Impact of Canal Water Flow On the Health of Cottonwood Trees Growing Adjacent to Colorado's Historical High Line Canal

Final Report for 2008

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W.R. Jacobi and B. Goodrich
Dept Bioagricultural Science and Pest Management
Colorado State University, Fort Collins CO. 80523-1177
970-491-6927, Fax 970-491-3862, William.Jacobi@colostate.edu
970-491-5155, betsy.goodrich@colostate.edu

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Summary for 2008

Meteorological Conditions:

- Only 9.7 inches of precipitation were recorded at the old Denver Stapleton Airport (Cooperative Station ID #052220) between January and October 2008. At or above average (30 year mean) precipitation occurred in February, August, September and October. Below average precipitation occurred during most months of spring and summer 2008: January, March, April, May, June, and July.

o January	0.21"	41% of normal
o February	0.51"	104% of normal
o March	0.55"	43% of normal
o April	0.31"	16% of normal
o May	1.61"	70% of normal
o June	0.71"	46% of normal
o July	0.15"	07% of normal
o August	3.02"	166% of normal
o September	1.56"	137% of normal
o October	1.03	144% of normal

Canal Flow:

- The HLC head gate was first opened for the 2008 season on April 28 and water flowed until May 5, 2008. The second run of water was from May 21 – June 11. The third run was from August 11 – August 29.
- Water flowed in the upper sections of the HLC for a total of 49 days during 2008.
- Approximately 11,030 acre feet of water flowed in the HLC during 2008, down from 15,146 in 2007.
- The first of three runs of water in the canal occurred April 28-May 5, prior to the emergence of leaves on the cottonwood trees (water potential readings began June 4, 2008)
- From Cherry Creek to Tollgate, water was observed flowing in the canal from June 4 through June 19 (at Sites 8 and 9 only on June 19). The canal was observed to be dry from June 19 (Sites 10 – 14) to August 13, with the exception of Site 8, which was observed to have flowing water on July 13 and July 30 – September 3. The canal was observed to be flowing from August 20 to September 3 at all sites in this section except Sites 11-14, where the canal was muddy; and at Site 10, which was dry on September 3.
- From Tollgate to Sand Creek, flowing water was observed on June 4 and 11. The canal was dry from June 16 – August 13, and flowing from August 20 - August 27. This section of the canal was dry on September 3.
- From Sand Creek Siphon to the Arsenal Lateral had no flowing water in 2008 (Sites 4, 17, 25, 23, 16, 3, 2). Flowing water was noted in the canal at Site 23 on August 20 and 27. Water in the canal at this site is highly unlikely but if the crew noted it, the water might be from storm water or surface water running into the canal at that location.
- Cherry Creek to Tollgate Creek (past Aurora Golf Course) water flowed for approximately 38 days between May 4 and August 29 (Based on Denver Water data).
- Tollgate Creek to Sand Creek Siphon received limited amounts of water for 37 days between May 4 and August 29 (Based on Denver Water data).
- **Denver Water staff gauge data read "no data available" past Cherry Creek for 19 days of headgate flow from August 11 – 29, so all calculations of water flow past Cherry Creek include all 19 days (we have no way to know if water did or did not reach the area all 19 days).**
- The HLC head gate was closed for the 2008 season on August 29, 2008.

Leaf Water Potentials and Average Crown Dieback:

Mean leaf water potentials and crown dieback of cottonwood trees at research sites between:

Cherry Creek to Tollgate (8, 9, 10, 11, 12, 13, 14)	Average = -0.43 MPa, Dieback 7.7%
Tollgate to Sand Creek[a] (18, 6, 7, 20)	Average = -0.45 MPa, Dieback 30.6%[b] and 13.3%[c]
Sand Creek to Arsenal Lateral (2, 23, 17)	Average = -0.87 MPa, Dieback 82.7%

[a] Leaf water potential average excludes Site 19 – no live trees to collect leaf water potential data
[b] Dieback average includes 100% dieback of all trees at Site 19
[c] Dieback average does not include trees at Site 19

- During the first run of water in the HLC (April 28 – May 5), predawn leaf water potential readings were not recorded. Water potentials were recorded between June 4 and September 3, 2008.
- During the second run of the HLC where water reached Cherry Creek (May 25 – June 11):
    - Mean initial predawn leaf water potential (June 4) for sites from Cherry Creek to Tollgate Creek (Sites 8-14) was -0.34 MPa, and ranged from -0.19 (Site 14) to -0.59 (Site 9). indicating that a few of the trees began the 2008 growing season in moderately stressed condition, even though water reached these sites for 3 days in early May and was flowing from May 25 through June 11, when first readings were collected.
    - Mean initial predawn leaf water potential (June 4) for sites from Tollgate Creek to Sand Creek Siphon (Sites 6, 20, 7) was -0.45 MPa (data from Site 6 was dropped on June 4), indicating that a few of the trees began the 2008 growing season in moderately stressed condition, even though water flowed in the HLC for 3 days in early May and was flowing from May 25 through June 11, when first readings were collected.
    - ***Cherry Creek to Sand Creek combined: Initial pre-dawn water potentials were generally high in 2008, even though water was flowing in the HLC, and ranged from -0.19 (Site 14) to -0.60 (Sites 20 and 7) MPa. The initial mean of all sites upstream of Sand Creek (Cherry Creek to Tollgate to Sand Creek) for the first reading was -0.36 MPa.***
    - Mean initial predawn leaf water potential (June 4) from study trees past Sand Creek Siphon was -0.80 MPa, indicated these trees were severely stressed at the beginning of the growing season (water did flow past Sand Creek Siphon and was not observed at these sites during this time).
- During the third run of water in the HLC (August 11 - 29):
    - Mean predawn leaf water potential for trees at sites from Cherry Creek to Tollgate Creek (Sites 8 - 14) was -0.38 MPa (range -0.24 to -0.56 MPa).
    - Mean predawn leaf water potential from Tollgate to the Sand Creek Siphon (Sites 6, 7, and 20) was -0.47 MPa (range -0.34 to -0.59 MPa).
    - ***Cherry Creek to Sand Creek combined: Water potentials were generally high, even when water was flowing, and ranged from -0.24 to -0.59 MPa. The mean of all sites upstream of Sand Creek (Cherry Creek to Tollgate to Sand Creek) during the third run of water in the HLC was -0.42 MPa.***
    - Mean leaf water potential of trees past Sand Creek Siphon (Sites 2, 23, 17) was -0.77 MPa (no HLC water flow except observed water at Site 23 on August 20 and 27).
- When the canal was not flowing (June 19 – August 10):
    - Mean leaf water potential of trees between Cherry Creek and Tollgate (Sites 8-14) was -0.47 MPa; individual daily observations from this time ranged from -0.29 (Site 13) to -0.74 (Site 8) MPa.
    - Mean water potential of trees between Tollgate and the Sand Creek Siphon was -0.42 MPa; individual observations ranged from -0.29 (Site 6) to -0.86 (Site 6 again) MPa.
    - ***Cherry Creek to Sand Creek combined: Water potentials were generally high and ranged from -0.29 (Site 13) to -0.86 (Site 6). The mean of all sites upstream of Sand Creek (Cherry***

Creek to Tollgate to Sand Creek) during this time when water was not flowing in the HLC was -0.44 MPa.

- Mean leaf water potential of trees past Sand Creek Siphon (Sites 2, 23, 17) was -0.85 MPa.

- At sites downstream of Sand Creek Siphon (Sites 2, 23, and 17), no water flowed in the HLC during 2008; but flowing water was observed flowing in the canal twice at Site 23; on August 20 and 27, 2008.

Introduction

Plains cottonwoods (*Populus deltoides* Bartram ex Marsh. var. *occidentalis* Rydb) line the banks of the High Line Canal. The trees are scattered along the canal and in most areas are large diameter (***old***) trees. Some locations have small diameter (***young***), more dense groups of trees. The Denver Water Department is interested in the long-term health of these trees from Cherry Creek to the Arsenal Lateral. This study was initiated to obtain information on cottonwood tree health water status and management option for trees growing along the canal during times of fluctuating water flow in the canal.

Working Definition of Drought Stressed Cottonwoods:

Determining when a cottonwood tree is drought stressed is not easy since there are many confounding variables such as duration of drought, time of year, the long term situation of the tree's soil moisture and thus susceptibility to acute or chronic drought. Below is our best assumption of what average growing season predawn leaf water potentials indicate. These values are based on our studies and published literature:

Stress Level	Seasonal Average Water potential	Symptoms
Slight	> -0.30 MPa	none
Moderate	– 0.3 – 0.5 MPa	potential wilting during hot weather
Severe	<-0.5 MPa	branch dieback in current/ subsequent years

Our analysis of water potential data indicates that if a tree is stressed (water potentials less than –0.30 to -0.40MPa) in the spring the tree will have some crown dieback the next year. During 2008, all sites except 11 and 14 had initial mean water potentials equal to or less than -0.30 MPa. Predawn leaf water potentials fell below (were more negative) than –1.0 MPa at least once in the 2008 growing season at Sites 2 and 17.

Study Objectives

Original objectives:

1. Determine how long it takes for cottonwood trees to become drought stressed when water is withheld from the canal.
2. Determine how rapidly the trees recover after water is provided after a period of drought.
3. Determine the amount of water needed to relieve drought conditions in cottonwoods.
4. Determine when or how often this minimal water is needed to keep the cottonwood trees alive.
5. Determine the changes in soil moisture as water is withheld or added to the canal at sites along the canal where trees and soil moisture are monitored.
6. Determine if rainfall has any impact on the water status of the cottonwoods.
7. Determine if lining the bottom of the canal with plastic will allow enough water to reach trees lining the canal.
8. Determine if lining the bottom of the canal with PAM will allow enough water to reach trees lining the canal.

Revised* objectives:

1. Determine if two weeks of water in the spring and two weeks of water in the summer/fall in the High Line Canal is enough water to keep cottonwoods healthy between Cherry Creek and Sand Creek.
2. Determine if lining the canal with PAM from Cherry Creek to Fairmont will allow enough water to maintain the health of cottonwoods tree.

*Revised in 2004

Materials and Methods

Initial Study (1997-1999):

In 1997, 15 research sites (Table 1) were selected along the High Line Canal between Green Valley Ranch at the Arsenal Lateral and the Cherry Creek Siphon. The sites represented the range of diameters (ages) of cottonwood trees growing along this section of the canal. At each site, five trees that were located within 30 m of each other were selected for monitoring. Each tree had branches within 3 m of the ground so that leaves could be obtained for predawn leaf water potential readings. Each tree was tagged at 1.5 m with a numbered aluminum tag. Tree diameters were taken at 1.5 m (tag height) utilizing a diameter tape and were recorded to the nearest tenth of a centimeter. Tree heights were taken via an inclinometer and recorded to the nearest foot. Radial ncrements were obtained from increment cores taken at 1.5 m and recorded to nearest millimeter, utilizing a dissecting scope and fine ruler.

Tree size and tree health data were collected in 1997 and 1998 (refer to Appendix A: Code Sheet for Tree Evaluation Data). Tree water potential readings were taken *predawn* (10 PM- 2 AM) in 1997 and 1998. The canal was rarely without water since water flowed in the canal from the Waterton Canyon headgate for 172 days during 1997 and 132 days during 1998. During these years, water was sent via the canal to the Rocky Mountain Arsenal, resulting in water being in the canal at it farthest reach for 71 days in 1997 and 62 during 1998. Most of the area surrounding the High Line Canal also received additional water from above normal precipitation that fell in the area during both 1997 and 1998. During both years, precipitation during July was three times the normal amount of precipitation expected for July in the Denver-metro area. Surface water runoff probably entered into the canal at several locations. Since the trees were not drought stressed during these summers, predawn water potentials remained above -0.5 MPa.

Table 1. Cottonwood Research Sites along the High Line Canal (1997 – 2008).

Site	Name	Tree Tag #	Notes
1	Green Valley dry	11-22	Old trees, dry site along High Line Canal downstream of Arsenal lateral, discontinued to collect data from these trees after the 1999 growing season because the trees had been pruned too high to reach the branches.
25*	Green Valley dry	915B – 917B	Young trees, located downstream of the earthen plug, downstream of Site 2, no canal water flows to this site, added to study in 2000.
2*	Green Valley wet	23-27	Old trees, just upstream of Arsenal Lateral, trees are on the east side of canal (neutron probe access tubes are on both the east and west side of the canal and are referred to as 2E and 2W, respectively. Neutron probe access tubes were added at 2W in 1999 and at 2E in 2000.
3	Arsenal Lateral-1	28-32	Young trees, at Green Valley Ranch, just downstream of diversion structure and east of Site 16, but on south side of the canal.
16*	Arsenal Lateral -2	901-903	Young trees, at Green Valley Ranch, just downstream of diversion structure and west of site 3,on south side of canal; trees. Added to study in 1999 and neutron probe access tubes were added in 2000.
23*	Arsenal Lateral –3	919 - 921	Young trees, at Green Valley Ranch, located between Site 3 and Site 16 but on the north side of the canal; neutron probe access tubes added in 2000.
17*	Wagner Equipment	904-906	Young trees, on west side of canal, just east of Wagner Equipment Company, south west of the intersection of Smith Road and Tower Road. Added in 1999.
4	Super Value	38-42	Old trees, on north side of Super Value Office, 1938 Tower Road.
5	Sand Creek Siphon	33-37	Old trees, along both sides of canal near junkyard, downstream of siphon. Dropped from study in 2000 due to site accessibility issues.
Sand Creek			
18	Salida and 14th	907-909	Old trees, along north side of canal. Added to study in1999.
6*	Colfax Loop	43-47	Old trees, north west of the intersection of Airport Road and Colfax Avenue, up stream of Airport Road on the north side of the canal, neutron probe access tubes. Added to study in 1999.
19	Colfax Loop West	910-912	Old trees, west of site 6, on north side of the canal. Added to Liner study site study in 1999.
20*	Laredo and 12th	913-915	Young trees, on north side of canal. Added from study in1999.
21	Le Petite Academy	916-918	Young trees located on east side of canal. Added to study in1999. Dropped from study in 2001 due to construction in area.
7	Aurora Community College	48-52	Young trees, north side of canal, behind Aurora Community College.
Tollgate Creek			
8	Aurora Golf Course	78-82	Old trees, on north side of canal and north of the Aurora Golf Course, just downstream of 2nd Avenue.
9	Moline Crossing	73-77	Young trees, on north side of canal, just downstream from and east of Moline Street.
10	Kentucky / Dayton	68-72	Old trees, on south side of canal, at the south east corner of the intersection of Kentucky Avenue and Dayton Avenue.
11	Mississippi "Y"	83-87	Old trees, west side of canal, downstream Leetsdale / Mississippi / Parker "Y".
12	Quebec Way Big	63-67	Old trees, on west side of canal, parallel to Quebec Way.
13	Quebec Way Small	88-92	Young trees, on west side of canal, parallel to Quebec Way.
14	Iliff downstream	58-62	Old trees, on west side of canal, just downstream from Iliff.
15	Los Verdes Golf	53-57	Young trees, upstream from Iliff Avenue. Dropped from study in August 1999 due to site accessibility issues.
Cherry Creek			

*** Site with soil moisture monitoring tubes**

Modifications of Materials and Methods 1999-2008:

1999

- In 1999 five additional *predawn* leaf water potential sites were added (16, 17, 18, 19, 20 and 21).
- CSU monitored *predawn* leaf water potentials of all surviving trees at the 15 sites established in 1997 plus the six additional sites added in the spring. Data were collected for each site bi-weekly from June 10 to August 26. During September, we focused primarily on Sites 2, 6, 17, & 20; collecting readings on September 1-2, 8-9, 20-21, 22, 25, & 29. *Predawn* readings were again collected on October 1.

- *Daytime* tree water potential readings were recorded for all sites on July 7 & 22. *Daytime* leaf water potential readings were recorded for Sites 2, 6, 17, & 20 on August 17, 23, & 31 and September 21, 22, 23, 24, & 29; and October 1. *Daytime* leaf water potential readings were also recorded for sites 12, 13, & 14 on September 29 and October 1.

- In 1999, CSU installed neutron probe access tubes and monitored soil moisture at four sites (2, 17, 6, & 20) with a neutron probe August 17, 31, September 20, 21, 22, 23, 24, 25, and 29 and October 1, 6, and 8 at 1', 3', 5', 7' and at the bottom of the tubes. We also recorded water table depths on the same dates as soil moisture data was collected.

2000

- We added four new soil moisture monitoring sites at Green Valley Ranch in September and October 2000. Two sites (16, 23) were put on the Arsenal Lateral, one site (2 east) on the east side of the main canal at site 2, and one site (25) along the dry canal section past the plug at the Arsenal Lateral.

- We monitored soil moisture at four sites (2, 17, 6, 20) with a neutron probe every week from July 11, 2000 to September 13, 2000 at 1', 3', 5', and 7' and at the bottom of the tubes. We also recorded water table depths on the same dates as soil moisture data was collected.

- We monitored *predawn* leaf water potentials of all trees at Sites 2, 17, 6, and 20 every two weeks in July and August and ending on September 13, 2000.

- A self-contained weather station that collects temperature, relative humidity, absolute humidity, dew point every 15 minutes and rain fall on an event basis of 0.01-inch units was installed in November 2000 at Green Valley Ranch.

2001

- Soil moisture and water table data collection at the 9 sites began February 22, 2001 with collections monthly from February to June, bi-weekly in June and weekly in July, August, and September.

- We monitored *predawn* leaf water potentials at the eight soil moisture research sites bi-weekly starting June 25, 2001 and weekly in July, and August, and September; ending September 26, 2001.

- A self-contained weather station that collects temperature, relative humidity, absolute humidity, dew point every 15 minutes and rain fall on an event basis of 0.01-inch units, was installed in November 2000 at Site 17: Wagner Equipment Site.

- We assessed tree health status and took pictures of each tree during May (spring) 2001; no fall assessment was conducted.

- In early April 2001, Denver Water installed by-pass pipes in the canal at two existing site
  (Wagner Equipment) and Site 2 (Green Valley Ranch). These by-pass pipes allow wa
  flow to the Rocky Mountain Arsenal and at the same time allow water to be restric
  research sites. By restricting the flow of water at these selected sites, it was hy
  adjacent to the canal at these sites would become dry and that the trees at the

reduced water potentials. When the trees became stressed water could be added to help answer some of the research questions.

2002

- In the spring of 2002 DW had a contractor place a 30 mil plastic liner in the bottom of the canal for 600 feet. The canal bottom was excavated for 12 inches, liner laid down and liner edges cut into the canal bank. Twelve inches of soil was replaced on top of the liner. The assumptions were that the water would not move down but would move horizontally into the canal bank and allow water to reach tree roots. To test this, CSU installed three soil moisture access tubes (12 feet in length) upstream 100 feet from the end of the liner, three tubes in the middle of the lined section of the canal where three cottonwoods were growing and three downstream 100 feet from the end of the liner.

- CSU also took soil moisture measurements weekly at 9 research sites, collected meteorological data at two sites, took soil moisture and leaf water potentials at two sites when water was tanked to the two sites and recorded tree health and crown conditions in the spring and again in the fall.

- Denver Water collected leaf water potential data on a weekly basis beginning on May 30 and ending on September 19, 2002.

2003

A PAMS infiltration test was performed by Denver water at Site 6 in early August and September 2003.

The objectives of this test were:

1. To assess the benefits of an application of PAMS as a water-based solution, exclusively.
2. To test a dry powder cross-link of PAMS that has been incorporated into the canal soil in addition to the water-based PAMS, which is sprayed on after the dry cross-link application.
3. To quantify water availability to the cottonwoods after PAMS is applied.

After each application of PAMS, two separate water loss tests were conducted over a period of eight days.

Pond Construction

- **Pond 1**, which was the control pond, was built by inserting earthen dams in the canal channel. This created a pond roughly 300 feet in length. The high water line at this location is 2 feet. A staff gage was installed to mimic this height. The subsequent average wetted periphery of this pond when filled was 16.5 feet. The total average area of this pond was roughly 4,950 square feet. Pond 1 was not treated with PAMS.
- **Pond 2** was built in the same manner as Pond 1, creating a pond roughly 300 feet in length. The high water line at this location is 2 feet. A staff gage was installed to mimic this height. The subsequent average wetted periphery of this pond when filled was 18 feet. The total average area of this pond was roughly 5,400 square feet, which meant Pond 2 was 9% larger than the control pond.[1]

Once the ponds were established, Pond 2 was treated with an aqueous solution of PAMS on August 1, 2003. It was applied using a 700-gallon hydro-mulch machine and spray applicator, at a rate of 30 pounds per canal acre. This application of PAMS was done three days prior to the filling of the pond sections with water. It was applied to the dry canal up to the high water mark of 2 feet. At the time of this application, the canal had not run water since July 2, 2003, and some vegetation was growing in it.

Seepage Test 1

For the first seepage test (see Table One), water was fed into Ponds 1 and 2 using 2.5-inch diameter fire hoses attached to a nearby fire hydrant. Pond filling began at 8 a.m. August 4, 2003 and continued until the 2-foot high-water mark was reached, which was at approximately 1 p.m. This water level was maintained in an attempt to saturate as much of the periphery as possible until 5 p.m. At that time, the water was shut off and the rates of recession on the staff gages were recorded periodically until 8 a.m. On August 5, the ponds were again filled and the procedure of the previous day was repeated. In the same way, this routine was carried out daily until August 8, at which time the final reading was taken at 8 a.m. Seepage Test 1 was completed.

Table One: Seepage Test 1

		STAFF GAGE HEIGHTS			STAFF GAGE REDUCTION		
DATE	TIME	POND 1	POND 2	DIFF	POND 1	POND 2	% DIFF
4-Aug	8:00 AM	0.00	0.00	0.00	0.00	0.00	0.00
	5:00 PM	2.00	2.00	0.00	0.00	0.00	FULL
	8:00 PM	1.70	1.84	0.14	0.30	0.16	47%
	11:00 PM	1.64	1.75	0.11	0.36	0.25	31%
5-Aug	2:00 AM	0	0	0.00	0.00	0.00	0.00
	8:00 AM	1.00	1.34	0.34	1.00	0.66	34%
	5:00 PM	**2.00**	**2.00**	**0.00**	0.00	0.00	FULL
	8:00 PM	1.68	1.80	0.12	0.32	0.20	37%
	11:00 PM	1.56	1.70	0.14	0.44	0.30	32%
6-Aug	2:00 AM	1.32	1.56	0.24	0.68	0.44	35%
	8:00 AM	0.98	1.34	0.39	1.02	0.66	35%
	5:00 PM	**2.00**	**2.00**	**0.00**	0.00	0.00	FULL
	8:00 PM	NA	NA	NA	NA	NA	NA
	11:00 PM	NA	NA	NA	NA	NA	NA
7-Aug	2:00 AM	NA	NA	NA	NA	NA	NA
	8:00 AM	0.81	1.25	0.44	1.19	0.75	37%
	5:00 PM	**2.00**	**2.00**	**0.00**	0.00	0.00	FULL
	8:00 PM	NA	NA	NA	NA	NA	NA
	11:00 PM	NA	NA	NA	NA	NA	NA
8-Aug	8:00 AM	0.84	1.22	0.38	1.16	0.78	33%

It is important to note that this difference in the total area is negligible and does not skew the test results, according to Lloyd Garner, Garner Consulting, who was the technical consultant on this test.

Seepage Test 2

On September 2, 2003 – again using Ponds 1 and 2, with Pond 1 being the Control Pond – Pond 2 was retreated with a dry application of PAMS. In this application, PAMS in a powder form was applied to the canal using a broadcast seeder, which was pulled behind a rubber-tired three-wheeler. The dry PAMS was applied up to the 2-foot high-water line and was incorporated into the soil using a tooth drag. Afterwards, a spray application of the aqueous PAMS was applied using the same PAMS-to-water ratio as in the first test, which was 30 lbs. per canal acre.

For this second seepage test (see Table Two), water was fed into Ponds 1 & 2 using separate 2.5-inch diameter fire hoses, which were hooked up to a nearby fire hydrant. Pond filling began at 8 a.m., September 2, 2003 and continued throughout the day until the 2-foot high water mark was reached on each of the staff gages. This water level was then maintained in an attempt to saturate as much of the periphery as possible until 5 p.m. At that time, the water was shut off and the rates of recession on the staff gages were recorded periodically until 8 p.m. On September 3, the ponds were again filled and the procedure of the previous day was repeated. In the same way, this routine was carried out daily until September 5, at which time the final reading was taken at 8 a.m. Seepage Test 2 was completed.

Table Two: Seepage Test 2

DATE		POND 1	POND 2	DIFF			
2-Sep	8:00 AM	0.00	0.00	0	0.00	0.00	0.00
	5:00 PM	**2.00**	**2.00**	**0**	0.00	0.00	FULL
3-Sep	8:00 AM	0.91	1.18	0.27	1.09	0.82	27%
	5:00 PM	**2.00**	**2.00**	**0**	0.00	0.00	FULL
4-Sep	8:00 AM	0.86	1.10	0.24	1.14	0.90	21%
	5:00 PM	**2.00**	**2.00**	**0**	0.00	0.00	FULL
5-Sep	8:00 AM	0.85	1.12	0.27	1.15	0.88	23%

Tree Data

According to Dr. Bill Jacobi, Colorado State University plant pathologist, the water potentials of trees on the periphery of both Ponds 1 and 2 changed after two days of water sitting in the ponds. On August 6, water potentials increased from -0.36 to -0.25 MPa in Pond 2 (PAMS-Treated Pond) and from -0.39 to -0.29 MPa in Pond 1 (the Control Pond). This indicated that the cottonwood trees were less stressed after water was put into the ponds. These numbers indicate there is no significant difference in the available moisture from the treated to the untreated ponds. There was a slight difference in the water potentials in the trees along the ponds for Seepage Test 2, but not a significant enough change to indicate the additional applications of PAMS had decreased the amount of water available to the root systems of the trees.

Conclusions and Recommendations From Denver Water Staff

- The overall results of Seepage Test 1 indicate there was an average of 35% water savings based on the staff gage data.
- Seepage Test 2 indicates that additional applications of the cross-link polymer and PAMS did not prevent more seepage and that, in fact, soil preparation prior to application may have destroyed the natural seal of the canal and actually caused an increase in seepage. This may indicate that high application rates of the product are of little consequence on certain soils in the canal and that the cross-link polymer is better suited for coarse conglomerate or sandy soils, where the cross-link particles can fill the larger voids of these soil types.
- Erratic seepage data (fluctuations) are probably due to the short water saturation periods. A longer saturation time (for example, 24 to 48 hours) on the pond tests would probably result in a smoother drop-off on the seepage curve and a leveling out of the seepage rate at some elevation on the staff gage.
- Excessively dry soil conditions contiguous with the canal could also contribute to erratic data. There have been high seepage rates on the canal this year due to the 2002 drought and the two-year period that water has not been run in the High Line Canal.
- Additional testing needs to be done. There should be additional PAMS tests on Ponds 1 and 2 beginning with the next irrigation season in order to quantify any residual effect the PAMS may have on the area.
- Additional areas should be flow tested in 1- to 3-mile sections of the canal and the results quantified.
- Ponds 1 and 2 should be surveyed to determine their actual capacity in order to refine the seepage data.
- Denver Water should continue to work with the United States Bureau of Reclamation (USBR) to refine any test results.

A simulated two-week canal run test was conducted the first two weeks of August 2003

- To simulate two weeks of water flow in the canal, water was added to basins at site 17 Wagner and site 2 Green Valley Ranch. On August 4 and 6, 2003 two 4,000 gallon trucks dumped water at each site, on August 8, 2003, 1 foot of water was added to basin at site 17 from a fire hydrant and 6 trucks were dumped at site 2. On August 10, 13, and 15 one foot of water was added to site 17 and 6 trucks dumped at site 2.
- Assumptions: Site 17, surface area water was added to: 166 feet long by 10 feet wide = 1,660 ft^2 x 1 ft deep = 12,418 gallons or 7.5 gallons per ft^2.
- Site 2, surface area water was added to: 60 feet long by 10 feet wide = 600ft^2 with 24,000 gallons dumped or 40 gallons per ft^2.

Other Activities in 2003

- CSU took soil moisture measurements January 28, 2003, April 12, 2003, and weekly from May 5, 2003 to September 24, 2003 at 9 research sites.
- CSU collected meteorological data at two sites during the year and leaf water potentials at the PAMS site and site 17 and 2 when water was tanked or added by fire hose to the canal at those two sites.
- CSU recorded tree health conditions in the spring and fall.
- CSU analyzed all soil moisture and water potential data, produced graphs and provided a progress report.
- Denver Water collected water potentials from trees at the research sites on a weekly basis from May 22, to September 24, 2003

2004

- CSU provided training for Denver Water staff to record leaf water potentials
- CSU recorded tree health conditions in the spring (June 4, 2004) and fall (September 8 and 15, 2004) at Sites 18, 6, 19, 20, 7, 8, 9, 10, 11, 12, 13, and14.
- Denver Water collected leaf water potential data on a weekly basis beginning on June 2 and ending on September 7, 2004.
- CSU analyzed all water potential data, tree health data, produced a progress report.

2005

- CSU recorded tree health conditions in the spring (June 9, 2005) and fall (September 7, 2005) at Sites 2, 3, 16, 23, 25, 17, 4, 18, 6, 19, 20, 7, 8, 9, 10, 11, 12, 13, and 14.
- Denver Water collected leaf water potential data on a weekly basis beginning on June 2 and ending on September 8, 2005.
- CSU collected predawn leaf water potential data on September 9, 2005 at Sites 2,3, 16, 17, and 4; water potential data from the trees at these sites ranged from - 0.50 MPa to – 1.00 MPa.
- Leaf water potential data was collected from trees located at Sites 6, 7, 8, 9, 10, 11, 12, 13, 14, 18, 19, and 20 (Table 2).
- CSU analyzed all water potential data, tree health data, produced a progress report.

2006

- CSU recorded tree health conditions in the spring (June 6, 2006) and in the fall (September 3, 2006) at Sites 2, 3, 16, 23, 25, 17, 4, 18, 6, 19, 20, 7, 8, 9, 10, 11, 12, 13, and 14.
- CSU collected spring predawn leaf water potential data on May 24 from trees located at sites 2, 3, 4, 6, 7, 8, 9, 10, 11, 12, 13, 14, 16, 17, 18, 19, 20, 23, and 25.
- Leaf water potential data was collected weekly from trees located at Sites 6, 7, 8, 9, 10, 11, 12, 13, 14, 18, 19, and 20.
- Denver Water collected the final predawn leaf water potential data for the 2006 growing season on September 13, 2006 from trees located at Sites 2, 3, 4, 6, 7, 8, 9, 10, 11, 12, 13, 14, 16, 17, 18, 19, 20, 23, and 25.
- CSU analyzed all water potential data, tree health data, produced a progress report.

2007

- CSU recorded tree health conditions in the spring (May 23, 2007) and in the fall (September 19, 2007) at Sites 2, 3, 16, 23, 25, 17, 4, 18, 6, 19, 20, 7, 8, 9, 10, 11, 12, 13, and 14.
- Leaf water potential data were collected weekly May 30 to September 6, 2007 by Denver Water student interns from trees located at Sites 2,17,18, 6, 20, 7, 8, 9, 10, 11, 12, 13, and 14 (Table 2).
- CSU analyzed all water potential data, tree health data, produced a progress report.

2008

- CSU recorded tree health conditions in the spring (June 18, 2008) and in the fall (September 5, 2008) at Sites 2, 3, 4, 6, 7, 8, 9, 10, 11, 12, 13, 14, 16, 17, 18, 19, 20, 23, and 25.
- Estimations of percent bark loss were made on old or recently dead cottonwoods in September 2008.
- Leaf water potential data were collected weekly June 4 to September 3, 2008 by Denver Water student interns from trees located at Sites 2, 6, 7, 8, 9, 10, 11, 12, 13, 14, 17, 20 and 23 (Table 2).
- Predawn leaf water potential data from June 11 was dropped in analyses due to large variations between first and second repetition readings and extremely high readings that were not within the range of data seen in previous readings.
- In addition to dropping June 11 observations, any individual tree leaf water potential data was also dropped if there was > 2 bar difference (0.2 MPa) between Reading 1 and Reading 2 (n = 13 dropped observations between June 4 and July 2, 2008). Initial predawn leaf water potential data were also dropped from two sites (Site 6 and 8), because they exceeded all historical ranges from these sites.
- CSU provided three onsite training opportunities for the interns July 11-18, 2008 after which the data quality improved.
- CSU analyzed all water potential and tree health data and produced a progress report.

Table 2. Cottonwood Research Sites from Which Predawn Leaf Water Potential Data Were Collected in 2008.

Canal Section and Site Number	Site Name	Tree Tag Numbers	Notes
Arsenal Lateral			
2	Green Valley East	23-27	Old trees, along east side of canal that runs through back of horse boarding stable on Tower Road. Water flow in the northeastern end of the canal has been significantly reduced over the past several years, and canal water has not reached this site since 2001. A simulated two-week canal run test (using water from nearby fire hydrant) was conducted the first two weeks of August 2003.
17	Wagner Equipment	904-906	Young trees, along west side of canal that runs along west side of Tower Road. Water flow in the northeastern end of the canal has been significantly reduced during the past several years, and canal water has not reached this site since2001. A simulated two-week canal run test (using trucked water) was conducted the first two weeks of August 2003.
Sand Creek			
18	Salida & 14th	907-909	Old trees, south of Colfax and east of Airport Road; trees on east bank of HLC. For some reason, During 2007, Denver Water Interns only collected water potential data from tree tagged #909.
6	Colfax Loop	43-47	Old trees, north west of the intersection of Airport Road and Colfax Avenue, up stream of Airport Road on the north side of the canal, neutron probe access tubes. Added to study in 1999.
20	Laredo and 12th	913-915	Young trees, on north side of canal. Added from study in1999.
7	Aurora Community College	48-52	Young trees, on north side of canal, just behind Aurora Community College buildings.
Tollgate Creek			
8	Aurora Golf Course	78-82	Old trees, on north side of canal and north of the Aurora Golf Course, just downstream of 2nd Avenue.
9	Moline Crossing	73-77	Young trees, on north side of canal, just downstream from and east of Moline Street.
10	Kentucky / Dayton	68-72	Old trees, on south side of canal, at the south east corner of the intersection of Kentucky Avenue and Dayton Avenue.
11	Mississippi "Y"	83-87	Old trees, on west side of canal, downstream from Leetsdale / Mississippi / Parker "Y".
12	Quebec Way Big	63-67	Old trees, on west side of canal, parallel to Quebec Way.
13	Quebec Way Small	88-92	Young trees, on west side of canal, parallel to Quebec Way.
14	Iliff downstream	58-62	Old trees, on west side of canal, just downstream from Iliff.
Cherry Creek			

Results from 2008

Water Flow in the High Line Canal (Tables 3a & 3b):

- The head gate of the High Line Canal was opened three times from April 28 through August 29, for a total of 49 days during the 2008 growing season.
- Water flowed downstream to Fairmount Cemetery for 38 days.
- Water flow east of Tollgate Creek was reduced to 37 days.
- No water flowed downstream of the Sand Creek siphon during 2008.
- Approximately 11,030 acre-feet of water **(1879 WATER RIGHT)** were put into the canal during 2008, approximately 32% the 34,200 acre-feet of water **(1879 WATER RIGHT)** that flowed in the canal during 1997.
- Average rate of flow at the Waterton Canyon head gate was 118.0 cubic feet per second (cfs), but flow rates significantly decreased as the water moved down stream, averaging only 12.0 cfs at monitoring site located at E. 6th Avenue and Chambers Road.
- Previously, we determined that in order to get adequate supply of water to sites downstream of Tollgate, flow rates of over 100 cfs at the head gate at Waterton Canyon are required.
- The head gate for the HLC was shut for 2008 water season on August 29, 2008.
- The number of days that water ran in the canal (by season of the year for 2000 through 2008) is provided in Table 3b (assuming the 19 days of water from the HLC got to Cherry Creek).

Table 3a. Yearly High Line Canal Headgate Irrigation Diversion History* (1970 - 2008).

Year	Total Days	Total Acre-Feet	Year	Total Days	Total Acre-Feet
1970	174	45368	1989	95	15338
1971	126	30430	1990	107	22976
1972	136	17218	1991	102	22326
1973	125	27742	1992	95	20310
1974	97	21532	1993	78	19716
1975	131	30830	1994	44	12564
1976	101	19102	1995	160	36848
1977	41	9958	1996	104	25278
1978	67	14192	1997	169	34200
1979	137	30686	1998	132	24900
1980	114	24442	1999	167	25500
1981	24	4334	2000	97	17716
1982	111	26164	2001	94	16806
1983	168	33180	2002	0	0
1984	161	32480	2003	68	17092
1985	159	33490	2004	44	7466
1986	136	25648	2005	58	11360
1987	137	22468	2006	42	8578
1988	117	23426	2007	52	15147
			2008	49	11030

*1879 WATER RIGHT

Table 3b. Distribution of HLC Run Days at Cherry Creek by Season (2000 – 2008).

Canal Run Days at Cherry Creek	2000	2001	2002	2003	2004	2005	2006	2007	2008
Spring *April1 - May 31*	28	44	0	16	13	37	0	20	11
Summer *June 1 - Sept 15*	0	30	0	9	4	13	7	35	30
Fall *Sept 16 - Oct 31*	14	7	0	14	14	0	8	0	0

Tree Health Assessments Spring and Fall 2008:

- The two most common diseases noted were Cytospora branch cankers and bacterial wetwood.
- Cytospora branch cankers were found on most trees within the research sites (n = 63/81 trees assessed, n =10 trees with >50% of tree affected by Cytospora branch cankers).
- Bacterial wetwood was found on n = 30/81 trees assessed within the research sites.
- No recent lightening damage was observed on any of the trees, nor was any additional new mechanical damage observed on trees within the research sites.
- Squirrel feeding damage continues to be a major cause of branch dieback due to the girdling of branches (n = 30/81 trees affected, severity ranged from 1-20% of the tree).
- Defoliating insects (affecting 29/81 trees assessed) and piercing/sucking insects and mites (affecting 27/81 trees assessed) were the predominant arthropod pests found present in 2008 but their combined damage was minimal (<10% of the tree affected). Leaf miners were present on 2/81 research trees and Catkin Gall Mite damage was apparent on 4/81 research trees in 2008.
- Tree health assessment was based on visual observations using standardized tree condition data codes, originally developed by Dr. Bill Jacobi in 1997, and slightly modified since then to accommodate the needs of this study. Disease assessment of the trees was based on external symptoms and no isolations were performed (Refer to Appendix A: Tree Condition Data Codes).

Tree Crown Dieback (Table 4):

- Average fall percent crown dieback values for research sites along the High Line Canal for 1999, 2002, 2004, 2005, and 2007 and 2008 are listed in Table 4.
- Tree crown dieback ranged from 0 - 100% in 2008.
- **Cherry Creek to Tollgate**: Crown dieback did not increase on most trees at Sites 14, 13, 12, 11, 10, 9, & 8 from fall 2007 to fall of 2008. Site 13 increased from 1% average dieback in 2007 to 6% in 2008.
- **Tollgate to Sand Creek**: Sites 7, 20, 19, 6, & 18 exhibited similar amounts of crown dieback in fall 2008 compared to fall 2007. Site 7 decreased from 12% average dieback in 2007 to 7% in fall 2008. All Site 20 trees remain with no crown dieback through 2008. All three trees located at Site 19 (where a canal liner was added in 2002) were dead as of September 2006.
- **Sand Creek to Arsenal Lateral**: Average crown dieback at Sites 4, 17 (along Tower Road), 25, 23, 16, 3, and 2 (Green Valley Ranch are) increased from fall 2007 to fall 2008. Five of seven trees at Site 2 and three of five trees at Site 3 had 100% dieback in 2008 (Tree 27 at Site 2 increased from 70% to 100% dieback). Tree 901 at Site 16 increased from 95% crown dieback in fall 2007 to 100% dieback in fall 2008.
- Since 2004, water flow in the High Line Canal has stopped at or before the Sand Creek Siphon; thus no canal water has reached trees at sites downstream of the intersection of Colfax Avenue and Tower Road for the past four years.

Table 4. Average Percent Crown Dieback of Cottonwood Trees at Research Sites (Fall 1999, 2002, 2004 - 2008).

Sites in Order Along Canal	1999		2002		2004		2005		2006		2007		2008	
	Average Crown Dieback	Days of Water Flow	Average Crown Dieback	Days of Water Flow	Average Crown Dieback	Days of Water Flow	Average Crown Dieback	Days of Water Flow	Average Crown Dieback	Days of Water Flow	Average Crown Dieback	Days of Water Flow	Average Crown Dieback	Days of Water Flow
Arsenal Lateral														
2 – Green Valley Ranch East	17	35	19	0	33	0	44	0	74	0	81	0	**98.3**	0
3 – Arsenal Lateral -1	14	35	21	0	50	0	56	0	71	0	79	0	**95**	0
16 – Arsenal Lateral -2	13	35	10	0	32	0	55	0	87	0	92	0	**96.7**	0
23 – Arsenal Lateral -3	NA	35	15	0	25	0	47	0	71	0	73	0	**76.7**	0
25 – Green Valley Ranch Dry	NA	35	38	0	72	0	75	0	78	0	82	0	**86.7**	0
17 –Wagner Equipment	2	35	2	0	7	0	20	12	57	0	60	0	**76.7**	0
4 –Super Value	17	35	23	0	40	0	43	12	44	0	43	0	**49**	0
Section Average	12.6	35	18.2	0	37	0	48.6	3	72.7	0	72.9	0	**82.7**	0
Sand Creek														
18- Salida	8	62	8	0	15	10	16	50	16	10	13	26	**13**	37
6 - Colfax Loop	17	62	17	0	28	10	25	50	31	10	34	26	**33**	37
19 - Colfax Loop west	12	62	33	0	92	10	90	50	100	10	100	26	**100**	37
20 - Laredo and 12th	0	62	0	0	0	10	0	50	2	10	0	26	**0**	37
7 - Aurora Community College	10	62	8	0	17	10	10	50	12	10	12	26	**6.7**	37
Section Average EXCL. Site 19	8.8	62	8.3	0	15	10	12.8	50	15.3	10	14.8	26	**13.3**	37
Section Average INCL. Site 19	9.4	62	13.4	0	30.4	10	28.2	50	32.2	10	31.8	26	**30.6**	37
Tollgate Creek														
8 - Aurora Golf Course	8	156	NA	0	8	31	8	50	9	13	9	45	**9**	38
9 - Moline Crossing	8	156	NA	0	10	31	9	50	9	13	6	45	**3**	38
10 - Kentucky / Dayton	14	156	NA	0	22	31	16	50	18	15	16.4	45	**16**	38
11 - Mississippi "Y"	6	156	NA	0	10	31	6	50	5	15	5	45	**5**	38
12 - Quebec Way Big	6	156	NA	0	7	31	2	50	2	15	3	45	**3**	38
13 - Quebec Way Small	0	156	NA	0	7	31	2	50	2	15	1	45	**6**	38
14 - Iliff Down Stream	20	156	NA	0	25	31	14	50	14	15	13.4	45	**12**	38
Section Average	8.9	156	NA	0	12.7	31	8.1	50	8.4	14	7.7	45	**7.7**	38
Cherry Creek														

Tree Mortality (Table 5):

- As of September 05, 2008; 17 research trees at 7 sites exhibited 100% crown dieback and were considered dead.
- Two additional trees died during 2008; one located at Site 2 and one at Site 16.
- All three trees at Site 19 were dead as of the fall of 2006.
- As noted in 2006, tree mortality during 2007 and 2008 occurred at research sites downstream of Tollgate, in areas with little to no supplemental water from urban landscapes and where the soil is sandy.

Table 5. Cottonwood Tree Mortality Incidence at Research Sites (2004 - 2008).

Site Number	Tree Number	Tree Flower Type	Tree Maturity	Year of Death
2	24	Female	old	2007
2	25	Male	old	2006
2	26	Female	old	2007
2	906B	Male	old	2007
2	27	Female	old	2008
3	30	Male	young	2007
3	31	Male	young	2006
3	32	Female	young	2005
23	919	Male	young	2006
23	921	Male	young	2006
25	916	Male	young	2005
25	917	Male	young	2005
16	901	Female	young	2008
17	906	Female	young	2007
19	910	Female	old	2004
19	911	Female	old	2006
19	912	Female	old	2006

Precipitation and Temperature Data in Study Area During 2008 (Tables 6a-c):

- Tables 6a, 6b, and 6c summarize monthly total rainfall, monthly average temperatures, and monthly average maximum temperatures, respectively, for the study area from 1999 through 2008.
- Unlike previous years, precipitation events during June and July in 2008 were rare, and no one event delivered 0.5" or greater to the area during this time (July total precipitation was 7% of the 30 year average).
- The area received above normal precipitation during the months of February, August, September and October.
- Total precipitation from May 1 to September 30, 2008 was 7.05 inches.
- Precipitation events of at least 0.50" occurred on Aug. 7 (0.61"), Aug. 17 (1.46") and Sept. 12 (0.92").
- Precipitation and temperature data for the research sites were obtained using the National Weather Service's Cooperative Station #052220 located at a latitude of 39°46'N and a longitude of 104°52'W (on the grounds of the former Denver Stapleton Airport) (Tables 6a-6c)

Table 6a. Monthly Total Rainfall (inches) (1999-2008).

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
1999	0.57	0.12	0.27	5.35	2.54	1.62	2.06	4.00	1.16	0.35	0.48	0.31	18.83
2000	0.51	0.23	1.37	0.81	1.68	0.91	1.46	3.84	1.57	0.45	0.75	0.28	13.86
2001	0.58	0.59	0.76	1.32	3.56	1.40	3.32	2.13	1.01	0.20	0.65	0.27	15.79
2002	0.39	0.18	0.74	0.09	1.35	1.10	1.04	0.72	1.86	0.79	0.23	0.00	8.49
2003	0.00	0.51	4.81	2.03	2.24	1.91	0.47	3.10	0.39	0.06	0.18	0.37	16.07
2004	0.38	0.55	0.18	2.13	1.41	1.78	2.56	4.94	1.34	0.98	0.88	0.13	17.26
2005	0.62	0.05	0.76	2.38	1.02	3.29	0.53	2.57	0.22	2.51	0.29	0.30	14.55
2006	0.33	0.18	0.05	0.62	0.61	0.03	2.22	2.72	0.79	1.82	0.33	2.15	12.65
2007	1.02	0.36	1.36	1.94	4.52	0.58	0.56	3.52	1.18	1.07	NA	NA	**16.11
2008	0.21	0.51	0.55	0.31	1.61	0.71	0.15	3.02	1.56	1.03	NA	NA	**9.66
30 yr*	0.51	0.49	1.28	1.93	2.32	1.56	2.16	1.82	1.14	0.99	0.98	0.63	15.81

* Average of Monthly Total Precipitation 1976-2005
** Through October 2007 or 2008

Table 6b. Monthly Average Temperatures (°F) (1999-2008).

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1999	35.5	40.2	44.7	44.0	55.8	65.5	75.3	71.1	59.5	51.7	47.1	35.4
2000	34.4	38.5	41.9	50.8	60.7	68.5	76.9	74.8	62.6	51.5	30.5	29.0
2001	31.2	28.4	40.1	49.4	57.4	69.4	76.5	73.0	65.4	51.4	43.1	33.6
2002	31.3	33.4	34.8	51.2	56.9	72.5	77.3	72.1	63.8	45.5	37.5	34.0
2003	37.4	29.3	39.8	51.7	57.3	63.8	77.9	74.3	60.0	56.4	36.0	33.5
2004	32.1	31.5	46.1	48.0	58.9	63.8	70.8	67.2	62.2	50.7	38.0	34.5
2005	33.1	36.0	40.0	46.4	56.6	65.7	76.2	70.3	65.2	51.7	43.1	30.1
2006	38.3	30.5	38.3	51.4	60.1	71.7	74.6	71.2	57.9	49.4	41.3	32.0
2007	21.8	30.2	45.2	46.1	58.1	67.6	75.4	73.8	64.0	53.2	NA	NA
2008	27.1	33.4	39.7	45.1	55.1	67.0	75.6	71.0	60.9	50.9	NA	NA
30 yr. avg*	31.1	34.3	40.9	48.8	57.8	67.9	74.3	71.8	63.5	51.2	38.8	31.6

* Average of Monthly Average Temperatures 1976-2005

Table 6c. Monthly Average Maximum Temperatures (°F) (1999-2008).

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1999	48.2	55.8	60.0	55.8	68.4	79.3	88.7	83.6	73.3	68.3	64.4	48.1
2000	48.4	52.6	54.3	66.0	74.7	83.4	92.0	89.3	78.5	66.1	42.1	43.1
2001	44.4	40.4	52.0	62.5	70.0	84.0	91.0	86.9	81.9	67.6	58.0	47.6
2002	45.4	48.7	49.3	67.6	71.2	88.2	92.8	87.9	78.4	59.5	50.6	48.6
2003	53.3	42.4	52.1	65.7	70.4	76.2	94.1	88.5	75.9	73.1	49.2	48.6
2004	47.7	44.1	61.4	60.4	73.7	77.5	85.0	81.6	77.1	65.0	50.3	48.1
2005	46.6	49.1	52.8	59.4	70.4	79.9	92.6	85.1	80.9	65.9	59.1	43.2
2006	52.5	45.2	52.0	67.3	75.3	87.4	88.4	83.8	72.2	63.4	55.6	43.8
2007	34.8	43.3	58.9	58.4	71.2	82.3	90.9	88.3	79.9	69.0	NA	NA
2008	40.5	46.8	53.6	60.4	69.8	82.1	92.1	84.5	75.1	65.4	NA	NA
30 yr. Avg*	43.2	46.8	52.2	61.2	70.6	81.7	87.7	85.7	77.3	66.3	52.2	45.2

* Average of Monthly Average Temperatures 1976-2005

Impact of Precipitation on Predawn Leaf Water Potentials (Table 7):

- Averaged predawn leaf water potentials of sites before and after precipitation events of 0.5 inch or more appear in Table 7.
- There were no instances of precipitation greater than 0.5 inches until August 2008.
- Significant differences between leaf water potentials pre- and post-precipitation are bolded and followed by different letters ($p < 0.10$).
- The precipitation on August 7, 2008 of 0.61" had a significant effect at Site 11, where mean leaf water potential significantly dropped from -0.40 to -0.30 MPa. Unfortunately, several sites did not have readings on August 6 (pre-precipitation) to compare to post-precipitation values (Site 2, 23, 17, 6 and 20).
- The precipitation event on August 17 of 1.46" had significant effects on several sites. Sites 20, 7, 8, 9 and 10 all had significantly more negative leaf water potentials when measured after the precipitation event. These values would not be expected if the water reached the tree roots so there is not a logical relationship between water potentials and rainfall at these sites.
- Sites 2 and 23 both had less negative mean water potentials after the precipitation event (which is to be expected at sites along the canal without water flow and where the land slopes to the canal), although these differences were not significant (p = 0.12 and 0.31, respectively).
- Some sites, such as 2, 6, 17, and 23 had water potentials more negative than -0.50 MPa even after the large precipitation events.
- The third flow of the canal also occurred between August 6 and 13, starting on August 11, which may complicate the comparisons of pre- and post-precipitation readings for sites between Cherry Creek and Tollgate (Sites 8 – 14) and Tollgate and Sand Creek (Sites 6, 7 and 20).
- Trees along the HLC did not respond to these two large precipitation events with less negative water potentials, indicating there was minimal stress relief from precipitation.

Table 7. Average Predawn Leaf Water Potentials (- MPa) *Before* and *After* Precipitation Events of *At Least* 0.5 Inch (2008).

Date	Site Mean												
	2	**23**	**17**	**6**	**20**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**
BEFORE rain on 8/07 (LWP recorded 8/06)	NA	NA	NA	NA	NA	0.30	0.37	0.30	0.32	***0.40a***	0.34	0.33	0.34
AFTER rain on 8/07 (0.61 in) (LWP recorded 8/13)	1.03	0.53	0.88	0.50	0.28	0.37	0.32	0.31	0.31	***0.30b***	0.33	0.39	0.31
BEFORE rain 8/17 (LWP recorded 8/13)	1.03	0.53	0.88	0.50	***0.28a***	***0.37a***	***0.32a***	***0.31a***	***0.31a***	0.30	0.33	0.39	0.31
AFTER rain 8/17 (1.46 in) (LWP recorded 8/20)	0.87	0.43	0.96	0.52	***0.41b***	***0.53b***	***0.57b***	***0.47b***	***0.51b***	0.39	0.29	0.40	0.31

NA = Water potential data not collected

Interactions of Research Site and Collection Date on Predawn Leaf Water Potentials (Tables 8a, 8b, and 8c)

*** Water potential data dropped for 6/11/08 readings because (1) approximately half of the tree water potential readings were greater than 2.0 bars apart from Reading 1 to Reading 2 (some readings as much as 4.5 bar difference) and (2) unexplainable, out of normal range spikes in tree water stress at Sites 20, 8-14 on 6/11/08 were noted.

- Predawn leaf water potential data collection for the 2008 growing season was initiated June 4, 2008.
- Predawn leaf water potential data was collected weekly throughout June, July, and August although not all sites were completed each week.
- Not all trees at each site were measured for leaf water potentials and the same trees were not chosen each week throughout the growing season.
- Predawn leaf water potential data collection for the 2008 growing season ended September 3, 2008.
- Tables 8a, 8b, and 8c contain the least squared means (lsmeans) of predawn leaf water potentials for measured study trees at each research site for 14 collection days and a seasonal mean.
- **Cherry Creek to Tollgate (Sites 8 - 14):** Mean= -0.43 (-0.19 to -0.58 MPa) (Table 8a).
- **Tollgate to Sand Creek (Sites 6, 20, 7):** Mean= -0.45 (-0.18 to -0.86 MPa) (Table 8b).
- **Sand Creek to Arsenal (Sites 2, 23, 17):** Mean= -0.87 (-0.25 to -1.24 MPa) (Table 8c).
- By July 2, 2008 (compared to July 25 in 2007) average predawn leaf water potentials at ALL sites were more negative than -0.30 MPa.
- Predawn leaf water potentials, for most trees at most sites, were fairly high and fluctuated through mid-July. The mean leaf water potentials at most sites decreased through August (increased precipitation and canal flow occurred in August).
- Average leaf water potentials did differ significantly based on date; this was expected.
- Average leaf water potentials did differ significantly based on site; this was expected.

Table 8a. Average Predawn Leaf Water Potentials[+] (MPa) of Cottonwoods Trees Along the High Line Canal Between Cherry Creek and Tollgate Creek (2008).

	Site						
Date	**8**	**9**	**10**	**11**	**12**	**13**	**14**
4-Jun	-	-0.58 *(n=5)*	-0.31 *(n=5)*	-0.25 *(n=3)*	-0.33 *(n=5)*	-0.34 *(n=5)*	-0.19 *(n=5)*
11-Jun	-	-	-	-	-	-	-
19-Jun	-0.34 *(n=5)*	-0.33 *(n=4)*	-0.39 *(n=5)*	-0.49 *(n=4)*	-0.52 *(n=3)*	-0.38 *(n=5)*	-0.52*(n=5)*
26-Jun	-0.46 *(n=5)*	-0.62 *(n=4)*	-0.45 *(n=5)*	-0.44 *(n=3)*	-0.45 *(n=3)*	-0.29 *(n=5)*	-0.40 *(n=5)*
2-Jul	-0.50 *(n=5)*	-0.43 *(n=4)*	-0.47 *(n=5)*	-0.54 *(n=3)*	-0.58 *(n=4)*	-0.44 *(n=4)*	-0.40 *(n=5)*
9-Jul	-0.60 *(n=5)*	-0.52 *(n=4)*	-0.46 *(n=5)*	-0.81 *(n=3)*	-0.55 *(n=4)*	-0.47 *(n=5)*	-0.43 *(n=5)*
16-Jul	-0.52 *(n=5)*	-0.46 *(n=4)*	-0.46 *(n=5)*	-0.49 *(n=3)*	-0.41 *(n=4)*	-0.58 *(n=5)*	-0.56 *(n=5)*
23-Jul	-0.48 *(n=5)*	-0.48 *(n=4)*	-0.58 *(n=5)*	-0.62 *(n=3)*	-0.60 *(n=4)*	-0.54 *(n=5)*	-0.53 *(n=5)*
30-Jul	-0.74 *(n=5)*	-0.68 *(n=5)*	-0.43 *(n=5)*	-0.50 *(n=3)*	-0.46 *(n=4)*	-0.48 *(n=5)*	-0.44 *(n=4)*
6-Aug	-0.37 *(n=5)*	-0.30 *(n=5)*	-0.32 *(n=5)*	-0.40 *(n=3)*	-0.34*(n=4)*	-0.32 *(n=5)*	-0.34 *(n=5)*
13-Aug	-0.32 *(n=5)*	-0.30 *(n=5)*	-0.31 *(n=5)*	-0.30 *(n=3)*	-0.33 *(n=4)*	-0.39 *(n=5)*	-0.32 *(n=4)*
20-Aug	-0.56 *(n=5)*	-0.47 *(n=4)*	-0.50 *(n=5)*	-0.39 *(n=3)*	-0.29 *(n=4)*	-0.40*(n=5)*	-0.31 *(n=5)*
27-Aug	-0.47 *(n=5)*	-0.42 *(n=5)*	-0.44 *(n=4)*	-0.44 *(n=4)*	-0.30 *(n=4)*	-0.41 *(n=5)*	-0.24 *(n=5)*
3-Sep	-0.42 *(n=5)*	-0.36 *(n=5)*	-0.28 *(n=5)*	-0.43 *(n=3)*	-0.28 *(n=4)*	-0.26 *(n=5)*	-0.24- *(n=5)*
Mean	**-0.48**	**-0.46**	**-0.42**	**-0.47**	**-0.41**	**-0.41**	**-0.38**

[+] The Mixed Procedure Least Squared Means
(-) = water potential not collected
n = number of sample trees

Table 8b. Average Predawn Leaf Water Potentials[+] (MPa) of Cottonwoods Trees Along the High Line Canal Between Tollgate Creek and Sand Creek (2008).

Date	Site			
	6	19	20	7
4-Jun	-	*(n=0)*	-0.45 *(n=3)*	-0.45 *(n=3)*
11-Jun	-	*(n=0)*	-	-
19-Jun	-0.29 *(n=3)*	*(n=0)*	-0.38 *(n=3)*	-0.44 *(n=3)*
26-Jun	-0.48 *(n=1)*	*(n=0)*	-0.37 *(n=3)*	-0.45 *(n=3)*
2-Jul	-0.39 *(n=3)*	*(n=0)*	-0.52 *(n=3)*	-0.42 *(n=3)*
9-Jul	-0.49 *(n=3)*	*(n=0)*	-0.46 (n=3)	-0.58 *(n=3)*
16-Jul	-0.30 *(n=3)*	*(n=0)*	-0.32 *(n=3)*	-0.34 *(n=3)*
23-Jul	-	*(n=0)*	-0.44 *(n=3)*	-0.48 *(n=3)*
30-Jul	-0.86 *(n=4)*	*(n=0)*	-0.46 *(n=3)*	-0.74 *(n=3)*
6-Aug	-	*(n=0)*	-	-0.30 *(n=3)*
13-Aug	-0.50 *(n=3)*	*(n=0)*	-	-0.37 *(n=3)*
20-Aug	-0.52 *(n=4)*	*(n=0)*	-0.41 *(n=3)*	-0.52 *(n=3)*
27-Aug	-0.52 *(n=4)*	*(n=0)*	-0.34 *(n=3)*	-0.59 *(n=3)*
3-Sep	-0.21 *(n=3)*	*(n=0)*	-0.18 *(n=3)*	-0.34 *(n=3)*
Mean	**-0.46**	**-**	**-0.38**	**-0.46**

[+] The Mixed Procedure Least Squared Means
(-) = water potential not collected
n = number of sample trees

Table 8c. Average Predawn Leaf Water Potentials[+] (MPa) of Cottonwoods Trees Along the High Line Canal Between Sand Creek and Arsenal Lateral (2008).

Date	Site		
	2	23	17
4-Jun	-	-0.42 *(n=1)*	-0.69 *(n=2)*
11-Jun	-	-	-
19-Jun	-1.00 *(n=2)*	-0.30 *(n=1)*	-1.02 *(n=2)*
26-Jun	-0.89 *(n=1)*	-0.60 *(n=1)*	-
2-Jul	-1.20 *(n=1)*	-0.45 *(n=1)*	-1.14 *(n=2)*
9-Jul	-0.83 *(n=1)*	-0.55 *(n=1)*	-0.97 *(n=1)*
16-Jul	-1.2 *(n=1)*	-0.40 *(n=1)*	-0.85 *(n=2)*
23-Jul	-1.24 *(n=2)*	-0.50 *(n=1)*	-0.97 *(n=2)*
30-Jul	-1.08 *(n=1)*	-0.72 *(n=1)*	-1.02 *(n=1)*
6-Aug	-	-	-
13-Aug	-1.03 *(n=1)*	-0.52 *(n=1)*	-0.87 *(n=1)*
20-Aug	-0.87 *(n=1)*	-0.42 *(n=1)*	-0.96 *(n=2)*
27-Aug	-1.03 *(n=1)*	-0.42 *(n=1)*	-0.81 *(n=2)*
3-Sep	-1.03 *(n=1)*	-0.25 *(n=1)*	-0.92 *(n=2)*
Mean	**-1.02**	**-0.46**	**-0.92**

[+] The Mixed Procedure Least Squared Means
(-) = water potential not collected
n = number of sample trees

Impact of Tree Maturity on Predawn Leaf Water Potentials:

- Previously we determined that average leaf water potentials did not show a significant interaction of tree maturity and canal condition
- Previously we determined that average leaf water potentials did not show a significant interaction of tree size and date.

Impact of Canal Condition on Predawn Leaf Water Potentials (Table 9):

- During the first run of water in the HLC (April 28 – May 5), predawn leaf water potential readings were not recorded. Water potentials were recorded between June 4 and September 3, 2008.
- During the second run of the HLC where water reached Cherry Creek (May 25 – June 11):
    - Mean initial predawn leaf water potential (June 4) for sites from Cherry Creek to Tollgate Creek (Sites 8-14) was -0.34 MPa, and ranged from -0.19 (Site 14) to -0.59 (Site 9). indicating that a few of the trees began the 2008 growing season in moderately stressed condition, even though water reached these sites for 3 days in early May and was flowing from May 25 through June 11, when first readings were collected.
    - Mean initial predawn leaf water potential (June 4) for sites from Tollgate Creek to Sand Creek Siphon (Sites 6, 20, 7) was -0.45 MPa (data from Site 6 was dropped on June 4), indicating that a few of the trees began the 2008 growing season in moderately stressed condition, even though water flowed in the HLC for 3 days in early May and was flowing from May 25 through June 11, when first readings were collected.
    - ***Cherry Creek to Sand Creek combined: Initial pre-dawn water potentials were generally high in 2008, even though water was flowing in the HLC, and ranged from -0.19 (Site 14) to -0.60 (Sites 20 and 7) MPa. The initial mean of all sites upstream of Sand Creek (Cherry Creek to Tollgate to Sand Creek) for the first reading was -0.36 MPa.***
    - ***These values are approximately 0.1 MPa more negative, on average, than 2007 data, so we assume the summer of 2008 data is may be erroneously 0.1 MPa more negative than previous years' data (most likely from operator variation in reading water potentials).***
    - Mean initial predawn leaf water potential (June 4) from study trees past Sand Creek Siphon was -0.80 MPa, indicated these trees were severely stressed at the beginning of the growing season (water did flow past Sand Creek Siphon and was not observed at these sites during this time).
- During the third run of water in the HLC (August 11 - 29):
    - Mean predawn leaf water potential for trees at sites from Cherry Creek to Tollgate Creek (Sites 8 - 14) was -0.38 MPa (range -0.24 to -0.56 MPa).
    - Mean predawn leaf water potential from Tollgate to the Sand Creek Siphon (Sites 6, 7, and 20) was -0.47 MPa (range -0.34 to -0.59 MPa).
    - ***Cherry Creek to Sand Creek combined: Water potentials were generally high, even when water was flowing, and ranged from -0.24 to -0.59 MPa. The mean of all sites upstream of Sand Creek (Cherry Creek to Tollgate to Sand Creek) during the third run of water in the HLC was -0.42 MPa.***
    - Mean leaf water potential of trees past Sand Creek Siphon (Sites 2, 23, 17) was -0.77 MPa (no HLC water flow except observed water at Site 23 on August 20 and 27).
- When the canal was not flowing (June 19 – August 10):
    - Mean leaf water potential of trees between Cherry Creek and Tollgate (Sites 8-14) was -0.47 MPa; individual daily observations from this time ranged from -0.29 (Site 13) to -0.74 (Site 8) MPa.
    - Mean water potential of trees between Tollgate and the Sand Creek Siphon was -0.42 MPa; individual observations ranged from -0.29 (Site 6) to -0.86 (Site 6 again) MPa.

- ***Cherry Creek to Sand Creek combined: Water potentials were generally high and ranged from -0.29 (Site 13) to -0.86 (Site 6). The mean of all sites upstream of Sand Creek (Cherry Creek to Tollgate to Sand Creek) during this time when water was not flowing in the HLC was -0.44 MPa).***
- Mean leaf water potential of trees past Sand Creek Siphon (Sites 2, 23, 17) was -0.85 MPa.

- At sites downstream of Sand Creek Siphon (Sites 2, 23, and 17), no water flowed in the HLC during 2008; but flowing water was observed flowing in the canal twice at Site 23; on August 20 and 27, 2008.
- Overall, mean water potential was not significantly different by canal condition:
  - Canal dry: 0.51 MPa, Canal muddy: 0.48 MPa, Canal flowing: 0.42 MPa
- Mean water potential was significantly different between readings taken during flowing and dry canal condition for Tollgate to Sand Creek and Sand Creek to Aresenal, but not for Cherry Creek to Tollgate (when all site were combined together "Average" value in Table 9).
  - Water potential was less negative while the canal was flowing compared to when it was dry.
  - Two observations of flowing water occurred past Sand Creek at Site 23 on Aug. 20 and 27.
  - No individual sites from Tollgate to Sand Creek had significant differences between dry and flowing canal conditions.
- Significant differences between dry and flowing canal conditions occurred at individual sites between Cherry Creek and Tollgate: Sites 11, 12 and 14 (Table 9).
  - Water potential was less negative when the canal was flowing compared to when it was dry.

Table 9. Average Predawn Leaf Water Potentials* Related to Canal Condition (2008).

Site	Average Water Potentials (MPa)		
	Dry Canal	Muddy Canal	Flowing Canal
Arsenal Lateral			
2 – Green Valley Ranch	-1.01	-	-
23 – Green Valley Ranch	-0.44	-	-0.39
17 – Wagner Equipment	-0.92	-	-
Sand Creek			
Average	**-0.86 a**	-	**-0.39 b**
Sand Creek			
6 - Colfax Loop	-0.47	-	-0.42
20 - Laredo and 12th	-0.36	-	-0.34
7 - Aurora Community College	-0.48	-	-0.42
Tollgate Creek			
Average	**-0.42 a**	-	**-0.51 b**
Tollgate Creek			
8 - Aurora Golf Course	-0.44	-0.46	-0.47
9 - Moline Crossing	-0.43	-0.33	-0.45
10 - Kentucky / Dayton	-0.39	-	-0.38
11 - Mississippi "Y"	**-0.48 a**	-0.43	**-0.33 b**
12 - Quebec Way Big	**-0.43 a**	-0.281	**-0.27 b**
13 - Quebec Way Small	-0.401	-0.25	-0.34
14 - Iliff Down Stream	**-0.40 a**	-0.23	**-0.21 b**
Cherry Creek			
Average	-0.44	-0.42	-0.35

*The Mixed Procedure Least Squared Means.Sites in bold and values followed by different letters (a, b) are significantly different among canal conditions at a particular site or canal section at the p=0.10 level

Impact of Predawn Leaf Water Potentials on Cottonwood Tree Crown Dieback:

- Trees between Cherry Creek and Tollgate averaged 7.7% dieback by September 2008, and leaf water potentials averaged -0.43 MPa.
- Trees between Tollgate Creek and Sand Creek (excluding site 19, the "liner study" site) averaged 13.3% dieback by September 2008 (down from 14.8% in September 2007 with one tree lost) (Table 4), and leaf water potentials averaged -0.45 MPa.
- Trees between Sand Creek and Arsenal Lateral averaged 82.7% dieback (up from 72.9% dieback by September 2007) (see Table 4) and had mean leaf water potential of -0.87 MPa. Trees at these sites had mean water potential readings ranging from -0.25 to -1.24 MPa over the 2008 growing season and averaged -0.87 MPa. Mean water potentials were more negative than -1.00 MPa at several points in 2008, Initial mean water potentials (taken June 4) ranged from -0.43 to -0.69 MPa. One additional tree at Site 2 was pronounced dead in 2008.

Research Site Summary of Predawn Leaf Water Potential Data and Percent Crown Dieback (1997 – 2008):

Green Valley Ranch

Site 2 Green Valley Ranch East

- Water potential readings taken 1997-2005, 2007 (from only 2 trees), and 2008 (two trees)
- Water potential readings taken May 24, 2006 averaged - 0.64 MPa
- Average water potential in 2006 was -1.09 MPa
- Crown dieback as of September 2006 was 74%
- Water potential readings taken June 1, 2007 averaged - 0.28 MPa
- Average water potential in 2007 was -0.53 MPa
- Crown dieback as of September 2007 was 81.4%
- Water potential readings taken June 16, 2008 averaged -1.00 MPa
- Average water potential reading in 2008 was -1.02 MPa
- Crown dieback as of September 2008 was 98.3%
- Tree 27 at Site 2 was dead in 2008

Site 3 Arsenal Lateral -1

- Water potential readings taken 1997-2003
- Water potential readings taken May 24, 2006 averaged -0.53 MPa
- Crown dieback as of September 2006 was 71%
- Water potential readings were not taken at this site in 2007 or 2008
- Crown dieback as of September 2007 was 79.0%
- Crown dieback as of September 2008 was 95.0%

Site 23 Arsenal Lateral -3

- Water potential readings taken 2001-2003, 2007 (from 1 tree) and 2008 (from 2-3 trees per reading)
- Water potential readings taken May 24, 2006 averaged -0.83 MPa
- Additional water potential readings were not taken at this site in 2006
- Crown dieback as of September 2006 of remaining two trees was 71%
- Water potential readings taken June 20, 2007 averaged -0.23 MPa
- Average water potential in 2007 was -0.35 MPa (only 1 tree)
- Crown dieback as of September 2007 of remaining two trees was 73%
- Water potential readings taken June 4, 2008 averaged -0.42 MPa
- Average water potential reading in 2008 was -0.46 MPa
- Crown dieback as of September 2008 was 76.7%

Site 25 Green Valley Ranch Dry

- Water potential readings taken 2001-2003
- Trees # 916 and #917 dead as of spring 2005
- Water potential readings taken May 24, 2006 averaged -0.65 MPa.
- Crown dieback as of September 2006 of remaining tree was 78%
- Water potential readings were not taken at this site in 2007 or 2008
- Crown dieback as of September 2007 of remaining tree was 82%
- Crown dieback as of September 2008 was 86.7%

Site 16 Arsenal Lateral 2

- Water potential readings taken 1999-2003
- Water potential reading taken May 24, 2006 was -0.70 MPa
- Crown dieback as of September 2006 was 86%
- Water potential readings were not taken at this site in 2007 or 2008
- Crown dieback as of September 2007 was 93%
- Crown dieback as of September 2008 was 96.7%
- Tree 901 was dead in 2008

Site 17 Wagener Equipment

- Water potential readings taken 1999-2008
- Water potential readings taken May 24, 2006 averaged -0.68 MPa
- Average water potential in 2006 was -1.04 MPa
- Crown dieback as of September 2006 was 56%
- Water potential readings taken June 1, 2007 averaged -0.21 MPa
- Average water potential in 2007 was -0.71 MPa
- Crown dieback as of September 2007 was 60%
- Water potentials readings taken June 4, 2008 averaged -0.69 MPa
- Average water potential in 2008 was -0.92 MPa
- Crown dieback as of September 2008 was 76.7%
-

Site 4 King Sooper (Previously Super Value)

- Water potential readings taken 1997-2001 and again in late summer of 2002
- Water potential readings taken May 24, 2006 averaged -0.53 MPa
- Crown dieback as of September 2006 was 44%
- Water potential readings were not taken at this site in 2007 or 2008
- Crown dieback as of September 2007 was 43%
- Crown dieback as of September 2008 was 49.0%

Sand Creek

Site 18 Salida

- Water potential readings taken 1999-2006
- Average water potential in 2006 was -0.77 MPa
- Crown dieback as of September 2006 was 15%
- Water potential readings were not taken at this site in 2007 or 2008
- Crown dieback as of September 2007 was 13%
- Crown dieback as of September 2008 was 13%

Site 6 Colfax Loop East

- Water potential readings taken 1997-2008
- Water potential readings taken May 24, 2006 averaged -0.38 MPa
- Average water potential in 2006 was -0.92 MPa

- Crown dieback as of September 2006 was 31%
- Water potential readings taken June 1, 2007 averaged -0.19 MPa
- Average water potential in 2007 was -0.36 MPa
- Crown dieback as of September 2007 was 34%
- Water potential readings taken June 19, 2008 averaged -0.29 MPa
- Average water potential in 2007 was -0.46 MPa
- Crown dieback as of September 2008 was 33%

Site 19 Colfax Loop west
- Water potential readings taken 1999-2006
- Tree # 910 officially dead as of fall 2004
- Average water potential in 2006 was -0.92 MPa
- Crown dieback as of September 2006 of remaining two trees was 100%
- As of September 2008, all three trees were dead with 100% crown dieback

Site 20 Laredo and 12th
- Water potential readings taken 1999-2008
- Water potential readings taken May 24, 2006 averaged -0.21 MPa
- Average water potential in 2006 was -0.57 MPa
- Crown dieback as of September 2006 was 2%
- Water potential readings taken June 1, 2007 averaged -0.18 MPa
- Average water potential in 2007 was -0.29 MPa
- Crown dieback as of September 2007 was decreased to 0%
- Water potential readings taken June 4, 2008 averaged -0.45 Mpa
- Average water potential in 2008 was -0.38 MPa
- Crown dieback as of September 2008 was still 0%

Site 7 Aurora Community College
- Water potential readings taken 1997-2008
- Average water potentials in 2006 was -0.80 MPa
- Crown dieback as of September 2006 was 12%
- Water potential readings taken May 31, 2007 averaged -0.25 MPa
- Average water potential in 2007 was -0.40 MPa
- Crown dieback as of September 2007 was 12%
- Water potential readings taken June 4, 2008 averaged -0.45 MPa
- Average water potential in 2008 was -0.46 MPa
- Crown dieback as of September 2008 was 6.7%

Tollgate Creek

Site 8 Aurora Golf Course
- Water potential readings taken 1997-1999, 2004-2008
- Average water potential in 2006 was -0.61 MPa
- Crown dieback as of September 2006 was 9%
- Water potential readings taken May 31, 2007 averaged -0.26 MPa
- Average water potential in 2007 was -0.42 MPa
- Crown dieback as of September 2007 was 9%
- Water potential readings taken June 19, 2008 averaged -0.34 MPa
- Average water potential in 2008 was -0.48 MPa
- Crown dieback as of September 2008 was 9%

Site 9 Moline Crossing
- Water potential readings taken 1997-1999, 2004-2008
- Average water potential in 2006 was -0.74 MPa
- Crown dieback as of September 2006 was 9%

- Water potential readings taken May 31, 2007 averaged -0.31 MPa
- Average water potential in 2007 was -0.51 MPa
- Crown dieback as of September 2007 was 6%
- Water potential readings taken June 4, 2008 averaged -0.58 MPa
- Average water potential in 2008 was -0.46 MPa
- Crown dieback as of September 2008 was 3%

Site10 Kentucky / Dayton

- Water potential readings taken 1997-1999, 2004-2008
- Average water potential in 2006 was -0.71 MPa
- Crown dieback as of September 2006 was 18%
- Water potential readings taken May 31, 2007 averaged -0.20 MPa
- Average water potential in 2007 was -0.31 MPa
- Crown dieback as of September 2007 was 16%
- Water potential readings taken June 4, 2008 averaged -0.31 MPa
- Average water potential in 2008 was -0.42 MPa
- Crown dieback as of September 2008 was 16%

Site 11 Mississippi "Y"

- Water potential readings taken 1997-1999, 2004-2008
- Average water potential in 2006 was -0.48 MPa
- Crown dieback as of September 2006 was 5%
- Water potential readings taken May 31, 2007 averaged -0.32 MPa
- Average water potential in 2007 was -0.37 MPa
- Crown dieback as of September 2007 was 5%
- Water potential readings taken June 4, 2008 averaged -0.25 MPa
- Average water potential in 2008 was -0.47 MPa
- Crown dieback as of September 2008 was 5%

Site12 Quebec Way Big

- Water potential readings taken 1997-1999, 2004-2008
- Average water potential in 2006 was -0.50 MPa
- Crown dieback as of September 2006 was 2%
- Water potential readings taken May 30, 2007 averaged -0.31 MPa
- Average water potential in 2007 was -0.34 MPa
- Crown dieback as of September 2007 was 3%
- Water potential readings taken June 4, 2008 averaged -0.32 MPa
- Average water potential in 2008 was -0.41 MPa
- Crown dieback as of September 2008 was 3%

Site13 Quebec Way Small

- Water potential readings taken 1997-1999, 2004-2008
- Average water potential in 2006 was -0.65 MPa
- Crown dieback as of September 2006 was 2%
- Water potential readings taken May 30, 2007 averaged -0.19 MPa
- Average water potential in 2007 was -0.35 MPa
- Crown dieback as of September 2007 was 1%
- Water potential readings taken June 4, 2008 averaged -0.34 MPa
- Average water potential in 2008 was -0.41 MPa
- Crown dieback as of September 2008 was 6%

Site14 Iliff down stream

- Water potential readings taken 1997-1999, 2004-2008

- Average water potential in 2006 was -0.68 MPa
- Crown dieback as of September 2006 was 14%
- Water potential readings taken May 30, 2007 averaged -0.22 MPa
- Average water potential in 2007 was -0.35 MPa
- Crown dieback as of September 2007 was 13%
- Water potential readings taken June 4, 2008 averaged -0.19 MPa
- Average water potential in 2008 was -0.38 MPa
- Crown dieback as of September 2008 was 12%

Project Conclusions
(based on 2000 - 2008 data)

Objective One A: Determine how long it takes for cottonwood trees to become drought stressed when water is withheld from the canal.

Conclusion: Cottonwood trees become drought stressed (<-0.3 MPa) in about 4-8 weeks, and severely stressed (<0.5 MPa) in 6-8 weeks after a two-week long spring canal run.

Supporting Information:

1. Based on water potentials, the best estimate of when a cottonwood growing along the canal becomes slightly stressed is when leaf water potentials are less than -0.3 MPa. This is based on leaf water potential trends seen at sites where soil moisture was not limiting, especially in 2001 (sites along the Colfax Loop and near Laredo and 12th Avenue). These trends were then compared to water potentials at other locations where soil moisture was limiting (sites at Green Valley Ranch).

2. In 2000, it took trees about 8 weeks to reach a leaf water potential less than -0.30 MPa (between May 25 and July 25, 2000).

3. In 2001, it took trees about 6-8 weeks to reach leaf water potentials less than -0.30 MPa (between May 24 and early July). Trees at some sites at Green Valley Ranch took 8 weeks(sites 2 and 25), trees at the Wagner Equipment site (site 17) along Tower Road took 7 weeks, trees along the Arsenal Lateral at Green Valley Ranch (sites 16 and 23) took 6 weeks, and trees along the Colfax Loop (site 6) and at Laredo and 12th (site 20) did not become stressed. Stress did not happen any faster in 2001 at by-pass pipe sites (sites 2 and 17) since there was some leakage in the by-pass pipe system at the beginning of the season. Soil moisture data suggests that some degree of soil moisture recharge occurred over the winter.

4. In 2002, most trees were drought stressed (less than -0.30 MPa) as soon as leaves expanded in the spring since there was no spring canal flow and it was a dry winter.

5. In 2003, it took trees about 6-8 weeks to reach leaf water potentials less than -0.30 MPa (between May 22 and early to late July). Trees at some sites at Green Valley Ranch (sites 16 and 23) took 8 weeks others took 5.5 to 6.5 weeks (sites 2 and 25), trees at the Wagner Equipment site (17) along Tower Road took 8.5 weeks, and trees along the Colfax Loop (site 6 and 19) took 7.5 and 6.5 weeks, and at Laredo and 12th (site 20) trees did not become stressed. The canal had runs in April 23-May 9, June 21-July 3, and September 9-19. Discussion of the impact of the summer runs can be found under objective three.

6. Soil moisture measurements from 2000 to 2003, indicated that during periods when water was in the canal, canal water moved rapidly into the soil adjacent to the canal (and probably also below the canal). However, farther at 25' away from the canal, there was very little movement of moisture in the upper 9' –12'of soil. Most of the research sites are located in areas where the soil is sandy, and soil moisture data indicated that water from the canal tended to move downward (vertically) into the profile, instead of moving away from the canal (horizontally).

8. Observation well measurements from 2000 to 2003 indicated that during periods when water was in the canal, free water in observation wells at three of the four sites increased. No water was ever found at Site 2 at Green Valley Ranch. At the Colfax loop site (Site 6), water moved downward and away from the canal down the slope. At Laredo and 12th (Site 20) water was found in the well at a shallow depth after a canal run. This is a change from previous years and must reflect some direct connection between the canal and the well. At the Wagner Equipment site (Site 17), the water table increased slightly. At these three sites, water tables were at depths of 17' -25'. We think this water is too deep to be available to the trees.

9. In 2004 most sites reached a leaf water potential less than –0.3 MPa in 4-6 weeks after the June canal run.

10. In 2005 most trees reached a leaf water potential less than –0.3 MPa in 3-4 weeks after the April to June canal run.

11. In 2005 most trees that had a leaf water potential less than –0.5 MPa and did so 6-8 weeks after the April to June canal run.

12. In 2006 the canal run on July 5 -21, 2006 made it to Site 9 (Moline crossing). Water from the July run did have a noticeably positive impact the water status of the trees at research sites located between Leetsdale Avenue @ Mississippi and Moline, as water potentials generally were higher for trees at research sites 9-14 on July 12 compared to water potential readings on July 5. Water from the July run had approximately seven day impact on the water status of the trees at research sites 9-14, as water potentials for all trees were below -0.600 or below by July 19;

13. In 2007, initial spring predawn leafwater potential readings (May 30 – June 6) for trees at sites upstream of Sand Creek Siphon ranged between -0.10 and -0.50 MPa, indicating that some of the trees began the 2007 growing season in stressed condition.

- The low water potentials were a bit unexpected since water flowed in the canal April 2-22, prior to the trees leafing out.
- Even though water flowed in the canal for approximately 20 days in April several trees at sites along the upstream end of the study area, between Cherry Creek and Tollgate Creek (Sites 8, 9, 10, 11, 12, 13, & 14) had initial (spring) water potential readings between -0.10 and -0.53 MPa.
- During the time of the second of three runs of water in the canal (June 4-19), water potentials ranged from -0.10to -0.50 MPa at sites upstream of the Sand Creek.
- During the time of the third of three runs of water in the canal (August 3 – 23), water potentials ranged from -0.15 to -1.55 MPa at sites upstream of the Sand Creek Siphon.
- From June 20 through August 2, the canal was not flowing; water potentials ranged from -0.05 to -0.83 MPa at sites uptream of the Sand Creek Siphon.
- The headgate of the canal was closed for the year on August 24; early September water potentials for sites upstream of the Sand Creek Siphon ranged from –0.20 to -0.98 MPa.
- At sites downstream of Sand Creek Siphon, NO water flowed in this section of the canal during 2007; predawn leaf water potentials of trees at Sites 17 and 2 ranged from –0.18 to -1.00 MPa.

14. In 2008, initial spring water potentials were generally more negative than in previous years (<-0.30 MPa. After the spring canal run in May-June the water potentials either did not change or decreased in 2-4 weeks.

Objective One B: Predawn leaf water potential patterns that relate to dieback in cottonwoods?

Conclusion: Analysis of water potentials and tree crown status on cottonwood trees along the High Line Canal has given some hints as to what amount of water stress amount causes dieback. The trees with the most dieback had spring water potential readings less than –0.34 MPa and less than –0.6 MPa summer readings (Sites 19, 25 and 6). Water potential readings below-0.9 MPa in the summer does not mean the tree will have dieback immediately since site 17 and 20 did not exhibit dieback in 2002, even thought they had low water potentials in 2002. Site 17 started to show dieback three years after the drought of 2002 and continuing summer drought since there was no canal water. The trees at sites with no canal run for 5 years have taken 4-5 years to die or increase in dieback. These trees had predawn water potentials in the fall of 2005 all less than –0.7 MPa so water potentials less than –0.6 MPa generally indicate trees are seriously stressed.

Objective Two: Determine how rapidly the trees recover after water is provided after a period of drought.

Conclusion: Drought stressed cottonwood trees respond to supplemental water within 24-72 hours after the addition of water to the canal.

Supporting Information:

1. In 2000, we only had one period when water was added to the canal. We saw a reduction of drought stress (indicated by an increase in leaf water potential) within 24 hours after water was added to the canal.

2. In 2001, we had one period when water was added to the canal. Leaf water potentials increased within 24 hours.

3. In 2002, we had one period when water was tanked to sites 2 and 19. Leaf water potentials increased within 24 hours.

4. In 2003, we had one period in August when water was trucked to site 2 and a fire hose used at site 17. Leaf water potentials increased within 48-72 hours. During a PAMS study in August at site 6, water was added to the canal and there was a response in 24-48 hours. The September PAMS seepage test did not afford any measurements on water potentials since we were not told about the test. Water potentials taken one week after the test did not show any impact of the added water.

5. In 2004, 2005, 2006, 2007 or 2008, there were no opportunities to assess the rapidity of tree recovery on a daily basis. Previous to 2008 most trees showed less stress one week after an August canal run but we do not know how soon after the canal was running that this response happened. In 2008 the data indicate a 2 week lag between the August canal run and a response in the water potentials.

Objective Three: Determine the amount of water needed to relieve drought conditions in cottonwoods.

Conclusion: Two weeks of canal flow, either from actual canal runs or simulated by fire hose and tanker trucks at two sites in 2003, suggest that two weeks of water will give about 3 to 4 weeks of relief from drought stress (-0.3 MPa) and probably 6-8 weeks of relief from severe drought stress (<-0.5 MPa).

Supporting Information:

1. In 2001, one day of canal flow relieved stress in trees, but the trees started showing stress a few days later. This decrease in leaf water potentials may have been stress or fall leaf senescence.

2. In 2002, a few days of water trucked into sites 2 and 19 relieved drought stress for about one week.

3. In 2003, the canal flowed for approximately 10 days (June 21 to July 3) and made it all the way to the Arsenal Lateral. Water potentials were above -0.30 MPa during this period. During and after this canal run water potentials did not increase even though soil moisture increased at sites 20, 19 and 6. We think there was no response to this canal flow because the trees were not really stressed enough to respond to the extra water. The canal flow of Sept 9-19 caused soil moisture increases at sites 6, 19 and 20 but not at 2, 23, 16, 17 and 25. Water potentials might have increased at site 19 and 6 but the data seems inconsistent. We cannot make any other assessments about this canal run since we were not informed about it and thus did not collect data during this period.

4. To simulate two weeks of water flow in the canal in 2003, water was added to basins at site 17 and site 2. On August 4 and 6 two- 4,000 gallon tank trucks dumped water at each site. On August 8, 1 foot of water was added to the basin at site 17 from a fire hydrant and 6 tank trucks were dumped at site 2. On August 10, 13, and 15, 1 foot of water was added to site 17 and 6 tank trucks dumped at site 2.

5. Assumptions: amount of water added each day.
    a. Site 17, surface area that water was added to: 166 feet long by 10 feet wide = 1,660 ft^2 x 1 ft deep = 12,418 gallons or 7.5 gallons per ft^2.
    b. Site 2, surface area that water was added to: 60 feet long by 10 feet wide = 600ft^2 with 24,000 gallons dumped or 40 gallons per ft

6. There probably would be longer stress relief if the water flowed for 2 weeks since the fire hose and tank truck water did not produce a constant volume of water in the canal. Soil moisture increased in sample tubes near the canal at site 2 but not at site 17. The amount of water added by hose at site 17 was about 7.5 gallons/ft^2 of canal bed and about 40 gallons/ft^2 at site 2. The amount of water added at site 2 probably more correctly represents a constant two-week flow of water. How long trees will be kept from being seriously drought stressed is not definitely known.

7. In August 2005, only one day of water reached trees downstream of Tollgate and there was a significant reduction in water stress in trees for two weeks.

8. In July 2006, 15 days of water reached trees between Cherry Creek and Tollgate. Trees had a reduction in water stress for a week.

9. In 2007 water reached trees between Cherry Creek and Tollgate on two occasions for a total of 46 days and reduced stress for 7 -14 days; water reached Sand Creek two times for a total of 26 days and reduced stress for 7-14 days.

10. In 2008, water reached trees between Cherry Creek and Sand Creek twice but there was no clear reduction on stress noted in May-June since there were no data collected prior to the canal run. The August 2008 canal run reduced water stress at a limited number of sites but monitoring ended before any of these trees showed decreasing water potentials, so the duration of the impact was not clear.

Objective Four: Determine when or how often this minimal water is needed to keep the cottonwood trees alive.

Conclusions: Under ideal conditions, it appears water should be added to the canal in July to keep trees above -0.3 MPa. Unfortunately water is not usually available until late summer or early fall. In previous years with a two-week canal run in the spring and again in September, trees have reached water potentials of –0.4.5 to –0.5.5 MPa but these have not resulted in significant dieback. Thus, two weeks of water in the spring and two weeks in the fall seems like a feasible plan.

Objective Five: Determine the changes in soil moisture as water is withheld or added to the canal at sites along the canal where trees and soil moisture are monitored.

Conclusions: Soil moisture increases when water is added to the canal and decreases when water is withheld.

Supporting Information:

1. In 2001, soil moisture decreased during the summer months after high soil moisture in the spring at sites with by-pass pipes and after the canal was turned off.

2. In 2001, soil moisture increased after water was added to the canal at most of the research sites: sites 20, 6, 23, 16, and 2 showed increases in soil moisture after canal water was added, whereas site 17 did not.

3. Based on the data collected at the Laredo and 12th site (site 20), it appears that soil moistures > 17- 20% will keep leaf water potentials > -0.3 MPa (indicating that the trees are not stressed). Soil moistures < 17% will allow leaf water potentials to decrease below -0.30 MPa (indicating that the trees are stressed).

4. In 2002, soil moisture was so low (≤ 17%) in the spring that most trees were stressed when they leafed out.

5. In 2003, soil moisture increased after water was added to the canal at most of the research sites: sites 20, 19, 6, 23, 16, and 2, but not at site 17.

6. Soil moisture was not collected after 2003.

Objective Six: Determine if rainfall has any impact on the water status of the cottonwoods.

Conclusions: Rain events do not provide enough soil water to relieve drought conditions for more than a few days. If rainwater flows into the ditch the impact is more pronounced.

Supporting Information:

1. Based on 2001, 2003, 2005, 2006 observations, summer precipitation events $\geq$ 1.0 inch reduces water stress in trees at all sites, but the duration was, only 3-7 days. The increase in leaf water potential shortly after a summer precipitation event ranged only from 0.05 to 0.10 MPa. The amount of rainfall needed to reduce stress is about 1.0 inch per precipitation event, and the history of such events indicates that rainfall cannot be relied upon to satisfy the entire moisture requirement of the cottonwood trees growing along the canal. At locations just downstream from Iliff the canal receives storm drainage so rain events of 0.5 inch can increase water potentials.

2. Rain during predawn leaf water potential assessments causes the readings to indicate that the trees are not stressed even though they might be stressed.

3. There was no significant impact of rainfall on the percent soil moisture at 1 foot below the soil surface at any of the sites.

4. In 2007 and 2008 there were no significant increases in water potentials after a rain fall of > 0.5 inch, although rain had no effect on several sites in 2008 or water potential data were not collected on dates to support this information.

Objective Seven: Determine if lining the bottom of the canal will allow enough water to reach the roots of trees growing adjacent to the lined section of the canal.

Conclusions: Water potentials of trees from sites with and without a liner increased at about the same rate when water was added to the canal. Soil moisture increased in soil adjacent to the liner at about the same rate where the liner was and as compared to up and downstream from the liner. Thus, we think the trees growing along lined sections of the canal can pick up enough water to keep from becoming stressed. However, the physical damage to roots from installing the liner may outweigh any benefits of the liner.

Supporting Information:

1. The Colfax Loop West site (site 19); was chosen to be the "liner study site" in April of 2002. Removal of soil from the canal bottom must have damaged the roots of the trees at this site, as indicated by predawn leaf water potentials at –0.7 MPa shortly after the trees leafed out in the spring. No other site started the growing season with trees this stressed. The amount of crown damage increased dramatically on these trees during the summer of 2002 from 25% to about 37%. In the spring of 2003 there was 81% dieback and an 86% dieback in the fall. The rapid decline in tree health is probably related to the very negative water potentials found in the spring (-0.7MPa) of 2002 with further decreases to –1.0 MPa in the fall. There were no canal flows in 2002.

- Removal of over two feet of soil in the canal bottom to install the liner probably damaged more roots than if only a foot of soil had been removed.

- The removal of ditch banks immediately up and downstream from these trees during the spring of 2002 most likely damaged roots also.

Tank trucks did dump about 24,000 gallons of water at the trees August 13-15, 2002. This did increase water potentials for two weeks but by September 15 the trees were stressed again.

In 2004 the objectives were changed to:

1. Determine if two weeks of water in the spring and two weeks of water in the summer/fall in the High Line Canal is enough water to keep cottonwoods healthy between Cherry Creek and Sand Creek.

- The crown health of trees between Cherry Creek and Sand Creek monitored during 2004-2008 with 7.7 to 8.0% dieback has not changed. It appears the water provided to these trees in the spring and fall and the local irrigation in the area helped the trees keep in acceptable health.

- The average summer water potential is a value that can predict dieback in trees. Trees with less than -0.6 MPa over two to five years have branch dieback and if the stress continues death will occur.

Appendix A: Tree Condition Data Codes

PERCENT CROWN DAMAGE

= % of tree crown (major branches) exhibiting symptoms of dieback

DISEASE & ABIOTIC DAMAGE

Codes:

D 1	=	NO Disease
D 2	=	*Cytospora* stem canker (severity = % of stem girdled)
D 3	=	*Cytospora* branch canker (severity = % of branches infected)
D 4	=	Stem decay (severity = % volume of first 16 feet of trunk)
D 5	=	Branch decay (severity = % of branches displaying decay)
D 6	=	Bacterial wetwood (severity = % of main branches showing symptoms [symptoms include oozing of odiferous liquid, lighter-colored streaks on bark, unhealed wounds])
D 7	=	Lightening damage (severity = % of main branches and trunk affected [symptoms include irregular, ragged vertical splitting of bark, beginning at the top of the tree and moving towards the ground; bark may be completely separated from wood of tree in severe cases])
D 8	=	Mechanical damage (severity = % of stem circumference damaged)
D 9	=	Leaf Spot (*Marssonina* and/or *Septoria*) (severity = combination of % of leaf area affected AND % of tree affected)
D 10	=	Squirrel damage to branches (severity = % of branches damaged by squirrel chewing activity)

Disease & Abiotic Damage Severity Rating:

1	=	1- 10 % of tree affected
2	=	11- 20 % of tree affected
3	=	21- 30 % of tree affected
4	=	31- 40 % of tree affected
5	=	41- 50 % of tree affected
6	=	51- 60 % of tree affected
7	=	61- 70 % of tree affected
8	=	71- 80 % of tree affected
9	=	81- 90 % of tree affected
10	=	91-100 % of tree affected

INSECT AND MITE DAMAGE

Codes:

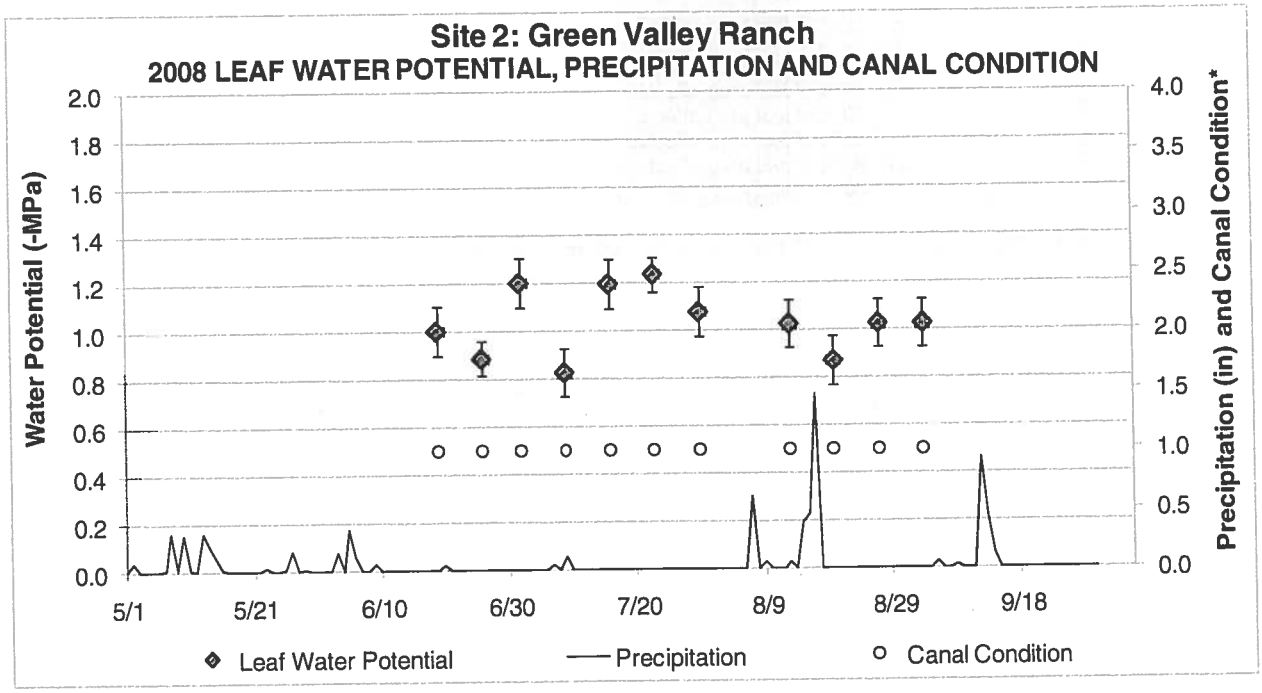
I 1	=	NO Insects OR Mites
I 2	=	Aphids
I 3	=	Defoliating Insects
I 4	=	Piercing/Sucking Insects and/or Mites
I 5	=	Wood Boring Insects
I 6	=	Leaf Miners
I 7	=	Leaf Rolling Insects
I 8	=	Petiole galls caused by Insects
I 9	=	Poplar Budgall Mite damage
I 10	=	Catkin Gall Mite damage

Insect and Mite Damage Severity Rating:

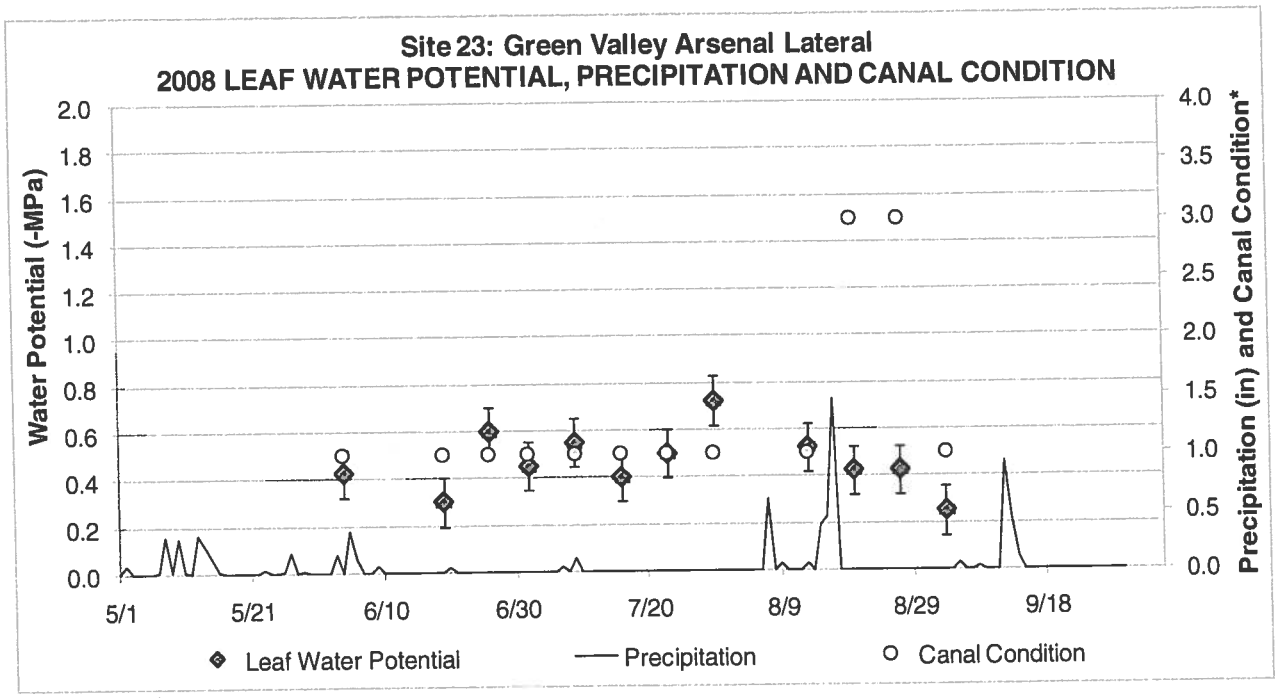
1	=	1- 10 % of leaf area affected
2	=	11- 20 % of leaf area affected
3	=	21- 30 % of leaf area affected
4	=	31- 40 % of leaf area affected
5	=	41- 50 % of leaf area affected
6	=	51- 60 % of leaf area affected
7	=	61- 70 % of leaf area affected
8	=	71- 80 % of leaf area affected
9	=	81- 90 % of leaf area affected
10	=	91-100 % of leaf area affected

For Wood Boring Insects, it is the percent of stem volume affected.

Appendix B: Charts of Average Predawn Leaf Water Potentials at each Site by Dates in Relation to Precipitation and Canal Water Condition.



* Canal Condition:
1 = Dry
2 = Muddy
3 = Flowing



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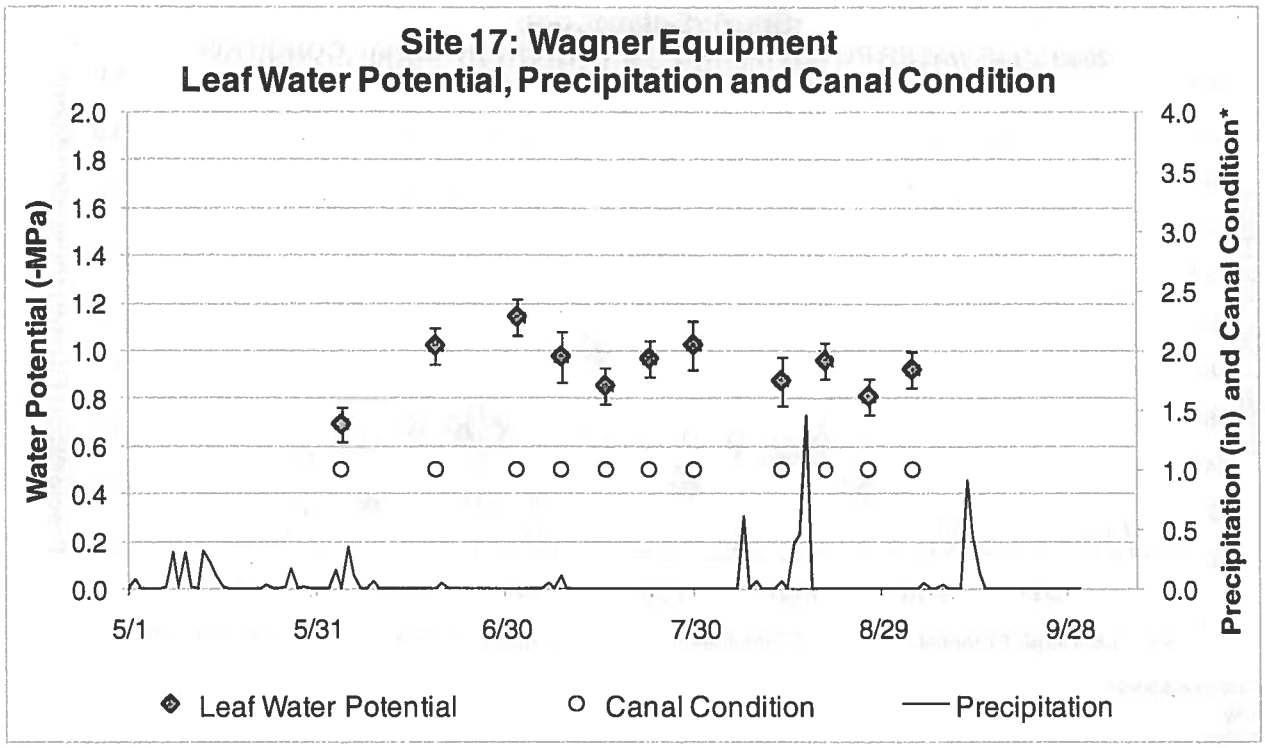

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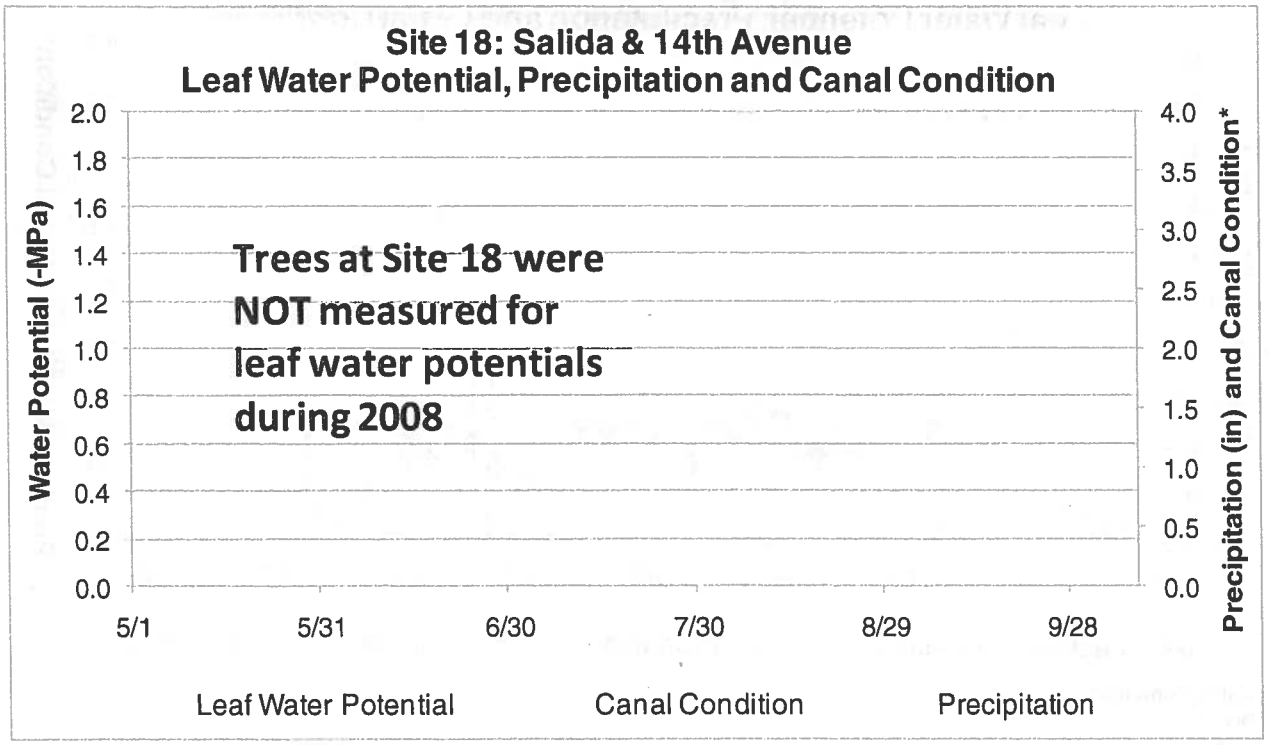

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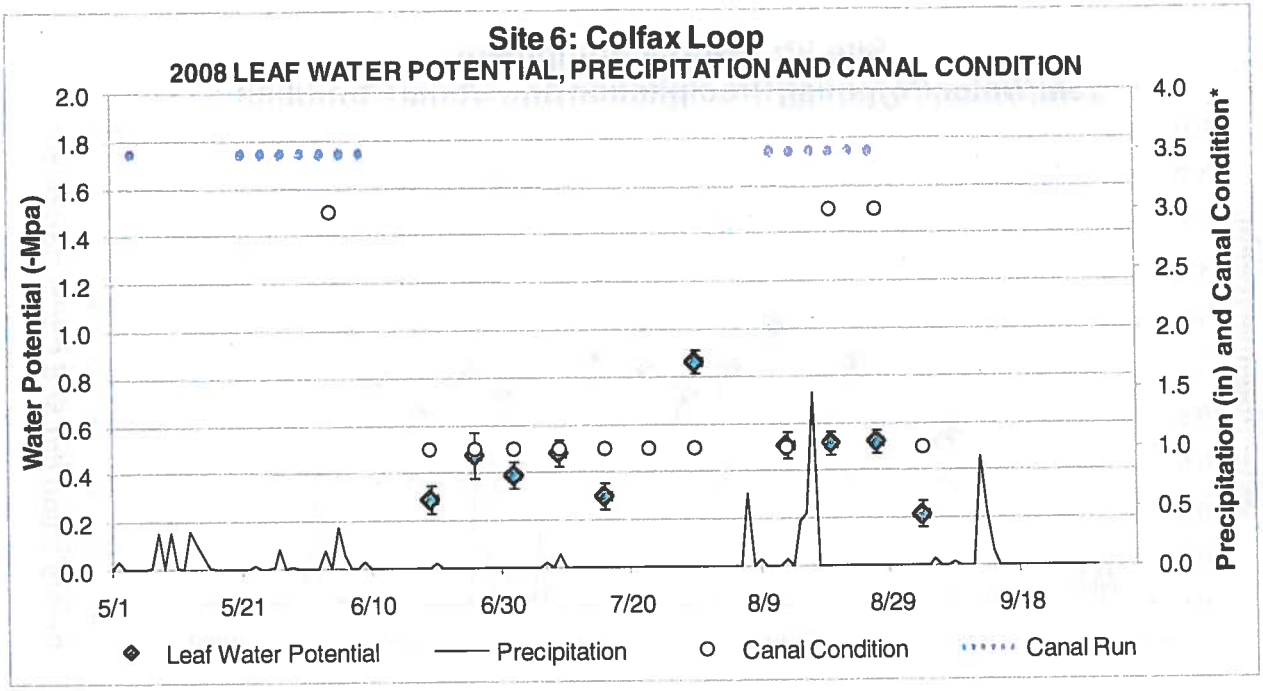

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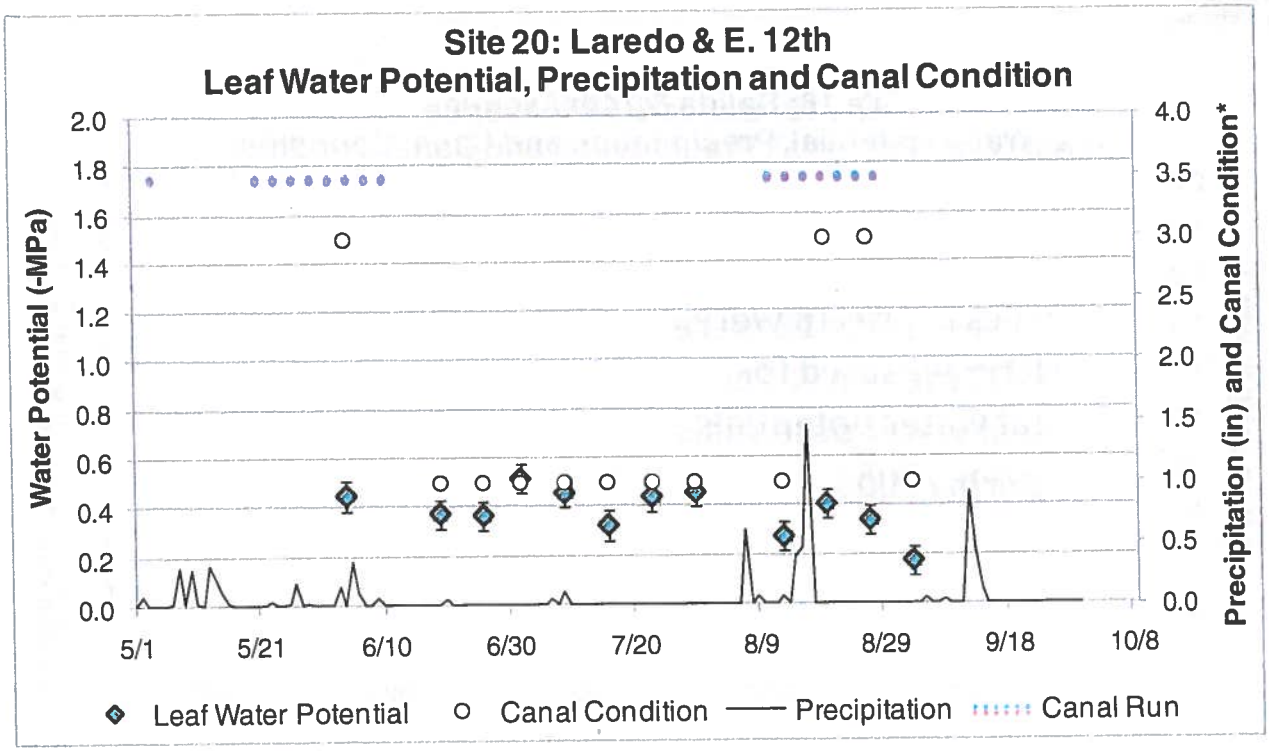

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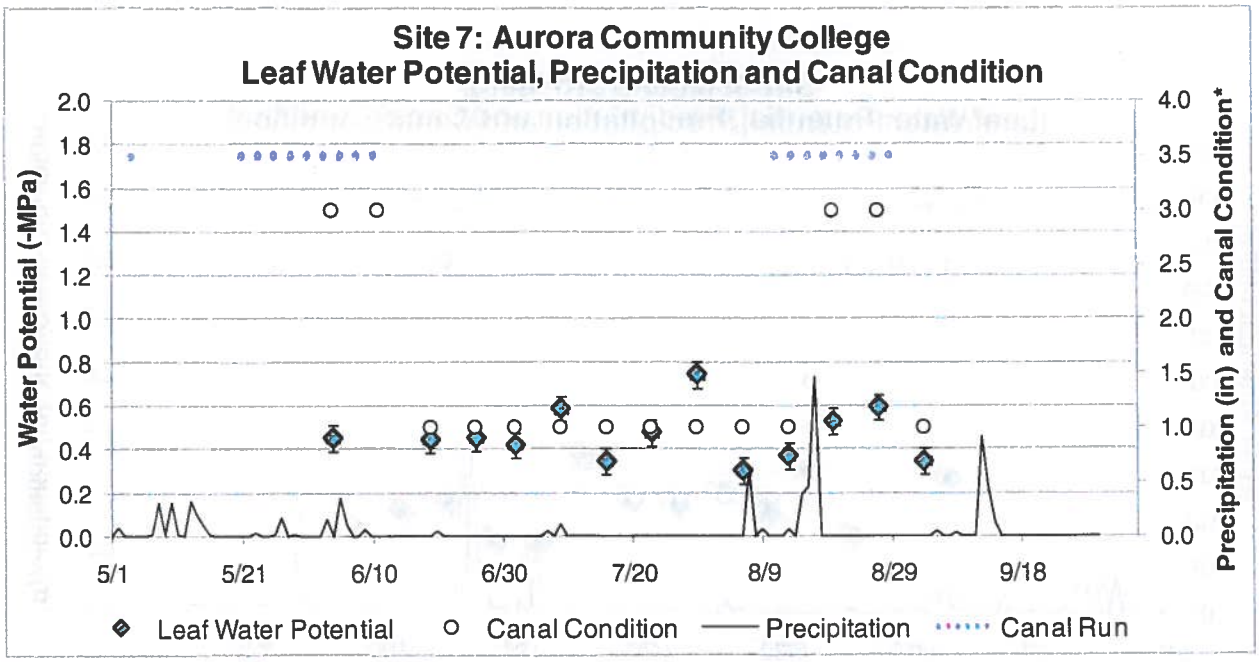

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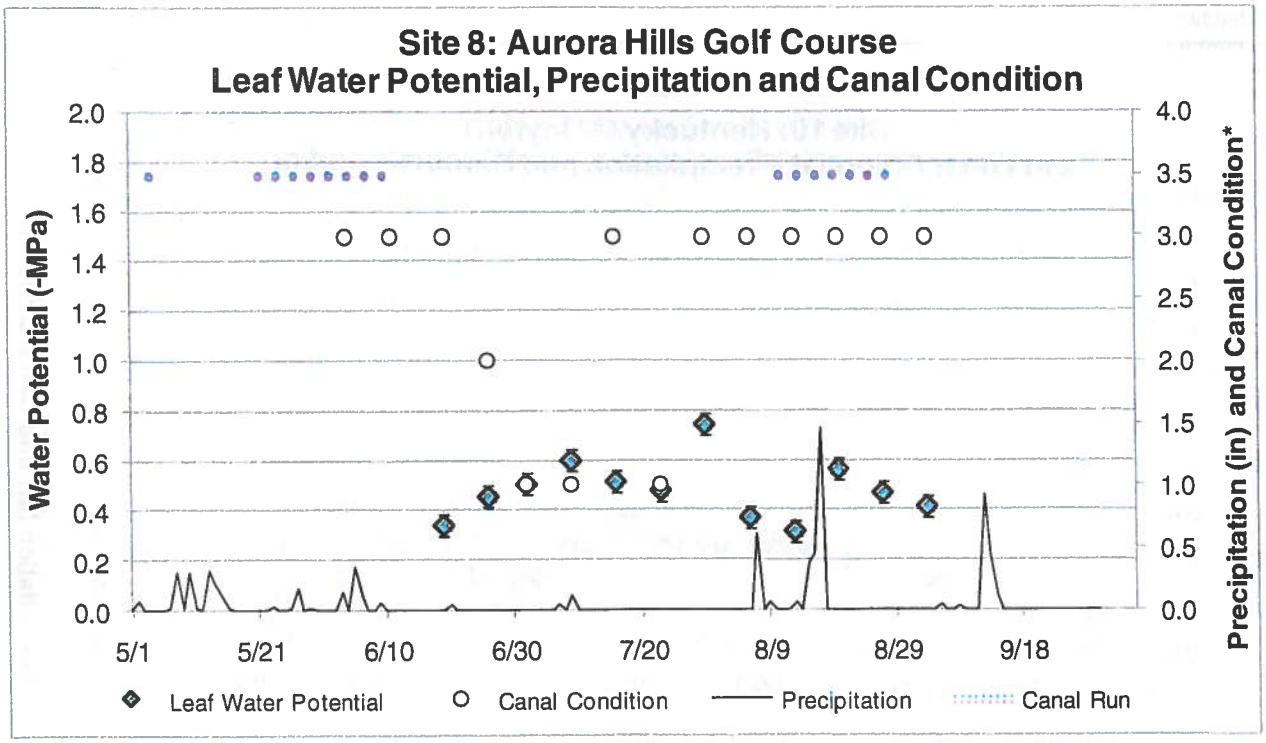

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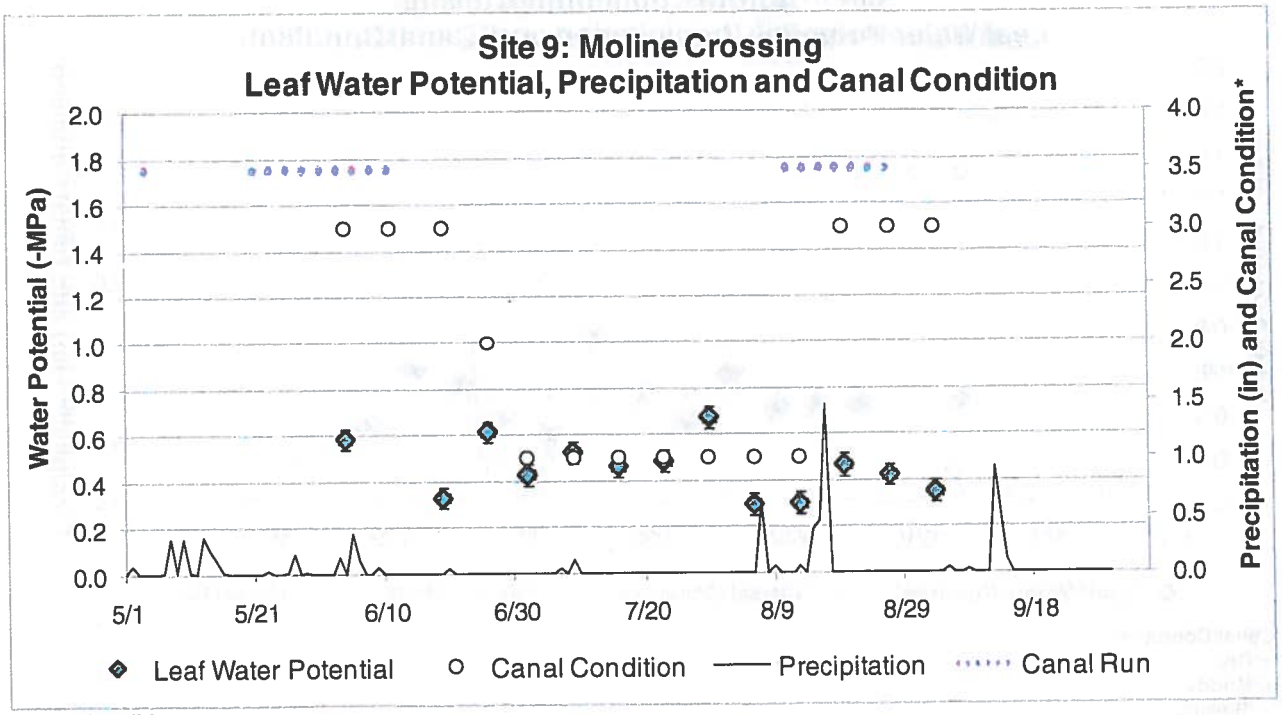

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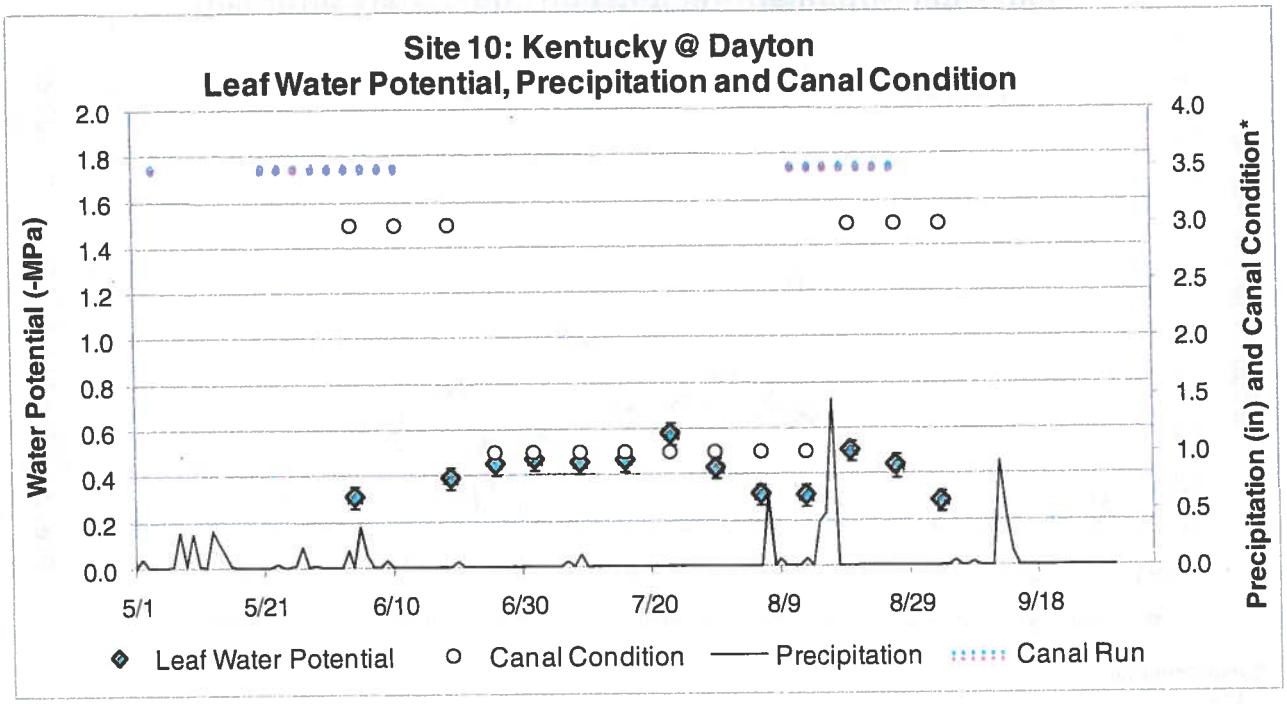

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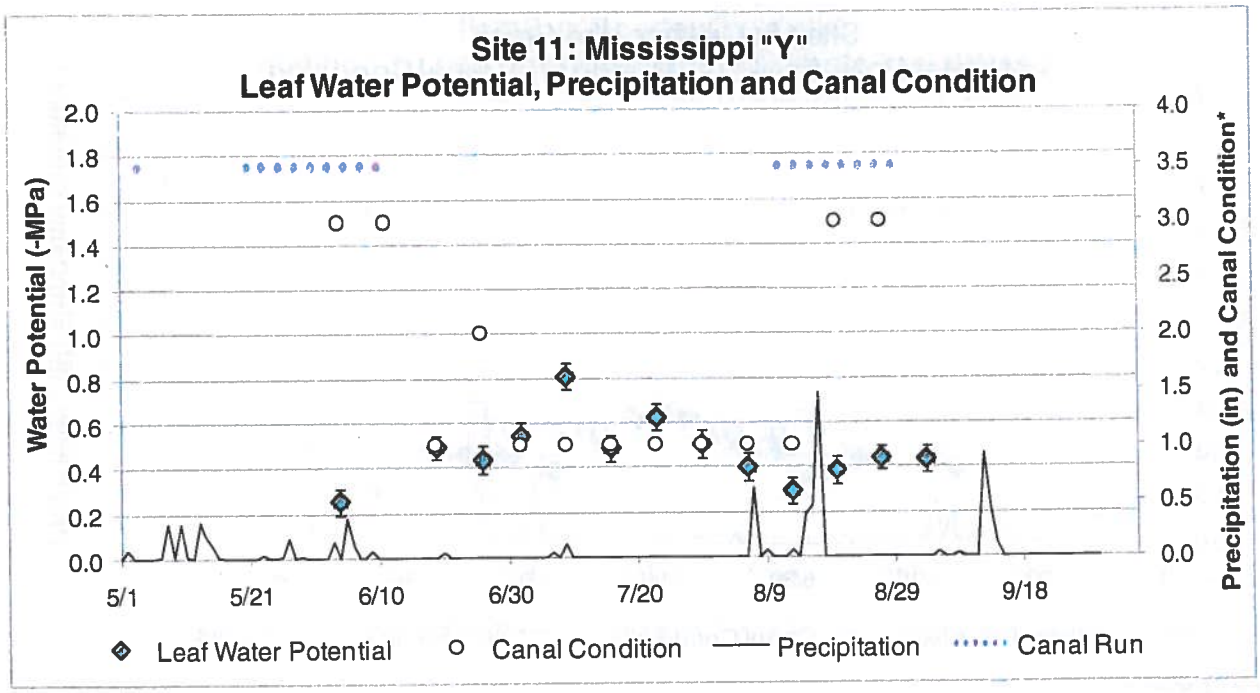

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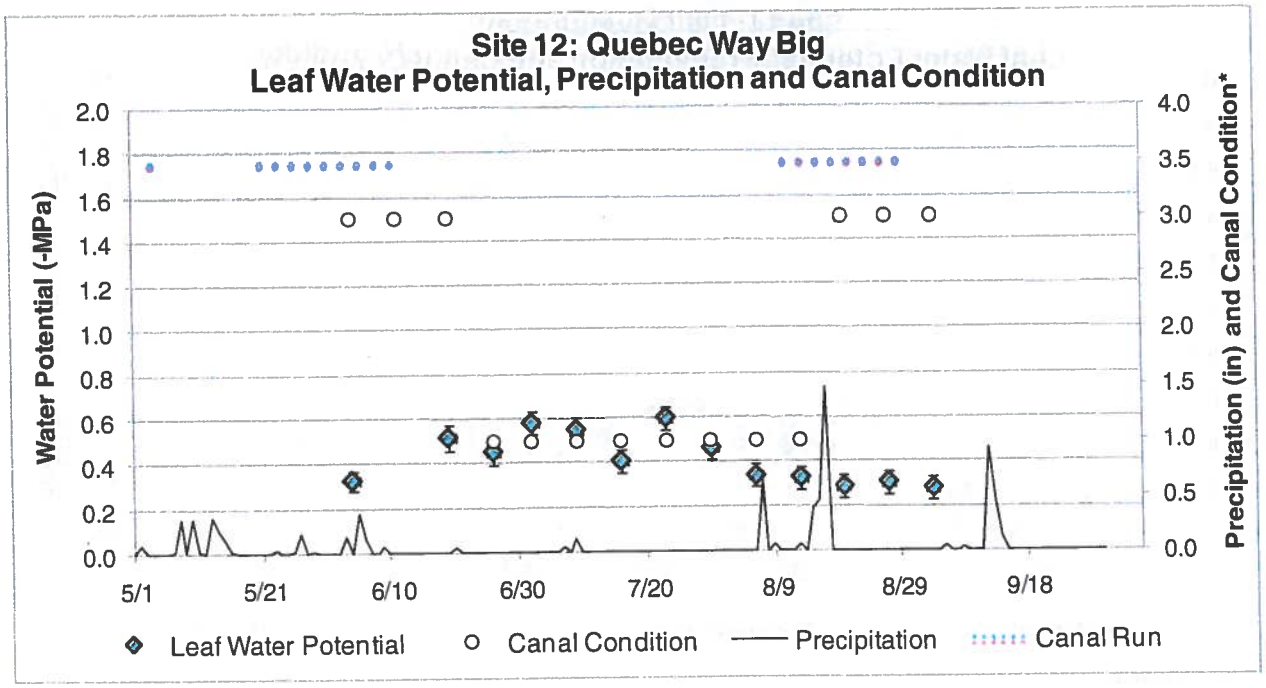

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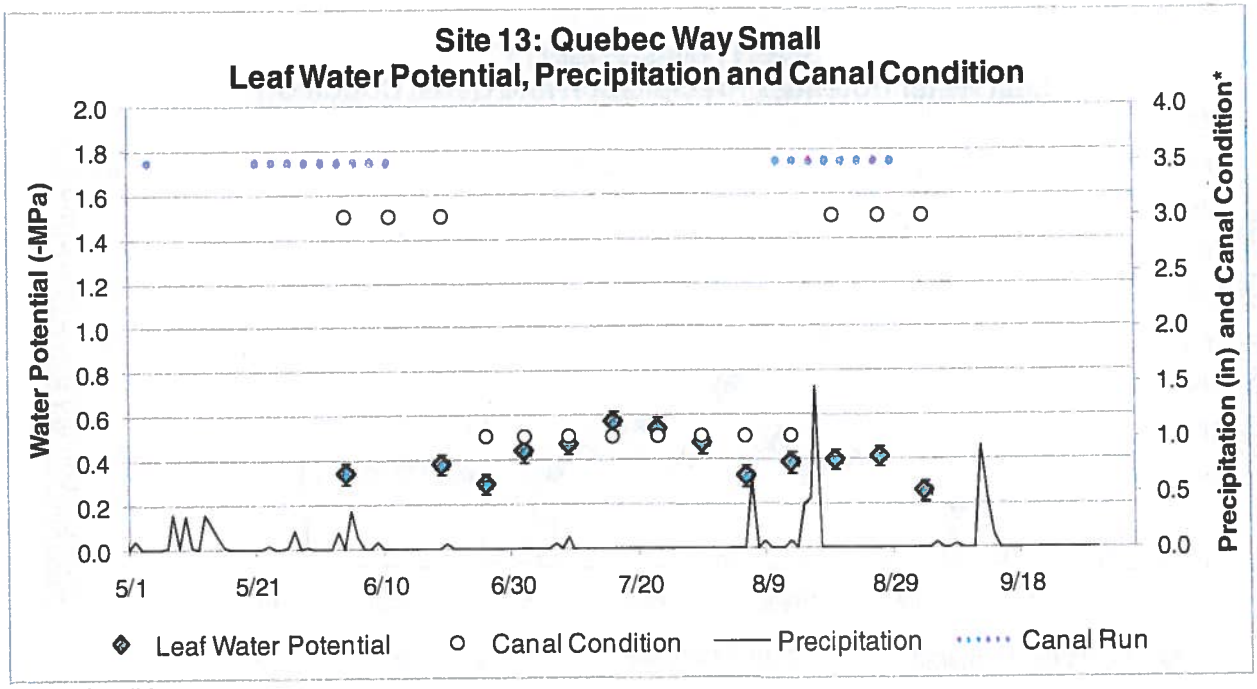

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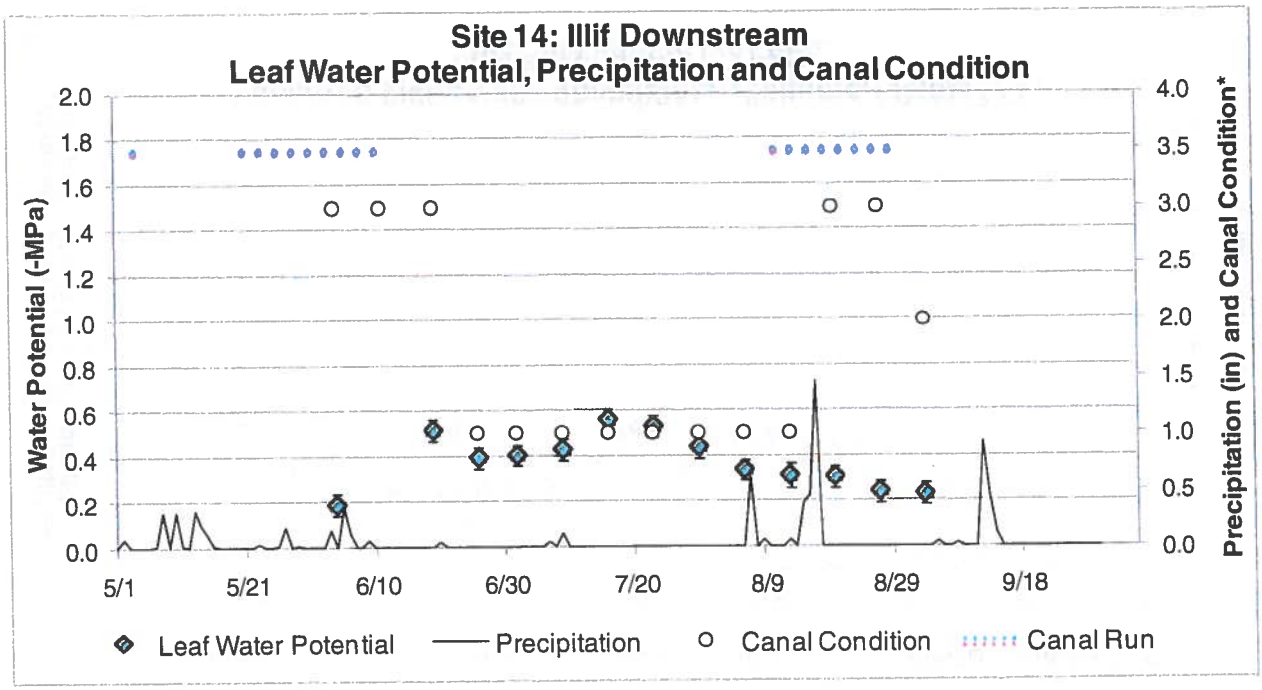

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