# Waterlogging, anoxia and wheat growth in surface irrigated soils

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**Abstract**

Surface irrigation systems are generally designed using engineering or operational criteria and these may not reflect best agronomic practice. In particular, long intake opportunity times (i.e. the time water is ponded above the soil surface during an irrigation) on heavy textured soils can lead to waterlogging and yield loss, so maximum opportunity times are recommended. However, recommended maximum opportunity times for surface irrigation systems in southern NSW are not based on experimental data and they vary widely (8 to 15 hours). Furthermore, there is evidence they might differ with soil type. To examine these two questions, pot and field trials were conducted using a representative crop (wheat) between 2008 and 2010 on soils typical of surface irrigated systems in southern NSW. It was shown there was:

- a strong correlation between wheat growth at anthesis and redox potential ($E_h$) when $E_h$ dropped below the oxygen limiting threshold of 350 mV.
- an explicable relationship between $E_h$ and matric potential ($\Psi_m$) in surface soils.
- a strong soil type effect on the duration of waterlogging stress following surface irrigation.

Using the collected data and an assumed model of behaviour, a maximum irrigation opportunity time of 10 hours was determined to be suitable for most soils. However, for sodic, massive grey vertosols, it was found that surface irrigation could result in waterlogging stress in wheat, no matter how short the opportunity time. Investment in capital intensive irrigation systems is not recommended on these soils without co-investment in soil management and both should be in accordance with expected returns.

**Key Words**

Waterlogging, redox potential, matric potential, surface irrigation, wheat.

# Introduction

Intake opportunity time (OT) is a key surface irrigation design parameter and refers to the time water is ponded above the soil and available for infiltration during surface irrigation. In soils with low infiltration rates, long OTs may be required to apply the target irrigation depth. However, long OTs on heavy textured soils can lead to waterlogging and this is recognised as one of the major production limiting factors in the irrigation districts of southern NSW (e.g. Grieve *et al.*, 1986). To overcome this, maximum OTs are recommended (e.g. Giblin and Lacy, 2003). However, these recommendations are not based on experimental evidence and they vary widely from 8 to 15 hours (North, 2008). Furthermore, these times are often exceeded, particularly in basin irrigation systems where opportunity times of 40-50 hours are common, and differences in the severity and duration of waterlogging following surface irrigation have been observed between major soil types (North *et al.*, 2010). Consequently, it is not clear whether current recommended maximum OTs for surface irrigation systems in southern NSW are appropriate or applicable to all soils.

The objective of this project was to obtain data to make soil specific recommendations regarding maximum OTs for surface irrigation systems in southern NSW. To achieve this, three main questions were asked:

1. The duration of waterlogging (i.e. soil saturation) resulting from surface irrigation is assumed equal to the OT plus the time ($T_d$) for the surface soil to dry/drain to the point where air can re-enter the soil. $T_d$ is unknown. What are typical values for $T_d$ following surface irrigation?
2. How long can surface irrigated soils in southern NSW be waterlogged before productivity falls? This is a design question. Wheat was selected as the design (most representative) crop and irrigation at ear emergence as the design event because it is the event that poses the greatest risk to productivity.
3. Soils can become anoxic when saturated and anoxia can reduce plant growth. However, the severity of a waterlogging event may not equate to the duration of soil saturation. Saturation is indicated by soil matric potential ($\Psi_m$) and anoxia in soils is indicated by a redox potential ($E_h$) < 350 mV (Setter and Waters, 2003). What is the relationship between $\Psi_m$ and $E_h$ across representative soil types?

The literature raised questions about differences between duplex soils and uniform heavy clays. In southern NSW, these soil groups comprise mainly red chromosols and grey vertosols (Isbell 1996) respectively.

# Methods

## *Question 1 – time to dry and drain to air entry following surface irrigation ($T_d$)*

Measurements of surface soil (1-6 cm) matric potential ($\Psi_m$) and ponded water depth were made at 11 sites during and after 15 spring irrigation events between 2007 and 2009 to assess the duration of soil saturation from single irrigation events. For the purposes of estimating $T_d$, it was assumed that the soils were no longer saturated and that air could enter the soils when $\Psi_m$ dropped to -10 kPa. Watermark™ sensors and Odyssey™ loggers were installed in pairs at six locations in an 8 m by 16 m area at each site prior to the measured irrigations in order to measure $\Psi_m$ and ponded water depth respectively.

## *Question 2 – affect of waterlogging duration on wheat growth at ear emergence*

To answer this question and determine the influence of soil type and temperature, the following treatments were applied to wheat (var. Livingstone) grown in pots in the glasshouse at Deniliquin:

1. five waterlogging durations: 3, 6, 9, 12 and 15 days of ponding, each with an unwaterlogged control;
2. topsoil from 2 soils: a Cobram loam (red chromosol) and a Wandook clay (sodic grey vertosol);
3. two soil/water temperatures during ponding: 17$^o$C (cool) and 26$^o$C (hot).

The soils (Table 1) were packed into 4 litre pots at densities of 1.45 and 1.28 g/cm$^3$ for the Cobram loam and the Wandook clay respectively (to match field dry bulk densities), sown on 30$^{th}$ June 2008, and thinned to 5 plants per pot. Treatment pots were put in tubs on 13$^{th}$ Sept when the wheat had reached full head and submerged so water covered the soil. Growth (dry shoot biomass and leaf area) of waterlogged plants was compared to the growth of plants in well watered control pots over 15 days, with the severity of waterlogging assessed using $E_h$ measured in the centre of the pots. The trial was a split-plot design with 3 replicates.

*Question 3 – relationship between $\Psi_m$ - $E_h$*

Six pairs of $\Psi_m$ (Watermark™) and $E_h$ (Hanna ORP 3214 P) sensors were monitored during and after irrigation or heavy rainfall events in the surface (1-6 cm) of 6 soils considered to be representative of the range of surface irrigated soils in southern NSW. The results of physical and chemical analyses conducted at NSW DPI laboratories on the surface 0-7.5 cm of these soils is shown in Table 1.

**Table 1. Properties of the surface soil (0-7.5 cm) at the six $\Psi_m$ - $E_h$ study sites (# I. Hume, unpublished data).**

| Local soil name (Smith, 1945) | Cobram loam | Wandook clay | Birganbigil loam | Wunnamurra clay | Neimur clay | Riverina clay |
|---|---|---|---|---|---|---|
| Soil type (Isbell, 1996) | Red chromosol | Sodic, massive grey vertosol | Red chromosol | Self mulching, grey vertosol | Massive grey vertosol | Sodic, massive grey vertosol |
| Clay (< 2 μm) % | 23 # | 31 # | 27 | 26 | 29 | 19 |
| Silt (2–20 μm) % | 26 # | 21 # | 32 | 34 | 37 | 31 |
| Fine Sand % | 34 # | 37 # | 28 | 30 | 29 | 39 |
| Coarse sand % | 17 # | 8 # | 13 | 10 | 5 | 11 |
| EC(1:5) dS/m | 0.24 | 0.44 | 0.05 | 0.08 | 0.11 | 0.2 |
| pH (water) | 6.2 | 5.1 | 6.4 | 6 | 7.4 | 6.1 |
| Org C % | 1.0 | 1.8 | 1.4 | 1.8 | 1.8 | 1.8 |
| CEC cmol(+)/kg | 9 | 14 | 15 | 16 | 28 | 14 |
| ESP | 0.8 | 6 | 3.3 | 2.4 | 4.8 | 12 |

# Results

## *Question 1 - time to dry and drain to air entry following surface irrigation ($T_d$)*

Assuming an air entry potential ($\Psi_{ae}$) of -10 kPa, the average value of $T_d$ in spring in southern NSW following 15 surface irrigation events across 11 sites was found to be 71 hours. There was considerable variability in $T_d$ (CV = 46%) because of differences in crop cover, internal soil drainage, and prevailing weather. Some of this variability was reduced by equating duration with potential crop evapotranspiration ($ET_o$) during the period of waterlogging (i.e. mm rather than hours). When this was done, two sites stood out as taking nearly twice as long to drain to -10kPa as it took the other sites: 21 mm for the Wunnamurra and Riverina clays compared to an average of 12 ± 2 mm (CV = 26%) for the rest.

## *Question 2 – affect of waterlogging duration on wheat growth at ear emergence*

There was a significant difference in dry shoot biomass between the treatment and control plants in the Cobram loam-26°C pots after day 6, in the Wandook clay-26°C by day 9, and in the pots in both the 17°C treatments by day 12, which suggests that both soil type and temperature affected wheat growth. However, it is considered that neither of these treatments affected growth directly. Instead, soil type (presumably through soil porosity) and temperature (presumably through diffusion and respiration rates) affected the level of gaseous $O_2$ in the soil and it was this that affected wheat growth (assuming $E_h$ is a good indicator of soil $O_2$ and that $E_h$ < 350 mV indicates anoxic soil conditions: Setter and Waters, 2003). This is seen in the lack of significant difference between soil type and temperature treatments in the relationship between the relative change in shoot biomass of the waterlogged plants and the cumulative time $E_h$ < 350 mV (Figure 1).

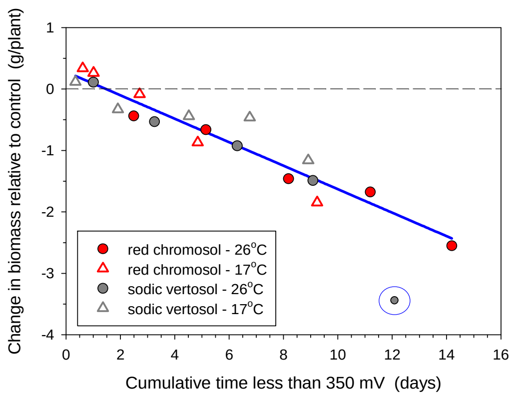


**Figure 1. The effect of anoxia ($E_h$ < 350 mV) on wheat (var. Livingstone) shoot biomass at anthesis. The line of best fit through all points is: *change in biomass = 0.28 – 0.19 × days soil < 350 mV* ($R^2$ = 0.92, se = 0.23, P < 0.001) where the *change in biomass* is that of waterlogged plants relative to a well watered, non-waterlogged control. The circled point was not included in the regression as all plants in this treatment had died by day 15.**

*Question 3 – relationship between $\Psi_m$ - $E_h$*

There was a general trend in all soils for $E_h$ to decrease whilst the soil was saturated and then to increase as the soil became drier than the $\Psi_{ae}$. If drying persisted, $E_h$ continued to increase and then stabilise at around 600 mV. If soils became saturated once again, $E_h$ would again decrease (Figure 2 shows examples). There were differences between the soils in the initial $E_h$ prior to irrigation (lower in the Riverina clay); the rate at which $E_h$ fell when the soil became saturated (twice as fast in the sodic Wandook and Riverina clays); the $\Psi_m$ at which $E_h$ began to increase following drying/draining ($E_h$ increased shortly after surface water drained in the light textured Cobram loam and not until $\Psi_m$ < -20 kPa in the heavy textured Niemur clay); and the rate of increase in $E_h$ upon drying (three times faster in the duplex soils (chromosols) than in the uniform clays (vertosols)). Only in the two sodic soils did $E_h$ dropped below 350 mV. In the Riverina clay, the duration of anoxia was at least 12 days (and possibly 14 days) following 12 hours of ponding.

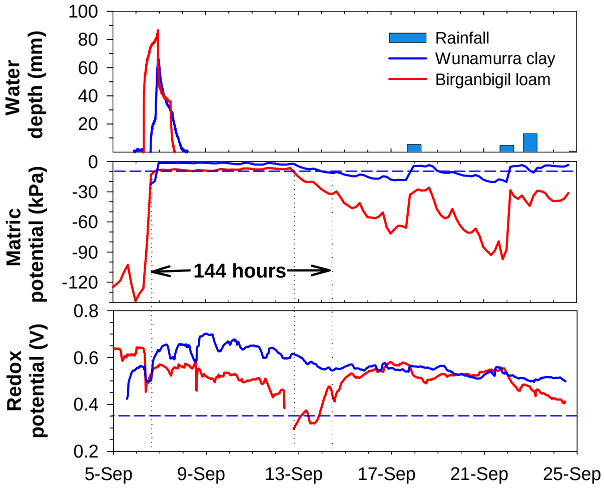


**Figure 2. Ponded water depth and rainfall (top); surface soil (1-6 cm) matric potential (middle); and redox potential at 5 cm in the Wunnamurra clay and Birganbigil loam in 2009. The dashed blue lines indicate (middle) field capacity and (bottom) $E_h$ at which soil $O_2$ is depleted (<350 mV). .**

## Discussion

Assuming a plant density of 200 plants/m$^2$ (Giblin & Lacy 2003) and a harvest index of 0.35 to 0.4, the reduction in wheat shoot growth of 0.19 g/plant per day $E_h$ < 350 mV (Figure 1) equates to a grain loss of 63-72 kg/ha per day that $E_h$ < 350 mV and the soil is presumably anoxic. This is similar to the grain loss of 69 kg/ha per day found at Griffith, NSW (Melhuish *et al.*, 1991). Other studies at Griffith (e.g. Meyer *et al.*, 1985) showed that soils with the poorest $O_2$ status throughout the season had the lowest grain yields and it was concluded this was caused by the cumulative effect of repeat flooding events. This study shows that once surface irrigation (or heavy rain) saturates the soil, $O_2$ levels begin to fall (as indicated by $E_h$). This continues until the soil dries to $\Psi_{ae}$ and gas exchange can occur and allow soil $O_2$ to rise. If another irrigation (or rain) occurs before soil $O_2$ has fully recovered, then $O_2$ levels will fall below the levels reached after the first event and it will take longer for $O_2$ to recover to initial levels. A progressive reduction in soil $O_2$ thus occurs (Fig. 2) and the cumulative effect of successive periods of anoxia is to reduce crop growth (Fig. 1).

Whilst this is only a limited sample, there did appear to be strong soil type effects and these effects generally accord with other studies (e.g. Setter & Waters, 2003). The Riverina clay had low $E_h$ prior to irrigation and this is attributed to high bulk density (data not presented), fine texture and sodicity (Table 1). The rate of decline in $E_h$ when the Riverina and Wandook clays were watered was roughly twice that in the other soils and this is attributed to sodicity, dispersion and swelling. The rate of increase in $E_h$ in the chromosols was 3 times that in the vertosols and this is attributed to coarser texture and a greater proportion of macropores.

The greatest risk to winter crops from waterlogging following surface irrigation in southern NSW is on clay soils in late September, early October when the crop is sensitive (anthesis), drying rates are slow, soils are moist, and the probability of rain is high. This is our design event for minimising risk from long opportunity times. Modelling the generalised response of $E_h$ to surface irrigation in these soils (rates of decline in $E_h$ with irrigation and of increase when $\Psi_m$ < -10 kPa of 0.9 mV/hr; 36 hrs of $E_h$<350 mV before wheat growth is reduced; 61 hrs to dry to $\Psi_{ae}$ after surface drainage is complete) and assuming a low $E_h$ of 400 mV prior to the design event allowed a design maximum OT of 10 hours to be calculated. For sodic soils, using 82 hrs as the time to dry to $\Psi_{ae}$ and 1.6 mV/hr as the rate of decline in $E_h$ resulted in a calculated negative opportunity time, indicating that reduced crop growth is inevitable if aeration is low prior to irrigation. Using a higher initial $E_h$ in the model (> 480 mV) showed crop damage could be avoided in these soils.

## Conclusion

The experiments conducted for this study have shown there is:

- a strong correlation between wheat growth at anthesis and redox potential ($E_h$) when $E_h$ < 350 mV.
- an explicable relationship between $E_h$ and matric potential ($\Psi_m$) in surface soils.

- a strong soil type effect on the duration of waterlogging stress following surface irrigation.

A maximum OT of 10 hours was determined as suitable for most heavy textured soils. The exception was sodic vertosols, where surface irrigation is likely to result in waterlogging stress in wheat no matter how short the OT. Investment in capital intensive irrigation systems is not recommended on these soils without co-investment in soil management and both should be in accordance with expected returns.

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