CHAPTER 7

GROWTH AND YIELD RESPONSE OF ONIONS (*ALLIUM CEPA* L.) TO WATER STRESS AT DIFFERENT GROWTH STAGES

7.1 Introduction

Onions are a shallow rooted crop that is sensitive to water stress conditions. The root depth of most onion cultivars extend down to 0.7 m soil depth. Most water and nutrient uptake occurs from the top 0.3 m of soil (Drinkwater & Janes, 1955; Voss & Mayberry, 1997). Onions, therefore, require frequent light irrigations throughout the season.

To achieve large bulb size and high bulb mass, water deficits should be avoided, especially during the yield formation period (bulb enlargement) (Kadayifci *et al.,* 2005). Nevertheless, crop cultivars vary widely in water use, mainly during times of water shortage. Some cultivars close their stomata to reduce transpiration during soil water deficit, which in most cases is associated with yield reduction. Stomatal closure limits the mass of CO_2 that enters stomata, which further limits photosynthesis and, therefore, also limits dry matter production (Al-Jamal *et al.,* 2000). Dry matter production of a crop depends on water uptake and its water use efficiency (Black & Ong, 2000).

Previous researchers (Shock *et al.*, 2004) have demonstrated the sensitivity of onions to small water deficits and the need to maintain high soil water potential for optimum yield and economic return. If water is withheld, young plants continue to grow until all available soil water within reach of the shallow root system is fully depleted. When this happens, the root hairs begin to die, the plants respond by wilting and, if drought conditions persist, the plants cease to grow. Absorption of soil water and nutrients for plant growth takes place through the outermost cells of the root hairs. Therefore, water stressed plants have to re-establish functioning root hairs before normal growth can resume. Onions show little capacity for reducing leaf water potential by osmotic adjustment to compensate for reduced water availability. Stressed onions usually result in stunted growth and bulb doubling or splitting and are usually higher in pungency (Voss & Mayberry, 1997).

There are four phenological growth stages in onions: from sowing to transplanting, the vegetative stage, yield formation or bulb enlargement, and the ripening or bulb maturity period that makes a total growth period of 130-175 days, depending on cultivar and climatic conditions (FAO, 2002). Knowledge of the crop growth phenology helps to save irrigation water under limited water supply conditions. Some researchers claim that small water savings can be made during the vegetative period, while others report towards the end of the ripening period, depending on the cultivar and soil water holding capacity (Kalb & Shanmugasundaram, 2001). Others report that bulb formation and enlargement periods are most sensitive to water stress (Singh & Alderfer, 1966). Onion plants stressed prior to bulb formation, result in reduced bulb sizes that are not acceptable for market grades. Those plants stressed after bulb formation are prone to re-growth problems, such as thick necks and scallions, which reduce marketable grade and increase storage problems (Casey & Garrison, 2003). In addition, internal bulb defects, such as multiple centres and translucent scales, can develop even after short duration stresses (Shock *et al.*, 1998; Shock *et al.*, 2004). This indicates that duration of water stress determines the degree of yield and grade loss. Singh and Alderfer (1966) observed that soil water stress at any growth stage leads to reduction in marketable yield at varying levels. They further observed that, with regard to yield reduction, onions are more sensitive to water stress during bulb enlargement than during the vegetative stage. On the other hand, Pelter *et al.*, (2004) reported that a three week stress at the early growth stage reduce onion yield more than when the same duration of stress is imposed at the end of the growing season. Further studies by Van Eeden and Myburgh (1971) revealed that stress imposed between 84-103 days after transplanting reduced total onion yield by 15%, compared to yield with no water stress. Van Eeden and Myburgh (1971) recommend that, when high yield of good quality is sought, it is advisable to irrigate onions before about half of the water in the root zone has been used. However, irrigation should be discontinued as the crop approaches maturity to allow tops to desiccate and to prevent a second flush of root growth. For a seed crop, however, the flowering period is very sensitive to water deficit (Kalb & Shanmugasundaram, 2001), while, during the vegetative growth period, the crop appears to be relatively less sensitive. In general, for high yield of good quality, the crop needs a controlled and frequent supply of water throughout the growing period, while over-irrigation leads to reduced growth (Ehler, 2005). The objective of this experiment, therefore, was to determine the critical growth stage of onions (cv. Texas Grano) to water stress applied at different growth stages and generate crop growth parameters for SWB modelling (the latter is dealt with in Chapter 8).

7.2 Materials and methods

The experiment was established at the Hatfield experimental station of the University of Pretoria in South Africa. The site is situated at 25^{o} 45' S and 28^{o} 16' E, at an altitude of 1 327 m. The area receives an average rainfall of 670 mm per annum, with the peak rainy season between October and March (Annandale et al., 1999). The soil was thoroughly prepared to ensure a suitable seedbed. Onion seedlings, cv. Texas Grano, of about 35 days old were planted on 15 May 2004. Plant spacing was 0.3 m between rows and 0.1 m between plants within rows. The experiment was arranged in a strip plot design with four replications. Other cultural practices were conducted according to the station's standard practices.

During transplanting, the crop received 47 kg ha^{-1} of N, 70 kg ha^{-1} of P and 47 kg ha^{-1} of K as a basal dressing. Top dressing of 43 kg ha^{-1} N, 20 kg ha^{-1} of P and 113 kg ha^{-1} of K was given 60 days after transplant (DATP), giving a total of 90 kg ha^{-1} nitrogen and phosphorus, and 160 kg ha^{-1} potassium.

Irrigation treatments applied were:

1. Replenishing the soil water deficit to field capacity after weekly neutron water meter measurements (NNN);
2. Stress during the vegetative growth stage, between 35-70 DATP (SNN), and replenishing soil water deficit to field capacity on a weekly basis for the rest of the growing season.
3. Stress during the bulb enlargement stage, between 70-110 DATP (NSN), and replenish soil water deficit to field capacity on a weekly basis for the rest of the growing season.
4. Stress during bulb maturity stage, between 110-145 DATP (NNS), and replenish soil water deficit to field capacity on a weekly basis for the rest of the growing season.

Where DATP denotes the days after transplant, N stands for non-stressed and S for stressed at a certain growth stage.

Soil water content (WC) was measured using a neutron water meter Model 503 DR CPN Hydroprobe (Campbell Pacific Nuclear, California, USA). The neutron water meter was calibrated for the site and weekly readings were taken before irrigation. Measurements were taken in the middle of each plot at 0.2 m depth increments, down to 0.8 m. Rainfall during the experimental period was recorded by a rain gauge installed at the weather station near the experimental field. Drip irrigation was used to irrigate each plot every week to refill the soil water content to field capacity, except for the stress treatment. The spacing between dripper lines was 0.5 m while the spacing between drippers in a line was 0.3 m. The drippers were pressure-compensated with a delivery rate of 2.2 l hr^{-1} at a pressure range of 100-150 kPa. Water use (ET) in mm and WUE (kg ha^{-1} mm^{-1}) were calculated using bulb yield at final harvest and the total seasonal irrigation water applied (mm) during the growing season. ET was calculated using eq 7.1, while eq 7.2 was used to calculate WUE.

$$ET\ (mm) = I + P - Dr - \Delta S - R \qquad (7.1)$$

Where

I = irrigation in mm, P = precipitation in mm, Dr = drainage in mm (assumed to be zero), ΔS = change in soil water storage in mm, and R = runoff in mm (assumed to be negligible)

$$WUE\ (kg\ ha^{-1}\ mm^{-1}) = BY/ET \qquad (7.2)$$

Where, BY = bulb yield in kg ha^{-1}

Fractional interception (FI) of PAR was measured every 14 days with a Decagon Sunfleck Ceptometer (Decagon, Pullman, Washington, USA), making one reference reading above and 10 readings beneath each canopy. Growth analyses were carried out every 14 days by harvesting above-ground plant material and bulbs from 1 m^2 of ground surface from each plot. Harvestable fresh mass was measured directly after sampling and dry mass of plant organs after drying it in an oven at 60°C for four to five days. Leaf area was measured destructively with an LI 3100 belt-driven leaf area meter (LiCor, Lincoln, Nebraska, USA) and LAI calculated from the data. Leaf area duration (LAD) is obtainable from LAI with respect to time or DATP, and expressed as:

$$LAD = ((LAI_2 + LAI_1)/2) * (t_2 - t_1) \quad (7.3)$$

LAD is expressed as $m^2\ m^{-2}$ days

Root depth was not measured during the growing season, but estimated from the depth of water extraction from the soil profile.

7.3 Results and discussion

Onions' critical growth stage to water stress was evaluated during the cool season of 2004, where stresses were applied at intervals of 35 days after which normal water management continued. The NNN treatment was not water stressed and used as a control for comparison. Results of the SWD indicated that, for the non-stressed treatment, the level of SWD between irrigation intervals of seven days remained less than 20 mm during the early growth period but increased to more than 40 mm during the later growth stages (Fig. 7.1). The low SWD at the beginning of the growth period was due to the cool time of the season with low daily ETo and low LAI. The first water stress was applied to SNN treatment for 35 days in the vegetative growth stage (Fig. 7.2). The cumulative SWD during this period was about 86 mm, after which normal irrigation was resumed until the final harvest. The next growth stage at which water stress was applied was the bulb enlargement stage, where irrigation was withheld between 70 and 110 DATP (Fig 7.3). During this stress period, cumulative SWD peaked at to more than 80 mm.

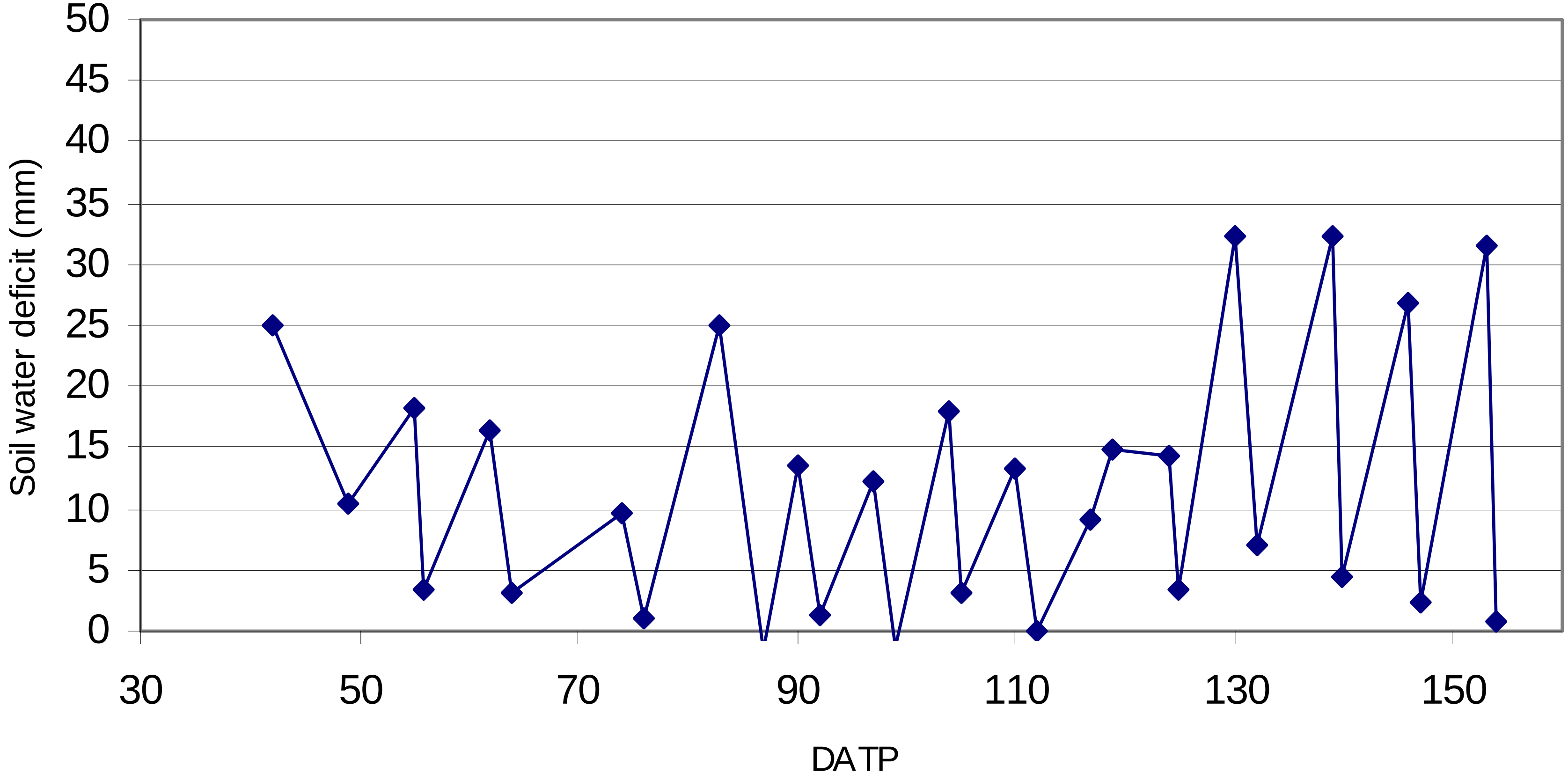

Figure 7.1 Soil water deficit (SWD) (mm) of onions, non-stressed treatment (NNN)

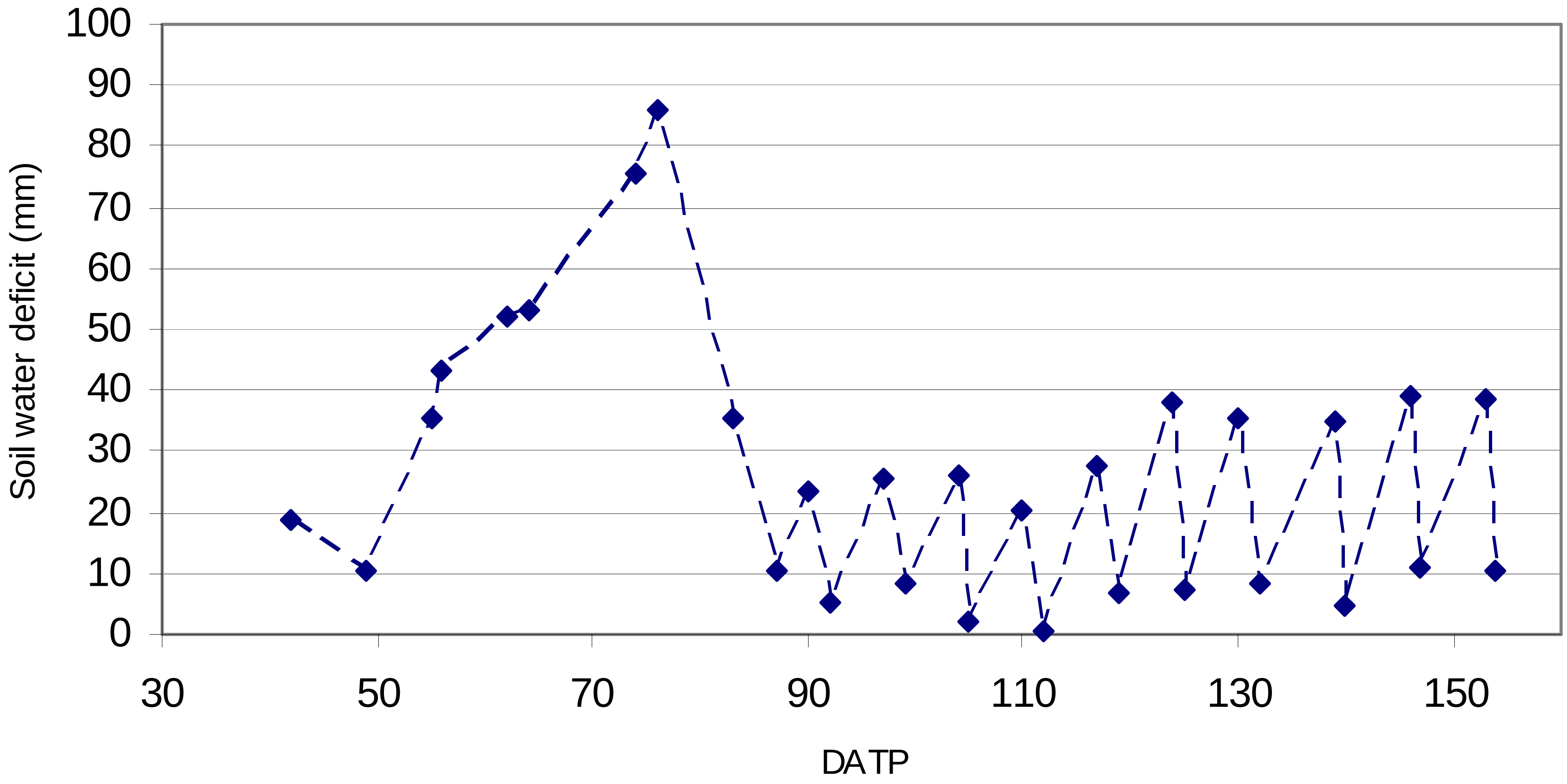

Figure 7.2 Soil water deficit (SWD) (mm) of onions, water stressed at vegetative growth stage (35-70 DATP) (SNN)

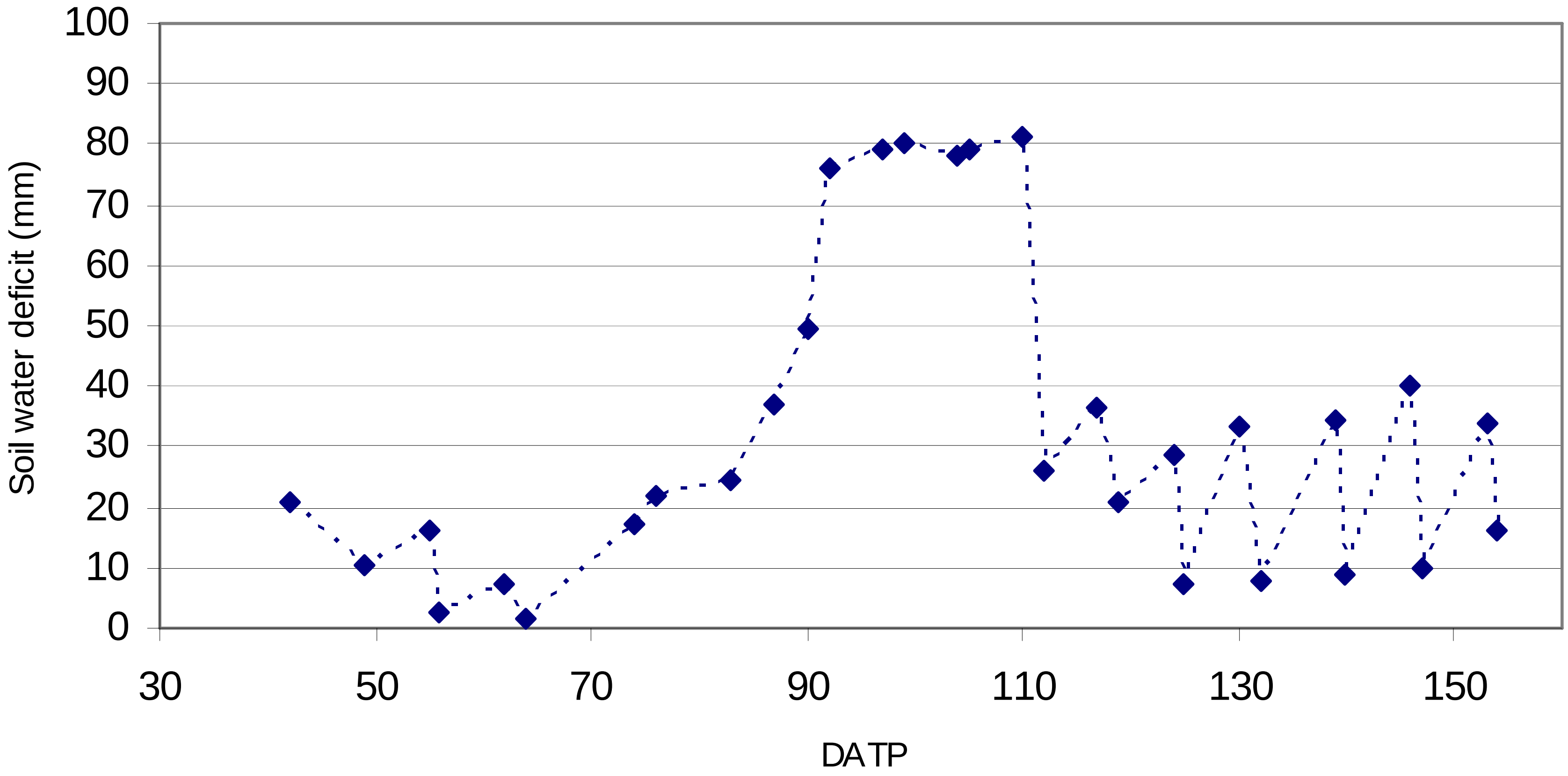

Figure 7.3 Soil water deficit (SWD) (mm) of onions, water stressed at bulb elongation (70-110 DATP) (NSN)

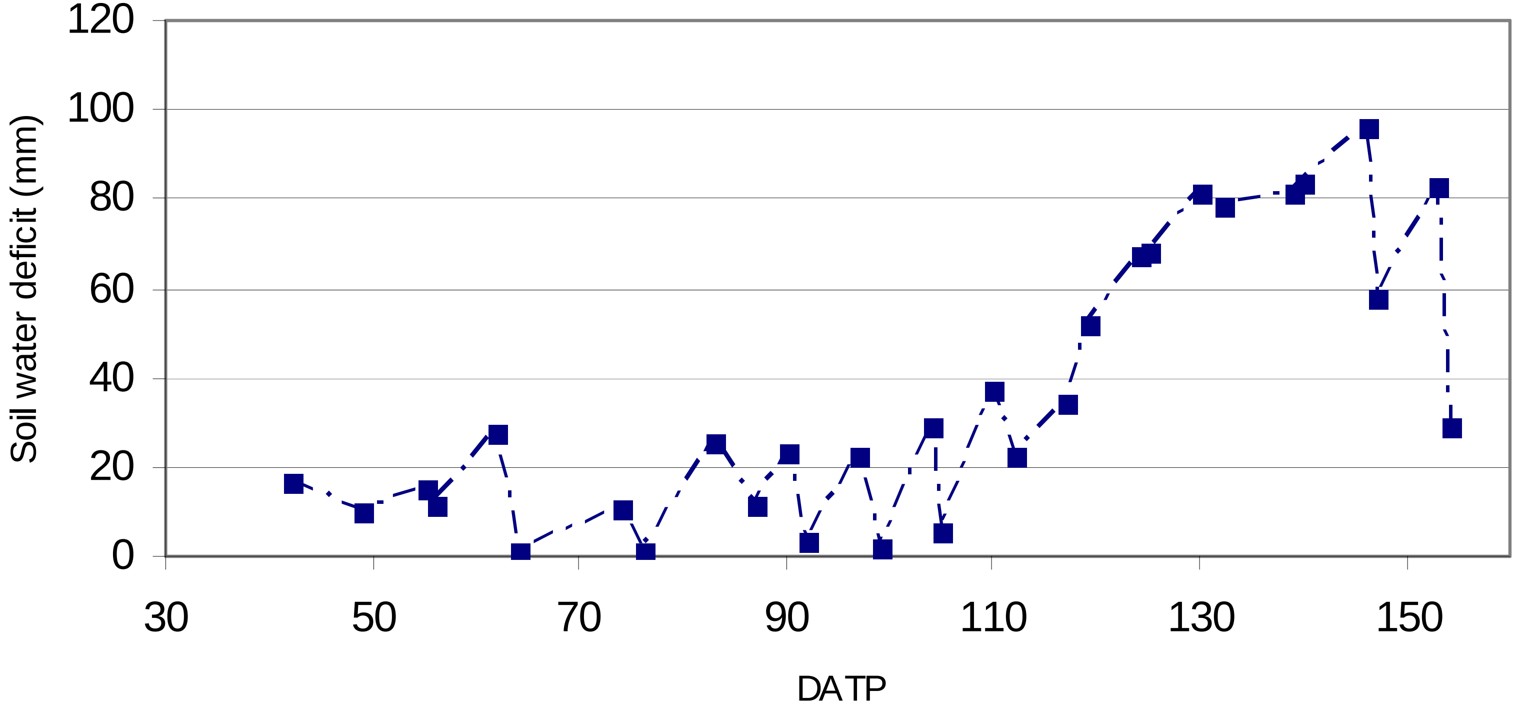

Figure 7.4 Soil water deficit (SWD) (mm) of onions water stressed at bulb maturity (110-145 DATP) (NNS)

Figure 7.3 shows a stabilised cumulative SWD at the peak of the graph, which is due to several small rainfall events that covered more or less the daily evaporative demand of the crop. The last growth stage at which water stress was applied, was the bulb maturity stage, between 110 and 145 DATP. The cumulative SWD during this stress period peaked at nearly 100 mm (Fig. 7.4). From the graph, it can be seen that, at the peak of the cumulative deficit, there are a number of occasions when the deficit, dropped suddenly, which, once again, indicates the prevalence of small rainfall events that relieved the deficit.

Figures 7.1-7.4 show the SWD during water stress applied at different growth phenological stages. The highest cumulative SWD was observed when water stress was applied during the bulb maturity stage of the crop. During this growth stage, even though several small rain showers occurred, the level of deficit was big enough to hamper the growth of the onions significantly, which shows that this stage is most critically influenced by soil water stress, followed by stress at bulb elongation. These findings support the result of Pelter *et al.* (2004), who stated that onions are sensitive to even a slight water stress, depending on growth stage, cultivars and climatic conditions. The water stress applied during vegetative growth stage did not affect the crop significantly (from the yield data). This was due to the fact that water stress was applied during the early growth stage, so that the crop still had enough time for recovery. The other reason could be due to the cool period of the season resulting in relatively low evaporative demand.

In time, onions that are water stressed at different growth stages, show a different growth trend in response to the stress. To evaluate the growth variation with regard to the time aspect, three harvests, were considered and subjected to statistical analysis. The three harvests considered were at 124, 138 and 152 DATP. The response of LDM, bulb dry matter (BDM), TDM, LAI and FI of PAR, are provided in Table 7.1 for 124 DATP; in Table 7.2 for 138 DATP; and in Table 7.3 for 152 DATP.

The highest LDM was obtained from the control treatment (NNN) where no water-stress was induced. The LDM obtained from this treatment was not significantly different from the SNN treatment, where water-stress was induced during the vegetative stage between 35 and 70 days after transplanting. Water-stress during bulb enlargement (70-110 DATP) and bulb maturity (110-145 DATP) significantly ($p<0.05$) affected the LDM accumulation (Table 7.1). At the harvest of 124 DATP, BDM and TDM were significantly affected ($p<0.05$) by water stress during bulb enlargement and maturity (Table 7.1). Table 7.1 further reveals that water-stress in onions at any growth stage result in LAI and FI reduction, although the level of decline varies among treatments.

Table 7.1 Leaf dry matter (LDM), bulb dry matter (BDM), total dry matter (TDM), leaf area index (LAI) and fractional interception (FI) of onions at 124 days after transplant (DATP) for four water regimes

Treatments	*LDM ($kg\ m^{-2}$)*	*BDM ($kg\ m^{-2}$)*	*TDM ($kg\ m^{-2}$)*	*LAI ($m^2\ m^{-2}$)*	*FI*
NNN	0.28a	0.23a	0.51a	1.41a	0.43a
SNN	0.26a	0.21ab	0.47a	1.08b	0.34b
NSN	0.10b	0.07c	0.17c	0.48d	0.29b
NNS	0.15b	0.18b	0.33b	0.83c	0.34b
SEM	0.02	0.01	0.01	0.01	0.01
CV.%	16.2	9.7	14.1	11.6	12.8

The effect of water stress on LDM accumulation did not change during the second harvest (138 DATP), where NSN and NNS treatments were still significantly affected as compared to the control treatment (Table 7.2). During this harvest, the LDM and LAI performed similarly, where NNN and SNN treatments had similar yields, whilst the NSN and NNS treatments resulted in significantly lower LDM and LAI values. On the other hand, the BDM and TDM were affected in a similar way (Table 7.2), where water stress applied at any growth stage induced a significant effect on both parameters. Table 7.2 further reveals that water stress during this stage (138 DATP) had a major effect on the BDM, which was the major component of TDM. The FI was not negatively influenced by water stress during this harvest, which could be due to a lack in uniformity during sampling.

Table 7.2 Leaf dry matter (LDM), bulb dry matter (BDM), total dry matter (TDM), leaf area index (LAI) and fractional interception (FI) of onion at 138 days after transplant (DATP) for four water regimes

	LDM	*BDM*	*TDM*	*LAI*	*FI*
Treatments	*(kg m^{-2})*	*(kg m^{-2})*	*(kg m^{-2})*	*(m^2 m^{-2})*	-
NNN	0.38a	0.44a	0.82a	1.93a	0.53a
SNN	0.37a	0.35b	0.71b	1.84a	0.51a
NSN	0.18b	0.12d	0.30d	1.06b	0.43a
NNS	0.19b	0.21c	0.40c	0.79b	0.49a
SEM	0.01	0.01	0.01	0.01	0.01
CV.%	7.1	5.4	8.4	14.2	14.8

Water stress applied at different growth stages of onions did not influence the tested parameters differently during the third harvest at 152 DATP (Table 7.3). The treatment stressed during the vegetative growth stage, 35-70 DATP, was not significantly different from the non-stressed treatment (Table 7.3) for LDM, BDM, TDM, LAI and FI, while the remaining treatments, NSN and NNS, were significantly inferior to others in all the measured parameters.

Table 7.3 Leaf dry matter (LDM), bulb dry matter (BDM), total dry matter (TDM), leaf area index (LAI) and fractional interception (FI) of onions at 152 days after transplant (DATP) for four water regimes

Treatments	*LDM* *(kg m^{-2})*	*BDM* *(kg m^{-2})*	*TDM* *(kg m^{-2})*	*LAI* *(m^2 m^{-2})*	*FI* -
NNN	0.39a	0.61a	1.00a	1.76a	0.46a
SNN	0.37a	0.60a	0.97a	1.68a	0.41ab
NSN	0.21b	0.28b	0.49b	1.02b	0.36bc
NNS	0.15c	0.27b	0.42b	1.01b	0.31c
SEM	0.01	0.01	0.01	0.01	0.01
CV.%	9.9	8.4	14.7	10.2	12.7

Many researchers disagree on the critical growth stages of onions to water stress. Al-Jamal *et al.* (2000) and Al-Kaisi & Broner (2005) report that water stress at any growth stage of onions result in dry matter and fresh yield reduction. The degree of reduction, however, varies depending on the cultivar and climate, while others (Pelter *et al.,* 2004) agree that onions are more sensitive to water stress during bulb elongation than during the vegetative stage. They also found that soil water stress at any growth stage decreased the yield of onions, but the greatest decrease was observed when irrigation was withheld between 5-7 leaf stages, which is about 70 DATP and beyond. Pelter *et al.* (2004) further report that soil water stress caused by withholding irrigation for longer periods at both 3 and 7-leaf growth stages, severely reduced onion bulb yield. Similarly, Al-Kaisi and Broner (2005) concluded that the most critical growth period of onions to water stress is the bulb formation and development stage, which is the growth stage beyond 70 DATP. From this experiment, it can be concluded that from the three growth stages when water stress was applied, the bulb development (70-110 DATP) and bulb maturity (110-145 DATP) stages were found to be most critical to growth and yield reduction. When the crop is water stressed during the vegetative growth stage (35-70 DATP) growth and yield reduction was not significant. This could perhaps be due to the cool period of the season, (low ET) and the crop having a long remaining period for compensatory growth, with the minimum yield loss.

The influence of water stress, applied at different growth stages of onions, on leaf growth and development was observed from the leaf area measurements, from which LAI was calculated. The LAI increment over the growing period followed a similar trend to the dry matter yield. The canopy growth for all treatments was not different until about 82 DATP, whereafter treatment differences occurred (Fig. 7.5).

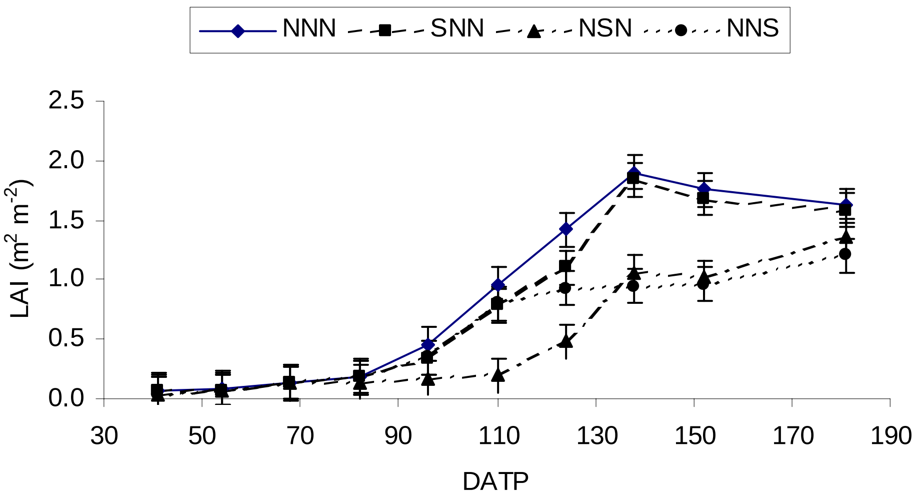

Figure 7.5 Onion leaf area index (LAI) for four water-stress treatments applied at different days after transplanting (DATP): Non-stressed (NNN), vegetative stage (SNN), stressed at bulb development (NSN) and stressed at bulb maturity (NNS)

Even though the control treatment (NNN) produced the highest LAI throughout the growth period, the SNN performed similarly and both reached the highest peak values at 138 DATP. On the other hand, LAI for the NSN treatment started to decline from about 82 up to 110 DATP, when irrigation was resumed. From this point (110 DATP), irrigation was ceased for NNS, where after the LAI started to decline until it converged to the same point as for the NSN treatment on 138 DATP. These two treatments performed poorly as compared to the other two treatments, until final harvest. This finding confirms that leaf growth and development are one of the crop parameters most severely affected by soil water stress during active crop growth. Liptay *et al.* (1998) report that even moderate water stress results in a reduction in plant leaf area and LAI. This result also agrees with the findings of Kuchenbuch *et al.*

(1986), who concluded that an increase in soil water stress resulted in a linear decrease in onion shoot growth and LAI. The trend of specific leaf area (SLA) during the growing season did not vary for all treatments. The SLA followed a decreasing trend, from more than 12 to around 4 $m^2 kg^{-1}$ for all treatments, with increasing DATP (Fig. 7.6).

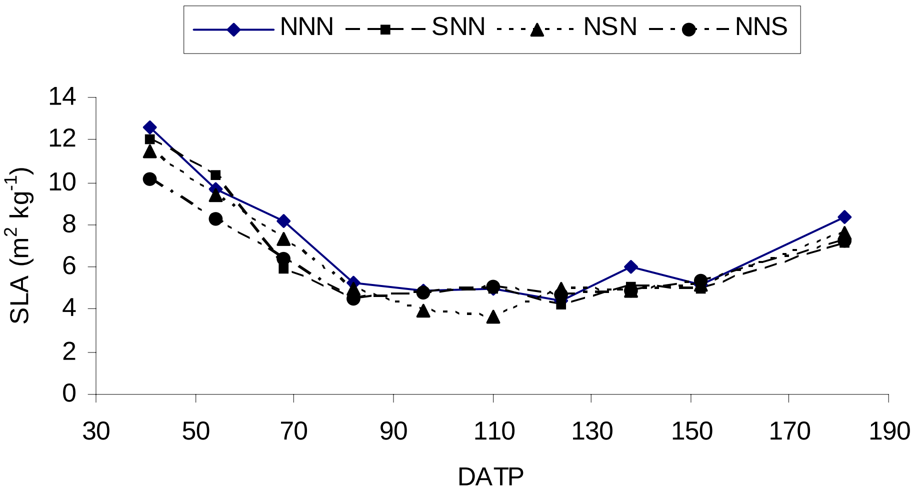

Figure 7.6 Onion specific leaf area (SLA) for four water stress treatments applied at different days after transplanting (DATP): Non-stressed (NNN), stressed at vegetative stage (SNN), stressed at bulb development (NSN) and stressed at bulb maturity (NNS)

The effect of water stress applied at different growth stages also manifested differently on the LAD that accounts for the elapsed duration of photosynthetic activities. The development of LAD for the non-stressed treatment was smooth until 150 DATP, when it reached its peak and decreased smoothly until final harvest (Fig. 7.7). The LAD showed a sharp increment at 82 and 96 DATP for the NNN treatment until its maximum development at 150 DATP. For the SNN treatment, however, even though there was a gradual increment seen at 82 and 96 DATP, a sharp increment was observed at 124 DATP, until its maximum growth at 150 DATP (Fig. 7.7). The NSN treatment had a slow growth between 96 and 124 DATP, where after showed a sharp increase until 150 DATP (Fig. 7.7), and again showed a decreasing growth trend until the final harvest. On the other hand, treatment NNS showed a sharp growth trend between 96 and 124 DATP and followed by a decreasing growth trend until final harvest. These two treatments were harvested while their LAD was actively increasing after relieved from the water stress.

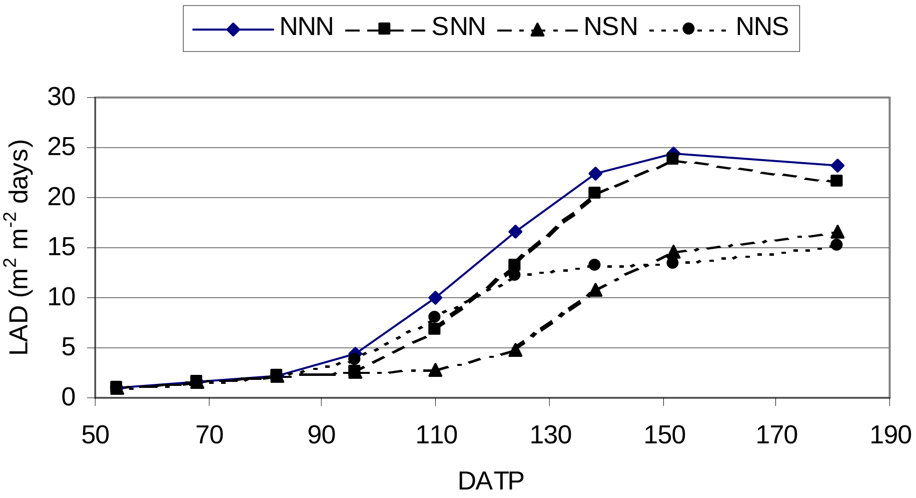

Figure 7.7 Onion leaf area duration (LAD) for four water stress treatments applied at different days after transplanting (DATP): Non-stressed (NNN), stressed at vegetative stage (SNN), stressed at bulb development (NSN) and stressed at bulb maturity (NNS)

Fig. 7.8 presents the relationships between LAD and TDM. Treatments NNN and SNN were found to have stronger relationships with the coefficients of determination (r^2) of 0.97 and 0.99, compared to NSN with r^2 of 0.95 and NNS with r^2 of 0.93 (Fig. 7.8). Figure 7.8 shows good relationships between LAD and TDM. Thus yield is directly correlated with size and duration of canopy to maintain good canopy cover and ensure high TDM and bulb yield.

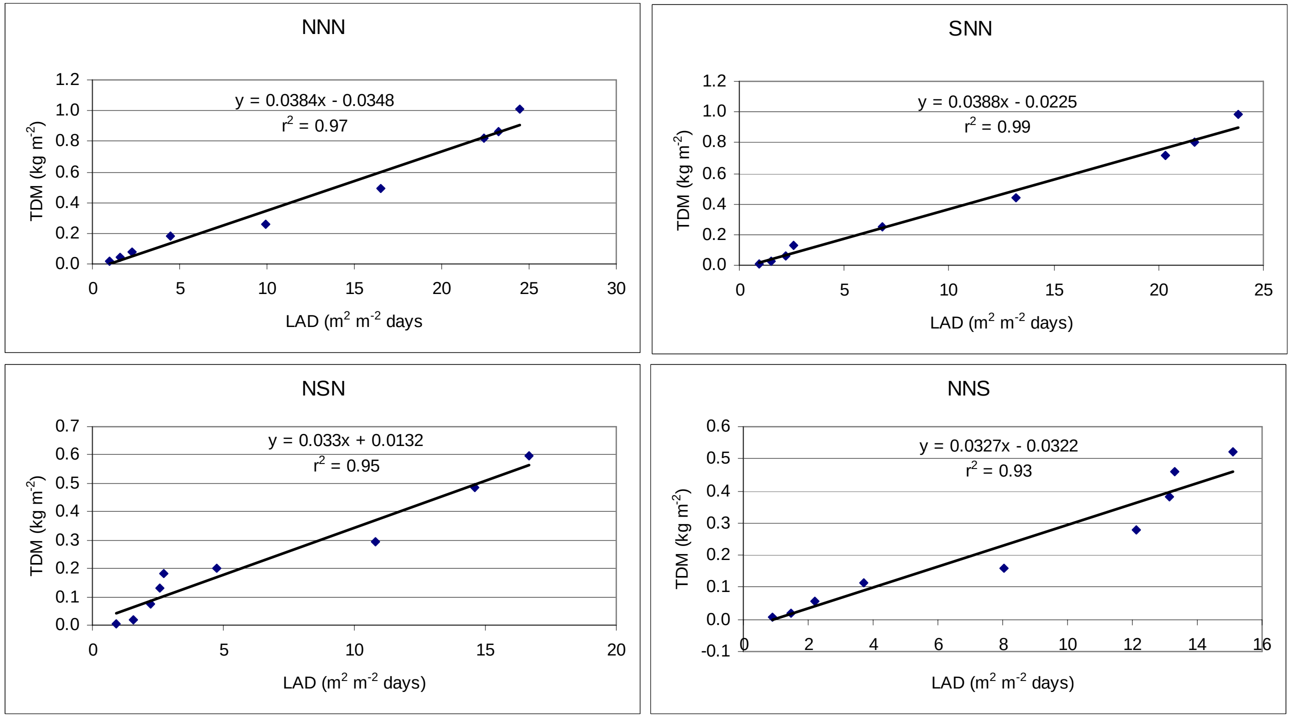

Fig. 7.8 Relationship between leaf area duration (LAD) and total dry matter (TDM) for treatments non-water stressed (NNN), water stressed during vegetative growth stage (SNN), water stressed during bulb development stage (NSN) and water stressed during bulb maturity stage (NNS) of onion.

The TDM increment during the growing season was also recorded to assess the effects of water stress induced at the different growth stages of onions. TDM did not differ until about 96 DATP, whereafter the NSN treatment started to decline (Fig. 7.9). On the other hand, TDM for NNS treatment started to decline from 124 DATP until it converged to a point with a reviving NSN on about 138 DATP. LAI of these treatments continued to increase slow by until the final harvest, as opposed to the NNN and SNN treatments that had significantly higher TDM values. This finding, once again, is in line with the results obtained by Martin (2004), who concluded that water stress imposed on onions during bulb maturity and ripening, significantly reduce TDM and bulb yield.

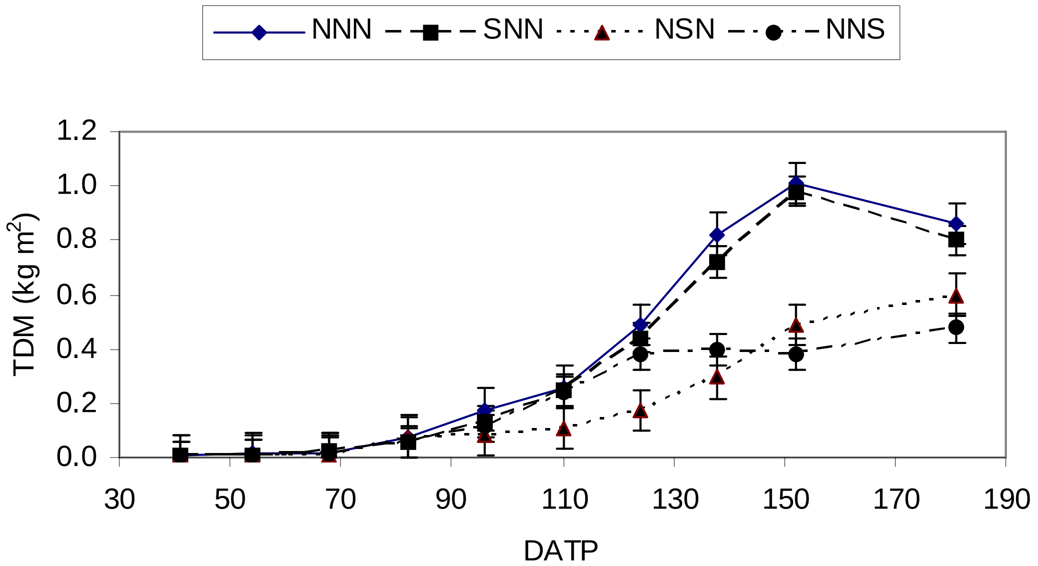

Figure 7.9 Onion total dry matter (TDM) yield for four water stress treatments applied at different days after transplanting (DATP): Non-stressed (NNN), stressed at vegetative stage (SNN), stressed at bulb development (NSN) and stressed at bulb maturity (NNS)

Fractional interception of the PAR followed the same increasing trend for all treatments until 82 DATP (Fig. 7.10). Even though not much variation was observed, FI for SNN was the lowest until 110 DATP, and reached its peak at 138 DATP. The FI response can be grouped into two, NNN and SNN treatments performed similarly with higher values, while NSN and NNS treatments produced similarly lower FI values. FI values reached peak values at 138 DATP and thereafter declined until harvest.

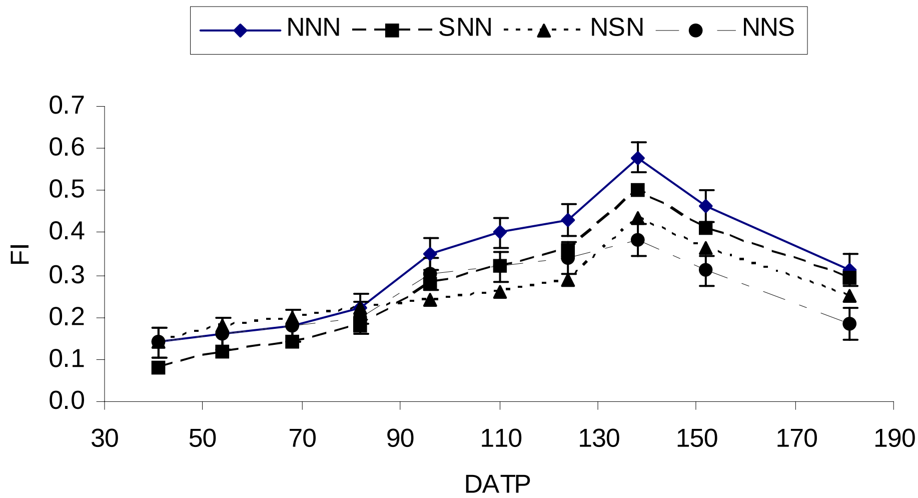

Figure 7.10 Fractional interception (FI) of photosynthetically active radiation (PAR) for four water stress treatments applied at different days after transplanting (DATP) of onions: Non-stressed (NNN), stressed at vegetative stage (SNN), stressed at bulb development (NSN) and stressed at bulb maturity (NNS)

The growth and development data of onions water stressed at different growth stages, revealed that the non-stressed (NNN) treatment produced the highest yield for all parameters evaluated, while the NNS treatment performed the poorest. For most parameters evaluated, NNN and SNN treatments performed similarly, but significantly better than the remaining treatments (NSN and NNS), with no significant difference between them. These results reveal that the most critical growth stages of onions to water stress are during bulb enlargement and bulb maturity (70-110 and 110-145 DATP), with the latter stage being the most critical. The experiment also indicated that water stress during the early growth stage (35-70 DATP) helped the crop to harden or develop good root growth that allowed compensatory growth with acceptable yield loss ($p>0.05$).

Table 7.4 reveals the water use and WUE data of onions as influenced by water stress applied at different growth stages. The highest irrigation amount, 537 mm, was applied by the non-stressed treatment, while the lowest amount, 440 mm, was used when water stress was applied during the vegetative growth stage (Table 7.4). Withholding irrigation water during the vegetative growth stage (35-70 DATP) saved 97 mm of water, which is about 18% with a yield reduction of about 6%. Similarly, the SNN treatment provided the highest WUE of 150 kg ha^{-1} mm^{-1}, followed by the NNN with 131 kg ha^{-1} mm^{-1} (Table 7.4). The remaining two treatments resulted in substantially lower WUE of 111 kg ha^{-1} mm^{-1} for NSN and 98 kg ha^{-1} mm^{-1} for NNS, which indicate that these treatments were severely affected by the water stress applied during their respective growth periods. The result, once again, confirms that stress at bulb enlargement and bulb maturity reduces the growth and yield of onions significantly.

Table 7.4 Onion water use and irrigation water use efficiency (WUE) for four water stress treatments applied at different days after transplanting (DATP): Non-stressed (NNN), stressed at vegetative stage (SNN), stressed at bulb development (NSN) and stressed at bulb maturity (NNS).

Treatment	FBY kg ha^{-1}	Total water applied (mm)	WUE kg ha^{-1} mm^{-1}
NNN	70200a	532	131
SNN	65870a	440	150
NSN	49470b	446	111
NNS	43260c	441	98
CV. (%)	24.67		

Means with the same letter are not significantly different.

FBY = Fresh bulb yield

The NNS treatment had the lowest yield, which, therefore, resulted in the lowest WUE. The SWD measurements during the stress period also substantiated the results obtained from the growth performance and both dry matter and fresh bulb yields. The treatment stressed during the early growth stage had ample time to recover lost vegetative growth after the stress and yield loss was consequently not severe ($p>0.05$). This result agrees with the finding of Kalb and Shanmugasundaram (2001) who concluded that, during the vegetative growth period, the crop appears to be relatively less sensitive to water deficits. On the other hand, the treatment stressed between 110 and 145 DATP (NNS) was in a stage where maximum dry matter was to be partitioned to the bulb and minimum to the shoot (Shock *et al*., 2004). This, coupled with the short period between stress relieve and harvesting, did not allow the crop to undergo compensatory growth.

7.4 Conclusions

Onions are sensitive to soil water stress, depending on the growth stage at which stress is applied and the level of drought tolerance of cultivars. The water stress experiment conducted on onions revealed that water stress induced at any growth stage affected the LDM, BDM, TDM, LAI, FI and fresh bulb yield, but the extent varied depending on the growth stage during which the stress was applied. Water stress applied during the vegetative growth stage (35-70 DATP) did not result in a significant reduction of plant growth and yield. On the other hand, water stress induced during the growth stages, between 70 and 110 DATP and between 110 and 145 DATP, significantly reduced the LDM, BDM and TDM yields. Water stress during these growth stages also significantly affected the bulb fresh yield, LAI and FI of PAR. However, the SLA was not affected by water stress applied at any growth stage and showed a decreasing trend for all treatments over time. With NNN and SNN treatments, the LAD consistently developed until it reached its highest peak and then gradually declined until harvest. On the other hand, with NSN and NNS treatments, the LAD was observed to intermittently increase and decrease up to the final harvest. The data on irrigation water management revealed that the highest water amount was used by the non-stressed treatment, while SNN treatment consumed the lowest water amount. On the other hand, the highest WUE was obtained from the SNN, with water saving of about 18%, which resulted in about 6% bulb yield reduction. The remaining two treatments, the NSN and NNS, resulted in very low irrigation water use efficiency. From this experiment, it could be concluded that the yield and yield components of onion (cv. Texas Grano) is most severely affected when water stress was induced during bulb maturity stage (110-145 DATP), followed by the bulb enlargement stage. On the other hand, when water stress is induced during the vegetative growth stage (35-70 DATP), the highest WUE could be obtained with an acceptable yield reduction.