

## 3.2 Managing irrigated cotton agronomy

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### Key points

- Appropriate irrigation scheduling improves water use efficiency, reduces water-logging, controls crop canopy growth, improves the effectiveness of rain and allows better management of soil structural problems.
- Cotton is most susceptible to water stress during flowering until just after cut-out. Research has shown that yield losses can be up to 2.7% loss of yield per day of stress during this period in high fruit retention crops.
- If water stress occurs, it is better late or early in the season, but not in the middle, during peak flowering and early boll fill stages. When irrigation water is limited, save water for the flowering period.
- The best approach to determining when to irrigate is to use a combination of plant visual symptoms, crop growth and development monitoring, measurements of available soil water and weather forecasts to predict when irrigation is required.
- To optimise yield potential and water use efficiency in cotton it is important to balance growth by matching nitrogen application and irrigation scheduling to crop requirements.
- Mepiquat chloride can be a valuable tool to check growth if it becomes too vigorous.

Irrigating cotton requires balancing excessive vegetative growth due to abundant water supply against limited yield potential due to water restriction. Correct agronomic management and irrigation scheduling improves water use efficiency, reduces water-logging, controls crop canopy growth, improves the effectiveness of rain and allows better management of soil structural issues.

This WATERpak topic explains how to optimise the management and irrigation scheduling of cotton. WATERpak Chapter 2.1 provides an overview of evapotranspiration, soil moisture and irrigation scheduling techniques as may be applied to any crop. WATERpak Chapter 2.7 discusses how to calibrate soil water based measuring devices and determine plant available water content (PAWC) whilst WATERpak Chapter 2.3 describes tools that can be used for irrigation and crop management.

There are a number of factors to consider when scheduling an irrigation including;

- Total water availability (WATERpak Chapter 2.2)
- Limited water situations (WATERpak Chapter 3.3)
- Crop growth status and potential yield (WATERpak Chapter 3.1)

- Future rainfall and future temperatures
- Practical farm management logistics such as the physical movement of water
- Current soil water content (WATERpak Chapter 2.1)

Whilst this chapter is primarily focussed on furrow irrigated systems, some discussion of scheduling under alternative systems (CPLM and drip) is also included.

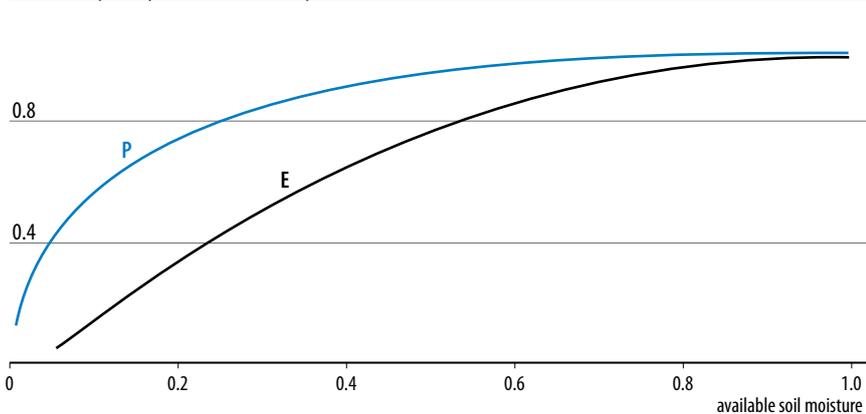
### Water use by cotton plants

Plants lose water through their leaves to keep cool and to move nutrients around the plant. They need to absorb water from the soil to replace what they have lost. This phenomenon is more severe over the hot summer months, as more than 95% of water used by the crop is for cooling itself. Photosynthesis is very sensitive to leaf temperature which the plant regulates by the movement of water through the leaf in a similar way to how perspiring cools humans. Water is also important for photosynthesis, cell expansion, growth, nutrient supply and turgor pressure (prevents the plant from wilting and controls stomatal opening).

Figure 3.2.1 shows that water deficit reduces cell expansion, which is observed by agronomists as reduced leaf expansion and stem elongation. Greater levels of water stress cause a decline in net photosynthesis and further reduce cell expansion. Photosynthesis is the process by which plants use CO<sub>2</sub> from the atmosphere to produce carbohydrates (assimilates) to support boll growth and fibre development. When the plant senses that moisture supply is becoming limited, vegetative growth slows and priority is given to boll development.

**Figure 3.2.1 : The relationship between available soil water and relative leaf net photosynthesis (P) and relative daily leaf expansion (E). Relative refers to the ratio between dry and control plants.**

1.2 relative photosynthesis (P) or leaf expansion (E)



Source: Constable and Rawson 1982

In descending order of sensitivity, Hearn (1994) summarized that water stress firstly reduces leaf expansion, then organ production (leaves and sites), then fibre length, then photosynthesis, then boll retention, then fibre thickening and finally root growth and function. Like many crops, cotton is most sensitive to water stress during peak flowering. Stress during peak flowering and boll filling is likely to result in double the yield loss compared to stress during squaring and late boll maturation (Table 3.2.1).

The extent of the yield loss will vary with circumstances. Yeates et al. (2010) found that Bollgard II cotton cultivars are more sensitive to water stress near cut-out flowering with a yield reduction of 2.7% per day of stress compared to 1.4% reported for non-Bollgard II cultivars in the past (Hearn and Constable 1984) (Table 3.2.1). This is because Bollgard II cultivars have higher fruit retention early in flowering and therefore a much higher boll demand for assimilate late in flowering.

**Table 3.2.1. Yield loss (%) per day of water stress (extraction of > 60% plant available water)**

	Past Conventional*	Bollgard <sup>#</sup>
Squaring	0.8	1.1
Peak flowering	1.6	1.7
Late flowering	1.4	2.7
Boll maturation	0.3	0.69 <sup>^</sup>

<sup>^</sup> 14 d post cut out

Source Yeates et al. 2010<sup>#</sup>; Hearn and Constable 1984<sup>\*</sup>

Water logging can cause yield losses as great as those experienced by water stress. For example, Hodgson (1982) reported yield losses of up to 2.4 % per day of stress due to water logging and low soil oxygen levels. Cotton's symptoms and responses to water logging are discussed in WATERpak Chapter 3.4 .

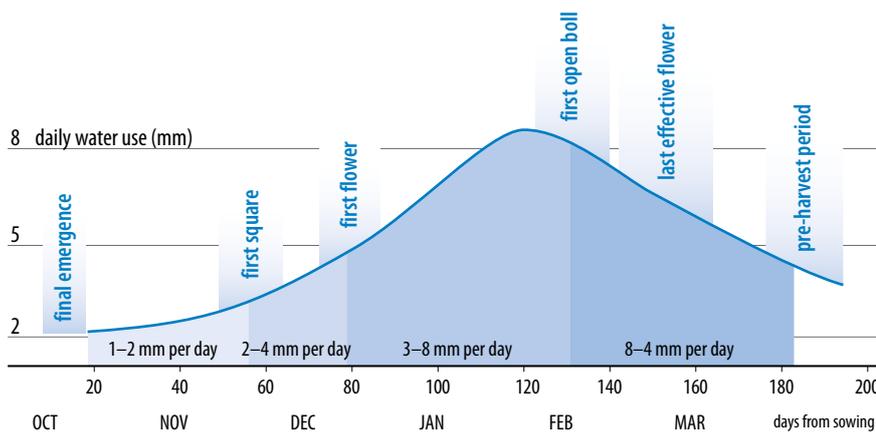
### Seasonal and Daily Crop Water Requirements

Research and field trials show that to obtain maximum yields, cotton crops need to use on average about 700-750mm (7-7.5 ML/Ha) of water. This can come from rain, stored soil moisture and irrigation during the season (see WATERpak Chapter 2.1 for further explanation of crop water use (ET<sub>c</sub>)). This figure will be less in shorter season areas.

The amount of water used is the sum of the evapotranspiration (leaf transpiration + soil evaporation), which is driven primarily by meteorological factors of solar radiation and air temperature and the crop's leaf area. As leaf area, radiation and temperatures increase during the season, so does the demand for water. The peak flowering and early boll development stages see increasing demand by the crop to fill bolls and are also the periods where crop growth rate is highest. Hence maximum demand for water occurs at this time.

This is demonstrated in Figure 3.2.2, which shows how the daily crop water needs vary with temperature and stage of the crop. Early in the season, the cotton plant's water use will be 2 to 4 mm per day, which will rise to a peak of 8 to 10 mm per day in late January. The daily water use drops to about 5mm/day in March. By studying your own daily water crop figures it is possible to plot your own curve like the one in Figure 3.2.2.

Figure 3.2.2. The daily water use of cotton plants



### Determining irrigation requirements

The optimum irrigation strategy for cotton in furrow irrigated systems has been well studied in Australia. There is no single strategy that will provide the optimum irrigations every year. The best approach to determining when to irrigate is to measure available soil water, take note of plant visual symptoms, monitor crop growth stage, and make use of weather forecasts to predict when irrigation is required.

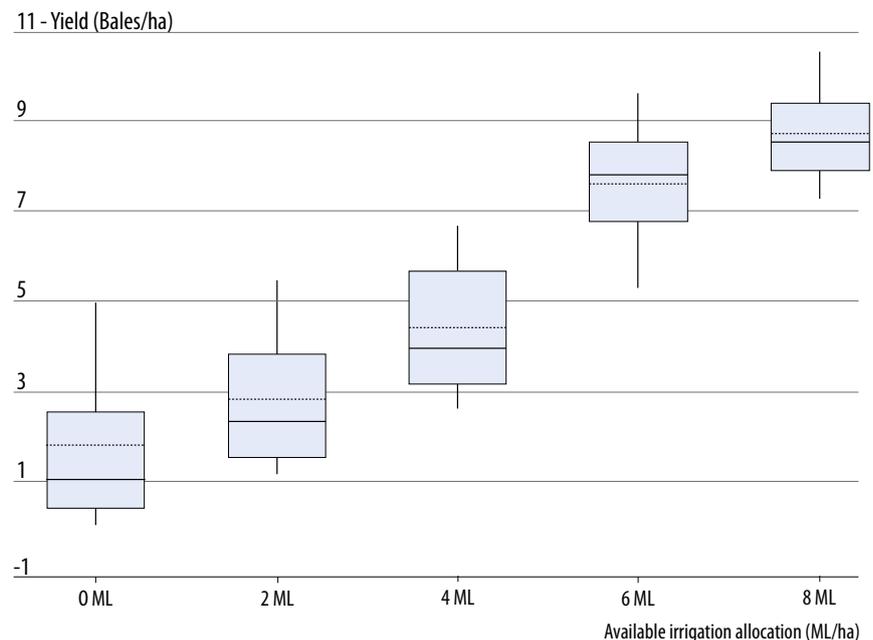
The widespread adoption of two gene transgenic Bt cotton (Bollgard II) cotton varieties has meant that management practices (including irrigation scheduling) have been re-examined in Australia and elsewhere. As a consequence of the improved insect control, early tipping of the terminal is minimal and the retention of squares (flower buds) and young bolls (fruit) is significantly higher in Bollgard II varieties when typical insect pest numbers occur. Higher retention of early fruit in Bollgard II cotton varieties creates a higher demand for assimilates earlier in the season and hence Bollgard II crops can be more sensitive to stress compared to crops with lower fruit retention.

Timely irrigation is more critical in Bollgard II crops particularly during flowering and at cut-out compared to crops with lower fruit retention and tipping. Ensuring adequate water availability is important to ensure adequate assimilate supply so that vegetative growth is not suppressed in preference to boll growth during early boll fill. An advantage of the rapid boll development of Bollgard II crops is earlier maturity and less seasonal water use than conventional varieties in seasons with typical pest numbers.

Seasonal irrigation requirements for individual locations can be estimated using tools such as [CottBASE](#) or [CropWaterUse](#). CottBASE is also able to predict the production risk that might be associated with different management options or seasonal conditions (e.g. SOI).

For example, Figure 3.2.3 shows an example of the predicted yield for five different irrigation allocation scenarios at Narrabri. A range of parameters such as nitrogen application, target deficit and plant available water content (PAWC) can be modified to represent individual conditions. Further information on these tools is available in WATERpak Chapter 2.3 .

Figure 3.2.3 – CottBASE predicted yield for different irrigation allocations for an example farm at Narrabri .



### Choosing a target soil moisture deficit

For furrow irrigated cotton, the best target deficit to avoid plant stress in average conditions is to aim for a deficit of approximately 50% of the plant available water content (PAWC). This is conservative for heavy clays and at times it may be possible to dry them to a 60% deficit without penalty. However, under conditions of high evaporative demand (very hot and dry conditions or hot winds) the target deficit as percentage of PAWC needs to be reduced because the stress occurs more rapidly and the crop can't adjust its growth and metabolism quickly enough.

It is also possible to infer an appropriate target deficit by interrogating continually logging soil moisture probes to estimate when the plant is about to stress. This process is discussed in detail in WATERpak Chapter 2.1. It is common for the target deficit to increase over the initial irrigations as the crop root zone expands. Recent work investigating the use of 'dynamic deficits' is discussed later in this chapter.

## Crop monitoring

The cotton plant exhibits many plant water stress symptoms that can be used to help schedule irrigation. However, many of these occur after stress has occurred so the best approach is to anticipate crop requirements rather than to react after symptoms of water stress appear.

Visual symptoms of plant stress include;

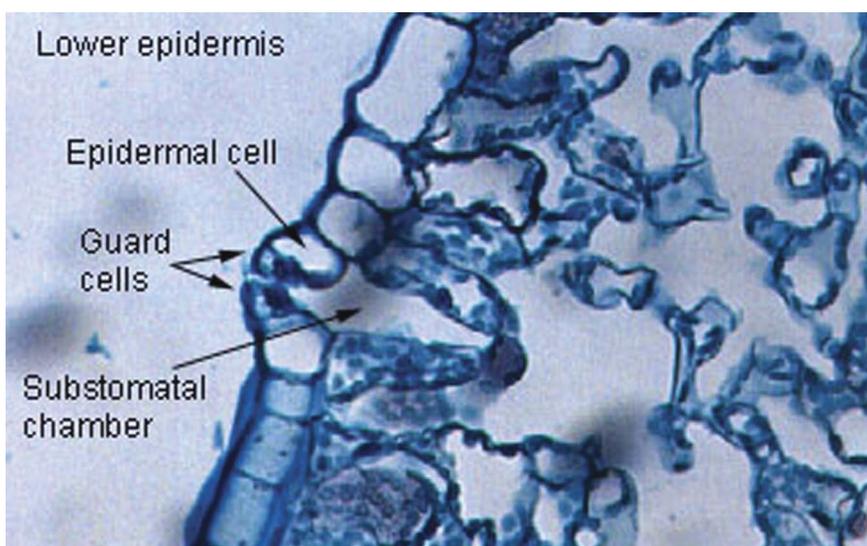
- A change in leaf colour from a bright to darker green (almost blue colour when severely water stressed). It is most important to look at the health of the youngest leaves that are still growing in size.
- Plant wilting is an obvious water shortage symptom; however, care should be taken not to confuse a “midday wilt” with water stress. Midday wilt is an internal transport problem, which occurs when cotton plant roots cannot absorb water quickly enough to meet the plant’s transpiration demand. Midday wilting occurs on very hot days; particularly when the air is dry. If the wilted plant recovers as the day cools down in the evening, this is a sign of “midday wilt” rather than a soil water shortage. Checking the soil moisture will help clarify any confusion. Due to its tropical origin, cotton, unlike many other plants, does not shut its stomates (Figure 3.2.4) in the heat of the day to conserve water. This allows gas exchange to continue and thus, the plant to keep growing at higher temperatures than many other crops. Only when severe stress occurs will the stomates respond and close. This usually occurs after leaf growth has stopped.
- Crops use water to keep cool so the leaves of water stressed crops are warmer to the touch. Around solar noon, crops that are not water stressed will be about 4 degrees Celsius cooler than the surrounding air temperature. Water stressed crops will be less than one degree cooler than the air temperature.
- The number of nodes (branches) above the most recent white flower on the

first fruiting position is another plant observation used by cotton growers to schedule irrigations. Crops with more **nodes above white flower (NAWF)** generally have more vigour and this can be used to help decide which crops should be watered when water is scarce. When water availability is good irrigation should be used to extend the flowering period as long as possible to match the available season length. The change in NAWF each week is a guide to when irrigation may be required to continue node production and hence new squares. Assuming fruit retention is maintained, the longer NAWF takes to go below 5 the better.

Besides soil moisture, crop development is one of the most important things to monitor to determine crop water requirements. Keep a check on squaring nodes, first position retention and NAWF. Use the Crop Development Tool on the [CottASSIST](#) website to help keep track of how the crop is progressing.

A cotton plant, when not stressed, grows in a predictable way, which allows its crop development to be predicted using daily temperature data (day degrees). The Crop Development Tool (CDT) allows crop managers to monitor both vegetative and reproductive growth of their crops compared to potential rates of development. Monitoring your crop will enable you to use this information as a prompt to further explore why the crop may or may not be on track, and manage the crop accordingly. For more information refer to WATERpak chapter 2.3.

Figure 3.2.4: Stomates on cotton leaf surface where CO<sub>2</sub> enters the leaf for photosynthesis while water simultaneously exits the leaf



Source: G Roth

## Crop management

A wide range of management factors can impinge on the water use efficiency of a crop. Insect management and soil structure are two major considerations and are covered in detail in the publications [Integrated Pest Management Guidelines for Cotton Production](#) and [SOILPak](#). In addition, nitrogen uptake is linked to the amount of plant available soil water and mepiquat chloride can provide a management option to slow excessive crop growth. Both are discussed in further detail here.

### Nitrogen impacts on water use

Approaches to the assessment of nitrogen requirements are spelt out elsewhere, in particular in [NUTRIpak](#). The optimum amount of nitrogen application before sowing is by and large determined by soil type and the nitrogen status of the soil. However there is a strong interaction between fertilizer application and the amount of water applied.

Excessive nitrogen fertiliser can negatively affect crop growth. When adequate water is available, high rates of nitrogen can promote vigorous vegetative growth. The primary effect of the more vigorous growth is to result in a higher rate of transpiration. Except for when the soil is wet to the surface, the rate of evapotranspiration from the crop is governed by the leaf area index (LAI); that is, the leaf area per unit ground area.

Vigorous crops have more and larger leaves and thus a higher LAI. This means that the rate of water consumption per day is higher in crops that have received high rates of N and water. This extra growth and water consumption may or may not lead to commensurate improvements in yield. Where good retention is achieved and there is adequate season length, strong growth will lead to high yield. However, the greater canopy size may instead lead to a reduction in retention due to shading of the lower leaves and fruit.

In tropical or sub-tropical conditions the combination of high water, high nitrogen and high temperature can trigger the “rank growth syndrome”. This is induced when high growth results in the shedding of fruit which in turn results in a lower carbohydrate demand by the fruit and hence there is more available for vegetative growth and thus there is continued vegetative vigour. The result is a large late crop with a possible reduction in yield.

A similar situation occurs in short season areas when too much nitrogen is applied. While the classical ‘rank growth syndrome’ may not be induced, the added vigour of the crop and delayed maturation of the crop may result in yield loss if the crop is truncated by cold weather. In either case, water consumption can be increased with little benefit in terms of yield, and possibly negative effects on yield.

If excessive nitrogen is unintentionally applied, the temptation is to apply water at the rate that the more vigorous crop demands it. This is not necessarily the best option. A slightly restricted water supply will reduce the vigour and reduce the overall risk of delayed development. The condition can also be dealt with by



monitoring the vegetative vigour of the crop and using mepiquat chloride as required.

At the other extreme, when water is limited, the crop is less responsive to applied nitrogen, simply because growth is limited by water stress. The water limitation causes a reduction in leaf area and overall growth rate. There is therefore less need for nitrogen to build these structures. High rates of nitrogen resulting in vigorous growth in limited water situations can lead to higher early water use, leaving less water availability for reproductive growth later in the season. Thus, in limited water situations the crop is likely to require less applied nitrogen.

Waterlogging reduces nitrogen uptake. There appears to be two mechanisms: firstly the ability of cotton's roots to extract nitrogen from the soil is impaired and secondly, the amount of nitrogen in available forms in the soil is reduced because of the chemical reactions that take place in the anaerobic soil. The application of foliar nitrogen prior to waterlogging may prevent part of the yield loss in certain circumstances but it cannot fully compensate for the impact of waterlogging (See [NUTRIPak](#) for more details).

Nitrogen and water management can be particularly important in CPLM and drip systems which can supply water with neither the stress of waterlogging nor the small amount of stress that might occur just before a furrow irrigation is applied. Fortunately, the precise control of water under these systems may provide some flexibility to manage soil moisture deficit and moisture stress, as discussed later in this chapter.

### Mepiquat chloride as a tool for managing excessive growth

Mepiquat chloride (MC) or Pix<sup>®</sup> suppresses the expansion of vegetative organs. During fruit growth, this may reduce the within plant competition between bolls and leaves for the available carbohydrate. The outcome can be a shift in the partitioning of dry matter to the bolls. However there is little evidence for this being a significant benefit in crops sown at normal times where water and nitrogen are well managed. In these situations, no yield advantage has been demonstrated and any advantage in dry matter partitioning disappears by maturity as the crop moves back to its inherent pattern of partitioning. Application of MC when the crop does not require it can lead to yield loss as it reduces crop growth.

MC is an advantage where a crop has become too vigorous. In this situation the suppression of leaf expansion and the subsequent shift in partitioning bring the carbohydrate supply and demand back toward the optimal balance. Interrupting the ongoing expansion of the crop also reduces the subsequent water usage. The outcome of these two responses mean there is the potential for both increased yield and increased water use efficiency.

It should be noted, of course, that reduced water or nitrogen availability will also control leaf expansion. The most efficient way to reduce the risk of excessive vegetative growth becoming a problem in the first place is correct nitrogen fertilisation and careful irrigation management. This will not cover every eventuality and the use of MC will be required from

time to time when growth becomes excessive. This pattern of growth may occur in warm production areas or late sowings, after heavy insect damage or unfortunately timed rainfall events which have "released the brake" on the plant through shifting conditions in favour of vegetative growth.

The best approach to balance growth and optimise yield potential and water use efficiency is to:

- monitor your crop growth and development;
- apply nitrogen fertiliser based on soil tests, petioles or cropping history;
- monitor internode lengths to determine whether MC is necessary; and,
- carefully schedule irrigation to match crop requirements.

## General rules for irrigation scheduling

The optimum irrigation strategy for cotton has been well studied in Australia. Whilst there is no single strategy that will perform optimally every year, there are a number of key decision points in determining an irrigation scheduling strategy appropriate for the situation at hand:

- decide whether to pre- irrigate or water up at sowing;
- determine when to apply the first irrigation;
- choose a target deficit to minimize stress during flowering and cut-out (see above); and,
- aim to dry the soil down to about 70% of PAWC by the time the crop has 60% bolls open.

### Irrigation at sowing: pre-irrigate or water up?

The decision for a cotton grower to pre-irrigate or water up furrow irrigated fields is, like so many others, a decision that has to be made specifically to suit a farm. In certain situations it may also be necessary to combine the two options by pre-irrigating to plant into moisture and then giving the crop a “quick flush” to ensure good plant stands. Every farm is different and the following questions need to be considered before making a decision:

- What method has traditionally given the best plant stands and early vigour?
- What is the most efficient way to store my water, in an on farm storage or in the soil?
- Do I have enough water available or do I need to scratch for the last little bit?
- Is my cotton grown on a “warm” or “cold” soil?
- Does my cotton traditionally have a lot of pressure from seedling disease?
- How will my water account or carry over rules impact on water availability?
- What is the likely rainfall pattern before and after planting?
- Am I likely to get enough rain before planting to plant into moisture?
- Is it likely to rain straight after flushing up?
- Do I often have herbicide damage problems?
- Is my soil likely to dry out quickly before planting?
- Is my planter set up for dry or moisture planting?
- Are the beds even enough to get uniform moisture levels after harrowing to seek moisture?
- How does my soil soak up and how badly does it erode?
- Can I apply a small amount during a flush and not be wasteful?

The likely advantages & disadvantages of the different options are summarized in Table 3.3.2.

Table 3.3.2. Advantages & disadvantages of the different options for the first irrigation (furrow irrigation fields).

Pre-irrigation	Watering-up	Pre-irrigation and late flush
<b>Likely advantages:</b>		
No time pressure to apply the water	Potential to take advantage from pre-plant rain events, so the irrigation may require less water	Helps in fixing up plant stand problems
In a heavy clay, water losses can be less than keeping it in an on-farm storage	Easier to plant, especially when beds are not 100% even	Can give the crop the necessary “Boost” to get going after a slow start
Soil temperature is less likely to drop after planting - potentially less disease pressure	Faster planting operation and less machinery needed	
<b>Likely disadvantages:</b>		
Soil drying out too quickly	Reduction in soil temperature after planting in cool conditions, cool and wet soils can result in higher disease pressure	Likely to use more water
Dry rows in uneven fields	Herbicide damage more likely	
Soil stays too wet when followed by rain	Sides of beds might erode when flushing for a long time	
Unable to capture rainfall before planting	Can germinate weeds at the same time as the crop Water logging if rain occurs after flushing	

Source: S Henggeler

## Scheduling in-crop Irrigations

Optimising in crop irrigations is a balancing act for cotton; the aim is to provide sufficient water to prevent plant stress but not excessive water to ensure vegetative and fruit growth is balanced. It is important to tailor your irrigations to meet the needs of your crops to optimise yield and water use efficiency. Like many crops, cotton has stages of development at which it is particularly sensitive to stress (Table 3.2.1 ). Irrigation scheduling should strive to avoid exposure to stress during flowering and early boll filling stages. High boll load early in flowering can lead to premature cut-out and lower yields.

### First in-crop irrigation

The first irrigation plays an important role in setting up for plant growth, fruit retention, fibre quality and boll weight. It requires a balancing act of not stressing the crop while ensuring water stored in the soil profile is fully explored by the cotton roots. The timing of this irrigation will vary depending on seasonal conditions and in crop rainfall.

Irrigating too early can lead to waterlogging. However, delaying the first irrigation will place the plant under stress and it is difficult to re-start a crop growing again if water stress has stopped growth. Under average conditions, many crops grown in heavy clay soils may not need irrigating earlier than halfway between squaring and flowering.

The demands of high fruit retention and absence of early main stem tipping afforded by Bollgard II® cotton mean that moisture stress prior to flowering may prevent canopy development and the plant may be too small to support the high early boll load. Recent research by Marcelo Paytas has shown for Bollgard II crops that when conditions are hot and dry and available soil water depletion in the root zone is at least 50%, irrigation up to 2 weeks prior to flowering will increase yield by 14 to 35% (Paytas et al. (2008, 2009).

Things to monitor or measure when scheduling the first in-crop irrigation:

1. Close examination of root extraction patterns and daily water use using soil moisture data is the best way to monitor the crops water status.
2. Monitoring fruit retention, changes in crop height and node number is essential to anticipate the need for water to increase canopy size ([Crop Development Tool](#)).
3. Check weather forecasts before irrigating; cool or wet weather near the time of the first irrigation can be detrimental to crop growth and water use efficiency

## Subsequent Irrigations

Once regular irrigation has started, extending the interval between irrigations without monitoring soil water levels can result in significant yield reductions. Water can be saved, but yield losses will occur. The other consideration is that by stretching the irrigation interval, greater amounts of water will be required to fill the profile at the next irrigation and this can have efficiency implications.

For all irrigated cotton crops, water stress should be avoided during peak flowering and early boll fill stages. For Bollgard II cotton, high fruit retention means that crops are most susceptible to water stress late in flowering and at cut-out (see Table 3.2.1). When irrigation water is limited, it should be saved for the flowering period as it is better if water stress occurs late or early in the season, but not in the middle.

In hot dry summers it is better to be early than late. Yeates et al. (2010) near Wee Waa found irrigating high retention Bollgard II at smaller deficits (40-50 mm deficit or 6 to 7 days) in hot, dry conditions during flowering increased yield by 17% and CWUI by 8%. Irrigation scheduling based on small deficits requires skill and a system that can apply water quickly. Otherwise application efficiencies will be lower and the crop may be more susceptible to waterlogging.

Conversely, in summers when the air is more humid and with storm events, there may be some room to stretch irrigations intervals providing that the plant is not under stress. Experiments showed where mild growing conditions (higher in-crop rainfall and less evaporative demand) were experienced, scheduling

irrigations to a greater deficit (80 mm) maximised yield and WUE, by allowing the opportunity to capture more in-crop rainfall rather than irrigating at a small deficit.

For high yielding (>12 bales per ha) crops with high fruit retention and a main stem that is not tipped, the plant must have enough vigour to grow bolls from squares produced on the top of the plant and on outside positions on fruiting branches (Table 3.2.3). All fruit compete for resources and any moisture stress will be a signal to the plant to favour the early bolls and not produce new squares or bolls. This is why water stress must be avoided during flowering in high fruit retention Bollgard II crops. Table 3.2.3 shows irrigation needed to be more frequent in the 2006/7 season because it was hot and dry while the 2007/8 season was milder and wetter so the plant was less stressed and could maintain photosynthesis with less frequent irrigation (i.e. with a larger soil moisture deficit).

Table 3.2.3. The importance of avoiding water stress during flowering. Shown is the effect of irrigation deficit on yield (b/ha) from squares present at 1st flower (1 flower/m) and yield on squares grown after first flower.

2006/7			2007/8		
Deficit (mm)	Yield from squares at 1st flower (bales/ha)	Yield from squares set after 1st flower (bales/ha)	Deficit (mm)	Yield from squares at 1st flower (bales/ha)	Yield from squares set after 1st flower (bales/ha)
39	6.3	6.0	35	5.7	7.3
68	6.3	4.4	54	6.4	7.4
82	6.3	4.2	78	5.9	6.7
124	4.2	1.9	126	6.2	5.8

Source Yeates et al. 2009

Careful monitoring of soil moisture extraction graphs, daily water use and crop development and growth will enable the correct timing of irrigations. Monitoring fruit load and crop development will also help in anticipating crop requirements. Soil moisture monitoring will indicate when the soil water levels reach the target deficit/refill point.

If irrigation is not applied prior to this point, then a yield reduction will occur depending on the stage of the crop. It should be noted that in circumstances when plant water requirement is very high (high wind and temperature combined with low humidity), plants can be stressed before the predicted soil water refill point is reached. To avoid yield loss in this case, irrigation should be scheduled early for Bollgard II crops during flowering.

## The final irrigation

The prime objective of the last irrigation is to ensure that boll maturity is completed without water stress. At the time of last irrigation all bolls have been set, vegetative growth is limited and the majority of carbohydrates are used to satisfy boll demands. Once a boll reaches 10-14 days old, the abscission layer to cause boll shed cannot form. It is for this reason that boll numbers are not significantly reduced by late water stress, although fibre development can be affected. Crops that come under stress prior to defoliation (60 to 70% open - 4 Nodes Above Cracked Boll), can suffer some yield and fibre quality reduction. The level of reduction obviously increases the longer the stress occurs.

End of season water requirements can be determined by estimating the number of days until defoliation and predicting the amount of water likely to be used over this period. By defoliation, plants can be allowed to extract past the normal refill point to around 70% of plant available water content, ensuring a dry soil profile for picking. For cracking clay soils, this may be around 125 to 150 mm of soil water. The number of days until defoliation can be predicted in two ways; by determining the date of the last effective flower (cut-out) or by counting the number of Nodes Above Cracked Boll (NACB).

The last effective flower method is useful as a forward planning technique for budgeting water requirements in advance. Good managers can optimise crop nutrition, irrigation and use of growth regulators to guide the crop towards a desired date for last effective flower.

The NACB method is useful for monitoring final irrigation requirements as the crop matures.

The procedure is as follows:

### Step 1 - Gather Data on Crop maturity

#### Last Effective Flower Method

Determine the predicted or desired date of last effective flower (cut-out). The Last Effective Flower Tool on the [CottASSIST](#) website is most useful. The last harvestable bolls take 600 to 650 degree days to reach maturity. Depending on sowing date, regions and temperatures this can be approximately 50 to 65 days. Day degrees can be determined for individual locations using the Day Degree Calculator on the [CottASSIST](#) website.

#### NACB Method:

Determine the level of crop maturity by counting the Nodes Above Cracked Boll (NACB). This is the number of nodes (fruiting branches) from the last cracked boll to the last harvestable boll on the top of the plant. The crop can be safely defoliated after 60 to 70 % of the bolls are open. If a boll can be cut easily, it is presumed to be mature. The crop should not be defoliated until less than 2% of bolls are immature.

Defoliation generally occurs when NACB is equal to 4. At this stage the top boll will have reached effective maturity and defoliation can occur without risk of reducing yield and quality.

### Step 2 - Determine the number of days until defoliation

#### Last Effective Flower Method

The [CottASSIST](#) website will provide the number of days between cut-out and defoliation.

#### NACB Method:

$$\text{Days to defoliation} = (\text{total NACB} - 4) \times 3$$

It takes about 42 day degrees for each new boll to open on each fruiting branch. If warm, sunny conditions prevail this could be around 3 days per node, however, mild and overcast conditions will slow opening.

### Step 3 - Estimate the average daily water use of the crop during this time.

Predict daily water use from recent soil moisture and  $ET_c$  data and predicted weather conditions. Alternatively, use online tools such as [CropWaterUse](#).

The crop daily water requirement starts to drop once bolls start opening (Figure 3.2.2). The [CropWaterUse](#) tool estimates weekly water requirements for different crops using historical weather data.

### Step 4 - Determine the total water requirement

$$\text{total water requirement} = \text{days to defoliation (Step 2)} \times \text{average daily water use (Step 3)}$$

### Step 5 - Compare the total required water to the remaining soil water

$$\text{current soil moisture deficit} + \text{total water requirement} > 70\% \text{ PAWC?}$$

If the sum of the current soil moisture deficit and the predicted water requirement from Step 4 is greater than 70% of PAWC, then irrigation will most likely be required.

Some examples of final water requirements are provided in Table 3.2.4.

Table 3.2.4. Example final water requirement calculations.

Last Effective Flower Method	Crop A	
Predicted cut-out date (from <a href="#">CottASSIST</a> )	04 Feb	
Predicted days until defoliation (from <a href="#">CottASSIST</a> )	62	
<b>Total Water Requirement</b> (from <a href="#">CropWaterUse</a> *)	<b>356 mm</b>	

NACB Method	Crop B	Crop C
Total fruiting branches	13	13
% open bolls	25-30%	Zero
NACB	9	13
Days to defoliation (NACB=4)	$(9-4) \times 3 = 15$	$(13-4) \times 3 = 27$
Estimated daily water use until defoliation*	5 mm/day	5.8 mm/day
<b>Total Water Requirement</b>	<b>75mm</b>	<b>156 mm</b>

\*The CropWaterUse tool can be used to predict water requirements using historical weather data and user defined crop growth patterns. Alternatively, daily water use can be estimated as done for Crop B and Crop C, by estimating daily water use and multiplying by the number of days.

Crop A needs 356 mm of water over the next 62 days. If the profile is currently full and the plant available water capacity is about 200 mm, the deficit could reach 140 mm (70% of 200 mm) by defoliation without detrimental effect. Therefore another 216 mm of water needs to be supplied by irrigation and rainfall. With a typical irrigation deficit of 90 mm for this example, at least 2 irrigations are required as well as 36 mm in rainfall. If no rainfall eventuated, crop progress would need to be monitored to see if a third irrigation were required.

For similar soil moisture conditions, Crop B requires 75 mm of water to finish it off. Therefore irrigation is not required as there is 140 mm of soil moisture available. Only irrigate if the rooting depth is constrained or evaporation is higher than that predicted when estimating daily water use. On the other hand, Crop C will most likely require one irrigation because the crop requires more than the allowable depletion of 140 mm (70 % of PAWC). Likely rainfall would need to be considered in any such decisions.

If the crop is one irrigation short, boll size will generally be reduced rather than there being any significant reduction in boll numbers. This will result in a yield reduction. Fibre quality may also be affected, for example reduced micronaire, although little effect on fibre length would be expected. If the crop is two irrigations short, boll numbers will be reduced. Provided the crop doesn't move into rapid stress, boll size may increase due to the shedding of smaller bolls (less than 10 to 14 days old). Fibre micronaire may be reduced on younger bolls. Significant yield reductions can occur especially in vegetative crops that stress prior to boll opening.

Recent research by Steve Yeates on Bollgard II varieties found stretching the irrigation interval to just one irrigation 21 days after cut-out (one irrigation instead of two after last effective flower) led to yield losses of 10 to 18 per cent if there was no rainfall and as little as 0 to 9 per cent if good timely rain (more than 40 mm) fell after this final irrigation. However, this yield reduction was still less than if one irrigation had been skipped during flowering.

In the same experiment there was little impact on fibre quality as a result of stretching irrigations after cut-out. Where there was no irrigation and no rainfall after cut-out, fibre length decreased by 0.02", strength decreased by 1.2 g/tex and micronaire increased by 0.28. Table 3.2.5 shows the effect of no irrigation and only 1 irrigation after cut-out on fibre quality, compared to a fully irrigated crop.

Table 3.2.5. Effect water stress after cut out on fibre quality. Comparison with fully irrigated\*

	2006 (Sicot 71BR) No irrigation or rainfall after cut out	2007 (Sicot 71BR) 1 irrigation after cut out + no rainfall	2008 (Sicot 70BRF) 1 irrigation after cut out + no rainfall
Length difference (inch)	-0.02	-0.03	+0.07
Length difference (inch)	-1.3	-1.4	+0.06
Length difference (inch)	356 mm	+0.17	+0.17

\* Data for handpicked areas where plastic sheet prevented rainfall on dry treatments. These experiments were conducted at Narrabri.

## Innovative concepts in irrigation scheduling of cotton

### Regulated Deficit Irrigation

Cotton can maintain boll growth for longer periods than vegetative growth when under mild water stress. Maintaining the soil moisture of cotton at a mild soil water deficit has been suggested as beneficial as it limits the potential for excessive vegetative growth while still providing adequate water for transpiration. Maintaining a small soil water deficit also maximises the opportunity to capture rainfall and minimises the occurrence of water logging.

It is difficult to maintain a constant mild soil moisture deficit using furrow

irrigation; however some growers of Bollgard II cotton have adopted an approach where they irrigate Bollgard II crops at smaller deficits with faster irrigation run times. The aim is to reduce the potential for waterlogging by not completely refilling the soil moisture profile at each irrigation. Soil infiltration characteristics will influence the success of such techniques and will need highly skilled irrigation management.

Regulated deficit irrigation (RDI) has been investigated using centre pivot and lateral move (CPLM) and drip irrigation systems. These irrigation systems enable a higher level of control of irrigation volume, timing and placement. Simon White (2007) found that maintaining a regulated deficit of 79% of predicted evapotranspiration (ET) produced a 31.5% improvement in gross production water use index (GPWUI) compared to applying 100% of predicted ET (normal practice with high system capacity CPLMs). Similarly, Yeates et al. (2007) using drip irrigation found the highest yields occurred using 75 to 83% of predicted pan evaporation during flowering compared with 100% of evaporation. The higher water rate produced rank growth and lodging. The largest benefits from maintaining a regulated deficit was associated with crop management (preventing excessive vegetative growth, increased fruit retention and earlier crop maturity) and the increased ability for capturing rainfall.

## Dynamic Deficits

Current irrigation strategies for cotton rely strongly on irrigation scheduling based on soil moisture content using fixed deficits for the majority of the season. Research by Steve Yeates, James Neilsen and Rose Brodrick has suggested there is an opportunity to refine irrigation scheduling by dynamically changing the soil water deficits to improve growth by avoiding plant stress during periods of high evaporative demand (lower deficits) and improve water use efficiency by reducing the need for irrigation during periods of low evaporative demand (larger deficits). Measurements of plant stress using leaf water potential showed that the plant stress response to soil water availability changed in response to differences in evapotranspiration ( $ET_0$ ).

Brodrick et al. (2012) found that there may be considerable utility in delaying irrigation timing and extending opportunities to capture rainfall when  $ET_0$  is low. This allows for more flexibility in cotton systems that require a significant number of fields to be irrigated at a point in time, and potential irrigation water savings. There was no difference in lint yield compared with a fixed deficit approach where irrigation timing was either earlier in response to forecasted high  $ET_0$  or delayed when the forecast was for low  $ET_0$ . However, delaying the irrigation in response to forecasted low  $ET_0$  enabled more rainfall to be captured than the other irrigation treatments leading to 0.8 ML/ha saving in irrigation water. These results indicate there is flexibility in irrigating cotton in response to future forecasts potentially saving water. However this study has highlighted the need for a definitive measure of plant stress to assist irrigation decisions to match plant requirements. Research is continuing to develop a framework to provide a method to identify plant stress (based on a continuous measure) which, coupled with current and future soil water deficits and with short term  $ET_0$  forecasts, would allow the dynamic deficit approach to be used confidently and accommodate local conditions.

## BIOTIC

BIOTIC is an irrigation scheduling tool developed in the U.S.A, based on canopy temperature using a temperature-time humidity threshold system (Upchurch et al., 1996). This system utilises wireless infrared thermometers (IRTs) that continuously measure canopy temperature. The existing thermal optimum approach to irrigation scheduling, BIOTIC, is limited in that it is designed for precision, low volume irrigation application systems. Therefore in its original form, BIOTIC has not been implemented in large soil moisture deficit systems, such as furrow irrigation. Recent research by Conaty (2010) in Australia has identified that this system could be adapted to suit deficit irrigation systems and is a subject of current research. WATERpak Chapter 2.4 contains additional details.

## Overhead or Drip Irrigation Systems

Centre pivot, lateral move (CPLM) and drip irrigation systems offer a number of advantages and challenges for irrigation scheduling. For example, germination can be easily accomplished using sprinklers on a CPLM system, avoiding the need for water intensive pre-irrigation. Similarly, smaller, more frequent irrigation applications can be applied by CPLM and drip irrigation systems, offering the flexibility to maintain the soil moisture deficit at a point which maximises rainfall capture and prevents waterlogging, moisture stress and rank growth (see RDI above).

However, in contrast to furrow irrigation systems, CPLM and drip systems do not have the ability to apply large volumes of water to 'catch up' if the crop experiences a period of high water use. Such a scenario is best avoided by managing the soil moisture reserve and purchasing an irrigation system with sufficient system capacity.

The soil moisture reserve can be managed by building soil moisture levels over the early life of the crop, when water use is low. It is also important to monitor weather forecasts and ensure that the soil contains sufficient moisture prior to predicted high water use periods. System capacity should be high enough to satisfy peak crop water demand but not so excessive that capital and running costs are too high. The calculation of system capacity is covered in detail in WATERpak Chapter 5.6.

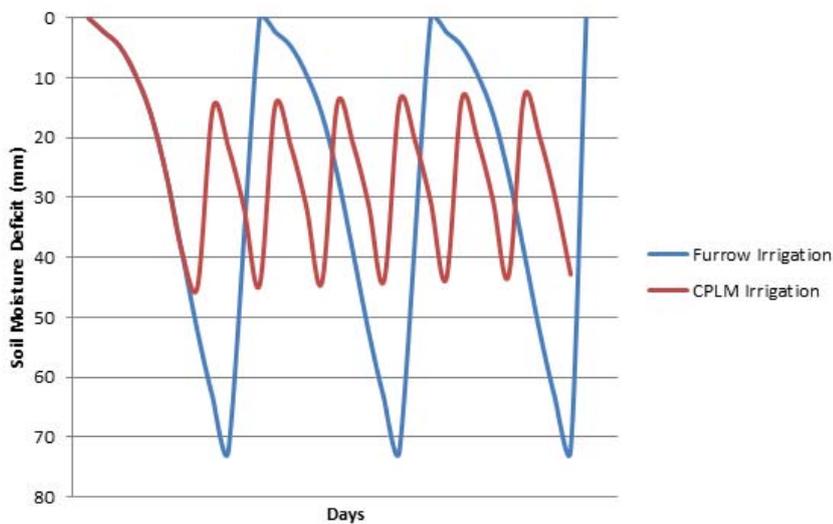
Centre pivot and lateral move systems usually apply much smaller amounts (for example, 30 mm) than



furrow systems. Furthermore, skilled operators will not necessarily refill the profile with every irrigation. For example in Figure 3.2.5, furrow irrigation is triggered at a soil moisture deficit of about 70 mm and irrigation completely refills the profile. In contrast, CPLM irrigation is triggered at a deficit of around 45 mm and 30 mm of irrigation is applied to take the soil moisture deficit to around 15 mm. It would be possible to modify the application strategy and timing throughout the season in response to different plant growth stages or anticipated weather conditions.

Drip irrigation systems may be operated in a similar manner or may be operated even more frequently (e.g. daily) with smaller applications.

Figure 3.2.5. Hypothetical example of the possible difference in soil moisture arising from different furrow irrigation and CPLM scheduling approaches.



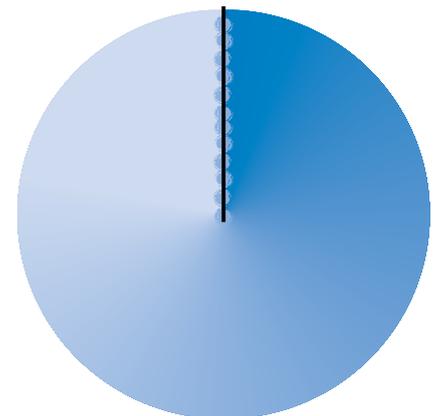
Timing and volume of irrigation water to be applied is best predicted by calculating the water used by the crop. This is done by calculating the evapotranspiration (ET) of the crop using a calibrated crop factor and reference evapotranspiration ( $ET_0$ ). See WATERPak Chapter 2.1 for more details on calculating daily crop water use using these methods. Tools such as [WaterSched2](#) may also be useful to assist with ET based scheduling. Deficit irrigation (less than 100%  $ET_c$  replacement) is often practiced in limited water situations but should be undertaken with care, particularly during flowering and peak evaporative demand.

In addition to scheduling drip irrigated and overhead irrigation systems using evapotranspiration data, it is also important to monitor both the crop and the soil water content. Monitoring your crop to ensure that it is not under stress is as important in these systems as for furrow irrigation systems.

One final important concept for scheduling with CPLM systems is to understand that the soil moisture deficit is not uniform across the field. Consider a centre pivot machine that is applying 30 mm of water to a 50 mm soil moisture deficit. The soil immediately in front of the machine (about to

be irrigated) would have a 50mm deficit whilst the soil immediately behind the machine (just irrigated) would have a 20 mm deficit (Figure 3.2.6). Assuming uniform daily water use, a point on the opposite side of the circle would be half way between these extremes, with a deficit of 35 mm. Such considerations can become complicated, particularly for new users and particularly after rainfall events. The [OVERSched](#) tool was developed to help visualise these soil moisture gradients so that irrigation management can be improved.

Figure 3.2.6. Visualisation of potential soil moisture gradient in a centre pivot field. One side of the machine has dry soil whilst the other side has moist soil.



## Further Reading

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