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**Hydraulic Laboratory Technical Memorandum PAP-1071**

# Canal Lining Drawdown Tests and Development of New Drawdown Criteria for the Charles Hansen Feeder Canal

**Colorado-Big Thompson Project**

**U.S. Department of the Interior**
**Bureau of Reclamation**
**Technical Service Center**
**Hydraulic Investigations and Laboratory Services Group**
**Denver, Colorado**

**December 2012**

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## Colorado-Big Thompson Project


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# Executive Summary

Two canal drawdown tests were conducted in the fall of 2011 and spring of 2012 on the Charles Hansen Feeder Canal for the purpose of developing empirically-based drawdown criteria for the canal that may allow more rapid drawdown of canal water levels and increased operational flexibility. A total of fifty-eight piezometers were installed through the concrete canal lining at 1/8 to 1/4-mile intervals along the 550 and 930 sections of the canal. These allowed water pressures behind the lining to be observed and manually recorded as the canal experienced a series of drawdowns. Most of the piezometers exhibited rapid equalization of pressures behind the lining as canal levels were dropped, but a few demonstrated slower responses that allowed significant differential heads to build up across the canal lining. Data collected from the piezometers that reacted the slowest were used as the basis for development of new drawdown criteria.

Existing drawdown criteria for the feeder canal limits drawdown to 6 inches in one hour and not more than 1 ft per day. In sections of the canal where soils behind the concrete lining are slow-draining, this can lead to nearly one foot of differential head loading across the lining (a drawdown of 6 inches in the first hour and an additional 6 inches applied just after the end of the first hour). This is followed by a 23 hour draining period in which pressure behind the lining drops slowly to bring the differential head back toward zero.

The new drawdown criteria developed for the canal call for a steady series of canal drawdown steps whose maximum size varies depending on the time interval between steps. Using data collected from these drawdown tests, the criteria are designed to keep differential heads across the lining to less than 1 foot, so the maximum loading applied to the concrete lining is similar to that experienced under the current criteria. One potential scenario would consist of 6 inch drawdown steps at 5 hour intervals. Other schedules are possible, with full details provided in Table 1of this report (pg. 22).

These newly developed drawdown criteria are intended to apply only to non-emergency operations. In emergency situations, more rapid drawdown of the canal may be necessary, though the risk of damaging the concrete lining would be increased under these circumstances.

This study did not include a risk assessment of the canal under either the existing drawdown criteria or the newly developed criteria, and thus questions about the effect of these changes on the risk of damage to the canal lining cannot be answered quantitatively. There is potential for an unsampled section of the canal to exhibit canal bank drainage rates that are more limiting than the slowest draining piezometers observed in these tests.

# Introduction and Study Objectives

The Charles Hansen Feeder Canal is a 13.2 mi long concrete-lined trapezoidal canal that conveys water northward from the tailrace of Flatiron Power Plant to the Big Thompson River and the southern end of Horsetooth Reservoir, as part of the Bureau of Reclamation's Colorado-Big Thompson Project. The canal contains open-channel sections designed for flows of 930 $ft^3/s$ and 550 $ft^3/s$, and includes several inverted siphon sections. The canal was constructed between 1949 and 1953. The design thickness of the concrete lining is 4 inches, and the canal is not known to be equipped with underdrains.

The need to make frequent and occasionally large changes to flow rates in the canal has prompted Reclamation's Eastern Colorado Area Office to request that the Technical Service Center in Denver conduct a study to determine appropriate drawdown criteria specifically for the Charles Hansen Feeder Canal. The canal is currently operated with a non-emergency limitation of no more than 6 inches of vertical drawdown in one hour and no more than 12 inches of drawdown in a 24-hr period. These limits are typical of those given for concrete lined canals in Reclamation's inventory, and probably were not developed through any specific analysis of this particular canal design. Nevertheless, it is clear that these criteria are designed to limit the differential hydrostatic loads applied to the canal lining during drawdown by residual pore water pressures behind the concrete lining. These differential hydrostatic loadings can cause displacement, heaving, buckling, and failure of the lining. At times, the drawdown criteria for the Hansen Feeder Canal require the undesired conveyance of large volumes of water from Pinewood and Flatiron reservoirs. The current drawdown criteria also limit the ability to make rapid operational changes. Almost nine days are required for complete dewatering of the canal if starting from the maximum depth of over 8 ft.

To address this issue, field tests were performed with the objective of measuring pore water pressures behind the canal lining during a series of actual drawdown events. These measurements were designed to allow the development of drawdown criteria specific to the Charles Hansen Feeder Canal.

# Literature Review – Canal Drawdown Criteria

Canals operating at steady state establish a saturated soil condition in the canal banks and a phreatic surface that is usually near the canal water surface elevation. When the operating water surface in the canal is lowered, water must drain away from the canal (through the soil/rock foundation), or back into the canal (through cracks and joints in the canal lining) to lower the phreatic surface in the banks. Depending on soil conditions, surrounding geology, and canal lining conditions (presence or absence of cracks, tightness of joints, etc.), the rate at which the phreatic surface equalizes with the canal water level varies. If the differential head between the banks and the canal becomes too large it can lead to slope stability problems (especially in unlined canals), or buckling, breaking, and displacement of concrete canal lining panels. Damage to canals is prevented by limiting the rate of canal drawdown to prevent differential heads from exceeding allowable limits based on the weight and strength of the canal lining.

Past research on the topic of canal drawdown rates and drainage of water from beneath concrete canal linings is very limited. Only two sources of information could be located:

- USBR Study Team Report "Review of Canal Underdrainage for Lining Protection" (1979)
- *Canal Systems Automation Manual*, Volume 1 (1991) by Buyalski et al.

An excerpt from the 1979 Study Team Report gives a good summary of the state of knowledge on this topic at that time:

*Analytical State-of-the-Art for Design*

*Little information exists on analytical approaches to pressures on canal lining resulting from drawdown. Some analytical work was done by the Bureau of Reclamation in the late 1940's and early 1950's by Jarvis, Johnson, Moody, and Zangar. However, the records of their work available to the team are not comprehensive and do not establish design parameters.*

*Present drawdown criteria originated in a March 19, 1961, conference on operating problems on canals. A quote from the report on the meeting addressed canal drawdown as follows:*

*"Various operating practices were reviewed concerning safe drawdown of canals. Present practices range from 1 foot per day with a maximum of 6 inches in any 1 hour in certain canals in Regions 2 and 7, to a maximum of 3 feet per day with a maximum of 1 foot per hour when conditions are favorable in the larger canals on the Columbia Basin Project. It was noted that fairly fast drawdown rates were being permitted where canals have been constructed in light soils having free draining characteristics, without ill effects. However, it was largely agreed that a drawdown of 1 foot per day was preferable for large canals."*

*The report did not offer any justification for this criteria. In 1949, C. N. Zangar analyzed drainage systems for control of uplift pressures on linings. He did not suggest drawdown criteria, but in an example for applying his mathematics, he used an allowable pressure of 3 feet on the bottom of the canal. He did not justify using 3 feet of pressure as a limit, nor did he specifically suggest this was a critical limit. The allowable pressures on lining have not been clearly defined or studied. Without this knowledge, we cannot develop rational criteria for under drainage.*

*At present, most designers suggest using the force necessary to lift 3 1/2 inches of unreinforced concrete as a limiting value. However, experiences such as in Reach 3 of the Tehama-Colusa canals (see Appendix A) indicated a somewhat higher limit may be practical. This is one of the basic research items that should be studied.*

Although the Study Team Report recommended that research be conducted on canal drawdown limits, it appears that these recommendations were not acted upon and no significant new research on this topic since 1979 could be located.

Buyalski et al. (1991) gives limited information about canal drawdown limitations, addressing them primarily in the context of the need for recognizing limitations when implementing automated controls. Buyalski does note that maximum acceptable drawdown rates should be established for individual canals, but this is seldom done and the criteria typically applied to concrete-lined canals with 1.5:1 (H:V) side slopes have been no more than 6 inches in one hour and 12 inches in 24 hours. Buyalski also notes that higher drawdown rates may be acceptable in areas of well-drained soil, in sections built on fill, in canals with heavy lining, or in sections having drains behind the lining. Buyalski mentions the influence of canal side slope, which may be a consideration for the Charles Hansen Feeder Canal, which has 1.25:1 (H:V) side slopes, steeper than the typical 1.5:1 mentioned by Buyalski. Steeper side slopes are generally able to tolerate less differential pressure, since the weight of the side slope slab is less able to resist overturning or sideways translation of the slab as the sidewall approaches a vertical orientation. The reduction in resisting force and moment is about 6 percent between equivalent thickness slabs at 1.5:1 and 1.25:1 slopes.

The conclusion from the literature review is that most Reclamation canals have been given conservative, generic drawdown limitations that are based on an aggregate of operating experience. Prior to this study, there has been no specific investigation to determine acceptable drawdown rates for the Charles Hansen Feeder Canal. The tests described here are an attempt to determine whether higher drawdown rates are acceptable for this canal.

# Drawdown Test Setup

Two canal drawdown tests were conducted. The first test in October 2011 was performed on the “550 section”, a 9.4-mi long reach of the canal from the Big Thompson River north to Horsetooth Reservoir with a design flow capacity of 550 $ft^3/s$. A significant portion of the 550 section is in tunnels and siphons, so the instrumented length of canal was about 5.3 miles. This canal has a 7 ft bottom width, 1.25:1 (H:V) side slopes, and a normal water depth of 8.2 ft. The second test in May 2012 was conducted on the “930 section”, a 3.8-mi long reach that begins at Flatiron Reservoir and ends near its crossing of the Big Thompson River. This section has a design flow capacity of 930 $ft^3/s$, a 13 ft bottom width, 1.25:1 side slopes, and a normal depth of 8.8 ft.

To measure water pressures behind the canal side walls, piezometers were installed prior to each field test. Piezometers were installed on the canal sides at approximate 1/8- to 1/4-mile intervals along the open channel portions of each canal reach. A total of 31 piezometers were installed in the 550 reach during

September 2011, and 27 piezometers were installed in the 930 reach during April 2012.

Piezometers installations were carried out as follows:

- Suitable locations were identified, attempting to select concrete lining panels that were in good condition (not excessively cracked).
- About 12 to 18 inches above the canal invert, a 5/8-in. diameter hole was drilled through the concrete lining into the soil beneath, using a corded hammer drill (2011) or battery-powered Hilti hammer drill (2012).
- A mechanical packer was installed into the hole. The packer consisted of a stainless steel tube with a flared, threaded end that was turned into a plastic sleeve that swelled as the packer was advanced, thereby creating a watertight seal.
- A pipe elbow and tubing adapter were attached to the packer.
- A length of ½” i.d. clear, flexible tubing was connected to the tubing adapter and laid on the canal bank up to the top of the canal lining. This tubing was secured in place along its length with several strap-type pipe clamps that were attached to the side wall of the canal with concrete anchors.
- A wooden yardstick was attached to the canal lining at and below the existing high water mark to serve as a staff gage.
- The tubing was marked at 6 inch intervals on the slope below the level of the staff gage to allow estimated water levels to be recorded if the canal was drawn down further than the bottom of the staff gage.

For the 930 reach, several improvements were added to make the piezometer installations more durable and functional, based on experience from the test of the 550 section.

- Hose clamps were used to secure the tubing to the tubing adapter
- The tubing was strapped with plastic tie wraps to a length of 1/2"-in. diameter galvanized steel electrical conduit which was then secured to the canal lining.
- Care was taken to always install the yardstick staff gages on the upstream side of the assembly, to prevent weed accumulations on the tubing from obscuring the staff gages.

Installation of piezometers into the 550 section was performed by Northern Colorado Water Conservancy District (NCWCD) personnel, with guidance from the TSC on selection of piezometer locations. Installation of piezometers for the 930 section was performed by TSC staff. The most downstream reach of the 930 section between the Dille Cutoff and the Big Thompson River could not be instrumented because there was a small flow in this section on the installation dates. Approximate piezometer locations were recorded using GPS and are illustrated in figures in Appendix 2. For the 550 test, the piezometers are mostly labeled by their approximate canal stations, with a few exceptions for which canal stations were not estimated. For the 930 test the piezometers are labeled sequentially with a lookup table provided in Appendix 2 for additional data.

Figure 1 shows examples of the piezometer installations in the two canal sections. A notable difference in the canal conditions was that the 550 section has had cracks heavily patched with Sikaflex caulking over most of the length of the canal. Most of the 930 section was less cracked, and only a few short reaches have had cracks patched. In the 930 section we did encounter several canal panels that had been replaced in recent years (since 1988 judging by dates scratched into the concrete surface) and were apparently much thicker than the original design specification (4 inches), since we were unable to drill a hole completely through the lining into the soil. When this occurred, we tried to select a new panel nearby that was older (original in many cases).

Figure 1. — Piezometer installations in the 550 section (left) and 930 section (right).

Installation of piezometers in the 550 section took place beginning September 22, 2011. The canal was refilled beginning on September 30, and the drawdown test was performed 11 days later on Tuesday, October 11. Installation of piezometers in the 930 section took place on April 18-19, 2012. Refilling of the canal began on April 26. The drawdown test of the 930 section took place 19 days later on May 15.

The tests consisted of drawing down the respective canals in stages and recording canal water levels and piezometer water levels prior to, during, and following the drawdown event. Observers were tasked with monitoring 3 to 6 piezometers throughout the day of each test, spread out over a distance of ¼ to ½ mile. The observers walked the canal access road and recorded the data at each piezometer location at intervals ranging from 5 to 25 minutes. Water and piezometer levels were observed from the canal bank opposite each piezometer site using handheld binoculars.

To improve the visibility of the water level in each piezometer tube, water tinted with green flourescein dye was added to most piezometers (except those not easily accessible), at the beginning of each test day. For the first test (550 section), there were several piezometers that were not accessible for adding dye. For the second test, piezometers were located intentionally in accessible locations, so all piezometers received dye. The process of adding dye caused some short-term increase in piezometer levels, as a significant volume of dye-colored water was added into each tube. At most piezometers, a piezometer level was not recorded prior to adding dye, since dye was added early in the morning before all observers were in place. However, at the instant at which dye was added it could be seen that the water level in all piezometers was at or below the canal water level. Most piezometers equalized rapidly following the addition of dye (within 10 to 30 seconds), but some equalized much more slowly. During the test of the 930 section there was one piezometer (Piezo 19) that behaved as though it were fully plugged; the piezometer level increased due to dye addition and never decreased again throughout the day, so data from this piezometer were not used. A second piezometer (Piezo 6) equalized so slowly (dropping about 1 to 2 inches per hour), that it registered pressures higher than the original canal water surface for most of the test period. This piezometer was analyzed since it did exhibit changes in drawdown rate as a function of canal conditions.

# Testing of the 550 Section

Testing of the 550 section took place on Tuesday, October 11, 2011, eleven days after refilling of the canal began. Three drawdowns of the canal were made, the first two in the morning targeted to be approximately 6 inches vertical, and the last targeted to be approximately 12 inches vertical. Although the changes were made in steps, attenuation of the flow change caused the actual drawdowns to be relatively gradual in nature throughout the day. The actual drawdown amounts varied along the canal due to backwater effects and were much larger in magnitude than the target value at some locations. Examples are shown in Figure 2 for the piezometer at approximate station 94+36 near the upstream end of the 550 section, and in Figure 3 for a station at the downstream end of the 550 section. From the start of the test to about 1:00 p.m. the drawdown was about 20 inches along the slope or 12.5 inches vertical (divide by 1.6 to convert slope distances to vertical, or multiply by 1.6 to convert vertical distance to slope distance). From 1:00 p.m. to 3:45 p.m. the drop at the upstream station was about 48 inches on the slope, or 30 inches vertical. At the downstream station the second drop was about 25 inches along the slope, or 16 inches vertical.

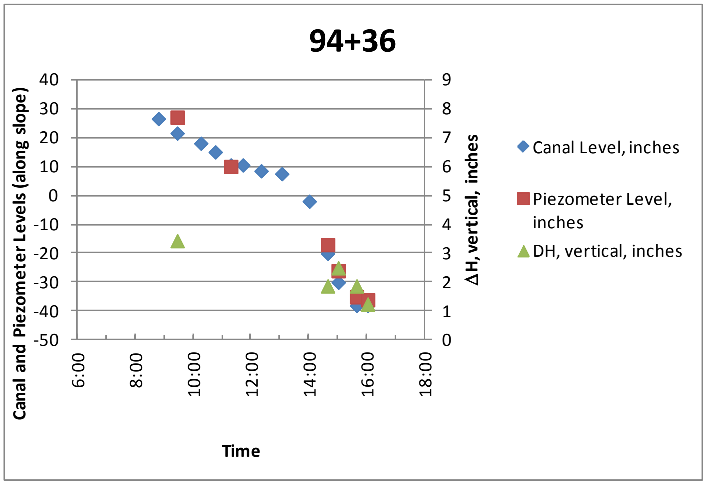


Figure 2. — Canal and piezometer levels during the drawdown test of the 550 section. This piezometer is located near the upstream end of the 550 section. DH is the vertical distance between the piezometer level and the canal level as displayed on the secondary y-axis (right). Piezometer levels were not visible (below the canal water surface) for most of the time from 10:00 a.m. to 2:00 p.m. Hence, there is no DH value shown at 11:15 a.m., because the value was negative and the secondary y axis is configured to show only positive values, which are of primary interest for this study.

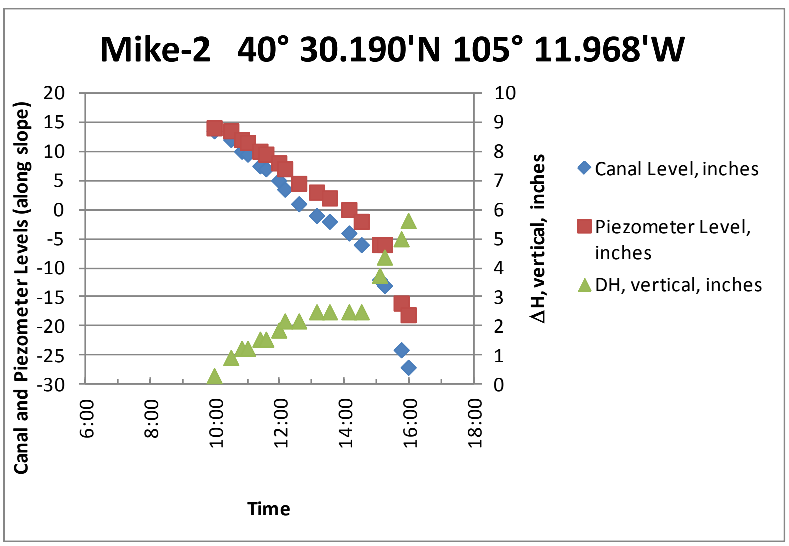


Figure 3. — Canal and piezometer levels at a section near the downstream end of the 550 section. This piezometer recorded the highest differential heads behind the lining of any piezometer during the 550 test.

Data were recorded from a total of 31 piezometers during the 550 test. Some piezometers failed to operate as expected, for unknown reasons. The behavior during the initial injection of dye in the morning and throughout the test provided some clues about the condition of the piezometers. A summary of the piezometer behaviors follows:

- 9 piezometers reacted to injected dye as expected; the water level increased immediately, followed by a relatively slow stabilization back to equilibrium…about 30 to 60 seconds to become steady).
  - 3 of these 9 piezometers exhibited measurable positive pressure behind the lining during the drawdown periods. Two indicated positive heads of 0.2 to 0.3 ft above canal level. One showed almost 0.5 ft of positive pressure behind the lining after the large drawdown adjustment was made late in the day.
  - 6 of the 9 piezometers (all in the downstream half of the instrumented reach) indicated zero to slight positive pressure behind the lining throughout the test.
- 7 piezometers (all in upstream half of instrumented reach) indicated negative pressure behind the lining and/or an unfilled void. When dye was injected it immediately ran through the piezometer and the piezometer rapidly stabilized (in a few seconds) with the dye level significantly below the water level in the canal (in some cases 2 to 3 ft below). These suggest that the soil behind the lining had not become saturated or that drainage from behind the canal was sufficient to prevent the phreatic surface from equalizing with the canal level.
- 9 piezometers immediately stabilized at the canal water level when dye was injected (within less than 5 seconds), and indicated pressure equal to the canal water level throughout the tests. This initially suggested that the tubing may have been come loose from the packer due to the force of the flow. For the test of the 930 section this connection was reinforced and similar behavior was still seen from some piezometers. This suggests that the observed behavior is not the result of an instrumentation issue, but rather indicates that the soils behind the canal lining are very porous and free-draining at these piezometers
- 5 piezometers provided no useful data for varied reasons
  - staff gages that were unreadable,
  - water levels not visible because dye was never added (piezometers in locations not readily accessible by foot on the opposite bank)
  - tubing pulled loose from the canal sidewall or pinned underneath staff gage.

Figure 4 shows the third useful piezometer with significant positive pressures behind the canal lining. (Figure 2 and Figure 3 showed the other two such piezometers). This site was near the 94+36 station shown in Figure 2, and experienced similar drawdown conditions during the tests.

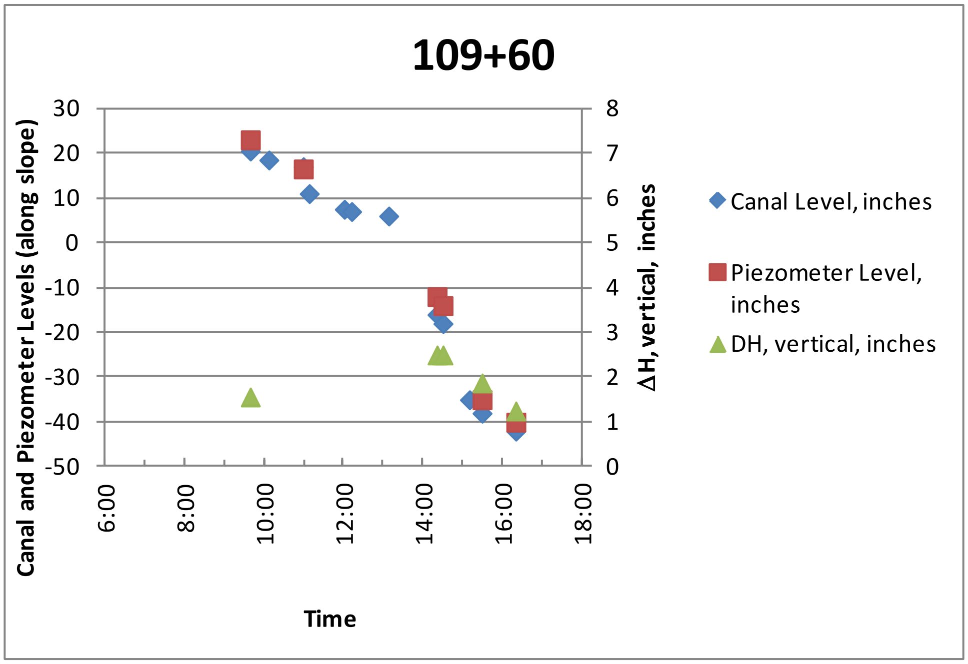


Figure 4. — Piezometer in upstream reach of the 550 section. No DH is shown at 11:00 because the value at this time was slightly negative.

## Discussion of 550 Test Results

Figures 2 through 4 show the highest pore water pressures recorded during the 550 test. Most piezometers in the 550 test indicated that pore water pressure behind the canal lining responds relatively rapidly to canal drawdown, or that the pressure behind the lining is always less than the canal level. The stations labeled 94+36 and 109+60 exhibited differential head behind the lining of about 3 inches of water or less under a sustained drawdown of about 11 inches per hour (vertical).

At the station labeled Mike-2 (Figure 3) near the downstream end of the 550 reach, the differential head built up and stabilized at about 2.5 inches of water (vertical) during a period when canal drawdown was averaging 2.7 inches/hr (vertical). It appeared that this drawdown rate and differential head loading could have been sustained. When the drawdown rate was increased in the afternoon to about 9 inches/hr, the differential head behind the lining began increasing, reaching a value of about 5.5 inches before monitoring was stopped at about 4:00 p.m. Figure 3 shows that the differential head was continuing to increase when the test was stopped, so equilibrium had not yet been reached. The canal level was dropping faster than the piezometer level.

To estimate the conditions at which equilibrium would have been achieved, we need to know the differential head at which the piezometer drawdown rate would match the canal drawdown rate of 9 inches/hr. Figure 5 shows the rate of decline in piezometer level as a function of the differential head across the lining. The y-axis positioning of the top two points (between 9 and 11 inches/hr) indicates that the rate of piezometer drop began to approximate the rate of canal stage drawdown (9 inches/hr), so this test was probably approaching equilibrium when monitoring was stopped. The corresponding differential head across the canal boundary was between 4 and 5 inches. A linear trendline fitted to all of the data gives a conservative estimate that a sustained differential head of 6 inches and corresponding piezometer drawdown rate of 9 inches/hr would have developed at this location, given a sustained canal stage drawdown rate of 9 inches/hr.

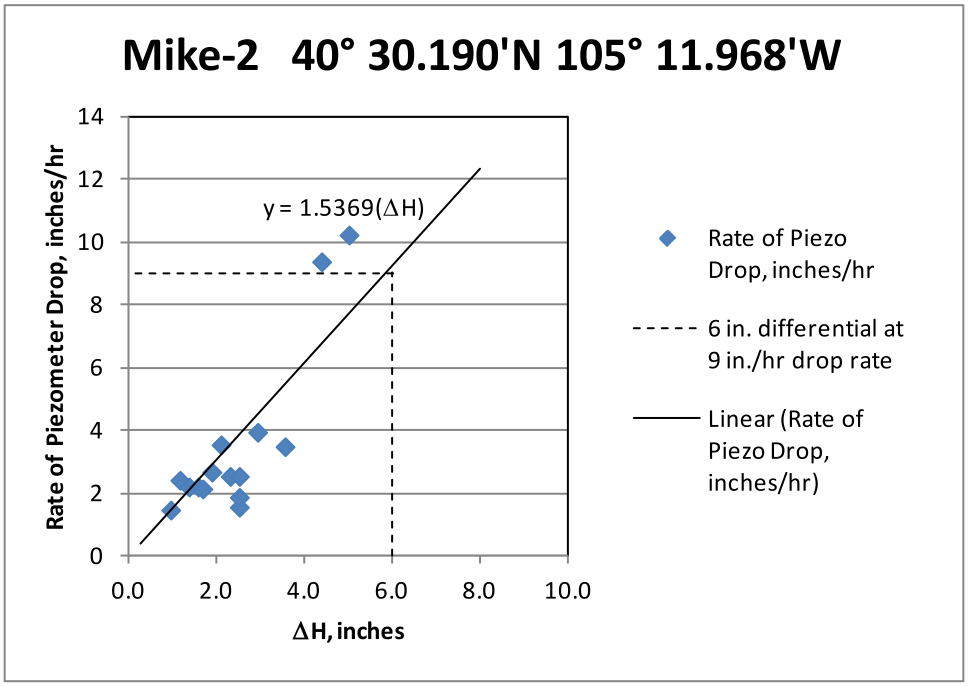


Figure 5. — Correlation between differential head across the lining and the rate of piezometer pressure drop.

# Testing of the 930 Section

Testing of the 930 section took place on May 15, 2012, after about 18 days of steady-state canal operation. Operations of the canal were managed to produce three drawdown periods. The first two were about 6 inches vertical, and the third was about 12 inches vertical at the upstream end of the reach, slightly less toward the downstream end of the reach. The first drawdown began early enough that it was not captured in most of the piezometer observations. Because the 930 section is closer to the source of inflow changes, attenuation was less pronounced in this test and the drawdowns came closer to the ideal of stepped changes in canal water level, especially in the upstream end of the reach.

A summary of the behavior of the piezometers follows:

- 26 of 27 piezometers provided useful information.
- 1 piezometer was plugged and its reading never changed after being filled with dye. It is possible that this packer hole did not penetrate through the canal lining.
- 5 piezometers indicated significant positive pressures behind the canal lining during the test.
- 14 piezometers tracked the canal water level very closely throughout the tests.
- 7 piezometers indicated pressures behind the canal lining that were always lower than the canal water level. Most of these were so low that they could not be observed. Piezometer 18 was about 10-12 inches below the canal level and tracked the canal during the test.

For the five piezometers that indicated positive pressures behind the canal lining, plots of the water level changes and differential head on the lining were prepared, along with plots that relate the rate of pressure drop to the differential head across the lining. These appear on the following pages, with discussion and interpretation of each plot.

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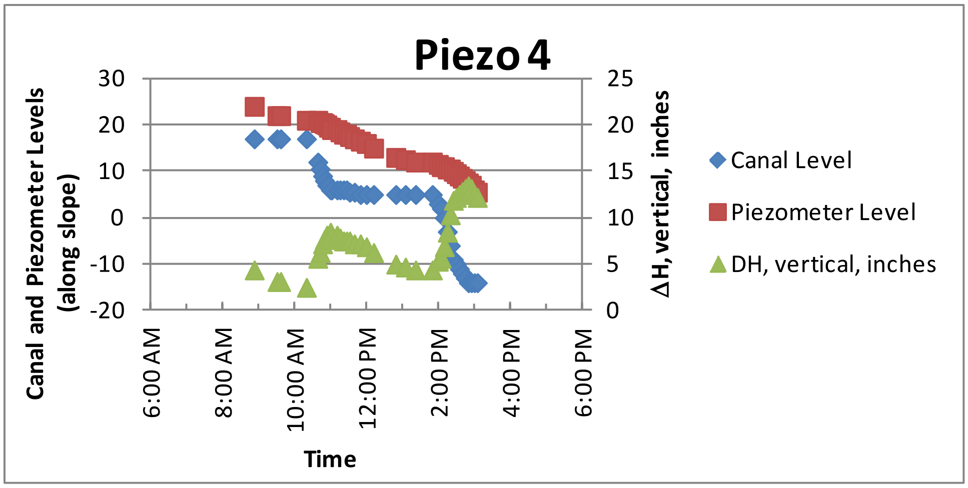


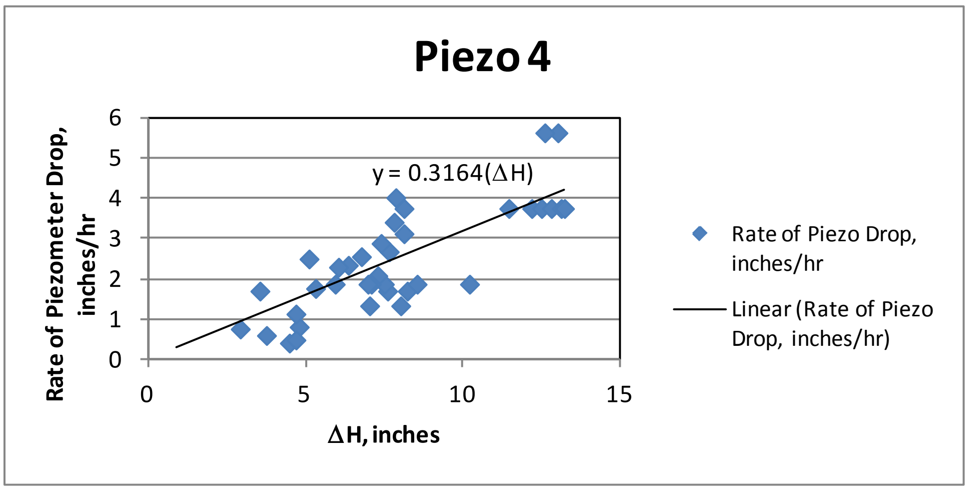
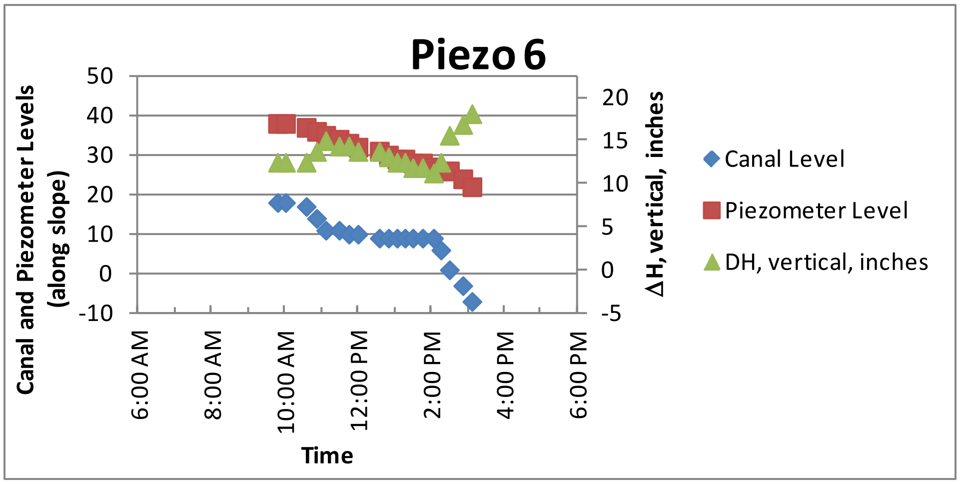




Figure 6. — Piezometer observations at station Piezo 4 during the 930 test.

**Piezo 4 —** This piezometer showed that the first two drawdowns produced differential heads that dissipated from 7.5 inches back toward levels of 2 to 4 inches before the next drawdown started. The third drawdown produced a differential head of about 12.5 inches that was beginning to dissipate when monitoring ended. There was a roughly linear relation between the rate of pressure drop behind the lining and the differential head across the lining.



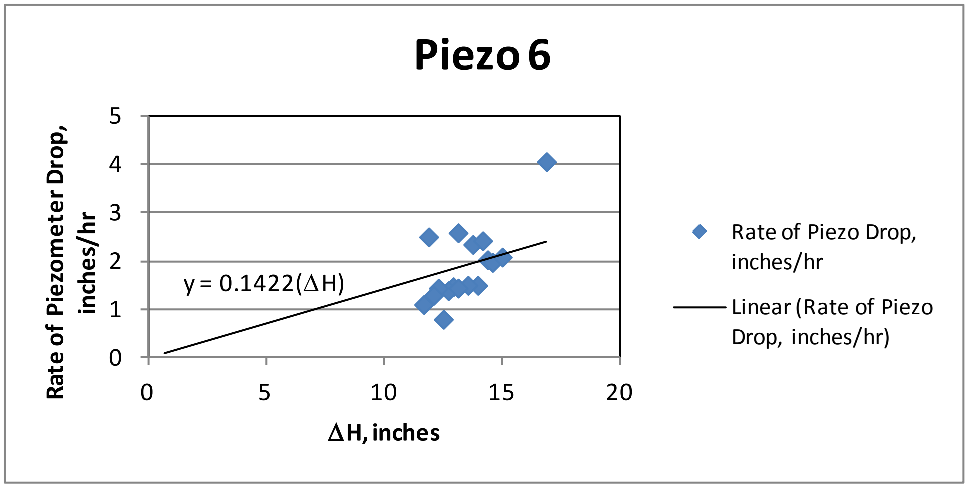
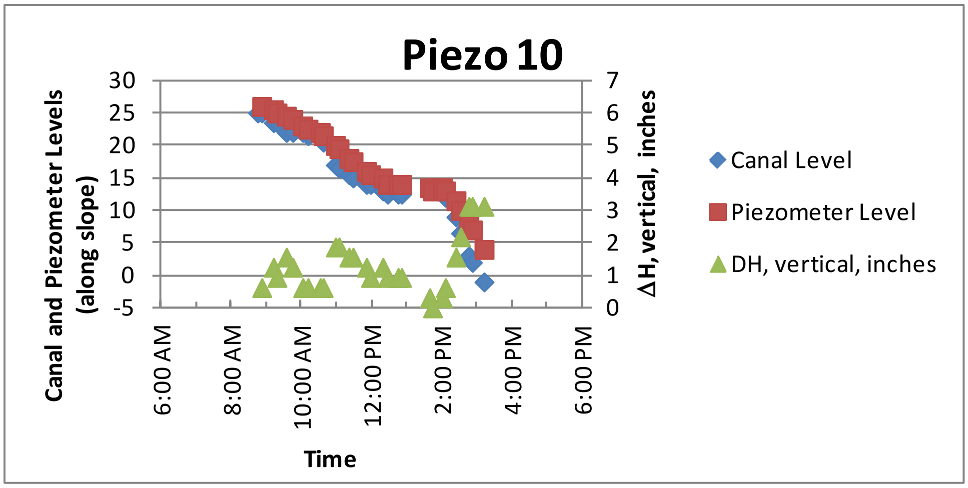




Figure 7. — Piezometer observations at station Piezo 6 during the 930 test.

**Piezo 6 —** This piezometer acted partially plugged when first charged with dye at the start of the day. The water level was at the canal level when dye was first added and enough dye was injected to raise the piezometer to about 12 inches above the canal level. The piezometer then began to decline slowly. This piezometer was not monitored for most of the first drawdown period. Prior to the initiation of the second drawdown, the piezometer was still higher than the original canal level. When the second drawdown began, the canal dropped about 4 inches vertical in 30 minutes, and the piezometer level continued dropping steadily at the same rate as before. When the third drawdown began, the rate of piezometer level decline increased, indicating a connection between the piezometer behavior and the canal level. The coefficient relating the rate of piezometer decline and the differential head was about half of the value obtained at Piezo 4. The maximum differential head was about 17 inches vertical, but it should be kept in mind that the piezometer pressures measured through most of the test were artificially inflated; adding dye to the piezometer tube raised the piezometer reading above the original canal steady state level and the original piezometer level, and the piezometer was draining back toward the initial steady state for most of the day.



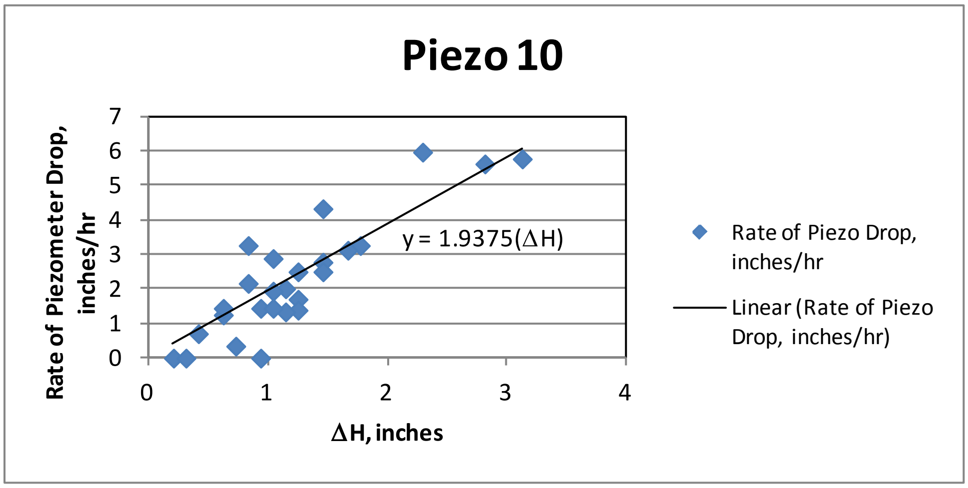
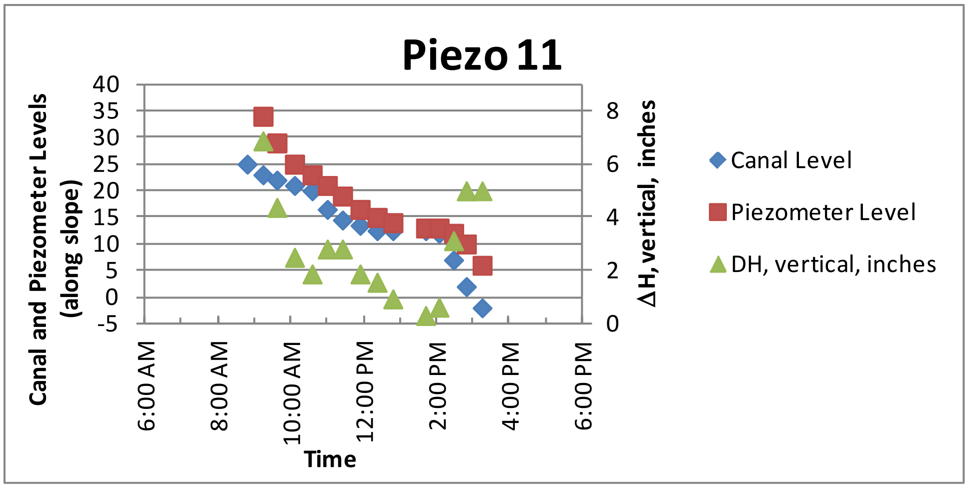




Figure 8. — Piezometer observations at station Piezo 10 during the 930 test.

**Piezo 10 —** Canal drawdowns at this station began to be attenuated and more gradual than in the upstream sections of the 930 reach. During the first two drawdown periods (approximately 8:30 a.m. – 12:30 p.m.), the canal drawdown rate was about 2 inches/hr (vertical). The piezometer tracked this drawdown with a positive pressure behind the lining of about 1 to 2 inches. After 2:00 p.m. the drawdown rate was about 7.5 inches/hr. The piezometer initially lagged with the differential head building up to about 3 inches, then stabilizing. The plot of piezometer decline versus differential head was roughly linear, and the coefficient relating the two was large, indicating free-draining soils behind the lining at this piezometer location.



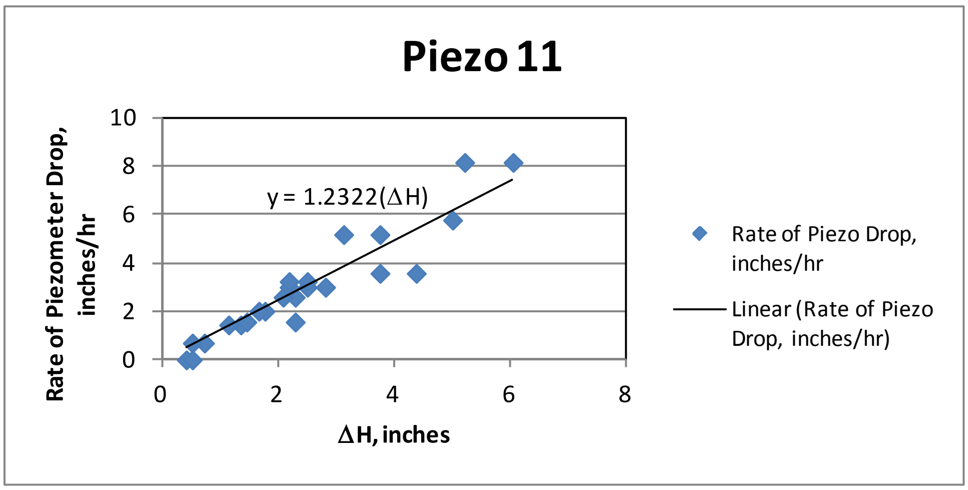
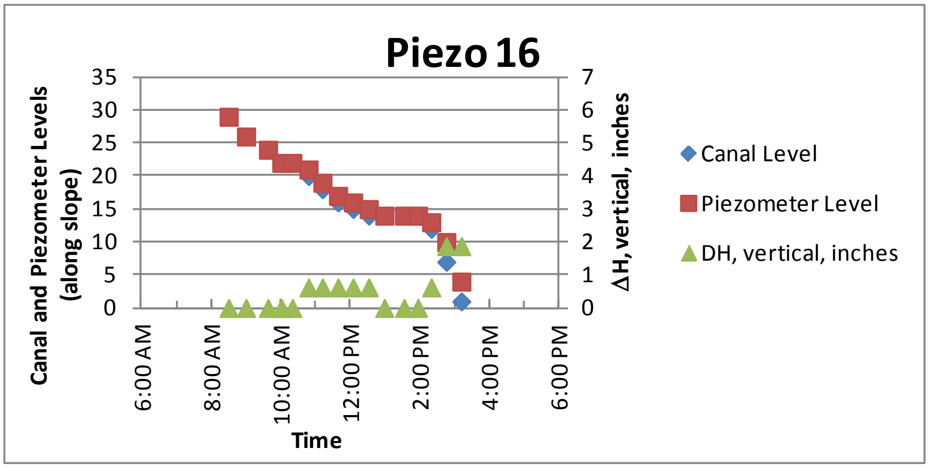




Figure 9. — Piezometer observations at station Piezo 11 during the 930 test.

**Piezo 11 —** This piezometer was located in the midst of the longest and deepest cut section on the canal. Early readings from this piezometer were distorted by the process of adding dye to the piezometer tube. Like all piezometers, the water level at the start of dye injection was equal to the canal level. After dye was added, the piezometer was registering a level well above the initial canal steady state elevation. Maximum differential heads were recorded during this time when the piezometer reading was above the initial condition. By the time that the second drawdown began to reach this location (just before 11:00 a.m.), the differential head had receded to about 3 inches vertical. The piezometer caught up to the canal before the third drawdown began around 2:00 p.m. During this drawdown the canal dropped at a rate of 7.5 inches/hr, and the differential head behind the lining increased to about 5 inches. The pressure behind the lining was holding steady when monitoring was stopped. The plot of piezometer decline versus differential head was roughly linear, and the coefficient relating the two was relatively large.



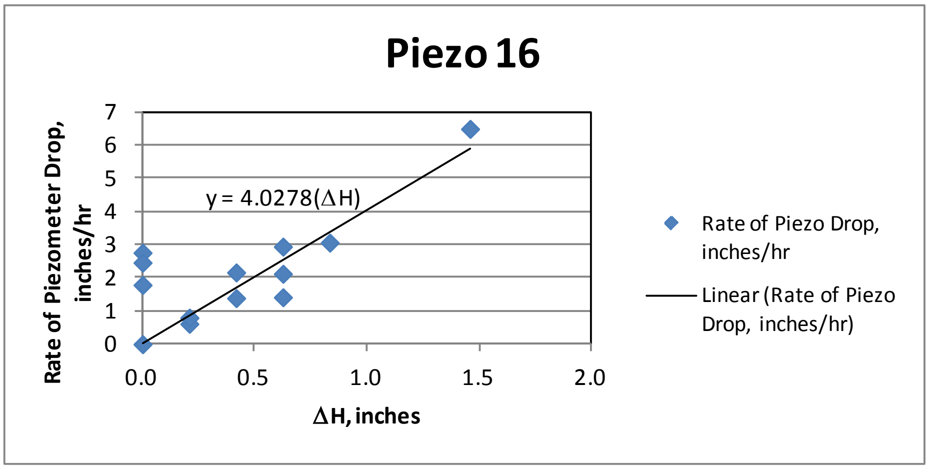




Figure 10. — Piezometer observations at station Piezo 16 during the 930 test.

**Piezo 16 —** This piezometer tracked the canal very closely during all of the drawdown periods. At the largest drawdown rate late in the afternoon (6.5 inches/hr, vertical), the differential head behind the lining increased to just 2 inches. Only small differential heads were needed to produce rapid rates of piezometer decline.

## Discussion of 930 Test Results

The slowest dissipation of pressures behind the canal lining occurred at Piezo 4 and Piezo 6 in this test. The coefficients relating the rate of piezometer pressure decline and the differential head across the lining were lower for these two piezometers than the slowest-draining piezometer in the 550 test (Mike-2). Piezo 6 exhibited the slowest drainage of all functional piezometers, so new proposed drawdown criteria are developed considering the data from this piezometer. Although the canal has not been dewatered and fully inspected since these tests were performed, it is assumed that no damage was done to the canal lining as a result of the drawdown conditions that occurred during the testing.

# Analysis

## Statistical Relevance of Collected Data

A total of 58 piezometers were installed for the two canal drawdown tests. Five piezometers in the 550 test were not monitored for various reasons or were deemed to be unreliable, and one piezometer in the 930 test was not functional. Thus, a total of 52 piezometers provided useful data. Piezo 6 exhibited the slowest drainage of pressure from behind the canal lining and is thus used in the section that follows to develop new drawdown criteria.

Because the piezometers represent a limited sample of the canal, there is a possibility that unsampled areas may contain tighter soils or other conditions that might lead to slower drainage of pressure than that observed at Piezo 6. An estimate of the probability of this occurrence is made to establish a level of confidence for the results of this study.

The sampling of canal bank drawdown characteristics using widely spaced piezometers can be compared to flood frequency analysis, in which a series of annual peak discharge values for a watershed are ranked and the recurrence intervals and probabilities of occurrence of each flood are estimated. If $N$ years of flood data are available, the highest ranked flood in the series is assigned a recurrence interval $T=(N+1)/m$, where $m$ is the magnitude ranking (i.e., the largest flood has rank $m=1$, the second largest $m=2$, etc.). In flood frequency, focus is on the recurrence interval in years; the associated exceedance probability in a future year for a flood of equal or greater magnitude is $p=1/T$.

Following this approach, Piezo 6 is the highest ranked piezometer in our study, exhibiting the slowest rate of pressure decline. Considering that there were 52 functional piezometers in our study, the recurrence interval is $T=(52+1)/1=53$. The associated probability is $p=1/53=0.019$. Considering the implication of adding one more piezometer to the study, the probability of that piezometer having a ranking higher than Piezo 6 (exhibiting slower pressure relief) is 0.019, or a 1.9% chance. This is not an assurance that a slower draining location does not exist along the length of the canal. In fact, it is a statistical certainty that a slower draining site does exist, and its location, physical extent and rate of drop would be determined if enough additional piezometers were installed. However, this result does indicate that about 98% of the canal reach is likely to drain at least as fast as Piezo 6.

The flood frequency analogy is appropriate for this application because the limited number of piezometers is believed to comprise a sample that is representative of the canal as a whole. Piezometers were established quasi-randomly throughout the entire reach of interest (except one very short reach that could not be dewatered during piezometer installation), and the sampling density was sufficient that it is unlikely to have missed any large areas that behave much differently from the sites that were sampled. The only bias introduced into the panel-choosing process was to select panels that were readily accessible for installation and monitoring, and to choose panels that were not already heavily cracked. That latter criterion should have produced a sample set that was conservatively biased toward panels that would exhibit slower rates of pore water pressure relief. Thus, the exceedance probability suggested by the analysis described above applies not only to panels that were actually sampled, but to the other panels throughout the canal reaches, which we believe have characteristics similar to the subset that was sampled. The results do not apply to any other canals (which might have different underlying soils).

## Developing the Drawdown Criteria

Determining a safe drawdown rate and developing an associated drawdown schedule is important to prevent damage to concrete canal linings. Other Reclamation canals have suffered serious damage due to rapid or excessive drawdown that created high pressure differentials across concrete linings.

Typical canal drawdown operations consist of a series of discrete changes in canal flow and depth that cumulatively produce a gradual, sustained rate of drawdown. These step changes can affect the canal rapidly near their origin (e.g., near a check structure), or more gradually at locations along the canal reach that are distant from the source of the change, due to attenuation. A specification of allowable drawdown rates must consider the allowable differential head loading that can be applied to the lining and the size of the step changes that are being made to apply that loading. Each time a drawdown step is executed, the differential head across the lining increases quickly and then decreases slowly as water drains from the soil behind the lining. The drawdown schedule should be created so that the maximum differential head immediately following each drawdown step does not exceed an allowable amount. <u>The time interval between changes must be set so that differential head behind the lining has enough time between drawdown steps to drop by an amount equal to or greater than the next change. This ensures that the next change will not exceed the maximum allowable differential head.</u>

Determination of a maximum allowable differential head is obviously crucial for establishing an acceptable drawdown limits. The Study Team Report (1979) discussed earlier stated that designers have typically considered the head required to lift the concrete lining as an initial limiting value, but there have been field experiences where larger differential heads were tolerable. The original design thickness of the concrete lining for the Hansen Feeder Canal is 4 inches, and the weight of this lining thickness can resist a differential head load of only 0.47 ft when lying flat on the bottom of the canal. For the 1.25:1 side slopes, the limit is further reduced to 0.36 ft. However, this is probably an overly simplistic analysis that does not consider factors such as the structural connection between floor and sidewall slabs, the effect of concrete above the water line, and material strength of the concrete. It is also clear that past operations have exceeded these limits.

Existing drawdown criteria for the Charles Hansen Feeder Canal allow a drawdown of 6 inches in the first hour, and a second step change of 6 inches can be made after one hour has elapsed (not to exceed 12 inches in 24 hours). This drawdown schedule will produce a differential head of 6 inches immediately following the first change, and using the pressure dissipation rate observed in Piezo 6, the approximate drop in <u>differential pressure</u> over the one hour following the first 6 inch change would be only 0.1422*6=0.85 inches. When the second change is made, the differential head would increase further to (6-0.85)+6=11.15 inches. This far exceeds the structural static limits discussed in the previous paragraph. It is also noteworthy that a differential head of about 18 inches was measured at Piezo 6 at the end of the test of the 930 section (Figure 7).

The history of normal operations for this canal and the knowledge that occasional emergency operations have exceeded normal drawdown rates without causing serious canal lining damage gives confidence that a maximum differential head of 1 ft is allowable. Thus, on the basis of prior operating experience *on this canal*, we conclude that a drawdown schedule that applies no more than a 1 ft differential head load is acceptable *for this specific canal*.

Taking this 1 ft differential head, proven acceptable during its historical application, as the maximum allowable differential head, we can develop drawdown recommendations that would repeatedly drop the canal level in steps without causing the differential head to exceed the allowable limit. The process for determining the drawdown step size and time interval between steps is outlined here:

- As described above ***for this canal only***, operating experience shows that a differential head loading of 1 ft of water can be applied. Thus, the first change in a drawdown cycle can be a step change from a state of rising stage or stage equilibrium of up to 12 inches. If the canal level has not been rising or at equilibrium for the preceding 48 hours, then the first change described above should not be made. Instead, the canal should be stabilized so the hydraulic effects in the canal from any recent changes have fully materialized, and then consider the current time as time zero. The first drop should then be determined as if it were the "next planned step change" described below.
- Next, note on Figure 7 that the rate of piezometer pressure drop in inches/hr is equal to 0.1422($\Delta H$), where $\Delta H$ is the differential head behind the concrete lining (expressed in inches of water). (Also note that most of the other piezometers showed the relation between these variables to be relatively linear, although there were insufficient data from Piezo 6 to draw this conclusion solely from the Piezo 6 data).
- If the next planned step change is to be a drop of $\Delta y$ = 3 inches, then the differential head just prior to that step change must drop to $\Delta H$ = 12-$\Delta y$ =

9 inches. The average differential head during the time preceding the next change will have been $\Delta H$ = (12+9)/2 = 10.5 inches (assuming the drawdown process is approximately linear). The average rate of pressure drop will be 0.1422*(10.5) = 1.49 inches/hr. Thus, the time interval to wait before making a 3 inch step change is $\Delta t$ = 3/1.49 = 2 hrs.

The preceding presentation of calculation steps is intended to illustrate the concepts for developing drawdown criteria, but in reality, the drawdown process is not linear, and the required waiting time is somewhat greater than that calculated above. An equation that accounts for the nonlinear behavior is developed in Appendix 1:

$$\Delta t = \frac{1}{0.1422} \ln\left(\frac{\Delta H_{\max}}{\Delta H_{\max} - \Delta y}\right) \qquad (1)$$

where $\Delta t$ is the required time interval in hours between step changes of $\Delta y$ inches (vertical), ln indicates the natural logarithm, and $\Delta H_{max}$ is the allowable differential head (12 inches). For small values of $\Delta y$ this produces essentially the same values of $\Delta t$ as the linear calculation process outlined above; for larger values of $\Delta y$ there is a significant increase in the computed $\Delta t$.

Equation 1 allows us to calculate $\Delta t$ for a given step size. If the time interval between steps is specified instead, the step size can be calculated directly from

$$\Delta y = \Delta H_{\max}\left(1 - e^{-0.1422\Delta t}\right) \qquad (2)$$

where $e$ is the base of natural logarithms, 2.7183.

Table 1 shows the time intervals required between step changes of different sizes, computed using Equation 1. The times in the table are rounded to the nearest hour, causing the effective drawdown rates for the 7 and 8 inch step sizes to be the same. The table shows the initial 1 ft drawdown step (which can be made only if starting from an equilibrium condition) and then the alternative Subsequent step changes in the shaded columns. Subsequent changes can be varied, as long as the associated required interval shown in the table is observed <u>before</u> each step change.

Table 1. — Drawdown criteria for the Charles Hansen Feeder Canal for a range of values of periodic step change. This table is designed to limit the differential head across the lining to no more than 1 ft, and was generated based on data collected from Piezo 6. The current drawdown criteria are also shown for comparison.

| Alternative drawdown criteria for the Charles Hansen Feeder Canal. | | | | |
|---|---|---|---|---|
| Initial step change in canal depth **(must have been at equilibrium for preceding 48 hours)** | Subsequent step change in canal depth, Δ*y* | Required interval between changes | Time required to drain… 550 section (8.2-ft depth) | Time required to drain… 930 section (8.8-ft depth) |
| (inches) | (inches) | (hours) | (hours) | (hours) |
| 12 | 3 | 2 | 58 | 62 |
| 12 | 4 | 3 | 65 | 70 |
| 12 | 5 | 4 | 69 | 75 |
| 12 | 6 | 5 | 72 | 78 |
| 12 | 7 | 7 | 86 | 94 |
| 12 | 8 | 8 | 86 | 94 |
| 12 | 9 | 10 | 96 | 104 |
| 12 | 10 | 13 | 112 | 122 |
| Existing drawdown criteria (* 6 inches in one hour, maximum of 12 inches per day) | | | | |
| 6 | 6 | 12* | 192 | 204 |

# Recommendations

Table 1 provides several alternatives for executing canal drawdown operations. The current drawdown criteria permit changes of 6 inches per hour, not to exceed 12 inches in 24 hours, for a sustained drawdown rate of 12 inches per day. Eight to nine days are thus needed to drain the canal from a full condition. The objective of these tests was to identify opportunities for increasing the drawdown rate to add operational flexibility during normal operations. Setting a small step change amount leads to faster effective drawdown rates because more frequent drawdown steps can be made and the differential head across the lining is maintained closer to the maximum allowable amount throughout the process. Step changes between 3 and 6 inches are likely to be most practical and provide significantly increased drawdown rates.

To apply Table 1 operationally to develop a drawdown schedule:

1. Determine whether during the preceding 48 hours the canal stage has fallen (as opposed to rising or equilibrium conditions). If it has fallen, skip step 2 and continue with step 3.
2. Schedule a drawdown change of up to 12 inches. To optimize drawdown time, it should be a drawdown change of 12 inches. No time delay is required.
3. Determine a desired drawdown step change not to exceed 10 inches.
4. Referencing Table 1, locate this desired drawdown step change in the “Subsequent step change in canal depth” column. Determine the

corresponding time, t, listed in the "Required interval between changes" column.

5. Taking the time of the most recent change as time X, schedule the desired drawdown step change at time = X + t. (Of course the operational description may actually prescribe a desired flowrate at time X + t, which would require referencing a stage-discharge table to go from the desired stage to flow.)
6. Repeat steps 3 – 5 until the final canal stage target is achieved.

For operational purposes, Table 1 may be entered with either the **Subsequent step change** or the **Required interval** to determine the value of the complementary parameter. For example, the scheduler may enter the table at the Required interval column to determine the maximum Subsequent change following an overnight, 8-hour break in operational adjustments. Also, subsequent changes can be varied if desired, as long as the required interval is observed <u>before</u> each step change. For example, a drawdown schedule could consist of an initial 12 inch step followed by a sequence of step changes of 3 inches every 2 hours during daytime and step changes of 8 inches every 8 hours during the nighttime. The size and timing of drawdown steps must be accurately controlled and tracked to avoid overloading the canal lining.

One practical drawdown schedule for the Charles Hansen Feeder Canal could be:

1. Start a drawdown operation with an initial 12 inch drop in the canal depth at time zero. **This initial large drop can only be permitted if the canal depth has been increasing or steady for the preceding 48 hours.**
2. At time = 5 hours drop the canal an additional 6 inches, and continue making 6 inch drops at 5 hour intervals (these values come from the second and third columns of Table 1).

The schedule outlined above would allow the 8.2-ft deep 550 section to be drained from capacity in 3 days, and the 8.8-ft deep 930 section could be drained from capacity in about 3.25 days.

Long-term monitoring of the canal should continue for the purpose of evaluating performance of the canal lining under any new operational criteria. Specific recommendations include:

1. When the canal lining is exposed and accessible, monitor existing cracks in the concrete lining to detect future widening, displacement or evidence of material transport from behind the concrete panels.
2. Currently sealed cracks should continue to be maintained to ensure that existing sealer does not degrade and change the canal conditions.
3. Piezometer holes created during this test should be plugged during the next available outage, unless there is an expectation that they may continue to be monitored in the future (perhaps during a future repeat of this drawdown test). This can be accomplished by removing the packers

and repairing the holes in accordance with the Reclamation Concrete Repair Manual, or by installing 3/8” NPT pipe plugs into the elbow fittings connected to each packer.

# Precautions

1. The recommendations given in this report are based on the operating history of the Charles Hansen Feeder Canal and on-site testing to measure differential heads behind the canal lining and the rate at which those pressures dissipate.  Rates of pressure dissipation are expected to be a function of site-specific factors, including canal lining integrity and underlying soil types and geologic conditions.  <u>These recommendations do not apply to any other canal.</u>
2. The testing performed on this canal did not define a threshold for canal lining failure.  The objective of this work was to obtain data that could be used develop conservative, safe operating policies.
3. The recommendations in this report apply only to non-emergency operations of the Charles Hansen Feeder Canal.  Faster drawdown rates may still be appropriate during emergency situations, but the risk of damaging the concrete would be increased.

# References

Buyalski, C.P., D.G. Ehler, H.T. Falvey, D.C. Rogers, and E.A. Serfozo, 1991.  *Canal Systems Automation Manual*, Volume 1.  U.S. Dept. of the Interior, Bureau of Reclamation, pp. 47-48.

“Review of Canal Underdrainage for Lining Protection”, USBR Study Team Report, E&R Center, August 24, 1979, Denver, CO.

# Appendix 1: Drawdown Equations

We begin by defining the piezometer level above the canal water level to be $\Delta H$. At time $t_1$ the differential head will be at the maximum allowable level, $\Delta H_1 = \Delta H_{max} = 12$ inches. At time $t_2$ the head will have dropped to $H_2 = \Delta H_{max} - \Delta y$. At time $t_2$ it will then be safe to make the next drawdown step $\Delta y$.

For Piezo 6, we determined from the test data that the rate of piezometer level drop is proportional to the differential head between the piezometer and the canal level. We can express this relationship with the equation

$$\frac{d(\Delta H)}{dt} = -0.1422(\Delta H)$$

(Note that the minus sign is included because $\Delta H$ is dropping with time. In Figure 7 we plotted the rate of drop versus the differential head and showed the rate of drop to be positive.)

We can rearrange this equation and then integrate to find the time interval required for the differential head to drop from $\Delta H_{max}$ to $\Delta H_{max} - \Delta y$:

$$\begin{aligned}
dt &= -\frac{1}{0.1422}\frac{d(\Delta H)}{(\Delta H)} \\
\int dt &= -\frac{1}{0.1422}\int \frac{d(\Delta H)}{(\Delta H)} \\
t\Big|_{t_1}^{t_2} &= -\frac{1}{0.1422}\ln(\Delta H)\Big|_{\Delta H_{max}}^{\Delta H_{max}-\Delta y} \\
t_2 - t_1 &= -\frac{1}{0.1422}\left[\ln(\Delta H_{max} - \Delta y) - \ln(\Delta H_{max})\right] \\
\Delta t &= \frac{1}{0.1422}\ln\left(\frac{\Delta H_{max}}{\Delta H_{max} - \Delta y}\right)
\end{aligned}$$

The equation derived above allows direct calculation of $\Delta t$ if the maximum allowable differential head and drawdown step size are known. To allow direct calculation of the step size with $\Delta t$ given, the equation can be solved for $\Delta y$:

$$\Delta y = \Delta H_{max}\left(1 - e^{-0.1422\Delta t}\right)$$

# Appendix 2:
# Piezometer Locations and Details

Table 2. — Listing of piezometer installations for the 550 section, from upstream to downstream.

| observer | id | Station | N | W | Notes during dye injection |
|---|---|---|---|---|---|
| Amy | 1 | 74+92 | 40° 25.388' | 105° 13.586' | No dye added. Could not observe. |
| Amy | 2 | 83+80 | 40° 25.511' | 105° 13.600' | No dye added. Could not observe. |
| Amy | 3 | 94+36 | 40° 25.717' | 105° 13.632' | seems like good piezometer |
| Amy | 4 | 104+12 | 40° 25.824' | 105° 13.655' | Piezometer level is far below canal. |
| Amy | 5 | 109+60 | 40° 25.931' | 105° 13.679' | seems like good piezometer |
| Amy | 6 | 116+92 | 40° 26.059' | 105° 13.679' | Piezometer level is far below canal. |
| Nicole | 1 | 152+00 | 40° 26.431' | 105° 13.110' | Piezometer level is far below canal. |
| Nicole | 2 | 163+00 | 40° 26.536' | 105° 13.152' | No dye added. Could not observe. |
| Nicole | 3 | 173+00 | 40° 26.689' | 105° 13.200' | No dye added. Could not observe. |
| Nicole | 4 | 180+00 | 40° 26.797' | 105° 13.248' | No dye added. Could not observe. |
| Nicole | 5 | 189+50 | 40° 26.892' | 105° 13.278' | Piezometer level is far below canal. |
| Nicole | 6 | 195+00 | 40° 27.025' | 105° 13.314' | Inconsistent behavior. Below canal level most of time. |
| Ribha | 1 | 200+00 | 40° 27.165' | 105° 13.394' | Piezometer level is far below canal. |
| Ribha | 2 | 210+00 | 40° 27.300' | 105° 13.426' | Responds too fast. Matches canal (maybe open on bottom) |
| Ribha | 3 | 218+00 | 40° 27.445' | 105° 13.474' | Reacts fast. Settles 18" below canal water surface. |
| Ribha | 4 | 238+00 | 40° 27.624' | 105° 13.568' | Good piezometer. Readings mostly below canal level. |
| Ribha | 5 | 242+00 | 40° 27.789' | 105° 13.501' | Piezometer level is far below canal. |
| Brandon | 1 | 259+00 | 40° 27.986' | 105° 13.462' | Responds too fast. Matches canal (maybe open on bottom) |
| Brandon | 2 | 265+00 | 40° 28.043' | 105° 13.505' | Responds too fast. Matches canal (maybe open on bottom) |
| Brandon | 3 | 271+00 | 40° 28.227' | 105° 13.561' | Responds too fast. Matches canal (maybe open on bottom) |
| Brandon | 4 | 283+50 | 40° 28.393' | 105° 13.546' | Good. Always matches canal level. |
| Brandon | 5 | 287+00 | 40° 28.463' | 105° 13.514' | Good. Always matches canal level. |
| Brandon | 6 | 302+00 | 40° 28.713' | 105° 13.521' | Responds too fast. Matches canal (maybe open on bottom) |
| Gabriel | 1 | unknown | 40° 29.524' | 105° 12.302' | Fast reacting. Matched canal level. |
| Gabriel | 2 | unknown | 40° 29.434' | 105° 12.086' | Fast reacting. Matched canal level. |
| Gabriel | 3 | unknown | 40° 29.400' | 105° 12.012' | Good. Matches canal level. |
| Gabriel | 4 | unknown | | | Good. Matches canal level. |
| Mike | 4 | unknown | 40° 29.827' | 105° 12.002' | Fast reacting. Matched canal level. |
| Mike | 3 | unknown | | | top of tubing was pulled loose. Did not read. I fixed it late in the day, but when I put dye in it reacted very fast and matched canal level. |
| Mike | 2 | unknown | 40° 30.190' | 105° 11.968' | good. This was the one piezometer that consistently showed a positive pressure behind lining. |
| Mike | 1 | unknown | 40° 30.272' | 105° 11.943' | Matched canal level at all times, but reacted slowly when dye was inserted. (as expected) |

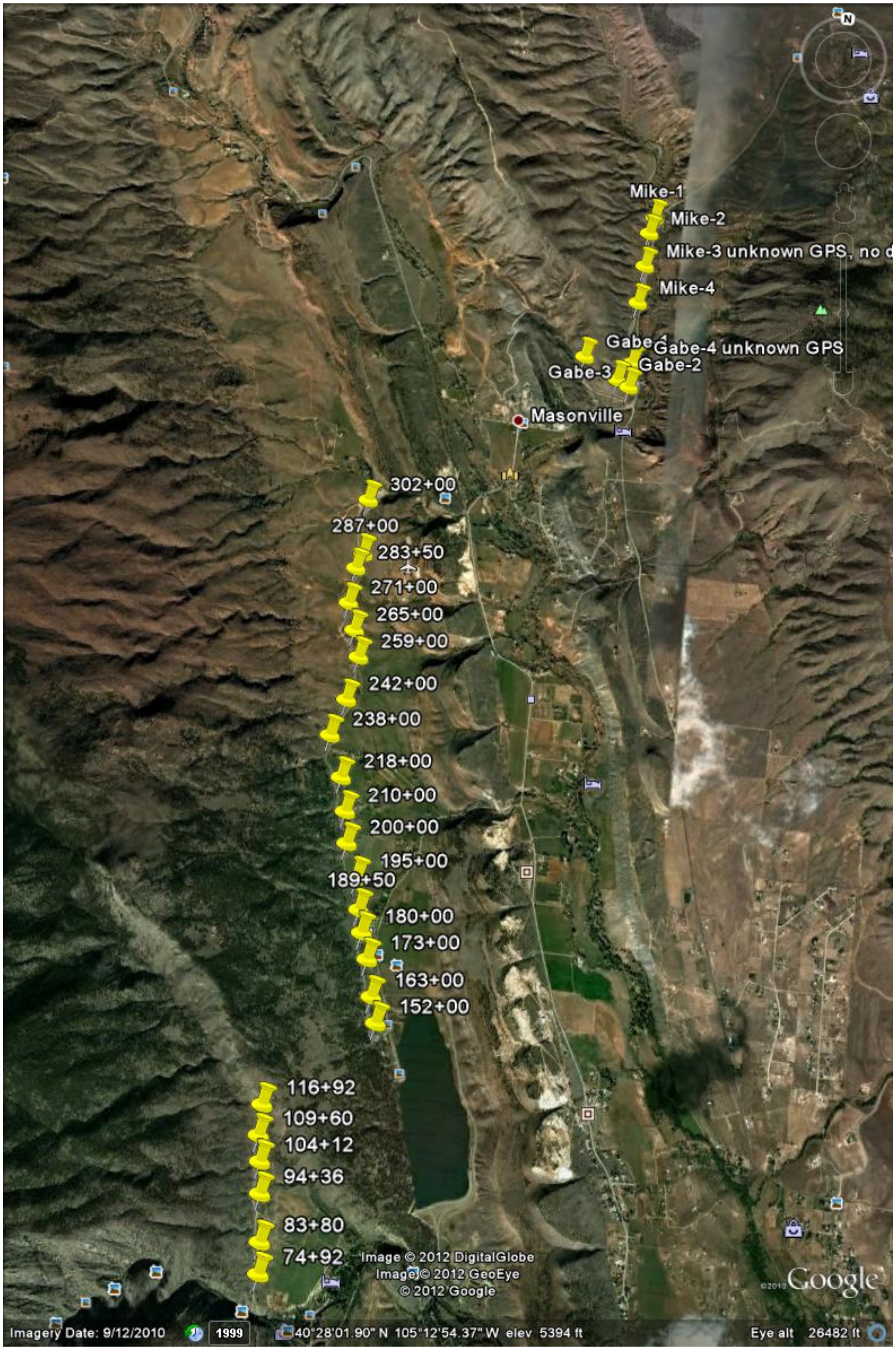



Figure 11. — Piezometer locations in the 550 section.


Figure 12. — Detail of piezometers in upstream reach of the 550 section.


Figure 13. — Detail of piezometers in middle reach of 550 section.

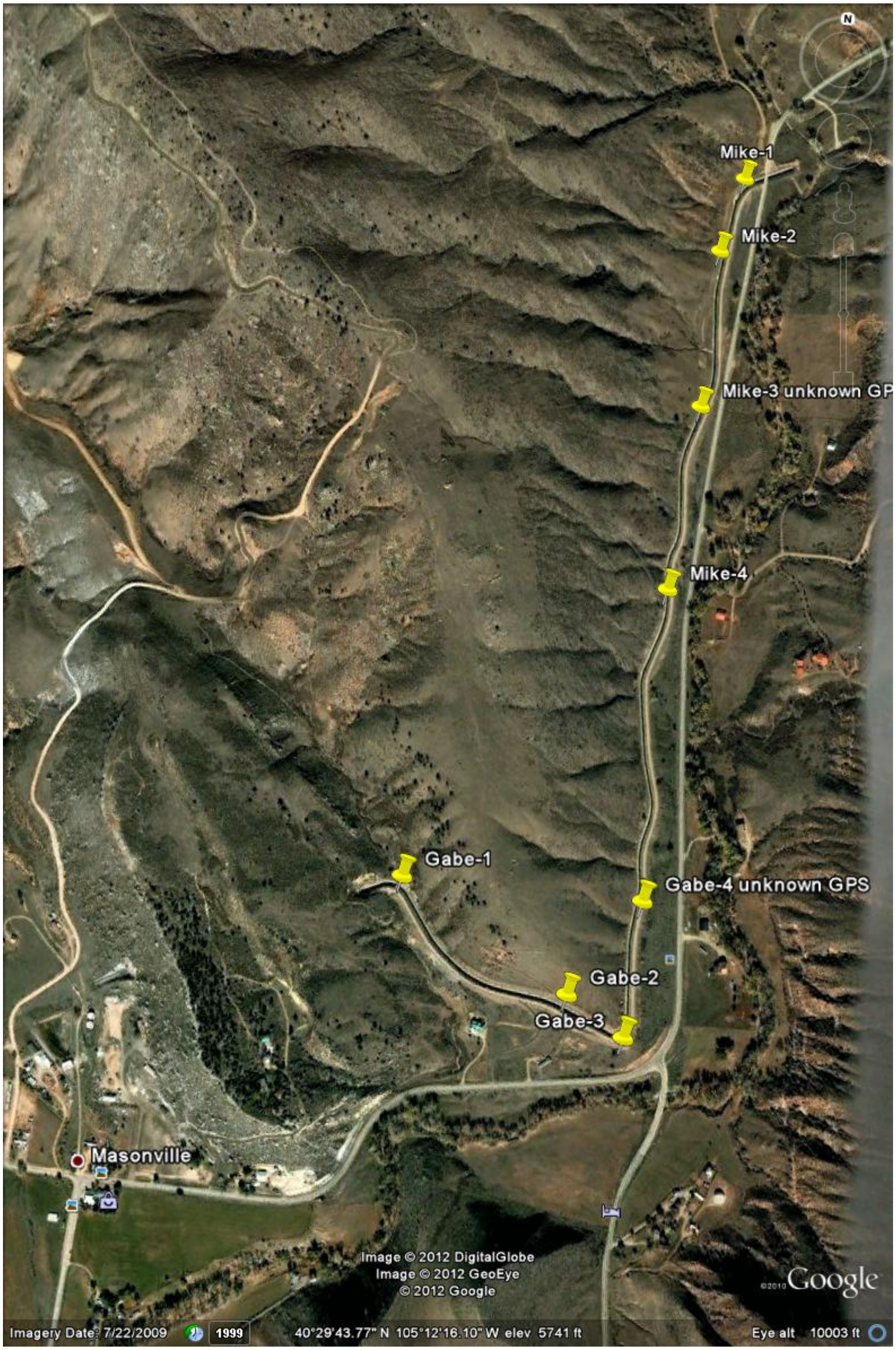



Figure 14. — Detail of piezometers in downstream reach of 550 section.

Table 3. — Listing of piezometer installations for the 930 section. Colors in first column indicate divisions between observers.

Hansen Feeder Canal - 930 cfs section

Piezometer locations - Downstream to Upstream

| Piezo No. | Approx. canal station | GPS WayPoint | Latitude | Longitude | |
|---|---|---|---|---|---|
| 27 | 226+00 | 39 | 40° 24.991' | 105° 13.492' | Below canal level at all times |
| 26 | 216+00 | 40 | 40° 24.913' | 105° 13.397' | At or below canal, except during last drawdown when it was 1" above canal |
| 25 | 211+00 | 41 | 40° 24.817' | 105° 13.338' | Below canal, except during last drawdown when it was about 1-2" above canal |
| 24 | 205+00 | 42 | 40° 24.715' | 105° 13.258' | Below canal level at all times |
| 23 | 199+00 | 43 | 40° 24.646' | 105° 13.210' | Below canal, except during last drawdown when it was about 1" above canal |
| 22 | 193+00 | 44 | 40° 24.557' | 105° 13.189' | Always below water surface and/or non-visible |
| 21 | 187+00 | 45 | 40° 24.482' | 105° 13.168' | Always below water surface and/or non-visible |
| 20 | 183+00 | 46 | 40° 24.407' | 105° 13.155' | Below water surface, except during final drawdown, when piezometer level exceeded canal level by only 1 to 2 inches (0.6 - 1.25 inches vertical) |
| 19 | 179+00 | 47 | 40° 24.302' | 105° 13.144' | Piezometer never moved after being filled with dye |
| 18 | 170+00 | 48 | 40° 24.193' | 105° 13.127' | Piezometer registered 10-12 inches below canal through test (tracked drawdown) |
| 17 | 163+00 | 49 | 40° 24.079' | 105° 13.118' | At or below canal level at all times |
| 16 | 160+00 | 50 | 40° 24.013' | 105° 13.101' | Useful piezometer. Slight positive pressures during drawdown periods. |
| 15 | 151+00 | 51 | 40° 23.963' | 105° 13.092' | Tracked canal perfectly throughout the test |
| 14 | 143+00 | 52 | 40° 23.856' | 105° 13.059' | Tracked canal perfectly throughout the test |
| 13 | 133+00 | 54 | 40° 23.733' | 105° 13.016' | At or below canal level at all times |
| 12 | 122+00 | 55 | 40° 23.644' | 105° 12.990' | Below canal level at all times |
| 11 | 110+00 | 56 | 40° 23.410' | 105° 12.995' | Useful piezometer. Small to medium positive pressures throughout the day. |
| 10 | 102+00 | 57 | 40° 23.344' | 105° 13.001' | Useful piezometer. Small positive pressures throughout the day. |
| 9 | 94+00 | 58 | 40° 23.240' | 105° 13.049' | Tracked canal perfectly throughout the test |
| 8 | 86+00 | 59 | 40° 23.149' | 105° 13.114' | Negative piezometer readings, or tracked canal perfectly throughout the test |
| 7 | 78+00 | 60 | 40° 22.992' | 105° 13.162' | Piezometer level below canal water level throughout test |
| 6 | 70+00 | 61 | 40° 22.923' | 105° 13.187' | Piezometer equalized very slowly after being filled with dye. |
| 5 | 62+50 | 62 | 40° 22.793' | 105° 13.223' | Tracked canal perfectly throughout the test |
| 4 | 49+00 | 63 | 40° 22.691' | 105° 13.456' | Useful piezometer. Significant positive pressures during drawdown periods. |
| 3 | 37+00 | 64 | 40° 22.600' | 105° 13.519' | Tracked canal perfectly, except just after filling with dye, when piezometer was only 1 inch above canal level |
| 2 | 24+00 | 65 | 40° 22.572' | 105° 13.659' | Tracked canal perfectly throughout the test |
| 1 | 12+50 | 66 | 40° 22.569' | 105° 13.764' | Tracked canal perfectly, except for two readings during which piezometer was only 1-2 inches above canal level |

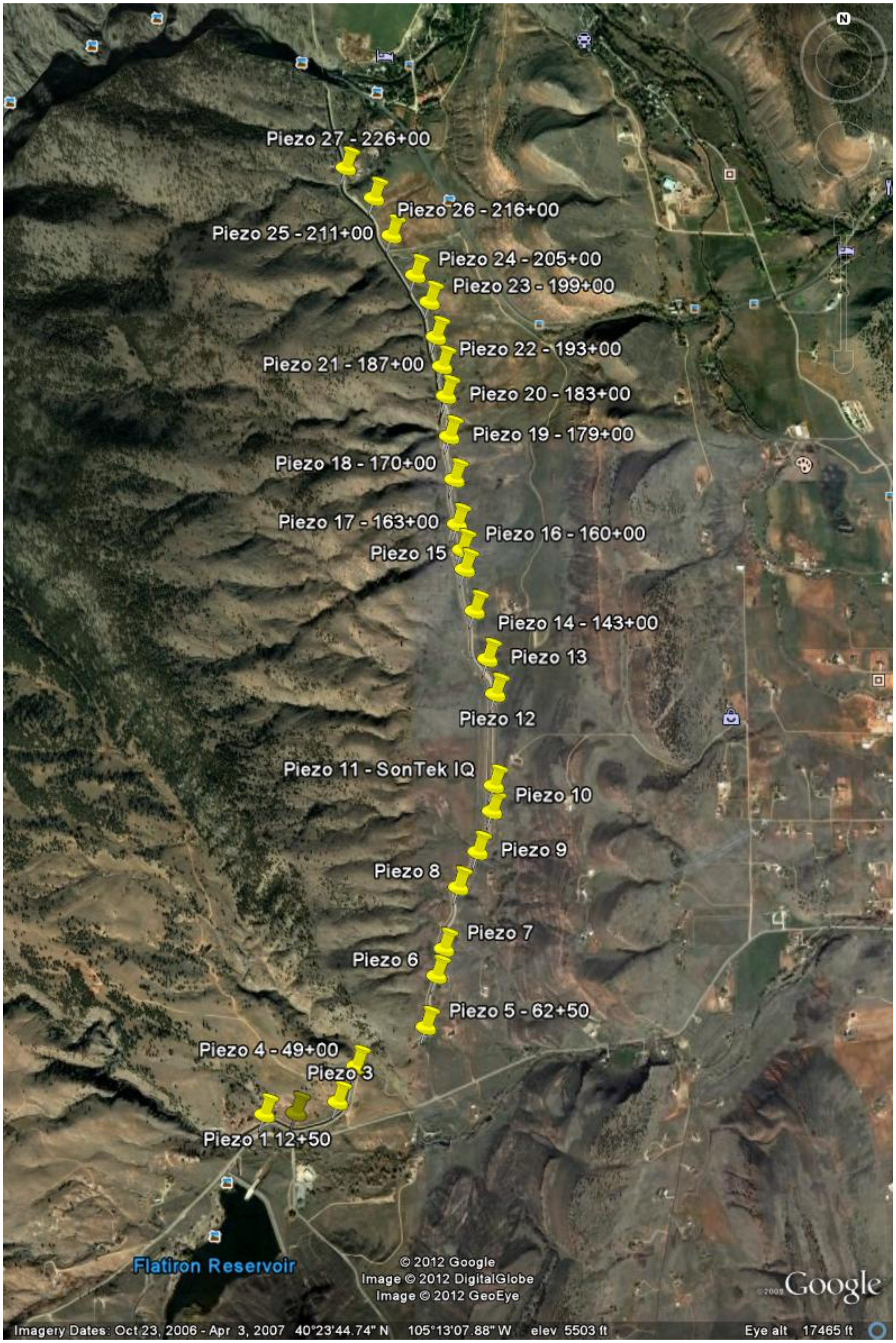



Figure 15. — Piezometers in the 930 section.


Figure 16. — Detail of piezometers in the 930 section.


Figure 17. — Detail of piezometers in the 930 section.

Figure 18. — Detail of piezometers in the 930 section.

Figure 19. — Detail of piezometers in the 930 section.

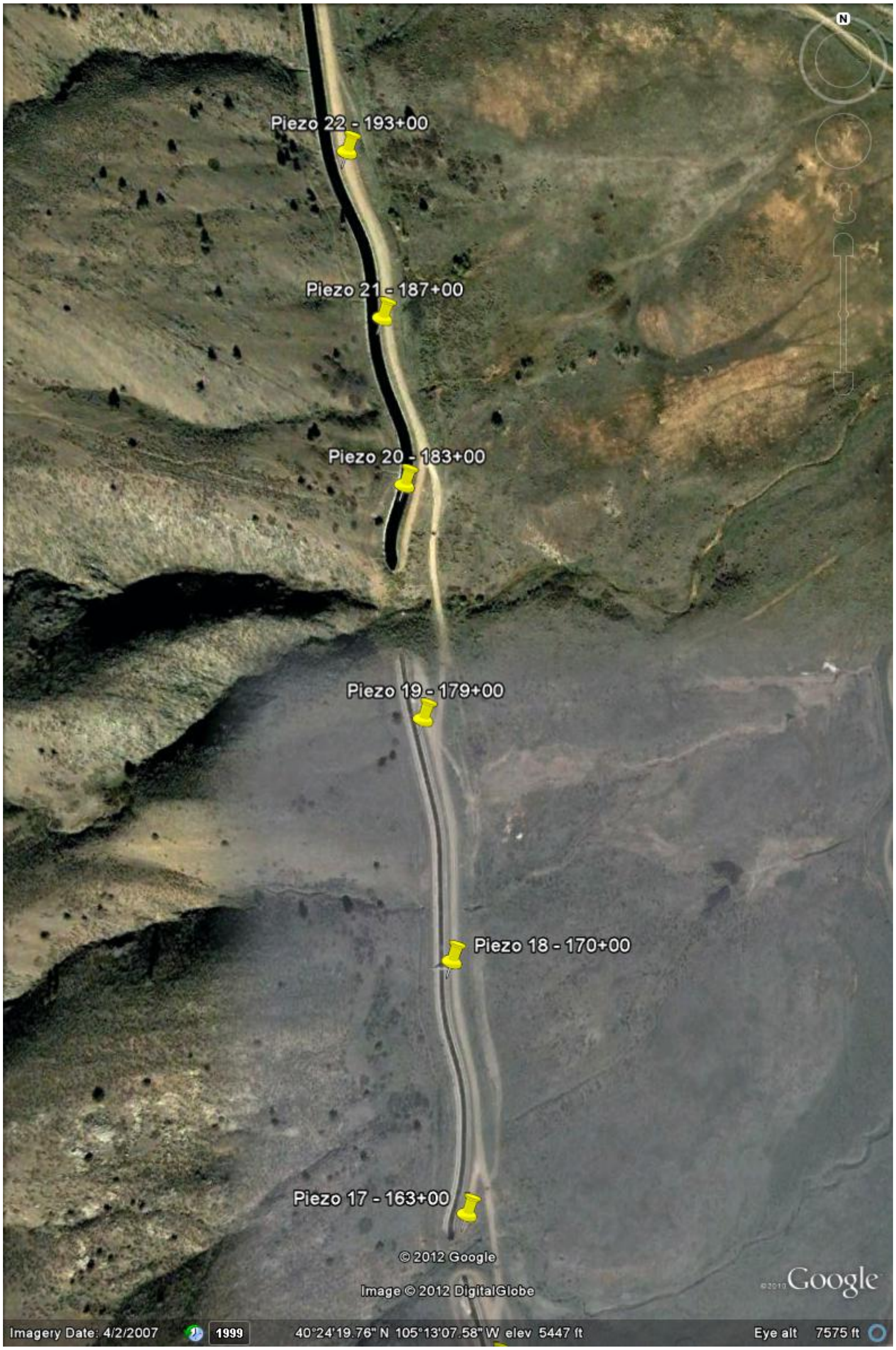



Figure 20. — Detail of piezometers in the 930 section.

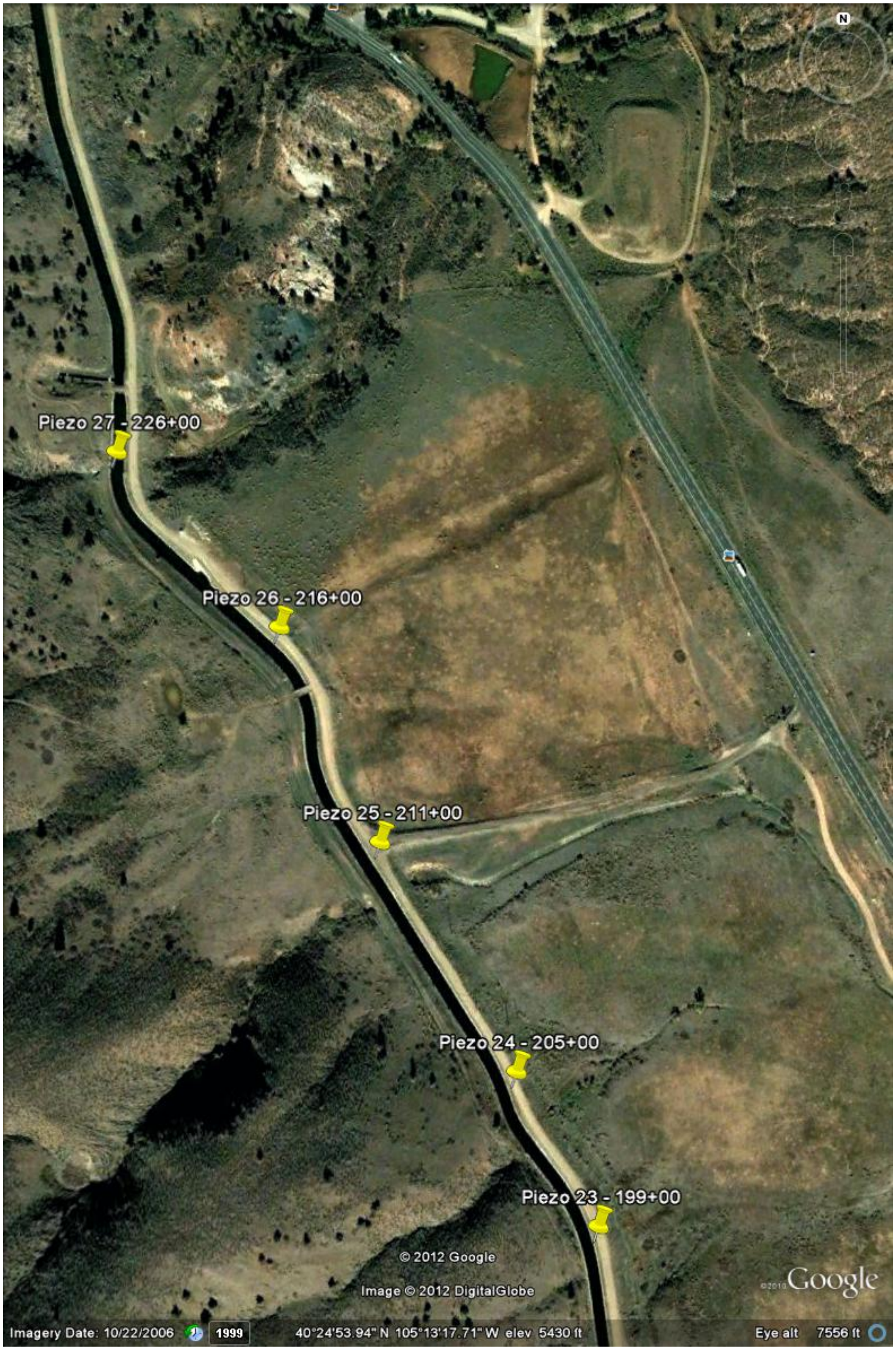



Figure 21. — Detail of piezometers in the 930 section.