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A Scoping Study on Measuring and Monitoring Tools and Technology for Precision Irrigation

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June 2005

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Introduction

Good quality water is a scarce and expensive resource in Australia and overseas, irrespective of its nature of occurrence (how / where it is found), quantity (volume) and quality and the purpose for which water is used (irrigation, stocks, household use). Sustainable management of this limited resource requires accurate assessment of supply, availability and storage as well as the volumetric demand for use in rural and urban areas. Water used for irrigating crops is a sizeable component of the available resource (even in situations where it is recycled and is of poor quality) and requires high measurement precision and good control in all aspects of its management for accurate accounting and to achieve high efficiency.

This scoping study is designed to advance high standards of precision in management of water and develop efficient methods of irrigation prescription to reduce losses and improve water use efficiency. All aspects of irrigation process are considered in this study to include various components of farm water storage and distribution systems to facilitate accurate accounting of water. In this study, we will attempt to:

- Identify key attributes and specifications for various tools (sensors and control systems) for precision irrigation management;
- Develop strategies to fill current gaps in the functionality of various tools and technology available for irrigation and
- Prioritise opportunities to refine and/or develop new tools and technology to increase on-farm precision and meet off-farm hydrology needs.

It can be seen from the diverse array of currently available irrigation tools that most of these have been designed for a given operation scenario. For example, a sensor and control system designed to help scheduling irrigation need not be precise or accurate if it needs to determine the timing of irrigation only. However, if it needs to provide an accurate estimate of volume of irrigation needed for a given application it may need a higher precision. A sensor and control system capable of accurate assessment of soil moisture, if not properly used, is less likely to improve precision in estimating volume required to irrigate.

Improving irrigation precision or efficiency may be possible at a local scale (e.g. in a farm), but can affect precision or efficiency at another scale or outside the farm boundary due to the interconnection of elements within the hydrologic cycle. Thus, gaining local efficiency does not necessarily translate into gaining regional efficiency. Keeping these issues in mind, this study identifies various links in the supply-distribution-use chain of the irrigation water to gain an understanding of various processes that affect volume of water directly or indirectly by affecting the gain/loss process. Tools and techniques which are currently available to measure volume or some aspect of the gain/loss process for water are discussed for each component along with the strengths and weakness associated with each tool/technique. Information is included to identify research and technology gaps to improve the performance of existing tools and techniques or to develop new tools/techniques. A list of research opportunities has been developed for each component of the supply-distribution-use chain of the irrigation water to address the technology gap.

1. Overview of Scoping Study

The supply-distribution-use of irrigation water consists of a number of elements (Fig. 1). The storage of water in farms for irrigation (such as in ring tanks) or in off-farm reservoirs is an important starting point for irrigation as it affects supply and availability of water for irrigation. As water is collected via a number of channels and distributed to various irrigation application systems including surface irrigation (furrow, border and basin), sprinklers (centre-pivot, lateral moves and micro-sprinklers) and drip (surface and sub-surface), a number of tools and technology is used to measure volume of water and to minimize losses. Application of irrigation water into fields increases availability of water to crops through infiltration, redistribution and retention and losses by runoff, drainage and evaporation. Transpiration by plants represents a significant component of water lost to atmosphere as a consumptive use of water. Simultaneous evaporation and transpiration from crop fields (Evapotranspiration or ET) is an important process that overlaps soil, plant and atmosphere components.

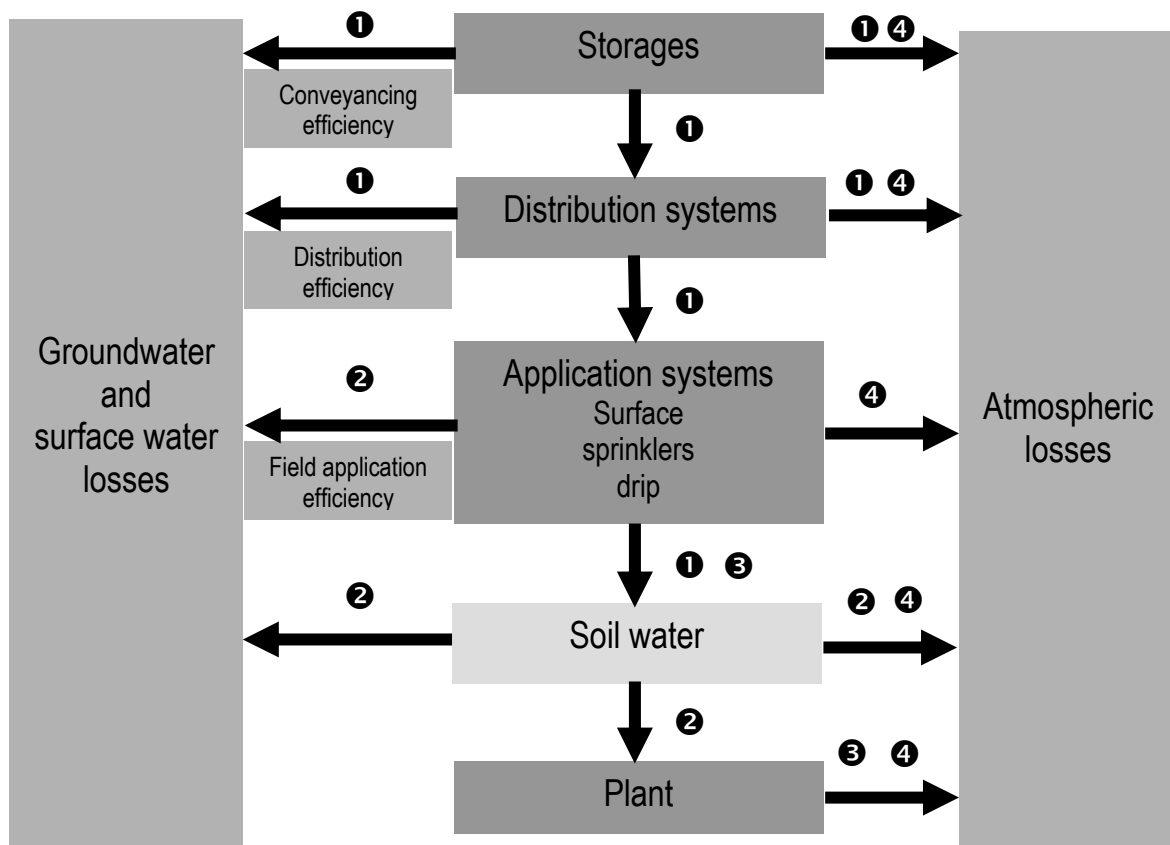


Figure 1. Components of irrigation supply-distribution-use chain showing association of various components with water use efficiency terms. Related scoping table numbers are also indicated.

To consolidate our review efforts, the findings of this scoping study are presented in four separate scoping tables:

Table 1 – Water flow measuring and monitoring tools

Table 2 – Soil water measuring and monitoring technology

Table 3 – Plant water use measuring and monitoring techniques

Table 4 – Tools and techniques to measure evaporation and evapotranspiration

Each table identifies the components of the water supply-distribution-use system, issues (or measurement condition) affecting volume of water or related gain/loss process, existing technology or tools available to measure or monitor the specific issues, strengths and weakness of the existing tools, technology gap to overcome weakness and any relevant reference material that forms the basis of the scoping study. Additional comments and research opportunities are included in each table to finalize the future outcomes of the reviewed tool/technology.

2. Measuring and Monitoring Tools for Irrigation

Table 1. Water flow measuring and monitoring tools

Scale	Measurement Condition	Technology	Strength	Weakness	Technology Gap	Existing reference material	Additional Comments	Research Opportunities
Storages and Distribution Systems	Channel flow	Dethridge meter	<ul style="list-style-type: none"> • Robust • Easy to use • relative low capital cost • does not require power • well accepted by irrigators • low head loss • No computer required for download 	<ul style="list-style-type: none"> • low accuracy +/-5% • flow range: 2 to 12 ML/day • can be tampered • safety hazard – OHS issues with installation and maintenance due to the weight. • wear and corrosion • high potential for inaccurate installation • can be damaged by debris in flow • wear • Can't be remotely monitored • Changes in flow rates can't be recorded • Start and finish times cannot be recorded. 	Replacement technology is needed and sort by regulators. 20,000 installations in G-M district	ANCID (2002) Know the Flow: Flowmetering Training Manual, Springer and Foley (2004), Communication: NSW Department of Primary Industries, Goulburn Murray Water	Regulation (metering) is enforced in some areas and will eventually be widespread. Irrigation metering standard is being developed by the National Measurement Institute. First draft release Jan 2005 : NM1 M 10-1 Industry is developing new technologies, including magflow meters. However, alternatives are 2-3 times more expensive	<ol style="list-style-type: none"> 1. Current metering standards are for potable water qualities operating under municipal conditions and are not appropriate for irrigation flows. There is a need to define the irrigation standards for metering 2. Potential to develop lower cost and more robust irrigation metering options 3. Cost benefit analysis of high capital/low maintenance metering vs low capital, high maintenance meters 4. Development of protocols for routine verification of meter performance in the field 5. What is the current level of performance of meters operating under commercial conditions in the field? 6. Improving the communication and presentation of metering data at various scales
		Flumes; simple or compound weirs	<ul style="list-style-type: none"> • robust • simple to measure • various depth measurements methods • simple installation • some design operates in low headloss conditions. 	<ul style="list-style-type: none"> • accuracy requires field verification, particular where downstream water levels interfere weir flow • some design have relatively high head loss • accuracy can be affected by debris, cleaning required • power needed to measure depth of water • accuracy deteriorates with wear • specialist repair skills 				

		<p>Ultrasonic doppler meter (invasive)</p> <ul style="list-style-type: none"> • can be fitted to open channels • in conjunction with depth sensor can be used in partial flow depth conditions • can measure bi-directional flow • low head loss • no wear 	<ul style="list-style-type: none"> • susceptible to debris, fish, animals (in dry situations) and wave action • require relatively dirty water to operate effectively • infield verification maybe required in open channel flow applications • high level special skills – required for calibration, setup, download and interpretation • power required • entrained gasses or suspended sediment effect the acoustic signal strength • Density gradient 	<p>limited field verification capability with component installations</p>			
		<p>Propeller meter (insertion)</p> <ul style="list-style-type: none"> • relatively high accuracy when installed correctly • Electronic or mechanical display registers 	<ul style="list-style-type: none"> • can be affected by debris • can be tampered • high wear • high maintenance • must be enclosed in conduit and operate in full pipe flow condition 	<p>field verification</p>			
	<p>Closed pipe flows</p>	<p>Propeller meter (closed conduit)</p> <ul style="list-style-type: none"> • high accuracy • accuracy okay in turbid water • can be applied to inclined pipes 	<ul style="list-style-type: none"> • susceptible to debris • can be tampered • wear • requires full pipe flow 	<p>field verification</p>			
		<p>Paddlewheel (insertion)</p> <ul style="list-style-type: none"> • high accuracy • high wear • accuracy okay in turbid water • easy to use 	<ul style="list-style-type: none"> • susceptible to debris • can be tampered • wear • require full pipe flow • high maintenance 	<p>field verification</p>			
		<p>Turbine meter</p> <ul style="list-style-type: none"> • high accuracy • accuracy okay in turbid water • easy to use • no power 	<ul style="list-style-type: none"> • susceptible to debris • wear 	<p>field verification</p>			

		<p>Ultrasonic meter (non invasive) Transit time meter</p> <ul style="list-style-type: none"> • Relatively high accurate when installed correctly and consistent over a full flow range • non invasive • telemetry capability • bi-directional • simple installation • same device is suitable for a wide range pipe diameters • accuracy unaffected by debris. • Low head loss 	<ul style="list-style-type: none"> • power supply required • customised settings required • requires high level specialist skills to setup and obtain accurate readings • Pipe must be full 	limited field verification capability		Some authorities are using this technology for field verification.	
		<p>Ultrasonic meter (invasive)</p> <ul style="list-style-type: none"> • can be fitted to existing pipe • in conjunction with depth sensor can be used in partial flow depth conditions 	<ul style="list-style-type: none"> • susceptible to debris and fish action in zero flows • can be tampered • infield verification maybe required in open channel flow applications • power supply required • sensor may need cleaning depending on water quality 	limited field verification capability with component installation.		Technology being trialled in some areas with limited success.	
		<p>Electromagnetic</p> <ul style="list-style-type: none"> • Relatively high accurate when installed correctly and consistent over a full flow range • non invasive • robust • telemetry capability • bi-directional • simple installation • unaffected by debris. • can be buried 	<ul style="list-style-type: none"> • power supply required • relative high cost • some designs require a relatively 'high' flow velocity operating range • customised settings required • full pipe flow required • dissolved chemicals can reduce accuracy 	field verification			
	Storage Volumes	<p>Land based RTK - GPS</p> <ul style="list-style-type: none"> • Traditional technique • Highly accurate • equipment readily available • service commonly provided by surveying profession 	<ul style="list-style-type: none"> • Requires storage to be empty • Time and costs increase for large storages 	None			

		Hydrographic surveying	<ul style="list-style-type: none"> • Can be undertaken when water in the storage • Enables rapid measurement of large storages 	<ul style="list-style-type: none"> • High capital cost of existing hardware and software requirements • Comparatively new service currently only provided by specialist providers 	Only preliminary evaluation of low cost sensors and software for on-farm usage completed Validation of accuracy for a range of on-farm conditions and at a range of storage scales required			7. Refine development of low cost sensor technology and extend validation to broader range of on-farm storage conditions and sizes
Field	Inflow /outflows	Impellor meters in siphons	<ul style="list-style-type: none"> • High accuracy • Ease of installation/use • Commonly datalogged • Comparatively low cost 	<ul style="list-style-type: none"> • Requires calibration to individual siphon size • Impellor wear • Currently Not able to be connected via telemetry 				8. Improved connectivity/telemetry of metering to integrated interfaces and databases at farm scale
		Siphon discharge rating	<ul style="list-style-type: none"> • Simple • Low cost 	<ul style="list-style-type: none"> • Low accuracy, • Calibration dependent on range of parameters which are often estimated (eg. internal diameter, siphon orientation, discharge characteristic, siphon length) • Often single point of time measurement 			Useful for estimating discharge under commercial conditions	
		Inflow measurement of individual bays		<ul style="list-style-type: none"> • Measurement of inflows to fields where gates, control structures or even holes in banks are used is difficult • low head constraints • wide variety of structures 	Inability to measure inflow into bays		Some current work being conducted by Aquatech Pty Ltd	9. Development of metering system to measure inflows at individual bay level
		Flumes	<ul style="list-style-type: none"> • Robust • Commonly used for outflow measurement • Can be datalogged 	<ul style="list-style-type: none"> • Low cost units often poorly calibrated • Concerns over appropriate installation and maintenance • Trash blockage issues under field conditions • High labour requirements 			Variety of commercial units available	

		Tipping buckets	<ul style="list-style-type: none"> • Accurate 	<ul style="list-style-type: none"> • Field installation typically requires a supporting pump and power supply • Accurate only over a narrow range • Accuracy can be impacted by sediment load • High cost • Rarely used in irrigation evaluations 				
		Weirs	<ul style="list-style-type: none"> • Low cost • Variety of designs for different operating conditions 	<ul style="list-style-type: none"> • Requires free flow operating conditions • Often significant banking back of water • Installation issues 				
	Infiltration	Inversion solution using advance measurements and inflow/outflow hydrographs for calculation of infiltration under surface irrigation	<ul style="list-style-type: none"> • provides spatial average infiltration over bay/furrow length • Commercial services (equipment and technological support) available in some areas/industries 	<ul style="list-style-type: none"> • currently requires specialist analytical support • requires both a range of hardware and software tools • currently requires multiple advance point sensors 	high cost and number of field sensors Complexity of analytical tools requires specialist support Interpretation of data for real-time control systems			<p>10. Opportunities to reduce the sensor and data requirements</p> <p>11. Simplification of software analysis tools</p> <p>12. Development of real-time controllers</p>

Table 2. Soil-water measuring and monitoring technology

Scale	Issue	Technology	Strength	Weakness	Technology Gap	Existing reference material	Additional Comments	Research Opportunities
Application system	Root zone storage	Most soil water monitoring technology (as below)	<ul style="list-style-type: none"> Familiar to growers, extension workers and researchers An estimate is fine for commercial situations 	<ul style="list-style-type: none"> Defining root zone for an actively growing crop is difficult. Spatial variation in root zone may occur with spacing and surface configuration (e.g. furrows) 	Root zone is assessed from manual measurement of rooting depth or from soil water depletion data.	Charlesworth (2004), Dane and Topp (2002), Goyne and Williams (2004)	This quantity refers to the volumetric water content of soil (mm of water) within the root zone	1. Reliable method or technique is needed to define root zone of an actively growing crop.
Root zone soil - water	Water content / potential	Thermogravimetric	<ul style="list-style-type: none"> The standard method against which all other soil water measuring tools/techniques are calibrated 	<ul style="list-style-type: none"> Destructive sampling required Labour intensive and expensive process 	Safe, easy to use soil moisture instruments with a wide measurement sphere (radius ~ 20 cm) is not available.	Charlesworth (2004), Dane and Topp (2002), Green and Topp (1992)		2. Need to develop safe, easy to use, low cost soil moisture instruments with a wide measurement sphere (radius ~ 20 cm) to enable many installations in the field. 3. Low cost communication networks are needed to link multiple sensors for reporting to single point 4. Improved calibration and smart software needed to determine volume of water and allow soil moisture trend analysis and irrigation scheduling.
		Neutron Moisture Meter	<ul style="list-style-type: none"> Robust Long history of use in both research and production systems Large measurement sphere Useful in cracking soils 	<ul style="list-style-type: none"> Need for licensed operation and storage Poor perception of radiation exposure risk Limited by manual operation and labour costs Not suited to high frequency application Predominantly used for research only 	Inexpensive sensors will allow sensing of soil moisture at many locations in the field. Low cost communication networks are needed to link multiple sensors for reporting to single point			
		TDR	<ul style="list-style-type: none"> Continually proven to give most accurate measurement without need for calibration 	<ul style="list-style-type: none"> High technical requirement - not suitable for production applications High cost May have problems with signal attenuation in high salt, clay and bulk density soils 	Easier and better methods are needed to calibrate and validate sensors		All measurements of soil water are designed to increase the efficiency of our 'irrigation decision'. We can irrigate solely to the soil moisture status. But this occurs at distinct points in a system and relies on selection of a totally representative site.	

		Manual capacitance probes	<ul style="list-style-type: none"> • Easy to use • Can serve many sites 	<ul style="list-style-type: none"> • Small sphere of influence • Labour costs of manual measurement • Not appropriate for monitoring high frequency application • Uncertain affects of salinity • Calibration issues (Is the instrument giving true SWC ?) • Calibration requires labour intensive destructive sampling 	Smart software is needed to show soil moisture trends and forecast irrigation schedule		<p>We can irrigate solely to ET, using a weather station etc. This has the advantage of being integrated over a much wider area. However, it is unlikely that our crop is developing at exactly the same rate as the crop factors we've chosen. The crop may carry a certain level of disease or be a slightly different variety to that used to develop the crop factors. Therefore, if used solely, the ET method is destined to produce over or under irrigation.</p>	
		Logging capacitance probes	<ul style="list-style-type: none"> • Automatic, unattended measurement • Easily see change in soil moisture status at various depths in a soil profile • Good for monitoring high frequency irrigation application and the effective time and depth of rainfall events 	<ul style="list-style-type: none"> • Small sphere of influence • Must select 'representative' site carefully • Uncertain effects of salinity • Calibration issues (Is the instrument giving true SWC ?) • Calibration requires labour intensive destructive sampling 			<p>We are not good at integrating the different forms of information. We need soil water measurements to check that our scheduling to ET is not running the soil water store up or down over the longer time period. We need flow readings to check how our system is distributing the water, and give us a DU with which the schedule (amount) can be altered if needed.</p>	
		Tensiometers/ gypsum blocks	<ul style="list-style-type: none"> • Relate well to plant stress • Tensiometers have high maintenance requirement and are prone to damage 	<ul style="list-style-type: none"> • Difficult to combine with ET or irrigation application measured in depth • Nor normally logged 				
		Wetting front detector	<ul style="list-style-type: none"> • Reduces data collected to minimum (presence of wetting front at relevant soil depth) • Large measurement sphere • Low cost • Good learning tool 	<ul style="list-style-type: none"> • No recording of history or trend in soil moisture status • Destructive install – best suited prior to crop establishment 				
	Field capacity and soil water characteristic	Gravimetric sampling and tensiometers	<ul style="list-style-type: none"> • Simple and robust technique • Can be performed by wide range of people 	<ul style="list-style-type: none"> • High labour requirement 				

		Haines apparatus	<ul style="list-style-type: none"> • Simple laboratory method to measure air entry potential of soil 	<ul style="list-style-type: none"> • Hard to use undisturbed samples • Very manual and time consuming process 				
		Pressure plate apparatus	<ul style="list-style-type: none"> • Results in useful water retention information <ul style="list-style-type: none"> o Multiple reps possible 	<ul style="list-style-type: none"> • Taking samples out of the field and imposing artificial boundary conditions • Uncertain link with larger scales • Measurement may take extended period 				
Infiltration - point measurement		Ring infiltrometer	<ul style="list-style-type: none"> • Oldest method for obtaining saturated hydraulic conductivity for a constant head • Low tech method, reasonably large measurement area 	<ul style="list-style-type: none"> • good for simulating flood irrigation, questionable for drip/sprinkler 				
		Disc permeameter	<ul style="list-style-type: none"> • Works well for point measurement 	<ul style="list-style-type: none"> • Higher level calculations required • Point measurement, may be skewed by cracks, level of contact etc. • Uncertain how measurement relates to larger scale. 		Dane and Topp (2002), Groenevelt et al. (2001)		
Water deficit and plant available water		Measurements of volumetric water content before irrigation and at field capacity	<ul style="list-style-type: none"> • <i>In situ</i> measurement possible using a variety of equipment 	<ul style="list-style-type: none"> • o Depending on equipment calibration the field capacity point may change 				5. Easier, more reliable, accurate and less expensive method of PAW estimate using current or new concept is required.
		Plant available water (PAW) estimated from field capacity (FC) and wilting point (WP) measurements on pressure plate and membrane apparatus	<ul style="list-style-type: none"> • Method and concepts are well known 	<ul style="list-style-type: none"> • Not suitable for grower or consultant without training • Applies to reference plant • Reliability is good in undisturbed samples 	Least Limiting Water Range (LLWR) and Integral Water Capacity (IWC) are more recent concepts similar to plant water availability which have not been evaluated in irrigated soils.		These are soil based measurements relating to time of critical water deficit (WP) or water logging arising from over irrigation (FC)	6. More realistic thresholds required.

	Deep drainage	Lysimeters	<ul style="list-style-type: none"> • Conceptually simple - a 'buried raingauge', • Able to extract soil water samples for analysis 	<ul style="list-style-type: none"> • Big investment in a point measurement • Large disturbance in installation • Needs large equipment to get undisturbed cores Disturbance increases uncertainty of measurement • Usual configuration is with constant head and this leads to problems with convergence and divergence around top of lysimeter • Fairly complex electronics where a vacuum must be controlled by a logger. 	Low cost drainage metering equipment				7. Deep drainage may be occurring in wide areas in irrigated fields. Alternative, simple and low cost techniques and/or models needed to quantify this loss.
		Tensiometers (Darcy method)	<ul style="list-style-type: none"> • Direct measure of soil-water potential energy • If paired, then direct measure of matric potential energy gradient • Simple concept, • Relatively low cost 	<ul style="list-style-type: none"> • Relies heavily on the choice/measure of hydraulic conductivity. • Ideally needs a water retention curve • If paired tensiometers, then assumes flow is one dimensional • Limited to wet soil conditions (<80 kPa) 					
		Inverse solution (eg. two point method, Infiltr, IPARM)	<ul style="list-style-type: none"> • Proven measurement and calculation method available off-the-shelf • Results are customised to paddock measured 	<ul style="list-style-type: none"> • Interpretation of results may not be straight forward 'recipe' and still needs input from people with experience 					
		Chloride balance	<ul style="list-style-type: none"> • Robust theoretical basis • Independent analysis useful for comparisons with other techniques 	<ul style="list-style-type: none"> • High variance and therefore data requirements • Limited to "long run" comparisons • High sampling and analytical cost 					

Table 3. Plant water use measuring and monitoring techniques

System	Issue	Technology	Strength	Weakness	Technology Gap	Existing reference material	Additional Comments	Research Opportunities
Plant requirement for water and its response to water stress	Water uptake	Sink in the water balance model	<ul style="list-style-type: none"> Conceptually sound 	<ul style="list-style-type: none"> No direct measurement exists Not suitable for grower or consultant complication can arise in separating this term from other terms in the model 	There are few tools and techniques that use measurement on plants or plant parts which could be used to schedule irrigation.	Fuentes et al. (2004)	This is the integration of the rate by which root system of a plant takes up water over time. Estimation is usually per unit area.	1. There is little technology available that could be directly used at the grower or consultant level to advise time or quantity to irrigate. Thus, new tool or technology is required to integrate with irrigation system.
	Water depletion	Loss of water between successive soil water sampling, data on rainfall is also required	<ul style="list-style-type: none"> is a simpler term than water uptake can be determined by grower/ consultant 	<ul style="list-style-type: none"> Not accurate in all situations 				
	Sap flux in trees	Heat pulse or heat balance sensors inserted in tree stems	<ul style="list-style-type: none"> good as a demonstration tool to show actual volume of water consumption by trees 	<ul style="list-style-type: none"> Not suitable for grower or consultant Need additional measurements for corroboration 		McClymont et al. (2004)		
	Volume of water stored within plant	Difference in Fresh weight and dry weight of plants					This volume is considered to be a small, insignificant proportion of daily water use.	
	Stem water potential	Water potential of non-transpiring leaf measured with a Pressure chamber	<ul style="list-style-type: none"> More robust than leaf water potential Equipment relatively cheap 	<ul style="list-style-type: none"> Destructive measurement Requires lot of practice to make reliable measurement Can be measured by a grower/ consultant with adequate training 	Need more testing to determine critical values for important crops	Chone et al. (2001)	Measured on detached, covered leaf at least an hour after detachment	2. Stem water potential, IR thermography and mobile sensing technology need further testing along with standard measurements to establish critical values and times of plant water stress.
	Canopy temperature and infra-red thermography	Infra-red thermometer and thermal imager	<ul style="list-style-type: none"> Good relationship with standard measurements for IR thermography Automation possible 	<ul style="list-style-type: none"> Canopy temperature is too uncertain and less reliable Thermography can be expensive 	Need more testing Cheaper technology is possible	Jones et al. (2002)		
	Leaf water potential	Water potential of a transpiring leaf measured with a Pressure chamber	<ul style="list-style-type: none"> A classical, standard measurement Equipment relatively cheap 	<ul style="list-style-type: none"> Destructive measurement Requires lot of practice to make reliable measurement Time/conditions of day dependant for consistency over time 			Measured immediately after leaf detachment	

	Transpiration and stomatal conductance	Steady-state diffusive porometer	<ul style="list-style-type: none"> • A classical, standard measurement 	<ul style="list-style-type: none"> • Diurnal trend masks usefulness of instantaneous value • Expensive and training required for measurement 				
	Other plant water stress indices	Stem diameter, Water content of leaves	<ul style="list-style-type: none"> • Relatively cheap • Easier for grower or consultant 	<ul style="list-style-type: none"> • Not accurate in all situations • Additional measurements required 				
	Satellite imagery and remote sensing of crop water stress	Spectral data and images of varying characteristics, resolution and coverage	<ul style="list-style-type: none"> • Applications are wide ranging 	<ul style="list-style-type: none"> • Accuracy is uncertain • Ground truthing can be expensive 	Mobile, low altitude sensors may provide better resolution and improve application			3. New mobile technology is needed to determine irrigation requirement that integrates well with irrigation system.
Plant component of atmospheric demand	Leaf area	Leaf area meter	<ul style="list-style-type: none"> • both portable and bench-top equipment available 	<ul style="list-style-type: none"> • Difficult for large canopies • Often estimated from subsampling 	Rapid in-situ estimation of leaf area		This determines the size of transpiring surface	4. More information on aerodynamic and canopy resistance and crop factors would be useful
	Vapour Pressure Deficit	Estimated from weather data	<ul style="list-style-type: none"> • Accuracy dependent on weather sensors • Automation possible 				Determines the magnitude of atmospheric demand	
	Evapotranspiration	Estimated using weather data, Penman-Monteith equation and crop factor	<ul style="list-style-type: none"> • Accuracy dependent on weather sensors • can be determined by grower/ consultant 	<ul style="list-style-type: none"> • Uncertainty with aerodynamic and surface resistance terms • Expensive crop factor 	More evaluation of resistance and crop factors are needed			

Table 4. Tools and techniques to measure evaporation and evapotranspiration

Scale	Issue	Technology	Strength	Weakness	Technology Gap	Existing reference material	Additional Comments	Research Opportunities
Storages (both on-farm and off-farm)	Evaporation	PHYSICAL SIMULATION – Class A pan, <i>i. adjacent to storage</i>	<ul style="list-style-type: none"> • simplicity • low cost • commonly available 	<ul style="list-style-type: none"> • NOT VALID due to major difference in the short-term (diurnal, few-days) aerodynamics and the energy balances for ML-scale versus sub-kL-scale • Calibrations (pan factors) highly variable and unreliable • Demonstrated to be unsuitable in daily/short term estimates [FAO-56] 	Major, due to difficulties in accounting for the major differences in the short-term (diurnal, few-days) aerodynamics and the energy balance for ML-scale versus sub-kL-scale	<ul style="list-style-type: none"> • recently – FAO-56 (with respect to daily/short-term utility) 	Considerable effort over many decades has failed to overcome the technology gap.	<ol style="list-style-type: none"> 1. Actual dam evaporative flux measurement via eddy correlation (point measurements). 2. Airflow and thermal modelling for regular storage structures (ring tanks) to permit areal generalization of evaporative flux measurements. 3. Development of <i>custom</i> “Dam AWS” validated against evaporative flux (eddy correlation) measurements and modelling.
		– Class A pan, <i>ii. floating in storage</i>	<ul style="list-style-type: none"> • pan & storage waters are: • subject to similar aerodynamics • in thermal equilibrium 	<ul style="list-style-type: none"> • Aerodynamic differences due to pan walls • Practically inconvenient 	<ul style="list-style-type: none"> • Operational practicalities 		Worthy of further investigation?	
		ATMOSPHERIC DEMAND – standard Automatic Weather Station (AWS) (Penman-Monteith) <i>i. sited adjacent to storage</i>	<ul style="list-style-type: none"> • simplicity • modest cost • commonly-available 	<ul style="list-style-type: none"> • NOT VALID due to “oasis effect” (i.e. major advection of energy) 	Major, – empirical calibration factors will be dependant on site, season, & weather-history.			
		– standard AWS (Penman-Monteith) <i>ii. sited over storage</i>	<ul style="list-style-type: none"> • valid measurement technique – if adequate fetch (i.e. for very large storages only) 	<ul style="list-style-type: none"> • required fetch distances =100m+ of water surface • Inadequate radiation sensing – require net radiation (=high-cost) • practically inconvenient 	<ul style="list-style-type: none"> • installation, operational and maintenance practicalities 			
		– <i>miniaturised</i> AWS (Penman-Monteith) – <i>sited over storage</i>	<ul style="list-style-type: none"> • reduced fetch requirement 	<ul style="list-style-type: none"> • sensors not readily available • prone to interference by modest (~10cm) wave action 	<ul style="list-style-type: none"> • sensor development required 		Worthy of further investigation?	
		– custom AWS for dam evaporation	<ul style="list-style-type: none"> • siting <i>adjacent</i> to storage • involves only low-cost sensors 	<ul style="list-style-type: none"> • Not known 	<ul style="list-style-type: none"> • Design only hypothesized at present: • theoretical basis requires further research: • system hardware yet to be designed 		Highly desirable.	<ol style="list-style-type: none"> 4. Research utility of optical absorption spectroscopy for dam evaporation measurement.

		<ul style="list-style-type: none"> – via 'Bowen Ratio' apparatus i. <i>sited adjacent to storage</i> 	<ul style="list-style-type: none"> • high precision 	<ul style="list-style-type: none"> • questionable validity due to "oasis effect" (i.e. major advection of energy) • high-cost instrumentation • unsuited to unattended operation 	<ul style="list-style-type: none"> • theoretical validity questions 		<p>Bowen Ratio techniques now largely superseded by eddy correlation for micrometeorological research.</p>	
		<ul style="list-style-type: none"> – via 'Bowen Ratio' apparatus ii. <i>sited over storage</i> 	<ul style="list-style-type: none"> • high precision 	<ul style="list-style-type: none"> • high-cost instrumentation • unsuited to unattended operation • required fetch distances =100m+ of water surface • practically inconvenient 	<ul style="list-style-type: none"> • installation, operation and maintenance practicalities 		<p>As above; plus highly impractical</p>	
		<ul style="list-style-type: none"> – via Eddy Correlation (Covariance) (<i>sited over storage</i>) 	<ul style="list-style-type: none"> • is the only direct measurement of water vapour flux • is not affected by oasis effect • is not affected by fetch limitations 	<ul style="list-style-type: none"> • high-cost instrumentation • analytically complex • unsuited to unattended operation 			<p>Is a 'research only' tool.</p>	
		<ul style="list-style-type: none"> – via Optical (with IR, UV & microwave) Absorption Spectroscopy (for water vapour) 	<ul style="list-style-type: none"> • Line integration to 100m/km scale – hence fetch effects incorporated 	<ul style="list-style-type: none"> • High-cost instrumentation • Unproven research utility 				
		<p>VOLUMETRIC WATER BALANCE</p> <ul style="list-style-type: none"> – via storage depth measurement 	<ul style="list-style-type: none"> • is a direct determination of water loss, measured independently of atmospheric demand • capable of sub-millimetre precision using pressure depth sensing 	<ul style="list-style-type: none"> • evaporation is derived as a residual only after all other terms in the water balance are known • high-precision measurements of inflows and outflows required to yield modest-precision evaporation information • high installation / establishment cost 			<ul style="list-style-type: none"> • Capable of use as a management tool by appropriate selection of periods for which other inflows and outflows are zero. • Capable of use to estimate dam seepage. 	
Distribution systems (open channels, ditches etc.)	Evaporation						How significant is this issue?	
		<ul style="list-style-type: none"> Simulation of open water surface – Class A evaporation pan 	<ul style="list-style-type: none"> • simplicity • low-cost • readily available 	<ul style="list-style-type: none"> • major advection of energy into the 'line' of open water (the 'Clothesline Effect') hence: • will provide rough estimate only. 				

		Atmospheric measurement: – standard AWS (Penman-Monteith)	<ul style="list-style-type: none"> readily available 	<ul style="list-style-type: none"> major advection of energy into the 'line' of open water (the 'Clothesline Effect') hence: will provide rough estimate only 				
		Assessment via water balance	<ul style="list-style-type: none"> does not involve uncertainties of atmospheric demand measurement 	<ul style="list-style-type: none"> requires knowledge of ALL inflows and outflows seepage is likely to be variable along the channel 				
In-field application systems – <i>Surface and Drips</i>	Evaporation	Simulation of open water surface – Class A evaporation pan	<ul style="list-style-type: none"> simplicity low-cost readily available 	<ul style="list-style-type: none"> pan must be located <i>within</i> crops will (very approximately) simulate the <i>average</i> evaporation in relation to relative areas of open water surface, wet soil and dry soil 				
		Atmospheric measurement: – standard AWS (Penman-Monteith)	<ul style="list-style-type: none"> readily available 	<ul style="list-style-type: none"> the wind profile of airflow through the cropping is unlikely to be as presumed by the use of Penman-Monteith calculation AWS must be sited <i>immediately downwind</i> of the cropping will then provide an estimate (only) of the <i>average</i> evaporation in relation to relative areas of open water surface, wet soil and dry soil 				
		– via Eddy Correlation	<ul style="list-style-type: none"> provides a direct measurement of water vapour flux is not affected by the characteristics of the wind profile of airflow through the cropping 	<ul style="list-style-type: none"> high-cost instrumentation analytically complex unsuited to unattended operation will measure the <i>average</i> evaporation in relation to relative areas of open water surface, wet soil and dry soil 				
In-field application systems – <i>Sprinklers</i>	Evaporation	- Via local (volume) water balance i.e. extrapolated catch-can precipitation subtracted from metered delivery	<ul style="list-style-type: none"> relative simplicity 	<ul style="list-style-type: none"> poor accuracy from catch-cans 				5. Apply tracer-dye technique to sprinklers to improve estimation of evaporative losses.

		<ul style="list-style-type: none"> - Via tracer-chemical (dye, salt) i.e. from relative increase in concentration in water reaching soil 	<ul style="list-style-type: none"> • simplicity – volume metering not required • good accuracy from colorimetry (of dye) 	<ul style="list-style-type: none"> • better suited to larger evaporation rates • tracer may pollute soil and water 				
		<ul style="list-style-type: none"> Atmospheric measurement – via Eddy Correlation 	<ul style="list-style-type: none"> • as described for other application systems 	<ul style="list-style-type: none"> • siting difficult • high cost • will measure total evaporative flux to include ET and evaporation from spray. 				
Crop field	Evapotranspiration (ET)	<ul style="list-style-type: none"> “FAO-56”, i.e. – derivation of daily ‘Reference ET_o’ and crop coefficient 	<ul style="list-style-type: none"> • simple • industry ‘best practice’ as an operational (rather than research) tool 	<ul style="list-style-type: none"> • approximate only (i.e. not a research tool) • daily totals only • crop and environmental factors are general-purpose’ (designed for world-wide application) 		FAO-56 “Crop Evaporation – Guidelines for Computing Crop Water Requirements”		
<i>Techniques below as per standard micrometeorological research</i>								
		<ul style="list-style-type: none"> – standard AWS (Penman-Monteith) sited over crop 	<ul style="list-style-type: none"> • relatively cheap • moderate accuracy • provides hourly totals, i.e. can assess diurnal variation 	<ul style="list-style-type: none"> • requires fetch of at least 10 times (& preferably 100 times) the measurement height • requires appropriate bulk stomatal resistance values for the crop • requires correction for non-neutral conditions • should use net radiometer (high cost) • siting inconvenient (with respect to irrigation operations) 	Appropriate crop-specific and crop-stress-related stomatal resistance data are seldom available.			
		<ul style="list-style-type: none"> – miniaturised AWS (Penman-Monteith) sited over crop 	<ul style="list-style-type: none"> • (as above) • reduced fetch requirements 	<ul style="list-style-type: none"> • (as above) 	<ul style="list-style-type: none"> • sensor development required 			
		<ul style="list-style-type: none"> – via ‘Bowen Ratio’ apparatus, sited over crop 	<ul style="list-style-type: none"> • high accuracy (with compensation for non-neutral stability) 	<ul style="list-style-type: none"> • high-cost instrumentation • requires fetch of at least 10 times (& preferably 100 times) the measurement height • siting inconvenient (with respect to certain irrigation operations) 				<ul style="list-style-type: none"> Bowen Ratio techniques now largely superseded by eddy correlation for micrometeorological research.

		– via Eddy Correlation (Covariance) <i>sited over crop</i>	<ul style="list-style-type: none"> • high accuracy • direct measure of evaporative flux • not limited by fetch requirements • applicable to non-broadacre & multi-layer canopies 	<ul style="list-style-type: none"> • high-cost instrumentation • analytically complex • siting inconvenient (with respect to certain irrigation operations) 				6. Accurate hourly evaporative flux measurements via eddy correlation (point measurements) to study crop response to irrigation.
		– via Optical (with IR, UV & microwave) Absorption Spectroscopy (for water vapour)	<ul style="list-style-type: none"> • Line integration at 10-to-100m scale • Direct measure of integrated evaporative flux with fetch/leading edge effects incorporated • Siting with in-field irrigation machinery potentially less inconvenient than eddy correlation and other micrometeorological tools. 	<ul style="list-style-type: none"> • High-cost instrumentation • Unproven research capability at 10m-scale 				7. Research utility of optical absorption spectroscopy for crop ET measurement.
	Interception	– via Eddy Correlation (Covariance) <i>sited over wet crop</i>	<ul style="list-style-type: none"> • <i>As per Eddy Correlation above</i> 					8. Accurate sub-hourly evaporative flux measurements via eddy correlation (point measurements) to study interception losses.
Evaporation of irrigation water or rain intercepted by crop		Estimate actual evaporation using Penman-Monteith, weather data and crop factor	<ul style="list-style-type: none"> • Estimation method is well known 	<ul style="list-style-type: none"> • Not suitable for grower or consultant without training • Accuracy not known • Uncertainty with resistance terms 	<ul style="list-style-type: none"> • Need volume and loss using Lysimetry 		Importance of this component of water is unknown. Water on leaf reduces transpiration. Direct water absorption by leaf from this source could be small.	9. Compare eddy correlation measurements with lysimetry or simulated leaf sensors to determine importance of interception loss.
		Artificial leaf	<ul style="list-style-type: none"> • Uses well known method of energy flux from a surface 	<ul style="list-style-type: none"> • Recent technology • Not yet used to measure free water from leaf surface 	<ul style="list-style-type: none"> • Need testing as above 			

3. Research Priorities and Opportunities

The scoping study has reviewed various tools and technology used in many components of the supply-distribution-use chain for irrigation water. For convenience, the study was divided into four different areas with some degree of overlap between these areas. For each of these areas, the technology gaps and research opportunities are summarized in Tables 5-8.

Table 5. Technology gaps and research opportunities in water flow measuring and monitoring tools used in storage and distribution systems and field applications.

Technology gap	Research opportunities
<p>For measurement of channel flow in storage and distribution systems: Replacement technology is needed for Dethridge meter and sort by regulators. 20,000 installations in G-M district are expected.</p> <p>Field verification of ultrasonic meters, propeller meters, paddlewheel, turbine meters and electromagnetic flow meters is limited.</p>	<p>Current metering standards are for potable water qualities operating under municipal conditions and are not appropriate for irrigation flows.</p> <p>There is a need to define the irrigation standards for metering. There is also potential to develop lower cost and more robust irrigation metering options.</p> <p>A cost benefit analysis of high capital/low maintenance metering vs low capital, high maintenance meters is necessary.</p> <p>Protocols for routine verification of meter performance in the field need to be developed.</p> <p>The current level of performance of meters operating under commercial conditions in the field needs to be determined.</p> <p>Communication and presentation of metering data at various scales also need improvement.</p>
<p>Measurement of storage volumes is currently limited by the availability of sensors and methods.</p>	<p>Refine development of low cost sensor technology and extend validation to broader range of on-farm storage conditions and sizes.</p>
<p>Inflow/outflow of water in fields is measured with manually operated Impellor meters.</p>	<p>Improved connectivity/telemetry of metering to integrated interfaces and databases at farm scale.</p>
<p>Measurement of inflow water into individual bays is not currently possible.</p>	<p>Development of metering system to measure inflows at individual bay level.</p>
<p>Infiltration measurements in the field involve high cost and number of field sensors. Complexity of analytical tools requires specialist support. Interpretation of data for real-time control systems</p>	<p>Opportunities to reduce the sensor and data requirements</p> <p>Simplification of software analysis tools</p> <p>Development of real-time controllers</p>

Table 6. Technology gaps and research opportunities in soil water measuring and monitoring technology.

Technology gap	Research opportunities
Root zone is assessed from manual measurement of rooting depth or from soil water depletion data.	Reliable method or technique is needed to define root zone of an actively growing crop.
Safe, easy to use soil moisture instruments with a wide measurement sphere (radius ~ 20 cm) are not available. Inexpensive sensors are needed to allow sensing of soil moisture at many locations in the field. Low cost communication networks are needed to link multiple soil moisture sensors for reporting to single point. Easier and better methods are needed to calibrate and validate sensors.	Need to develop safe, easy to use, low cost soil moisture instruments with a wide measurement sphere (radius ~ 20 cm) to enable many installations in the field. Low cost communication networks are needed to link multiple sensors for reporting to single point Improved calibration and smart software needed for volume measurements as well as for soil moisture trend analysis and irrigation scheduling.
Least Limiting Water Range (LLWR) and Integral Water Capacity (IWC) are more recent concepts similar to plant water availability which have not been evaluated in irrigated soils.	Easier, more reliable, accurate and less expensive method using current or new concept of plant available water (PAW) estimate should be evaluated using more realistic water potential thresholds.
Low cost deep drainage metering equipment is not available.	Deep drainage may be occurring in wide areas in irrigated fields. Alternative, simple and low cost techniques and/or models needed to quantify this loss.

Table 7. Technology gaps and research opportunities in plant water use measuring and monitoring techniques.

Technology gap	Research opportunities
There are few tools and techniques that use measurement on plants or plant parts which could be used to schedule irrigation.	There is little plant based technology available that could be directly used by a grower or consultant to advise time or quantity to irrigate. Thus, new tool or technology is required to integrate with current irrigation system.
Need more testing to determine critical values of stem water potential for important crops. Need more testing of IR thermography and similar mobile technology.	Stem water potential, IR thermography and mobile sensing technology need further testing along with standard measurements to establish critical values and times of plant water stress.
Mobile, low altitude sensors may provide better resolution and improve application than conventional satellite imagery and remote sensing to measure crop water stress.	New mobile technology is needed to determine irrigation requirement that integrates well with irrigation system.
Estimation of ET is uncertain without adequate evaluation of resistance and crop factors.	More information on aerodynamic and canopy resistance and crop factors is needed.

Table 8. Technology gaps and research opportunities in measuring and monitoring of evaporation and evapotranspiration.

Technology gap	Research opportunities
Evaporation from on-farm and off-farm storage areas simulated with Class A pan located adjacent to storage or over the storage areas is not valid due to scale differences, oasis effect and aerodynamic differences.	Actual dam evaporative flux measurement via eddy correlation (point measurements). Airflow and thermal modelling for regular storage structures (ring tanks) to permit areal generalization of evaporative flux measurements. Development of <i>custom</i> "Dam AWS" validated against evaporative flux (eddy correlation) for measurements and modelling. Research utility of optical absorption spectroscopy for dam evaporation measurement
Evaporation from sprinkler irrigation systems can not be measured accurately with water balance or eddy correlation techniques.	Apply tracer-dye technique to sprinklers to improve estimation of evaporative losses.
Evapotranspiration from crop fields estimated with micrometeorological data and FAO56 are approximate.	Accurate hourly evaporative flux measurements via eddy correlation (point measurements) to study crop response to irrigation. Research utility of optical absorption spectroscopy for crop ET measurement.
Methods to quantify irrigation water intercepted by crop and its effect on evapotranspiration are not available.	Accurate sub-hourly evaporative flux measurements via eddy correlation (point measurements) to study interception losses.
Evaporation of water intercepted by crop from sprinklers or rain could be measured using lysimetry, eddy correlation or simulated leaf sensors.	Compare eddy correlation measurements with other methods (e.g. lysimetry or simulated leaf sensor) to determine importance of interception losses.

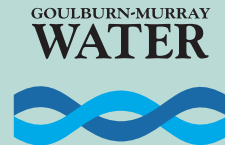
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