The Effect of Irrigation Schedules on Water Table Depth and Root Zone Soil Moisture

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EXTENDED ABSTRACT

Indiscriminate use of irrigation water, particularly in existing areas of shallow water table, can result in further water table rise leading to water logging and secondary salinity problems. Hence, it is essential that irrigators have a clear understanding of how their often ad-hoc irrigation scheduling practices impact on both the local water table level and on-farm soil moisture content, which influences crop yield, a primary motivator of irrigators.

We have studied the impact of irrigation scheduling on both water table rise and root zone soil moisture content in a desk-top study. A Richards' equation based soil moisture model has been used to study the effect of flood irrigation frequency and duration of inundation on the water table depth and root zone soil moisture content. While the study was not intended to represent a specific study site, the results should be applicable to typical flood irrigation regions in semi arid regions having a shallow water table depth, such as that in south-eastern Australia.

Using a series of simulations, we explored the effect of altering time between flood irrigation events from 5 to 20 days, and duration of flood irrigation events from 1 to 6 hours. The initial water table level, soil type and climatic data used for the simulations are typical of semi-arid south-eastern Australia. Therefore, the results should provide at least a qualitative indication of relative effects of different irrigation scenarios on water table depth and root zone soil moisture.

This study shows that the time interval between flood irrigation events has a more significant impact on the depth to water table than the duration of inundation. In order to control or limit future water table rise, the interval between irrigation events should be sufficiently far apart; at least 14 days in our situation. This is almost a 50% increase in the time between irrigation events as compared to typical practice being 4 hours every 10 days. Moreover, an inundation period of 2 hours was found to be sufficient to mitigate any undue water stress on the crops. This is a further water saving with a 50% decrease in the inundation duration. Hence a 2 hour flood irrigation event once every 14 days during the irrigation season was found to be more sustainable than the current practice.

This study indicates that in addition to improved irrigation techniques, the key to avoiding water table rise is improved efficiency in scheduling irrigation to meet as precisely as possible the water needs of the crop, rather than applying irrigation water in a more ad-hoc approach.

1. INTRODUCTION

Irrigation water is used to maximise crop yield by minimising water stress in the root zone. However, this is often done in an ad-hoc manner. Indiscriminate use of irrigation water has led to problems of rising water tables causing widespread land degradation (Schofield et al., 1989; Anderson et al., 1993). Thus in areas where the water table is rather shallow (less than 2m), the most significant problem facing irrigators has become not how much water is available or used, but the long term impact this has on the agricultural productivity of the area, and the environmental impact in general. Recent estimates indicate that one-half of the existing irrigation areas around the world have shallow water tables, and require careful irrigation management practices to prevent water-logging and secondary salinisation (Pratharpar et al., 1996).

The predominant cause of waterlogging and salinisation is an increase in recharge to the water table, which occurs when excess water infiltrates past the root zone of the plant. The high rate of water table recharge is exacerbated when irrigation application rates exceed the consumptive use of plants. Smith (1998) suggests that the irrigation application efficiency for Australia is likely to be only 60 percent, with flood irrigation as low as 40 percent.

High water table levels have the same effect as water-logging, with the added problem of salinity when the ground water is saline. Water-logging and salinity are a potentially serious problems for the agricultural industry, because of the significant negative impact on crop yield and long-term impact on agricultural productivity; they can reduce the potential yield by as much as 30-80 percent for many crops and pastures in the greater than 400 mm rainfall zone (McFarlane and Williamson, 2002).

Several researchers have studied solutions related to waterlogging and secondary salinisation problems in shallow water table areas. For example, a Soil, WAter and Groundwater SIMulation model (SWAGSIM) has been developed by Prathapar et al. (1996) to facilitate evaluation of shallow water table management options in south-eastern Australia; Pavelic et al. (1997) have used an integrated modeling approach to explore a range of land management options to control salinity in a 105-km^2 site on a coastal plain in southern Australia; Silberstein et al. (1999) have studied the growth and hydrologic impact of a small 21-year old plantation growing over a shallow saline water table in south-eastern Australia by using the TOPOG-Dynamic simulation model; and Silberstein et al. (2002) have used a steady state hydrological model to study the occurrence of seasonal water logging across a 639 ha catchment in south-western Australia. It was found that there are some solutions could reduce both rates of groundwater recharge and the area of salinised land such as a plantation rotation (Silberstein et al., 1999), the establishment of deep-rooted trees (Silberstein et al. 2002, Pavelic et al., 1997) or use of shallow groundwater pumps (Prathapar et al., 1996). However, the cost of revegetation for reclaiming salinised land is high.

While there are several studies that look at solutions to salinity and water-logging problems associated with shallow water tables, no studies addressing the impact of timing between irrigation events and length of inundation on water table levels have been found. The identification of appropriate irrigation schedules to limit, and even reverse, the rise in water table level can have a significant impact on land and water management of shallow water table areas. While ceasing or significantly limiting irrigation will no doubt be the best environmental solution, this would in most instances render the land agriculturally unviable. As such, any recommendation on irrigation scheduling must also address the likely impact on root zone soil moisture content and its effect on crop yield.

In this research, a soil moisture model has been used to simulate the depth to water table and average root zone soil moisture content in response to different irrigation schedules for a typical flood irrigation district in south-eastern Australia. The changes in water table depth and associated root zone soil moisture content have been analysed for a range of irrigation scenarios, including no irrigation, and an appropriate schedule recommended.

2. MODELS

In order to study the response of root zone soil moisture content and water table depth to the interval between and duration of flood irrigation events, the movement of soil moisture through the unsaturated zone and recharge to a local water table must be simulated. This is because the logistical constraints and potential environmental impacts associated with field-based studies, and time requirements to undertake such studies, would be untenable.

The simplest approach to water balance modeling is to use a lumped soil moisture model of the unsaturated zone. Current practice of simulating the unsaturated zone is mostly based upon this type of approach (Sarma and Mani, 1992; Rogério and Chandra, 1996). In principle, this method involves a simple book keeping of various mass balance components of the unsaturated zone (infiltration, evapotranspiration, change in water storage and recharge to the water table). Usually only the water movement in the root zone is modeled, with the rest of the unsaturated zone assumed to be at field capacity. The infiltration is determined after deducting the runoff from rainfall and applied irrigation. The excess infiltration (above field capacity and after accounting for actual evapotranspiration) is assumed to be available as recharge.

An alternate approach to simulation of soil moisture in the unsaturated zone and recharge to the water table is based on the theory of Philip and de Vries (1957). With the recent advances in computing power this has become one of the most widely used modeling tools to date (Milly, 1982; Silberstein et al, 1999; Dam and Feddes, 2000). Under the assumptions of negligible vapour flux and isothermal conditions, the unsaturated flow equations of Philip and de Vries (1957) simplify to the well-known Richards' equation:

$$\frac{\partial \theta}{\partial t} = \nabla\left[\frac{K_\theta}{C_\theta}\nabla\theta + K_\theta\right] \tag{1}$$

where θ is volumetric soil moisture content, C_θ is soil capillary capacity factor ($C_\theta = \partial\theta / \partial\psi$), ψ is the matric potential and K_θ is the isothermal moisture conductivity.

This study used an implicit finite difference approximation to the one-dimensional θ-based Richards' equation to simulate soil moisture content and depth to the water table at the point of application. The input data of the model include i) soil properties such as volumetric porosity, saturated hydraulic conductivity, saturated matric potential, residual volumetric soil moisture fraction, Brooks and Corey parameters for the soil-water characteristic curve and unsaturated hydraulic conductivity relationship, ii) meteorology data such as precipitation, potential (or actual) evapo-transpiration, and iii) timing and duration of irrigation events.

Three key simplifying assumptions have been made in the application of this model. First, we have assumed there are no lateral flows by using a one dimensional soil moisture model. This assumption is appropriate because the topography of flood irrigation areas is typically quite flat and flood irrigation is applied uniformly across reasonably large expanses of land. The second assumption is that there is no water flow across the bottom boundary of the soil column. As we modeled to a depth of 4 m, and the initial water table depth was taken to be at 1 m depth (typical of many irrigation districts in south-eastern Australia), this assumption was not considered to have any major impact on our results. The final assumption was uniform soil properties throughout the soil column. The major impact of this assumption on the results would be through changes in hydraulic conductivity and soil porosity with depth. However, the deep soils in south-eastern Australia and the shallow water table depth means that the active zone is limited to the top 1 m or so, a zone of slowly varying soil type. Hence this assumption is not likely to have a significant impact on the results provided the dominant soil type has been correctly identified. Moreover, given that this study is largely synthetic in nature, correct specification of soil type is not a major consideration.

3. NUMERICAL EXPERIMENTS

A set of numerical experiments have been undertaken to explore the effect of irrigation frequency and duration on both the depth to water table and soil moisture content in the root zone. While this study is not intended to represent a specific study site, we have used typical soil properties, water table depth, meteorological data and irrigation application for a typical irrigation district of northern Victoria (south-eastern Australia), in order to represent some realism.

The topography in the region is very gently sloping to level, with approximately 60 percent of the agricultural land in the district irrigated (mainly pasture for dairying) and the remainder used for dryland grazing. The irrigation season is from 15 August to 15 May, and the typical irrigation method is flood irrigation with 4 hours of inundation every 10 days. The water table depth in the region has been rising at a rate of around 0.2m/year over the past 20 years and is currently between 0 and 3m below the soil surface, with a typical value of around 1m (Department of Natural Resources and Environment, 2002).

The dominant crops in this region are perennial pasture (lucerne) and annual pasture (white clover and ryegrass) which have an active root depth of approximately 0.5m, while the main soil types are loam and sandy loam. Because of a lack in specific data on soil hydrologic properties and the generic nature of this study, we adopted the typical Brooks and Corey parameters for a loam soil from Rawls et al (1982); volumetric porosity 0.463, saturated hydraulic conductivity 13.2 mm/h, saturated matric potential 40.12 cm and residual volumetric soil moisture 0.027.

Mean annual rainfall and class A pan evaporation for the region is 460 mm and 1600 mm respectively. The maximum mean monthly rainfall occurs in May (48 mm), and the minimum occurs in February (25 mm), while the maximum mean monthly pan evapotranspiration occurs in January (264 mm) and the minimum occurs in June (35 mm). Mean summer maximum and minimum temperatures are 32^{o}C and 15^{o}C respectively, and mean winter maximum and minimum temperatures are 14^{o}C and 3.2^{o}C respectively (Bureau of Meteorology, 1988). Meteorological data used in our simulations were obtained from a local climate station for the year 1996. The simulation model used Penman-Monteith potential evapotranspiration, factored by a soil moisture stress index, in order to estimate actual evapotranspiration.

Based on the current water table situation of this area, the initial water table depth was assumed equal to 1 m. The initial soil moisture content of the top layer was set to 30 % v/v and increased linearly with depth to a saturated soil moisture content at the water table. Using the data described above and an irrigation interval of 10 days with a 4 hour inundation period, the simulated seasonal variation in water table depth was found to have good agreement with the observed water table fluctuation at a bore in the region.

In this study, soil moisture profiles and water table depth have been simulated for 2 years under a range of irrigation scheduling options, with the same meteorological data used for both years of simulation. This allowed for spin-up effects associated with the assumed initial conditions to be mitigated. The simulations assumed that availability of irrigation water was unlimited. Several irrigation scenarios were established, with irrigation frequency ranging from 5 to 20 days and inundation ranging from 1 to 6 hours including the typical irrigation of frequency and inundation of 10 days and 4 hours respectively. A simulation scenario with no irrigation was also made. No irrigation water was applied from 15 May until 15 August in any of the simulations.

4. RESULTS AND DISCUSSION

The simulation model has been used to predict the sensitivity of water table depth and root zone (top 0.5 m) soil moisture content for the case of no irrigation and the 15 irrigation scenarios described in Table 1. Comparison is made with results from the typical (4 hours every 10 days) irrigation schedule as the control. Average monthly water table depth and root zone soil moisture content have been used in the analysis as we are more interested in the longer term impacts than short term fluctuations due to rainfall and irrigation events. However, as crop response to soil moisture content may be more sensitive to short periods of low soil moisture content, we include an assessment of minimum monthly soil moisture content in our analysis.

Table 1 summarises the water table depth results for the second year of simulation for each scenario tested while Table 2 summarises the minimum monthly root zone soil moisture results in order to check the possibilities of crop water stress. Figures 1 and 2 show the average monthly water table depth and root zone soil moisture content respectively for some of the key scenarios tested.

The purpose of irrigation is to supply water to eliminate crop water stress in the root zone and maximise crop yield. The crop water stress point is the limit of soil moisture content at which the water in the soil ceases to become readily available to the roots for photosynthesis. If the amount of soil moisture content in the root zone falls below this point then the crop growth will be reduced due to lack of freely available water.

In the case of no irrigation, the water table depth draws down significantly during the first few months and becomes stable at a depth of around 3 m during the second year. However, the soil moisture content in the root zone is below (about 10%) the crop water stress limit of about 30% (Wood et al., 2002). This reinforces the point that this area requires regular irrigation for agricultural production.

The results in Table 1 indicate that the depth to water table varies considerably for different irrigation intervals. It can be seen that the shorter the irrigation interval the greater the rise in water table level. However, even with a short irrigation duration (1 hour) the water table still continues to rise above that for the control for intervals of 5 and 7 days. This indicates that these intervals are not appropriate in term of control of a rise in the water table.

Table 1: Monthly average water table depth (cm) of different irrigation scenarios

Irrigation Scenarios	Jan.	Feb.	Mar.	April	May	June	July	Aug.	Sep.	Oct.	Nov.	Dec.	Average
2h/5days	**46.4**	43.5	41.2	33.4	40.6	48.5	**28.9**	30.7	33.0	39.9	45.3	45.3	39.7
1h/5days	45.4	43.5	41.5	33.6	37.2	43.5	**28.9**	32.1	33.3	40.2	45.9	**46.0**	39.3
2h/7days	**52.2**	47.5	42.9	34.7	42.2	47.0	**28.9**	32.9	37.4	44.3	47.2	49.8	42.2
1h/7days	**59.3**	50.0	42.8	34.8	49.7	61.6	**28.9**	33.1	37.3	44.8	48.3	52.8	45.3
6h/10days	**63.3**	58.5	48.3	39.4	41.1	48.5	**28.9**	32.8	39.3	46.7	55.5	54.9	46.4
4h/10days*	**64.1**	59.3	49.7	39.8	41.3	48.5	**28.9**	33.0	39.5	47.1	55.7	55.9	46.9
2h/10days	**61.6**	60.1	50.7	40.3	41.4	48.5	**28.9**	33.2	40.6	47.9	56.1	56.8	47.2
1h/10days	**76.6**	66.9	50.6	40.5	41.4	48.5	**28.9**	33.3	40.8	52.6	57.9	61.8	50.0
6h/14days	**70.4**	65.8	50.4	41.8	54.8	61.0	**28.9**	33.0	46.9	51.3	66.3	63.8	52.9
4h/14days	**70.5**	66.5	50.9	42.3	55.8	61.7	**28.9**	33.1	47.0	51.8	66.1	64.4	53.3
2h/14days	**71.9**	68.8	51.3	42.7	56.5	61.7	**28.9**	33.2	47.4	53.9	68.2	67.4	54.3
1h/14days	**114.9**	110.9	97.8	69.7	56.7	61.6	**28.9**	33.3	47.0	56.0	78.6	91.4	70.6
6h/20days	**84.4**	82.6	67.0	57.0	50.9	64.0	**28.9**	33.9	40.1	56.7	73.1	80.9	60.0
4h/20days	**85.1**	82.4	69.6	57.3	51.1	64.0	**28.9**	33.9	40.3	57.3	73.5	82.0	60.4
1h/20days	111.7	121.2	**124.3**	99.1	72.4	82.5	39.7	**34.0**	41.5	59.8	85.5	111.5	81.9
No irrigation	310.0	**305.5**	321.5	328.8	329.4	330.0	327.2	339.9	**353.2**	344.6	349.7	343.0	331.9

Note: * indicates typical irrigation schedule; bold numbers indicate the maximum and minimum values.

Table 2: Monthly minimum soil moisture content (% v/v) in the rootzone (top 0.5m) of different irrigation scenarios

Irrigation Scenarios	Jan.	Feb.	Mar.	April	May	June	July	Aug.	Sep.	Oct.	Nov.	Dec.
2h/5days	40.00	39.70	40.30	41.70	40.10	39.80	43.10	42.20	41.90	40.50	40.00	36.10
1h/5days	39.17	39.62	40.28	41.69	40.92	40.50	43.13	42.03	41.84	40.44	39.97	39.56
2h/7days	38.70	38.20	40.00	41.40	40.50	40.10	43.10	42.00	41.60	39.20	38.40	38.40
1h/7days	36.92	38.19	39.99	41.34	39.03	38.67	43.13	42.03	41.57	39.15	38.33	38.16
6h/10days	36.00	36.30	38.90	39.60	40.00	39.80	43.10	42.00	40.30	37.80	37.50	37.10
4h/10days*	35.90	36.20	38.70	39.50	40.00	39.80	43.10	42.00	40.20	37.60	37.50	37.00
2h/10days	35.80	36.20	38.60	39.50	39.90	39.80	43.10	42.00	40.20	37.60	37.40	36.90
1h/10days	33.80	34.70	38.60	39.40	39.90	39.80	43.10	42.00	40.10	37.20	36.20	36.90
6h/14days	33.80	34.20	37.20	39.70	39.10	38.80	43.10	42.00	39.60	35.50	36.10	35.00
4h/14days	34.80	34.10	37.20	39.60	39.10	38.70	43.10	42.00	39.60	35.40	36.10	34.90
2h/14days	33.20	34.00	37.20	39.60	39.00	38.70	43.10	42.00	39.60	35.40	35.50	34.80
1h/14days	**28.42**	**28.29**	31.45	35.49	39.03	38.67	43.13	42.03	39.58	35.32	34.57	31.79
6h/20days	**28.79**	32.92	33.24	37.35	38.64	38.56	43.13	42.03	39.95	34.22	32.69	32.22
4h/20days	**29.55**	32.84	33.14	37.27	38.64	38.56	43.13	42.03	39.95	34.13	32.61	32.13
1h/20days	**27.11**	**25.95**	**25.22**	32.93	34.43	36.79	40.53	42.03	39.91	33.74	32.23	**27.26**
No irrigation	**9.95**	**10.08**	**9.97**	**9.87**	**10.01**	**9.93**	**9.80**	**9.91**	**9.88**	**9.66**	**9.82**	**9.68**

Note: * indicates typical irrigation schedule; bold numbers indicate the soil moisture content below the crop water stress limit.

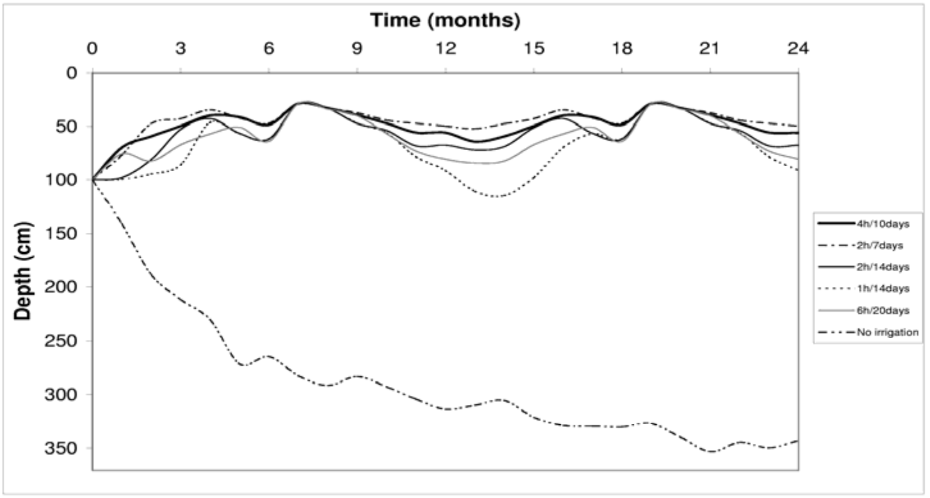

Figure 1: Monthly average water table depth for some typical irrigation scenarios**.**

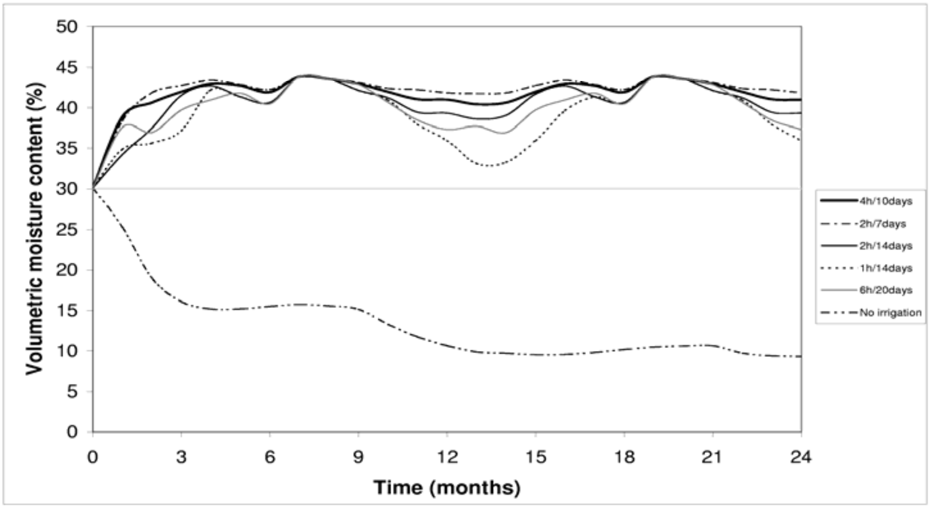

Figure 2: Monthly average volumetric soil moisture content in the root zone (top 0.5m) for some typical irrigation scenarios. The horizontal line shows the soil moisture limit in order to mitigate crop stress.

Although the average monthly soil moisture content in the root zone of every irrigation scenario is greater than the crop water stress level in Figure 2, Table 2 shows the minimum soil moisture for the month does not satisfy the crop water requirements for some irrigation schedules. These include the scenario of 14 day interval and 1 hour duration and all scenarios of 20 days interval. Although this latter interval can lower the water table level considerably (see Table 1), this interval is too long even with the case of 6 hours irrigation duration, because there is a period in which the soil moisture content in the root zone falls below the limit of crop water stress. For all the other irrigation intervals with irrigation durations from 2 to 6 hours, the soil moisture contents in the root zone satisfy the plant requirements.

For the purpose of crop water supply to eliminate the crop water stress in the root zone, and control or limit rise in the water table, the results show that the most appropriate irrigation schedule in the region is one irrigation every 14 days for 2 hours.

5. CONLUSIONS

A Richards' equation based soil moisture model has been used to study the effect of frequency and duration of flood irrigation on the water table and root zone soil moisture content. While the study was not intended to represent a specific study site, the results should be applicable to typical flood irrigation regions of south eastern Australia and provide a qualitative indication of relative effects of different irrigation scenarios on water table depth and root zone soil moisture.

The study shows that the time interval between flood irrigation events has a more significant impact on the depth to water table than the duration of inundation. In order to control or limit future water table rise, the interval between irrigation events should be sufficiently far apart and the inundation duration should be decreased; 14 days and 2hrs respectively in this application.

The key to avoiding water table rise is improved efficiency in both irrigation techniques and scheduling to meet as precisely as possible the needs of the crop. This can be improved by frequently monitoring soil moisture content, and/or applying numerical models to predict soil moisture content with observed meteorology data, soil, crop and irrigation information.

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