A quantification of differences of soil moisture under perennial and annual pastures

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Abstract. The Neutron Moisture Meter NMM is used to quantify the water in the soil profile of six pastures on the coastal, NW wheatbelt region of Western Australia. Most sites show a large difference in water use by perennials, some 50 to 150 mm in the upper 1.4 m of the profile, a significant extra water use in a ∼500 mm rainfall region. That use is a climatic trend combined with cropping. The decreased rainfall has had a significant effect and the annuals and cropping are lowering soil moisture levels. The perennials take more water upper and lower in the profile depending on the situation; but they tend to even out the water use over the year.

Keywords: soil, moisture, water, profile, perennials, annuals, NMM, Neutron Moisture Measurement, water balance, modelling, Carbon water balance

Abbreviations: DAFWA – Department of Agriculature and Food–formerly Department of Agriculture, Western Australia, West Australian Department of Agriculture and also Agriculture WA; NMM – Neutron Moisture Measurement

1. Introduction

Greacen (1981) presents the general background for the theory and operation of the Neutron Moisture Meter NMM. It is a down-the-hole logging technique that makes pointwise measurements of proton concentrations by measuring the return of slow neutrons from the soil. Because of differences in soils and particularly bound water effects, it is necessary to calibrate the NMM probe within the exact soil and position. Calibration is with separate, close and similar holes; half are wetted; a trench intercepts the profile and casing to take individual volumetric and gravimetric samples with bulk density.

The calibration provides the water content values through depth for the six sites in this paper. The sites were set up to be well removed from the water table, more than 5 m below the bottom of the holes. Hence consideration of the free drainage condition and deeper soil properties allows extrapolation of the calibration set from ∼ 1.6 m to ∼ 6 m.

A background and history of calibration approaches is presented, along with previous work on the water in the soil profile. It seems that the overwhelming view is that perennial pastures use more water than annuals, from deeper in the profile, and, very likely, with more production. It does depend on the detail, the climate and management; the location, the species and the mix. Here we present some further detail at the selected sites in the northern coastal plain Also presented is some modelling (Carbon, 1975) with the hope of gaining a best extrapolated to 6 m and with best estimates of soil hydraulic parameters (moisture characteristic, capillary flow or deep drainage), to produce robust judgements about future scenarios.

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2. Review of Calibration Procedures

Knowledge of water in the soil profile requires frequent, accurate measurements; the method should be rapid, reliable, simple, cost effective and nondestructive. The use of neutron scattering and moderation is well understood both theoretically and experimentally (Graecen 1971); a robust, contemporary method that uses a Neutron Moisture Meter NMM, a probe containing a radioactive source of fast neutrons mounted close to a detector of slow neutrons. Interactions with protons in the soil (mostly soil water) produce slow neutrons; the returned signal (count) is directly proportional to the proton concentration. Bound hydrogen and moderation (slowing) by other atoms in the soil and water can effect the response, as well as the soil bulk density. Calibration in the field with the given soil is generally necessary to obtain volumetric soil water content values from the count rate.

The interaction between soil and the neutrons suggests that one merely needs one point on the curve for calibration (Holmes 1956). The conservative approach, however, is to define the entire calibration curve for the range of moisture contents in the field.

Stone (1990a) considered a decade in which calibration transfer standards were examined for variance and suitability of method using drums of hydrogenous media (Stone et al. 1995). Thirteen NMM probes were read periodically in drums of hydrogenous media (water, alum, and urea) each with individual probe shields. Supplemental studies examined effects of temperature, minor changes of the position of the probe in the shield, and stability of the hydrogenous media over time. One conclusion was that NMM counting variability can be a no limiting portion of the variability in laboratory calibration drums. With careful probe handling and frequent inspection of the probe for physical integrity, inadvertent changes in calibration attributable to temperature, probe positioning in shield, as well as stability of the media were negligible. Nonetheless, changes in calibration in some probes were noted and corrected by recalibration; periodic checking appears essential in maintaining the integrity of calibration of neutron probes. The stability of the media is a consideration; with brilled urea the count rate was found to slowly increase over the decade perhaps from slow compaction of the media; there was a significant drift only after 10 yr.

One problem is an appropriate averaging volume. McHenry (1963) showed that whereas neutrons as far as 60 cm away can influence the slow neutron density, the preponderant neutrons in the 'sample' come from 15 to 20 cm from the source. Reginato and Nakayama (1988) suggest that the zone of influence of the neutron source in moist soil is approximately a spheroid of 40 cm radius.

Holmes (1956) and reviews by Stone (1990a and b) indicate that the count is a function of source and detector geometry, the nature of the neutron source, the nuclear species in the detector, and the mineral distribution of the soil. The distribution varies with soil type and density, the diameter of the access tube and its composition (Greacen and Hignet 1979; Shirazi and Isobe 1976). Frequent reading in a reference is a valuable way to certify the proper operation of the device, a check on electrical systems and physical integrity of the probe components. Stone and Nofziger (1995) report a statistical method of periodically checking the calibration; readings are made in three media containers and the shield. Shield readings were made with the shield positioned on one of the access tubes. The probes were moved randomly to another container after each 2000 count events. Five such moves gave a total of 100,000 counts in each of three containers and the shield; it provided a greatest acceptable difference between the latest count rate and the mean of the previous count rates.

Commonly, the neutron count in the soil is not used directly but the calibration is based upon a normalised field rate (Stone et al. 1955). The neutron readings in the soil medium are divided by a reading in a reference medium, readily at hand is the count within the shield in which the probe is transported; the ratio is generally reproducible. The older technology was sensitive to power supply voltage and electronic drift; the soil reading changes by the same ratio and changes in count rate caused by radioactive decay are compensated. However, contemporary electronics have little drift so the ratio method is not warranted (Hudson and Wierenga 1988). Since the ratio of radioactive counts contains more error than a single reading, the normalisation introduces error. Nonetheless, Haverkamp et al. (1984) point out that with replicated readings in the reference medium and the use of large radioactive count can make any additional error caused by the ratio method negligible.

Readings in the shield used to transport the probe in the field are still used by many workers as reference for normalising readings in calibration. However, because of positioning effects cited by McCauley and Stone (1972), use of the shield as a standard does create some problems. Positioning errors in the shield as small as 1 mm can cause detectable differences in count rate. Shifts of components within the probe may introduce such differences monitoring so such changes is necessary.

Greacen (1981)discusses the relative merits of laboratory and field calibration; he suggests that both are useful if one applies corrections to a common bulk density and adjusts for any bound hydrogen. Some workers prefer calibration in laboratory containers of packed soil. This offers the advantages of complete geometric reproducibility and convenience. Use of a finite media does raise the question of neutron loss from insufficient sample size and lack of the stratification as present in the field. It seems direct field calibration commands the best acceptance from the scientific community; bulk density corrections are not applied.

Calibration of neutron probes in laboratory media can work for probes of similar design. Nakayama and Reginato (1982) and Reginato and Nakayama (1988) describe a method using three drums having 'apparent' water contents, of stable hydrogenous media containing alum, urea, and water. A 'master' probe is calibrated in the field previously uncalibrated probes in the laboratory. Large laboratory containers minimise errors from neutron loss and in the exact placement of the probe (McCauley and Stone 1972).

Here we use Occham's razor and consider only the variation of the raw NMM counts and how they predict volumetric water content values θ_v, particularly the difference between the annuals and the perennials. In a simplest way, one could just take the counts from the two situations, subtract them, sum them over the profile; to a first approximation this gives a qualitative estimate of the water use by annuals relative to perennials. With modern electronics, it seems there is no statistical value in using relative counts anyway (McCauley and Stone 1972). See Figures 1; all the measurements used the same NMM probe; there is no systematic drift in the electronics; the procedures used are steadfast. That doesn't mean that relative counts normalised to either the shield or the drum values are not warranted. It only means there is no clear advantage and simplicity adds confidence in the final product. The standard shield and drum counts, which are replicated 10 times with every set of measurements, will only be used if there is a clear and known failure in the calibration, as quality assurance.

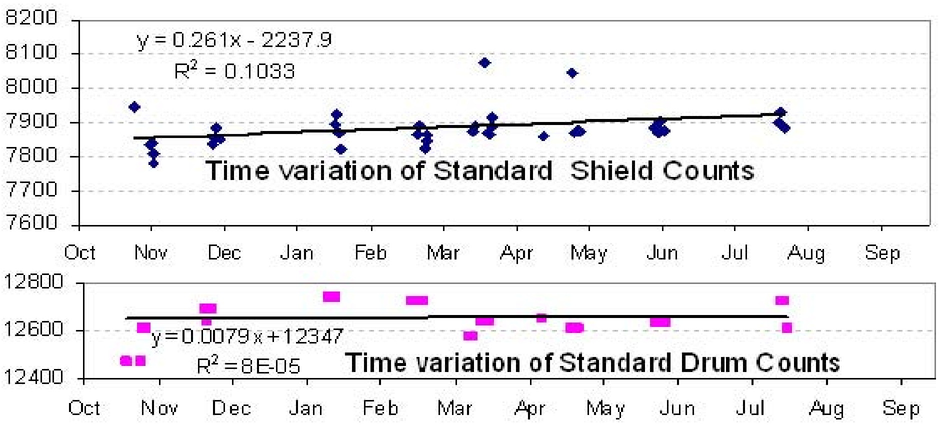


Figure 1. The Shield (upper figure) and Drum (lower figure) values show no significant tendency with the progression of the project. These are average values from 10 measurements with NMM data at the Nixon, Carson and Parker sites∼ 2006

3. Relevant Papers

The potential value in using perennial pastures is large, in Australia and Western Australia (Bennett et al. 2003). In NSW recharges of 6 to 11% can be reduced to 0 to 3% with Deep-rooted perennials in the 400 to 700 mm rainfall zone. In WA, though annuals may reduce the recharge by half when compared to fallow plots with various varieties of annuals and management strategies, there is little increase in water uptake (Ward, 1996). It has been shown that perennials (kikuyu) have the ability to remove 20 to 150 mm more water than annuals (subterranean clover and capeweed)in the top 1.8 m of the soil profile on the Esperance sandplain, with 500 mm/yr rainfall (Hall et al. 1997). There are a number of perennials that are adapted to the northern agricultural regions of WA, and Rhodes' Grass has been shown to extract about 60 mm more water from the profile, to $\sim$ 3 m depths (Ward 2006).

Modelling with the Agricultural Production Systems Simulator APSIM model for lucerne and associated biomass measurements have shown convincingly that lucerne increases storage of carbohydrates in root reserves, as well as reducing drainage (Dolling et al. 2005). On beef weaner production 40 km north of Esperance WA, McDowell et al. (2003) have shown that with 40% kikuyu planted with subterranean clover, deep drainage was just over half that with a whole farm of annual pasture. Over three years the combined system was shown to have a 19% higher gross margin than annual pasture, and there was no need for supplemental feed in summer.

Considering the present measurements, McDowell et al. (2003) also made NMM measurements of Θ_v to 1.8 m, with 1.3 m of sand over clay, installed using the method of Hall et al. (2002), but calibrated using the count ratio CR method with separate layers:

surface sand	$CR = 2.6\theta_v + 0.06$	or	$\theta_v = 0.385CR - 0.023$
deeper sand < 3 m	$CR = 3.0\theta_v + 0.15$	or	$\theta_v = 0.333CR - 0.05$
lower clay < 1.3 m	$CR = 1.44\theta_v + 0.38$	or	$\theta_v = 0.694CR - .263$

In the present work the relative count $CR \simeq C/7900$ for the Shield and $CR \simeq C/12650$ for the Drum of water. The universality of the relative approach is that the above expressions relate to the present work if one presumes the *standard* count was in a Drum of water. Then:

$$\begin{array}{lll} \text{surface sand} & \theta_v = \frac{C}{32890} - 0.023 & \text{or } \theta_v = 0.000030404\,C - 0.023 \\ \text{deeper sand} < 3m & \theta_v = \frac{C}{37950} - 0.05 & \text{or } \theta_v = 0.000026350\,C - 0.05 \\ \text{lower clay} < 1.3m & \theta_v = \frac{C}{18216} - .263 & \text{or } \theta_v = 0.000054897\,C - 0.263 \end{array} \tag{1}$$

Calibration sets that are similar to values derived from the present, mostly sandy profiles (see Figure 4, page 9)

On Figure 2 their results are compared with AgET (Argent and George 1997). The model tended to over predict evapotranspiration. This is possibly because θ_v is used as a surrogate for water potential in redistribution of water and conveyence to roots; the model is a good estimator in a wet environment. AgET is also dependent on estimates of actual evapotranstiration and crop factors. In any case, 60% to 80% of the actual water storage was accounted for. The modelled results suggested that combined deep drainage and runoff from the annuals was 7 times the perennial kikuyu treatment. With the perennials the depth of the A horizon was 1.1 m compared to 0.65 m. The measurements (Figure 2) do show that there is about half the soil water storage with kikuyu treatment; the calculated deep drainage was just over half.

Noteworthy is the study of Bell et al. (2006); water use in perennial pastures as compared to legumes. NMM readings (also counts per 16 s) were converted into count ratios by dividing the count number by a standard count (based on 10 replicates) in the shield prior

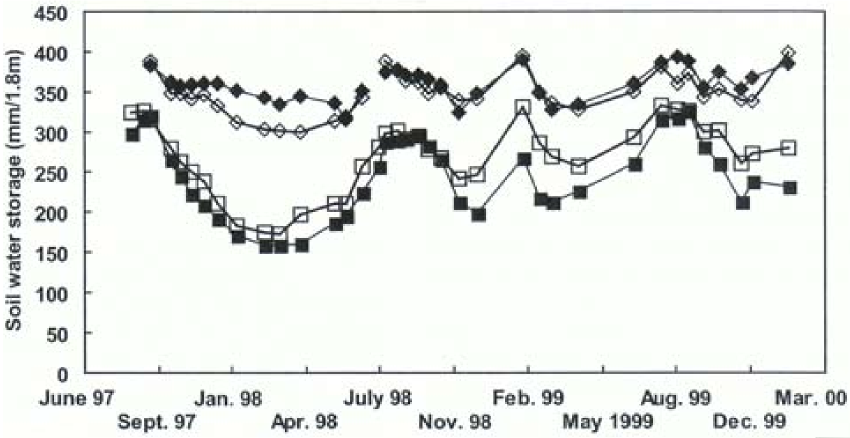


Figure 2. Modelled (open symbols) and actual (closed symbols) of soil storage (mm/1.8 m) for Subclover (diamonds) and with 40% kikuyu (squares). From McDowall et al.(2003)

to beginning the measurements. Count ratios were converted into Θ_v values using linear regression at soil depths of 0.1, 0.3, 0.5, and 0.7 m, using the 0.7 m calibration at greater depths. The authors also identified a greater water use in perennial pastures. The annual pasture comparison was the burr medic and subterranrum clover; the perennials were lucerne and *Dorycnium hirsutum.* With *D. hirsutum* the soil was drier; 8-23mm first year, 43-57 mm second year, and 81 mm third year. There was $<$ 19 mm of additional water use under the lucerne. At New Norcia, the additional water use of perennials was only to depths of 1 m; at Merredin, perennials extracted their water from deeper in the profile–the maximal water use extended to 1 m, 1.8 m and 2.2 m over the three year period.

4. Sites

Six sites were chosen for the study. They are all on notionally sandy soils on gently rolling dunes in the northern portion of the swan coastal plain as shown on Figure 3. All samples (1:5) were notionally apedal, on an earthy fabric weakly cemented with neutral acidity and low EC $\sim 10mS/m$

Forsyth, $(29°18'57.350"S, 115°8'46.568"E)$ The soil is a yellow/brown loose and deep sandy duplex with an upper convex slope. The surface is dark brown, single grain apedal sand that is water resistant. This colour grades to a brown and light yellowish brown at 50cm. Deeper there is a coarse sandy light clay that is moddled, pedal and massive with ferruginous nodules and gravels; this becomes a sandy light clay at 150cm; at greated depths this becomes a red sandy clay loam. The annual paddock adjoins the perennial paddock of Rhodes Grass; during 2006 both paddocks had mostly been taken over by unplanted radish, ryegrass, patterson's curse and double gee.

Gillam, $(29°14'1.438"S, 115°9'36.681"E)$ a loose, pale very deep apedal sand. The Surface is a water repellent very dark greyish brown apedal sand, platy cultivation pan with coarse macropores. Clear boundary at 17 cm into a brown sand; from there a gradation to a yellow sandy loam at 100cm and a clear boundary at 130cm. The sandy loam becomes massive with ironstone gravels with a clear boundary at 150 cm. Deeper to 180 cm there is a gritty light clay with red mottles with fine quartz gravels. The perennials, mostly Rhodes

Figure 3. Monitoring sites □ and significant cities ⊙

Grass, are in a grazed paddock; annuals, mostly radish and capeweed, are in an enclosed, fenced area, cut with a mower periodically to simulate grazing.

Parker, $(28°59'39.223"S, 115°35'56.627"E)$ about 20 m above the Irwin River by a scarp facing upslope to the south about 100m away. The soil is on alluvial terrace, a hardsetting, deep soil of alluvium and colluvium, a red, deep loamy duplex. Dark reddish brown sandy loam, apedal and massive with a cultivation, compacted clear layer-traffic pan at around 20 cm. Below, reddish brown sandy loam with 10% gravels to 35 cm, grading to a yellowish red with 20% gravels and a clear boundary at 65 cm. Then a coarse sandy light clay, pedal with 20% gravels to 80 cm grading to a yellowish red medium clay with 5% gravels at 80 cm. Thence to a yellowish red sandy medium clay to 125 cm and a sandy light medium clay further below 160-200+ m. The perennial pasture was a shotgun mix with a 20 x 20m area sprayed out with roundup for annuals in May 2005. The whole paddock has had sheep grazing on it periodically since Nov05.

Nixon, $(31°0'56.939"S, 116°15'6.928"E)$ a very deep soil of loose, weathered gneiss. The surface is a dark yellowish brown sand with a platy cultivation

Traffic pan, water repellent with a sharp boundary at 10 cm. From there is a yellowish brown clayey sand, more cultivation pan, with a clear boundary to 25 cm. A brownish yellow clayey sand with some medium to fine earthy hollow cemented tubules (termites) grades to 2% quartz fine gravels with diffuse boundaries at 65, 105, 145, 185 and below 200 cm. The perennial paddock is a mix of lucerne and rhodes grass seeded 2002; the annual paddock is some medic but mostly capeweed and erodium; both the perennials and annuals have had cattle periodically grazing since Nov05.

Carson, ($27°58'5.403"S, 114°26'53.151"E$) in gently undulating plains of West Binu about 100km north of Geraldton. Loose very deep yellow eluvial/aeolean sands. Very dark gray surface sands to 20cm; a gradual boundary to 100cm with brownish yellow clayey sand below. The perennials are a pasture evergreen mix sown in Sep03; the annuals are mostly capeweed and erodium in a laneway between perennial paddocks. Both the perennials and annuals have had cattle periodically grazing since Nov05.

Wilson, ($30°56'56.189"S, 115°29'43.423"E$) on yellow deep sands, undulating rises from Tamala limestone. The surface is very dark brown humic sand with a clear cultivation pan boundary at 20 cm. From there, there is a gradual boundary at 30 cm and a diffuse boundary at 60 cm with yellowish brown clayey sand below. In the 180-220 cm region and below there may be coarse faint white mottles as well as pale blotches and softer consistence. The perennials were seeded Aug04 with a shotgun mix of 2 rhodes cultivars, panic, signal; it is now mostly rhodes grass though there are some trials of tagasaste. The annuals are mostly capeweed and erodium with some medic, across the laneway and on the same contour as the perennials. Both the perennials and annuals have had cattle periodically grazing since Nov05.

4.1. Construction Methods

The specific detail followed during the project is as follows:

1. When the 4 lines of six m deep NMM monitoring tubes were installed at each site, six 2 m deep tubes at 10 m from the lines were also installed for destructive calibration.

2. After an extensive dry period(early autumn), 3 of the 2 m deep tubes were wet up with at least 250 L water over about a 2 hour period: 1 square meter bunds were set up around each tube to contain the water. Each litre of water applied should equals 1 mm depth over the square meter, so the tubes were getting the equivalent of a 250 mm rainfall event.

3. Once the water had infiltrated the soil surface, the bunded square meter areas were then covered with black plastic to stop evaporation and left to infiltrate for 48 hours.

4. After the 48 hours the 3 wet and 3 dry tubes had NMM readings taken at 20 cm depth intervals down to 2 m.

5. Then a backhoe was used to dig 2 m deep holes as close to the tubes as possible(about 10 cm away).

6. Then 2 samples for θ_v or bulk density and 1 gravimetric soil moisture sample were taken at the same depths that the NMM readings were taken. These samples were put in sealed, air tight plastic bags

7. In the lab, a wet weight was taken of all the samples. They were then placed in an oven at 105 degrees for 48 hours, when a dry weight was taken.

At each site 10 standard NMM were made with the supplied shield (plastic and parafin wax) and another 10 in a 44 gallon Drum of water, following the procedure recommended by Graecen (1971). The data presented herein, however, do not use these data; to apply Occam's razor, perhaps remove random error, and present the NMM themselves as a robust, useful measure to farmers.

It is expected that the water potentials are continuous through the profile if there are significant variations in the hydraulic conductivity with depth. This is not so with Θ_v values, particularly where there is a clear change of texture (i.e., from sand to clay)–then the θ_v values become discontinuous. Figure 1 shows variations in θ_v with depth which do not change greatly. But the companion b and a values seem to have amplified changes, and are nearly discontinuous. Perhaps the b and a values may help in specification of physical/hydrological characterisation of the soil profile (bore log).

*****Dave Nicholson, please check details****** Standard bore hole preparation (Hall et al. 2002) consisted of using a mechanised auger (***details of type, etc.) to make a 75 mm hole to a depth of $\sim$ 5.5 m. A $\sim$ 6 m long access tube of 50 mm standard class *** PVC water tubing sealed at the lower end was carefully inserted into the hole. The cavity around the tube was *** packed with a wet clay slurry (4:1 kaolin:lime). The first measurements were made about 30 days later, when an equilibrium should have been established between the clay and the soil.

5. Calibration Data

The sites each had 6 representative monitoring boreholes set aside for destructive sampling. These were cased to 6 m and clay-packed following standard preparation for all the monitoring bores. When the calibrations were made, 4 of the holes were bunded with clay dykes of about 1 m diameter. Then the profile was gradually wetted with 250 litres of water, to wet the profile. After 48 hours was allowed to equilibrate the flows, NMM were made through the profile and, immediately, holes were dug with a backhoe to form 'T' shapes on the surface, to a depth of 1.5 to 2 m, to intersect with the line of 8 holes. This allowed access and samples were collected with collecting cylinders (volumetric water content and bulk density) and larger samples for gravimetric analysis.

At each site this overall calibration was replicated for a total of 12 calibration holes; the second set of data were kept aside for a blind statistical check on judgements made in regard to water in the profile and effects of the sites.

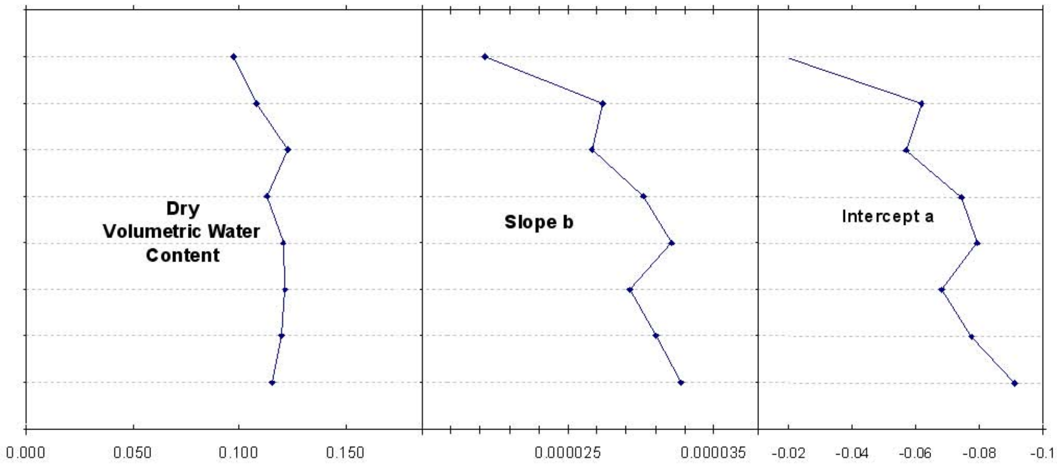


Figure 4. Dry values of Volumetric Water Content as measured at the Nixon Site. Shows companion regression values, the slope b and intercept a. The vertical scale is downward from the surface in 20 cm increments to 160 cm

Regression lines were drawn to relate the NMM measurements to the volumetric water content values. This produces a slope b and an intercept a where

$$\theta_v = b \cdot count + a \tag{2}$$

In the continuing monitoring process, down the cased bore holes, the appropriate regression line was applied to the NMM count values from the particular height to convert the count directly into volumetric water content values θ_v. This only applied to depths less than about 1.4 to 2 m however; holes with access and appropriate coring equipment was not available to sample below depths of 1.4 to 6 m. Depending on the bore log at each site and the expected conveyance/storage properties, the calibration between ∼1 m and 2 m was extrapolated to 5.5 m. It was not possible to simply use the calibration at the lowest level – the errors in this gross extrapolation produce unreasonable values of the θ_v, either beyond the expected field capacity or negative values. In the choice of b and A values, it was expected that little, if any, water is extracted by roots from the lowest levels; data from free-draining long columns suggests that the water potential and volumetric water contents should not change with depth, in these lowest depths (Bouwer 1978, page 236),i. e., there is a zero gradient of water potential and water content.

Figure 4 presents the dry volumetric water content values as measured at the Nixon site during the calibration on 4May06. The b and a show similar breaks in the profile, perhaps enhanced. There is a connection with the bore logs and the changes in water content with time; it presents a reasonable estimate as to where the soil hydraulic properties change with time, as well as giving a best estimate of water content in the range of calibration, at the given depth.

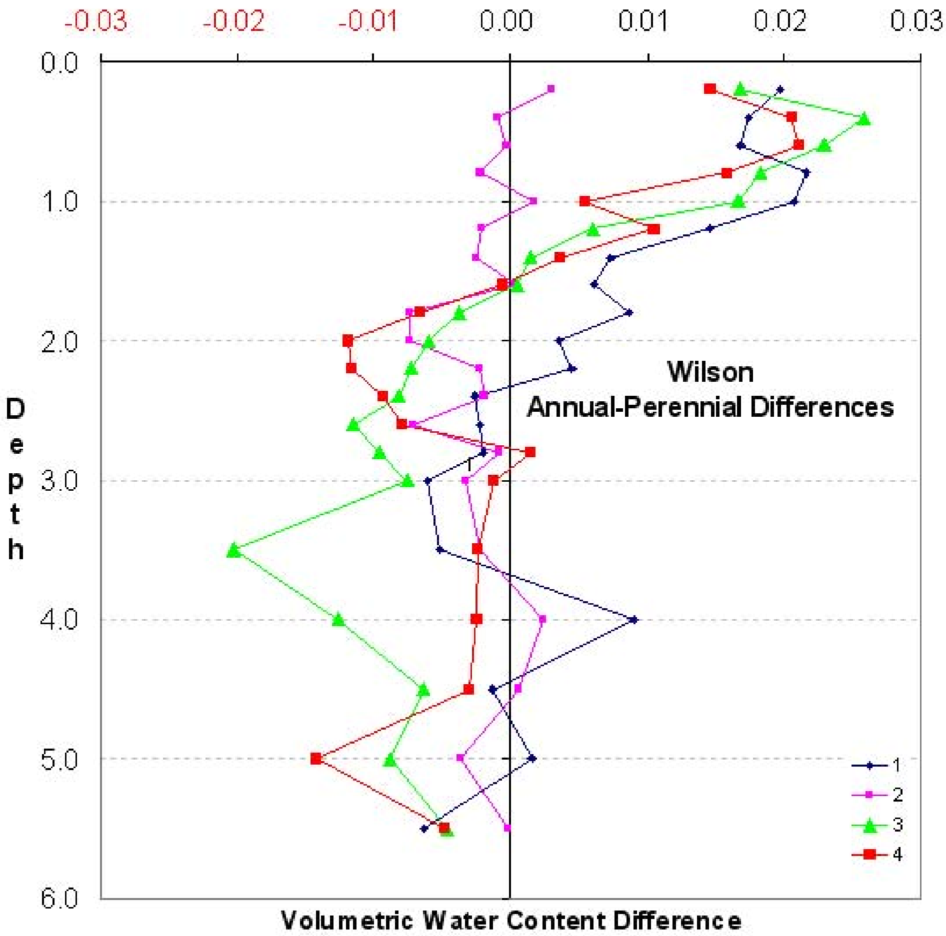


Figure 5. Differences in Volumetric Water Contents measured at the Wilson Farm, 25Nov05. Shows 4 similar, companion holes; 1, 2, 3, 4

6. Data Summaries

Figure 5 shows the differences between annuals and perennials as 4 replicated measurements at the Wilson Farm. Positive values mean the annuals have used most water; negative values mean perennials have used most of the water. The variability between holes is quite large but the graphing does give a general overview. It is clear that, the annuals have taken water down to about 1.8 m; Perennials, lower levels.

The points on Figures 6 and 7 do not show differences; they are the average of 4 replicated) Θ_v values through the profile and through the year, November to November. It is hard to make out relative tendencies on such plots but it is clear that the annuals and the perennials behave similarly at depths below 3 m. Also, the Θ_v values under the annuals is larger, with a little less spread, possibly because of different rooting conditions or simply because the water content values are larger.

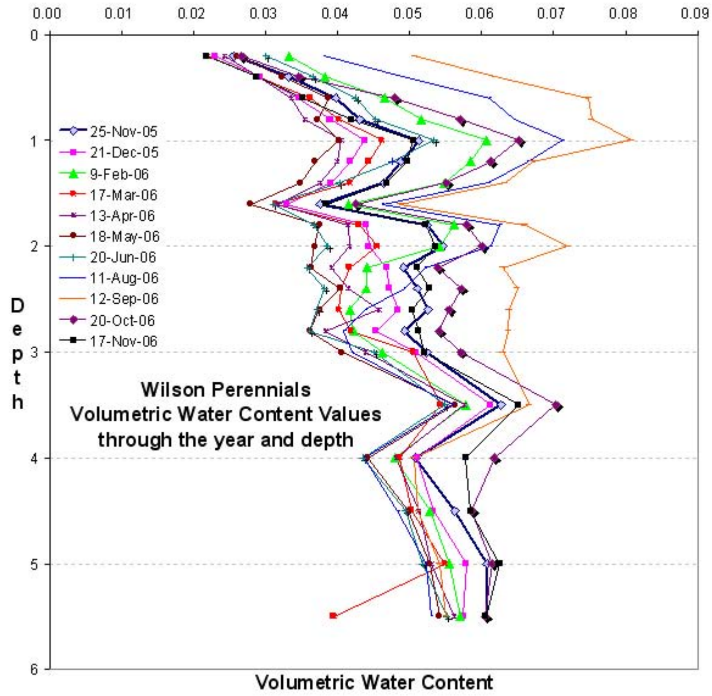


Figure 6. Perennial Volumetric Water Content Profiles at the Wilson Farm, through ∼ 6 m and ∼ 2006.

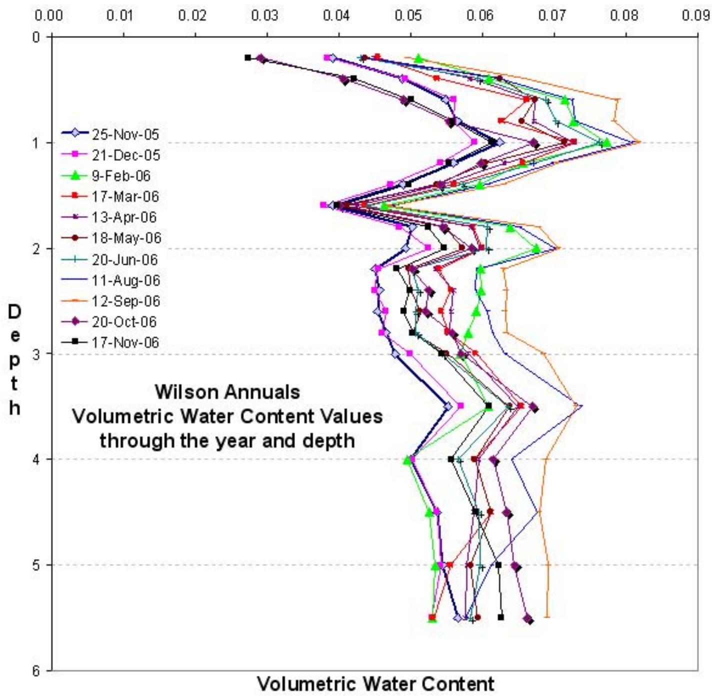


Figure 7. Annual Volumetric Water Content Profiles at the Wilson Farm, through ∼ 6 m and ∼ 2006.

7. Contour Plots

The next few figures (8 to 10, pages 13 to 15)present false colour contours that represent average values of Θ_v. See the colour charts on the right sides of the figures. The dark blue or black corresponds to a $\Theta_v > 0.14$; moderate blue, $0.06 < \Theta_v > 0.08$; white $\Theta_v < 0.02$; of course, the units of Θ_v are $\frac{cm^3 water}{cm^3 soil}$.

Note that both the perennials (right figure) and the annuals (left figure) have large amounts of water in the profile $\sim$ September; but the greatest Θ_v (Max) doesn't always occur in September. The Max may also appear early in the year $\sim$ February, perhaps with plant deaths. The highest contour, however, is with the annuals, the darkest colour that shows up at $\sim$ 1 m. The annuals (right figure) show large amounts of water ($\sim$ 0.7) throughout most of the whole year particularly $\sim$ 3 m. The perennials show more even and lower profiles of water throughout the early parts of the year and deep in the profile. The annual profile also shows a significant amount of water near to the surface $\sim$ 0.04; the perennials are quite dry at the surface except in September.

All the figures show dry surfaces through the year, with wet periods in winter though Forsyth, Parker and Nixon have surface values and a profile that is well above field capacity. In all, the perennials show lower Θ_v, though this is marginal at Gillam and Parker. Note the brief 'window' of moist surface July-October at Gillam; this goes from to 2 months for perennials to 3 months for annuals. This period would be a 'window' for water accrual or loss.

There is a tendency for the dry surface (lighter colour) to drift deeper with time. See the Nixon data (Figure 9, page14); this appears as a 'finger' reaching down and along through most of the year. Overall the perennials seem to take more water deeper into the profile but, with the extrapolation used in the calibration it would be a mistake to take this suggestion seriously.

Nonetheless, a buildup of water deep in the profile is shown with the Forsyth perennials (Figure 8a), the Gilliam site, particularly the perennials, and the Carson perennials (Figure 10a, page 15). It is curious that the annuals, particularly, have left much of the water $\sim$ 2.5 m at the Forsythe, Parker, Nixon and Carson sites. This many simply be a lack of withdrawal by shallow-rooted species, but again, even these mid-profile data were not fully calibrated. Parker (Figure 9) shows much the same Θ_v values below the perennials as the annuals. However, the water contents are much lower, particularly deep in the profile.

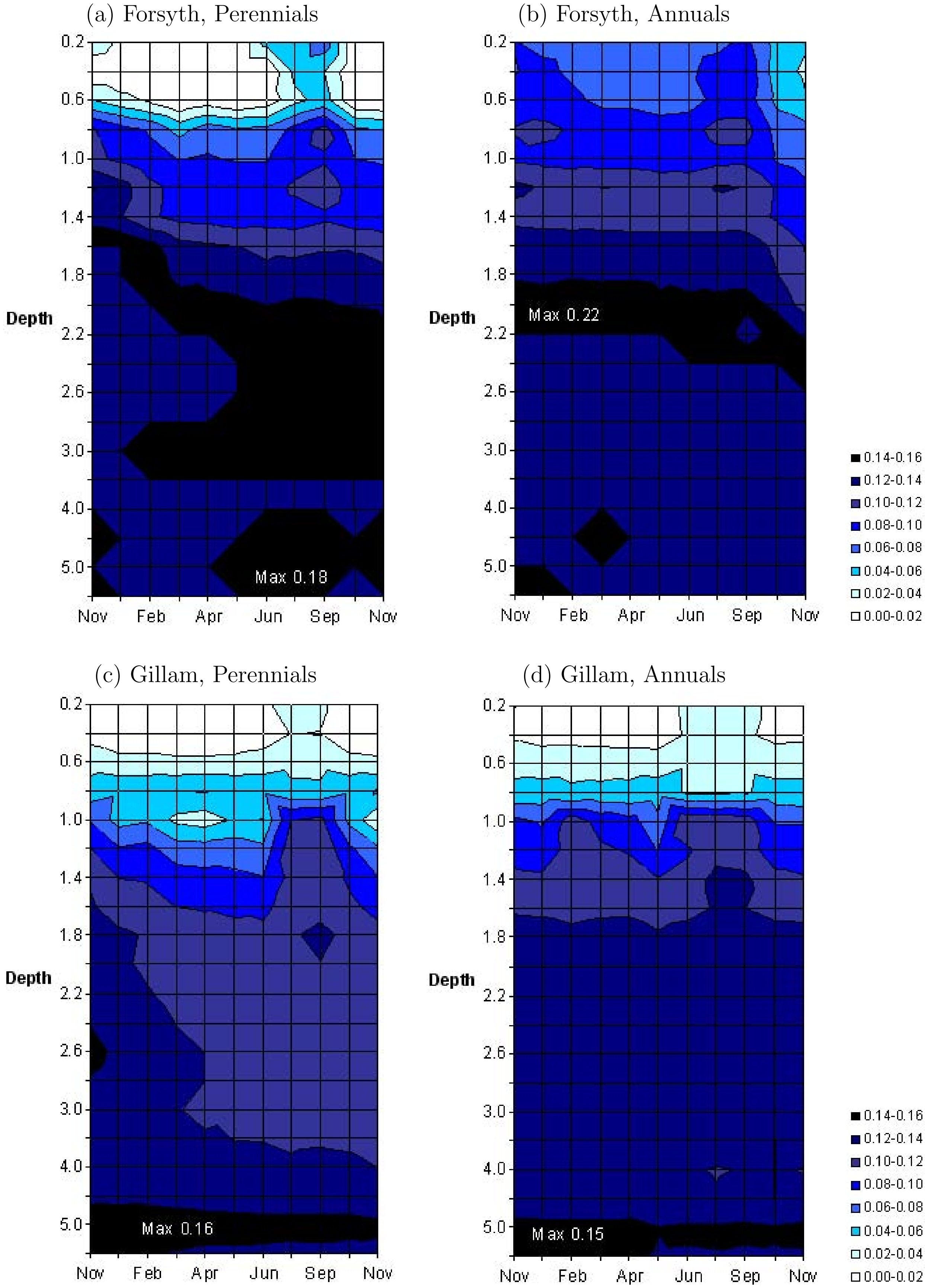


Figure 8. Wet Sites, Forsyth and Gillam, Contoured Water Contents, ∼ 2006.

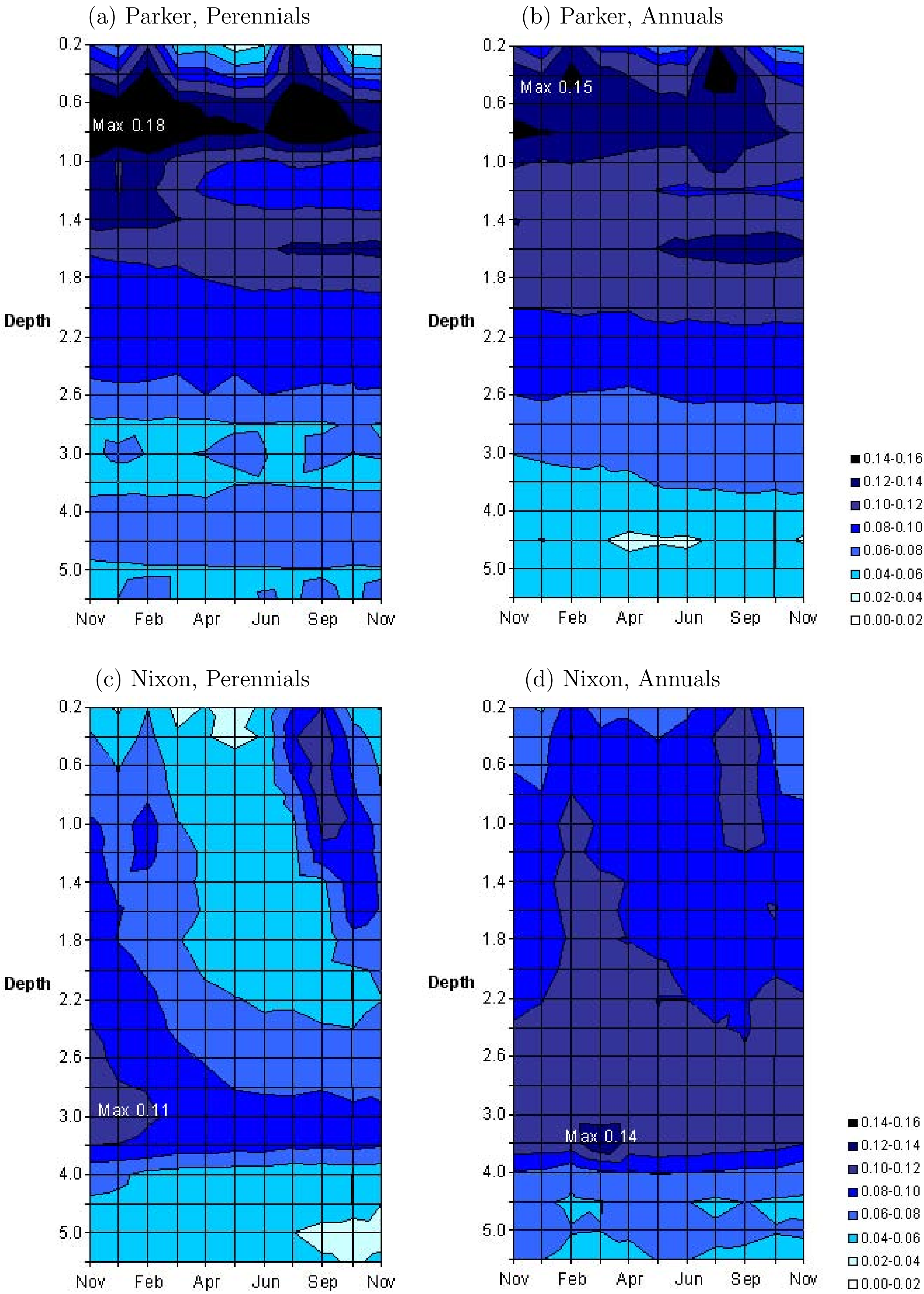


Figure 9. Moderate Sites, Parker and Nixon, Contoured Water Contents, ∼ 2006.

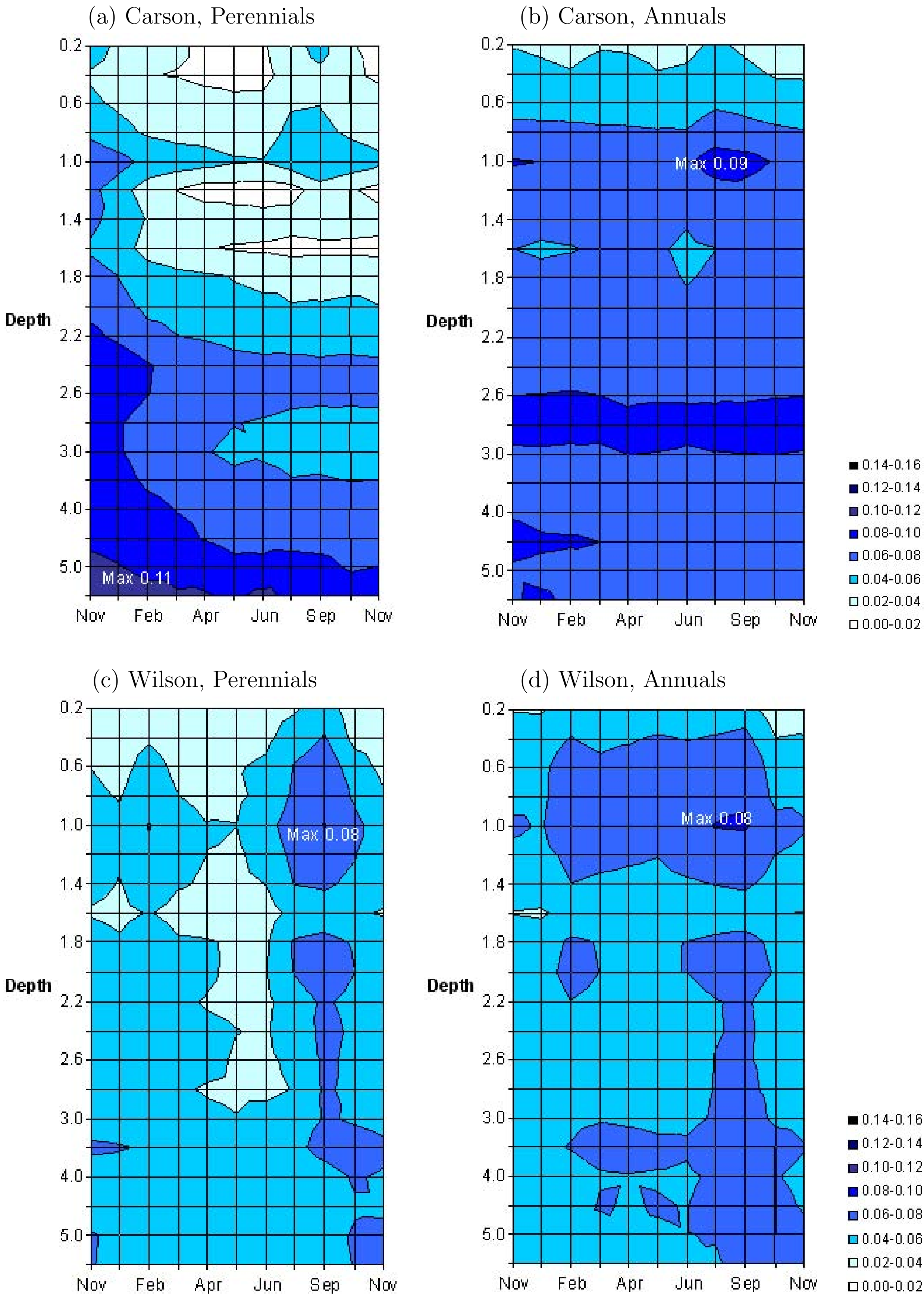


Figure 10. Dryer Sites, Carson and Wilson, Contoured Water Contents, ∼ 2006.

8. A Summary of mm in the Profile

The next few figures 8 show the integrated moisture in the profile to 4.5 m. That is the sum

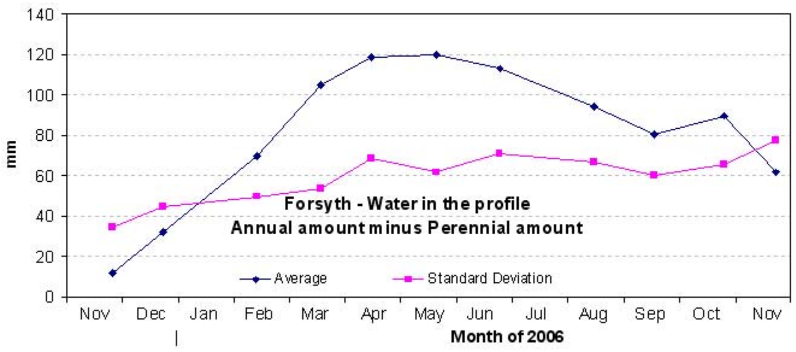
$$\sum_{\text{lower }\Delta}^{\text{upper }\Delta} \left\{ \frac{cm^3\,\text{water}}{cm^3\,\text{soil}} \cdot \Delta \right\} \tag{3}$$

Figure 11 presents summary data for Forsyth. Figure 11(a) shows that the annual-perennial difference is large throughout the year and that in summer, the Nov measurements, insignificant; the replicated measures have a standard deviation larger than the difference. Figure 11(b) shows that the extra storage in the annuals within the top 1.4 m is around half of the storage in the profile. Otherwise, the trends through the year are similar, with significantly more water left under the annuals. In Figure 11(c) it is clear that the perennials use more water over the whole year and, at Forsyth in 2006 the annuals removed 103 mm from the profile; the Perennials, 153 mm. The last figure (11(d)) reveals that the perennials used about half of the water in the upper 1.4 m of the profile in Summer, overall they used $\sim$ 30% more water. The annuals in the upper regions started the year with 135 mm and ended with 85 mm, a loss over the year of 50 mm; in the same region, the perennials started with 111 mm and ended with 51 mm, a loss over the year of 61 mm.

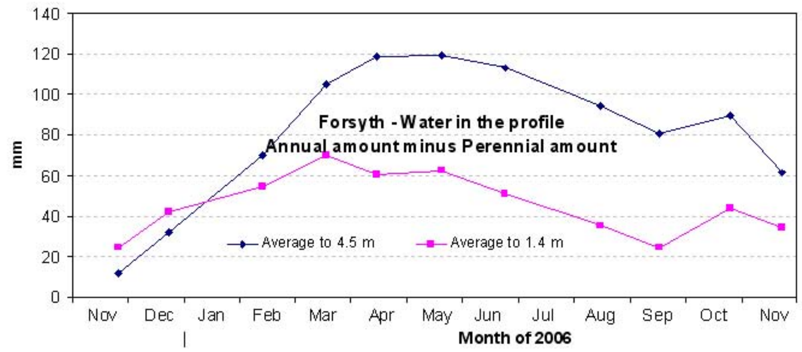
The Gillam data are for fenced pastures; for the upper and lower reaches of the profile (Figure 12) shows 400 to 500 mm of water in the profile, (Figure 12(c)) with only a small difference between annuals and perennials, (Figure 12(a)) and much of the difference is little more than the standard deviation. Figure 12(b) suggests the extra storage in the annuals within the top 1.4 m is around half of the storage in the profile. Otherwise, the trends through the year are similar, with significantly more water (40 mm) left under the annuals at the end of the year. Considering that there was a lot less water in the annuals 17Nov05, $\sim$ 90 mm more water is present in the whole profile on 15Nov06. Figure 12(d)) reveals that most of the water ($\sim$ 70%) in the profile is in the upper layer, within 1.4 m of the surface; within that layer, the perennials removed about 35 mm in 2006.

In contrast, the Parker data show errors (standard deviations) that easily overwhelm the profile water values (Figure 13(a)), leaving no statistical basis for there being any differences between the annuals and perennials. Nonetheless there seems to be similar values in the summer months ($\sim$375 mm, see Figure 13(c)). On 25Nov05 there were 384 mm of water under the annuals which decreased to 363 mm on 17Nov06, a 21 mm loss in the profile in 2006; perennials started with 410 mm and ended with 369 mm, losing 31 mm.

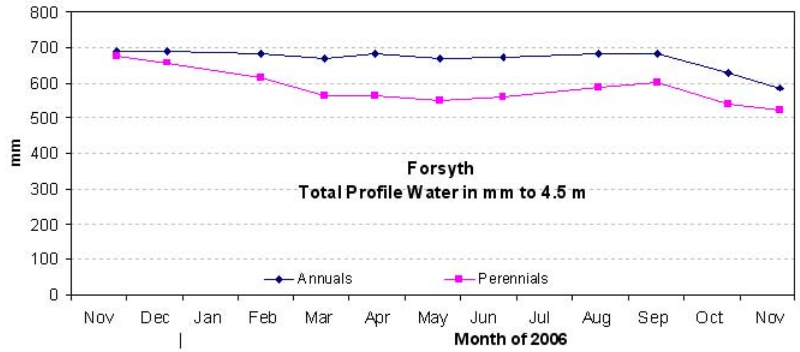
(a) The extra water below the annual pasture to 4.5 m. Note the large standard deviation ∼ Nov



(b) Storage to 1.4 m compared to 4.5 m



(c) Total storage, Annuals and Perrenials, to 4.5 m



(d) Total storage, Annuals and Perrenials, to 1.4 m

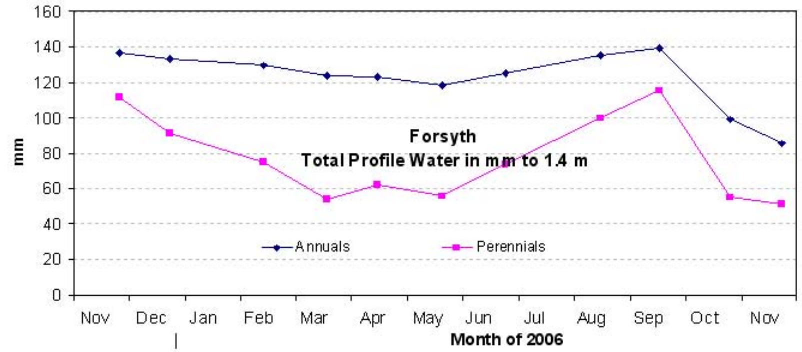
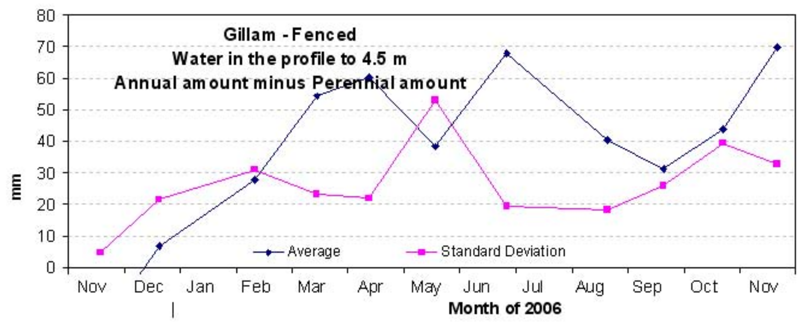
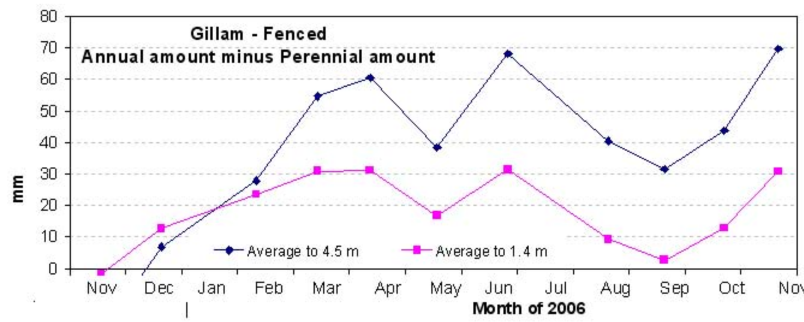


Figure 11. Forsyth, mm of water in the profile ∼ 2006.

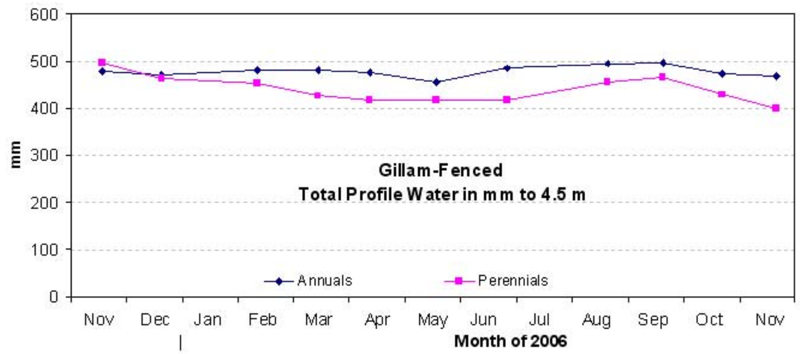
(a) The extra water below the annual pasture to 4.5 m. The obscured value of 17Nov05 is -20 mm.



(b) Storage to 1.4 m compared to 4.5 m



(c) Total storage, Annuals and Perrenials, to 4.5 m



(d) Total storage, Annuals and Perrenials, to 1.4 m

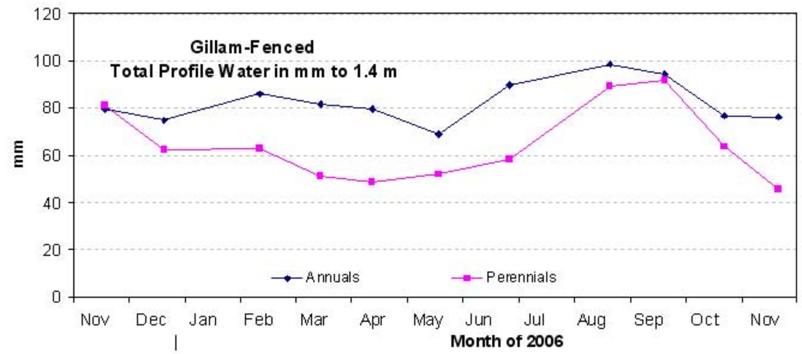
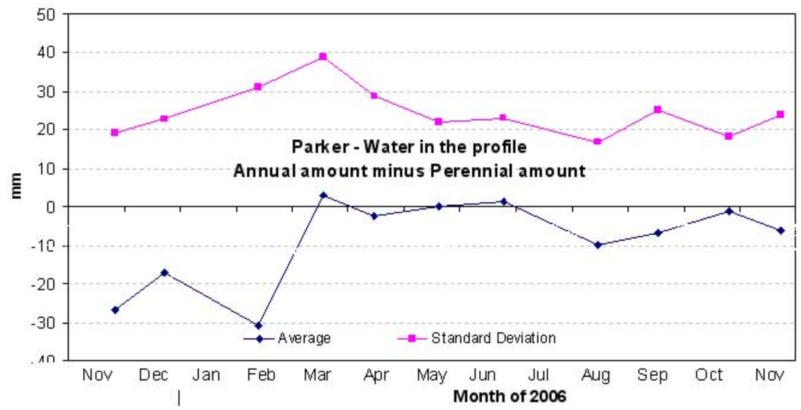
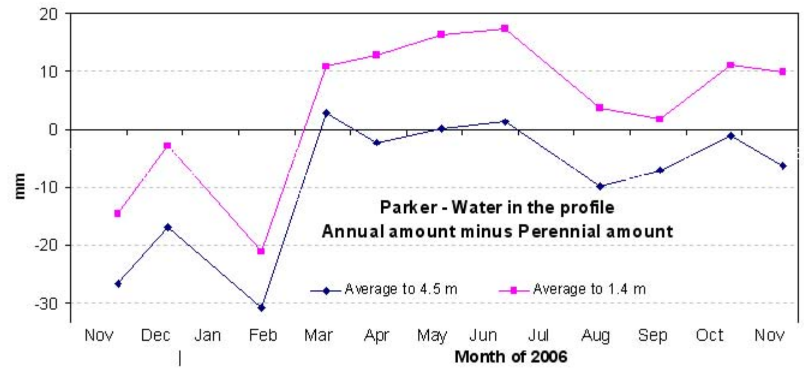


Figure 12. Gillam, mm of water in the profile ∼ 2006.

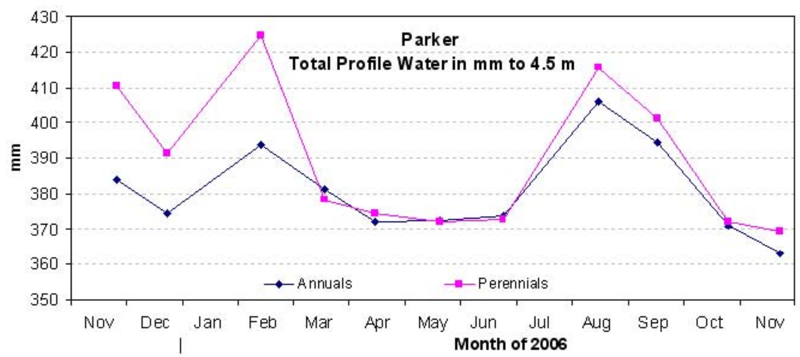
(a) The extra water below the annual pasture to 4.5 m. Note the large standard deviation ~ Nov



(b) Storage to 1.4 m compared to 4.5 m



(c) Total storage, Annuals and Perrenials, to 4.5 m



(d) Total storage, Annuals and Perrenials, to 1.4 m

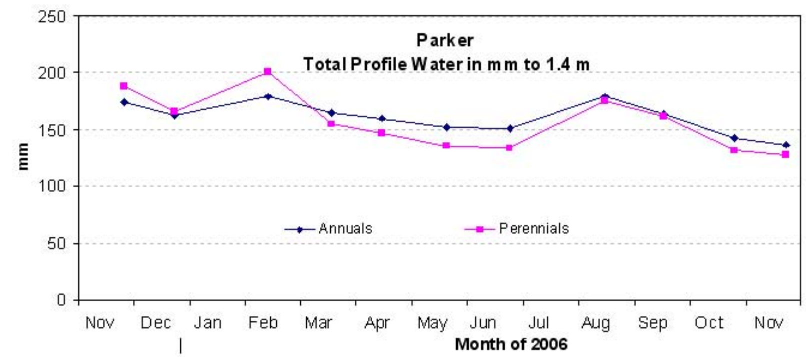
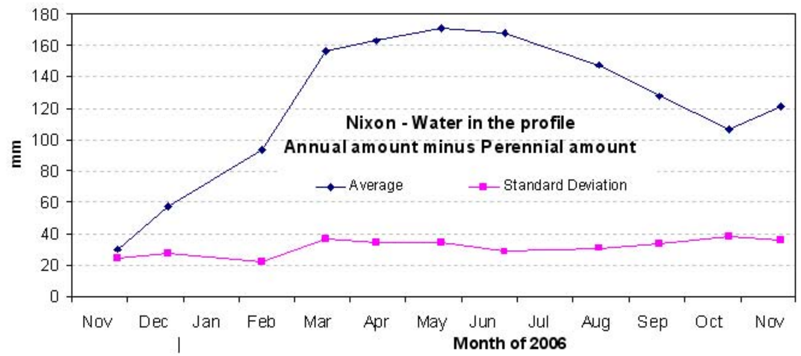
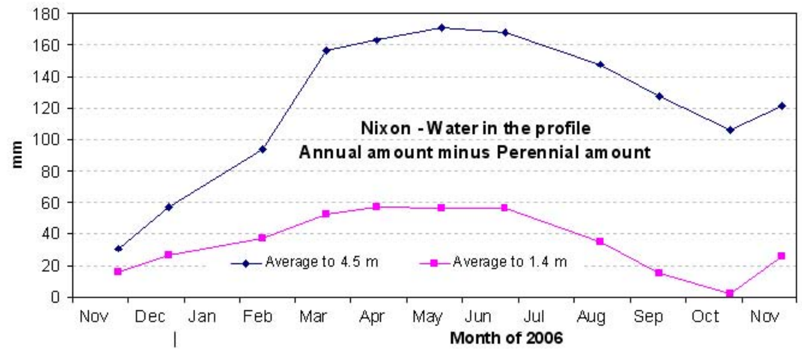


Figure 13. Parker, mm of water in the profile ~ 2006.

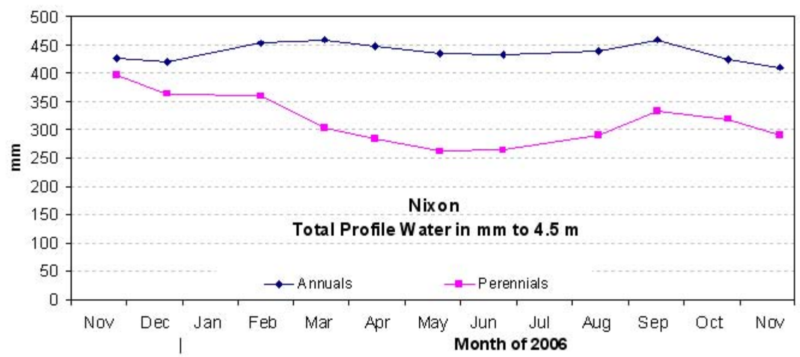
(a) The extra water below the annual pasture to 4.5 m. Note the large standard deviation ∼ Nov



(b) Storage to 1.4 m compared to 4.5 m



(c) Total storage, Annuals and Perrenials, to 4.5 m



(d) Total storage, Annuals and Perrenials, to 1.4 m

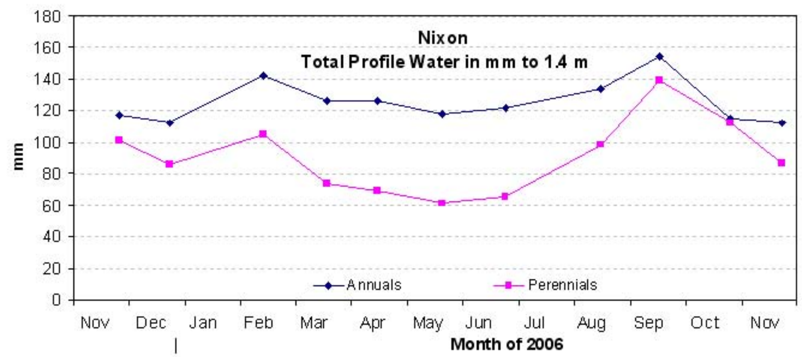
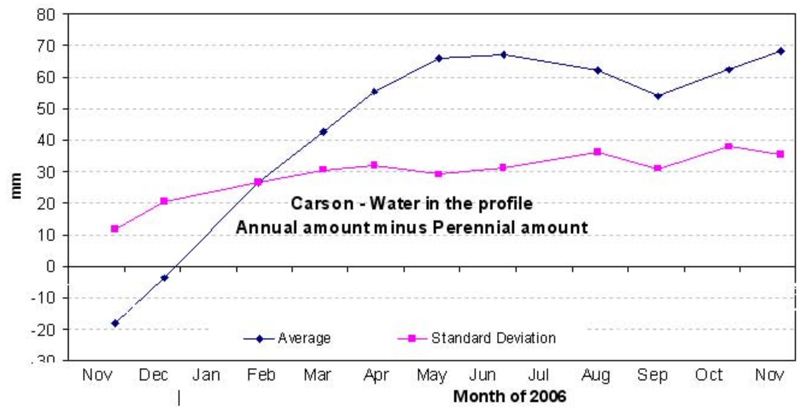
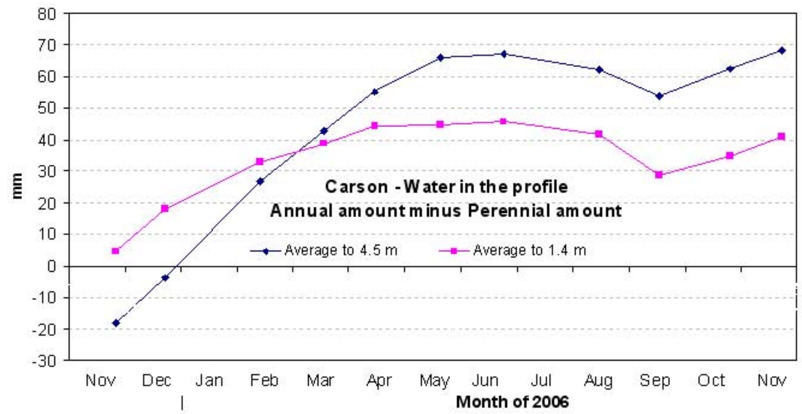


Figure 14. Nixon, mm of water in the profile ∼ 2006.

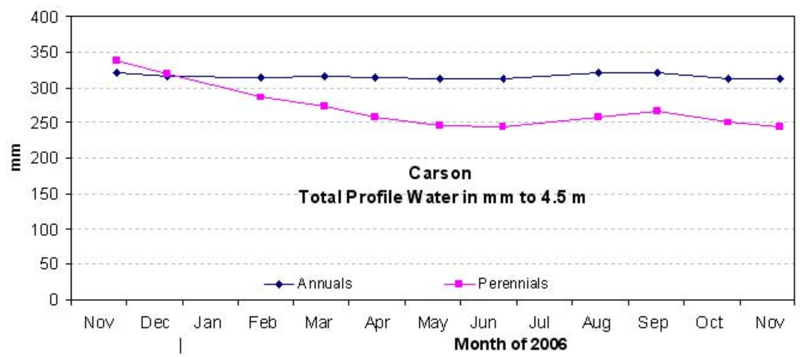
(a) The extra water below the annual pasture to 4.5 m. Note the large standard deviation ~ Nov



(b) Storage to 1.4 m compared to 4.5 m



(c) Total storage, Annuals and Perrenials, to 4.5 m



(d) Total storage, Annuals and Perrenials, to 1.4 m

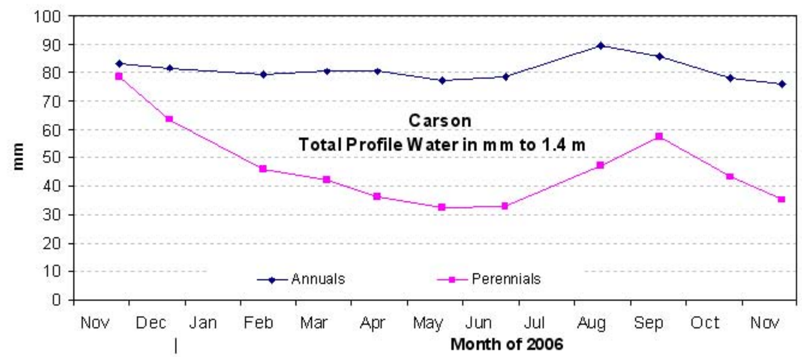


Figure 15. Carson, mm of water in the profile ~ 2006.

(a) The extra water below the annual pasture to 4.5 m. Note the large standard deviation ~ Nov

(b) Storage to 1.4 m compared to 4.5 m

(c) Total storage, Annuals and Perrenials, to 4.5 m

(d) Total storage, Annuals and Perrenials, to 1.4 m

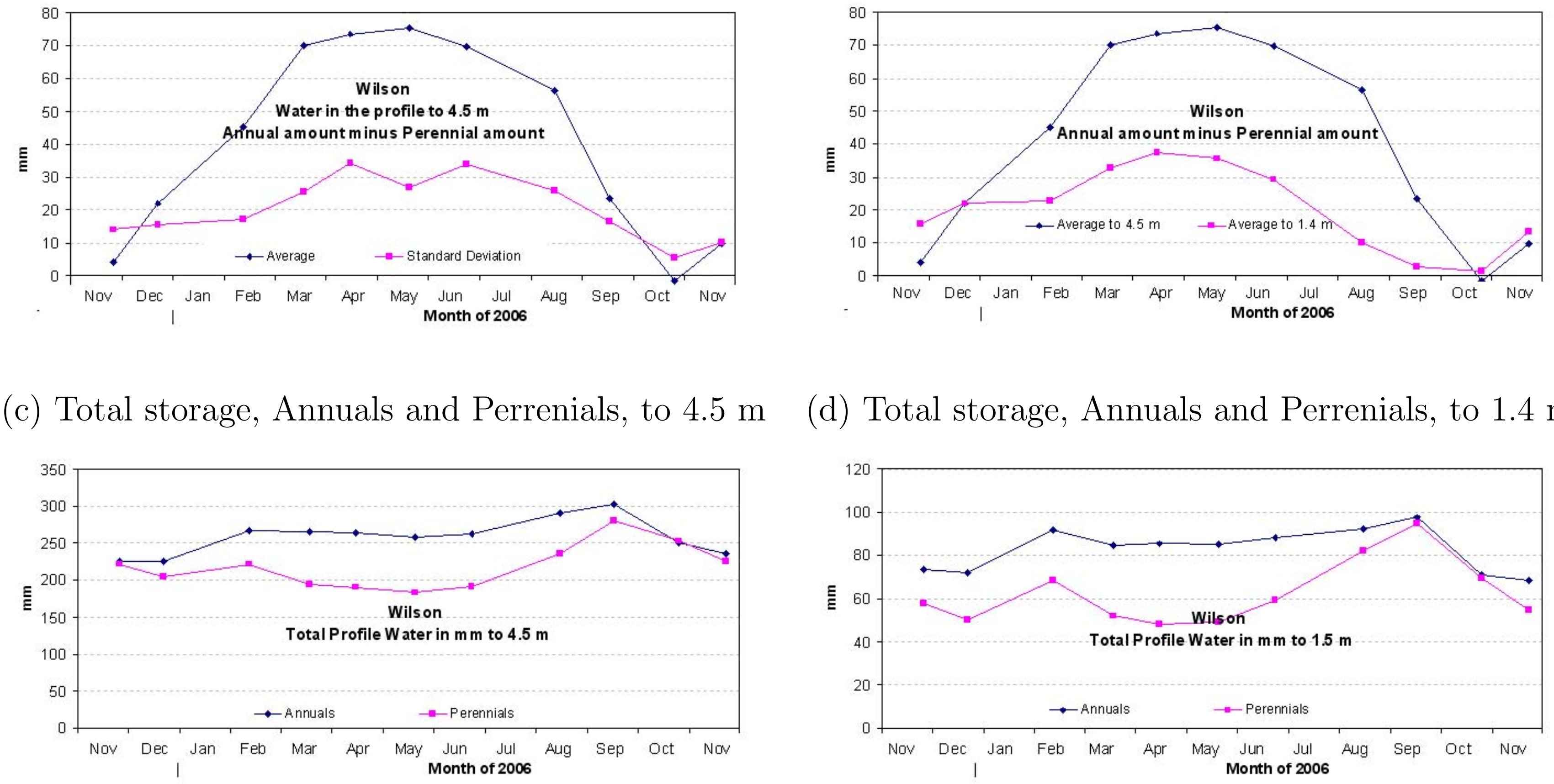


Figure 16. Wilson, mm of water in the profile ~ 2006.

The statistics at the Nixon site are good (Figure 14(a), page 20) as the standard deviation is low for the different profiles the whole of 2006. Here, the water that the annuals left over in the profile was 91 mm. Only $\sim$ 30% of this was in the upper 1.4 m (Figures 12(b), (c) and (d)). The Carson site (Figure Carson-summary) presents a similar story with $\sim$ 50% of the soil water in the upper layer, though there is too large a variability between individual bores with the small amounts of water in Nov, Dec and Jan. Perennials lost $\sim$ 90 mm over the year, half from the upper layer; annuals, $\sim$ 8 mm, mostly from the upper 1.4 m of the profile. The Wilson site also presents benefits of perennials in terms of water useage, confirmed with measurements in the upper 1.4 m (Figure 16(b)); about 50% of the profile water. Most of the effects are in summer with (in this case alone) a gain of 9 mm for the annuals, 4 mm for the perennials.

9. The Barry Carbon Model

The Barry Carbon model was formalised by Carbon and Galbraith (1975) with the presentation of its conceptual layout and Fortran codes. It is a 1D vertical model that uses a soil-limit to plant growth that has proven to be robust and functional in a wide variety of scenarios, including Jarrah Forest, sorghum, and lawns (Carbon, 1973; Carbon, 1975; Cock and Scott, 1990). It uses the Whistler et al.(1970) radial, steady state solution for flow to roots and, because of the soil limit to growth and the fact that plants are opportunistic, the roots and plant growth can be simulated without great detail root sizes and root lengths.

Further work in Western Australia by Phil Scott (1983) and Paul Raper (1985) showed that the model could simulate detailed growth in grapevines interlaced with barley in orchard rows. Phil Scott considered use of unsaturated hydraulic conductivities using the Childs and Collis-George (1950) technique, from the soil moisture characteristic. Paul Raper added a special algorithm for evaporation from the surface, similar to the Whistler et al. (1970) approach. The model was refurbished by Smith (1998) as a simplest GUI version for Groundwater Training called *Corn*. A version has been fitted into complex, 2D+ topographical models of broadacre and forested situations (Croton and Barry, 2001; Croton and Bari, 2001); it allows estimates of unsaturated and saturated, underground and surface flows, recharge and runoff, to streams and dams as details within catchments.

The intent is to use the rudimentary characteristics of Barry Carbon balance to revise the related transient method of Staple and Lehane (1954) as a estimator of 'best' unsaturated soil properties (see Scott 1996). The simple 1D model is analogous to a bucket brigade whereby the water received from rainfall is passed down through the profile within vertical bins. Along the way, the water is redistributed by unsaturated (or saturated–if a water table is present) Darcian groundwater flow or is taken up by roots. At the surface, water evaporates as limited by the soil at the surface or is transpired by the leaves (through the roots). Water remaining at the bottom of the computed domain passes out as deep drainage (or upward as capillary rise). When the bottom is free draining, the water potential is considered constant and volumetric water content is at field capacity. Two parameters predict the unsaturated hydraulic conductivity in every bin; two parameters predict the overall growth of roots through the profile. The root growth is an exponential form that has most of the roots close to the surface; this has been found appropriate for most plants, annual and perennial, provided the phenology and management specifics (germination, flowering, senescence, cropping) are known.

The Corn model has a table of hydraulic and root properties and another table of daily rainfall and evaporation. It is fitted with a Gnuplot output that produces a coloured contour map or picture (similar to the Figures on pages 13-15). An illustration of the output is shown on Figure 9, colour-contour map/pictures that represents θ_v values with colour (grays) at given vertical (depth) and horizontal (time) crossection with a depth of 6 m along the vertical and a year along the horizontal. Real rainfall for Paynes Find is used; guesses were made for moisture transport properties and there is no plant growth. (Indeed, It is possible to run the model for several years, repeating the rainfall record to get a *quasi-steady climatological soil moisture* profile.) Initial θ_v values are from the Nixon farm. With permeable sand characteristics, there is penetration through the profile with each rainfall. In this *fallow* situation it is clear that, even with deep drainage, water accumulates deep in the profile. There is not a decent level of evapotranspiration–which normally would come from the transpiration of plants. Completing the simulation properly still requires organising correct meteorological, phenological and management data sets and fitting the unknown parameters it get a best calibration, a best hydrological conveyance, and realistic plant growth.

In future the model should evolve to

1. -produce a best fit (maximum likehood) to the NMM values between 1.4 and 6 m. This simply means using a Trial and Error fitting of about 6 parameters: 2+ for soil water conveyance and storage, 2 for plant roots, and 2 for the *a* and *b* values of the NMM, extrapolating the calibration data from 1.4 m to 6 m.

2. -interlace the bore logs and soil profile data to determine the need to consider macropore flow, layering, as well as anisotrophic and hysteretic effects. It may not be possible to treat layers simply as homogeneous.

3. -with the best parameters for each site, allow *What-If* games to be played to different senarios. That is, planting perannials with different climatic data, different locations, or different management options; cropping, fencing, rotations, mixing with annuals, etc.

The horizontal corresponds to 600 Julian days from 1Jan05, $\sim 2\frac{1}{2}$ years simulation. The vertical is in m, a total of 6 m. The gray scale in the lower right grades from a Θ_v of 0.0 to a Θ_v of 0.3 going from white to black. Rainfall/evaporation is from Paynes Find for 2006, repeated. Initial Θ_v values are measured values from the Nixon site, 24Nov05. The saturated $\Theta_v = 0.3$; saturated $K =$ 10 m/day; the Brooks & Cory soil moisture $\eta = 5$; all these properties are for a sand.

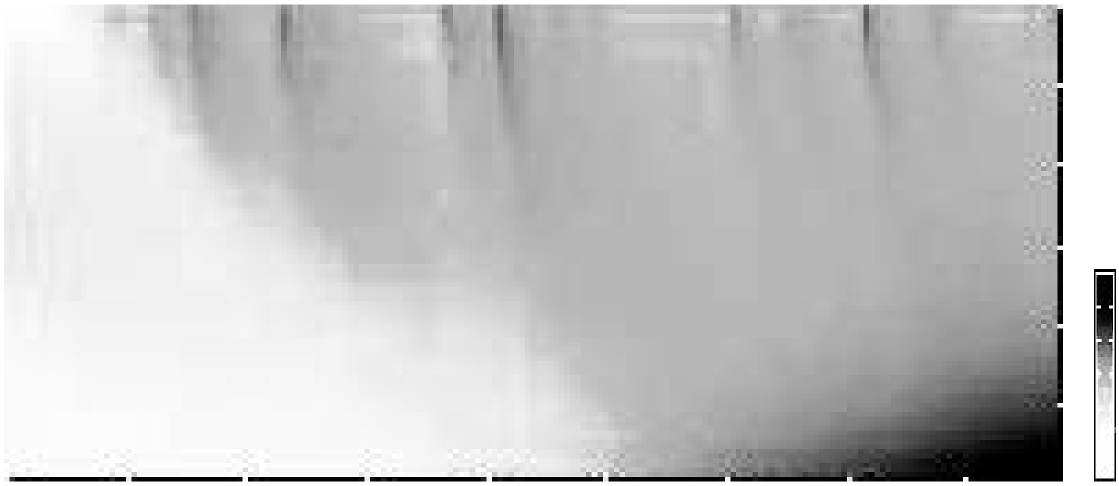


Figure 17. Simplest Model Output

Table I. Comparison of Annual Water Loss in the Profile

The Diminished Water Storage through the Year with Perennials and Annuals November 2005 to November 2006 mm less water stored in the profile

Data Set		Perennials Overall to 4.5 m depths	Perennials Overall to 1.4 m depths	Annuals Overall to 4.5 m depths	Annuals Overall to 1.4 m depths	Differences Annuals-Perennials to 4.5 m depths	Differences Annuals-Perennials to 1.4 m depths
Forsyth	1^{st}	152.8	60.6	103.2	51.2	49.7	9.4
	2^{nd}	120.6	69.8	68.2	59.2	50.8	9.0
Gillam	1^{st}	98.3	35.7	8.7	3.4	89.6	32.3
	2^{nd}	106.0	35.8	9.4	3.5	96.6	32.3
Parker	1^{st}	41.3	61.4	20.7	36.9	20.6	24.4
	2^{nd}	45.8	54.3	27.9	34.7	17.9	19.5
Nixon	1^{st}	91.3	14.7	16.2	5.2	75.1	9.5
	2^{nd}	96.3	14.9	17.0	5.2	79.4	9.6
Carson	1^{st}	136.9	43.5	6.4	7.1	130.5	36.4
	2^{nd}	161.0	37.1	5.4	6.2	155.7	31.0
Wilson	1^{st}	-3.6	2.7	-9.3	4.9	5.7	-2.3
	2^{nd}	-4.4	2.8	-10.7	5.4	6.3	-2.6

10. Closing

It is clear that the perennials produce an even usage of water with time and through the depth profile, with a higher water use. That water use may be seen in two ways; a decrease with under-recharge or as a decrease with withdrawal (by plants and evaporation), year to year. The ever-decreasing amount of rainfall contributed, overall, to a substantial decrease in the profile in 2006. With perennials substituted for annuals, it appears that the decrease is $\sim$ 50 mm to $\sim$ 150 mm more. In a fallow situation, of course, the lack of transpiration may well result in ever-increasing profile water, with various consequences, including waterlogging and salinity.

A summary of differences through the year (November-November) is presented on Table I. The data are separated into Perennials and Annuals and the Annual-Perennial Difference; each of these columns are for two different profiles, to 4.5 m and to 1.4 m. Generally, the story from both profiles is the same; that means that the extrapolations could not have been all that misleading; the values are at least consistent.

The Table clearly shows that most sites show a significant removal of water, mostly by the perennials. in summer in some cases (Wilson, Figure 10 on page 15) there is a 'near-to-equilibrium' in the profile with little, if any, change in the total water use with time.

In the Table the Parker site exhibits an *anomaly*; the losses to 1.4 m are greater than the losses to 4.5 m. This is not impossible, it shows the site was gaining water in the lower regions while losing water in the upper regions during this November-November period (See the contours on page 9). Surprisingly the perennials show more of the effect. Remember the extrapolation, however, and the relative insignificance of the these data (Figure 13(a)).

Most of the sites show less water over the November-November period. The Wilson site, however, could show a rather insignificant, gain particularly with the annuals, at lower depths. The reality is that the site is near to being sustainable; with the competing weather and management difficulties, let us hope it is in for a continuing level of profit.

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