

**Water Usage of Cottonwoods  
At Selected Sites Along  
The High Line Canal**

**W.R. Jacobi and R. D. Koski  
Dept Bioagricultural Science and Pest Management  
Colorado State University, Fort Collins CO 80523  
970-491-6927, Fax 970-491-3862, William.Jacobi@colostate.edu  
970-491-5155, rkoski@lamar.colostate.edu**

**Highlights of Report Submitted to Denver Water Department  
December 7, 2005**

## Introduction

Plains cottonwoods (*Populus deltoides* 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. In 2004, water flows were in volume with two canal runs – one in June and one in August reduced or eliminated. This study was initiated to obtain information on tree health and water status of trees growing along the canal during times of fluctuating water flow in the canal.

### Working Definition of Drought Stressed Cottonwoods:

When a cottonwood's leaf water potential decreases below  $-0.30$  MPa the tree becomes **slightly** drought stressed relative to a tree with adequate soil moisture. Water potentials of  $-0.3$  to  $-0.5$  MPa during the growing season are **moderately** stressful but there may be no immediate outward evidence of damage such as crown dieback. What water potentials signal branch death and crown dieback the following year is not easy to determine. Trees that had no canal water and drought conditions for two years of 2001-2002 exhibited crown dieback. Our analysis of water potential data indicates that if a tree is stressed (water potentials less than  $-0.3$  MPa) in the **spring** the tree will have some crown dieback the next year. Leaf water potential less than  $-0.5$  MPa during the growing season is considered a **severely** stressed tree on a long-term basis. Several trees reached  $-1.0$  MPa in 2002 and did not exhibit increased dieback in 2003.

## Study Objectives

### Original objectives of this study are to:

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 of this study are 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
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 Highline 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 centimeter. Tree heights were taken via an inclinometer and recorded to the nearest foot. Radial Increments were obtained from increment cores taken at 1.5 m, 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. Both years were unusually wet and the canal was rarely without water since surface water flowed into the canal at several locations. Thus water potentials remained below 0.5 -MPa and we assume the trees were not significantly drought stressed during those summers.

**Table 1. All cottonwood research sites along the High Line Canal 1997 - 2005**

| <u>Site</u>            | <u>Name</u>                 | <u>Tree Tag #</u> | <u>Notes</u>  |
|------------------------|-----------------------------|-------------------|---|
| 1                      | Green Valley dry            | 11-22             | Old trees, dry site along High Line Canal down stream 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 down stream 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 down stream 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 to study 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, down stream of siphon. Dropped from study in 2000 due to site accessibility.  |
| <b>Sand Creek-----</b> |                             |                   |   |
| 18                     | Salida and 14 <sup>th</sup> | 907-909           | Old trees, along north side of canal. Added to study in 1999.   |
| 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 sitestudy in 1999.  |
| 20*                    | Laredo and 12 <sup>th</sup> | 913-915           | Young trees, on north side of canal. Added from study in 1999.  |
| 21                     | Le Petite Academy           | 916-918           | Young trees located on east side of canal. Added to study in 1999. Dropped from study in 2001 due to construction in area.  |

|                       |                             |       |  |
|-----------------------|-----------------------------|-------|--|
| 7                     | Aurora<br>Community College | 48-52 | Young trees, on north side of canal, just behind Aurora<br>Community College buildings.                                  |
| <b>Tollgate Creek</b> |                             |       |  |
| 8                     | Aurora Golf Course          | 78-82 | Old trees, on north side of canal and north of the Aurora Golf<br>Course, just down stream of 2 <sup>nd</sup> Avenue.    |
| 9                     | Moline Crossing             | 73-77 | Young trees, on north side of canal, just down stream from and<br>east of Moline Street.                                 |
| 10                    | Kentucky / Dayton           | 68-72 | Old trees, on south side of canal, at the south east corner of<br>the intersection of Kentucky Avenue and Dayton Avenue. |
| 11                    | Mississippi "Y"             | 83-87 | Old trees, on west side of canal, down stream from Leetsdale /<br>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 down stream           | 58-62 | Old trees, on west side of canal, just down stream from Iliff.   |
| 15                    | Los Verdes Golf             | 53-57 | Young trees, next to footbridge, just up stream from Iliff<br>Avenue. Dropped from study in August 1999.                 |
| <b>Cherry Creek</b>   |                             |       |  |

\* = site with soil moisture monitoring tubes

## Modifications of Materials and Methods 1999-2005:

### 1999

- In 1999 five additional predawn water potential sites were added (16, 17, 18, 19, 20 and 21).
- We monitored *predawn* tree water potentials of all surviving trees at the 15 sites established in 1997 plus the six additional sites added in the spring. Data was 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* tree 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* tree water potential readings were also recorded for sites 12, 13, & 14 on September 29 and October 1.
- In 1999, we 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* tree 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 data collection at the 9 sites began February 22, 2001 with collections monthly from February to June, biweekly in June and weekly in July, August, and September.
- Water table data collection began February 22, 2001 with collections monthly from February to June, biweekly in June, weekly in July, August, and September.
- We monitored *predawn* leaf water potentials at the eight-soil moisture research sites biweekly starting June 25, 2001 and weekly in July, and August and 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 recorded the health status and took pictures of each tree during May 2001 but did not take fall assessments since there was no noticeable change in tree status.
- In early April 2001, Denver Water installed by-pass pipes in the canal at two existing sites – Site 17 (Wagner Equipment) and Site 2 (Green Valley Ranch). These by-pass pipes allow water to continue to flow to the Rocky Mountain Arsenal and at the same time allow water to be restricted from these two research sites. By restricting the flow of water at these selected sites, it was hypothesized that the soil adjacent to the canal at these sites would become dry and that the trees at these two sites would have 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 a 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') up stream 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 down stream 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 conditions in the spring and crown condition 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.<sup>1</sup>

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**

| <u>DATE</u>  | <u>TIME</u>    | <u>STAFF GAGE HIGHTS</u> |               |             | <u>STAFF GAGE REDUCTION</u> |               |               |
|--------------|----------------|--------------------------|---------------|-------------|-----------------------------|---------------|---------------|
|              |                | <u>POND 1</u>            | <u>POND 2</u> | <u>DIFF</u> | <u>POND 1</u>               | <u>POND 2</u> | <u>% DIFF</u> |
| <b>4-Aug</b> | 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          | <b>FULL</b>   |
|              | 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%           |
| <b>5-Aug</b> | 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%           |
|              | <b>5:00 PM</b> | <b>2.00</b>              | <b>2.00</b>   | <b>0.00</b> | 0.00                        | 0.00          | <b>FULL</b>   |
|              | 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%           |
| <b>6-Aug</b> | 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%           |
|              | <b>5:00 PM</b> | <b>2.00</b>              | <b>2.00</b>   | <b>0.00</b> | 0.00                        | 0.00          | <b>FULL</b>   |
|              | 8:00 PM        | NA                       | NA            | NA          | NA                          | NA            | NA            |
|              | 11:00 PM       | NA                       | NA            | NA          | NA                          | NA            | NA            |
| <b>7-Aug</b> | 2:00 AM        | NA                       | NA            | NA          | NA                          | NA            | NA            |
|              | 8:00 AM        | 0.81                     | 1.25          | 0.44        | 1.19                        | 0.75          | 37%           |
|              | <b>5:00 PM</b> | <b>2.00</b>              | <b>2.00</b>   | <b>0.00</b> | 0.00                        | 0.00          | <b>FULL</b>   |
|              | 8:00 PM        | NA                       | NA            | NA          | NA                          | NA            | NA            |
|              | 11:00 PM       | NA                       | NA            | NA          | NA                          | NA            | NA            |
| <b>8-Aug</b> | 8:00 AM        | 0.84                     | 1.22          | 0.38        | 1.16                        | 0.78          | 33%           |

<sup>1</sup> 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**

| <u>DATE</u>  |                | <u>POND 1</u> | <u>POND 2</u> | <u>DIFF</u> |      |      |             |
|--------------|----------------|---------------|---------------|-------------|------|------|-------------|
| <b>2-Sep</b> | 8:00 AM        | 0.00          | 0.00          | 0           | 0.00 | 0.00 | 0.00        |
|              | <b>5:00 PM</b> | <b>2.00</b>   | <b>2.00</b>   | <b>0</b>    | 0.00 | 0.00 | <b>FULL</b> |
| <b>3-Sep</b> | 8:00 AM        | 0.91          | 1.18          | 0.27        | 1.09 | 0.82 | 27%         |
|              | <b>5:00 PM</b> | <b>2.00</b>   | <b>2.00</b>   | <b>0</b>    | 0.00 | 0.00 | <b>FULL</b> |
| <b>4-Sep</b> | 8:00 AM        | 0.86          | 1.10          | 0.24        | 1.14 | 0.90 | 21%         |
|              | <b>5:00 PM</b> | <b>2.00</b>   | <b>2.00</b>   | <b>0</b>    | 0.00 | 0.00 | <b>FULL</b> |
| <b>5-Sep</b> | 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 on both 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 indicates 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. 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, 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<sup>2</sup> x 1 ft deep = 12,418 gallons or 7.5 gallons per ft<sup>2</sup>.
- Site 2, surface area water was added to: 60 feet long by 10 feet wide = 600ft<sup>2</sup> with 24,000 gallons dumped or 40 gallons per ft<sup>2</sup>.

## **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 Activities**

- CSU provided training for Denver Water staff to record 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, 14.
- 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 Activities**

- 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, 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.

**Table 2. Cottonwood research sites along the High Line Canal in 2005**

| Site                  | Name                                 | Tree Tag # | Notes  |
|-----------------------|--------------------------------------|------------|--|
| 18                    | Salida and 14 <sup>th</sup>          | 907-909    | Old trees, along north side of canal. Added to study in 1999.  |
| 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<br>Liner study site | 910-912    | Old trees, west of site 6, on north side of the canal. Added to study in 1999.   |
| 20*                   | Laredo and 12 <sup>th</sup>          | 913-915    | Young trees, on north side of canal. Added from study in 1999.   |
| 7                     | Aurora<br>Community College          | 48-52      | Young trees, on north side of canal, just behind Aurora Community College buildings.   |
| <b>Tollgate Creek</b> |                                      |            |  |
| 8                     | Aurora Golf Course                   | 78-82      | Old trees, on north side of canal and north of the Aurora Golf Course, just down stream of 2 <sup>nd</sup> Avenue.   |
| 9                     | Moline Crossing                      | 73-77      | Young trees, on north side of canal, just down stream 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, down stream 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 down stream                    | 58-62      | Old trees, on west side of canal, just down stream from Iliff.   |

## Results from 2005

### Water Flow in the High Line Canal:

- Seasonal water flow in the High Line Canal continues to decline, especially since the Rocky Mountain Arsenal has shifted to the use of recycled water.
- In 2005, only 11,360 acre-feet of water were put into the canal, approximately one-third the 33,983 acre-feet of water that flowed in the canal during 1997 (Table 3).
- Canal flow was from April 22 through June 14, but only from April 26 through June 14 (50 days) at research sites downstream of Leetsdale and Mississippi (Site 14) and the Sand Creek Siphon (just south east of Colfax Avenue and Tower Road) and then again for 4 days on August 18, when 16 cfs of water were delivered to Sand Creek Siphon.
- The headgate for the HLC was shut for 2005 water season on October 7, 2005. Final water potential readings were taken on September 7, 2005.
- In spring 2005, with average flow rates of 95 cfs at Waterton Canyon, it took four days for the water to reach the first research site located near Leetsdale and Mississippi, and four days for the water to reach our mid-point research site at the Aurora Community College near Sixth and Chambers, and the flow rate at the Sand Creek Siphon near Colfax and Tower never exceeded 32.0 cfs per day and 12.5 cfs at Sand Creek.

**Table 3. High Line Canal water diversion history.**

| Year | Acre-Feet<br>at Waterton<br>Canyon |
|------|------------------------------------|
| 2005 | 11360                              |
| 2004 | Not available                      |
| 2003 | 17092                              |
| 2002 | 0                                  |
| 2001 | 16806                              |
| 2000 | 17766                              |
| 1999 | 24322                              |
| 1998 | 27085                              |
| 1997 | 33983                              |

### Tree Health Assessment:

- Tree health assessment was based on visual observations using standardized tree condition data codes, originally developed by Dr. Jacobi in 1997, and slightly modified since then to accommodate the needs of this study (Refer to Appendix A: Tree Condition Data Codes). Disease assessment of the trees was based on external symptoms and no isolations were performed.
- The two most common diseases noted were Cytospora branch cankers and bacterial wet wood. Cytospora branch cankers were found on most trees within the research sites, occurred in 95% of the research sites, and the severity ranged from 0.00 to 3.33.
- Bacterial wet wood was found on most trees within the research sites, occurred in 95% of the research sites, and the severity ranged from 0.00 to 2.40.
- Stem decay was found on several trees within the research sites, occurred in 26% of the research sites, and the severity ranged from 0.00 to 1.33.
- Branch decay was found on several trees within the research sites, occurred in 32% of the research sites, and the severity ranged from 0.00 to 1.43. The presence of decay in stems and branches is a serious issue and should be looked at more thoroughly so as to minimize hazards to visitors using the path adjacent to the canal. We did not spend time determining the hazard potential of any of these trees.
- Lightning damage occurred on trees on some of the most eastern sites (16% of research sites), and no new mechanical damage was observed on trees within the research sites.
- Squirrel feeding damage often resulted in branch dieback due to the girdling of branches; squirrel-feeding damage occurred in 74% of the research sites, and the severity ranged from 0.00 to 2.00. Some sites had squirrel houses; trees at these sites averaged 10-20% damage. Other sites did not have squirrel houses and still exhibited damage due to squirrel feeding activities.

- Defoliating Insects and piercing/sucking insects and mites were the predominant arthropod pests found present in 2005.

### Tree Crown Dieback:

- The subjective rating of percent crown with decline or dieback is the only measure of overall tree health other than specific insect and disease ratings. Averaged crown dieback for the cottonwood trees at the research sites for the years 1999, 2004, and 2005 appear in Table 4.
- The trees ranged from 0-90 % dieback in 2005 with 0% crown dieback in trees located at Site 20, and 90% dieback in one of the two surviving trees located at Site 19 (where a canal liner was added in 2002).
- In 2005, all sites located downstream of the Sand Creek Siphon (Colfax Avenue and Tower Road) exhibited increased crown dieback compared to fall of 2004 (Sites 4 and 17 along Tower Road, and Sites 2, 3, 16, 23, and 25 in Green Valley Ranch area).
- In 2005 all sites upstream of Site 20 at Laredo and 12<sup>th</sup> exhibited less crown dieback in the fall of 2005 than they did in the fall of 2004.

**Table 4. Percent crown dieback in fall of 1999, 2004, and 2005.**

| Sites in Order Along Canal       | 1999 | 2004 | 2005 |
|----------------------------------|------|------|------|
| <b>Arsenal Lateral</b>           |      |      |      |
| 2 – Green Valley Ranch Big       | 17   | 33   | 44   |
| 3 – Arsenal Lateral -1           | 14   | 50   | 56   |
| 16 – Arsenal Lateral -2          | 13   | 32   | 55   |
| 23 – Arsenal Lateral -3          | NA   | 25   | 47   |
| 25 – Green Valley Ranch Dry      | NA   | 72   | 75   |
| 17 –Wagner Equip.                | 2    | 7    | 20   |
| 4 –Super Value                   | 17   | 40   | 43   |
| <b>Sand Creek</b>                |      |      |      |
| 18- Salida                       | 8    | 15   | 16   |
| 6 - Colfax Loop                  | 17   | 28   | 25   |
| 19 - Colfax Loop west            | 12   | 92   | 90   |
| 20 - Laredo and 12 <sup>th</sup> | 0    | 0    | 0    |
| 7 - Aurora Community College     | 10   | 17   | 10   |
| <b>Tollgate Creek</b>            |      |      |      |
| 8 - Aurora Golf Course           | 8    | 8    | 8    |
| 9 - Moline Crossing              | 8    | 10   | 9    |
| 10 - Kentucky / Dayton           | 14   | 22   | 16   |
| 11 - Mississippi “Y”             | 6    | 10   | 6    |
| 12 - Quebec Way Big              | 6    | 7    | 2    |
| 13 - Quebec Way Small            | 0    | 7    | 2    |
| 14 - Iliff Down Stream           | 20   | 25   | 14   |
| <b>Cherry Creek</b>              |      |      |      |

### Mortality:

- Four trees died at three research sites during 2005, 1 at Site 3, 2 at Site 25, and 1 at Site 19.
- Another tree at Site 19 exhibited 95% dieback, and the third tree at this site exhibited 75% dieback.
- Several trees died near Site 4 and Site 18 during 2004, but no new deaths were observed during 2005.
- Most mortality seen along the canal from Cherry Creek to the Arsenal Lateral was between the second crossing of Colfax and the Arsenal, areas with little to no supplemental water from urban landscapes and where the soil is somewhat sandy. These areas are getting less water in a canal run since the water only gets to these areas after several days of opening of the headgate at Waterton Canyon, and usually requires flow rates of over 100 cubic feet per second (cfs) to move the water that far downstream.

## Predawn Leaf Water Potentials

### Impact of Precipitation on Leaf Water Potentials:

- In 2005 only precipitation of over one inch caused a significant increase in water potential. The event was August 4-5, 2005 and the trees at 18, 19, 7, 8, and 9 all responded to that rain event (Appendix B).
- Water potentials at sites 14, 13 and 11 responded to a 0.4 inch rain event in late July because those sites are along sections of the canal where storm water runs into the canal.
- 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 5a and 5b summarize monthly total rainfall and monthly average maximum temperatures, respectively, for the study area from 1999 through 2005.
- Total precipitation from January through September, 2005 was only 11.44 inches, which is 1.59 inches below the normal for that nine-month period.
- Below normal precipitation fell during the months of February, March, May, July, and September; the driest month was February, during which precipitation was 92% below normal (only 0.05 inches of precipitation was recorded at the Denver International Airport monitoring station during the month of February 2005).
- Above normal precipitation fell during the months of January, April, June, and August; with the greatest monthly amount of precipitation falling during June (3.29 inches which was 192.40% of normal).
- Most of the precipitation in June fell during the first two weeks of the month, but this moisture did not prevent some trees (one at Site 12, one at Site 13, two at Site 14, and one at Site 19) from experiencing moisture stress (predawn leaf water potential of less than – 0.30 MPa) during the mid and later parts of June when no water was flowing in the canal.
- Dates of precipitation events of one-half inch or more: 06/04/05, 06/05/05, 06/10/05, 06/11/05, 08/04/05, 08/05/05.
- Averaged leaf water potentials for trees at research sites before and after precipitation events of one-half inch or more appear in Table 6.

**Table 5a. Monthly total rainfall (inches)**

|             | 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 | 16.25  |
| 2005        | 0.62 | 0.05 | 0.76 | 2.38 | 1.02 | 3.29 | 0.53 | 2.57 | 0.22 | NA   | NA   | NA   | *11.44 |
| 50 yr. Aver | 0.53 | 0.63 | 1.28 | 1.75 | 2.51 | 1.71 | 1.94 | 1.51 | 1.17 | 1.03 | 0.89 | 0.58 | 15.56  |

\* January through September 2005

**Table 5b. Monthly average maximum temperatures (Fahrenheit degrees)**

|             | 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 | NA   | NA   | NA   |
| 50 yr. Aver | 43.2 | 46.8 | 52.2 | 61.2 | 70.6 | 81.7 | 87.7 | 85.7 | 77.3 | 66.3 | 52.2 | 45.2 |

**Table 6. Leaf water potentials (-MPa) before and after precipitation events of at least one-half inch.**

| Date                        | Site         |              |              |              |              |              |              |              |              |              |              |              |
|-----------------------------|--------------|--------------|--------------|--------------|--------------|--------------|--------------|--------------|--------------|--------------|--------------|--------------|
|                             | 6            | 7            | 8            | 9            | 10           | 11           | 12           | 13           | 14           | 18           | 19           | 20           |
| <b>05/23/05 before rain</b> | NA           | NA           | NA           | NA           | NA           | NA           | NA           | NA           | NA           | NA           | NA           | NA           |
| 06/01/05                    | NA           | NA           | NA           | 0.140        | 0.155        | 0.184        | 0.154        | 0.188        | 0.148        | NA           | NA           | NA           |
| 06/08/05                    | 0.113        | 0.179        | 0.175        | NA           | NA           | NA           | NA           | NA           | NA           | 0.150        | 0.194        | 0.179        |
| 06/15/05                    | 0.130        | 0.142        | 0.125        | 0.143        | 0.145        | 0.116        | 0.108        | 0.118        | 0.163        | 0.142        | 0.200        | 0.158        |
| <b>07/27/05 before rain</b> | <b>0.463</b> | <b>0.358</b> | <b>0.525</b> | <b>0.425</b> | <b>0.295</b> | <b>0.256</b> | <b>0.371</b> | <b>0.308</b> | <b>0.370</b> | <b>0.546</b> | <b>0.331</b> | <b>0.258</b> |
| 08/10/05                    | 0.343        | 0.204        | 0.373        | 0.328        | 0.268        | 0.266        | 0.308        | 0.330        | 0.290        | 0.300        | 0.194        | 0.163        |

**Impact of Research Site and Collection Date on Leaf Water Potentials:**

- Predawn leaf water potential data collection for the 2005 growing season was initiated on June 1<sup>st</sup>.
- Predawn leaf water potential data was collected weekly throughout June, July, and August.
- Predawn leaf water potential data collection for the 2005 growing season ended on September 8<sup>th</sup>.
- Table 7 contains the averaged predawn leaf water potentials for all the study trees at each research site for the 14 collection days.
- Least square means of predawn leaf water potentials ranged from - 0.108 MPa to 0.384 -MPa at the 12 sites monitored in 2005. Averaged water potentials of > - 0.300 MPa occurred at all of the 12 research sites monitored throughout most of June, but then began to decrease at several research sites by early July.
- 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 7. 2005 predawn leaf water potentials of cottonwoods along High Line Canal**

| The Mixed Procedure Least Squares Means Estimated Mean (-MPa) |       |       |       |       |       |       |       |       |       |       |       |       |
|---|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|
| Date  | Site  |       |       |       |       |       |       |       |       |       |       |       |
|   | 6     | 7     | 8     | 9     | 10    | 11    | 12    | 13    | 14    | 18    | 19    | 20    |
| 06/01/05  | NA    | NA    | NA    | 0.140 | 0.155 | 0.184 | 0.154 | 0.188 | 0.148 | NA    | NA    | NA    |
| 06/08/05  | 0.113 | 0.179 | 0.175 | NA    | NA    | NA    | NA    | NA    | NA    | 0.150 | 0.194 | 0.179 |
| 06/16/05  | 0.130 | 0.142 | 0.125 | 0.143 | 0.145 | 0.116 | 0.108 | 0.118 | 0.168 | 0.142 | 0.200 | 0.158 |
| 06/23/05  | 0.213 | 0.229 | 0.198 | 0.160 | 0.220 | 0.250 | 0.188 | 0.185 | 0.260 | 0.204 | 0.275 | 0.208 |
| 06/30/05  | 0.210 | 0.225 | 0.255 | 0.233 | 0.248 | 0.231 | 0.250 | 0.268 | 0.240 | 0.179 | 0.313 | 0.167 |
| 07/07/05  | 0.233 | 0.375 | 0.243 | 0.325 | 0.353 | 0.331 | 0.371 | 0.443 | 0.365 | 0.233 | 0.281 | 0.167 |
| 07/14/05  | 0.430 | 0.346 | 0.395 | 0.308 | 0.363 | 0.275 | 0.292 | 0.348 | 0.473 | 0.350 | 0.388 | 0.300 |
| 07/21/05  | 0.490 | 0.433 | 0.483 | 0.395 | 0.338 | 0.447 | 0.442 | 0.548 | 0.540 | 0.381 | 0.419 | 0.367 |
| 07/28/05  | 0.463 | 0.358 | 0.525 | 0.425 | 0.295 | 0.256 | 0.371 | 0.308 | 0.370 | 0.546 | 0.331 | 0.258 |
| 08/10/05  | 0.343 | 0.204 | 0.373 | 0.328 | 0.268 | 0.266 | 0.308 | 0.330 | 0.290 | 0.300 | 0.194 | 0.163 |
| 08/17/05  | 0.485 | 0.346 | 0.500 | 0.500 | 0.478 | 0.525 | 0.375 | 0.500 | 0.580 | 0.371 | 0.319 | 0.221 |
| 08/24/05  | 0.583 | 0.321 | 0.445 | 0.373 | 0.250 | 0.369 | 0.279 | 0.278 | 0.405 | 0.513 | 0.431 | 0.213 |
| 08/31/05  | 0.590 | 0.304 | 0.480 | 0.368 | 0.353 | 0.428 | 0.458 | 0.418 | 0.435 | 0.467 | 0.425 | 0.258 |
| 09/07/05  | 0.715 | 0.452 | 0.496 | 0.459 | 0.367 | 0.374 | 0.327 | 0.466 | 0.459 | 0.547 | 0.445 | 0.233 |

**Impact of Tree Maturity on Leaf Water Potentials:**

- Although leaf water potentials were sometimes significantly different between big trees and small trees, significant differences were due to site differences and the date of collection, and not due to tree maturity.

- Average leaf water potentials did not show a significant interaction of tree maturity and canal condition.
- Average leaf water potentials did not show a significant interaction of tree size and date.

### Impact of Canal Condition on Leaf Water Potentials:

- Canal flow in 2005 occurred from April 24 through June 14, and then again for 4 days with only one day of water reaching Sand Creek on August 18, 2005.
- The headgate for the HLC was shut for 2005 water season on October 7, 2005. Final water potential readings were taken on September 7, 2005.
- Water flow in the canal positively impacted predawn leaf water potentials, at locations getting canal water in August (14,13,12,11,10,9) but trees down stream from Tollgate did not receive enough water to reduce water stress.
- There were usually significantly greater water potentials above – 0.30 MPa when the canal was flowing (Table 8).

**Table 8. 2005 Leaf water potentials related to canal condition.**

| Site                             | Average Water Potentials (-MPa) |             |               |
|----------------------------------|---------------------------------|-------------|---------------|
|                                  | Dry Canal                       | Muddy Canal | Flowing Canal |
| 18 - Salida                      | 0.3652a                         | NA          | 0.1458a       |
| 6 -Colfax Loop                   | 0.4163a                         | NA          | 0.1213a       |
| 19 - Colfax Loop west            | 0.3395a                         | NA          | 0.1969a       |
| 20 - Laredo and 12 <sup>th</sup> | 0.2296a                         | NA          | 0.1687a       |
| 7 - Aurora Community College     | 0.3298b                         | 0.3208b     | 0.1604a       |
| <b>Tollgate Creek</b>            |                                 |             |               |
| 8 - Aurora Golf Course           | NA                              | 0.3911b     | 0.1500a       |
| 9 - Moline Crossing              | 0.3479b                         | NA          | 0.2183a       |
| 10 - Kentucky / Dayton           | 0.3252b                         | NA          | 0.1833a       |
| 11 - Mississippi "Y"             | 0.3283b                         | NA          | 0.2229a       |
| 12 - Quebec Way Big              | 0.3247b                         | NA          | 0.1806a       |
| 13 - Quebec Way Small            | 0.3771b                         | NA          | 0.1942a       |
| 14 - Iliff Down Stream           | 0.3796c                         | 0.5400b     | 0.2400a       |

The Mixed Procedure Least Square Means and Differences of Least Square Means

Values followed by the same letter are not significantly different among canal conditions at a particular site at the P=0.10 level

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

- The following assumptions can be made pertaining to the impact of predawn leaf water potentials on tree crown dieback based on analysis of predawn leaf water potential data and tree crown dieback data collected from 1999-2005:
- The trees with the most dieback had spring water potential readings less than – 0.34 MPa and less than – 0.9 MPa summer readings (Sites 19, 25 and 6).
- A predawn leaf water potential reading below -0.9 MPa during the summer did not mean the tree would exhibit branch dieback (trees at Site 20 did have predawn leaf water potential readings as low as - 0.90 MPa during the summer of 2002, but did not develop branch dieback in 2003).
- of the dieback was probably related to shading affects rather than just insufficient soil moisture.
- Trees at sites 2, 3, 17, 4, 6, 7, 16, 18, 19, 23, and 25 have exhibited a steady increase in dieback due to the reduced amounts of canal water that were delivered to these sites.
- During 2004 and 2005, the High Line Canal flow stopped at Sand Creek Siphon, so no supplemental canal water reached the trees at the sites downstream of Colfax Avenue and Tower Road.
- Trees at Site 20 have exhibited little or no dieback over the duration of this study.
- Trees located at sites upstream of Site 20 (sites 7, 8, 9, 10, 11, 12, 13, and 14) have received at least some canal water in all recent years except in 2002 when no water was allocated to flow in the High Line Canal due to prolonged periods of severely below normal precipitation throughout most of Colorado.
- Water potentials on September 9, 2005, at sites downstream of Sand Creek were:
  - Site 2– Green Valley Ranch Big: - 0.70 MPa to – 1.00 MPa 44% dieback

- Site 3- Arsenal Lateral-1: - 0.85 MPa to – 0.95 MPa 56%
  - Site 16- Arsenal Lateral-2: - 0.85 MPa to – 0.95 MPa 55%
  - Site 17- Wagner Equipment: – 0.9 MPa 20%
  - Site 4- Super Value: - 0.50 MPa to – 0.70 MPa 25%
- Trees located at the most downstream sites, sites 2, 3, 16, and 17, had the most negative water potentials for this particular day, with average water potentials ranging from - 0.78 MPa to – 0.90 MPa
  - These trees have not seen canal water since 2003 and no water in 2002. So it seems to take **3-4 years** after water is withdrawn to have death or partial death occur.

## Research Site Summary of Predawn Leaf Water Potential Data and Percent Crown Dieback:

### Site 2 Green Valley Ranch Big

- Water potential readings taken 1997-2003
- Crown dieback 15% up to 18% in 2003
- No water potential data have been collected from trees at this site since 2003
- Predawn leaf water potentials obtained from these seven trees on September 9, 2005 ranged from - 0.700 MPa to – 1.000 MPa
- Crown dieback had increased to 44% as of September 2005

### Site 3 Arsenal Lateral -1

- Water potential readings taken 1997-2003
- Crown dieback 7% to 14% from 1997 to 2000
- No water potential data have been collected from trees at this site since 2003
- Predawn leaf water potentials obtained from the four remaining trees on September 9, 2005 ranged from - 0.850 MPa to – 0.950 MPa
- Crown dieback had increased to 56% as of September 2005

### Site 23 Arsenal Lateral 3

- Water potential readings taken 2001-2003
- Crown dieback 10% to 30% from 2001 to 2003
- Average tree water potential in 2003 ranged from - 0.338 MPa to - 0.363 MPa
- No predawn leaf water potential data collected during 2005
- Crown dieback of remaining two trees had increased to 47% as of September 2005

### Site 25 Green Valley Dry

- Water potential readings taken 2001-2003
- Crown dieback 20% to 55% from 2001 to 2003
- Average tree water potential in 2003 ranged from – 0.380 MPa to – 0.429 MPa
- Trees # 916 and #917 officially dead as of spring 2005
- No predawn leaf water potential data collected during 2005- one day need to add these.
- Crown dieback of remaining one tree had increased to 25% as of September 2005

### Site 16 Arsenal Lateral 2

- Water potential readings taken 1999-2003
- Average tree water potential in 2003 ranged from - 0.361 MPa to - 0.390 MPa
- Crown dieback 7% to 13% from 1999 to 2003
- Predawn leaf water potentials obtained on September 9, 2005 from these three trees ranged from - 0.850 MPa to – 0.950 MPa
- Crown dieback had increased to 55% as of September 2005

### Site 17 Wagener Equipment

- Water potential readings taken 1999 - 2003.
- Crown dieback 0% spring of 1999,
- Average tree water potential in 2003 ranged from - 0.226 MPa to - 0.236 MPa

- Predawn leaf water potentials obtained from these three trees on September 9, 2005 were all - 0.900 MPa
- Crown dieback had increased to 20% over the summer of 2005

#### Site 4 Super Value

- Water potential readings taken 1997-2001 and again in late summer of 2002
- Crown dieback 13% to 15% from 1997 to 2001
- Predawn leaf water potentials obtained from these five trees on September 9, 2005 ranged from - 0.500 MPa to - 0.700 MPa
- Crown dieback had increased to 43% as of September 2005

### **Sand Creek**

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#### Site 18 Salida

- Water potential readings taken 1999-2005
- Crown dieback 8% to 8% from 1999 to 2001
- Predawn leaf water potentials obtained from these three trees during the 2005 water season ranged from - 0.113 MPa to - 0.700 MPa, and tree averages for the year ranged from - 0.312 MPa to - 0.358 MPa
- Crown dieback had increased to 10% as of September 2005

#### Site 6 Colfax Loop East

- Water potential readings taken 1997-2005
- Crown dieback 11% to 25% from 1997 to 2003
- Predawn leaf water potentials obtained from these five trees during the 2005 water season ranged from - 0.050 MPa to - 0.900 MPa, and tree averages for the year ranged from - 0.357 MPa to - 0.426 MPa
- Crown dieback holding steady at 25% as of September 2005

#### Site 19 Colfax Loop west

- Water potential readings taken 1999-2005
- Tree # 910 officially dead as of fall 2004
- Crown dieback 12% to 82% from 1999 to 2003
- Predawn leaf water potentials obtained from the two remaining trees during the 2005 water season ranged - 0.113 MPa to - 0.550 MPa, and tree averages for the year ranged from - 0.278 MPa to - 0.370 MPa
- Crown dieback of remaining two trees had increased to 90% as of September 2005

#### Site 20 Laredo and 12th

- Water potential readings taken 1999-2005
- Spring 2005 readings were never less than -0.24 MPa
- Predawn leaf water potentials obtained from these three trees during the 2005 water season ranged - 0.100 MPa to - 0.400 MPa, and tree averages for the year ranged from - 0.196 MPa to - 0.256 MPa
- Crown dieback remained at 0% as of September 2005

#### Site 7 Aurora Community College

- Water potential readings taken 1997-2005
- Crown dieback 5% to 7% from 1997 to 2001
- Predawn leaf water potentials obtained from these three trees during the 2005 water season ranged from - 0.138 MPa to - 0.450 MPa, and tree averages for the year ranged from - 0.289 MPa to - 0.312 MPa
- Crown dieback had increased to 10% as of September 2005

### **Tollgate Creek**

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Site 8 Aurora Golf Course

- Water potential readings taken 1997-99, 2004-05
- Crown dieback: no change at 8%
- Predawn water potentials in 2005 ranged from  $-0.12$  to  $-0.5$  MPa. No severe stress

Site 9 Moline Crossing

- Water potential readings taken 1997-99, 2004-05
- Crown dieback: no change at 9%
- Predawn water potentials in 2005 ranged from  $-0.14$  to  $-0.5$  MPa. No severe stress

Site10 Kentucky / Dayton

- Water potential readings taken 1997-99, 2004-05
- Crown dieback: no change at 9%
- Predawn water potentials in 2005 ranged from  $-0.14$  to  $-0.48$  MPa. No severe stress

Site 11 Mississippi "Y"

- Water potential readings taken 1997-99, 2004-05
- Crown dieback: no change at 6 %
- Predawn water potentials in 2005 ranged from  $-0.12$  to  $-0.53$  MPa. No severe stress

Site12 Quebec Way Big

- Water potential readings taken 1997-99, 2004-05
- Crown dieback: increased health at 2%
- Predawn water potentials in 2005 ranged from  $-0.11$  to  $-0.46$  MPa. No severe stress

Site13 Quebec Way Small

- Water potential readings taken 1997-99, 2004-05
- Crown dieback: increased health at 2%
- Predawn water potentials in 2005 ranged from  $-0.12$  to  $-0.47$  MPa. No severe stress

Site14 Iliff down stream

- Water potential readings taken 1997-99, 2004-05
- Crown dieback: increased health from 25 to 14%
- Predawn water potentials in 2005 ranged from  $-0.16$  to  $-0.58$  MPa. No severe stress

## Project Conclusions

(based on 2000 - 2005 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 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 12<sup>th</sup> 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 12<sup>th</sup> (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 12<sup>th</sup> (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 12<sup>th</sup> (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 did so 6-8 weeks after the April to June canal run.

### **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 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 since site 17 and 20 did not exhibit dieback but did have low water potentials in 2002. The trees at sites with no canal run for 3 years have taken 4 years to 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 or 2005, there were no opportunities to assess the rapidity of tree recovery.

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

**Conclusion:** Two weeks of canal flow, 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). The problem with this question is that we have never gotten two weeks of canal run or simulation of two weeks run so we are speculating based on some weak simulations.

#### **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<sup>2</sup> x 1 ft deep = 12,418 gallons or 7.5 gallons per ft<sup>2</sup>.
  - b. Site 2, surface area that water was added to: 60 feet long by 10 feet wide = 600ft<sup>2</sup> with 24,000 gallons dumped or 40 gallons per ft<sup>2</sup>.
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<sup>2</sup> of canal bed and about 40 gallons/ft<sup>2</sup> 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.

**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:** Overall, 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 12<sup>th</sup> 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 ( $\leq$  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.

**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 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.

**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 down stream 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 ( $-0.7$  MPa) 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 down stream from these trees during the spring of 2002 most likely damaged roots also.

If the trees had gotten water in 2002 from canal flow or other sources they would probably have recovered. 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 crowns of trees monitored during 2004 and 2005? Thus it appears the mild summer and the water provided in April -June and for one day in August in 2005 helped the trees keep in acceptable health.
- We have found that spring stress is the best indicator of future health so those trees like those at site 19 will have more dieback than other sites.
- Leaf water potentials increased when water was added to the canal at all locations getting several days of water.
- Trees farther down the canal did not receive much if any water in August so these show low water potentials by the end of the summer.

**2. Determine if lining the canal with PAM from Cherry Creek to Fairmont will allow enough water to maintain the health of cottonwoods trees lining the canal.**

- We did not hear if PAM was ever carried out or where. We have no data on this issue.

## 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  | = | <i>Cytospora</i> stem canker (severity = % of stem girdled)  |
| D 3  | = | <i>Cytospora</i> 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 ( <i>Marssonina</i> and/or <i>Septoria</i> ) (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.