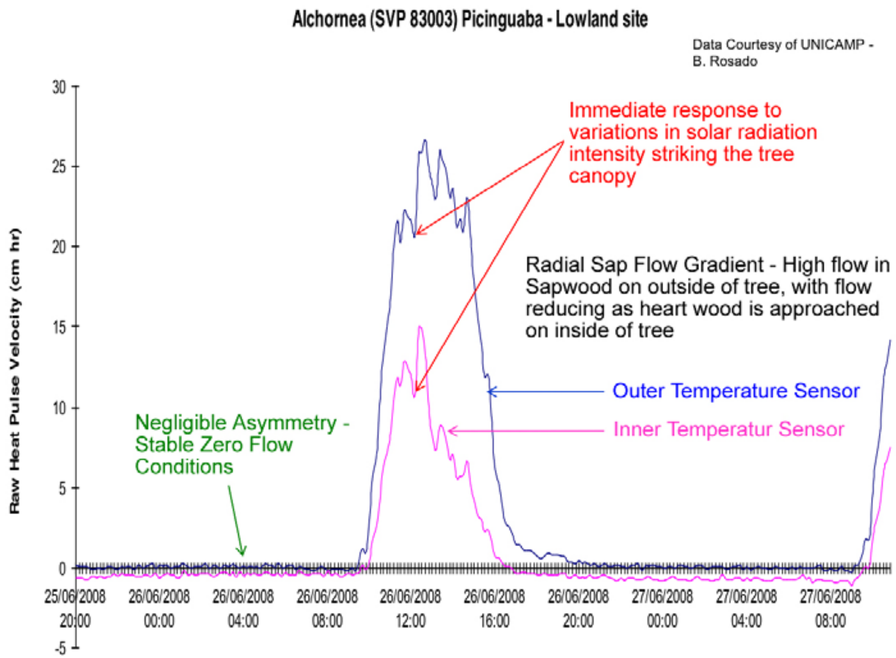
Comparison of HRM and TDP Methods of Sap Flow Measurement



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TDP and HRM Compared

TDP is a constantly heated sap flow principle that assumes there is no background temperature gradient between the probes and the plant (due to the use of thermal insulation around the sensors and the stem). However, the data shows that Natural Thermal Gradients (NTG) from the soil (which cannot be incorporated into the TDP measurement) are significant (up to 1 ^{o}C or greater) hence, the temperature gradient measured is not a true indication of the actual sap flow. The result is a substantial overestimation due to the background temperature gradient in the mornings and again underestimation in the evenings. None of which are of a constant magnitude to even begin to attempt compensating for.

Another cause of underestimation of sap velocity using TDP is the thickness of the sapwood. The standard TDP-30 sensor has a length of 30 mm consisting of a full length line heater and only a single thermocouple located at the halfway point (15 mm) along the needle. The sensor design is adequate for use in boreal Pinus species with thick sapwood of at least 30 to 40 mm but is inadequate for most other species. TDP sensors cannot be used to accurately measure sap flow of Eucalyptus species for example, because on average the sapwood thickness is approx only 20 to 25 mm thick. Therefore, the TDP sensor will almost always have the heater extend variable (but significant) depths into heartwood or non-conducting xylem. This results in highly variable and underestimated sap velocity because the non-conducting xylem (heartwood) artificially increases the dTmax as it does not dissipate the heat.

When these two conflicting, variables causing both positive and negative errors of unknown or measurable quantities it is clear that the TDP principle has significant limitations in application. An opinion that is supported by the majority of papers published using the TDP technique. Papers most recently published from the 7th International Sap flow workshop, Seville Spain 2008 that have grappled with these issues rather than successfully using the TDP sensor as a tool for researching plant water relations include Sevanto, et.al., Conceicao & Ferreira, Ferreira et.al., and Chavarro, et.al.

Alternatively, the Heat Ratio Method (HRM) sensor is a modified heat pulse technique that consists of three needles two measurement needles located equidistance above and below a central line heater. Because it is a pulsed technique using a short 2 to 6 second pulse of heat and a 100 second measurement window the effect of NTG's are avoided as ambient temperature changes within the

Top: HRM measuring small stem

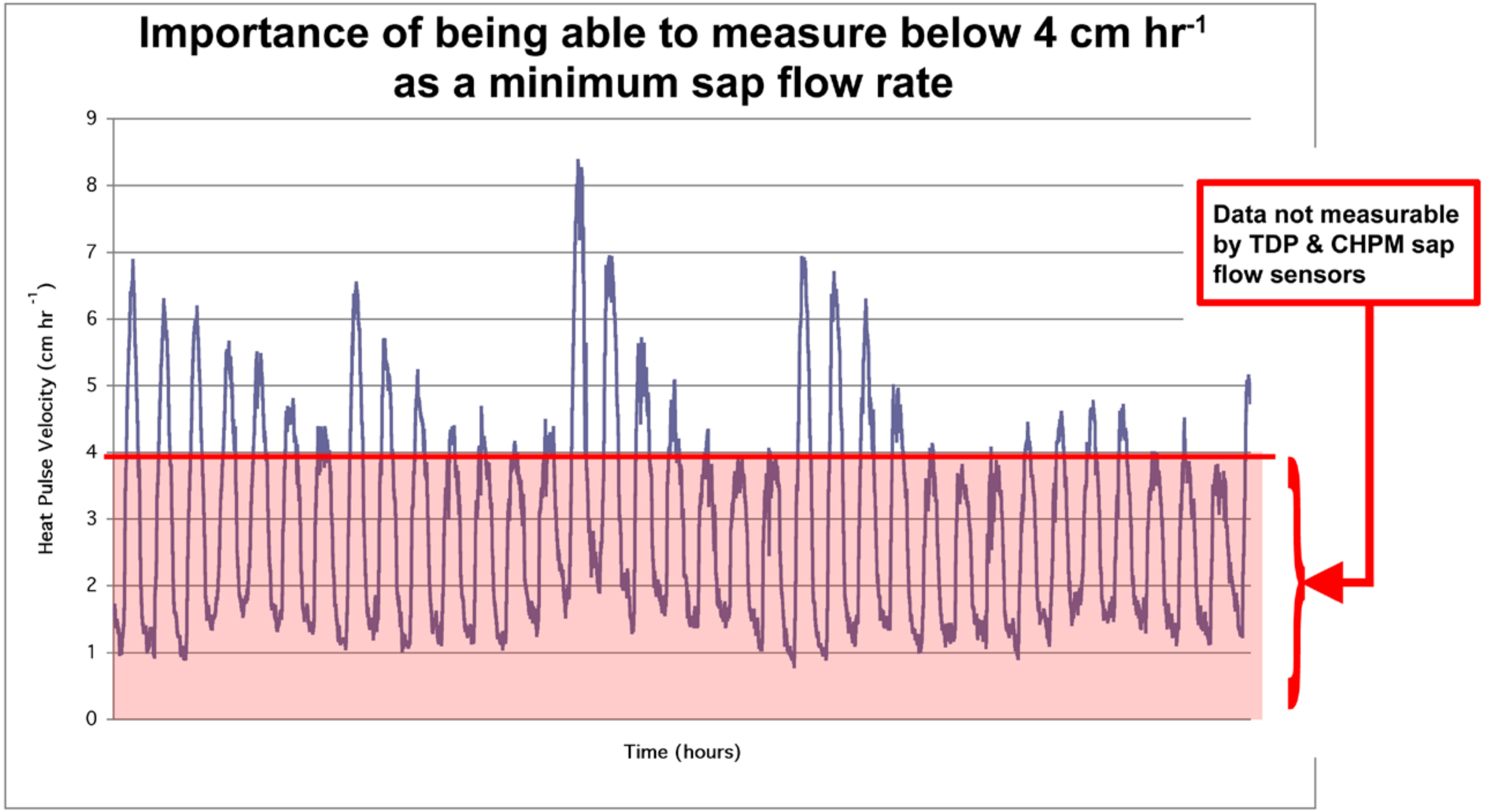
Above: HRM measuring large trunk (Needles being inserted)

Left:TDP requiring radiation shielding measurement interval are insignificant or non-existent. This has additional benefits in practical deployment as the sensors also require no thermal shielding to thermally isolate the measurement site against NTG's as with TDP.

The HRM needles are 35 mm in length and have two temperature measurement locations spaced at 7.5 mm from the tip and 22.5 mm from the tip. This provides a measurement of radial velocity across the sapwood and quantifiably measures the velocity gradient and or identifies when the needle extends into non-conducting xylem so the inner measurement point can be discounted.

The HRM can measure very low flow (approx 1 cm hr-1), zero flow and reverse flow in a range of stem sizes making it very robust and flexible. The TDP (as with most other commercial sap flow methods) cannot measure zero or reverse flow and typically only measure to minimum level of approx 4 cm hr-1 at low flow. Which on average results in approx 40% of all sap flow not being recorded.

In a world of ever decreasing water availability the need to accurately quantify plant water relations and screen for plants with the ability to redistribute water within its growing environment specifically, through mechanisms such as hydraulic lift and reverse flow is crucial. The requirement to adopt new techniques and methodologies that can measure these mechanisms is paramount and any researcher or environmental manager who has not adopted instrumentation that can is working in the past and wasting valuable time and resources.



Comparison of HRM and TDP Methods of Sap Flow Measurement

Specification	HRM	TDP
Measurement Range		
Measurement Units	Heat Pulse Velocity cm hr^{-1} Sap Velocity cm hr^{-1} Sap Flow g hr^{-1}	Sap Flux Density cm^3 hr^{-1} cm^{-2}
Measurement Range	-20 to 60 cm hr^{-1}	4 to 40 cm hr^{-1}
Measurement Accuracy	0.1 cm hr^{-1} (Corrected Sap Velocity)	?
Measurement Resolution	0.01 cm hr^{-1} (Corrected Sap Velocity)	0.1 (mV)
Measures Reverse Flow	Yes - very accurately between 0 to -20 cm hr^{-1} (at 0.01 cm hr^{-1} resolution)	No
Measures Low Flow	Yes - very accurately between 0 to 10 cm hr^{-1} (at 0.01 cm hr^{-1} resolution)	No - The minimum measurable velocity is approx 4 cm hr^{-1}
Measures High Flow	Yes - very accurately between 10 to 60 cm hr^{-1} (at 0.01 cm hr^{-1} resolution)	No
Measures Multiple Radial Points	Yes - with two independent measurement points in the same radial radial profile, spaced 15 mm apart. This can be used to characterise flow in the inner and outer xylem	No
Application		
Used on large diameter stems	Yes - for trees of any diameter but restricted to those with shallow sapwood (40 mm) or for the outer 40 mm of xylem (sapwood). By using a 35 mm long needle with two measurement points flow can be accurately characterised in both the inner and outer xylem making the measurement more accurate by being able to correct for the radial variation across the sapwood. For species that have a larger sapwood thickness or where an accurate radial profile is required it is recommended to use the Heat Field Deformation (HFD) multipoint sap flow instrument.	Yes - But, only for the outer 20 mm of xylem
Used on Small diameter stems	Yes - any woody stem larger than 10 mm diameter is suitable	No - The sensor needle must be fully inserted in sapwood otherwise large errors occur due to Natural Thermal Gradients (NTG) which cannot be measured
Used on Roots	Yes - The HRM has facilitated the understanding of phenomenon such as hydraulic lift and hydraulic redistribution in root systems of trees during times of drought	No

Specification	HRM	TDP
Measurement Principles		
Is wound response accounted for?	Yes	No
Is wound response relevant?	Yes - all species occlude cells and repair intrusive wounds which causes a non-conductive zone of tissue that affects heat transfer and ultimately measurement sensitivity and accuracy if not taken into account and corrected for processing of raw data.	
Heat Source	Heat Pulse	Continuous
Requires Radiation Shielding	No - The time required for the heat pulse and the measurement to be completed is so short (100 seconds) no significant changes in ambient air temperature or effects of direct incident radiation will occur that can affect the measurement.	Yes - Requires extensive thermal and radiation shielding both around the sensor and distances of between 50 cm to 1 m above and below the sensor to be insulated. Preferably all the way to the ground level and if possible covering of the surrounding root area on the ground.
Is the technique affected by Natural Thermal Gradients (NTG)?	No	Yes - The use of high energy input can be used in an attempt to overcome this problem but causes other problems like increased wounding and requires needle spacings to be significantly increased (by a factor of 3) to establish a difference in temperature between the two needles however, this dramatically reduces the sensitivity of the measurement increasing the amount sap velocity is either underestimated or overestimated.
Does sensor need to be inserted only in sapwood?	No - multiple measurement points enable measurement of radial gradient and determination of sapwood/heartwood border should the needles extend beyond the sapwood into heartwood.	Yes - it is crucial to the fundamental principle that the entire length of the needle be completely inserted in sapwood and sapwood only. If the needle extends into the heartwood or non-conducting xylem sap velocity will be grossly underestimated anything up to 50 % error. Conversely, if any amount of needle is located in bark or air then the sap velocity can be grossly overestimated by indeterminate amounts rendering the data useless.
Can the sensor needle be located in air when used with small diameter stems?	Yes - the end measurement point or inner measurement point can be turned off if sitting in air	No
Do Heat Storage lags affect the measurement?	No - A short heat pulse is generated for each measurement eliminating the effect of ambient thermal conditions.	Yes - Because it is a continuously heated sensor
Data Processing & Analysis		
Calibration method	Use of specific wood properties and wound coefficients to convert heat Pule Velocity data to corrected sap velocity (cm hr^{-1}) and sap flow (gm hr^{-1}).	Utilises an empirical calibration however, detailed data corrections for dTMax are required using extensive modelling of data to achieve approximations of sap flow. These are not accurate direct measurements.
Raw Data Processing Required	No - Raw units measured are Heat Pulse Velocity in cm hr^{-1}	Yes - conversion from analogue microvolts to temperatures then apply empirical calibration conversion to sap velocity (cm hr^{-1})
Software	Yes - 3D graphics software with user interface for entering and adjusting tree specific wood properties.	No - Excel Spreadsheet

Specification	HRM	TDP
Data Logging		
Data Output	Raw Heat Pulse Velocity (cm hr^{-1}) Corrected Sap Velocity (cm hr^{-1}) Corrected Sap Flow (gm hr^{-1})	Temperature difference (Millivolts or °C)
Temporal Logging Resolution	Minimum 10 minutes - This is to ensure all heat input from the previous measurement has been fully dissipated through the xylem within the measurement zone to prevent any compounding on heat which may affect subsequent measurements. Optional resolutions of 15, 20, 30 and 60 minutes for long term deployments	Minimum 1 minute but the large quantity of data becomes cumbersome and exhibits greater "noise". Typical logging resolution is 15 minutes to 60 minutes
Number of sensors per logging system	100	32 (with Multiplexer)
Stand alone Logging Capability	Yes	No
USB Communications	Yes	No
Memory Capacity	2 GB Standard expandable to 32 GB	None
Power		
Internal battery	12 V lithium 900 mA Hr	None
Internal Voltage Regulation	Yes	None
24 Hr Power Consumption	0.49 Amps @ 10 minute temporal resolution	1.92 Amps @ 10 minute temporal resolution
Number of days battery back-up without solar charging for 16 sensors on a 85 Ahr 12 V battery	10.75 Days	2.75 Days

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