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11
12 *Attorneys for Plaintiffs*

13 **UNITED STATES DISTRICT COURT**
14 **NORTHERN DISTRICT CALIFORNIA**

15
16 **BESS BAIR, et al,**
17 **Plaintiffs,**
18 **v.**
19 **STATE OF CALIFORNIA**
20 **DEPARTMENT OF TRANSPORTATION,**
21 **CINDY McKIM, in her official capacity as**
22 **Director of the State of California**
23 **Department of Transportation,**
24 **Defendants.**

Case No. 3:10-cv-04360 WHA
**SUPPLEMENTAL DECLARATION OF
JOE R. McCBRIDE IN FURTHER
SUPPORT OF PLAINTIFFS' MOTION
FOR PRELIMINARY INJUNCTION**

(National Environmental Policy Act; Wild and
Scenic Rivers Act; Administrative Procedure
Act)

Hearing Date: June 30, 2011
Time: 2:00 p.m.
Courtroom: 9
Judge: Hon. William H. Alsup

1 I, JOE R. McBRIDE, declare as follows:

2 1. I am a consulting professional forester, California License No. 1306 and am a
3 Professor of Forestry and Landscape Architecture at the University of California, Berkeley. My
4 professional qualifications are discussed in more detail in Declaration In Support Of Plaintiffs'
5 Motion For Preliminary Injunction filed on May 25, 2011 ("May 25th Dec.") and Exhibit 1
6 attached thereto.

7 2. I make this declaration based on my personal knowledge, expertise, experience,
8 and the materials and activities described in my May 25th Dec., Exhibit 2 attached thereto, and
9 the documents attached hereto. If called as a witness, I would and could testify to the following:

10 **I. MY CONCLUSIONS REGARDING THE PROJECT'S IMPACT**

11 3. At the conclusion of my May 25th Declaration, I stated unambiguously "it is my
12 opinion that a substantial, irreparable damage would occur to the trees in the Project area as a
13 result of the proposed project. It is my opinion that this would, in turn, cause negative impacts to
14 the overall health of the forest in the vicinity of the Project area."

15 4. This conclusion, which I still hold, was based on the numerous negative effects
16 that I determined the Project would have, which I detail in the preceding paragraphs of my May
17 25th Dec.

18 5. Though I believe that my May 25th Dec. was unambiguous in this regard, I
19 understand that Caltrans in their Opposition to Plaintiffs' Motion for a Preliminary Injunction
20 ("Caltrans' Opposition") has misinterpreted certain statement that I made therein. I offer the
21 following in order to correct any perceived ambiguities.

22 **A. Impacts from Proposed Soil Cutting and Fill**

23 6. In Paragraph 39 of my May 25th Dec., I refer to the "demise of [certain] trees as
24 result of soil cutting and filling."

25 7. As I explained in the previous Paragraph 37 of my May 25th Dec., as a general
26 matter, "trees in the vicinity of the Project would be negatively impacted by soil cutting and
27 filling." As I went on to explain in this paragraph, "[t]he severity of this impact would depend
28 upon the depth of soil cutting and filling in relation to the distance of the tree." (In paragraph 20

1 of my May 25th Dec., I noted that one of the many deficiencies in the Caltrans' analysis was its
2 failure to distinguish the effects that *extensive* soil cutting and filling in the vicinity of a redwood
3 would have from the effects that *minimal* soil cutting and filling in the vicinity of a redwood
4 would have.)

5 8. I explained in Paragraph 37 that the soil cutting and filling called for by Project
6 "would result in decrease in soil moisture and feeder roots of the trees in locations where cutting
7 takes place and a decrease in soil moisture and oxygen in the areas of fill. This would, in turn,
8 cause a decrease in the trees capacity to absorb water, oxygen, and soil nutrients as well as
9 severing structural roots that support the tree." (The terms "feeder roots" or "fibrous roots" are
10 commonly used to describe small, fibrous roots, in contrast with the terms "woody roots" or
11 "large roots," which are used to refer to larger more woody roots. Roots transition from fibrous
12 or feeder roots to woody or larger roots at approximately 1/8 inch in diameter.)

13 9. As I explained in Paragraphs 11-14 of the Declaration, these phenomena are know
14 to result in both significant reductions in the health and vigor of affected redwoods as well as the
15 death of such trees from toppling or "tree failure," as it is technically referred to.

16 10. In this regard, it is important to note that redwoods live for a very long time,
17 exceeding the life expectancy of most other tree species. Moreover, redwoods have very few
18 natural pest enemies. In most cases the demise of a redwood is understood as being almost
19 always caused by external factors, particularly loss of structural support as a result of damage to
20 its root system, which in interaction with wind can cause the tree to topple over and die, and/or
21 factors that prevent the tree from gaining sufficient water, oxygen, and/or soil nutrients.

22 11. In Paragraph 38, I identify thirty-seven (37) trees, in the vicinity of which the
23 Project calls for soil cutting of 12" or greater and/or soil filling of 12" or greater. These trees,
24 which I identify by number, include a giant ancient redwood with a diameter at breast height
25 ("DBH") of 216" or 18' (tree No. 9), a giant ancient redwood with a DBH of 120" or 10' (tree
26 No. 11), a giant ancient redwood with a DBH of 132" or 11' (tree No. 22), a giant ancient
27 redwood with a DBH of 115" or 9.6' (tree No. 38), a giant ancient redwood with a DBH of 132"
28 or 11' (tree No. 75), a giant ancient redwood with a DBH of 136" or 11.3' (tree No. 76), a giant

1 ancient redwood with a DBH of 144” or 12’ (tree No. 84), and a giant ancient redwood with a
2 DBH of 120” or 10’ (tree No. 96).

3 12. As I stated unambiguously in Paragraph 38 my May 25th Dec., all thirty-seven of
4 these trees, including the giant ancient redwoods listed above and a number of other very large
5 redwoods, “would be severely impacted” by the soil cutting and filling proposed by Caltrans in
6 their vicinities. (emphasis added)

7 13. Moreover, these severe impacts are likely to include the deaths or “failures” of
8 particular trees. Accordingly, in Paragraph 39, I referred to the “demise” of certain trees that the
9 proposed soil cutting and filling would cause and the knock-on effects that the demise of these
10 trees would have on other redwoods in their vicinities.

11 **B. Impacts From Proposed Culvert Work And Proposed Irrigation**
12 **Minimization Measures**

13 14. In my May 25th Dec., I stated in Paragraph 40: “[t]rees adjacent to culverts that
14 are to be replaced would suffer loss from both structural and feeder roots.”

15 15. As discussed above, elsewhere in my May 25th Dec., including Paragraphs 11-14,
16 I described the known consequences that result from these impacts including the reduction in the
17 health and vigor of affected trees and tree failures.

18 16. I identified, in Paragraph 40, seven trees that “can be expected to be negatively
19 impacted due to their proximity to existing culvert that would be replaced or modified, resulting
20 in decreased tree nutrition and die back of the root systems.” These trees include a giant ancient
21 redwood with a DBH of 115” or 9.6’ (tree No. 38).

22 17. I understand that Caltrans on page 6 of its Opposition claims that this analysis
23 “ignore[s] the additional irrigation measures the Project includes to address this.” This is
24 incorrect.

25 18. As stated in my May 25th Dec. at paragraph 9, “I reviewed reports and reviews on
26 the road realignment project, including, in particular, the Environmental Impact
27 Report/Environmental Assessment and Programmatic Section 4(f) Evaluation and Finding of No
28 Significant Impact (“EA/FONSI”) and its appendices.” This review included a review of

1 Caltrans' proposed minimization measures including irrigation of the roots.

2 19. It is my opinion, and it was my opinion, when I wrote my May 25th Dec. that
3 these minimization methods would not be effective and, in fact, are likely to negatively affect the
4 health of redwoods in the areas where these methods are used.

5 20. As to the proposed irrigation in the root zones, in particular, I am concerned with
6 the potential summer irrigation might have on the oxygen supply in the root zone. On well-
7 drained soil, irrigation water quickly percolated down through the soil profile allowing for air to
8 move into the soil from the atmosphere. If compaction of the soil takes place during soil filling
9 and/or the replacement of culverts, which I stated in my May 25th declaration I believe would
10 occur as a result of proposed Project activities, easy percolation of irrigation water will not
11 occur. This would result in water logged soils and that can present serious problems for root
12 respiration in the summer time. Soil saturation of redwoods in the winter is not so much a
13 problem as the metabolism of the trees is shut down. The situation is different during the
14 summer months when the root system needs oxygen for nutrient uptake and root respiration.
15 Thus, I believe that the use of irrigation in the manner proposed by Caltrans would have
16 adverse, rather than ameliorative, effects on the redwoods.

17 **C. Impacts From Desiccation Resulting From The Project**

18 21. In my May 25th Dec., I identified thirty-five (35) trees "that would experience
19 increased wind velocities in their vicinities and related desiccation as a result of the road
20 realignment project." I further stated: "This, in combination with the reduction in soil moisture
21 due to soil compaction and the cutting of feeder roots, described above, would result in the death
22 of tops of trees and can lead to tree failure." (emphasis added).

23 22. The thirty-five trees that would be impacted in this way include a giant ancient
24 redwood with a DBH of 120" or 10' (tree No. 11), a giant ancient redwood with a DBH of 156"
25 or 13' (tree No. 21), a giant ancient redwood with a DBH of 115" or 9.6' (tree No. 38), a giant
26 ancient redwood with a DBH of 180" or 15' (tree No. 62), a giant ancient redwood with a DBH
27 of 132" or 11' (tree No. 69), a giant ancient redwood with a DBH of 120" or 10' (tree No. 99),
28 and a giant ancient redwood with a DBH of 108" or 9' (tree No. 100).

1 23. As I explained in my May 25th Dec., several elements would increase wind
2 velocity in the vicinity of these trees, including the planned removal by Caltrans of fifty-four
3 (54) small trees that presently act as wind buffers, Paragraph 44, the “demise” of other trees that
4 presently act as buffers in their vicinities as a result of the proposed soil cutting and filling in
5 their vicinities, Paragraph 39, and the increased wind velocities caused by increased number of
6 large trucks moving through the grove (which I understand is the goal of the Project) and the
7 increase of speed of vehicles traveling through the Grove, which I believe would be a likely
8 result of Caltrans’ planned road realignments.

9 24. Again, as I stated in my May 25th Dec., based on all of the above described
10 impacts and other impacts detailed in my May 25th Dec., it is my opinion that substantial,
11 irreparable damage would occur to the trees in the Project area as a result of the proposed
12 project.

13 **II. DEFICIENCIES IN CALTRANS’ ANALYSIS OF THE PROJECTS’ IMPACT**

14 25. As I made clear in my May 25th Dec., the giant ancient old growth redwoods that
15 still remain in the world, including those in Richardson Grove, are an irreplaceable natural
16 resource.

17 26. In light of this and accepted science concerning redwood physiology and the
18 effects of human activity thereon, I identified a number of disturbing shortcomings in the
19 analysis that Caltrans conducted concerning the Projects likely impact on the trees in the Project
20 area.

21 27. In response to certain statements I understand were made in Caltrans Opposition it
22 is necessary for me to add the following concerning such shortcomings:

23 **A. Failure To Conduct A Tree-By-Tree Analysis**

24 28. In Paragraph 20 of my May 25th Dec. I stated: “Based on my review of the
25 Caltrans documents I am concerned that Caltrans did not specifically evaluate the impact to each
26 tree within the impact zone along highway 101.” In other words, Caltrans did not conduct the
27 tree-by-tree analysis that is commonly accepted as the proper method to evaluate the effect of a
28 proposed project on trees in the project area.

1 29. I based this conclusion on several factors.

2 30. As I state in Paragraph 20 of my May 25th Dec., no distinction was made in any
3 of the documents, including the statements prepared by the Caltrans arborist or the Save-the-
4 Redwoods League arborist, regarding the relative impact of the Project on certain trees versus
5 others, despite the fact that the Project called for widely varying levels of soil cutting and fill
6 activities in vicinities of different trees. Rather, the documents, including both arborists'
7 statements, contained only general statements concerning the overall effect on all of the trees in
8 the vicinity of the Project. This demonstrates a failure to have analyzed the particular impact of
9 the Project on each tree. Again, given the irreplaceable nature of every giant ancient redwood
10 still in existence, such an analysis is required.

11 31. As I stated in Paragraphs 21-25, Caltrans failure to conduct the required tree-by-
12 tree analysis is also evident in the substantial inaccuracies concerning basic fundamental facts in
13 the EA/FONSI. Caltrans undercounted by a third the number of trees in the structural root zone
14 of which soil cutting and fill activities would take place: I identified one hundred and eight (108)
15 trees in this category, while Caltrans identified only seventy-four (74). Indeed, nine (9) of these
16 one hundred and eight (108) trees do not show up at all on Caltrans maps, including a very large
17 redwood with a DBH of 91" or 7.6'. A proper tree-by-tree analysis would not contain such
18 omissions. Moreover, it cannot be claimed that these omitted trees were included in any impact
19 analysis (tree-by-tree or otherwise), as they are not identified as impacted at all in Caltrans'
20 documents and, in the case of nine (9) such trees, are not even acknowledged to exist in those
21 documents.

22 32. In Paragraph 26 of my May 25th Dec., I identified analogous shortcomings in the
23 manner in which Caltrans reported the size of the trees in the impact zone. Several of the trees
24 that were identified by Caltrans as likely impacted by the Project were assigned inaccurate DBH
25 sizes. This, again, indicates that Caltrans did not conduct the required tree-by-tree analysis of the
26 Project's impacts. In order to conduct such an analysis, one extrapolates from the DBH of a tree
27 to the likely extent of its platform roots, which the Project activity would impact. Given that
28 Caltrans in many instances assigned incorrect DBHs to trees in the impact zone, it cannot be

1 claimed that they properly analyzed the impacts of the Project on each of these trees.

2 33. I understand that in support of its claim that it did, in fact, conduct a tree-by-tree
3 analysis, Caltrans cites in its Opposition Tables 9 and 10 of the EA/FONSI. However, as
4 indicated above, these tables fail to include information concerning the extent of the Project's
5 activities in the vicinities of thirty-four (34) of one hundred and eight (108) trees that would be
6 impacted by the Project. Moreover, as I stated in Paragraph 24 of my May 25th Dec., the
7 information contained in these tables do not correspond with each other or the maps created by
8 Caltrans. In some instances, in fact, the documents contained widely conflicting information
9 concerning the extent of soil cutting and filling to be done around particular trees. It is difficult to
10 credit Caltrans' assertion that it conducted a proper tree-by-tree analysis when the information
11 based on which it purportedly conducted such an analysis is conflicting.

12 34. Furthermore, as stated above and in Paragraph 20 of my May 25th Dec., Caltrans,
13 nowhere in the Project documents, describes the specific impacts that the Project would have on
14 particular trees, but rather only makes broad general statements regarding the Project's impacts
15 on all trees. Not only can these broad general statements not be credited in light of the widely
16 varying levels of soil cutting and filling that the Project calls for in the vicinities of particular
17 trees, it belies the claim that Caltrans conducted a tree-by-tree analysis of the Project's impacts.
18 In contrast with these broad general statements, I respectfully draw the Court's attention to the
19 Table A, attached as Exhibit 3 to my May 25th Dec., on which I describe, based on a tree-by-tree
20 analysis, my specific conclusions concerning the Project's likely particular impacts on each tree
21 in the Project area

22 **B. Failure To Properly Evaluate And Explain The Effectiveness Of Various**
23 **Proposed Minimization Methods**

24 35. Another shortcoming of Caltrans' analysis its reliance on certain minimization
25 methods, the effectiveness of which is unexplained and which, in my opinion, would likely cause
26 additional harm to the redwoods.

27 36. As stated in Paragraphs 31 of my May 25th Dec., it is my opinion the use of brow
28 logs "would have negative effects to the trees around which the procedure is employed."

1 37. Nowhere in the Project documents, including the arborists' reports, is there
2 citation to anywhere in literature supporting the effectiveness of this mechanism and I can find
3 no reference to this procedure in the leading text on arboriculture (Harris et al, 1999). I
4 understand, based on the email from Caltrans' arborist Darin Sullivan dated May 12, 2009 (a true
5 and correct copy of which is attached hereto as **Exhibit 1**), that the Caltrans' arborist justified the
6 use of brow logs as effective in allowing oxygen and air movement around the base of the trees
7 where the brow logs are proposed to be used, and that emission of carbon dioxide from the
8 breakdown of the brow logs would not be a problem. However, as I explained in my May 25th
9 Dec., oxygen moves vertically not horizontally to redwood roots; therefore the use of brow logs,
10 would do nothing to improve movement of oxygen to roots not located at the base of the tree.
11 Moreover, as to carbon dioxide concerns, the use of brow logs would do nothing to ameliorate
12 the effect that fill located away from the base of the trees would have on the ability of the tree
13 roots in those locations to expel carbon dioxide: the movement of carbon dioxide away from the
14 roots occurs vertically not horizontally.

15 38. As I stated above, it is also my opinion that the use of irrigation in the manner
16 proposed would have adverse effects on the redwoods.

17 39. Nowhere in the Project documents, including the arborists' reports, is there
18 citation to anywhere in literature supporting the effectiveness of this mechanism.

19 40. Moreover, I understand, based on that Caltrans intends to use as a guideline for
20 levels of irrigation in the vicinity of culvert work a University of Arizona Extension document
21 titled "Methods of Measuring for Irrigation Scheduling—WHEN," attached hereto as part of an
22 email from Caltrans arborist Darin Sullivan dated 7/8/09 (a true and correct copy of which is
23 attached hereto as **Exhibit 2**). This document is inadequate for this purpose, as it does not
24 account for the effect of compaction of the soil, which, as I discussed above, would in
25 combination with the proposed irrigation have adverse effects on the redwoods.

26 **III. MY QUALIFICATIONS**

27 41. As I explained in my May 25th Dec., I have a B.S. in Forestry from the University
28 of Montana, M.S. (Forestry) and Ph.D. (Botany) degrees from the University of California,

1 Berkeley. I have, further, published over 292 scientific articles and reports, including 35
2 environmental impact reports focused on impacts to vegetation and 46 vegetation management
3 plans. Of these 81 reports, 15 concerned properties supporting redwood forests. I am, and have
4 been for 42 years and 41 years, respectively, a Professor of Forestry and Professor of Landscape
5 Architecture at the University of California, Berkeley. A true and correct copy of my current
6 resume is attached as Exhibit 1 to my May 25th Dec.

7 42. As a professor of Forestry, for 42 years I have instructed graduate and undergraduate
8 students in forest ecology, which includes tree physiology and human impacts thereon.

9 43. To be qualified to author the articles and reports I have authored concerning
10 subjects related to tree physiology and human effects thereon, I was required to have expert
11 knowledge concerning these subjects.

12 44. More specifically, for dozens of articles and reports that I have written concerning
13 redwoods, I was required to have expert knowledge specifically concerning redwood physiology
14 and human impacts thereon.

15 **IV. CONCLUSION**

16 45. In conclusion and summary, the redwoods of Richardson Grove represent some of
17 the last standing giant ancient redwoods in the world. Several of these redwoods are very large,
18 and, thus it reasonable to assume that they are very old. They are, therefore, irreplaceable: once
19 destroyed they are gone and will not be replaced by equivalent trees from millennia.

20 46. Based on my experience, training, expertise, review of relevant documents, and
21 site visit, it is my unqualified opinion that the Project would cause substantial, irreparable
22 damage to these trees.

23 ///

24 ///

25 ///

26 ///

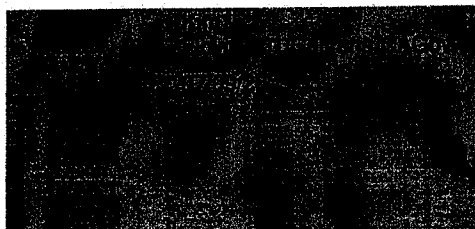
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EXHIBIT 1

of the small root hairs from any excavation work around the trees. It was mentioned to monitor the moisture of the leave. I don't think this should be required if the soil is maintained at a moist level. If this work done in the dry season, the area around the trees should be irrigated to compensate for any root loss.

Darin Sullivan
Department of Transportation, District 1
Tree Maintenance Supervisor
Certified Arborist #WE-7422A
(707) 825-0234 Cell (707) 489-0000
Kim Floyd/D01/Caltrans/CAGov

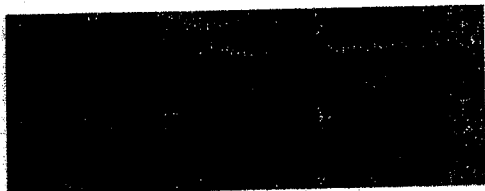


To Eric Lund/D01/Caltrans/CAGov@DOT
cc Darin Sullivan/D01/Caltrans/CAGov@DOT, Deborah
Harmon/D01/Caltrans/CAGov
Subject NSSP Richardson Grove

Eric,

While I am on vacation can you please work with Darin on what will likely be our 5th (?) nssp for the project. Darin is going to prepare directions to the RE and arborist on site regarding keeping the moisture level of the roots "consistent"

EXHIBIT 2



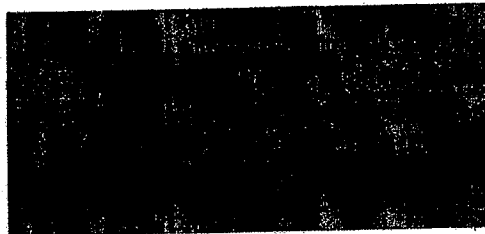
To Kim Floyd/D01/Caltrans/CAGov@DOT
cc Eric Lund/D01/Caltrans/CAGov@DOT, Deborah Harmon/D01/Caltrans/CAGov@DOT
bcc
Subject Re: NSSP Richardson Grove

Hi Kim, I added a file you might use when writing up the specifications.



methods of measuring for irrigation scheduling.pdf

Darin Sullivan
Department of Transportation, District 1
Tree Maintenance Supervisor
Certified Arborist #WE-7422A
(707) 825-0234 Cell (707) 489-0000
Kim Floyd/D01/Caltrans/CAGov



To Darin Sullivan/D01/Caltrans/CAGov@DOT
cc Eric Lund/D01/Caltrans/CAGov@DOT, Deborah Harmon/D01/Caltrans/CAGov
Subject Re: NSSP Richardson Grove

Darin,

We need more information on at what level we need to water and how much water. Eric will need to write up a specification for this as part of the contract. Should we get together to discuss
Darin Sullivan/D01/Caltrans/CAGov



To Kim Floyd/D01/Caltrans/CAGov@DOT
cc Eric Lund/D01/Caltrans/CAGov@DOT
Subject Re: NSSP Richardson Grove

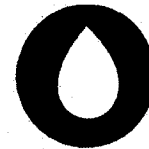
Hi Kim, I found myself sometime to reply to the water concern on the project at Richardson Grove.

Water is vital to plants. Tree absorb water and minerals dissolved in water from the soil. Without sufficient soil moisture, a tree cannot take up essential elements, photosynthesis is reduced and the tree will decline.

The amount of water needed by the plants varies with the species and size of the plant, the air temperature, humidity, light levels and wind movement over the leaves. Transpirational water loss from the leaves is controlled by the stomatal opening and closing in response to the environmental stimuli. when transpirational water losses exceed the plants ability to take up water from the soil, the plant wilts.

With respect to the large redwood trees I feel the disturbed soil should be monitored for moisture content. The soil should not be aloud to dry out. (Kept at field capacity) This is very important because of the loss

METHODS OF MEASURING FOR IRRIGATION SCHEDULING— WHEN

Arizona Water
Series No.30

Edward C. Martin

Introduction

Proper irrigation management requires that growers assess their irrigation needs by taking measurements of various physical parameters. Some use sophisticated equipment while others use tried and true common sense approaches. Whichever method used, each has merits and limitations.

In developing any irrigation management strategy, two questions are common: "When do I irrigate?" and "How much do I apply?" This bulletin deals with the *WHEN*.

Soil Moisture Techniques

One method commonly used to determine when to irrigate is to follow soil moisture depletion. As a plant grows, it uses the water within the soil profile of its rootzone. As the water is being used by the plants, the moisture in the soil reaches a level at which irrigation is required or the plant will experience stress. If water is not applied, the plant will continue to use what little water is left until it finally uses all of the available water in the soil and dies.

When the soil profile is full of water, reaching what is called *field capacity* (FC), the profile is said to be at 100% moisture content or at about 0.1 bars of tension. Tension is a measurement of how tightly the soil particles hold onto water molecules in the soil: the tighter the hold, the higher the tension. At FC, with a tension of only 0.1 bars, the water is not being held tightly and it is easy for plants to extract water from the soil. As the water is depleted by the plants, the tension in the soil increases. Figure 1 shows three typical curves for sand, clay and loam soils. As Fig. 1 shows, the plants will use the water in the soil until the moisture level goes to the *permanent wilting point* (PWP). Once the soil dries down to the PWP,

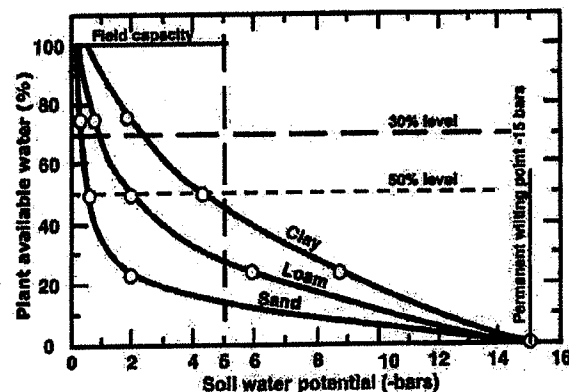


Figure 1. A diagram of typical tension and water amounts for sand, clay and loam. (Taken from the National Engineering Handbook, 210-VI).

plants can no longer extract water from the soil and the plants die. Although there is still some moisture in the soil below the PWP, this water is held so tightly by the soil particles that it cannot be extracted by the plant roots. The PWP occurs at different moisture levels depending on the plant and soil type. Some plants, which are adapted to arid conditions, can survive with very little moisture in the soil. With most agronomic crops, PWP occurs when the tension in the soil is at 15 bars. This means that the soil is holding on very tightly to the water in its pores. In order for plants to use this water, they must create a suction greater than 15 bars. For most commercial crops, this is not possible. At 15 bars, most plants begin to die. The difference between field capacity and PWP is called the *plant available water* (PAW).

Irrigation targets are usually set as a percent depletion of the PAW. This depletion level is referred to as Management

Allowable Depletion (MAD). The bulk of irrigation research recommends irrigating row crops such as grain or cotton when the MAD approaches 50%. For vegetable crops, the MAD is usually set at 40% or less, because they are more sensitive to water stress. These deficit amounts insure that water stress will not be so severe as to cause any appreciable yield losses. Careful monitoring of the PAW needs to be done throughout the season so that the appropriate point of irrigation can be anticipated. The following approaches can be used to determine soil moisture content.

THE "FEEL METHOD"

Determining soil moisture by feeling the soil has been used for many years by researchers and growers alike. By squeezing the soil between the thumb and forefinger or by squeezing the soil in the palm of a hand, a fairly accurate estimate of soil moisture can be determined. It takes a bit of time and some experience, but it is a proven method. Table 1 gives a description of "how the soil should feel" at certain soil moisture levels. In this table soil moisture information is given using inches per foot (in./ft). This term (in./ft) refers to how many inches of water are available in a foot of soil. For example, looking at sand (Table 1, column 1) we can see that the wilting point is about 1.0 in./ft. This implies that sand holds one inch of water per foot of soil. As the soil dries, it becomes harder to make a soil ball; soon the soil is crumbling in your fingers. Irrigation should occur somewhere in the shaded area, earlier for crops sensitive to water stress.

Let's look at clay loam. At a 0.4 in./ft deficit, a ribbon can be easily made when the soil is squeezed between the thumb and forefinger. Since the wilting point occurs at about 1.8 in./ft., a 0.4 deficit would equate to a 22% deficit (using Equation 1).

$$(0.4/1.8) * 100 = 22\% \quad (1)$$

Sandy loam soil makes a good ball at 0.6 in./ft deficit (about 40% deficit), but will not make a ball at all and only sticks together at 1.0 in./ft (about 66% deficit). Once you become familiar with the feel of the soil, it becomes easier to estimate soil moisture content. However, it takes time to become familiar with the feel of the soil and this method requires a great deal of experience.

NEUTRON PROBE

The neutron probe has been used extensively in research situations to determine soil moisture. A neutron probe or neutron moisture gauge contains a radioactive source that sends out fast neutrons. These fast neutrons are about the size of a hydrogen atom, a critical component of water. When fast neutrons hit a hydrogen atom, they slow down. A detector within the probe measures the rate of fast neutrons leaving and slow neutrons returning. This ratio can then be used to estimate soil moisture content. However, because every soil has some background hydrogen sources that are not related to water, calibration is important for each soil. To measure soil moisture with a neutron probe, an access tube is installed into

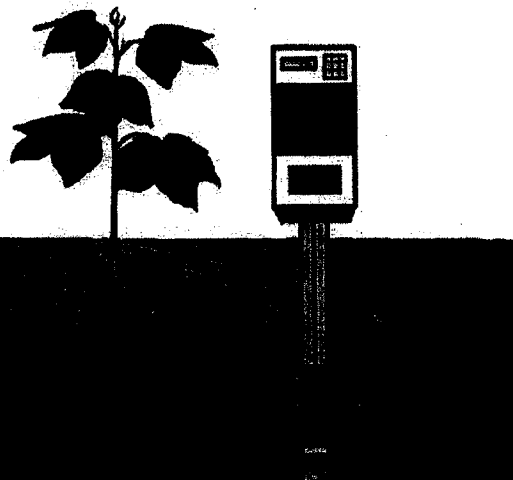


Figure 2. Diagram of a neutron moisture gauge (neutron probe).

the ground. Then, the probe (which contains the radioactive source and the detector) is lowered to the desired depth (Fig. 2). Probes are quite expensive (approximately \$6,400), and because they contain radioactive material, require an operating license.

ELECTRICAL RESISTANCE

Another method that has been used for several years to determine soil moisture content is electrical resistance. Devices such as gypsum blocks and Watermark sensors use electrical resistance to measure soil moisture. The principle behind these devices is that moisture content can be determined by the resistance between two electrodes embedded in the soil. The more water in the soil, the lower the resistance. In the early stages of development, it was discovered that a salt bridge can form between the two electrodes, giving false readings. Today, electrodes are embedded in more stable material and are not as susceptible to salt bridging. The practical use of these devices is limited as they operate best in the high range of soil moisture. To measure soil moisture, the blocks are buried in the ground at the desired depth, with wire leads to the soil surface. A meter (\$200-\$300) is connected to the wire leads and a reading is taken (Fig. 3). Retrieval of these instruments is difficult in clay soils, but they are relatively inexpensive (approximately \$25 ea.).

SOIL TENSION

As previously mentioned, as soil dries out, the soil particles retain the water with greater force. Tensiometers measure how tightly the soil water is being held. Most tensiometers have a porous or ceramic tip connected to a water column.

Table 1. Description of the soil texture parameters used to determine soil moisture using the feel method.

Soil Texture Classification					
Moisture Deficiency Inches/ft	Coarse (Loamy Sand)	Light (Sandy Loam)	Medium (Loam)	Fine (Clay Loam)	Moisture Deficiency Inches/ft
	(Field Capacity)	(Field Capacity)	(Field Capacity)	(Field Capacity)	
0.0	Leaves a wet coating on hand	Leaves a wet coating on hand	Leaves a wet coating on hand	Leaves a wet coating on hand	0.0
0.2		Makes a good ball			0.2
0.4			Forms a plastic ball. Slicks when rubbed	Will stick and pull apart easily	0.4
0.6	Sticks together slightly	Makes a good ball		Makes a thick ribbon	0.6
0.8	Very dry; loose, flows through fingers	Makes a weak ball	Forms a hard ball	Sticks when rubbed	0.8
1.0	Wilting point	Sticks together but will not ball	Forms a good ball	Makes a good ball	1.0
1.2			Forms a weak ball		1.2
1.4		Wilting Point		Clods crumble	1.4
1.6					1.6
1.8	A "Ball" is formed by squeezing a handful of soil firmly			Wilting Point	1.8
2.0	A "Ribbon" is formed between thumb and forefinger				2.0
2.2					2.2
2.4			Wilting Point		2.4

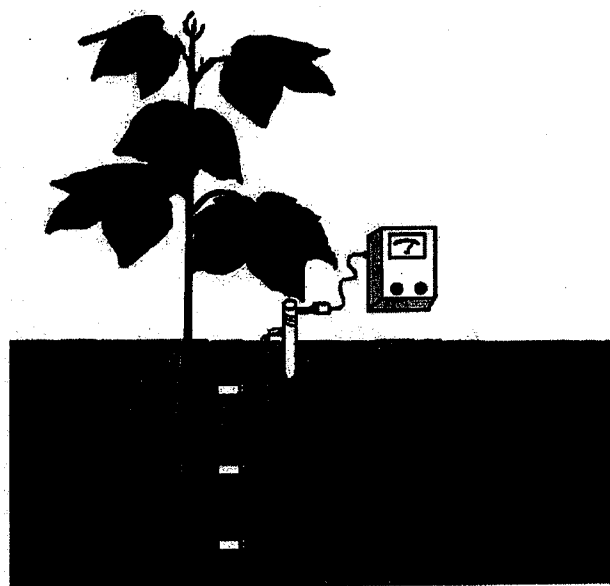


Figure 3. Diagram of resistance blocks. Here, three blocks are anchored by a stake in the field.

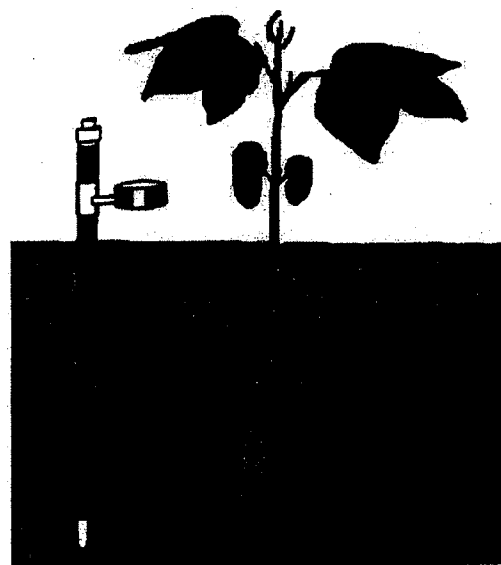


Figure 4. Diagram of a tensiometer. In some cases, the gauge is replaced with a connection for a transducer that measures suction.

The tensiometers are installed to the desired depth (Fig. 4). As the soil dries, it begins to pull the water out of the water column through the ceramic cup, causing suction on the water column. This force is then measured with a suction gauge. Some newer models have replaced the suction gauge with an electronic transducer. These electronic devices are usually more sensitive than the gauges. Tensiometers work well in soils with high soil-water content, but tend to lose good soil contact when the soil becomes too dry. Like the resistance blocks, they are difficult to remove from clay soils. Costs range from \$30 for small tensiometers with gauges to \$2000 for the electronic meters (reads multiple sites).

NEW TECHNOLOGY

New devices and methods become available to growers every year. Two new techniques for soil moisture determination are instruments using Time-Domain Reflectometry (TDR probes) and Capacitance (C-Probes, Frequency-Domain Reflectometers [RDR]).

TDR instruments work on the principle that the presence of water in the soil affects the speed of an electromagnetic wave (slows it down). The TDR sends an electromagnetic wave through a guide (usually a pair of parallel metal spikes) placed into the ground at the desired depth. It then measures the time it takes the wave to travel down the guide and bounce back (reflect back) up the guide. The time is recorded and

converted to a soil moisture reading. The wetter the soil, the longer it takes for the electromagnetic wave to travel down the guide and reflect back.

C-Probes and FDRs use an AC oscillator to form a "tuned" circuit with the soil. After inserting probes that are either parallel spikes or metal rings into the soil, a tuned circuit frequency is established. This frequency changes depending on the soil moisture content. Most models use an access tube installed in the ground (similar to the neutron probe).

TDR, FDR and C-Probes have all worked well, but have their limitations. They read only a small volume of soil surrounding the guides or probes. FDR and C-Probes are also sensitive to air gaps between the access tube and the soil. Many of these newer instruments require professional installation to operate properly. In soils where caliche and other hard pan layers exist, installing these probes may be difficult. This type of problem is compounded when the soil is dry. Cost for the probes range from \$5,000-\$10,000.

Plant Indicators

Also useful in determining WHEN to irrigate are plant indicators. Plant indicators enable the grower to use the plant directly for clues as to when to irrigate, not an indirect parameter such as soil or evaporative demand. Observing a plant characteristic can give you a good idea of the status of the field's moisture content.

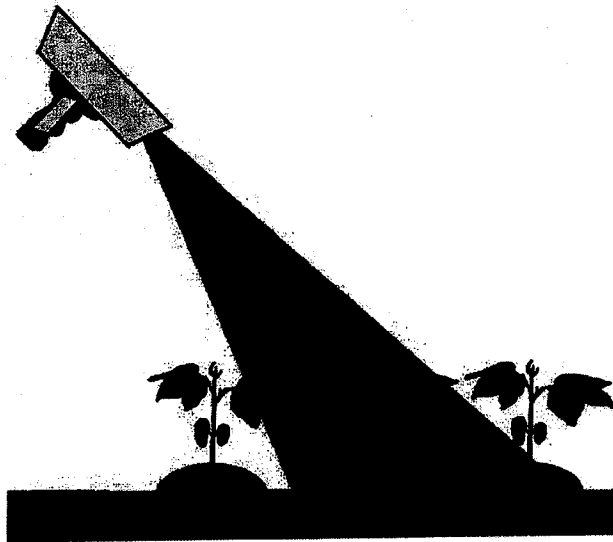


Figure 5. Diagram of an infrared sensor. This is a hand-held model.

INFRARED/CANOPY TEMPERATURE

An infrared (IR) thermometer measures the thermal temperature of the plant leaves or a crop canopy. Similar to humans perspiring to keep cool, plants transpire through openings called stomata. Once plants go into water stress, they begin to close their stomata and cease to transpire, causing the plant to "heat up" and the canopy temperature to rise. Infrared readings can detect this increase in plant temperature.

When using this method, baseline temperatures need to be taken prior to measurements. The baseline temperature should be taken in a well-watered field, free of water stress. On days when the air temperature is very high, some plants will stop transpiring for a brief period. If infrared readings are being taken at that time, they may read that there is a water stress when, in fact, it is just a normal shutdown period. Compare field readings with your well-watered readings to make your decision. IR also requires taking temperature readings on clear days at solar noon. This normally occurs between noon and 2:00 p.m. This is to assure that the measurement you are taking is at maximum solar intensity. During the monsoon season, this may be difficult to achieve due to cloud cover. Early in the season, IR readings will often measure soil temperature when canopy cover is sparse. These readings usually result in higher temperature readings since the soil tends to heat up quickly. Figure 5 is a diagram of a hand-held IR gun.

Computerized Irrigation Scheduling

The use of computer programs to help schedule irrigation was introduced in the 1970's. However, only recently with the introduction of fast, personal computers have they begun to gain wider acceptance. Several methods can be used to determine crop water use and help growers schedule irrigation. The most common is to use an equation to calculate the water use or evapotranspiration (ET) for a reference crop and relate that to other crops. ET refers to water loss from soil evaporation and plant transpiration. In the beginning of a crop's growing season, the plants are small and most of the water loss is through soil evaporation. As the plants grow and a canopy develops, the soil becomes shaded and most of the water loss is through plant transpiration.

Reference equations include alfalfa-based equations (ET_r) and grass-based equations (ET_o). There are several equations, each with its own advantages and disadvantages. In Arizona, the Modified-Penman equation is widely used. This equation uses weather data to predict the water use of grass. Other equations used with some success are the Blaney-Criddle, Jensen-Haise, Hargreaves and more recently the FAO 56 Penman-Monteith (Allen et al., 1998) and the Standardized Reference ET equation (ASCE-EWRI, 2005).

In addition to using equations to calculate a reference ET, evaporation pans are used to determine a reference ET which is then related to the crop ET. Also, there are energy equations and several other approaches to determining reference ET. Table 2 gives a list of popular methods.

As previously stated, in Arizona the Modified-Penman equation has been used for several years with success. Figure 6 shows a graph of the calculated reference ET (ET_o) using the Modified-Penman equation for dry onions grown in Central Arizona in 1996. Figure 6 also shows the measured crop water use for the crop (evapotranspiration of the crop - ET_c). Using the following equation:

$$ET_c = ET_o * K_c$$

the crop coefficient (K_c) can be calculated. Using several years of weather data and crop water use data, crop coefficients can be determined and a specific crop curve can be developed (Fig. 7). Using thermal time (Heat Units), these crop curves can be used in areas where daily temperatures differ.

Equally as important as the crop curve in irrigation scheduling are the soil water parameters. The PAW of the soil must be known as well as the FC.

In its simplest form, irrigation scheduling is similar to a checkbook balancing system. For most crops in Arizona, the soil is at or very near 100% moisture at planting time or just after irrigation. At those times, using ET_o equations with crop coefficients, daily crop water use can be determined. This is subtracted from the total water in the soil and a new soil water

Table 2. List of equations used to calculate reference ET.(Jensen et al., 1990).

Method	Time Step	Reference Crop	Reference Crop Type
Penman Monteith FAO 56	Hourly or Daily	Grass Reference (ETo) and Alfalfa Reference (ETr)	Depends on surface roughness and canopy
ASCE Standardized Equation	Hourly or Daily	Grass Reference, ETo	A hypothetical reference crop
Modified-Penman, FAO-24	Daily	Grass Reference, ETo	Well-watered grass, 3-6 in. tall
Jensen Haise	5 days	Alfalfa Reference, ETr	Well-water alfalfa 11.8-19.7 in. tall
Hargreaves	10 days	Grass Reference, ETo	Well-watered grass, 3-6 in. tall
Blaney-Criddle	Monthly/5-10 days	Grass Reference, ETo	Well-watered grass, 3-6 in. tall
FAO-24 Pan	5 days	Grass Reference, ETo	Well-watered grass, 3-6 in. tall
Kimberly-Penman (1982)	Daily	Alfalfa Reference, ETr	Full cover alfalfa

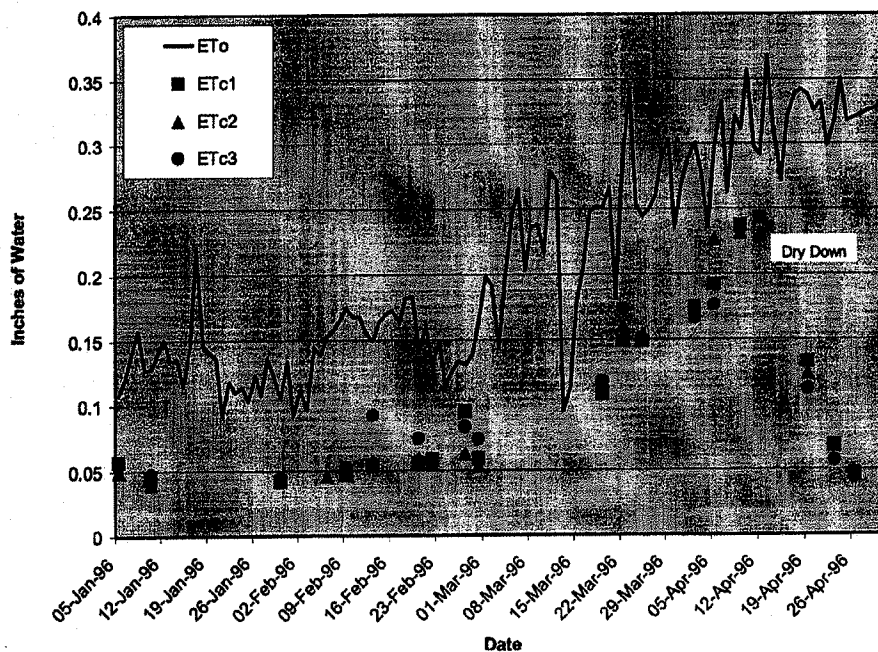


Figure 6. Reference evapotranspiration (ETo) and measured crop evapotranspiration (ETc) for dry onions in 1996, Maricopa, AZ.

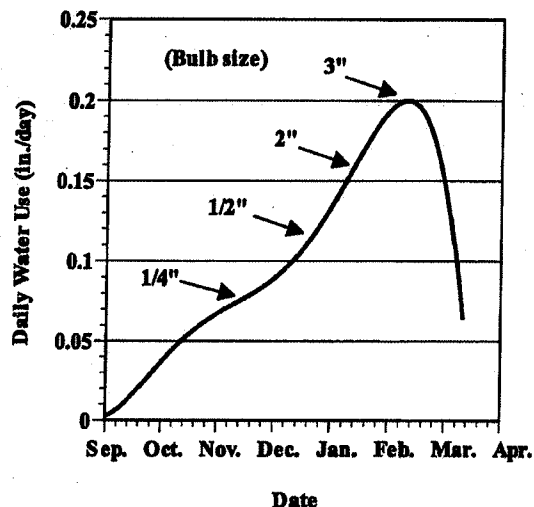


Figure 7. Crop coefficient curve for dry onions developed from ETo and Etc data from Fig. 6 and two other years of data from Maricopa, AZ.

content can be determined. This continues until the amount of depletion of PAW in the soil reaches a predetermined setting (the MAD). For many crops, the MAD is set to 40-50% in the rootzone of the crop. However, some crops, such as vegetable crops, are more sensitive to large fluctuations of soil moisture and the MAD are set to lower levels.

Conclusion

The most common irrigation scheduling methods used by growers are: scheduling according to the calendar (number of days since the last irrigation), looking at the crop for color change or digging in the field and feeling the soil to estimate soil moisture. Calendar scheduling does not take into account weather extremes, which may cause problems from year-to-year. Looking at the crop requires experience and a good eye—some growers have it, some do not. Even when you have a good eye, by the time the plant shows visible signs of stress, a yield loss has already occurred. Feeling the soil can give good estimates, but is often too time consuming for many growers. Also, when using this technique, one needs to take into account the soil profile of the active rootzone. Estimating rootzone depth can be difficult.

In this paper, we discussed some of the options available to assist growers in determining *WHEN* to irrigate. Whichever method is decided on, choosing a definite approach is always wise. Guessing can lead to unnecessary frustration, yield loss or excess water costs by the end of the season. Take your time and do some investigation before you invest in

any new soil moisture measuring system. An excellent place for information is on the Internet. A site called <http://www.sowacs.com> contains information on many of the instruments described in this publication. The site hasn't been updated recently, but it still contains some good links and information and is worth a visit.

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Issued in furtherance of Cooperative Extension work, acts of May 8 and June 30, 1914, in cooperation with the U.S. Department of Agriculture, James A. Christenson, Director, Cooperative Extension, College of Agriculture & Life Sciences, The University of Arizona.

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