Furrow irrigation in the Australian cotton industry: alternative water delivery systems and their potential for automation

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Abstract

Furrow irrigation, and particularly the use of overbank siphons, is the most popular method in the irrigated cotton industry in Australia. The proportion of the use of pressurised systems in this industry is widely expected to increase but nonetheless furrow irrigation will remain dominant for the foreseeable future. However, furrow irrigation is labour–intensive and often an inefficient method of water application. The desire to reduce labour costs is driving attempts to automate the furrow system. These efforts are mainly focussed on the in-field mode of water delivery into the furrows.

This paper reviews the use of overbank siphons to deliver water to the furrows and the alternative water delivery systems, that is, pipes through the bank (PTB), bankless channels, lined head ditches and gated pipe. The potential for use of each these methods in automated systems is explored. Due to limited published data on the hydraulic design of large diameter gated layflat irrigation tubes, a study was undertaken in the Hydraulics Laboratory at the University of Southern Queensland to establish its flow characteristics under low heads and high flow rates typical in the cotton industry.

The reviews demonstrate that siphons are technically difficult to automate. The techniques that have successfully been used to automate check gates in bay irrigation systems can easily be adapted to bankless channels, PTBs and lined head ditches. Large diameter gated layflat irrigation tubes with appropriate outlets can supply high flow rates at low heads and can be automated.

Introduction

Furrow irrigation is by far the dominant irrigation method in the Australian cotton industry. In 2003-2004 for instance, this system accounted for 95% of all the cotton grown under irrigation (ABS 2008). On the other hand, in 2000 about 2% and 4% of the total Australian irrigated cotton crop was grown using drip irrigation and large mobile irrigation machines, respectively (Raine *et al.* 2000). Furrow irrigation requires less initial capital cost compared to the other irrigation systems and is the preferred method of irrigation of row crops like cotton. The system also generally utilises unskilled labour and has low maintenance and energy costs.

A typical cotton property in Australia contains a water reservoir which in most cases would be an earthen ring tank, with the source of water being a river or creek. Water is either pumped or flows by gravity via open channels to the field, and is dammed in a head ditch which runs along one edge of the field to be irrigated. The level of water in the head ditch has to be higher than the field level for water to flow by gravity into the furrows. For this reason, the banks of the head ditch have to be higher than the field level.

Overbank siphons are the predominant means of transferring water from the head ditch into the furrows. The greatest disadvantage of the siphons is the high labour requirement. They have to be manually 'primed' at the start of each irrigation and options for automation are very limited. Pipes through the bank (PTB) are another means used by irrigators to channel water from the head ditch into a group of furrows. A PTB is typically about 300 mm internal diameter buried underneath the bank facing the field to be irrigated. There is potential for automating the opening and closing the PTB inlet.

Bankless channel systems are relatively new to Australia. Published literature suggests that they were initially used in the 1990's to improve the water use efficiency of rice based farming systems (Grabham *et al.* 2008). As the name suggests, the head ditch in this system has no bank on the field side. The paddock is subdivided into separate bays which may be level or with a small slope upwards away from the channel. Gates installed in the channel are used to block the water forcing it to flow into each bay in turn.

Humpherys (1969) describes two techniques of distributing water to irrigation furrows by use of lined head ditches. The first involves installing tubes on the field side of the lined ditch and in the second notch openings are used. In both cases the outlets are spaced according to the furrow spacing and the levels are set to provide uniform outflows. Lined head ditches are rarely used in Australian irrigated agriculture, however, these types of outlet have been used in unlined ditches for bay irrigation in southern Australia.

Gated pipe (rigid or layflat) is another option used in furrow irrigation. Rigid gated pipes are rarely used in the Australian irrigation sector mainly because of difficulty experienced in transportation. Layflat is widely used in the sugar industry, but has so far not been successfully applied in the cotton industry because of the high flow rates required (Smith and Gillies 2009). Large diameter layflat gated pipes are currently seen as appropriate for use for cotton irrigation as an alternative to siphons. Layflat fluming is also relatively low cost, easily transportable and requires little storage space. However, there is limited published data on the hydraulic performance of large diameter gated layflat pipes. A study was conducted in the Hydraulics Laboratory at the University of Southern Queensland with the following specific objectives: (i) to assess the ability of this product to deliver high flow rates; (ii) to assess the uniformity of outlet discharges at these high flow rates; and (iii) to develop head-discharge equations describing the outflows through the plastic outlets supplied with the fluming. The data obtained would also be used to validate the simulation program GPIPE developed by Smith (1990).

The purpose of this paper is to review the siphon method of water application to irrigation furrows and the alternative delivery systems (PTBs, bankless channels, lined head ditches and gated pipe) vis-a-vis their potential for use in automated furrow systems. Results from a laboratory study undertaken to investigate the hydraulic characteristics of large diameter gated layflat fluming are also reported.

Siphons

The use of overbank siphons is a feature of furrow irrigation in the cotton industry in Australia. The siphons commonly in use range from 50 to 77 mm internal diameter while the lengths vary from 3.5 to 4.5 m. These siphons are mostly made of low density polyethylene One or more siphons may be used per furrow, with the use of more than one siphon being most common where alternate furrow irrigation (AFI) is practiced.

For water to flow from the head ditch into the furrows, one end of the siphon must be submerged in the water in the head ditch, while the other end could either be free draining (Fig. 1) or submerged in the furrow stream (Fig. 2). In the first case the head driving the flow is taken as the difference between the water level in the head ditch and the outlet end of the siphon. In the latter case the head is taken as the difference between the water levels in the head ditch and the furrow stream.

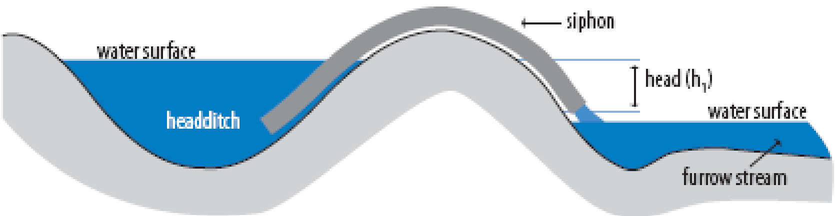

Fig. 1: Siphon operating with free flow (*Source: Purcell 1994*)

Fig. 2: Siphon operating with submerged flow (*Source: Purcell 1994*)

The recommended equation for calculating the siphon discharge (Wigginton 2008) is that proposed by Bos (1989). The equation is expressed as follows:

$$Q = \frac{\pi D^2}{4}\left[\frac{2g\Delta h}{1.9 + fL/D}\right]^{0.5} \quad \text{....Eqn. 1}$$

where Q is the discharge (m^3/s)
D is the siphon internal diameter (m)
g is the acceleration due to gravity (9.81 m/s^2)
Δh is the operating head (m)
f is the friction loss coefficient
L is the siphon length (m)

In Eqn. 1 above the siphon diameter term is squared while all the factors influencing the siphon discharge are raised to power 0.5. The implication here is that siphon internal diameter is the single most important factor affecting the siphon discharge. For instance, a 10% increase in diameter of a 50 mm diameter, 4 m long siphon operating under a head of 500 mm leads to a 23.6% increase in discharge. On the other hand, a corresponding 10% increase in operating head results in only a 5% increase in discharge. Where the available operating head in the head ditch is limiting, irrigators have the option of using more than one siphon or siphons of larger diameter in order to increase furrow inflows. Any of these options will obviously decrease the number of furrows that can be irrigated at a time.

Published data suggest that there can be significant furrow-to-furrow inflow variability in the siphon application method. Trout and Mackey (1988) measured a coefficient of variation (CV) of 15% (with a range of 7 to 24%) in siphon tubes supplying 60 consecutive furrows. Carter and Grabham (2008) reported variations ranging from 27 to 152% of the mean siphon flow.

Spatial variability in siphon discharge at the field scale may be caused by: (i) level and slope in the head ditch which affects head available on the siphons; (ii) differences in lengths, cross-section area and roughness of the siphons; and (iii) differences in the orientation and level of points of discharge of the siphons. Fluctuation in the level of water in the head ditch is an important cause of siphon discharge variation with time.

The uniformity of furrow inflows is a major determinant of irrigation performance at the field scale (Smith and Gillies 2009). The accuracy of an evaluation based on a single furrow will therefore will therefore be affected as a result of siphon discharge variability. Smith and Gillies (2009) have shown that it is possible to design head ditches to minimise variability in outflows.

Perhaps the main drawback of siphons in the irrigation industry is that they have to be started or primed manually. This involves dipping one end of the siphon into the water in the head ditch and sucking the water in by way of creating suction. Other problems associated with the use of siphons include blockage by trash in the head ditch and drastic reduction of water level in the head ditch which may lead to cessation of discharge. SPACEPAC Pty. Ltd., a company based in Australia markets a motorised priming unit for priming their large overbank siphons (SPACEPAC 2010). But this technique is not feasible for control of individual furrow siphons.

The increased labour cost especially in the developed countries has made the need to automate furrow irrigation more relevant. Automation of siphon discharge is technically difficult. Siphons operate independently from each other and tens or hundreds of siphons may be in use at any one time. It would probably be infeasible to automate each one of these siphons. The other challenge facing the automation of siphons is the fact that head ditches are typically kept empty and are only filled with water just before an irrigation event.

Alternative water delivery systems

Pipes through the bank (PTB)

PTBs are used to draw a large quantity of water from the head ditch into a group of irrigation furrows. In the cotton industry pipes of about 300mm internal diameter are used to deliver water to about 16 furrows. To constrain the water to flow only into the intended furrows, rotor bucks or earthen embankments are constructed in the space between the PTB outlet and the cropped area.

Hydraulically, PTBs are similar to syphons and may be designed using the same methods (equation 1). The discharge through the PTB is a function of the pipe characteristics (internal diameter, length and roughness) and the head of water above the inlet in the head ditch. For most irrigators, the available head in the supply ditch influences the size of PTB used and hence the number of furrows that can be irrigated by one PTB.

There is limited published data on the performance of PTB-fed furrow irrigation systems. In a preliminary investigation on siphon-less irrigation systems, Hood and Carrigan (2006), found no significant difference between the irrigation performance of the PTB and the conventional siphon-irrigated furrows. It is however expected that the larger the number of furrows served by one PTB, the harder it is to attain uniform flow into each furrow. Carter and Grabham (2008) point to the possibility of accelerated flows in some furrows occasioned by wheel tracks and trash build-up. Maintenance of the rotor bucks is often required throughout the irrigation season.

The majority of the PTBs in use in the cotton industry have a flap valve and an extended arm at the inlet point in the head ditch side of the bank used to control flow (Fig. 1). The opening and closing is often done manually, but there is a great potential for automation. This was demonstrated at a furrow irrigation automation trial site at in the Gwydir Valley (Fig. 2) whereby each PTB inlet mechanism was automated allowing remote control using the 'Aquator' system (AWMA 2009).

The use of PTBs may lead to significant labour savings even when they are operated manually. Wood and Carrigan (2006) estimated a labour saving of 60% when compared to siphons. When automated and remotely controlled as in Fig. 2 above, labour requirement will be limited to periodic inspection.

Bankless channel

A common configuration of bankless channel irrigation is shown in Fig.5. The upward slope towards the tail-end of the bay ranges from 0.01 to 0.08%, while the elevation difference between the bays is about 0.15 m (Grabham *et al.* 2009). The bankless bays are irrigated in sequence, starting with the one nearest the supply inlet. Gates are installed along the bankless channel aligned with each bank separating the bays and are used to block water forcing it to flow along the furrows of a single bay. Once the bay has been irrigated, the gate is opened thus water from the supply channel as well as the drainage from the previous bay is admitted into the next bay.

Fig. 3: Manually operated PTB (*Source: Wood and Carrigan 2006*)

Fig. 4: Automated (PTBs)

A novel evaluation method suitable for bankless channel irrigation systems is described in Grabham *et al.* (2009). This evaluation suggested that the performance of bankless systems is poor, with considerable variability in the discharge to each bay, the depth applied to each bay, and also in the furrow discharges within each bay.

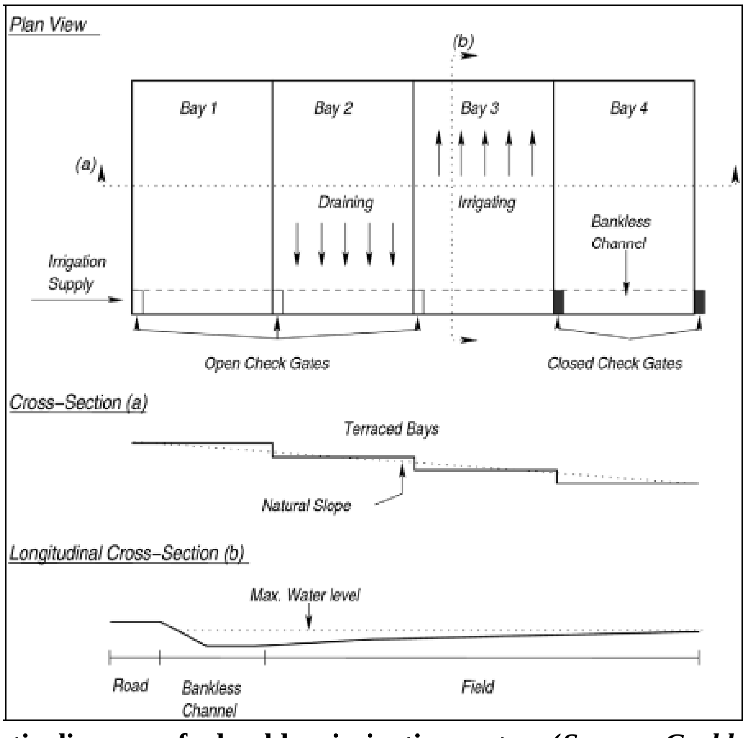

Fig. 5: Schematic diagram of a bankless irrigation system (*Source: Grabham et al. 2008*)

Bankless channels offer significant potential for labour savings since water flows automatically along the furrows when backed up by the closed gate. Also, there is a possibility of automating the check gates by using the techniques that have successfully been applied in the conventional bay irrigation. As runoff from one bay is utilised in the subsequent bay, the cost associated with recirculating the tail water is eliminated.

Lined head ditches

Concrete-lined head ditches with slots or openings to each furrow similar to the ones described by Humpherys (1969) have the potential to supply uniform furrow flows. Automation of these openings is also feasible. The drawback of this system is that it is a fixed system and is likely to interfere with the operation of machinery near the edges of the field. The cost is also likely to be high especially if each individual outlet is automated. Lined head ditches are rarely used in the irrigation industry in Australia.

Gated pipe

Gated pipes used for distributing water into irrigation furrows can either rigid (made of plastic or aluminium) or layflat (made of polyethylene) with outlets to each furrow. The outlets, which can either be fixed or adjustable, are normally spaced according to the crop row spacing. Rigid gated pipes are rarely used in the Australian irrigation sector mainly because of difficulty experienced in transportation. Layflat is widely used in the sugar industry, but has so far not been successfully applied in the cotton industry because of the high flow rates required (Smith and Gillies 2009).

Trout and Mackay (1988) reported a coefficient of variation (CV) of 25% in furrow inflows from a gated pipe (rigid) delivery system. This variability is a matter of the hydraulic design of the gated pipe system. Computer simulation programs for instance GPIPE (Smith (1990) can be used to reduce this variability.

Large diameter layflat irrigation tubes are available in the market but little is known about their hydraulic characteristics. A study was undertaken in the Hydraulics Laboratory at the University of Southern Queensland to establish the flow characteristics of large diameter gated layflat under low heads and high flow rates.

Laboratory Experiments on Large Diameter Gated Pipe

Experimental procedure

Trials were conducted on a 12 m long 425 mm diameter layflat manufactured by C.E. Bartlett Pty Ltd, known by the trade name ‘flexiflume’. Ten flexiflume outlets were installed in the layflat at 1 m spacings. These outlets consist of a streamlined 50 mm valve seat and a removable and adjustable valve/deflector.

Water used for the experiments was drawn from an elevated header tank. To maintain a constant head in this tank, water was continuously pumped from an under-floor sump at a rate sufficient to cause the elevated tank to overflow. The upstream end of the layflat was connected to the supply pipe from the tank while the downstream end was clamped at about 1 m from beyond the last outlet. Flow rate was controlled by a butterfly valve in the supply pipe.

A total of seven trials were conducted at various pressures and flow rates. Four trials were performed with the adjustable valves in the fully open position and three trials were conducted with the valve/deflectors removed. For each of these tests the following outlet characteristics were measured: discharge, height of outlet above the ground and the pressure head. The total inflow and the dimensions of the layflat were also measured. The pressure head was measured using a bank of manometers while the discharge was measured using a collection bin and electromagnetic flow meter. The maximum inflow and pressure into the layflat was limited to 59.5 l/s and 1105.5 mm, respectively.

Results and Discussion

Outlet discharge and characteristic equations

The patterns of outflow along the layflat for each of the trials are shown in Figure 6. For trials done with valve inserts removed, there appeared to be no particular pattern of outflows. On the other hand there was a general decrease of outlet discharge towards the downstream end for trials done with valves in fully open position. For all trials the outlet discharge of the last outlet (outlet number 10) was found to be consistently higher than the immediate preceding outlet (Fig. 7). The distribution uniformity in discharge ranged from 92.7 to 99.7%, with greater variability observed at the higher flow rates.

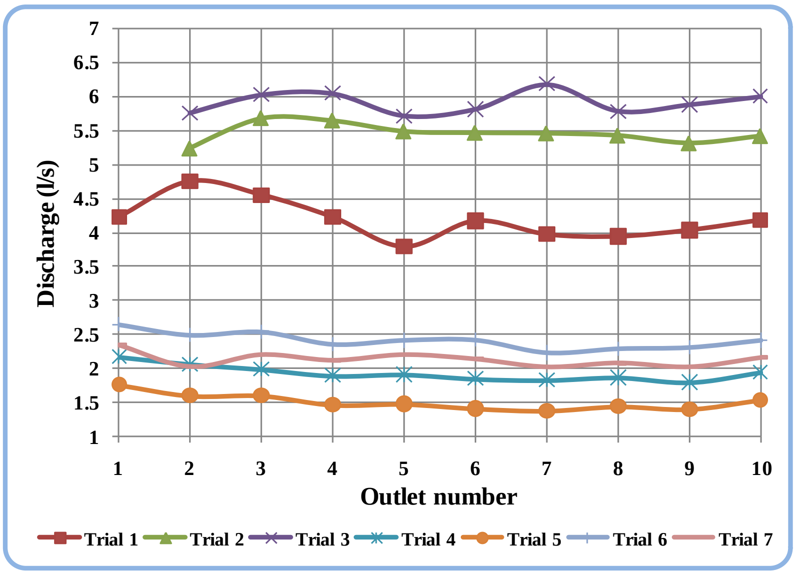

Fig. 6 – Discharge variation along the length of the layflat

The maximum average outlet discharge with the valve inserts removed was 6 l/s at a pressure in the layflat of 600 mm. A much lower outlet flow rate of 2.5 l/s at a pressure head of 1100 mm was measured for valves in the fully open position.

Two-parameter non-linear regression analyses (Fig. 7) gave outlet characteristic equations for outlets with valves removed (Eqn. 2) and outlets with valves in fully open position (Eqn. 3).

$$Q = 0.3525H^{0.4431} \quad \textbf{(Eqn. 2)} \qquad\qquad Q = 0.0491H^{0.5584} \quad \textbf{(Eqn. 3)}$$

where Q is the outlet discharge (l/s) and H is the pressure head at the centre of the outlet. The equations ignore the effect of velocity in the pipe on the outflow characteristic (see Smith 1990). In this case the velocity head, calculated upstream of each gate starting from the downstream end ranged from 0 to 1.92 % of the total head of fluid, decreasing towards the downstream end, and was therefore insignificant. More research will be required to quantify this effect for longer runs of layflat where velocity head accounts for a larger proportion of the total energy.

It is obvious that flexiflume gates with the valve in the fully open position are unsuitable for the high flow rates required at the low heads available in the cotton industry. Removal of the valve gives the higher flows but significant erosion in the furrow is likely to occur. The use of socks on the outlets might mitigate this erosion but the effect of the socks on the gate characteristic needs to be investigated. New outlet configurations will be required for higher flow rates or lower pressures.

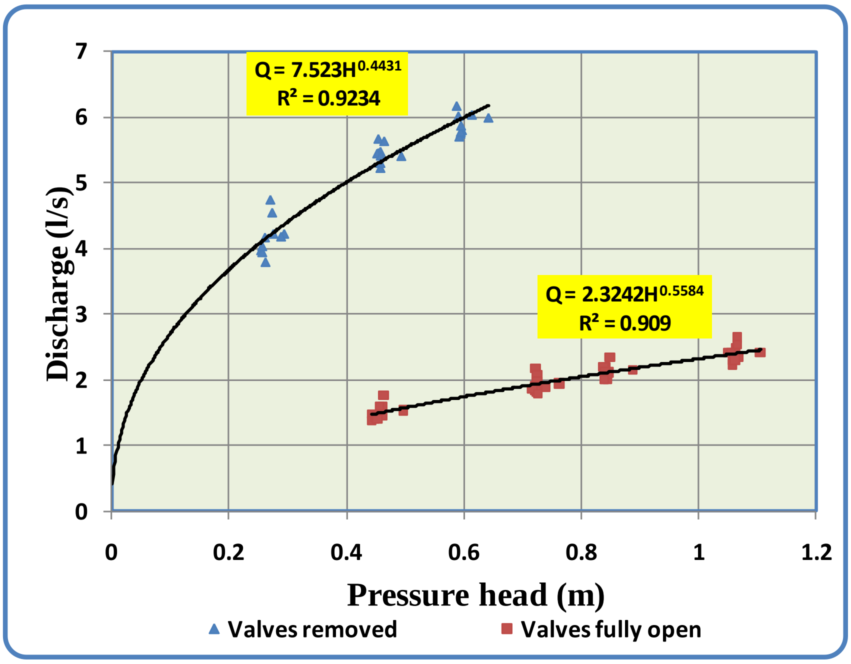

Fig. 7: Discharge-pressure relationship

The above equations were incorporated into the hydraulic simulation program GPIPE (Smith 1990) and the predicted discharges correlated well with the measured values (Figure 8).

Pressure head

As indicated by the above H-Q relationships the higher flow rates require higher pressures. The use of the adjustable valves (even when fully open) significantly increased the pressure in the layflat. There was a minor variation of pressure head along the length of the layflat (Fig. 9) with the (low) friction losses being balanced by the pressure recovery (Smith, 1990) at each outlet. For each of the seven trials, the pressure head of the last outlet was the highest. The shape of the layflat at the last outlet was affected by the proximity of the clamp and thus the level of the outlet was lower than the rest. This resulted in a higher pressure and subsequently increased discharge from this outlet.

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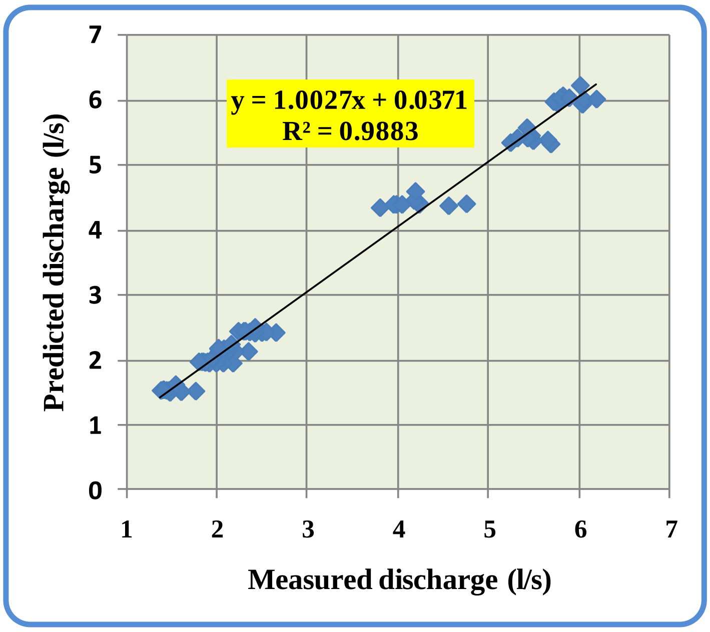

Fig. 8: Measured versus predicted flows

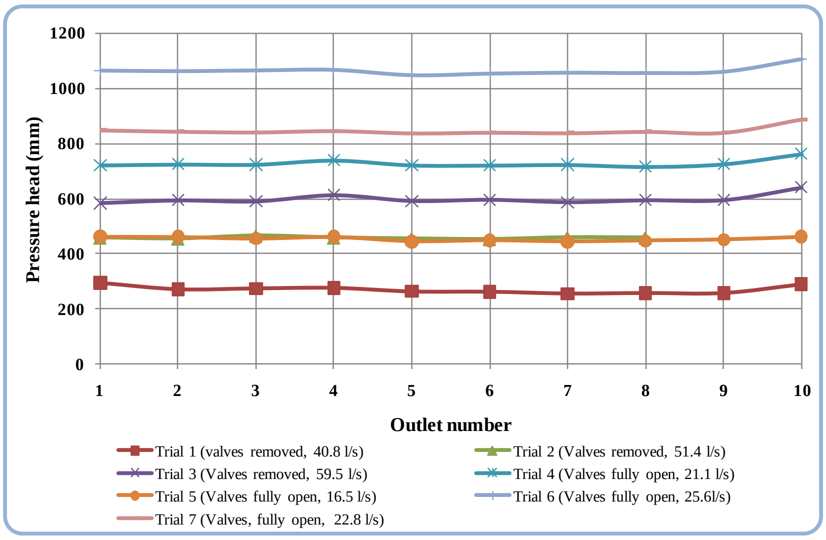

Fig. 9 – Variation of pressure along the layflat

Layflat geometry

The relationship between pressure and the cross-sectional shape of the layflat is important in the hydraulic behaviour of these systems. The plot of head-diameter (H/D) and height-width (d/w) ratios for this study (Figure 10) gave a curve (Fig. 11) similar to that obtained by Humpherys and Lauritzen (1964, Fig. 4), suggesting that their geometrical and friction loss relationship apply to flexiflume and can be used in the simulation program GPIPE (Smith 1990).

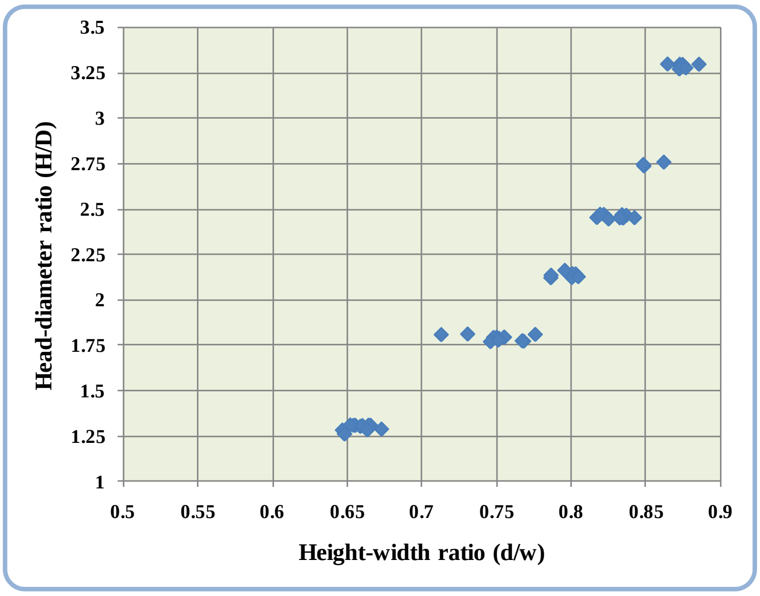

Fig. 10 – Relationship of head-diameter and height-width ratios of the layflat

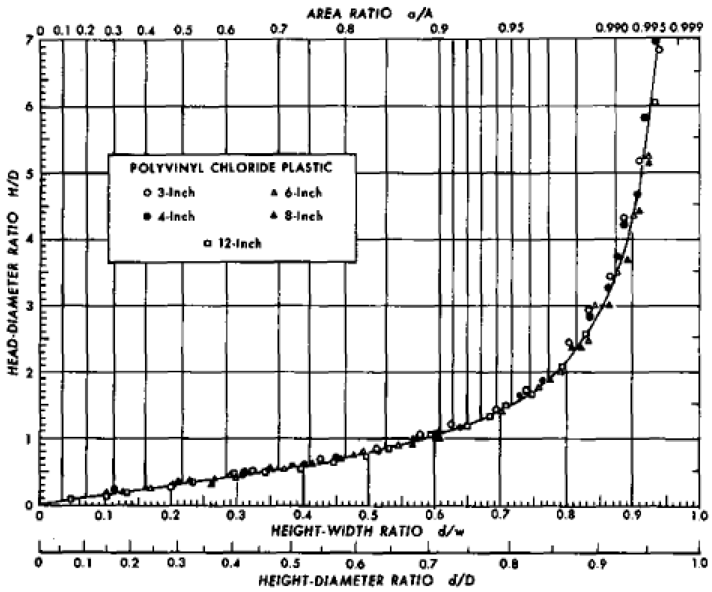

Fig. 11 - Area ratio for layflat tubing related to hydrostatic head, and tube height and width (*Source: Humpherys and Lauritzen 1964, Fig. 4*)

Conclusion

The use of overbank siphons is well entrenched in the irrigation industry in Australia and particularly in the furrow-irrigated cotton sector. However, complete automation of water delivery using overbank siphons apppears to be infeasible. Therefore, alternative water delivery systems need to identified and evaluated for use in automated furrow systems.

Automation technologies that have proved successful in bay irrigation can readily be adapted for use in the bankless channel and PTB systems. However, there is lack of of conclusive published data on the irrigation performance of these systems. The fact that in both of these systems water is delivered to a group of furrows raises concerns of uniformity of furrow inflows. Lined heads ditches may offer better inflow uniformities but the initial cost may be a detterant factor. In addition this is a fixed system and may interfere with the operation of machnery.

The laboratory study undertaken at the University of Southern Queensland confirms that large diameter gated latflat with valves removed from the outlets has the capacity to supply high flow rates under low heads typical of the cotton industry in Australia. However, this increases the erosion risk which needs to be addressed. The use of socks is a possible solution but the effect of socks on the gate characteristic needs to be investigated.

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