Improving the Performance of Basin Irrigation Layouts in the Southern Murray-Darling Basin

Sam North, Don Griffin, Michael Grabham and Malcolm Gillies

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Definitions

Basin irrigation systems are defined as surface irrigated areas which have no longitudinal slope and complete perimeter dikes to pond water and prevent run-off (Walker and Skogerboe, 1987). These are differentiated from border check irrigation systems which have slope in the longitudinal direction and free draining conditions at the lower end. The National Engineering Handbook (U.S. Natural Resources Conservation Service, 1997) differentiates between three principal surface irrigation systems: level, graded and contour. Graded systems are those where water flows in the direction of the land slope. Adapting the nomenclature and definitions in these sources, basin systems in southern NSW can be differentiated into:

1. Contour systems - have slope in the lateral direction (i.e. across the width of the bay) but not in the longitudinal direction (i.e. down the length of the bay). They can be classified as either:

   a. **Natural contour** systems if check banks follow the natural contour. Laser grading to remove reverse grades may have been conducted within bays.

   b. **Parallel contour** systems if they have been land-formed so that the check banks along the contour are parallel to each other.

2. Level systems - are completely level within each irrigation bay (i.e. no slope in either longitudinal or lateral directions) and the bays are generally rectangular in shape with a bench (or terrace) between them. They can be classified as either:

   a. **Level basin** systems are used for growing rice “on the flat” and in rotation with pastures and winter cereals in a mixed farming enterprise.

   b. **Level furrow** systems are used for growing row crops on “hills” or raised beds in a cropping enterprise and are not generally suited to pasture production.

The terms side ditch and bankless channel are used synonymously in this document. Swinton (1994) defines them as a supply channel, running with the slope down one side of an irrigation block, which does not have a bank on the inside of the bay. Checks are placed across the channel at each contour bank to control flows. The bed of the channel is below bay level and it acts as both supplier and drain.
Executive Summary

The National Land and Water Audit showed that, in Australia, irrigated agriculture generated 51 per cent of the total profits from agriculture in the five year period to 1996 to 1997, from only 0.5 per cent of the total agricultural land area. However, drought (and possibly climate change), water reform, and increasing competition between consumptive water users as well as between consumptive users and the environment, has reduced water availability and increased water prices for irrigators in the major Australian irrigation areas of the southern Murray-Darling Basin (MDB). This has driven a need to improve irrigation water productivity in these areas.

In the southern MDB, 83 per cent of all irrigated land is irrigated using surface systems and the biggest opportunities to improve irrigation water productivity in this region lie with those industries that use the most water through these systems: i.e. pasture production for dairy and grazing, and annual cropping (Meyer, 2005). The two main types of surface systems found in the southern MDB are border check, which predominates in the dairy and grazing industries, and basin systems, which occur in the rice growing annual crop systems of southern NSW. Considerable work has been done over many years to improve border check systems (e.g. Campbell, 1989; Austin & Predergast, 1997; Mehta & Wang, 2004). However, the same cannot be said for basin systems.

Study Objectives

The overall objective of this project was to improve the design and performance of basin irrigation systems in the rice growing areas of the southern Murray-Darling Basin (MDB) so they can be used to achieve higher yields for a wider range of crops than is currently possible, with reduced operating and environmental costs.

To achieve this, there were a number of specific objectives:

1. Determine the current state of knowledge, practice and tools for basin irrigation system design and performance evaluation;

2. Develop clear recommendations for “best practice” basin irrigation system design(s) based on hydraulic and economic performance; and

3. Develop tools and techniques that can be used to evaluate basin irrigation system performance.
Current Knowledge, Practice and Tools

A scoping study was conducted to answer the first of these objectives and two reports on the outcomes of this have been published by the CRC for Irrigation Futures (North, 2008; Gillies et al. 2008). These are available as downloadable publications from the CRC IF website (http://www.irrigationfutures.org.au). The key findings were:

1. The profitability of basin systems may be increased by:
   a. The adoption of practices which improved soil health, with increases in productivity of 20-30 per cent reported. No local studies were found; and
   b. Better and more flexible irrigation systems which allow the crops returning the most per ML to be selected.

2. The irrigation application efficiency of “old” contour basin systems may be increased from 55-60 per cent to 80-90 per cent, though this has not been confirmed for the typical basin systems found in the southern MDB.

3. Current design recommendations are nearly 20 years old and do not provide guidance on design for more recent changes such as high flow rates, side-ditch delivery, terracing and level furrow systems.

4. Currently recommended irrigation opportunity times ranged from eight to 24 hours. No experimental evidence was found to support this recommendation.

5. No computer aided design tool was found for basin systems in the southern MDB.

Recommendations for “Best Practice” Basin Irrigation System Design

Opportunity Times are Excessively Long

Irrigation opportunity times in nearly all the contour basin systems examined were far too long (i.e. 40 to 50 hours) and would have led to waterlogging losses in sensitive (non-rice) crops. This was due solely to excessively long drainage times, not slow inflow rates. Observations of drainage times in basins with side-ditch delivery systems and commonly occurring slopes (1:1400 to 1:1800) were generally four times longer than fill times. This is four times greater than what irrigators currently believe.

Side-Ditch Delivery Systems are the Principle Cause of Long Opportunity Times

Side-ditch delivery systems in contour basin systems fail because the driving head in the inlet/outlet structures is lost when water backs up in the downstream bay. This causes a marked reduction in the delivery capacity of the structure and reduces the outflow from the upstream bay. To improve the water productivity and cropping flexibility of contour basin systems in the southern MDB, it is recommended that:
1. Contour basin layouts should be evaluated prior to new works being done so that the limiting factors in the current design can be determined. Evaluations can be done simply and effectively by surveying levels and recording the depth and duration of ponding in each bay during an irrigation;

2. Basin systems in the southern MDB should be designed to ensure they can be watered and drained within 10 hours,
   
i. For non-swelling soils with better internal drainage, the recommended maximum irrigation opportunity time is 18 hours,

   ii. For sodic, NSMC soils, frequent irrigation will result in reduced productivity of waterlogging sensitive crops and pastures, no matter how short the opportunity time. It is recommended that a maximum opportunity time of 10 hours be adopted for these soils and that soil management practices be implemented to improve their physical fertility; and

3. If irrigation opportunity times in side-ditch delivery layouts are longer than those recommended and slow drainage is identified as the principal cause, then the side-ditch should be dispensed with and each basin should be supplied independently.

**Operational Performance of Basin Systems**

Machinery efficiency data showed there are, potentially, savings in the order of 10-20 per cent for every machinery operation in a basin system if turning and trafficking in bays can be reduced and GPS steering guidance adopted in large, more regular areas. The operational advantages of drive-over-bank systems was clearly shown.

**Tools and Techniques for Evaluating Basin Irrigation Systems**

Simple protocols were developed for evaluating basin systems (as described above). However, there was considerable difficulty in accurately measuring water flows for determining irrigation application efficiencies and whole bay infiltration rates. It was found that Acoustic Doppler Velocity (ADV) meters were able to accurately measure flows in full flowing pipes but not in partially full pipes or through check structures (stops). This was due to non-uniform flow in the latter two situations so that the measurements from one ADV meter did not represent the mean velocity of the channel cross-section. It was considered that the simplest method of overcoming the variability of flow through stops used in basin systems is to use three single path, ADV meters (placed at 1/6, 1/2 and 5/6 of the width of the stop) and average the measured velocities.
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1. Introduction

This report forms the final of the Cooperative Research Centre for Irrigation Futures’ (CRC IF) Project 3.56, and the Murray Land and Water Management Plan’s Project ENV 6/05, which commenced in July 2006 and was completed in December 2009. This final report is a summary document which describes the background to the project, the general methods and conduct of the project, and the main findings and recommendations. Comprehensive technical reports describing some of the individual experiments conducted during the course of the study are reported separately.

1.1. The Study Objectives

The overall objective of this project was to improve the design and performance of basin irrigation systems in the rice growing areas of the southern Murray Darling Basin (MDB) so they can be used to achieve higher yields for a wider range of crops than is currently possible, with reduced operating and environmental costs.

To achieve this, there were a number of specific objectives:

1. Determine the current state of knowledge, practice and tools for basin irrigation system design and performance evaluation;
2. Develop clear recommendations for “best practice” basin irrigation system design(s) based on hydraulic and economic performance; and
3. Develop tools and techniques that can be used to evaluate basin irrigation system performance.

1.2. Expected Research Outcomes and Outputs

Outcomes

1. Improved water productivity of the non-rice phase of the rice rotation;

2. Reduced risk of waterlogging and an increased range of crops that can be grown profitably; and

3. Reduced operating (i.e. machinery and labour) and environmental (i.e. deep drainage) costs.

Outputs – Research Deliverables

The project was to have two major outputs:

1. Establishment of a protocol for evaluating basin irrigation system performance, including a description of the tools and techniques to be used;
2. Software to aid Basin irrigation design and a “Best Practice” manual for basin irrigation layouts. This is to include:

- Design characteristics of an "ideal" basin irrigation system, including features that could be incorporated into existing layouts to improve performance,

- Information regarding the cost and benefits of alternative basin irrigation designs, and

- Infiltration characteristics for a range of Murray valley soils.
2. **Background to the Study**

There were a number of key drivers for this research. They included:

- Inadequate drainage in most basin irrigation systems leading to a high risk of waterlogging for winter crops and increased groundwater accessions;
- Static or decreasing terms of trade for most agricultural commodities; and
- Greater competition for, and increasing scarcity of, irrigation water.

Irrigation layouts that are ideal for the production of paddy rice are the antithesis of that needed for intermittently irrigated upland crops. Previous research has demonstrated the benefits of bed farming in basin layouts. However, there is a reluctance to shift to this system in the Murray valley because most cropping enterprises use large tractors, dual tyres and wide-line machinery to achieve efficiencies of scale and this machinery is not suited to cropping on beds. The choice of machinery is driven by the high proportion of dryland and unirrigated areas on most farms in the district. Therefore, there is a need for flexible layouts suited to the machinery and scale of cropping operations in the valley, capable of being used to produce high yields from upland crops as well as rice with all the labour/cost advantages of basin systems.

There have been a number of “new” basin irrigation layouts built in recent years which have sought to address these issues. However, the hydraulic performance of these non-standard designs has not received an objective evaluation and, consequently, clear guidelines for their design and sound reasons to justify their widespread adoption haven’t been independently established.

In the Murrumbidgee valley, the “bankless channel” basin irrigation system that was developed in the 1970s became widely adopted by the rice industry during the 1990s, and was then further developed to accommodate row crops. Terraced, level basin systems with permanent beds (i.e. level furrow systems) are now currently used to irrigate a wide range of crops, including maize, canola, cotton, sunflowers, soybeans, faba beans, winter cereals and lucerne, and the popularity of this system is such that a large proportion of irrigation developments and redevelopments for these crops are bankless systems. As well as this, the versatility and operational advantages of the system have resulted in some siphon fed row crop irrigators converting to bankless systems. The advantages driving this conversion include labour savings, infield operational efficiencies and the potential for automation of the system. Anecdotally, irrigators who have installed the system feel they have either maintained or improved
their application efficiency. However, these claims are not substantiated. Furthermore, there are currently no known, reliable design, evaluation or management tools for optimising the efficiency of this system.
3. General Methodology

Stage 1. Scoping Study

A review of the literature and of current practices was conducted between February and September 2006 by the project partners. This included the following:

1. A survey of irrigation designers to determine current best practice basin irrigation design and identify their “needs” in terms of design information;

2. A review of current district practices to ascertain the range of variation in basin irrigation design and performance (hydraulic and agronomic);

3. A review of existing basin irrigation design models and software to identify their strengths and weaknesses and the gaps in knowledge; and


The methodology adopted took the form of semi-structured interviews and a review of available literature. A range of interviews were conducted, including:

- A focus group meeting in April 2006 which involved 12 participants (irrigation surveyor-designers, farmers, earth moving contractors and advisory staff);

- Thirty-five farmers in eight discussion group meetings during July 2006; and

- In-depth interviews with two local irrigation designers and feedback and comments from two other designers.

A technical workshop was held in May 2007 and the findings of the scoping study were presented to a range of stakeholders (irrigation surveyors-designers, farmers, researchers, and advisory staff) and the characteristics of an “ideal” basin irrigation design was discussed.

Discussions were also held in May 2007 with a number of researchers to help select “best bet” tools and techniques to be used to evaluate basin irrigation performance.

The range of computer models available for modelling irrigations and determining whole bay infiltration characteristics was reviewed and it was found there was a lack of suitable models. One existing model (IPARM) was subsequently modified to see whether it could be used and a second model (CISCO) was developed.
Stage 2. Evaluation of Basin Layouts

Stage 2.1. Evaluation of Methodologies

Single beam, continuous signal, Acoustic Doppler Velocity (ADV) meters were considered to be the best available method for measuring flows in basin systems. Because accurate flow measurement is critical to the proper evaluation of any irrigation system, a hydraulic test facility was constructed on the Murray Valley Field Station to check the accuracy of the ADV meter velocity readings (Figure 1 and Figure 2).

The depth measurements from the ADV meters were also checked and conventional stream gauging techniques were used to determine whether the velocity of the water sampled by the ADV meters was representative of the mean cross-sectional velocity through a range of stops and installations.

Figure 1. Diagram of the hydraulic test facility built on the Murray Valley Field Station for checking the flow velocities measured by the Unidata™ Starflow ADV meters used in this study.
The methodology for evaluating basin performance identified during Stage 1 was trialled during one irrigation in spring 2006 and two autumn irrigations in 2007. These took place on the Murray Valley Field Station (MVFS), “Avenal” (Colin McCrabb) and McCaughey Field Station.

**Stage 2.2. Replicated Trials**

It was planned to collect data on the performance of a range of design permutations (e.g. standard v-shaped toe-furrows vs. wider trapezoidal toe furrows; flat bays vs. wide beds vs. standard beds; individual bay drainage vs. interconnected bays) in replicated plots at a field site that had been established on a property north of Deniliquin. It was also planned to compare sowing down the slope with conventional sowing across the slope, in order to evaluate the effect on irrigation and drainage times (and determine the relative roughness coefficients).

One of the key criteria lacking for irrigation basin design is the maximum irrigation opportunity time (i.e. the duration that water is ponded on the soil surface and available to infiltrate the soil). A glasshouse pot trial, a field trial and soil and water depth measurements collected in-situ during the irrigation evaluations were used to assess the impact of waterlogging duration on soil aeration and wheat crop growth. The soils
used were representative of the four major soil types found in basin systems in the southern MDB: red brown earth, transitional red brown earth, non-self mulching clays and self mulching clays.

Stage 2.3. In-Field Evaluation of Basin layouts

The range of basin irrigation designs present in the irrigation districts of the southern Murray Darling Basin (MDB) were identified and categorised during Stage 1. Co-operators with representative examples of these different designs were found and measurements obtained to characterise their hydraulic performance (i.e. application efficiency and times for water on/off).

In the Murray valley, the following data was collected from thirteen irrigations in six basin types (Table 1):

1. Flow rates - onto and off three to four bays in the block being irrigated using ADV meters (Unidata™ Starflow meters);
2. Water depth;
   a. At nine locations within the one intensively monitored basin,
   b. Close to the outlet in each basin to show water depth above the bay surface at the lowest point of each basin, and
   c. Downstream of each structure as a back up to the Starflow meters;
3. Soil moisture content - to 60 cm depth in the one bay that was more intensively monitored;
4. Wetting front advance was walked and mapped using a differentially corrected GPS (DGPS) every hour during the irrigation of the intensively monitored bay; and
5. Survey data was collected from all paddocks. Areas were obtained using the DGPS. Levels were obtained at each sensor location (depth and ADV meter) and at other key locations, such as at structures and corners of bays, using a dumpy level.

In the Murrumbidgee valley, a three bay, drain-back level furrow system was evaluated. Discharge at the bay scale was measured using Doppler flow meters (Mace™ Agriflow) in the pipes delivering and draining each bay in the system. Crop water use was calculated from reference evapotranspiration (ET₀) weather data. Daily measures of the modified Penman-Monteith calculated ET₀ data from Griffith, NSW (Meyer, 1999;
Meyer et al., 1999) and a local crop factor for cotton were used to determine crop evapotranspiration ($ET_c$).

Table 1. The categories of basin layouts from which irrigation performance data was collected and the dates and locations of irrigations evaluated.

<table>
<thead>
<tr>
<th>Layout type</th>
<th>Date</th>
<th>Location</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lasered, parallel contour basin</td>
<td>Nov 2008</td>
<td>‘McCaughey’</td>
</tr>
<tr>
<td>Lasered, parallel contour; side-ditch delivery</td>
<td>April 2007</td>
<td>‘McCaughey’</td>
</tr>
<tr>
<td></td>
<td>Aug 2007</td>
<td>‘Bilcurra’</td>
</tr>
<tr>
<td></td>
<td>Sept 2007</td>
<td>‘East Rostella’</td>
</tr>
<tr>
<td></td>
<td>Oct 2007</td>
<td>‘McCaughey’</td>
</tr>
<tr>
<td>Lasered parallel contour; individual supply &amp; drain</td>
<td>Oct 2006</td>
<td>Murray Valley Field Station</td>
</tr>
<tr>
<td>Drive-over bank systems (“V-bay”)</td>
<td>Oct 2008</td>
<td>‘McCaughey’</td>
</tr>
<tr>
<td></td>
<td>Oct 2009</td>
<td>‘Amarran’</td>
</tr>
<tr>
<td>Drain back level basin system</td>
<td>Oct 2009</td>
<td>‘McCaughey’</td>
</tr>
<tr>
<td>Drain back level furrow system</td>
<td>Summer 2008</td>
<td>Commins Bros</td>
</tr>
</tbody>
</table>

Stage 2.4. Collection of Economic Data

Typical production data (operating costs and yields) was collected so the operating and maintenance costs of alternative basin designs could be compared. Two principle methods were used to collect the data for this component of the project:

i. Subjective data on yields and maintenance costs obtained from interviews, group discussions and surveys; and

ii. Objective data on machinery efficiency obtained from logging machinery operating time, distance travelled and area covered using small GPS trackers.

The GPS trackers were placed in tractors and headers to collect time and motion data from sowing, spraying and harvesting operations in 50 paddocks covering a wide range of basin systems and machinery widths. Once collected, the track data was downloaded and processed to obtain the total path length in the paddock. This path length was multiplied by the machinery width to determine the total area trafficked during the operation. The actual paddock area was obtained from satellite imagery (Google Earth) and this was adjusted to account for the area occupied by banks. The per cent overlap was calculated by dividing the total area trafficked by the actual paddock area.
Stage 3. Desktop Study

The hydraulic models identified in Stage 1 (i.e. IPARM and CISCO) were validated using the data collected during Stage 2. The models needed to be able to accurately determine the infiltration characteristics on a whole-bay basis. It was intended to use the infiltration characteristics obtained from these models to determine an optimal bay size for a given slope and inflow rate.
4. Results

Stage 1. Scoping Study

The scoping study (Stage 1) was completed in March 2007. Two reports on the outcomes of the scoping study have been published by the CRC for Irrigation Futures (CRC IF) and are available as downloadable publications from the CRC IF website


The key findings from the scoping study were:

1. The profitability of basin systems may be increased by:
   a. The adoption of practices which improved soil health, particularly those that reduced compaction and increased organic matter. Increases in productivity of 20-30 per cent have been reported but there have been no local studies comparing the operational efficiency of alternative basin designs; and
   b. Better and more flexible irrigation systems which allow the crops returning the most per ML to be selected. A possible increase in gross margins of 100-120 per cent has been reported.

2. There was good evidence that the irrigation application efficiency of “old” contour basin systems may be increased from 55-60 per cent to 80-90 per cent. Evidence from the U.S.A. showed the average irrigation efficiency of level basins is 85 per cent. However, the irrigation efficiency of typical basin systems in southern NSW has not been measured.

3. Current “best practice” design recommendations for contour basin systems are generally accepted and widely adopted and there is good recognition of the factors which contribute to poor productivity, particularly soil type and waterlogging. However, current design recommendations were found to be nearly 20 years old and do not provide guidance on design for more recent changes, such as high flow rates, side ditches, terraces and level furrows.
4. The current design recommendation is that the time taken to fill the basin should be less than half opportunity time (i.e. time for water on and off). It was found that currently recommended opportunity times ranged from 8 to 24 hours, but there was no experimental evidence to support this. Furthermore, this recommendation does not take into account the length of time it takes for a soil to return to aerobic conditions following the cessation of drainage and there is evidence to show that this differs with soil type (duplex soil < heavy clay < sodic soil).

5. No computer aided design tools were found for the types of basin systems used in the southern MDB. Some software was available to help optimise the physical layout of individual basins, but there was no (supported) software to aid the optimal design of interlinked basins.

A number of areas where further work was required were identified. These informed the conduct of Stages 2 and 3 of the project and became priority research areas.

1. Collect data from a range crops (other than rice) to support recommended maximum opportunity times for duplex, heavy clay and sodic soils. This should include field data that (1) characterises the timing and duration of waterlogging on these soil types and (2) tracks soil redox potentials of naturally waterlogged crops; and

2. Develop a simulation model that will allow soil infiltration characteristics to be determined using inverse modelling of field data from both contour and level basin systems.

Figure 3. A discussion group meeting.
Stage 2. Evaluation of Basin Layouts

Stage 2.1. Evaluation of Methodologies

Two reports of the investigations to determine the best methods of measuring flows in basin systems have been prepared:


The results of the tests conducted to check the readings from the depth sensors in all eight Starflow ADV meters is shown in Table 2. It can be seen that all loggers had slopes slightly less than unity and five of the eight loggers had intercepts significantly different from zero. These results are based on three tests and the calibration curves obtained were highly significant. These relationships were used to convert the depths recorded by the Starflow ADV meters to an actual depth for use in the velocity-area calculations of discharge (i.e. water depth × width × velocity).

<table>
<thead>
<tr>
<th>Logger No.</th>
<th>Slope</th>
<th>Intercept</th>
<th>Pr_{int} &gt; t</th>
<th>n</th>
<th>R²</th>
<th>Pr &gt;F</th>
</tr>
</thead>
<tbody>
<tr>
<td>554</td>
<td>0.978</td>
<td>15.69</td>
<td>&lt; 0.0001</td>
<td>12</td>
<td>1.000</td>
<td>&lt; 0.0001</td>
</tr>
<tr>
<td>864</td>
<td>0.985</td>
<td>1.54</td>
<td>0.389</td>
<td>11</td>
<td>1.000</td>
<td>&lt; 0.0001</td>
</tr>
<tr>
<td>938</td>
<td>0.985</td>
<td>16.86</td>
<td>0.0002</td>
<td>11</td>
<td>1.000</td>
<td>&lt; 0.0001</td>
</tr>
<tr>
<td>1362</td>
<td>0.985</td>
<td>9.76</td>
<td>0.0006</td>
<td>11</td>
<td>1.000</td>
<td>&lt; 0.0001</td>
</tr>
<tr>
<td>1373</td>
<td>0.987</td>
<td>-1.70</td>
<td>0.194</td>
<td>11</td>
<td>1.000</td>
<td>&lt; 0.0001</td>
</tr>
<tr>
<td>1443</td>
<td>0.985</td>
<td>21.54</td>
<td>&lt; 0.0001</td>
<td>11</td>
<td>1.000</td>
<td>&lt; 0.0001</td>
</tr>
<tr>
<td>1521</td>
<td>0.988</td>
<td>12.40</td>
<td>0.030</td>
<td>11</td>
<td>0.999</td>
<td>&lt; 0.0001</td>
</tr>
<tr>
<td>1213*</td>
<td>0.978</td>
<td>0.76</td>
<td>0.85</td>
<td>4</td>
<td>1.000</td>
<td>&lt; 0.0001</td>
</tr>
</tbody>
</table>

Notes: The regression model had the form: Starflow depth = slope × actual depth + intercept. *Logger number 1213 had malfunctioned and was not working at the time of the second test.

Single beam, continuous signal, Acoustic Doppler Velocity (ADV) meters were considered the most suitable methodology for use by a commercial service to evaluate basin irrigation system performance. However, there were a number of questions regarding the ability of the method to measure a flow that accurately equated to the mean cross-sectional flow through the conduit or channel being measured.
For pipes flowing full, this was tested in the hydraulic test facility. Velocity measurements from the Starflow meters were checked against mean cross-sectional velocities of 300, 450 and 600 mm/sec in a 3 m long, 300 mm diameter pipe. Table 3 shows there was a strong linear relationship between Starflow velocity and mean cross-sectional velocity for all eight Starflow meters, though some meters were more accurate than others. Four Starflow meters (numbers 554, 1362, 1213 and 1521) all had slopes close to unity and, in comparison to the other four meters, intercepts close to zero. The relationship between Starflow velocity and mean cross-sectional velocity for these meters was close to the 1:1 line, indicating that the flow volume measured by the ADV meters is representative of the velocity profile through the cross-sectional area of a full flowing pipe.

The other four Starflow meters (numbers 864, 938, 1373 and 1443) had a lower slope (average of 0.93) and an average intercept of 40 mm/sec. This was primarily due to Starflow velocity readings at the 300 mm/sec flow rate being roughly 20 per cent higher than the actual cross-sectional mean. This difference was not apparent at the 450 and 600 mm/sec flow rates. It is unclear why this occurred, but it may have been due to errors in the measurement of the head above the 745 mm rectangular weir at the lower flow rate. This requires further investigation. Nevertheless, velocity readings from these four loggers did appear representative of cross-sectional mean velocities at the 450 and 600 mm/sec flow rates. Because this was the range of velocities generally encountered in the field evaluations, it was concluded that single beam ADV meters could be reliably used in full flowing pipes without calibration.

Table 3. Results of the linear regression of Starflow velocity on mean cross-sectional velocity through a 3 m long, 300 mm diameter PVC conduit.

<table>
<thead>
<tr>
<th>Logger No.</th>
<th>Slope</th>
<th>Intercept</th>
<th>( R^2 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>554</td>
<td>1.02</td>
<td>-16.90</td>
<td>0.78</td>
</tr>
<tr>
<td>1362</td>
<td>1.00</td>
<td>-2.46</td>
<td>0.80</td>
</tr>
<tr>
<td>1213</td>
<td>1.02</td>
<td>-0.68</td>
<td>0.84</td>
</tr>
<tr>
<td>1521</td>
<td>0.97</td>
<td>7.54</td>
<td>0.92</td>
</tr>
<tr>
<td>864</td>
<td>0.92</td>
<td>38.31</td>
<td>0.87</td>
</tr>
<tr>
<td>938</td>
<td>0.95</td>
<td>38.83</td>
<td>0.88</td>
</tr>
<tr>
<td>1373</td>
<td>0.94</td>
<td>42.00</td>
<td>0.77</td>
</tr>
<tr>
<td>1443</td>
<td>0.91</td>
<td>41.35</td>
<td>0.80</td>
</tr>
</tbody>
</table>

For open channel flow, the situation was not quite so clear cut. When velocities obtained from meters placed in the mid-line of stops where compared with cross-sectional mean velocities calculated from readings made every 10 cm across a stop at
a range of flows, it was found the ratio of the two (i.e. the velocity index) was not consistent. Figure 4 shows measurements taken in two 900 mm MILcast stops in the same layout in December 2008. These stops were the same make and size, yet it can be seen that each would require a different velocity index in order to convert the Starflow velocity measured mid-stream in these stops to a cross-sectional mean velocity.

![Figure 4](image)

**Figure 4.** Relationship between the mid-stream velocity and cross-sectional mean velocity through two similar stops (900 mm MILcast) in the layout evaluated at McCaughey on December 10, 2008.

Some insight into the reasons for the variability in the velocity index is provided by Figure 5. This shows the initially high velocities flowing “around the corner” between the two bays when the stop was first opened, with higher velocities against the bank side of the stop (i.e. towards the outside of the block). As velocities decreased, eddies formed off the sloping leading edges of the sides at the entrance to the stop. These two eddies then met over the measurement section and reduced the mid-stream velocity below that expected with more uniform flow conditions. Uniform flow conditions were eventually established once the velocity dropped to around 250 mm/sec at 8 pm, four hours after the stop had been opened.
In order to examine this further, a SonTek™ FlowTracker handheld ADV was used to profile the flow through a number of stops. This was done by measuring velocity at 0.2, 0.6 and 0.8 of the depth from the water surface every 10 cm across the width of a stop. Measurements in a 900 mm MILcast stop showed the distribution of velocities across the stop was not bilaterally uniform around the mid-line. Furthermore, the distribution of velocities varied with discharge, with flows concentrating in the centre of the stop as discharges fell (Figure 6). Evidenced for this is seen in the increase in the velocity index (i.e. ratio of cross-section mean velocity to mid-stream velocity).

As well as stop type and discharge, it appears installation and entrance conditions also have an influence on the distribution of flows through a stop (Figure 7). The large number of permutations makes determination of a standard calibration for all types of stops difficult. To examine whether it was possible to create a more uniform flow, a flow straightener was constructed and placed in front of a stop (see cover of report). The effect of this was to reduce the velocity index from 1.13 to 1.06, indicating that it had the desired effect and made the flow more uniform. This can be seen in Figure 8.

Flow at 15 per cent of the width of a rectangular, smooth sided channel is said to roughly equal to the mean channel velocity (Waterdata Consultants Pty Ltd, 2006), so ADV measurements at this location should provide a cross-sectional mean channel velocity. However, it can be seen that placing a meter at this location would not necessarily have resulted in it measuring the cross-sectional mean velocity because
flows through the stops were generally concentrated down one side (Figure 6 and Figure 7).
Figure 6. Velocity (cm/sec) distribution in a 900 mm MILcast stop (Bay 1 to 2) at ‘Amarran’ during an irrigation on September 6-7, 2009.

Note: The direction of flow is out of the page.
- Top left - 10:30 am: Depth = 45 cm; cross-section mean velocity = 52.7 cm/s (18.5 ML/day); mid-line velocity (2 point method) = 63.2 cm/s. Ratio = 1.20.
- Top right - 2:45 pm: Depth = 46 cm; cross-section mean velocity = 40.1 cm/s (14.3 ML/day); mid-line velocity (2 point method) = 46.0 cm/s. Ratio = 1.15.
- Bottom left - 4:10 pm: Depth = 46 cm; cross-section mean velocity = 37.8 cm/s (13.5 ML/day); mid-line velocity (2 point method) = 46.8 cm/s. Ratio = 1.24.
- Bottom right - 11:00 am on 7th: Depth = 43 cm; cross-section mean velocity = 38.7 cm/s (12.9 ML/day); mid-line velocity (2 point method) = 51.1 cm/s. Ratio = 1.32.
Figure 7. Velocity (cm/sec) distribution in two Padman R4 stops showing the effect of stop installation on the distribution of flow.

Note: Left - ‘Amarran’ - from farm channel to first bay. Cross-section mean velocity = 57.2 cm/s (14.1 ML/day). Mid-stream velocity = 58.8 cm/s. Ratio = 1.03. Right - ‘McCaughey’ - stop between 3rd and 4th Bay installed “back-to-front”. Cross-section velocity mean = 42.6 cm/s (10.9 ML/day). Mid-stream velocity = 54.3 cm/s. Ratio = 1.27. (Reverse flows shown in pink).
Figure 8. Velocity (cm/sec) distribution in a 900 mm MILcast stop between Bay 1 and Bay 2 at McCaughey (Sheepwash 5) during an irrigation on October 13, 2009.

Note: Left – velocity profile without the flow straightener in front of the stop. Cross-section mean velocity = 61.3 cm/s. Mid-stream velocity = 69.3 cm/s. Ratio = 1.13. Right – velocity profile with the flow straightener in front of the stop. Cross-section mean velocity = 61.0 cm/s. Mid-stream velocity = 64.6 cm/s. Ratio = 1.06.
The data from FlowTracker measurements in a number of 900 mm MILcast stops at a range of flow rates shows that the velocity index may be relatively constant for this type of stop (Figure), though an $R^2$ greater than 96 per cent would give greater confidence in the relationship (Styles, 2005). This gives some assurance that a common velocity index might be found, provided the conditions under which it was applicable could be defined. However, when the mid-stream velocities from the FlowTracker were compared with those from the Starflow loggers, it was found that the Starflow velocities from three of the comparisons were 30 to 60 per cent lower than the FlowTracker velocities (Figure). Further investigations are required to determine the source of this error before any confidence can be placed in the Starflow velocity measurements.

Figure 9. Relationship between cross-section mean velocity and mid-stream velocity obtained from FlowTracker ADV measurements in a range of 900 mm MILcast stops (●) and one Padman R7 stop (○).

Note: The line of best fit (i.e. velocity index) to the data from the MILcast stops is shown.
Figure 10. Average Starflow velocity readings from mid-stream in a range of 900 mm MILcast stops, plotted against the mid-stream velocity determined from the FlowTracker ADV using the 2 point method and measurements at 0.2 and 0.8 of the water depth.

Stage 2.2. Replicated Trials

Drought and low to zero irrigation allocations meant the planned replicated field trials could not go ahead. However, a facility for conducting this work had been built at ‘Billinudgel’ and this could still be used when water becomes available.

The details and the findings of the work done to determine a maximum irrigation opportunity time are provided in a separate technical report (North, S.H. and Griffin, D. (2010) Determining maximum irrigation opportunity times for basin irrigation systems. In press) and are summarised here.

The glasshouse experiment showed there was a significant negative relationship between the length of time that the soil redox potential ($E_h$) is below the threshold value of 350 mV (i.e. anaerobic) and the growth of wheat (Figure 11). These results clearly show soil/water temperature, soil type and ponding duration do not reduce wheat plant growth per se, as would be inferred from a direct examination of the results (Figure 12). Rather, the treatments (soil type, temperature and duration) affect the aeration status
of the soil and it is the aeration status that affects plant growth. The results also confirm that the $E_h$ of 350 mV is a good indicator of limiting oxygen levels in local soils.

Figure 11. The change in shoot biomass of waterlogged wheat in the glasshouse experiment, relative to the change in biomass of the well watered control plants, plotted against the cumulative time that the $E_h$ of the soil in the pots growing the waterlogged plants was less than 350 mV.

Notes: The line of best fit through all the data was ($R^2 = 0.92$; se estimate = 0.23; $P < 0.001$): $\text{change in biomass (g/plant/day)} = 0.28 - 0.19 \times (\text{no. days the soil is } < 350 \text{ mV.})$

The point circled in blue was not included in the relationship as the plants were dead.
Figure 12. Results of leaf area analysis from plant cuts at 3, 6, 9, 12 and 15 days. Error bars show the standard error of the mean (n = 3).
The field trials provided evidence of: (1) the rate of decline in \( E_h \) when the surface of a range of representative soils were waterlogged (Figure 13) and (2) the rate of increase in \( E_h \) when waterlogging conditions ceased (Figure 14). Other field data showed that \( E_h \) deceased when soil water potential was < -10 kPa (i.e. wetter than field capacity, Figure 15). This information was used to calculate a maximum irrigation opportunity time.

![Figure 13](image13.png)  
**Figure 13.** The change in \( E_h \) (mV) at four field sites from the time the soils were irrigated to the time they had dried to field capacity and aeration started to recover.

![Figure 14](image14.png)  
**Figure 14.** The change in \( E_h \) (mV) at three field sites from the time the soils had dried to field capacity and aeration was recovering.
Figure 15. The change in daily average redox potential with average daily matric potential following irrigations at three field sites. Note: A positive value indicates redox was increasing.

Stage 2.3. In-Field Evaluation of Basin Layouts

*Murray valley*

The level of uncertainty surrounding the accuracy of the Starflow ADV measurements meant application efficiency and distribution uniformity could not be calculated for the 13 contour basins in which measurements were collected. However, as there is no runoff in these systems and they are generally only irrigated intermittently, then the value of these indices for assessing irrigation performance may not be critical. In comparison, the observations of water depth and ponding duration in all the bays irrigated in a block have been of great value in showing excessively long drainage times and how water is backed up through the side-ditch in these systems. The discharge and water depth data collected from one irrigation in a lasered, parallel contour, side-ditch delivery system at ‘McCaughey’ illustrates this clearly.

The water depth data from the more intensively studied bays (generally the second or third bay in the block) show irrigation opportunity times were generally between 40 to 50 hours in the contour basin system most commonly used by rice growers in the Murray valley (i.e. lasered, parallel contour, side-ditch delivery). The fact these types of layouts are generally seen as an industry standard is something of a concern.
The seasonal application efficiency ($E_a$) for the three bay, level furrow system evaluated in the Murrumbidgee valley was 93 per cent. Crop evapotranspiration ($E_{tc}$) for the evaluated field (Figure 16) and net water inputs to the system are shown for the full irrigation season (Figure 17). Crop water demand was consistently met by water input at the field scale for the duration of the season.

Seasonal $E_a$ at the bay scale varies. The final bay in the three bay series received 63 per cent and 42 per cent more water than the first and second bays respectively (Figure 18). The impact of the variable irrigation application rate on the system’s ability to adequately meet crop water demand is demonstrated in Figure 19, with total water applied to Bays 1 and 2 below $E_{tc}$. The field application efficiency ($E_a$) for bays 1, 2

Figure 16. Discharge (top) and water depth (bottom) data collected during the irrigation of a lasered, parallel contour, side-ditch delivery contour system at McCaughey in October, 2007.
and 3 is 77, 87 and 109 per cent respectively. Consequently, the crop demand in bays 1 and 2 was not met by the irrigation system, while 9 per cent more water was applied to field 3 than was required by the crop.

The bankless channel (i.e. side-ditch) distributed supply water across the inlet width of the bay, delivering water to each of the furrows. In a precisely levelled field with uniform furrow dimensions, a uniform discharge could be anticipated. Variations in elevation, compaction and cross-sectional profile modification result from field traffic and the inherent error in field levelling precision. Consequences of field variability are evident in the spread of furrow discharge and advance time across a bay.

Figure 17. Water flowing in the bankless channel (side-ditch) at the start of irrigation in the level furrow system on Commins’ property, Whitton.
Figure 18. Cumulative ET and applied irrigation water to field W4.

Figure 19. ML per ha applied to each bay in the evaluated layout over the entire growing season.
Figure 20. ET demand and irrigations applied. Irrigation application data to December 6, 2009, is estimated.

**Stage 2.4. Collection of Economic Data**

*Labour Saving and Greater Convenience*

Irrigators involved in this study described a number of non-financial benefits that arose when layouts were modified so that precision guidance and auto-steer systems could be used. These include reduced operator fatigue; less back and neck strain; the ability to employ less skilled operators; improved timeliness of paddock operations because more ground can be covered in less time; and more uniform crop establishment (J. Fowler, H. Kooloos and R. Ford, pers. comm.). These benefits were not priced in this study, but are likely to be significant.

*Water Productivity*

Participants in the eight discussion groups interviewed during the course of this study reported average wheat yields of between 3 and 4 t/ha in their contour layouts from a pre-irrigation and one spring irrigation. The best yields expected were reported to be 5 to 6 t/ha, based roughly on the same irrigation strategy. There appeared to be a definite increase in wheat yields when layouts were improved: the group that had done the least amount of lasering reported average yields of only 2.5 to 3 t/ha and another group reported a 1.2 t/ha difference in average yields between “old” (3.6 t/ha) and “new” (4.8 t/ha) layouts. These figures broadly agree with the reported average wheat

Machinery Efficiency

The results from the 50 paddocks where data was collected are summarised in Table 4 and an example of the output from the GPS loggers is shown in Figure 2.

Table 4. Summary of the GPS track data collected from tractors (sowing and spraying) and headers during paddock operations in 2007, 2008 and 2009.

<table>
<thead>
<tr>
<th>Layout type</th>
<th>Banks</th>
<th>Operation</th>
<th>GPS Guidance</th>
<th>Machinery Width (m)</th>
<th>% Ground Covered</th>
<th>n</th>
</tr>
</thead>
<tbody>
<tr>
<td>Drive over banks</td>
<td>n/a</td>
<td>Sowing</td>
<td>Yes</td>
<td>5.55</td>
<td>98 ± 3</td>
<td>6</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Heading</td>
<td></td>
<td>5.2</td>
<td>107 ± 2</td>
<td>2</td>
</tr>
<tr>
<td>Lasered contour</td>
<td>Parallel</td>
<td>Sowing</td>
<td>Yes</td>
<td>5.55</td>
<td>101</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Spraying</td>
<td></td>
<td>7 – 8</td>
<td>115 ± 7</td>
<td>5</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Sow &amp; Head</td>
<td></td>
<td>12 – 18</td>
<td>117 ± 7</td>
<td>13</td>
</tr>
<tr>
<td>Lasered contour</td>
<td>Non-parallel</td>
<td>Sow &amp; Head</td>
<td></td>
<td>7 – 8</td>
<td>123 ± 8</td>
<td>8</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Spraying</td>
<td></td>
<td>12 – 18</td>
<td>135 ± 13</td>
<td>3</td>
</tr>
<tr>
<td>Natural contour</td>
<td>No banks</td>
<td>Sowing</td>
<td></td>
<td>7.55</td>
<td>113 ± 8</td>
<td>5</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Spraying</td>
<td></td>
<td>12 – 18</td>
<td>120 ± 4</td>
<td>5</td>
</tr>
<tr>
<td>Natural contour</td>
<td>Banks</td>
<td>Sowing</td>
<td></td>
<td>5.5</td>
<td>129</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Spraying</td>
<td></td>
<td>18</td>
<td>158 ± 7</td>
<td>4</td>
</tr>
</tbody>
</table>

Note: The proportion of ground covered during each machine operation in each paddock was calculated (i.e. per cent ground covered = travel path length × machine width ÷ actual paddock area × 100). This data was grouped according to layout/bank type (subjectively categorised) and machinery width and a mean “overlap” value calculated for each category (± 95 per cent confidence interval; n = number of paddocks in sample).

The type of operation and use of GPS steering guidance is also indicated.

Figure 21. An example GPS logger track from header operations in a lasered, parallel contour basin system. The percentage of ground covered by the header in this paddock was 128 per cent. (i.e. 28 per cent overlap).
Maintenance Costs

Objective data on operating and maintenance costs were collected from surveys handed to 30 mixed croppers during discussion group meetings at Finley, Deniliquin and Wakool. The following questions were asked:

1) How often do you disc/grade banks to re-touch them and clean toe-furrows?
2) How often do you spray the block and the banks to control weeds?
3) How often do you spray the banks only to control weeds?
4) Do you think that weeds growing on banks and in the corners of bays increases the cost of controlling weeds IN your crops? If yes, by how much?
5) How often do you normally touch-up lasered blocks?
6) What sort of structures do you have?
7) How often do your structures need strengthening or leaks fixing?
8) What percentage of your RICE country is laid out to natural contours, squared up bays or drive-over banks?

The responses to each question were collated and are summarised graphically.
Stage 3. Desktop Study

The computer model IPARM was developed to calculate the infiltration parameters required by the modified Kostiakov equation (Gillies and Smith, 2005). IPARM uses a simple volume balance approach to estimate the infiltration parameters from commonly collected field data including advance, inflow and drainage volumes. Several data sets were used to verify the procedure in furrow irrigated systems (i.e. one dimensional flow). A simple modification was also made to facilitate the use of variable inflows (Gillies et al., 2007), such as those occurring in basin systems where inflows are initially high and then decline. Evaluation of the procedure with a number of data sets from furrow irrigated fields demonstrated significant improvements in the estimation of infiltration parameters.

IPARM was developed to determine the whole bay infiltration characteristics in sloping furrow irrigation systems, not level basin or contours. For this study, a new model was considered necessary, so the modelling team developed a model which they called SISCO. This model was evaluated using the data collected in the Murrumbidgee valley from a level furrow system (i.e. beds in bays) and it was found that it was capable of simulating in one dimension and determining the infiltration characteristics of a single furrow. It was not capable of simulating multiple furrows simultaneously to determine the whole bay infiltration characteristic as each furrow in the bay needed to be individually assessed. Because of this, it is not presently able to be used to determine a whole bay infiltration characteristic for use by designers to establish an optimal bay size.

A limitation of the model is that it relies on an even wetting front advance along the length of the bay. Data from level basins (i.e. without beds/hills) and from border check systems did show SISCO was able to determine whole bay infiltration characteristics in these systems. However, wetting front advance in contour basin systems is far from uniform and may even vary between irrigation in the same bay. Because the basins in these systems have side-fall, a major component of the wetting front advance is perpendicular to the flow, with the bay wetting up from the low side while flows occur down the bay. As the relationship between wetting front advance, inflow and surface storage is markedly different in contour basins, the model could not be applied to these systems.
Figure 22. Screen shot showing the outcome of one simulation of a furrow irrigation using CISCO. The lines shown are the water surface (top), the soil surface (middle) and the infiltrated depth (bottom).

Figure 23. Screen shot showing the input parameters required by CISCO.
5. Discussion

The dry conditions and zero irrigation allocations in 2006, 2007 and 2008 restricted the data that could be collected during the course of this project. This had a major impact on the length of time it took to validate the selected flow measurement technique (i.e. ADV meters). It was initially expected that this process would be completed within the first irrigation season. The lack of water in the district meant it had to occur concurrently with the paddock evaluations and it therefore continued over the life of the project.

5.1. Methods for Evaluating Basin Systems

The experiments and field trials done to evaluate the use of ADV meters found they are capable of accurately measuring flows in full pipes. It is commonly recommended that, when used in pipes, these meters should have 10 pipe diameters of straight section upstream and 5 diameters downstream. This is a situation unlikely to be found for the pipes used in basin systems. However, the study findings show that this may not appreciably affect the accuracy of ADV meters and the accuracy of the measurements of the full pipe flow at the Murrumbidgee valley sites can be reasonably assured.

The ADV meters were not capable of accurately measuring flows in open channels. Accurate measurements were not obtained in partially full pipes when the depth of flow was less than 100 to 200 mm. This was primarily a function of the meter, as it became a significant obstruction to the flow in small pipes (i.e. 300 mm diameter) despite its very low profile. This may not be such a problem for the Mace™ Agriflow meters, which are smaller than the Unidata™ Starflow meters evaluated. However, overcoming this may not improve the accuracy of ADV meters in low flow depths because of insufficient reflectors in the sample volume (King et al., 2002).

It was also shown that the meters were not able to accurately measure flows through stops (MIL 900 mm and Padman R7). This was primarily due to the fact that the velocity of the sample volume was not representative of the mean channel cross-section in these structures. Furthermore, the difference between the sampled velocity and the mean channel velocity was not uniform or consistent enough at a range of water heights to allow a universal calibration to be derived. There are also unresolved questions regarding the accuracy of the flow velocities measured by the Starflow meters.

A number of recommendations are made as to the best methods for achieving accurate flow measurement in basin systems. Principle amongst these are that ADV meters
used to measure flows in stops in basin systems should either be used with fluming (to produce uniform flow conditions), or a flow rating procedure (e.g. the QIP procedure: Styles, 2005) should be used for each stop type and standard installation.

Despite the problems in measuring flows, the procedures used in both the contour basins in the Murray valley and in the level furrow systems in the Murrumbidgee valley provided invaluable performance data. In the contour systems, data was collected from 13 irrigation events in five different basin systems. This body of data has not previously been available and forms a considerable resource for future analysis and decision making with regard to contour basin layouts. It was found that the measurement of water levels in all basins in an irrigation block provided the best assessment of the system’s performance. These measurements clearly showed whether water was backing up and occluding drainage, and showed the effect of this on irrigation opportunity times. It was also found that the DGPS mapping of wetting front advance produced better data, more quickly and easily, than a grid of water depth sensors. This enabled the number of depth sensors to be reduced to nine in the bay used to determine infiltration characteristics.

In the level furrow systems, a variety of evaluation methods were investigated and a method developed for their evaluation. This method was then employed and used to successfully evaluate a level furrow system at several spatial scales. The evaluation revealed that application efficiency ($E_a$) can vary substantially, depending on the spatial scale at which it is applied. At the field scale $E_a$ was 92 per cent. However, irrigation performance of individual bays within the field had a range of $E_a$ from 77 to 109 per cent. It is anticipated that investigating the irrigation performance of individual bays will reveal a greater range of $E_a$.

### 5.2. Best Practice Basin Design

Despite the uncertainty regarding the accuracy of the flow measurements through stops, a number of very clear and important findings have emerged from this study.

*Opportunity Times are Excessively Long*

Irrigation opportunity times in nearly all contour basin systems evaluated were far too long and would have led to waterlogging losses in sensitive (non-rice) crops. This was found to be due to excessively long drainage times, not slow inflow (i.e. supply) rates.

In summary, it was found irrigation opportunity times were generally between 40 and 50 hours in the basin irrigation system most used for growing rice in the southern MDB
(i.e. lasered, parallel contour, side-ditch delivery systems). This is considerably greater than most irrigators in these districts currently expect from their systems. Irrigators interviewed during Stage 1 reported their drainage times were of a similar duration to their watering times. This was not found. Rather, observations of drainage times in side-ditch delivery contour systems with commonly occurring slopes (1:1400 to 1:1800) were generally four times longer than fill times – i.e. four times greater than what irrigators currently believe.

Reducing irrigation opportunity times in basin systems is essential if deep drainage losses are to be reduced to improve irrigation application efficiency and avoid production losses from waterlogging. For the side-ditch contour basin systems found in the Murray valley, irrigators should focus their resources on reducing drainage times, not on increasing flow rates to decrease irrigation times. Shorter opportunity times were measured (i.e. 12-14 hours) and they are potentially more widely possible in all layouts if the following design principles are adhered to.

**Side-Ditch Delivery Systems are the Principle Cause of Long Opportunity Times**

Side-ditch delivery systems in contour basin systems principally fail because of the loss of head that occurs in the inlet/outlet structures when water backs up in the downstream bay. This causes a marked reduction in the delivery capacity of the structure, reducing the rate of outflow from the upstream bay. The magnitude of this reduction can be easily estimated from the theoretical head-discharge relationships for pipes and broad crested weirs (e.g. Brater, et al., 1996).

For example, if a structure is to carry a 20 ML/day flow, then the head needed to drive this would be roughly 180 mm for a 450 mm pipe (Figure, left) and 320 mm for a 900 mm wide stop (Figure, right). In practice, these structures would only transmit 20 ML/day at the start of drainage and the rate of discharge would decrease as the water level fell in the basin being drained.
In layouts with side-ditch delivery systems, irrigation and drainage are linked, so the fall in water level in the draining bay is matched by a rise in level in the filling bay. In addition to this, a head of water is required on the filling bay to drive water to the other end of the basin (there is no slope in the advance direction). As a consequence, water backs up against the drainage structure in side-ditch systems and this causes the driving head to fall rapidly. This loss of head occurs more quickly than if it was due to the drop in water level in the draining bay alone. Consequently, the head difference between the draining bay and the filling bay will fall to around 50 mm. When this occurs, a 450 mm diameter pipe designed to transmit a flow of 20 ML/day will, in practice, only be able to transmit a flow of roughly 10 ML/day (Figure left) and a 900 mm stop will only transmit a flow of roughly 1.5 ML/day (Figure right). If the inflow into the side-ditch at the top of the irrigation block is 10 ML/day, then the water level in the bay being drained through the 450 mm pipe would not change and the water level in the bay being drained through the 900 mm stop would rise.

It might be thought the solution to this is to install larger structures, but this doesn’t take into account two factors. The first factor is that there is a head loss that occurs through each structure and this may be of the order of 20 to 30 mm (Rural Water Commission of Victoria, 1988). The second, and possibly more significant, factor is that the head of water needed to drive water to the end of the basin was found to be between 70 mm and 150 mm (median = 100 mm) in this study. Given the recommended side-fall on contour basins is 50 mm (Swinton, 1994; Swinton, 2000), then 100 mm of water on the bottom corner of a bay, plus 20 mm of head loss in each structure, will cause water to back up into the two bays immediately upstream. The inflow into the block therefore has to raise the water level in at least two bays in order to fill the bay being irrigated, rather than just one. This compounds the problem, because this extra water then needs
to be drained through the same structures that are being used to deliver the 10+ ML/day coming into the block. This was clearly apparent in the majority of side-ditch systems that were studied, with bays not draining freely until inflow into the whole block was shut off.

**Terracing**

As already discussed, the head of water observed on the contour bays evaluated in this study was between 70 and 150 mm. This water level is the sum of the driving head and the side-fall across the bay. Given the side-fall on these bays was usually 50 mm, then the driving head may reasonably be assumed to be between 20 and 100 mm, with a median value of 50 mm. If bays are terraced flat, then a terrace of 100 mm may be sufficient to prevent water backing up against the inlet and slowing the drainage from the upstream bay under most situations. However, this is based on limited evidence and should be accepted with some circumspection.

The following considerations need to be born in mind. Firstly, a minimum side slope of 1:2,000 is recommended for contour basins. This is required to ensure drainage of excess winter rainfall and is based on the discussions held with growers during Stage 1. Secondly, widening flat bays to manufacture a 100 mm terrace does not increase the overall slope on the block and it will not improve drainage times to the same extent as a shift to individual supply – though some improvement may be expected from the reduction in the storage volume needed to fill the bay (bearing in mind the risk of waterlogging in flat bays). Thirdly, flattening out bays involves earthmoving and this is costly and there is always the temptation to reduce this up-front cost by not ‘top-soiling’. If top-soiling is not undertaken, then the long term (20+ years) reduction in productivity in cut areas (which is assured) will likely negate any benefits arising from terracing (which cannot be assured).

**Bay Size for a Given Flow Rate**

Work to determine the infiltration characteristics of the soil in contour basins was not completed because of the problems surrounding accurate flow measurement and the inability of CISCO to model two dimensional flows. Because infiltration characteristics of the study basins were not determined, it is not possible to make recommendations regarding an optimum bay size. Work is required to develop a suitable model, as the optimum bay size is a function of the supply inflow rate, the soil infiltration rate, the slope on the bay (and hence surface storage) and the size of the outlet structure.
Despite this, it was shown the principle cause of waterlogging in contour basin systems was inadequate drainage in side-ditch delivery systems. This is contrary to popular belief, as the focus in the irrigation districts of the Murray and Murrumbidgee valleys over the past few years has been to increase flow rates in order to decrease watering times. The findings of this study show this is unlikely to improve irrigation efficiency in side-ditch contour basins, and may in fact make it worse.

Furthermore, delivery flow rates cannot be increased on-farm without either changing the district supply scheme (e.g. increasing district channel capacity and/or changing to the way channels are operated, and increasing flow rates through the delivery meter,) or changing on-farm delivery infrastructure (i.e. storing and pumping flows, increased channel size, larger structures). The capital cost of this would be considerable.

It is important to realise the key inflow parameter for surface irrigation systems is flow rate per unit bay area. Rather than increasing flow rates to shorten watering times, it may therefore be more cost effective to match the bay size to the existing flow rate and achieve machinery and operational efficiency by constructing drive-over banks. This may necessitate shorter watering times in smaller bays, but irrigator's concerns regarding "quality of life" issues could be addressed by developing automated structures.

**Operational Efficiency of Basin Systems**

There are a number of very clear messages that come out of the GPS data collected from farmer paddocks during this study. If it is accepted that the best system is one in which turning is minimised, trafficking is not restricted by check banks, and GPS and auto-steer are practicable, then the following efficiency gains can be reasonably assured:

- The adoption of GPS steering guidance can result in a 10 to 15 per cent reduction in the amount of overlap in regularly shaped basins.
- A saving in time, fuel and other inputs of between 30 to 60 per cent is possible by converting natural contour systems to drive-over-bank systems and adopting GPS guidance.
- Squaring up bays and making banks parallel can reduce inputs by between 10 to 40 per cent.
Using the GPS data together with the results from the survey of irrigators, it is possible to identify some of the benefits and issues associated with adopting drive-over banks, squaring up bays or converting from side-ditch to head ditch supply systems:

1. Converting layouts to drive-over banks may potentially save around $15 to $20 per ha per year given the following assumptions. All cost data is taken from NSW I&I crop budgets (Singh & Fowler, 2010; Singh & Whitworth, 2010):

   • Banks are generally disced once every two to three years. The estimated cost of reforming banks is $1 per ha and $12 per ha for banking up. Drive-over banks would reduce this cost to once every four years for a one in four year rice rotation (i.e. $3 per ha per year);

   • Bays and banks are generally sprayed twice a year and banks on their own once per year. The estimated cost of weed control in bays is $15 to $28 per ha per spray, depending on the chemical used. Spot spraying of banks would be less than this. Roughly 70 per cent of irrigators surveyed believed weeds on banks and in corners of bays increased their weed control costs. Many could not estimate the magnitude of this cost, but the responses from those who did ranged from $5 per ha to $25 per ha, with a median value of $10 per ha. This is roughly equivalent to the elimination of one spraying operation per year (i.e. $15 per ha per year).

2. All 30 of the irrigators surveyed had between 20 to 40 per cent of their irrigation country still in natural contours, while only two respondents had some area with drive-over banks. The country still in natural contours is likely to be the more “difficult” country to land-form (e.g. higher slopes, dissected by creeks or tree lots), so there may not be as much potential to improve these systems as first appears. However, it is still a high proportion. Given the shortage of irrigation water and the cost savings from being able to traffic broader areas, there may be a case to push the banks down in these layouts and convert them to dry land production. Scarce irrigation water could then be concentrated on more efficient and productive layouts.

3. The irrigators surveyed at Finley predominantly irrigated through stops, while irrigators at Deniliquin and Wakool had a mix of stops and pipes. Irrigators prefer to install pipes in cracking soils as they leak less than stops and it is presumed the difference between the Finley and Deniliquin/Wakool groups is because cracking soils are not as prevalent in the east of the district. Despite this, the frequency with which structures needed to be maintained was similar across the three groups, although Deniliquin irrigators appeared to do (or need) the least maintenance and Finley irrigators the most. Any changes to basin irrigation systems needs to factor
in the cost of fixing leaking structures. The fact that structures in supply channels
do leak into bays is one reason for the popularity of side-ditch delivery systems.
This issue will need to be addressed if a shift from side-ditch to head ditch delivery
is recommended to overcome the problems associated with water backing up and
slowing irrigations in side-ditch layouts.

Machinery width did not affect efficiency in squared up layouts per se, though this
analysis did not factor in the increased ground speed that may be possible. However,
efficiency is markedly reduced (by around 10 to 30 per cent) in more convoluted or
dissected layouts when wider implements are used. This is likely to be a major
impediment to increased farm profitability in these systems as the efficiencies of scale
available to dry land croppers will not be able to be realised.

Anecdotal support for these conclusions was received from growers in the Murray
valley who had adopted precision agriculture technologies or drive-over banks.

- Wayne Brooker (Cobram) and one Moulamein farmer (unknown) reported a five
to six per cent reduction in the amount of overlap with a move from using a
foam marker when spraying to using two cm auto-steer;

- Tim Garden (Bunnalloo) had experienced a 12 per cent improvement in
machinery and labour efficiency by adopting steering guidance and eliminating
of overlap;

- Nick Morona (Deniliquin) reported his cropped area was increased by six per
cent for the same level of inputs when he changed to drive-over banks.

Additionally, irrigators in the Murrumbidgee valley involved in this study, as well as
others who have adopted level furrow systems felt it had a significantly lower labour
requirement and greater machinery and operational efficiency than more traditional
basin and furrow systems.
6. Conclusions and Recommendations

The overall objective of this project was to improve the design and performance of contour basin irrigation systems so they can be used to achieve higher yields for a wider range of crops (other than rice) with reduced operating and environmental costs. A considerable amount of data has been generated by the project in our work towards this objective, and this is a considerable achievement in itself as this sort of information has previously been completely lacking for these systems. Furthermore, the project has clearly identified that, to achieve higher yields, the priority in side-ditch delivery, contour basins should be to improve their drainage and reduce the duration of waterlogging that occurs during and after irrigation. The principle cause of the excessively long drainage times in these systems was also identified: i.e. the hydraulic connection between basins created by the side-ditch delivery system.

Furthermore, the data collected from machinery operations over a large number of paddocks and layouts shows there are significant savings to be had by reducing turning and trafficking in bays and adopting GPS steering guidance in large, more regular areas. It was clearly shown this saves time and it should also save money by reducing inputs. The operational advantages of drive-over-bank systems were also clearly shown. The benefit of adopting such a system is that operational and machinery efficiency can be increased without having to increase the size of basins. This would negate the need for higher flow rates and a considerable capital outlay to increase the size of infrastructure for questionable benefit at a very risky time for most irrigation businesses.


6.1.1. Reassess Side-Ditch Delivery Systems

To improve the water productivity of contour basin systems, it is recommended that:

1. Contour basin layouts be evaluated prior to planning or conducting any work. This can be done simply and effectively by conducting a survey of levels and then measuring water depths in all bays in a block during an irrigation. This should show how the system might be improved, as well as showing the nature and extent of any supply or drainage problems; and

2. If it is shown that water is backing up in side-ditch delivery layouts, then they should be modified so that each basin is individually supplied.
6.1.2. Maximum Irrigation Opportunity Times

The following recommendations are made:

3. To increase cropping flexibility and ensure maximum production and water productivity from as wide a range of crops and pastures as realistically feasible, it is recommended basin systems in the southern MDB be designed to ensure they can be watered and drained within ten hours;

4. For non-swelling soils with better internal drainage, the recommended maximum is 18 hours; and

5. For sodic, NSMC soils, frequent irrigation will result in reduced productivity of waterlogging sensitive crops and pastures, no matter how short the opportunity time. It is recommended a maximum opportunity time of ten hours be adopted for these soils and that soil management practices are implemented to improve their physical fertility. The efficacy of these practices may be assessed by measuring redox potential and determining the rate at which soil oxygen levels recover following irrigation. The goal when implementing any soil improvement practice should be to ensure oxygen levels in the surface soil recover after irrigation to an $E_h$ of at least 480 mV before the next irrigation needs to be applied.

These recommendations are comparable to the current recommendation of 12 hours for water to be on and off bays. However, they have the advantage of being based on experimental evidence showing the effect of ponding time on soil aeration and the impact of these on crop growth in the three soil types found in basin systems in the southern MDB.

6.1.3. Design Software

The project has made considerable progress towards producing software to aid in the design of basin systems. This work is incomplete, but the body of data generated by the project that is now available to validate any improved models is a considerable asset. Work on model development is on-going and, when finished, the data should allow the whole bay infiltration characteristics of a range of Murray valley soils to be determined relatively easily.

6.2. Tools for Evaluating Basin Systems

Protocols have been developed to evaluate basin systems. The single greatest obstacle to achieving this was the accurate measurement of water flows. It is considered the simplest method of overcoming the variability of flow through stops in
basin systems will be to measure multiple paths across the flow width. This will be done most easily using three single path, ADV meters (placed at 1/6, 1/2 and 5/6 of the width of the stop) and then averaging the measured velocities. This may not be the cheapest method, but it is the method most likely to be the quickest and the easiest. More specific recommendations include the following:

**Measuring Flows in Pipes**

1) Pipes flowing full;
   - Place the meter in outlet end of the pipe and ensure the signal is pointing to the centre of the pipe and correctly aligned with the axis of the pipe,
   - ADV meter velocity is equal to mean cross-sectional velocity through pipe.

2) Pipes not flowing full;
   - Water depths of less than 0.1 to 0.2 may result in inaccurate velocity measurements. Avoid this situation.

**Measuring Flows in Checks and Stops**

1) If fluming is used it should conform to the following criteria;
   - Placed upstream of the stop,
   - Width - wider than the stop so that smooth, uniform, sub-critical flow prevails through the measurement section (i.e. the stop provides downstream control to the flow through the measurement section),
   - Length – 1 m long for a maximum flow depth of 500 to 600 mm, and
   - Hydraulically efficient entry to prevent establishment of eddies and turbulent flow off the inlet edges (no sharp edges).

2) If only one, single path ADV meter is available per stop, use flow rate indexing procedures to determine the relationship between ADV meter velocity and mean channel velocity (Styles, 2005);
   - Install ADV meter in centre-line of fluming,
   - Accurately measure the dimensions of the measurement section,
   - While the ADV meter is measuring velocity and stage, use standard stream gauging procedures to determine the weighted mean channel velocity (as a minimum, the two point method should be used with velocities measured at 0.2 and 0.8 of water depth from the water surface),
   - Average the recorded ADV meter velocities for the measurement period,
• Repeat these measurements for a wide range of velocities (and a range of heads if possible) – the ratio of the highest to lowest flows measured during the rating procedure should be 2:1,

• Regress mean channel velocity on ADV meter velocity and determine the equation of the line of best fit. This relationship is the “index velocity rating” – the regression coefficient should be better than 96 per cent to ensure confidence in the results, and

• The index velocity rating is then used to convert ADV meter velocity to mean channel velocity for that structure (and also similar structures in similar basins in the same paddock).

If many, single beam ADV meters are available, install three meters in the fluming in each stop at 1/6, 1/2 and 5/6 of the flume width. Mean channel velocity is then equal to the average of the three velocities measured by these meters.
7. **Further Work**

It has been recommended contour basins on flat grades be watered individually, rather than through a side-ditch. It is recognised in making this recommendation that only one evaluation was done in this type of system, and that was on a relatively small bay. However, the evidence of water backing up and of drainage being impeded in all contour basin systems with side-ditch delivery that were evaluated (even those with a slope of 1:1,000) was consistent and overwhelmingly supports this recommendation. Furthermore, there are a number of individually supplied contour basin systems currently in operation in the Murray valley (albeit without the drive over banks) and the irrigators who use them speak highly of their performance (B. Moore, Mayrung; J. O’Donnell, Deniliquin, pers. comm.).

There is, however, a need to refine this recommendation, as there will be a combination of paddock slope, surface storage volume (a function of bay slope, bay size and presence/absence of hills or beds) and flow rate for which side-ditch systems may work. For example, there is evidence from this project that the level furrow systems studied in the Murrumbidgee valley can have quite high application efficiency and distribution uniformity. In order to refine this recommendation and provide more specific advice to irrigators, it will be necessary to use the data generated by the project, build on the modelling work done, and develop a model that operates at the whole bay and whole paddock scales.

Further work is also required to extend the results and findings of the study and promote adoption of the recommended practices. Irrigators in the group discussion sessions held during Stage 1 of the project were asked to outline the evidence they would need to convince them of the merits of any “new” irrigation design. Overall, irrigators felt they needed to see a new design in operation and have it compared to existing layouts before they would consider adopting it. There is merit in asking some of the irrigators who already have contour systems with individually supplied basins whether their layouts could be used for demonstration purposes.

Further analyses should also be done using the information on operational and maintenance costs that was collected. This work should include a full benefit-cost analysis of the major types of alternative basin designs.

The scoping study also identified a need for automation in basin systems, and the irrigators interviewed requested information on the performance of outlet structures. Both these issues were considered outside the scope of this project but are considered
important and there is merit in a new project which has the aim to find the “best” structure and automate it.
8. Presentations and Field Days

17.10.2006  Darwin, ANCID Conference - Bankless Channel Irrigation – An overview and case studies

07.09.2007  Toowoomba, USQ Student Reports - Performance Evaluation and Optimisation of Bankless Channel Surface Irrigation Systems

09.02.2008  Griffith, Water Expo – Bankless channel irrigation: What we don’t know…yet!

20.05.2008  Melbourne, Irrigation Australia Conference – Bankless Channel Irrigation Systems: Observations from initial evaluation trials

15.08.2008  Broadbeach, Australian Cotton Conference – Bankless Channel Irrigation: Towards an alternative.

09.09.2008  Canberra, CRC for Irrigation Futures Annual Research Forum - Understanding Bankless Channel Irrigation

23.07.2009  Griffith, GRDC Update - Optimising bankless channel surface irrigation systems

04.08.2009  Tatura, CRC for Irrigation Futures Variability Forum - Variability in Bankless Channel Irrigation Systems

20.10.2009  Swan Hill, Irrigation Australia Conference - Bankless Channel Irrigation Systems: Irrigation Performance Assessment

26.11.2009  Moree, Gwydir Valley Irrigators Field Day - Bankless Channel Irrigation Systems

18.03.2010  Jerilderie, SSSA Riverina Branch Meeting - Bankless Channel Irrigation Systems: Irrigation Performance Assessment
References


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– NOTES –