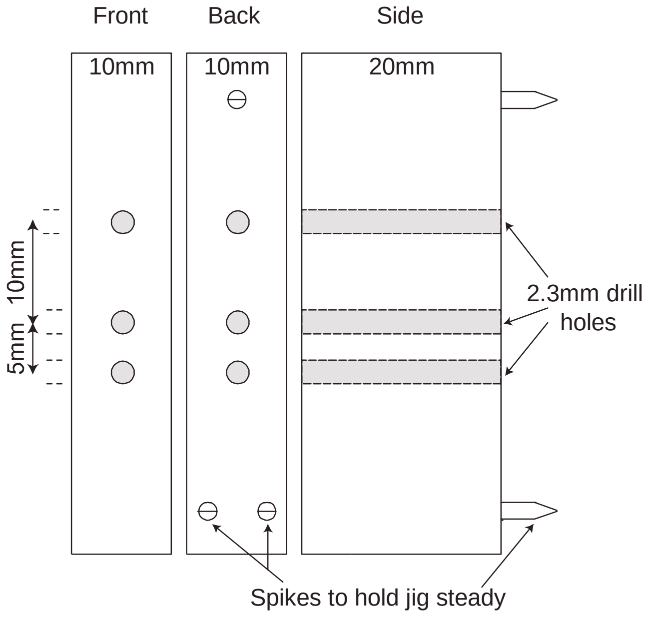

Figure 13. Drilling jig used to ensure accurate installation of probes.

Before inserting the probes we follow the method of Hatton *et al.* (1995) to estimate probe separation. We insert blank probes (2.2mm diameter) into the holes and measure their spacing at a distance outside of the tree equivalent to the sensor implant depth. If separation errors exceed 0.1mm from the standard 5 and 10mm spacings we reject the holes and start again.

Before inserting probes into the tree we coat them in fungicidal wound grease made from a mixture of petroleum jelly and fungicidal powder (available from most garden supply shops). This grease not only protects the tree from infection but also aids in probe insertion. Thermistor probes are inserted to the marked depth without applying too much pressure. Occasionally, redrilling may be necessary. The heater probe is then inserted to a depth about 5mm deeper than the thermistors. This ensures the thermistor sensors, which are located at the tip of the probe, receive heat from the heater probe, which is heated along its entire length. An installed thermistor pair and heater is shown in Figure 14. Once probes are installed they should be covered with foil to prevent differential heating from interfering with measurements. We use construction sisilation foil for this purpose.

Figure 14. Installed heater and thermistor probes.

Installed heat pulse sensors and heaters should be moved periodically to prevent degradation of measurements due to the blocking of transport vessels around the sensor as the tree reacts to the intrusion of the probes. The period of time over which blockages may form will vary from species to species, therefore, we suggest that a study comparing the velocity of old holes against new ones should be undertaken over time to ascertain how frequently probes need to be moved.

When replacing failed or damaged thermistors in the field we cut off the damaged probes and then connect new ones to the end of the heater or thermistor cables using ScotchLok connectors (3M, Part No. UY2) These connectors are a crimping type connector which are filled with a water proof sealant which is extruded when the connector is squeezed using pliers. These connectors do not require the wire to be stripped back and represent a large cost saving when considering the time required to solder new connections.

Testing of thermistors should be undertaken periodically to ensure that sensor error is not affecting v_h measurements. If one sensor in a pair is making inaccurate readings then v_h measurements will be over or under estimated. To test our thermistors we install them in batches of 16 into a block of timber, this ensures that all sensors are subjected to the same environmental condition. Using a simple data logger program we take a reading from each thermistor at 10 minute intervals for at least 24 hours. We then analyse the collected data and reject any thermistors that stray from the mean reading by more than 1.5%. This procedure ensures data integrity.

4 Sample Data

Figure 15A shows the raw heat pulse data (*T2*) collected for a single tree over an eight day period. This tree had a DBH of 20cm and was fitted with thermistor pairs installed at two different depths. This figure illustrates clearly the diurnal fluctuations in T2 over the two days and also shows the different responses at the two different depths. The faster the *T2* time the faster the sap is flowing. A *T2* of 600 represents no flow.

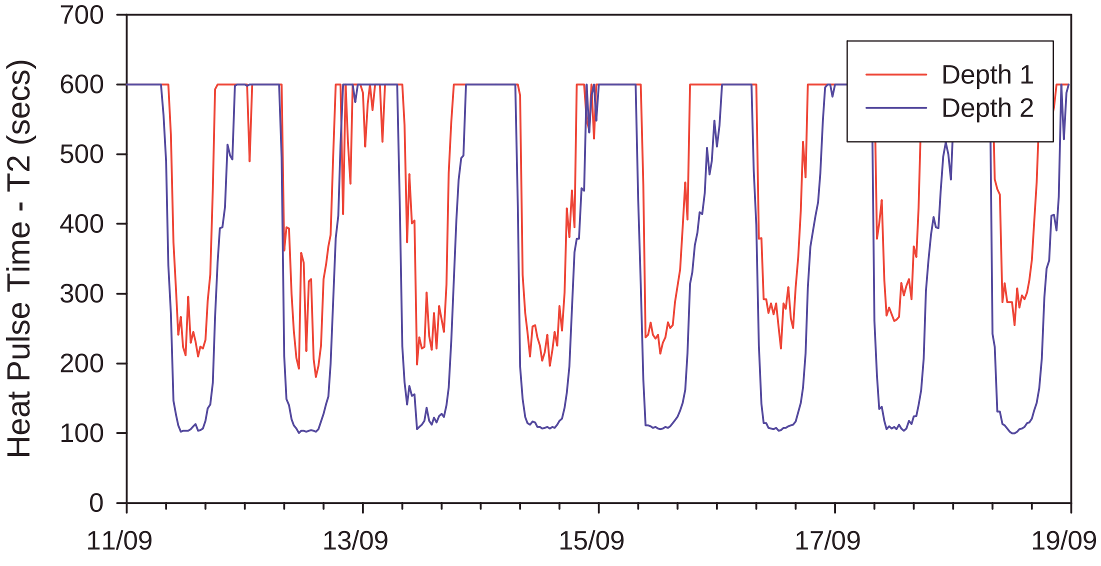

Figure 15. Sample heat pulse data showing heat pulse times (T2).

Using Equations 1 through 10 the raw *T2* values are converted to sapflow (*Q*). Figure 16 shows the diurnal trends in *Q* over the eight day period.

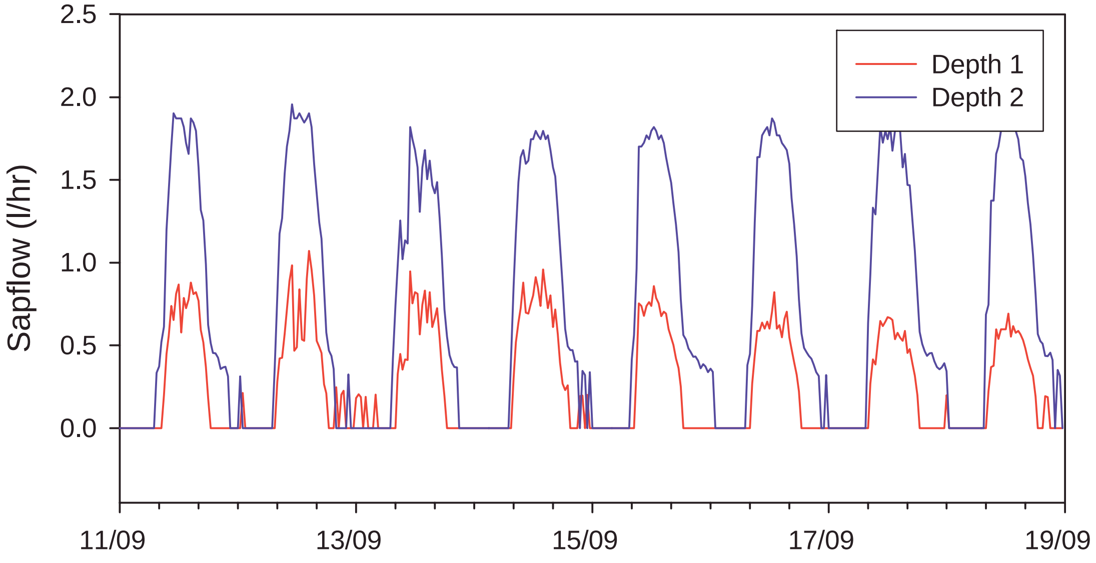

Figure 16. Sample heat pulse data showing heat pulse times converted to sapflow.

Once Q has been calculated the methods of Edwards and Warwick (1984), or in our case, Hatton *et al.* (1990) can be used to estimate tree water use (Figure 17).

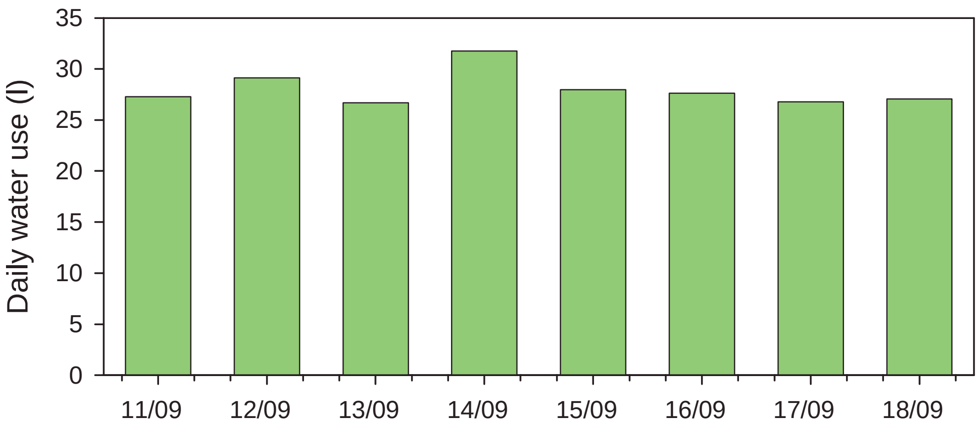

Figure 17. Daily water use calculated from sapflow data.

5 Summary

In this report we have described a measurement control system for monitoring the water use of trees. The system that we have designed is based on the widely used heat pulse, or compensation, technique that has been refined over a number of years. The system we describe does not represent a completely new method for measuring tree water use, it is simply a variation on other techniques that we believe will appeal to researchers, like us, who have encountered the limitations of commercially available systems. The technique we describe puts system design and programming in the hands of the user.

To help potential users decide which system would best suit their needs and capabilities, we present an overview of system characteristics, capabilities and costs in Table 4.

Table 4. Comparison of capability and typical costs of available sapflow systems.

	Greenspan Technology Sapflow sensor	**Edwards Industries Heat Pulser**	**Our custom system**
Technical/theoretical capability required	Low	Med	High
Flexibility for monitoring widely spaced (>30m) trees	✓		
Quick installation	✓		
Analysis software provided	✓	✓	
Error diagnosis and servicing possible in the field		✓	✓
Ability to add extra environmental sensors		✓	✓
Good software support		✓	✓
Fast Single download for all sensors		✓	✓
Remote access possible through telemetry		✓	✓
Custom probe lengths available		✓	✓
Good low-flow resolution		✓	✓
Proven performance of components in harsh conditions			✓
Noise cancellation			✓
Ability to easily source ALL replacement parts			✓
More than 16 measurements per CR10x logger[1]	NA		✓
Approximate price for 16 measurement points[2]	$15,600	$7700	$6700 32 points-$10,900

[1] Our custom system can take 32 measurement points but there is then no room for additional sensors

[2] Prices are in $AUD and are given only as an approximate guide. Prices do not include batteries, storage boxes, or additional solar and communication equipment.

Our system has the following strengths:

- **All system components are readily available, easily sourced, and have a proven track record of field performance.** Our system is based around quality, robust components to maximise data quality and minimise system malfunction.
- **The entire system is controlled by a single commonly used data logger.** The CR10X data logger we have used has proven field capabilities and is widely used in the scientific community. Software for these data loggers is regularly updated to keep up with latest operating systems, and additional features, such as capability to download and control data loggers with handheld devices, are supported. Being controlled by a single data logger, the data from all thermistors is contained in an easily downloaded file.
- **Capable of making measurements under low sapflow conditions.** The CR10X has the capability to make high resolution differential measurements, thus minimising measurement error and greatly improving the capability of the system to measure sapflow during low flow conditions.
- **The wiring configuration is designed to minimise electronic interference.** Many regions are becoming increasingly exposed to electronic noise from mobile phone towers, power cables, and transmitters and, as we have experienced, this can cause problems for existing commercial systems. Electronic interference causes problems for heat pulse systems because they measure at very low (mV) voltage ranges. We developed this system because of electronic noise problems in some of the areas in which we work.
- **Multiple measurements are made possible through the use of a multiplexer.** Using a multiplexer our system can make up to 32 concurrent thermistor measurements. The multiplexer takes analogue rather than digital readings, thereby, further reducing the possibility of electronic interference. Measurements are made using Campbell AM 16/32 which, again, is easily sourced, robust and widely used.
- **The system has low power consumption.** Unlike heat balance systems, which require continuous application of heat, the heat pulse system only needs to apply short pulses of heat. This means that a system can be run for long periods (~month) from a single 100Ah battery, or can be run indefinitely by using a solar panel to maintain battery charge.
- **System errors can be diagnosed and fixed in the field.** The individual thermistor probes and heaters can be easily replaced in the field in response to system errors, thereby, minimising down-time and data loss. Measurement errors and their cause are indicated by the data logger. The LoggerNet software also allows the user to numerically and graphically track both the measurements of individual sensor pairs, providing a further means by which to identify errors.
- **Probes and heaters are made from stainless steel**. The use of high grade stainless steel results in corrosion resistant probes which are also far less susceptible to damage from curious wildlife (i.e. rodents). The rigid design of the thermistors makes installation easy and results in far less breakages of the delicate internal wires than probes made from other materials such as Teflon. The high quality thermistors used, combined with the ability of the CR10X data logger to accurately measure very low voltages, results in accurate heat pulse measurements.
- **Probe spacings can be changed for different applications.** Being based around individual probes means that the user has the option of selecting any sensor spacing they desire. For example, Burgess *et al.* (2001) describes a method for measuring reverse and low sapflow rates based on a -0.6, 0, 0.6 spacing rather than the standard -0.5, 0, 1.0 spacing.
- **System is highly flexible.** A full heat pulse system uses only one differential channel and one excitation channel on a CR10X data logger leaving many possibilities for

additional measurements. We usually control our entire field monitoring system, including weather instruments, rain gauges, and groundwater wells, from a single logger. Where possible we fit our data loggers with mobile phone telemetry devices which allow us to remotely interact with the station, download data, monitor measurements and modify the control program.

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