EVALUATION OF METHODS FOR PREDICTING SEEPAGE LOSS RATES FOR THE HARD LINED IRRIGATION CANALS OF THE LOWER RIO GRANDE VALLEY OF TEXAS

A Thesis

by

ERIC WALLACE LEIGH

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Chair of Committee,	Ronald Kaiser
Committee Members,	John Giardino
	James Gilley
Intercollegiate Faculty Chair,	Ronald Kaiser

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ABSTRACT

This project investigated the measured loss rates and observed canal lining conditions by the Texas AgriLife Extension Service to evaluate the Davis-Wilson empirical formula and to further develop a canal condition rating system for predicting loss rates. This research is to help irrigation districts of the Lower Rio Grande Valley of Texas to identify and prioritize the high loss deteriorated lined canals for rehabilitation and management. The ponding test method was used to estimate the loss rates on 32 canal sections. The condition rating scores were evaluated for 26 of these canals.

Test calculation revisions and testing errors were first evaluated to understand the potential impacts to the seepage loss rates and condition rating system. The condition rating system had good results for canals with a ranking of 1, predicting losses less than 0.38 ($ft^3/ft^2/day$). Canals with rankings of 2 and 3 had a larger range in loss rates. This could be attributed to either the subsoil types having more influence as the lining conditions become more deteriorated or errors in the rating system. The Davis-Wilson empirical formula had poor results at predicting loss rates for the local lining conditions. The seepage loss rates were used to calibrate the formula and derive new coefficients (C-values). The C-values were correlated with the scores of the condition rating system (i.e. Ranking 1 = C-values 1-11). Relationships were also found between the canal dimensions, water loss rates, and conditions ratings. In general, larger, deeper canals were in better condition and had lower loss rates. Smaller canals had more variability in both loss rates and condition ratings.

DEDICATION

I would like to dedication this to my loving and supportive parents.

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First, I would like to thank Dr. Val Silvy. She was much more than a program coordinator. She gave hope and inspiration. Sadly, she will never know how much she truly helped me. Val, you will be forever missed.

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NOMENCLATURE

cfd – cubic feet per square foot of wetted area per day ($ft^3/ft^2/day$)

ETo – Reference Crop Evapotranspiration

Valley – Lower Rio Grande Valley of Texas

USBR – United State Bureau of Reclamation

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CHAPTER I

INTRODUCTION

In 1996 and 1998, localized droughts took their toll on south Texas. The water shortages in agriculture and municipal use spurred on the Texas and the United States Legislatures to establish state and federal initiatives to curb future water deficiencies. In 1997, Texas passed Senate Bill 1 that created 16 statewide regional water-planning groups to broadly identify water shortages and demands. In 2000, the U.S. Congress passed Public Law 106-576, that focused specifically on the rehabilitation of irrigation district conveyance systems of south Texas entitled "The Lower Rio Grande Valley Water Resources Conservation and Improvement Act of 2000 (Act)"(Rister et al. 2003). In addition, the Lower Rio Grande Valley of Texas (The Valley) area has seen a continually growth in population, making water resource supplies ever more stretched. To meet the new water demands, many believe that water will be converted from the irrigation and agricultural sectors to lessen the impacts on municipal and industrial users. Increasing overall irrigation efficiency from delivery to field application has become a priority.

As Texas irrigation districts have begun to improve technologies and management efficiency, the majority of their canal systems and an estimated 43% (Fipps 2005) of farm deliveries are void of measurement structures and thus not metered. Irrigation scheduling is generally based on a first-come, first-serve policy (i.e. not setup for maximizing efficiency). Many of open channel (canals) systems, built on soil types having higher permeability rates, were lined with concrete beginning in the 1960's. Over the years, these lined canals have cracked and deteriorated through natural processes, and through testing can have seepage losses higher than unlined canals.

Over the past decade, the Texas AgriLife Extension Service has been working with the irrigation districts of the Valley to quantify water losses from irrigation canals and to determine the potential water savings from rehabilitation projects. The Extension team has performed over 50 seepage-loss tests on a variety of lined and unlined irrigation canals. Many of the test result reports can be found at the Texas Water Research Institute (TWRI) website (http://twri.tamu.edu). While district engineers used some of these test results to complete rehabilitation funding applications, there has been no further use of these test results in district management as applied to conveyance efficiency.

The primary purpose of this project is to assess the seepage-loss test measurements by the Texas AgriLife Extension Service and evaluate various methods for identifying conditions of perched lined irrigation canals that lead to high loss rates.

1.1. Research Objectives

1) Revise the seepage-loss test calculations and rates for selected lined canals, and evaluate potential impacts of testing errors and calculation differences. Determine relationships between the canal geometry attributes and water loss rates.

2) Determine the level of predictability for the Davis-Wilson empirical formula compared to the revised seepage loss rates. Calibrate the empirical formula with the revised seepage-loss rates each tested canal to derive improved coefficients.
3) Evaluate a newly developed condition rating scale for lined canals, and correlate the rating scale with the improved coefficients of the empirical formula.

CHAPTER II

LITERATURE REVIEW

2.1. Factors Influencing Canal Seepage

Around the world, seepage losses (lost infiltrated water) from canal systems have been and continue to be a major problem for irrigation districts and overall water supplies. Irrigation engineers as far back as 1875 were attempting to assess these seepage losses (ICID 1968). The ICID (1968) reported that seepage losses can to account for up to one-third of total diverted irrigation water, and measured losses were seen as high as 60 percent (Dhillon 1967). However, seepage losses can vary significantly due to many factors that affect the rate and quantity of canal seepage. Christopher (1981) estimated that on average 25 percent of diversions were lost to seepage before reaching the fields.

The principle factors that influence seepage include 1) permeability of the soil material of the canal banks and bed (wetted perimeter), and the surrounding soils; 2) depth of water in the canal; and 3) depth of groundwater table in relation to the wetted perimeter (Akkuzu 2012, Alam and Bhutta 2004, ICID 1968, Kraatz 1977). Secondary factors are sedimentation, canal operational time and flow rate, shape of the canal’s wetted perimeter, uniformity of the soil or canal lining, and soil and water chemistry such as temperature and salinity.

Permeability, also referred to as saturated hydraulic conductivity or the steady-state infiltration rate, is a measurement of how well saturated soils convey water (Eisenhauer, Martin and Hoffman 2008). Permeability is dictated by the physical properties of soil. The soil type (referring to the grain size) influences the pore size (voids) and the percentage of pore space (porosity), and the subsequent forces that act upon the water molecules namely adhesion, cohesion (capillary), and gravity (Kraatz 1977, Eisenhauer et al. 2008). The larger the voids between soil particles, the greater amount of water will be lost to gravity (Eisenhauer et al. 2008). Coarser textured soils (e.g. sand) will have higher infiltration and permeability rates. However, given that the soil types of canals are never completely uniform and will change in time due to some of the other factors listed above, so will permeability rates. Measured canal seepage rates of various soil types from the Lower Rio Grande Valley are shown in Table 1.

Table 1. Seepage loss rates reported for soils of the Valley ($ft^3/ft^2/day$) (Bloodgood 1946)

Soil Type	Average	Range
Clay	0.20	0.09 to 0.30
Silty clay loam	0.30	
Clay loam	0.40	
Silt loam	0.60	
Loam	1.00	
Fine sandy loam	1.25	1 to 4
Sandy loam	1.50	

The depth of water in a canal can be viewed simply as a measure of energy placed on the canal’s wetted perimeter, and is often expressed as energy per unit of volume (pressure) or energy per unit of weight (head) (Eisenhauer et al. 2008). The driving forces that move water are pressure and gravity. If these forces are greater than the adhesion and cohesion forces in the soil profile, then the water will move to the lowest energy level. Therefore, as the water depth increases in the canal, seepage losses and infiltration rates will increase (Kraatz 1977, Carpenter 1898, ICID 1968).

The groundwater table and the capillary fringe zone (created by water being pulled up from the water table by capillary tension), slows the seepage water and acts as an impermeable boundary, at which point the water starts moving laterally. The closer the water table is in relation to the wetted perimeter, the less room there is for water to move down and out of the canal. Thus, the distance between the canal water level and the water table increases (called the hydraulic gradient), the rate of seepage also increases (Kraatz 1977, ICID 1968). The maximum seepage rates are reached when the distance is approximately five times greater than the surface width of the canal (Dhillon 1968). A case study in Punjab soils found that seepages rates were no longer influenced when the water table was greater than three feet from the canal bed (Dhillon 1968). When the elevation of the water table is shallow and near or even above the bed of an earthen canal, the occurrence of seepage will be greater from the canal sidewalls (Kraatz 1977, Byrnes and Webster 1981).

Factors that affect the permeability rates of canal soils throughout an irrigation season include soil saturation and expansion, entrainment of soil air, microbial activity, soil disintegration, and sedimentation. The longer the canal is in operation, the lower the rate of seepage (ICID 1968). Several processes can occur during the start up of an earthen irrigation canal. First, assuming the canal is void of water, canals with soils that contain specific levels and types of clay will reduce seepage when they become sealed from soil expansion due to saturation. Second, the amount of entrained air in a particular soil type essentially blocks water from being lost. As this soil air is dislodged, water will fill the voids and permeability rates will increase (ICID 1968, Byrnes and Webster 1981). The next two factors, microbial activity and disintegration of soil aggregates, were disputed in two separate studies as whether soil disintegration was even a factor versus the conclusion that microbial activity was only seasonal (Byrnes and Webster 1981**).** Some of these processes will reoccur if a canal is allowed to completely empty and dry out (ICID 1968). Lastly, irrigation water that carries significant amount of suspended materials such as silt will eventually settle (due to reduced flow velocity), sealing the soil pores and creating an additional soil layer, thus reducing the permeability (Davis and Wilson 1919, Kraatz 1977). The USBR (1968) asserts that silt deposition will cause seepage rates fluctuate throughout the year; reporting a 59% difference for a canal that tested at varied seasonal from 0.58 to 0.24 cfd.

Water temperature and chemistry are other minor factors that influence seepage. When water temperature rises, it becomes less viscous, allowing easier movement and increasing seepage rates (Davis and Wilson 1919, ICID 1968). Carpenter (1898) proclaims that seepage losses can be twice as great at 80°F than from 32°F.

Naturally occurring elements, specifically calcium, magnesium, and sodium, has been identified to affect the water chemistry and impacting canal seepage. Simply calcium and magnesium can increase permeability and sodium can decrease permeability of soils (Byrnes and Webster 1981). “The importance of these factors on the seepage rate is difficult and costly to assess.” (ICID 1968)

2.2. Influences of Canal Linings

Canal liners were introduced into south Texas as early as the 1930’s to prevent seepage losses and to reclaim waterlogged farmlands (Bloodgood 1946). Some other benefits of lining include greater velocities, reduced maintenance, operating cost, and erosion protection. R. G. Hemphill, Associate Irrigation Engineer with the USDA, reported on studies from the Lower Grande Valley of Texas in 1927, that seepage losses from “concrete linings depend on the density, thickness, joints, cracks, and the soil upon which it is placed” (Bloodgood 1946). In 1946, the United States Bureau of Reclamation (USBR) began an extensive canal lining testing program to evaluate the materials and installation techniques under the LCCL (Lower Cost Canal Lining) Program (Morrison and Starbuck 1984).

Studies have shown that most liners will not completely eliminate seepage losses. Seepage losses will increase through cracking and deterioration over time (Kraatz 1977, Swihart and Haynes 2002). Wachyan and Rushton (1987) stated that the “perfect lining of a canal would prevent all losses, but an examination of actual canals indicates that even with the greatest care the lining does not remain perfect.” Kraatz (1977) reports seepage rates for an assortment of concrete canals ranging from 0.03 to 1.64 cfd of wetted perimeter. Shotcrete lined canals had rates ranging from 0.89 to 1.15 cfd of wetted perimeter after 15 years of usage, reporting large cracks as cause for the latter. The USBR (1968) suggests that acceptable seepage rates for good canals might be between 0.03 to 0.10 cfd; and poorly lined canal and unlined might have rates of 0.50 cfd or greater. Other studies have suggested that seepage losses on lined canals with cracks covering up to 0.01% of the wetted area can equal or exceed unlined canals (Merkley 2007).

The effectiveness of canal liners first depends on the liner’s hydraulic conductivity (K) and/or condition, then on the permeability of the native or subsoil (underlying soil), the depth to the water table and capillary fringe zone, and if the area underneath the canal bed has access to air (Bouwer 1969, Swihart and Haynes 2002). This theory (Bouwer 1969) is modeled for natural profiles of soil hydraulic conductivity referred to as Condition C for clogged soils and semi-permeable linings (Figure 1). When the wetted perimeter of the canal becomes clogged or is artificial lined, thus lowering the K than that of the subsoil, the subsoil will most likely become unsaturated and seepage will mainly be in a downward direction (Bouwer 1969, Pavol 1982). For this to occur the position of the water table and capillary fringe zone must be well below the canal bed and that air can circulate/penetrate into the soil pores. When water seeps through the cut or hole in the canal liner, flow will be mostly due to gravity and the permeability of the subsoil. If the subsoil is a finer textured soil like clay, little water will be lost (Swihart and Haynes 2002).

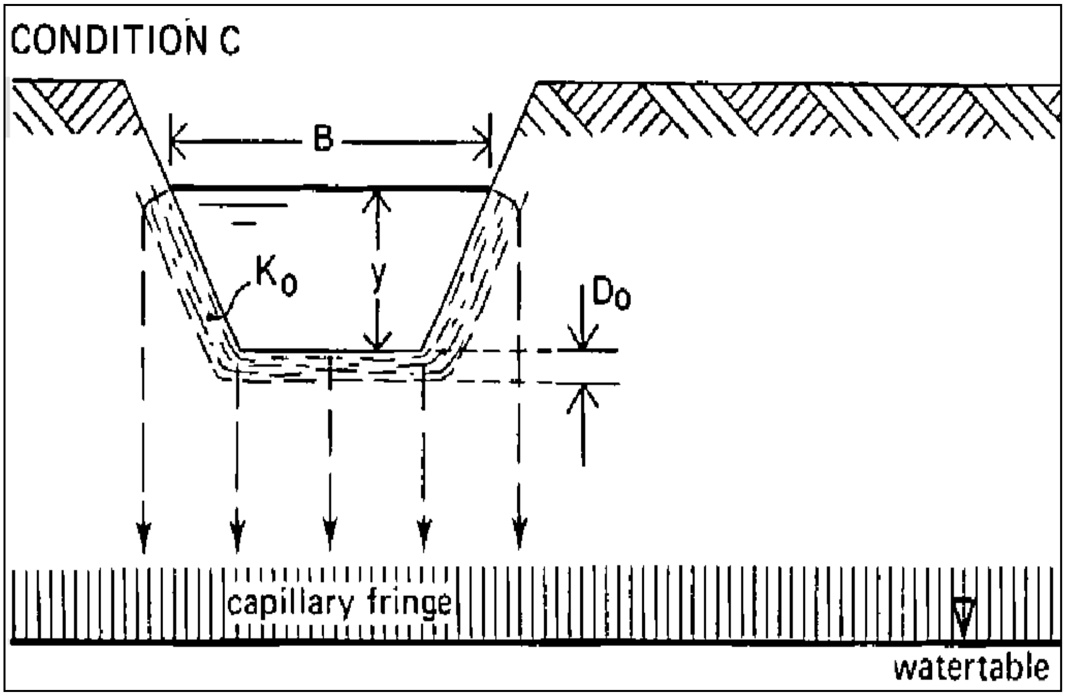


Figure 1. Diagram of Bouwer’s Theoretical Model Condition C (Bouwer 1969)

For applications of canal liner placement, lining areas of the wetted perimeter that have soil types with a low hydraulic conductivity or that become naturally clogged from sedimentation will have little loss and maybe futile (e.g. the canal bottom) (Bouwer 1969). Whereas if the water table position or impermeable layer is a short or equal distance from the canal bottom then lining the canal banks alone may be effective (Bouwer 1969).

Basic lining types used throughout the years have included both hard and soft-surfaced liners and a combination of both. Hard-surfaced liner types include masonry (stone, rock, and brick), reinforced and non-reinforced concrete and gunite (shotcrete), and asphalts (Swihart and Haynes 2002, Kraatz 1977). Soft-surfaced liners include compacted soils and Bentonite clays, plastic types also called geomembranes (e.g. PVC), fluid-applied geomembranes, and synthetic rubbers. The combination of both lining types, e.g. a geomembrane with hard surface covering, adds a protective layer for the more susceptible soft surfaced liner**.**

Hard surfaced liners introduced new advantages. Canals could be built with greater depths, and steeper side slopes and bed gradients, allowing greater velocities that would erode earth canals (Kraatz 1977). In combination with reduced roughness coefficients, canals can operate at higher flow velocities providing shorter irrigation times and limiting the chance for sedimentation (Davis and Wilson 1919, Pavol 1982). Although concrete type liners will eventually begin to crack and deform due to heat stresses and ground movement, they still will retain the sighted benefits (Pavol 1982, Swihart and Haynes 2002). Swihart and Haynes (2002) reported that concrete-type liners had a 70 percent overall (reduction) long-term water savings from pre-lining conditions, and depending on the environment could have a service life between 40 to 60 years.

O. A. Faris, Associate Irrigation Engineer with the USDA, reported in 1933 on a series of seepage loss studies on concrete and gunite lined canals in the Lower Rio Grande of Texas (Bloodgood 1946). Test details and results provided in Table 2. They conducted ponding tests and noted both the number and size of contraction cracks and designed expansion joints. The studies went as far as excavating the soil underneath the canal lining to verify leaks from expansion joints and contraction cracks. They concluded that not all cracks were actually open and leaking water, and that open cracks could be attributed to lack of reinforcement and shifting soils.

Table 2. 1933 USDA lined canal ponding test results in the Lower Rio Grande Valley of Texas (Bloodgood 1946)

Test Canal	Segment Length (ft)	Crack Count	Crack Size	Test Notes	Loss Rate (cfd)
CCWID11: 2-in reinforced concrete, no expansion joints	2510	191 transverse	0 to 1/16 inch	40 hr (silt removed)	0.146
CCWID1-Lat.26: 1 ¾-in concrete, no expansion joints	729	7 transverse per 100 ft, 1 bottom longitudinal per length	Not stated	37.5 hr	0.43
CCWID1-Lat.26: 1-in reinforced gunite, no expansion joints	1700	15 transverse per 100 feet	0 to 1/16 inch	37.5 hr	0.125
HCWC&ID6-Lat.C: 1 ¾-in reinforced concrete with expansion joints	1285	No cracks. Only transverse expansion joints	¼ inch expansion joints /12ft	42.5 hr	0.129
HWC&ID6-Lat.B5: 1 ¾-in reinforced concrete with expansion joints	1250	No cracks. Only transverse expansion joints	¼ inch expansion joints /12ft	24 hr	0.300
HCWC&ID1-Lat 4M: 1-in reinforced gunite, no expansion joints	Sta.90+20 to Sta.102 +20	33 transverse contraction cracks in reach	0 to 3/16 inch	27 hr, 1 inch silt on canal bottom	0.080

Exposed soft-surfaced liners are more susceptible to cuts and tears, animal traffic, vandalism, district maintenance equipment, and weathering i.e. UV light (Kraatz 1977, Swihart and Haynes 2002). Karimov and Leigh (2009) reported that soft-surfaced liners varied significantly based on the different materials and location of installation.

Most liners were in better condition when they were installed in areas where animal and human traffic was considered low. Swihart and Haynes (2002) reported that exposed geomembranes had a 90 percent overall (reduction) long-term water savings with a life between 20 to 30 years. The fluid-applied geomembranes were found to fail within the first five years of use.

The combination of having a soft-surfaced liner with a hard-surfaced overlay was reported as being the best lining system (Karimov et al. 2009). The soft liner maintains a water tight barrier while the hard liner protects the soft liner from damage and weathering. This lining systems water savings was estimated at 95 percent in the Swihart and Haynes study (2002), with a 40 to 60 years life expectancy.

2.3. Methods for Estimating Seepage Loss

The difficulties in determining the boundary conditions and hydraulic properties of the canal soils make calculating seepage rates complicated (Bouwer 1969). Therefore, researchers and engineers have found it necessary to develop various empirical formulas and direct measurement methods to estimate seepage losses from irrigation canals.

2.3.1. Direct Measurement Methods

The three most common direct measurement methods include the a) inflow-outflow test, b) the use of seepage meters, and c) the ponding test. These tests provide a timely and localized estimation of water loss rates that can be used in irrigation district planning and management.

The Inflow-outflow test method compares the difference of the water flowing into a canal section with water flowing out. Measurements are performed with either current meters, portable or existing measurement structures, or a combination of both. Alam and Bhutta (2004) and Warnick (1951) both concluded in their tests evaluations of the both ponding and inflow-outflow methods that the inflow-outflow method was more affected by flow measurement errors specifically when seepage losses were lower than the rated accuracy of the flow meters. These errors maybe reduced on longer test sections thus accounting for more seepage.

A seepage meter consists of a confining cylinder pushed into the side or bottom of a canal to measure the permeability rate on a small isolated location. Seepage loss estimations depend on the number of tests performed and averaged over the length and perimeter of a canal section. Disadvantages are that they are normally limited to being used in less than 2 feet of water (Brockway and Worstell 1968), and can only be used on earthen/unlined canals.

The ponding test method determines the volume of water lost over a prescribed period of time by measuring the vertical drop of water from a ponded section of canal. According to a majority of studies the ponding test is the most preferred method, having better accuracy and fewer effects from measurement errors.

Ponding test sections are separated by building temporary dams, constructed of earth or compacted earth and usually covered with plastic or canvas (Alam and Bhutta

2004, ICID 1968). Brockway and Worstell (1968) tested canals with using wooden framed bulkheads with a plastic covering. Warnick (1951) noted that canvas only dams were used on smaller canals and then added earthen dams in support for larger canals. Leigh and Fipps (2008b) had the earthen dams continually compacted by the backhoe bucket when being built; but plastic or canvas coverings were not used and was noted that some water did seep through during testing. When possible they took advantage of existing checkgate structures by building earthen dams around a closed gate structure to help support the dam and minimize leakage.

The lengths of the ponding test sections have ranged between 100 feet to 1.5 miles, but typical suggestions from literature call for smaller test sections. Alam and Bhutta (2004) tested sections of 300 meters long (approx. 984 ft), but Warnick (1951) preferred shorter sections between 300 to 500 feet. Leigh and Fipps (2009) normally tried to avoid sections that included the influence of leaking turnout gates and valves and chose to test sections no longer than 600 feet. They classified their tests into two categories “seepage loss” and “total loss” tests to distinguish water losses being attributed from either the canal lining condition only or all sources of loss.

Concerns of this test method are that the test canal will be inoperable for several days and that test does not simulate seepage during normal operational conditions (Warnick 1951, ICID 1968, Alam and Bhutta 2004). These conditions assume saturated canal banks and subsoils, and that sediments are suspended due to the flow velocities. To address these concerns, Alam and Bhutta (2004) suggests starting the tests and taking water level measurements soon after a period of normal use; while Brockway and

Worstell (1968) performs two tests after allowing the test section to be saturated at normal operating level for least 12 hours. The second tests are assumed to be closer to normal operational seepage rates.

Testing errors generally occur from canal surveys, calculation methods, and staff-gage readings. Accurately reading the staff-gages can be difficult depending on the time of day, distance away from the tester, and if stilling wells are not used to dampen water level swells in windy conditions. A misreading of 0.1 foot are common and can lead to calculation errors (USBR 1968). But all of these errors can usually be detected and reduced by employing multiple gauging stations, verifying drop rates are similar during the test, and averaging.

Evaporation losses should be considered and evaluated as a part of the overall canal losses during a ponding test. However, investigators consider evaporation rates during a 24-48 hour ponding test to be insignificant compared to the overall seepage loss rates, rarely exceeding one-half inch, and are usually ignored (Akkuzu 2012, Carpenter 1898, Leigh and Fipps 2009). However, if the seepage losses from a canal were measured to be small, evaporation maybe be a larger percentage of the overall losses and therefore more significant (ICID 1968, Warnick 1951). Evaporation rates can be obtained through several methods short of setting up evaporation pans at each test location. Local weather station networks can provide estimated pan evaporation or reference crop evapotranspiration rates. But evaporation losses from canals are normally lower depending on canal size and adjusted by factors of 0.6 to 0.8 (Leigh and Fipps 2009, Iqbal et al. 2002).

Lastly, ponding test results are calculated and reported in a number of ways. The simplest is just the change in water level per change in time i.e. in/hr, ft/day but does not take into account the represent canal geometry. Other methods include the water volume lost per unit area of wetted perimeter of canal per 24 hours (i.e. m^3/m^2/day, gal/ft^2/day), volume lost per length of canal per 24 hours (i.e. ac-ft/mile/day), volume per second per million square feet of wetted perimeter (Leigh and Fipps 2008b, Kraatz 1977). Swihart and Haynes (2002) presents loss rates as a percent of reduction when pre- and post tests are performed. Estimations are also expressed in losses by the number of days of use during the irrigation season or year.

Kraatz (1977) suggested calculating the seepage rates of the ponding tests based strictly on a 24-hour test by the following formula:

$$S = \frac{W(d_1 - d_2) \times L}{P \times L} \qquad (1)$$

where S is the average seepage in ft^3/ft^2/day; W is the average width of water surface of the ponded reach (ft); d_1 is the depth of water at the beginning of measurement (ft); d_2 is the depth of water after 24 h (ft); P is the average wetted perimeter (ft); and L is the length of canal reach (ft).

The USBR (1968) presents (Equation 2) a similar equation to that of Kraatz (Equation 1) but extends any test period of a test to a 24-hour loss rate given.

$$S = \frac{L(d_1 - d_2) \times W \times 24}{L \times P \times T} \qquad (2)$$

where S is seepage rates in ft^3/ft^2/day; W is the average width of water surface of the ponded reach (ft); d_1 is the depth of water at the beginning of measurement (ft); d_2 is the depth of water after 24 h (ft); P is the average wetted perimeter (ft); L is the length of canal reach (ft); and T is the time of run (hrs).

2.3.2. Empirical Formulas

Empirical formulas are used when direct measurement of canals is not available or practical. They are based on relationships found between water losses and the hydraulic conditions. Some formulas developed for very specific, localized conditions, and others estimate more generalized situations (i.e. unlined or lined canals); others require canal discharge/velocity or the saturated permeability of the canal soils (Kraatz 1977, Dhillon 1968).

The Davis-Wilson formula (Equation 3) (Dhillon 1967, Cordovat 1957, Davis and Wilson 1919, Kraatz 1977) relates seepage losses directly to the cube root of the water height in the canal, and considers infiltration to be equal around the wetted perimeter. This Davis-Wilson was the only formula cited for estimating seepage losses for lined canals, but also provided suggested constant values for an array of soil types (Table 3). The square root of the mean canal velocity is regarded to be inversely proportional and not significant (Cordovat 1957).

$$S=C\times\frac{WP\times L}{4\times 10^6+2000\sqrt{v}}\times H_w^{1/3} \qquad (3)$$

where S is seepage losses (ft^3 per second per length of canal); L is the length of canal (ft); WP is the wetted perimeter (ft); H_w is the mean water depth in the canal (ft); v is the velocity of flow in the canal (ft/sec); and C are the constant values depending on lining are given in Table 3.

Table 3. Suggested constant values (C) for Davis-Wilson Formula.

Values of C	Type of lining and thickness
1	Concrete (3 to 4 inches thick)
4	Clay puddle or mass clay (6 inches thick)
5	Thick new coat of crude oil or light asphalt
6	Cement plaster (1 inch thick)
8	Clay puddle (3 inches thick)
10	Cement grout or asphalt
12	Clay soil, unlined
15	Clay loam soil, unlined
20	Medium loam, unlined
25	Sandy loam, unlined
30	Coarse sandy loam, unlined
40	Fine sand, unlined
50	Medium sand, unlined
70	Coarse sand and gravel, unlined

The Molesworth-Yennidumia formula (Kraatz 1977, Dhillon 1968, Doorenbos 1963) used by the Egyptian Irrigation Department is given as:

$$S=C\times L\times WP\times\sqrt{R} \tag{4}$$

where S is conveyance losses (ft^3/sec per length of canal); L is the length of canal (ft); WP is the wetted perimeter (ft); R is the hydraulic mean depth (ft); and C is coefficients for soil type (stiff clay = 0.00271; very sandy = 0.00542).

Mowafy (2001) evaluated several empirical and analytical formulas with seepage tests performed on different sections the Ismailia Canal in Egypt. His results showed that the Molesworth-Yennidumia empirical formula (Equation 4), along with the analytical formulas, had good agreement with the test results. Salemi and Sepaskhah (2001) modified the coefficients of empirical formulas for an assortment of soil textures and vegetation densities of small earth canals compared with measured seepage rates using the inflow-outflow method in the north area of Isfahan Province, Iran. They found that the coefficients needed to be increased about 8 times to properly estimate seepage losses, and concluded that the modified Davis-Wilson and Molesworth-Yennidumia formulas were the best two formulas for the study area.

The Moritz formula (USBR 1967, Kraatz 1977) was proposed by the USBR for estimating seepage losses per mile of unlined canal is given as:

$$S=0.2\times C\times\sqrt{Q/V} \qquad (5)$$

where S is seepage losses (ft^3/sec/mi); Q is the discharge (ft^3/sec); V is the velocity of flow in the canal (ft/sec); and C are the constant values depending on soil type are given in Table 4.

Table 4. Constant values (C) for Moritz Formula

Soil type	Values of C
Cemented gravel and hard pan with sandy loam	0.34
Clay and Clayey Loam	0.41
Sandy Loam	0.66
Sandy soil with rock	1.68
Sandy and gravelly soil	2.20

Akkuzu (2012) evaluated both the Moritz (Equation 5) and David-Wilson (Equation 4) equations and compared to inflow-outflow tests on lined canals. Akkuzu found that the seepage loss estimations by both formulas were significantly below the tested values and concluded that this was due to the poor conditions of the concrete canals. Akkuza used a metric version of the Moritz equation, using a constant value (C) of 0.1 for concrete lined canals.

The Muskat formula was derived by for canals with homogeneous, isotropic soils and deep water tables (Robinson and Rohwer 1959):

$$q=\frac{K(B+2H)}{WP} \tag{6}$$

where q is seepage rate (ft^3/ft^2/day); K is permeability (ft/day); B is the width of water surface (ft); H is the depth of water (ft); and WP is the wetted perimeter (ft).

The USBR evaluated Muskat's formula in conjunction with seepage loss tests performed on earth canals in Wyoming and Nebraska. They found it to be unreliable in predicting seepage rates due to the fact that the canal soils were primarily heterogeneous and anisotropic (Robinson and Rohwer 1959).

CHAPTER III

STUDY AREA

The Lower Rio Grande Valley (The Valley) is a four county area at the southern portion of Texas which includes Cameron County, Hidalgo County, Starr County, and Willacy County (Figure 2). The area first developed due to increased irrigation and agricultural production. In recent years, the area has under gone significant urban growth causing considerable fragmentation of the agricultural lands. The most populated county, Hidalgo County, has had the highest percent increase in urban area of 35% (Leigh, Barroso Jr. and Fipps 2009).

The approximately 700,000 acres of agricultural lands relies on the Rio Grande River and the 28 irrigation districts for water (Fipps 2005). The total combined irrigation delivery and distribution networks of the Valley consists of over 1400 miles of main and secondary lined and unlined canals, almost 2000 miles of underground pipeline, 76 miles of resacas, and 33 storage reservoirs with a volume totalling 61,501 acre-feet (Fipps 2005). Fipps (2005) estimated the conveyance efficiency of the districts at an average of 69.7%. The networks are mostly gravity-flow, pumped from the Rio Grande River into perched canals (Figure 3). Drainage ditches often flank both sides of the canal levees. Due to the elevation of the lined canals, the groundwater table has been recorded up to approximately ten feet from the bottom of the canal bed (Figure 4). The majority of the irrigation networks and control structures are manually operated by sluice gates, valve gates, and wooden turnout valves to serve the farmlands.

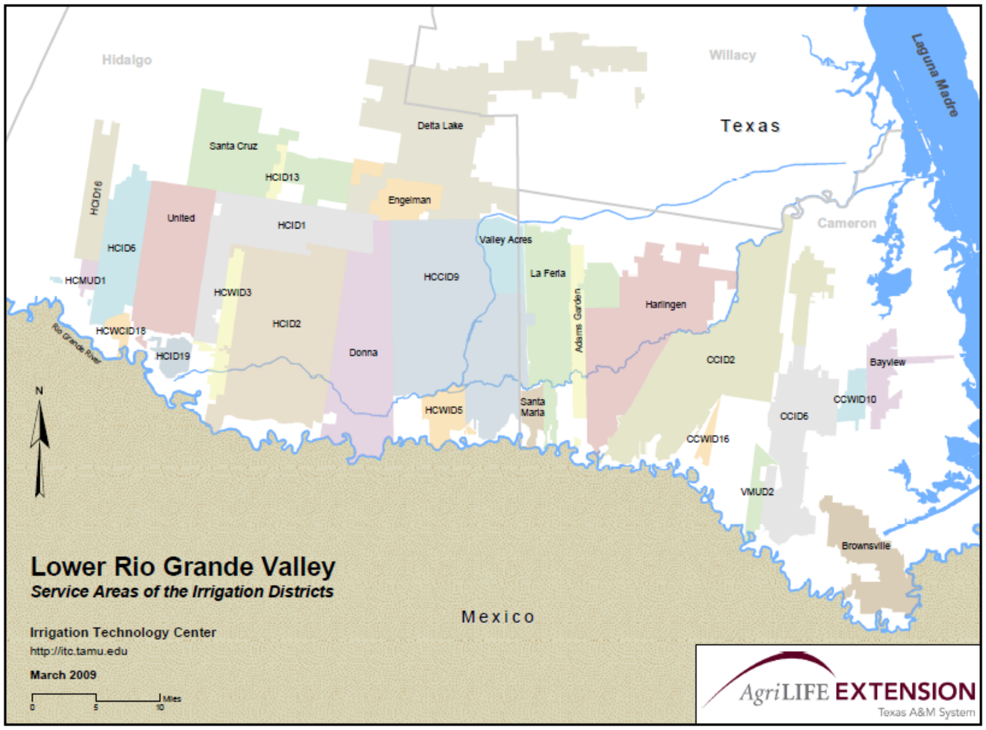
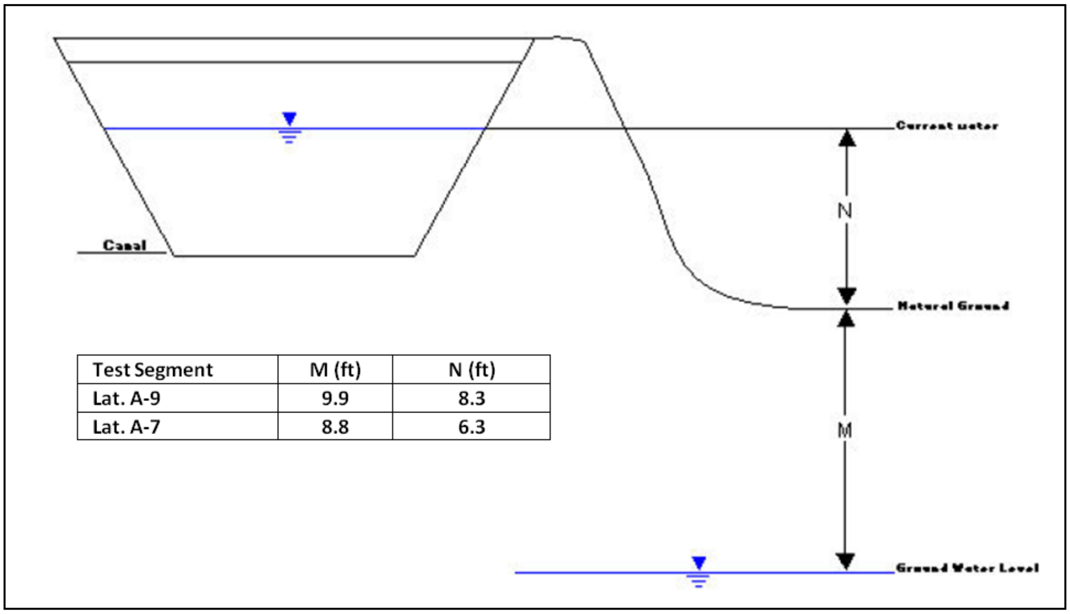


Figure 2. Service areas of the irrigation districts of the Valley (Leigh 2009)

The irrigation season stretches almost all year around due to the growing season averaging 333 days/year (Collins, Lacewell and Norman 1979). Irrigation scheduling is generally based on a first-come, first-serve policy, and only an estimated 57% (Fipps 2005) of farm deliveries are metered. The major of farms of the Valley were allotted two acre-feet per acre based on historical uses by the districts. Farms that are not metered use an estimation of water use at six inches per acre, allowing for two inches from transportation losses, totaling 2 acre-feet through three irrigations (Stubbs et al. 2005).

Figure 3. Raised concrete lined canal with supporting levees.



Test Segment	M (ft)	N (ft)
Lat. A-9	9.9	8.3
Lat. A-7	8.8	6.3

Figure 4. Groundwater measurements of Lateral A of HCID2 (Leigh and Fipps 2006).

CHAPTER IV

STUDY INFERENCES

As discussed in the literature review, there are many factors that affect to the seepage losses in canals. The water-loss tests and canal condition evaluations will naturally have errors and influences that sway test results and analysis to varying degrees. These can include naturally occurring factors, human and testing errors, and other differences from site specific attributes. Some are more easily accounted or estimated for than others, and will differ due to seasonal and climate variations, as well as change according to level of district operations and maintenance programs. Based on literature and knowledge of the study area the following inferences have been made:

a) Perched lined canals with groundwater levels significantly below the canal bed have minimal to no effect on seepage losses. According to Bouwer's Condition C theory on artificial lined canals, as the subsoil is unsaturated, seepage is caused mostly by gravity provided that the groundwater is considerably below the canal bed. Subsoil types will then vary seepage rates. Lined canals in the Valley are normally constructed on top of levees. The groundwater table was measured at ten feet below the canal bed on Lateral-A of Hidalgo County Irrigation District No.2., and is assumed similar for the other lined canals in the study.

b) Zero velocity during ponding tests has little to no effect on seepage rates. Additional sediment fall out will be negligible compared to the current levels of sedimentation, as irrigation districts infrequently clean silt from canals. The velocity factor in the Davis-Wilson empirical formula is inversely proportional and not significant (Cordovat 1957).

c) Permeability rates of the sub-soils of both the test canals and levees will have more influence on seepage rates as the canal liner becomes more and more deteriorated. Most canals are adjacent to drainage ditches. Here the presumption is that the soils used to build the canals were excavated from these drainage ditches and the surrounding areas. Soil types will of course vary from test to test but will also vary within each test section. The permeability rates and the soils types that would have originally been found at the test canal locations is given in Table 5 (Jacobs 1981, Williams, Thompson and Jacobs 1977).

d) Larger canals and/or mains would normally be used more throughout the year and therefore more consistently kept full. Smaller canals are more typically used in monthly cycles during the irrigation season and thus often low or empty between uses. This will affect bank storage and therefore affect seepage loss fluctuations differently.

Table 5. Soil types of test canals of Cameron and Hidalgo County, Texas.

Soil Type	Permeability Rate Range (in/hr)	
	Low	High
Hidalgo fine sandy loam	0.6	2
Hidalgo sandy clay loam	0.6	2
McAllen fine sandy loam	0.6	2
Brennan fine sandy loam	0.6	6
Raymondville clay loam	0.06	0.6
Reynosa silty clay loam	0.6	2
Runn silty clay loam	0.06	0.6
Harlingen clay	0.001	0.06
Racombes sandy clay loam	0.63	2
Willacy fine sandy loam	2	6.3
Cameron silty clay	0.2	6

CHAPTER V

MATERIALS AND METHODOLOGIES

5.1. Ponding Tests Analyses

The original seepage-loss test calculations and rates by the Texas AgriLife Extension team were evaluated and revised for errors in methodology and continuity. The new calculations were based on Equation 7, which uses the average wetted perimeter for determining seepage losses per wetted foot of canal bed. Seepage-loss rates were modeled and adjusted to 24-hour rates. Additional, relationships between the canal geometric properties and the revised seepage loss rates were assessed.

$$S=\frac{W(d_1-d_2)\times L}{P\times L} \tag{7}$$

where S is seepage rates in $ft^3/ft^2/day$; W is the average width of water surface of the ponded reach (ft); d_1 is the depth of water at the beginning of measurement (ft); d_2 is the depth of water after 24 h (ft); P is the average wetted perimeter (ft); L is the length of canal reach (ft); and T is the time of run (hrs).

5.1.1. Original Test Procedures and Results

The Texas AgriLife Extension (formally known as Texas Cooperative Extension) performed over 30 ponding tests on hard surfaced lined canals. Ponding test results and basic canal dimensions tested between 1998 and 2003 are provided in Table 6 and 7. The tests were classified into two categories “seepage loss” and “total loss” tests to distinguish water losses being attributed from either the canal lining condition only or all sources of loss.

Table 6. Results of seepage type ponding tests on hard lined canals conducted by Texas Cooperative Extension in the Lower Rio Grande River Basin (Leigh and Fipps 2006).

Test ID	Year	Canal Width (ft)	Canal Depth (ft)	Class	Loss Rate	
					gal/ft^2/day	ac-ft/mi/yr
16HC2	03	12	4	M	1.41	121.3
DO1	03	5	3	S	1.68	65.2
LF1	03	12	5	M	1.77	152.9
LF2	03	10	6	M	4.61	369.1
MA4	03	12	5	S	8.85	529.7
SJ4	00	15	4	M	1.17	111.2
SJ5	02	14	5	M	1.38	145.5
UN1	01	12	6	M	2.32	217.7
UN2	01	8	3	M	2.09	121.2
Classification of canal: M = main, S = secondary						

The procedures used to perform the ponding tests between 1998 and 2005 have evolved as far as the use of technology and canal lengths. Survey-grade GPS equipment was employed in place of the measuring tapes and level transits to measure canal dimensions. Larger and more visible staff gages were used, and the often problem riddled pressure transducers and shaft encoders were relied on less to measure water levels. Test segments were sometimes shortened to avoid any influences of leaking values and gates.

Table 7. Results of total loss type ponding tests on hard lined canals conducted by Texas Cooperative Extension in the Lower Rio Grande River Basin (Leigh and Fipps 2006).

Test ID	Year	Canal Width (ft)	Canal Depth (ft)	Class	Loss Rate	
					gal/ft^2/day	ac-ft/mi/yr
16HC1	03	14	5	M	1.89	192.4
BV1	99	10	5	M	7.97	510.5
BV2	99	9	4	M	8.53	451.5
DL1	00	20	6	M	0.16	18.8
DL2	00	7	4	S	4.12	236.2
DO2	03	6	4	S	2.18	121.5
DO3	03	6	3	S	2.71	107.2
ED1	00	6	4	S	34.32	1519.6
ED2	00	6	4	S	21.5	858.2
ED3	00	3	2	T	10.22	308.2
ED4	00	4	3	S	18.72	567.7
ED6	99	9	4	M	8.53	451.5
HA2	00	10	4	M	2.26	135.2
HA1	00	15	4	S	0.64	45.5
ME1	98	38	7	M	1.26	281.9
ME2	98	-	4	M	1.88	163.5
SJ1	99	12	5	M	2.58	126.8
SJ6	03	12	3	M	1.88	163.0
SJ7	03	19	4	M	1.98	227.1
UN3	02	12	6	M	2.02	154.3
Classification of canal: M = main, S = secondary, T = tertiary						

Earthen dams were constructed to seal off the test segments. District backhoe operators would use the backhoe bucket to compact earthen dam to throughout the build (Figure 5). Plastic or canvas coverings were not used and water infiltration into the dam would be considered as an error in the test results. The dams were built in one of the three following procedures:

- The downstream dam was constructed when the canal was partial full. Next, the canal was brought to normal operating level, and then upstream dam was constructed.

- The downstream and upstream dams were constructed in full canal.
- The downstream and upstream dams were constructed in a partial full canal, then pumps were used to fill test segment (Figure 5).

Figure 5. Earthen dam being built by backhoe (Leigh and Fipps 2008c)

During the construction of the earthen dams, two or more staff gages were setup throughout the test segment equally spaced (Figure 6). Then the cross-sections of the canal were surveyed for each staff gage location (Figure 7). Once the water level in the canal reached the desired testing stage (usually close to normal operational level), water levels were recorded at each staff gage and taken for 24 to 48 hours, at varying hourly intervals. Example field data is shown in Table 8.

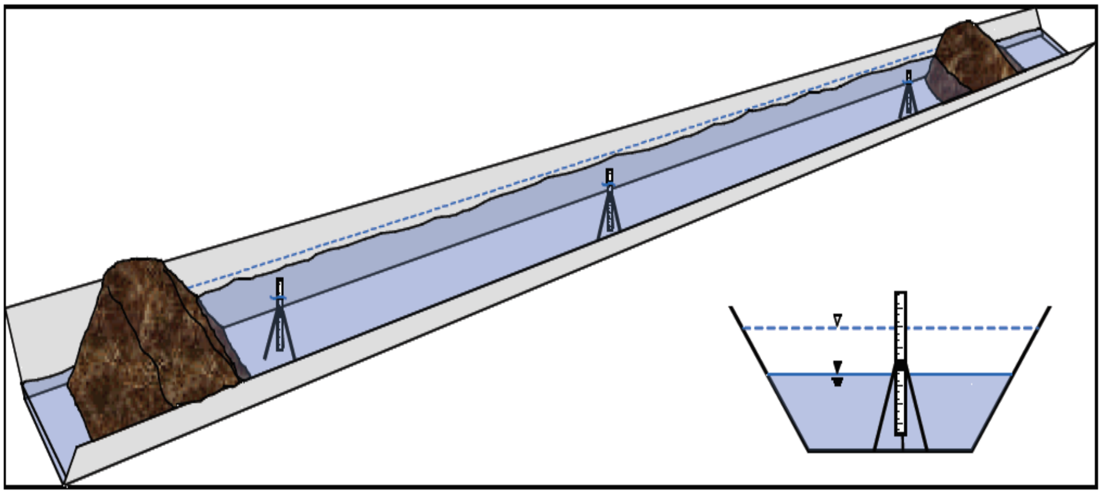


Figure 6. Ponding test depiction (Leigh and Fipps 2009)

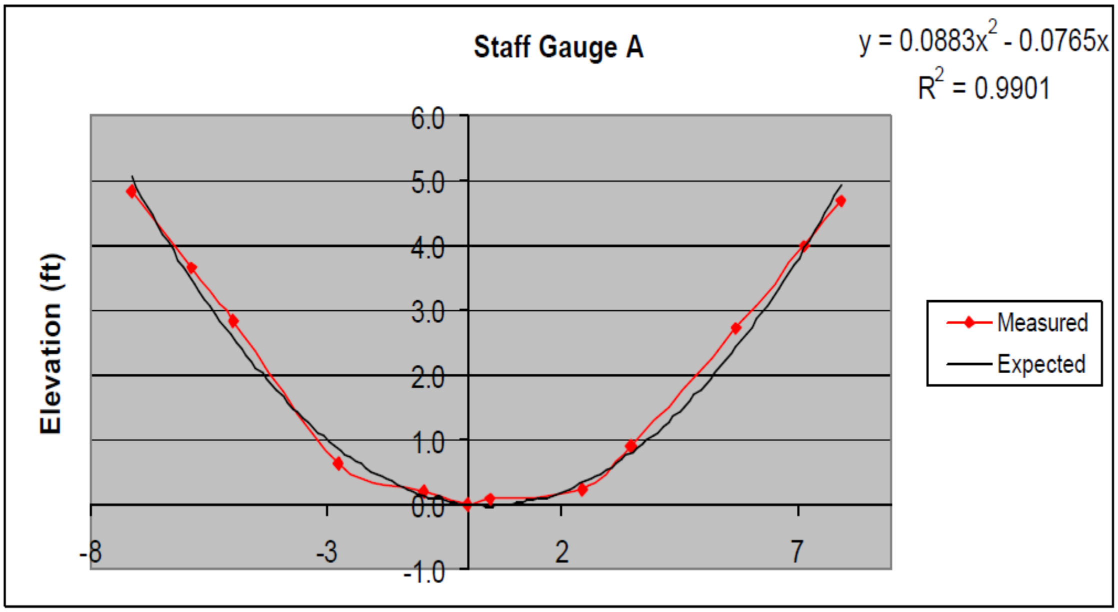


Figure 7. Cross-section of staff gage A of ponding test 16HC1 (Leigh and Fipps 2008a)

Table 8. Field test data for ponding test 16HC1 (Leigh and Fipps 2008a)

District: Hidalgo County Irrigation District No. 16				Test ID: 16HC1		
Canal: Main Canal B				Lining Type: Lined		
Starting Water Span Widths (feet): A: 12.8, B: 12.54, C: 13.1, D: 13.8, E: 12.7, F:14.0				Date: July 18-20, 2003		
Test Segment Length: 3700 feet				Start Time: 3:31 pm Finish Time: 4:07pm		
Test Starting Depths (feet): A: 3.75 , B: 3.94, C: 4.18, D: 4.45, E: 4.43, F: 4.73						
Location: At the start of Main Canal B and stops at the next downstream check structure.						
Staff Gage Readings						
Date	A		B		C	
	Time	Feet	Time	Feet	Time	Feet
Jul 18	15:31	4.73	15:34	2.41	15:35	4.95
	16:26	4.72	16:28	2.38	16:30	4.94
	17:24	4.68	17:25	2.36	17:26	4.91
Jul 19	11:45	4.39	11:47	2.06	11:48	4.62
	17:50	4.3	17:51	1.98	17:52	4.55
Jul 20	13:43	4.08	13:46	1.75	13:48	4.31
	16:08	4.05	16:07	1.72	16:06	4.28
True depth adjustment factor (ft)		-0.98		1.53		-0.77

5.1.2. Original Test Calculations

The cross-sectional area of loss and the starting canal wetted perimeter were both multiplied by 1 linear foot of the canal length to give a volume of loss and a starting wetted area respectively in Equations 8 and 9 (given below). Seepage loss rates were determined by dividing the volume of water lost by the starting wetted area and the total test run time (days) shown in Equation 10. Units are given in cubic feet per square foot per day ($ft^3/ft^2/day$).

$$V=A_{Loss}\cdot 1L \qquad (8)$$

where A_{Loss} is the cross-sectional area of loss (ft^2); L is the length of the canal (ft); and V is the volume of water loss (ft^3).

$$WA_s = WP_s \cdot 1L \tag{9}$$

where WP_s is the starting wetted perimeter (ft); and WA_s is the starting wetted area (ft^2).

$$S = \left(\frac{V}{WA_s}\right) \div T \tag{10}$$

where T is the test run time (days); and S is the seepage loss rate (ft^3/ft^2/day).

Canal dimensions and geometric properties (i.e. cross-sectional area and wetted perimeter) were modeled by either a 2nd order polynomial trend-line or into a simplified trapezoidal shape. Computational procedures are given in the following sections.

5.1.2.1. Trapezoidal Computational Method

The starting and ending cross-sectional areas for trapezoidal test canals were determined by Equation 11.

$$A = b \cdot d + Z \cdot d^2 \tag{11}$$

where A is the canal cross-sectional area (ft^2); b is the bottom width of canal (ft); d is the depth of water (ft); and Z is the side wall ratio (horizontal to vertical). The starting and ending cross-sectional areas were subtracted from each other (Equation 12).

$$A_{Loss} = A_s - A_e \tag{12}$$

where A_s is the starting cross-sectional area (ft^2); and A_e is the ending cross-sectional area (ft^2).

The starting trapezoidal wetted perimeter was calculated with the following equation:

$$WP_s=b+2d\sqrt{Z^2+1} \tag{13}$$

5.1.2.2. Polynomial Computational Method

Each canal top width was determined by solving for *x* in the 2nd order polynomial (Equation 14) using the Quadratic formula (Equation 15). The x values added together represent the top width at the water line (Equation 16). The area of loss was calculated by averaging the canal top widths at the beginning and ending of the test measurement periods, and then multiplied by the change in depth (Equation 17).

$$c=a\cdot x^2-b\cdot x \tag{14}$$

$$\pm x=\frac{-b\pm\sqrt{b^2-4a\cdot c}}{2a} \tag{15}$$

$$t=x_1+\left|-x_2\right| \tag{16}$$

$$A_{Loss}=\left(\frac{t_1\cdot t_2}{2}\right)\cdot h \tag{17}$$

where c is the recorded water depth (ft); x_1 and x_2 are the left and right distance from the canal center (ft); h is the change is water depth (d_1-d_2) (ft); and t is the canal top width at the water level (ft).

The wetted perimeter was estimated using equation 18, for parabolic shaped channels.

$$WP_s = t + \frac{8d^2}{3t} \tag{18}$$

5.1.3. *Revised Test Calculations*

Revisions to the all test calculations have included the following. The wetted perimeters of the starting and next selected measurement period were first averaged (Equation 19). Then WP_{Av} was used in calculating the average wetted area (Equation 20) and new seepage loss rate (Equation 21):

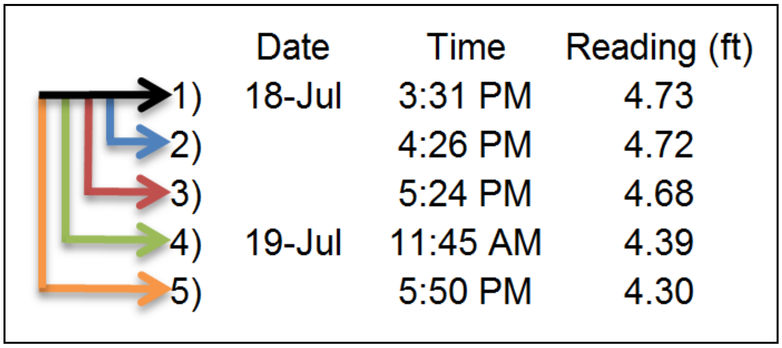
$$WP_{Av} = \frac{WP_s + WP_n}{2} \tag{19}$$

$$WA_{Av} = WP_{Av} \cdot 1L \tag{20}$$

$$S = \left(\frac{V}{WA_{Av}}\right) \div \boldsymbol{T} \tag{21}$$

where WP_n is the wetted perimeter of selected measurement (ft); WA_{Av} is the average wetted perimeter (ft); and WA_{Av} is the average wetted area (ft^2).

Loss rates are determined for each measurement period between the start of the test to each subsequent measurement as illustrated in Figure 8. The loss rates calculated for each measurement period for Test 16HC1 are given in Table 9. For each test this loss rate data was graphed as a time series and modeled with the power function in Excel.



	Date	Time	Reading (ft)
1)	18-Jul	3:31 PM	4.73
2)		4:26 PM	4.72
3)		5:24 PM	4.68
4)	19-Jul	11:45 AM	4.39
5)		5:50 PM	4.30

Figure 8. Calculation measurement periods for test 16HC1.

Table 9. Measurement Period Loss Rates for Test 16HC1.

Time (days)	Loss Rate (cfd)
0.08	0.446
0.84	0.315
1.09	0.305
1.93	0.269
2.02	0.268

5.1.4. Error Analyses

5.1.4.1. Valve Leak

Leaks from valves and gates are not always easy to be verified and even more difficult to be measured (Leigh and Fipps 2006). Hence, only one valve leak was ever measured for all the ponding tests reported by Leigh and Fipps (2008a). The loss rate measured at the beginning of the test was assumed as the approximate loss rate which would occur under normal canal operations. This leak loss rate of 22.41 (ft^3/day) was divided by the total volume lost per day of the tested canal (19,254 ft^3/day) to determine leak percentage. For comparing the leakage loss rate to the seepage loss rate (cfd), the leak loss rate was divided by the tested canal wetted area (63,649 ft^2).

5.1.4.2. Evaporation

Daily historical reference crop evapotranspiration (ETo) rates from the Texas AgriLife Research Weslaco Annex Farm weather station reported on the Texas ET Network website of the Irrigation Technology Program (texaset.tamu.edu) were used to determine yearly ETo averages and approximate evaporation losses for each test canal. Monthly historical rates are also reported on to evaluate the variance that occurs throughout the year.

In determining evaporation losses for individual ponding tests, the daily ETo averages of the first two days of a testing period were averaged and assumed as the average ETo rate. Then the average ETo rates were adjusted by factors 0.6 and 0.8 as evaporation of losses in canals are lower.

The ETo rates in ft/day were converted to cfd to allow for comparison with the seepage loss rates. Each ETo rate was multiplied by the canal top width (ft) at the starting test water level and by 1 linear foot of the canal length to give a volume of loss (ft^3/day). This volume was then divided by the starting canal wetted perimeter (ft) over 1 foot length of canal or wetted area (ft^2) (see Equations 8 – 10).

5.1.4.3. Dam Infiltration

The evaluation of the seepage loss through an earthen dam was determined by examining a series of ponding tests performed on a canal that was tested before and again after it was relined with a geomembrane and hard surface covering.

First, to evaluate the scale of the potential influence in accordance to the total wetted test area, the percent of wetted area that the dams occupy during a ponding test was determined. The percent of dam wetted area was also calculated for all the ponding tests. The wetted area of the earthen dams was approximated by doubling the average wetted cross-sectional area of the canal from the start of the test (Equations 22–24).

$$\mathrm{WA_{dam}}=\mathrm{A_s}\cdot 2 \tag{22}$$

$$\mathrm{WA_{test}}=\mathrm{A_s}\cdot 2+\mathrm{P_s}\cdot \mathrm{L} \tag{23}$$

$$\%\ \mathrm{of\ WA_{dam}}=\frac{\mathrm{A_s}\cdot 2}{\mathrm{A_s}\cdot 2+\mathrm{WP_s}\cdot \mathrm{L}} \tag{24}$$

where A_s is the starting cross-sectional area (ft^2); WP_s is the starting wetted perimeter (ft); WA_{dam} is the dam wetted area (ft^2); and WA_{test} is the test wetted area (ft^2).

Last, the seepage rates were compared directly after assuring that the canal geometric properties (i.e. cross-sectional area and wetted perimeter) were comparable. Last, the ETo rates for both tests were estimated in the same method as the previous section. The test water loss rates were compared after subtracting the ETo rates (including the adjustment factors 0.6 and 0.8).

5.1.5. Trend Analysis: Canal Geometry vs. Seepage Rates

The relationships between the canal geometric properties and the revised seepage loss rates were evaluated using regression analysis using the Microsoft Excel software program. Linear and non-linear trend-lines were assessed and R^2 value was determined for the following geometric properties:

- Wetted perimeter (ft^2) vs. Seepage loss rates (cfd)
- Cross-sectional Area (ft^2) vs. Seepage loss rates (cfd)
- Depth of water (ft) vs. Seepage loss rates (cfd)

5.2. Empirical Formula Evaluation

5.2.1. Prediction

The Davis-Wilson formula (Equation 25) was first evaluated by setting the equation variables to the beginning test dimensions of each ponding test and solving for S. There is no flow velocity during a ponding test so v = 0. The C value was set to 1 for concrete canal lining with 3 to 4 inches of thickness. The seepage loss results were converted to ft^3/ft^2/day. The Davis-Wilson empirical formula is written as:

$$S = C\times\frac{WP\times L}{4\times10^6+2000\sqrt{v}}\times H_w^{1/3} \tag{25}$$

where S is seepage losses (ft^3 per second per length of canal); WP is the wetted perimeter (ft); H_w is the mean water depth in the canal (ft); v is the velocity of flow in the canal (ft/sec); and C equals 1 for concrete lining 3 or 4 inches thick.

5.2.2. Calibration

New coefficients (*C* Value) were derived for the Davis-Wilson empirical formula for each ponding tested canal. The Davis-Wilson formula was solved for *C* (Equation 26). The revised seepage loss rates were set for *S*, and the beginning test dimensions again were used for the other equation variables. This same process was used for evaluating the revised seepage loss rates adjusted for evaporation rates (test average, and 0.6 and 0.8 adjusted ETo rates).

$$C = S\times\frac{4\times10^{6}+2000\sqrt{v}}{WP\times L}\times\frac{1}{H_{w}^{1/3}} \tag{26}$$

5.3. Canal Condition Rating Systems

5.3.1. Original Rating System

In assessing seepage losses for the Rio Grande Planning Region (Region M), Fipps (2000a) developed a canal condition rating system to evaluate the lining of hard-surfaced liners based on size and frequency of cracks and breaks, and also accounts notes the density of vegetation growing in and around the canal embankment. Both canal condition and vegetation will vary depending on the level of district maintenance, plant type and season. The rating categories included general condition, crack sizing, crack frequency, and the density of vegetation in the canal and embankment (Table 10).

Table 10. Rating system categories for lined canals (Fipps 2000a)

Rating Score	Rating Category and Description			
	Lining Condition	Crack Size	Crack Frequency	Veg. in canal and levee
1	Excellent	A few hairline crack	Sparse	Normal rain-fed
2	Good	Hairline to pencil	Greater than 10’	Above average
3	Fair	Predominately pencil-size	5’ to 10’ apart	Moderate
4	Poor	Pencil-size & a few large cracks	3’ to 5’ apart	Dense
5	Serious problems	Predominately large cracks	Less than 3’ apart	Dense and lush

The rating system provides an approximation of the size and quantity of cracks throughout a canal’s wetted area. In most cases, canals rated were a half to a quarter full of water, making the rating assessments only for the canal sidewalls. Crack orientation (e.g. running transversely or longitudinally) and length are not explicitly defined. The Crack Frequency category descriptions are more of the overall average crack coverage of a canal lining than actually counting and measuring cracks. This rating system assumes a linear relationship between the categories and the scores in each category. The initial ratings were based on a 4 to 20 scale then converted to a 1 (serious problems) to 10 (excellent) scale. Fipps (2000b) presented the data on 15 canal segments which had an R-square value of 0.6 based on the seepage loss rates and the overall condition ratings of concrete lined canals (Figure 9).

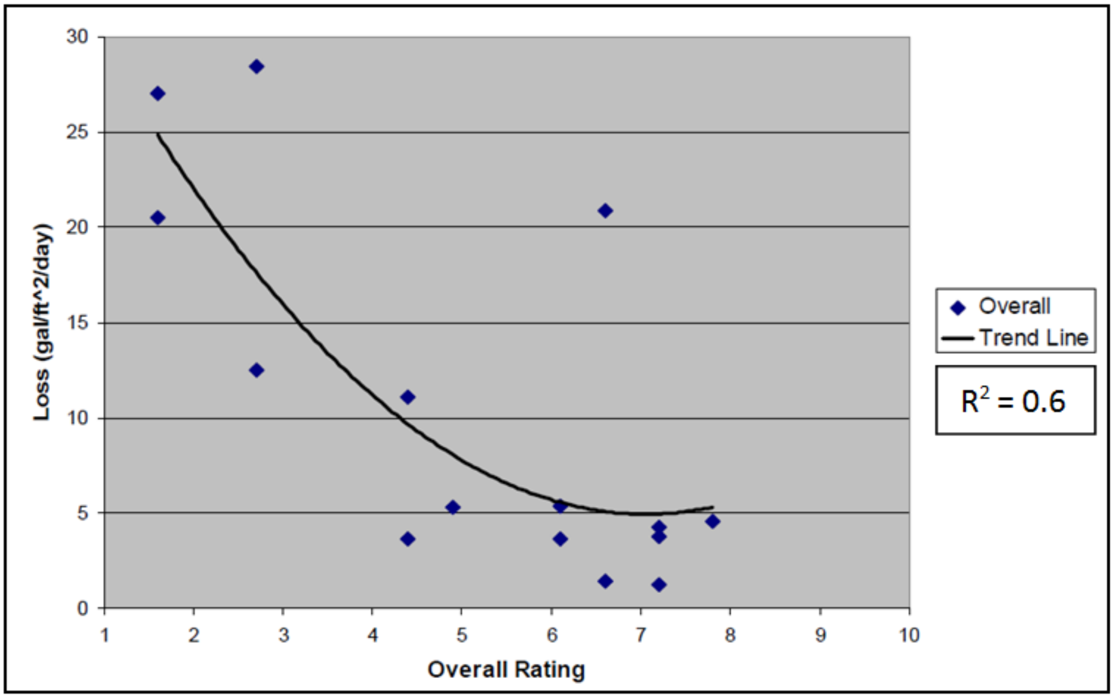


Figure 9. Seepage loss rate versus overall condition ratings (Fipps 2000b)

5.3.2. Simplified Rating System

Presented here is a new lined condition rating system. This system provides a more simplified process for categorizing lined canals at varying levels of potentially water loss based on the lining condition. First, the number of condition rating categories are reduced, only evaluating the crack size and frequency categories. This helps eliminate influences of seasonal vegetation variations and rating subjectivity from the vegetation and general condition rating categories, respectively. Second, the rating descriptions and the scores for the rating categories are condensed from a five scale system to a three scale system. The adjustments made from the rating categories in the descriptions and scores are given in Tables 11 and 12. The approximate ranges for each crack size description are as follows:

- Hairline: 0 to $^1/_{16}$ inch;
- Pencil: $^1/_{16}$ to ½ inch;
- Large: > ½ inch.

Table 11. Crack size rating adjustment scale.

Original		Adjusted	
Crack Size Descriptions	Score	Score	Crack Size Descriptions
a few hairline cracks	1	1	hairline to pencil size
hairline to pencil size	2		
predominately pencil size	3	2	pencil size and/or a few large cracks
pencil size and a few large cracks	4		
predominately large cracks	5	3	predominately large cracks

Table 12. Crack frequency rating adjustment scale.

Original		Adjusted	
Frequency Descriptions	Score	Score	Frequency Descriptions
Sparse	1	1	greater than 10' apart
greater than 10' apart	2		
5' to 10' apart	3	2	5' to 10' apart
3' to 5 ‘ apart	4	3	less than 5' apart
less than 3' apart	5		

The categorical scores for a rated canal section are then added together for total scores of 2, 3, 4, 5, and 6 (Table 13). Larger cracks and a higher frequency of cracks are perceived to increase the water loss rates. Hairline to pencil size cracks greater than 10 feet apart have the best total score of a 2, and predominately large cracks less than 5 feet apart has the worst total score of 6. The final scores are to represent the average condition for a stretch of canal.

Table 13. Condition category combinations and rating scores.

Crack Frequency	Score	Crack Size	Score	Rating
greater than 10' apart	1	hairline to pencil size	1	2
greater than 10' apart	1	pencil size and a few large cracks	2	3
greater than 10' apart	1	predominately large cracks	3	4
5' to 10' apart	2	hairline to pencil size	1	3
5' to 10' apart	2	pencil size and a few large cracks	2	4
5' to 10' apart	2	predominately large cracks	3	5
less than 5' apart	3	hairline to pencil size	1	4
less than 5' apart	3	pencil size and a few large cracks	2	5
less than 5' apart	3	predominately large cracks	3	6

Lastly, the total scores are sorted from least to greatest are consolidated into a 1 to 3 scale ranking system shown in Table 14. The scores of 2 and 3 are ranked a 1; the score of a 4 are ranked a 2; and the scores of 5 and 6 are ranked a 3.

Table 14. Condition category combinations and ranking scores.

Crack Frequency	Crack Size	Rating	Ranking
greater than 10' apart	hairline to pencil size	2	1
greater than 10' apart	pencil size and a few large cracks	3	
5' to 10' apart	hairline to pencil size	3	
greater than 10' apart	predominately large cracks	4	2
5' to 10' apart	pencil size and a few large cracks	4	
less than 5' apart	hairline to pencil size	4	
5' to 10' apart	predominately large cracks	5	3
less than 5' apart	pencil size and a few large cracks	5	
less than 5' apart	predominately large cracks	6	

5.3.3. Condition Rating Analysis and Davis-Wilson Correlation

The old condition rating scores of the tested canals were converted to the new condition rating system. The relationships between the rating/ranking scores and the revised seepage loss rates were evaluated using regression analysis (R^2 value) using the Microsoft Excel software program. The condition rating/ranking scores and the derived Davis-Wilson C-values (coefficients) for each ponding tests were graphed and evaluated using regression analysis. The minimum and maximum C-values and test loss rates were assumed to be the correlation range for each condition ranking score.

In addition, the six seepage loss tests performed by the USDA in 1933 in the Valley (Table 15) were rated according to the new condition rating system and analyzed in conjunction with the Texas AgriLife Extension tests. The seepage loss rates with test times above 30 hours were adjusted (increased) to represent a 24hr test rate based on similar power functions from Extension tests.

Table 15. 1933 USDA lined canal test details used for analysis (Bloodgood 1946)

Test Canal	Segment Length (ft)	Crack Count	Crack Size	Time (hr)	Loss Rate (cfd)
CCWID11	2510	191 transverse	0 - 1/16 in	40	0.146
CCWID1-Lat.26-1¾	729	7 transverse/100 ft. & 1 bottom long./length	Not stated	37.5	0.430
CCWID1-Lat.26-1	1700	15 transverse per 100 ft	0 - 1/16 in	37.5	0.125
HCWC&ID6-Lat.C	1285	Expansion joints /12 ft	¼ in	42.5	0.129
HWC&ID6-Lat.B5	1250	Expansion joints /12 ft	¼ in	24	0.300
HCWC&ID1-Lat 4M	Unknown	33 transverse	0 - 3/16 in	27	0.080

Segment length and crack count for each test was used to estimate the crack frequency category for each of the following tests:

- Test CCWID11: Segment length (2510) was divided by number of transverse cracks (191) equals 13 ft/crack.

- Test CCWID1-Lat.26-1¾: Segment length (729) multiplied by the number of cracks/distance (7/100) = 51 cracks. Segment length (729) divided by number of cracks (51) equals 14.3 ft/crack. The bottom longitudinal crack was assumed to be the same as transverse cracks spaced ever 7 feet (729/7 = 104), making the total number of cracks 155 at a spacing of 4.7 ft/crack. The crack sizes were not stated but the hairline to pencil size range was assumed.

- Test CCWID1-Lat.26-1: Segment length (1700) was multiplied by the number of cracks/distance (15/100) = 255 cracks. Then the segment length (1700) was divided by number of cracks (255) equals 7 ft/crack.

- Tests HCWC&ID6-Lat.C and HWC&ID6-Lat.B5: both had stated that only expansion joints were present at a spacing of 12 ft.

- Test HCWC&ID1-Lat 4M: Only 33 transverse cracks were stated. The segment length was given in terms of station references, and so length was considered unknown. The canal test segment was assumed to be length of at least 600 ft, with spacing at approximately 10 ft.

CHAPTER VI

RESULTS AND DISCUSSION

6.1. Revised Ponding Test and Error Analyses

6.1.1. Revised Seepage Loss Rates

Of the 32 ponding tests evaluated, 29 were first recalculated using the average wetted perimeter (versus the starting wetted perimeter) to determine the loss rate per square foot of canal. The revised calculations resulted in increased seepage losses for all cases. There was a 13% average loss rate increase, with a 58% maximum increase and a median of 7%. Seven tests out of the 29 had loss rates increases over 21%. The general trend for the change of wetted perimeter is provided in Figure 10.

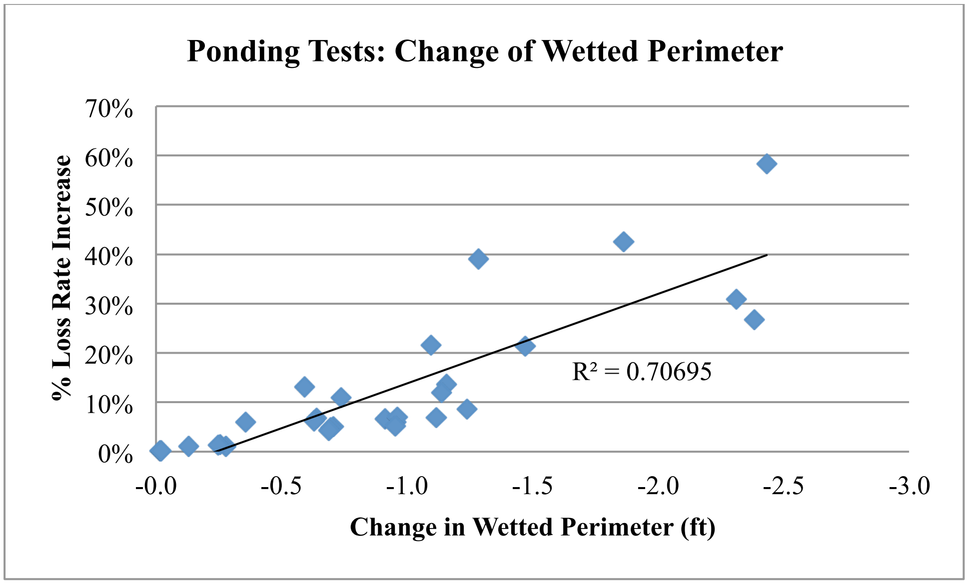


Figure 10. Test changes in wetted perimeter versus loss rate increases.

Next, the original testing time periods used to calculate the 24-hour loss rates were found to have a range from 2 to 50 hours, with an average of 33 hours. Due to this variability, new 24-hour loss rates were determined by plotting each loss rate stage and then fitted with a power function. An example of test 16HC1 is given in Figure 11.

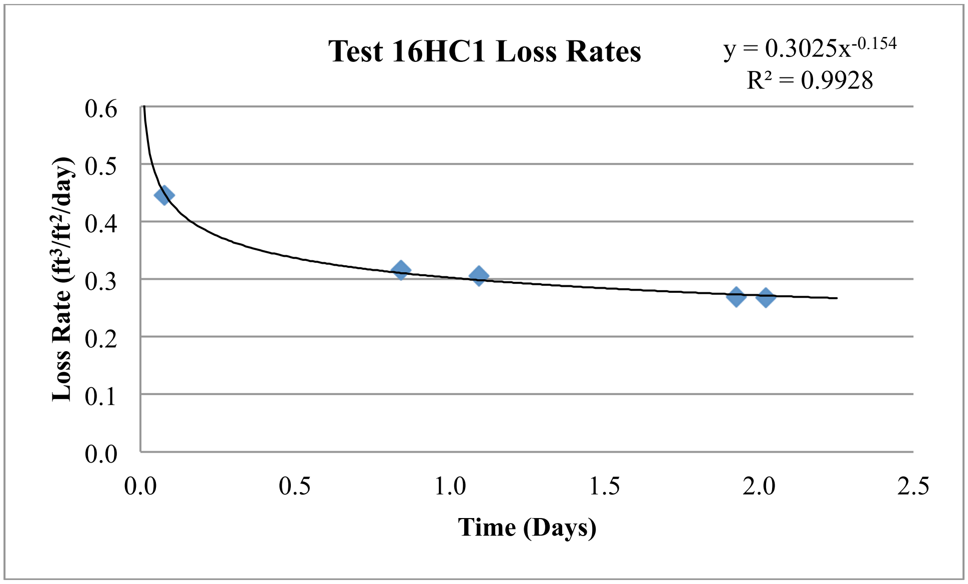


Figure 11. Test 16HC1 loss rates fitted with power function.

Tests that originally used calculation times greater than 40 hours had underestimated loss rates (Table 16). There was a 40% (0.13 cfd) average increase, with a 126% maximum increase and a median of 28%. Tests with times between 19-26 hours showed a 12% (0.03 cfd) average increase, with a 40% maximum increase and a median of 7% (Table 17). Tests calculated with less than 3.5 hours were all overestimated with an average reduction of 41% (1.2 cfd) in loss rates (Table 18).

Table 16. Statistical summary of test loss rates with original time periods greater than 40 hours.

Statistics	Original Loss Rate (cfd) using starting WP	Loss Rate using Avg. WP		Revised 24-hr Loss Rate	
		cfd	% Change	cfd	% Change
Avg.	0.24	0.28	12	0.37	40
Max	0.62	0.78	58	1.39	126
Min	0.05	0.05	1	0.07	0.2
Median	0.25	0.27	7	0.31	28

Table 17. Statistical summary of test loss rates with original time periods between 19-26 hours.

Statistics	Original Loss Rate (cfd) using starting WP	Loss Rate using Avg. WP		Revised 24-hr Loss Rate	
		cfd	% Change	cfd	% Change
Avg.	0.43	0.47	13	0.47	12
Max	1.13	1.62	43	1.59	40
Min	0.02	0.02	0.1	0.02	0.1
Median	0.31	0.33	7	0.33	7

Table 18. Statistical summary of test loss rates with original time periods with less than 3.5 hours.

Statistics	Original Loss Rate (cfd) using starting WP	Loss Rate using Avg. WP		Revised 24-hr Loss Rate	
		cfd	% Change	cfd	% Change
Avg.	2.85	3.31	17	1.63	41
Max	4.54	5.03	39	2.48	65
Min	1.36	1.54	6	0.80	13
Median	2.75	3.34	12	1.63	43

The original test run times and the loss rates calculations using both the starting and average wetted perimeters are given in Table 19. The last column in the table provides the revised 24 hour loss rates solved by the power equations. These revised loss rates range from 0.02 to 2.48 cfd. Only two tests were substantially higher than the range reported by Kraatz (1977) for concrete canals of 0.03 to 1.64 cfd.

Table 19. Test original run times and calculated loss rates.

Test	Original Calculation Time Period (hr)	Loss Rate (cfd) using		Revised 24-hr Loss Rate (cfd)
		Starting WP	Avg. WP	
16HC1	48.5	0.25	0.27	0.30
16HC2	48.3	0.19	0.20	0.23
BV1	25.9	1.04	1.37	1.36
BV2	19.0	1.13	1.62	1.59
DL1-16	19.5	0.02	0.02	0.02
DL1-20	19.5	0.02	0.02	0.02
DL2	23.6	0.55	0.63	0.62
DL3	47.8	0.05	0.05	0.07
DO1	47.8	0.24	0.29	0.37
DO2	49.9	0.32	0.38	0.58
DO3	47.2	0.36	0.57	0.67
ED1	2.3	4.54	5.03	2.48
ED2	1.8	2.94	3.11	1.04
ED3	3.2	1.36	1.54	0.80
ED4	3.5	2.56	3.56	2.22
HA1	24.0	0.08	0.08	0.08
HA2	25.0	0.30	0.33	0.33
LF1	48.0	0.24	0.25	0.31
LF2	48.2	0.62	0.78	1.40
ME1	25.8	-	0.23	0.21
ME2	24.0	-	0.18	0.18
SJ01	24.0	0.32	0.34	0.34
SJ04	45.9	0.15	0.16	0.17

Table 19. Continued.

Test	Original Calculation Time Period (hr)	Loss Rate (cfd) using		Revised 24-hr Loss Rate (cfd)
		Starting WP	Avg. WP	
SJ05	46.4	0.19	0.19	0.18
SJ06	47.9	0.25	0.27	0.32
SJ07	46.8	0.26	0.28	0.30
SJ08	23.3	-	0.38	0.38
SJ09	47.9	0.27	0.29	0.35
SJ10	42.8	0.08	0.08	0.09
SJ11	43.1	0.07	0.07	0.08
SJ15	41.8	0.02	0.02	0.02
UN1	47.0	0.31	0.33	0.46
UN2	49.3	0.28	0.31	0.41

6.1.2. Leak Analysis

In the most of test reports, the individual tests are classified as either being a "total" or "seepage" loss test. A "total" loss test specifies that the test contained farm turnout valves or gates and may have contributed to the water losses in addition to seepage. Nine tests were classified as being seepage loss, 22 tests were classified as total loss tests and one was unknown. The reports provide varying detail on the number of turnout gates or values and verified as leaks per section. The tests that provided gate and leak descriptions is given in Table 20.

Table 20. Tests that reported gate and valves leaks.

Test ID	Description
16HC1	3 leaking turnout gates, 1 measured
DL3	2 turnout valves
DO2	4 turnout gates, 1 verified
DO3	3 turnout gates, unverifiable
SJ6	2 visible turnout gate leaks
SJ7	Several, unidentified
SJ9	Several, unidentified
SJ11	Several, unidentified

The leak reported by Leigh and Fipps (2008a) was measured during canal test 16HC1 from within a standpipe (Figure 12). The loss rate of 0.444 liters/min or 22.41 ft^3/day was recorded at the start of the test. This rate was assumed to be the approximate rate of loss that would occur during normal canal operations. The percentage of this leak was determined in comparison to the total volume lost per day from the test section (19,254 ft^3). The valve leak was determined to be 0.12% of the total loss with a loss rate of 0.0004 cfd (Table 21). Hypothetically, if this leak-ratio was applied to several gates on the same this test canal, the losses would only be around 0.5% of the total losses. If applied to larger or on higher loss canals this leak would be even a lower percentage from the total loss. In conclusion, a larger sample population is required to extrapolate and more accurately estimate the percentage of losses occurring from other leaks.

Figure 12. Valve leak measured from test 16HC1
(Leigh and Fipps 2008a).

Table 21. Test 16HC1 leak analysis results.

Test Canal			Valve Leak		
Loss Rate (cfd)	Vol. Loss (ft^3/day)	Wetted Area (ft^2)	Loss Rate* (ft^3/day)	% Vol. Loss	Loss Rate (cfd)
0.303	19254	63728	22.41	0.12%	0.0004

*Rate converted from GPM (Leigh and Fipps 2008a)

6.1.3. Evaporation Analysis

The impacts of evaporation on ponding tests results will change throughout the year. The historical range of the monthly Reference Crop Evapotranspiration (ETo) rates can vary by almost five inches from the summer to winter months. The highest rates occur in July and August (6.7-7.0 inches) and the lowest in December (2.3-2.6 inches) as shown in Table 22.

Table 22. Total ETo inches by month for reported LRGV cities.

City	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
Weslaco	2.5	2.6	4.0	4.9	6.1	6.5	7.0	6.6	4.8	4.0	2.9	2.3	54.1
Brownsville	2.7	3.0	4.5	5.2	6.0	6.3	6.7	6.7	5.2	4.3	3.0	2.6	56.2

Source: Texas ET Network (texaset.tamu.edu)

Yearly averaged ETo rates are summarized in Table 23 for the 8-year period (1998-2005) when the ponding tests were conducted. The average ETo rate over the eight year period was approximately 0.012 ft/day, with a range of 0.011 – 0.014 ft/day. Next, the ETo rates were adjusted by factors 0.6 and 0.8, used for canal estimation, reducing the 8-year average is 0.007 and 0.010 ft/day, respectively.

A statistical summary of the ETo rates approximated for all the ponding tests is provided in Table 24. The overall average ETo rate for all tests was 0.011 ft/day, with a range of 0.003 – 0.021 ft/day. The ETo rates were adjusted into $ft^3/ft^2/day$ for each test ranging from 0.001 to 0.010 cfd and 0.002 to 0.013 cfd for adjustment factors 0.6 and 0.8, respectively. The highest adjusted ETo rate of 0.013 cfd was found to be only 3% of total canal losses, while the highest percentage of loss (28%) is only 0.005 cfd. In conclusion, evaporation losses are negligible when compared to the most seepage loss rates, but can be significant on canals with minimal the seepage losses.

Table 23. Yearly averaged ETo rates from 1998 – 2005 (ft/day)*.

Year**	Avg	Max	Min
1998	0.012	0.024	0.001
1999	0.012	0.022	0.002
2000	0.011	0.023	0.001
2001	0.012	0.028	0.000
2002	0.013	0.026	0.000
2003	0.012	0.025	0.000
2004	0.013	0.025	0.002
2005	0.014	0.025	0.002
Average	0.012	0.025	0.001

* Texas AgriLife Research Weslaco Annex Farm weather station

** Years do not represent 365 day years due to maintenance and errors

Table 24. Statistical summary of ETo rates for ponding tests.

Statistics	Avg. Test Period ETo (ft/day)	0.6 of ETo*		0.8 of ETo*	
		(ft^3/ft^2/day)	% of Loss	(ft^3/ft^2/day)	% of Loss
Avg.	0.011	0.005	3.0	0.007	4.0
Max	0.021	0.010	21.1	0.013	28.2
Min	0.003	0.001	0.1	0.002	0.1
Median	0.011	0.005	1.8	0.007	2.4

*ETo canal adjustment factors

6.1.4. Dam Infiltration Analysis

When evaluating the potential influences that the two earthen dams have on a ponding test (loss rates), two factors are important: percent of wetted area and infiltration. The percent of wetted area occupied by the earthen dams was determined for all the test canals. A statistical summary of the wetted areas for all test canals and dams is given in Table 25. The average percent of wetted area for all dams was only 0.2% (47 ft^2), with maximum of 0.7% (167 ft^2) and a minimum of 0.02% (5 ft^2).

Table 25. Statistical summary of test canals and dams.

Stat.	Test Length (ft)	Starting Avg. Test Canal			Total Dam Wetted Area (ft^2)	Total Test Wetted Area (ft^2)	% Dams Wetted Area
		Cross Sectional Area (ft^2)	Wetted Perimeter (ft)	Wetted Area (ft^2)			
Avg	2743	24	13	34,501	47	34,549	0.21%
Max	9525	84	21	145,471	167	145,638	0.69%
Min	600	3	5	6,295	5	6,301	0.02%

While the earthen dams occupy a small percentage of a total canal test's wetted area, there will be a greater potential for infiltration and loss through them. The dams will have varying soils types, compaction and saturation levels. To help circumvent these effects, the dams were built in a time frame and manner that would have allowed for significant saturation before measurements were conducted.

Here two ponding tests, SJ5 and SJ15, were compared that tested the same section of Lateral A-7 in Hidalgo County Irrigation District No.2 (HCID2). Test SJ15 had been relined with a geomembrane and hard surface covering nine months prior. The section contained no valves or gates thus water losses were assumed to only occur from infiltration (canal perimeter and earthen dams) and evaporation. The testing canal geometric dimensions were comparable. The wetted perimeter and cross-sectional area for the second test SJ15 only increased by 0.4 ft and 1.7 ft^2, respectively. The wetted areas of the dams were approximately 0.5% of the total tested wetted area (Table 26).

Table 26. Testing geometric dimensions and properties of Lateral A-7.

Test*	Water Depth (ft)	Cross-Sec. Area (ft^2)	Wetted Perimeter (ft)	Dam WA (ft^2)	Total WP (ft^2)	% Dam WA
SJ5	4.75	37.20	16.67	74.40	13508	0.55%
SJ15	4.81	38.92	17.09	77.83	13850	0.56%
Difference	0.06	1.72	0.42	3.43	343	0.01%

*Canal Test Lengths: 806 ft

The tests were evaluated with the logic that if both tests were geometrical similar and that water losses were only occurring from infiltration and evaporation, that the new canal lining would prevent the majority if not all of the losses through the canal perimeter for test SJ15. When comparing the total loss rates there was an 87% reduction. The remaining 13% is attributed to infiltration through the earthen dams and evaporation. After evaporation rates (ETo) were determined and subtracted, including the average ETo rates and adjustment factors 0.6 and 0.8, dam losses were approximately between 4 to 8 % (0.008 to 0.014 cfd) of the total losses (Table 27).

Table 27. Loss rates of Tests SJ5 and SJ15 on Lateral A-7 ($ft^3/ft^2/day$).

Test	Total Loss Rate	Avg. ETo Rates	Water Loss Rates (without ETo rates)		
			- Avg. Eto	- 0.8 ETo	- 0.6 ETo
SJ5 (100%)	0.184	0.010	0.174	0.176	0.178
SJ15 (% of)	0.023 (13%)	0.016	0.008 (4%)	0.011 (6%)	0.014 (8%)
% Dam Infiltration Losses			4%	6%	8%

Finally, since the wetted area that the dams occupy is minor but also proportional to each canal cross-sectional area, the loss rates are assumed here to be proportional to the canal size. If this theory holds true, then the losses for dam infiltration could also be assumed between 4 to 8% of total losses for other tests.

6.1.5. Trend Analysis: Canal Geometry vs. Seepage Loss Rates

In evaluating relationships between the canal geometric attributes and the revised seepage loss rates, the general trend appears to be that the larger canals lose less water than smaller canals. Canals with a starting wetted perimeter greater than 14 feet have loss rates below 0.50 cfd (Figure 13). Under 14 feet, the loss rates become more erratic, from as low as 0.08 cfd to as high as 2.48 cfd. As would be expected, similar trends can be seen for the starting cross-sectional area and water depth (Figures 14 and 15). Cross-sectional areas over 20 ft^2 and water depths over 3.0 feet had loss rates consistently under 0.50 cfd.

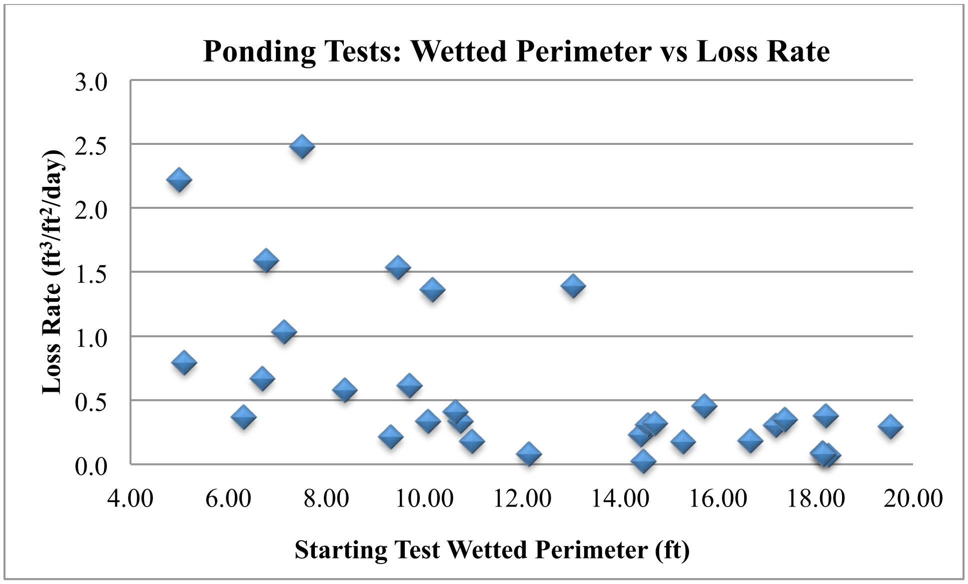


Figure 13. Starting wetted perimeter versus loss rates.

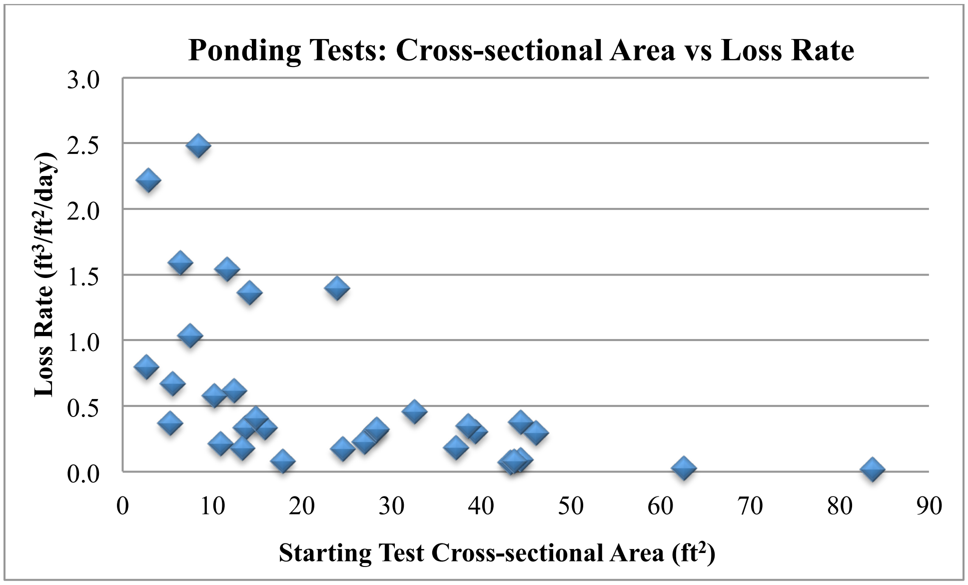


Figure 14. Starting cross-sectional areas versus loss rates.

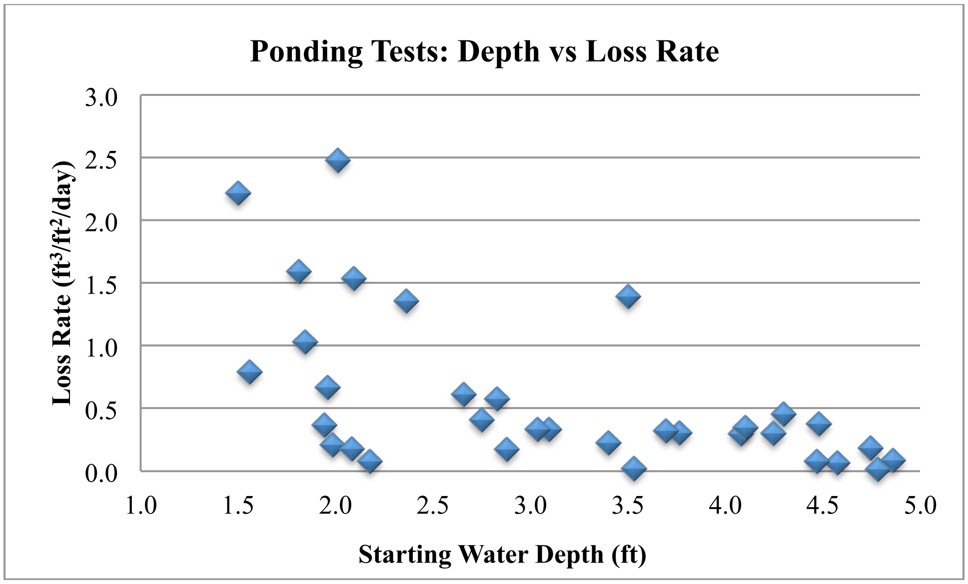


Figure 15. Starting water depths versus loss rates.

6.2. Davis-Wilson Empirical Formula Results

Seepage loss rates were estimated with the Davis-Wilson formula with a C-value of 1 for concrete lined canals 3 to 4 inches thick (Table 28). When comparing the Davis-Wilson to the revised loss rates the majority of tests showed an overestimation by an 87% average difference, with a 48% minimum difference. Only two tests (DL1-16 and DL1-20) were underestimated by the Davis-Wilson formula, with a 60% average difference. The numerical and percent differences for each test are also given in Table 28. The overall level of predictability was poor for the lining conditions of the concrete canals of the Valley.

The revised loss rates were then used to calibrate the Davis-Wilson formula to derive new C-values (Table 28). All tests were plotted by the revised loss rates and starting water depths and labeled with the newly derived C-values in accordance to the C-value trend lines in Figures 16 and 17. Each C-value trend follows a positive sloping power function curve, so as depth increases, also loss rate increases. Tests with loss rates less than 0.50 cfd are shown in Figure 17. These tests had C-values less than 14.

Table 28. David-Wilson Empirical Formula Analyses Results.

Test	Revised Loss Rate (cfd)	Davis-Wilson at C=1 (cfd)	Diff.	% Diff.	Calibrated C-Values
16HC1	0.303	0.035	0.268	88%	8.6
16HC2	0.229	0.032	0.196	86%	7.0
BV1	1.360	0.029	1.331	98%	47.3
BV2	1.592	0.026	1.565	98%	60.4
DL1-16	0.025	0.033	-0.008	32%	0.8
DL1-20	0.019	0.036	-0.017	89%	0.5
DL2	0.616	0.030	0.586	95%	20.6
DL3	0.069	0.036	0.033	48%	1.9
DO1	0.370	0.027	0.343	93%	13.7
DO2	0.579	0.031	0.548	95%	18.9
DO3	0.669	0.027	0.642	96%	24.7
ED1	2.480	0.027	2.453	99%	91.0
ED2	1.035	0.026	1.009	97%	39.1
ED3	0.795	0.025	0.770	97%	31.7
ED4	2.220	0.025	2.195	99%	89.8
HA1	0.080	0.028	0.052	65%	2.8
HA2	0.332	0.031	0.300	91%	10.5
LF1	0.310	0.034	0.276	89%	9.2
LF2	1.395	0.033	1.362	98%	42.5
ME1	0.214	0.027	0.187	87%	7.9
ME2	0.180	0.028	0.153	85%	6.5
SJ01	0.336	0.031	0.305	91%	10.7
SJ04	0.175	0.031	0.144	82%	5.7
SJ05	0.184	0.036	0.148	80%	5.1
SJ06	0.322	0.033	0.288	90%	9.6
SJ07	0.296	0.035	0.261	88%	8.6
SJ08	0.379	0.036	0.343	91%	10.6
SJ09	0.349	0.035	0.314	90%	10.1
SJ10	0.092	0.037	0.055	60%	2.5
SJ11	0.080	0.036	0.044	55%	2.2
UN1	0.456	0.035	0.421	92%	13.0
UN2	0.409	0.030	0.378	93%	13.5

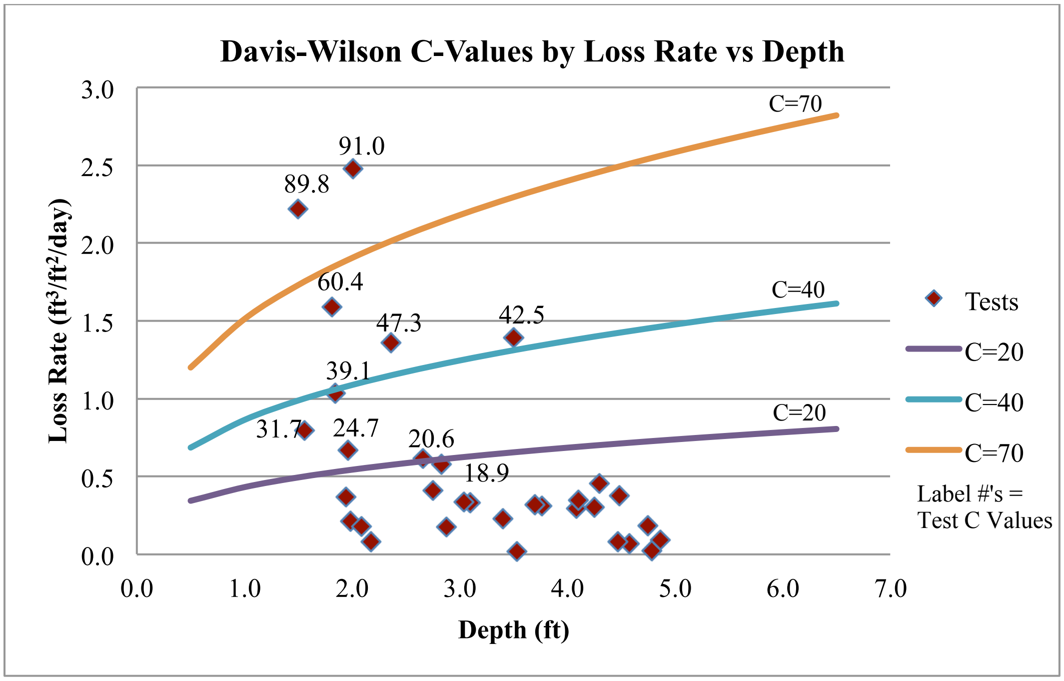


Figure 16. Davis-Wilson calibrated C-values results.

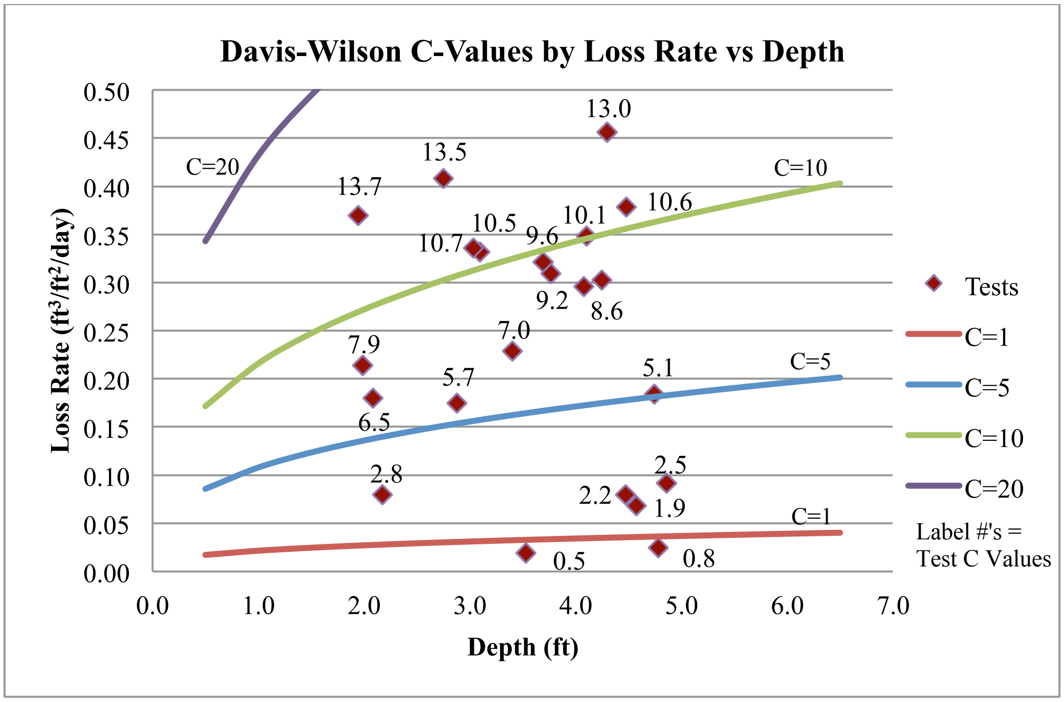


Figure 17. Davis-Wilson calibrated C-values results below a 0.50 cfd.

6.3. Canal Condition Rating and David-Wilson's C-Value Correlation

6.3.1. Condition Rating

The new rating system sought to simplify the field scoring by reducing the number of categories and score possibilities, as well as to minimize subjective opinions and seasonal variations--specifically the general condition and vegetation categories. The scoring system focuses only on estimating crack frequency or quantity and size of cracks both in a scale of 1-3, with a possible total rating score of 2-6. The total rating scores were then reduced into a 1-3 ranking with a score of 1 being the best, and a score of 3 being the worst.

Out of the 32 ponding tests evaluated, 26 of these tests had condition ratings. A statistical break down of the condition ratings by seepage loss rate is given in Table 29. To begin in summary, the total rating scores of 2 and 3 all had loss rates less than 0.40 cfd. Rating scores of 3 had a lower minimum and lower average then the 2 ratings. Rating 4-6 had the most variability in loss rates, with the 4 ratings having the largest range. The lowest loss rate for the 4 ratings (0.41) was just above the highest for rated No. 3 (0.38) loss rate. The highest 4 rating had a loss rate 2.22: test ED4 was noted by the tester for high valve leaks. Rating scores of 5 had the second lowest loss rate of all rating categories. Tests with a rating of 6 were all above 1.0 cfd, with a high of 2.4 cfd.

The standard deviations generally increased as the rating scores increased. Ratings 2 and 3 had low standard deviations of 0.07 and 0.13, respectively, compared to the standard deviations for rating 4-6 which were all approximately ± 0.03 from 0.70. The rating scores (2-6) are plotted against the canal loss rates in Figure 18. The linear trend line had a positive slope with an R-square value of 0.4188.

Table 29. Statistics for test loss rates (cfd) by condition rating.

Rating No.	No. Test	Avg.	Min	Max	Std. Dev.
2	5	0.26	0.17	0.32	0.07
3	9	0.20	0.02	0.38	0.13
4	6	0.98	0.41	2.22	0.70
5	3	0.59	0.07	1.36	0.68
6	3	1.70	1.04	2.48	0.73

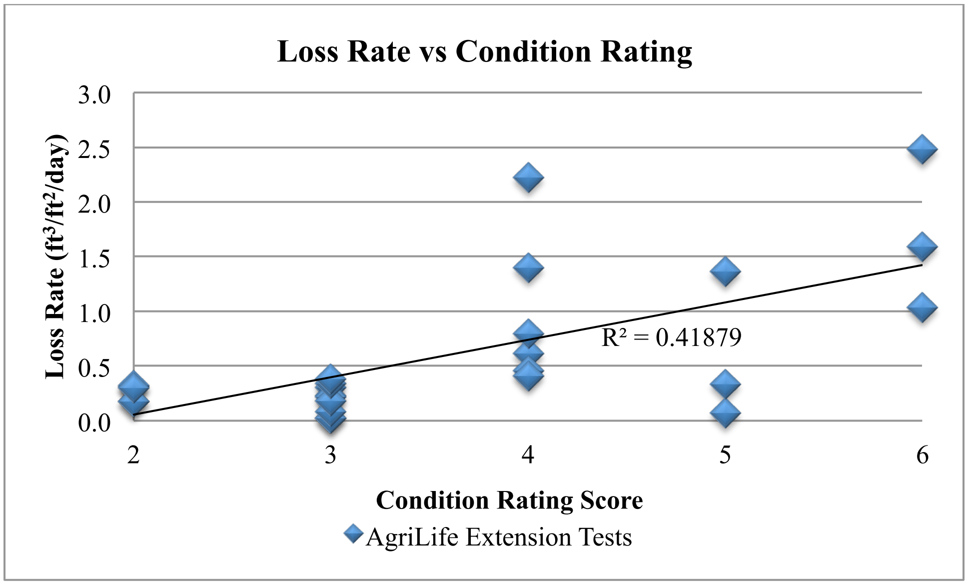


Figure 18. Extension tests by loss rate vs. condition rating.

The ratings were then condensed into the 1-3 scale ranking (Table 30). Ratings 2 and 3 were combined for a ranking of 1. Rating 4 was just converted into a 2 ranking.

Ratings 5 and 6 were also combined for a ranking of 3. The statistical summary data also results in a consolidation of sorts from the rating values. Ranking No. 1 had the lowest standard deviation of 0.12, compared with rankings 2 and 3 that had much higher standard deviations of 0.70 and 0.88, respectively. The ranking scores (1-3) are plotted against the canal loss rates in Figure 19. The linear trend line had a positive slope with an R-square value of 0.3838.

Table 30. Statistics for test loss rates (cfd) by condition ranking.

Ranking No.	No. Test	Avg.	Min	Max	Std. Dev.
1	14	0.22	0.02	0.38	0.12
2	6	0.98	0.41	2.22	0.70
3	6	1.14	0.07	2.48	0.88

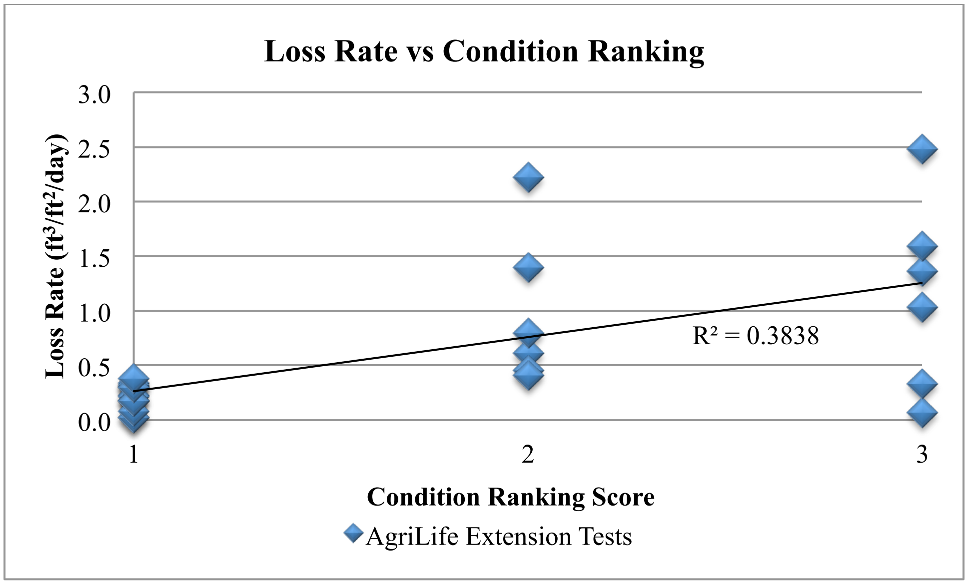


Figure 19. Extension tests by loss rate vs. condition ranking.

The test canals and their rating scores are sorted by loss rates (least to greatest) in Table 31. Of the 16 canals with loss rates below 0.40 cfd, 88% had a 1 ranking. All four canals with loss rates between 0.40 and 0.80 cfd had a 2 ranking. 67% (4 of 6) of the canals with loss rates 1.03 cfd had a 3 ranking.

Table 31. Rating scores of test canals sorted by loss rate values.

Test ID	Revised 24-hr Loss Rate (cfd)	Rating (2-6)	Ranking (1-3)
DL1-20	0.02	3	1
DL1-16	0.02	3	1
DL3	0.07	5	3
HA1	0.08	3	1
SJ04	0.17	2	1
ME2	0.18	3	1
SJ05	0.18	2	1
ME1	0.21	3	1
16HC2	0.23	3	1
SJ07	0.30	2	1
16HC1	0.30	3	1
LF1	0.31	2	1
SJ06	0.32	2	1
HA2	0.33	5	3
SJ01	0.34	3	1
SJ08	0.38	3	1
UN2	0.41	4	2
UN1	0.46	4	2
DL2	0.62	4	2
ED3	0.80	4	2
ED2	1.04	6	3
BV1	1.36	5	3
LF2	1.39	4	2
BV2	1.59	6	3
ED4	2.22	4	2
ED1	2.48	6	3

Next, relationships found between canal geometry and seepage loss rates were revisited and the condition rating system was applied. Rated tests were labeled with the condition ranking score in figures 20 and 21. It can be seen that larger and deeper canals are generally in better condition than smaller canals and have lower loss rates.

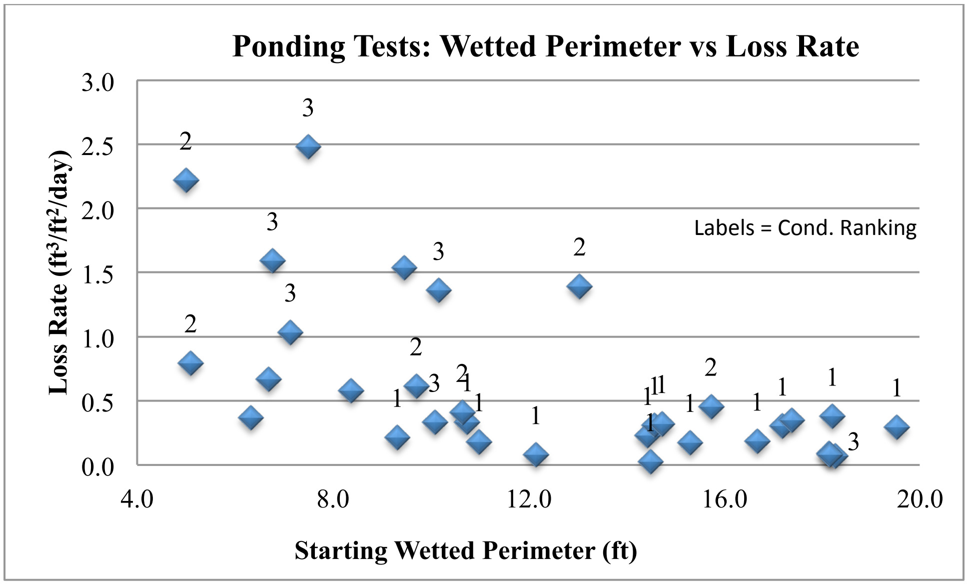


Figure 20. Starting wetted perimeters vs. loss rates with condition rankings.

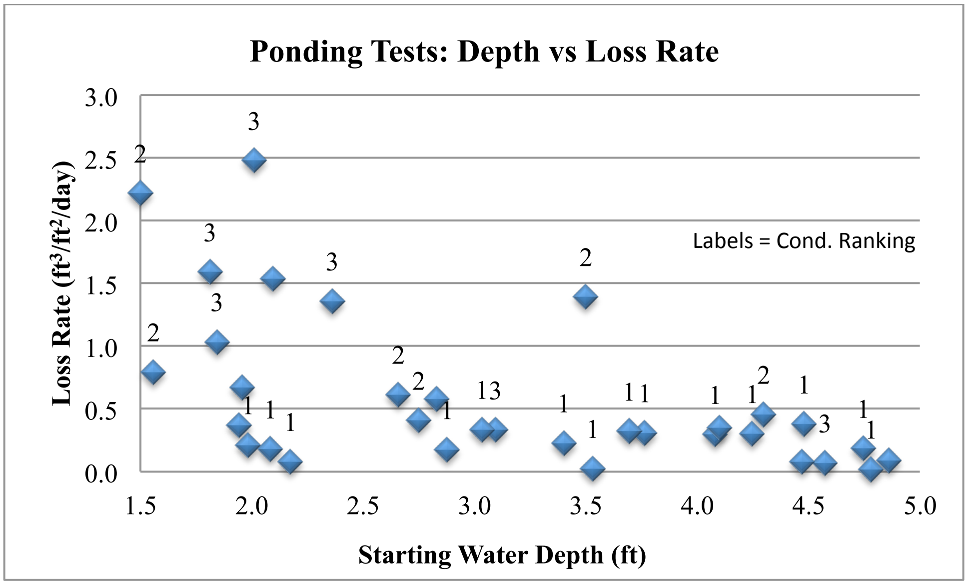


Figure 21. Starting water depths vs. loss rates with condition rankings.

Last, the six 1933 USDA seepage tests, found in literature, were rated and ranked in accordance with the new condition rating system (Table 32). The average seepage loss rates for the USDA tests and the Extension tests are compared by condition rating in Table 33. USDA tests had a lower average seepage loss rate then the AgriLife Extension tests for ratings of 2. Both test averages with 3 ratings were well closely aligned at 0.19 and 0.20 cfd. Only one USDA test was rated at a score of 4 or higher. This test, CCWID1-Lat.26-1¾, had a distance/crack frequency at an estimated 4.7 ft/crack and was rated a score of 3. This test had a loss rate of 0.46 cfd which was just above to the lowest Extension 4-rated test of 0.41 cfd. The 1933 USDA tests were plotted in conjunction with the Extension tests by rating in Figure 22. The linear trend line has a positive slope and increased the R-square value to 0.4416 from 0.4188.

Table 32. Condition rating scores of 1933 USDA tests.

Test Canal	Distance (ft)/crack	Freq. Rating	Crack Size	Crack Rating	Rating	Ranking	24hr Loss Rate (cfd)
CCWID11	13	1	0 - 1/16 in	1	2	1	0.16
CCWID1-Lat.26-1¾	4.7	3	≤ pencil	1	4	2	0.46
CCWID1-Lat.26-1	7	2	0 - 1/16 in	1	3	1	0.13
HCWC&ID6-Lat.C	12	1	¼ in	2	3	1	0.13
HWC&ID6-Lat.B5	12	1	¼ in	2	3	1	0.30
HCWC&ID1-Lat 4M	≥ 10	1	0 - 3/16 in	1	2	1	0.10

Table 33. Test loss rate averages (cfd) by condition ratings.

Rating	No. Test	USDA Avg.	Extension Avg.	Comb. Avg.
2	2	0.13	0.26	0.22
3	3	0.19	0.20	0.19
4	1	0.46	0.98	0.91

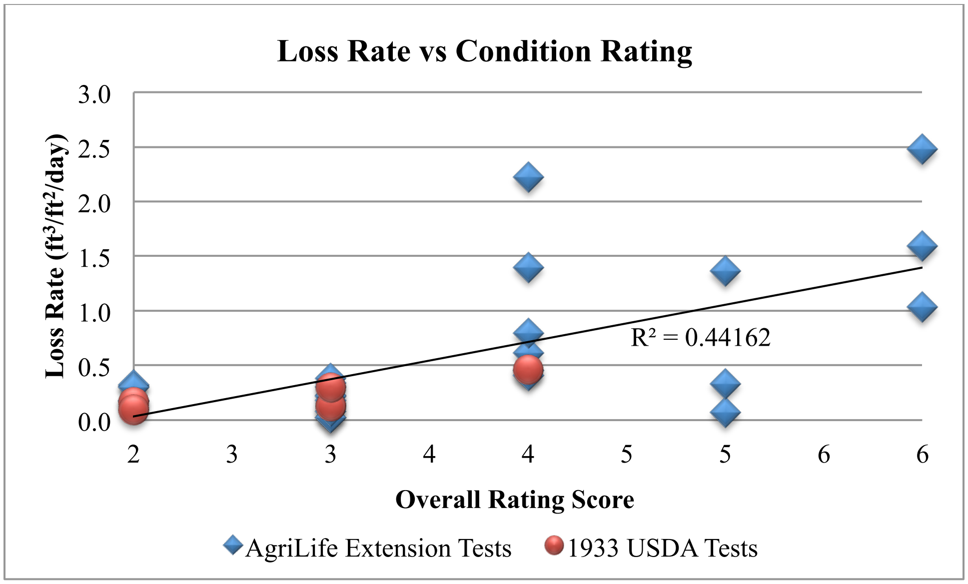


Figure 22. Extension and USDA tests by loss rate vs. condition rating.

The ratings of the 1933 USDA tests were then converted into a ranking scale (Table 34). Five of the six USDA test had a ranking of 1. The USDA loss rate test average was below the Extension test average for rankings of 1. The 1933 USDA tests were plotted in conjunction with the Extension tests by ranking in Figure 23. The linear trend line had an increase in R-square value of 0.4157 from 0.3838. The USDA tests correlated well with the Extension tests and the rating system.

Table 34. Test loss rate averages (cfd) by condition rankings 1 and 2.

Ranking	No. Test	USDA Avg.	Extension Avg.	Comb. Avg.
1	5	0.16	0.22	0.20
2	1	0.46	0.98	0.91

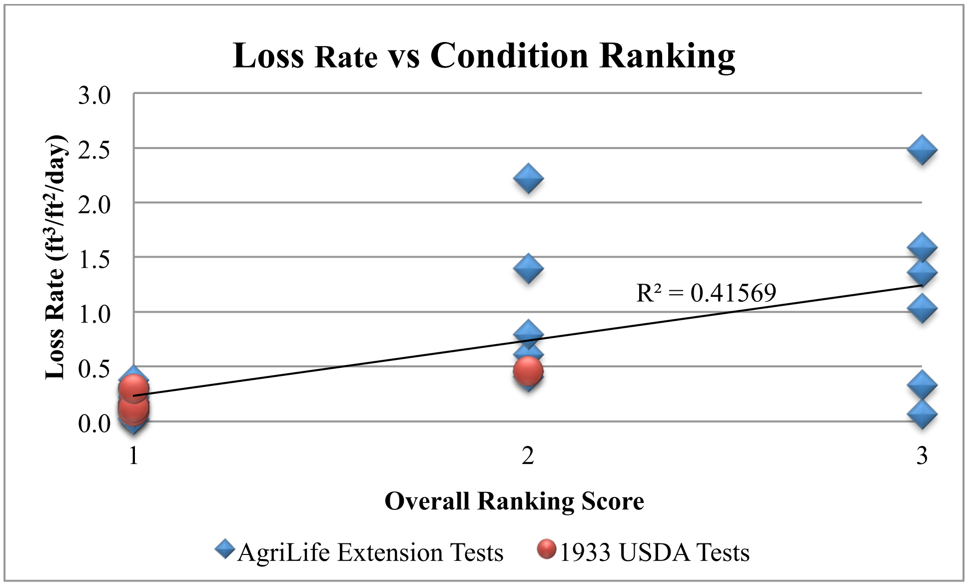


Figure 23. Extension and USDA tests by loss rate vs. condition ranking.

6.3.2. Condition Rating and C-Value Correlation

Each condition ranking score has a C-value range correlated by their associated seepage loss test (Table 35). As can be seen, ranking-1 has a C-value range of 1 to 11 (loss rates), with an average of 7 (loss rate). Rankings 2 and 3 have boarder C-value range. While ranking 2 has a C-value range starting at 13, just above the maximum range of ranking 1, the maximum C-value of 90 falls just a point below the maximum range value for ranking 3 of 91. The minimum C-value for ranking 3 of 2 starts just one point above the minimum range for ranking-1. The tests were plotted according to their condition rating score and derived Davis-Wilson C-value in Figure 24. There is no surprise as the pattern of the C-values is very similar to that of the test loss rates back in Figure 19.

Table 35. C-value range and statistics by condition ranking and loss rate.

Ranking	No. Test	C-value			
		Avg.	Min	Max	Std. Dev.
1	14	7	1	11	3
cfd		0.22	0.02	0.38	0.10
2	6	35	13	90	29
cfd		0.98	0.41	2.22	0.70
3	6	42	2	91	33
cfd		1.14	0.07	2.48	0.88

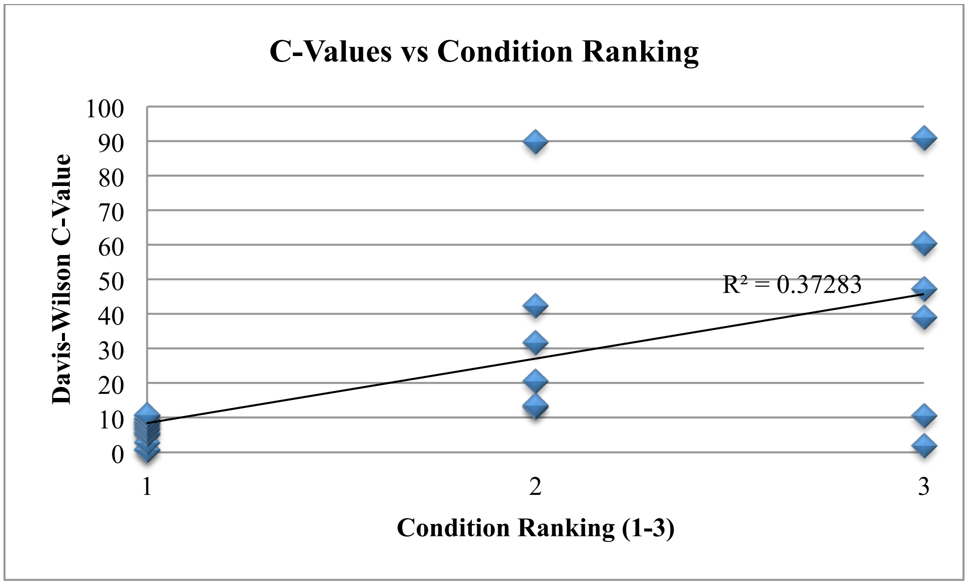


Figure 24. Extension tests by C-value vs. condition ranking.

CHAPTER VII

CONCLUSIONS AND RECOMMENDATIONS

7.1. Conclusions

This study utilized seepage loss test results by the Texas AgriLife Extension Service to evaluate a simplified condition rating system and the Davis-Wilson empirical formula. In addition, impacts of testing errors and calculation differences were investigated; and relationships between canal dimensions, lining conditions and water loss rates were identified.

The condition rating system used a 1 to 3 (good to bad) scale to rank the condition of the concrete lined canals and demonstrated well at predicting seepage losses. Canals with a ranking of 1 had the best results. In fact, 88% of the test canals that had loss rates below 0.40 cfd were ranked a 1. Even the additional 1933 USDA tests analyzed had corresponding results, bring that percentage up to 90%. The canals with rankings of 2 and 3 had a greater variability in loss rates, having high standard deviations of 0.70 and 0.88 cfd, respectively. Some of these variations could be attributed to silting, leaking turnout gates, and varying subsoil types which would have a greater influence as the lining conditions become more deteriorated. Despite those shortcomings, 100% of the canals (5) with loss rates between 0.40 and 0.80 cfd were ranked a 2; and 67% (4 of 6) of the canals with loss rates above 1.03 cfd were ranked a 3.

The results for the Davis-Wilson empirical formula were quite poor at predicting loss rates for concrete lined canal in less than perfect conditions. Calibration with the condition rating system and seepage loss rates was required for use. The C-values for the formula were correlated with the condition rating system (i.e. Ranking 1 = C-values 1-11).

The potential impacts of testing errors and calculation differences were investigated. The test calculation revisions made a significant difference on the condition rating system results. Nine (34%) of the rated tests had an average loss rate change of 51% (0.74 cfd), compared to the other 17 tests with changes of only 13% (0.03 cfd). Testing errors had less influence. Loss estimations from dam infiltration would be between 4 to 8% of the total losses per test. The average ETo rate per canal was 0.006 cfd, with a high of 0.013 cfd. Valve leaks are dependent on the number of valves per test. But if the one leak measured with a loss rate of 0.0004 cfd the losses will be negligible. The percent of influence that evaporation and leaks have will change with the total rate of loss measured.

Lastly, relationships were found between canal dimensions and conditions and water loss rates. Larger, deeper canals were in better condition and had lower loss rates per cfd. The smaller canals become inconsistent with wetted perimeters under 14 feet and water depths below 3.0 feet.

7.2. Recommendations

7.2.1. Irrigation District Application

The developed condition rating system and correlated Davis-Wilson empirical formula could be applied to prioritize rehabilitation and estimate seepage losses for the deteriorating lined irrigation canals of the Lower Rio Grande Valley of Texas. Canals ranked a 1 could be assumed to have a loss rate less than 0.38 cfd or a C-value of 11. Canals ranked 2 or 3 will have potentially higher loss rates. Furthermore, the relationship found between canal dimension and loss rate could be used to direct canal investigations (i.e. wetted perimeter under 14 feet and water depth below 3.0 feet).

7.2.2. Future Research and Investigations

The rankings 1 had a loss range from 0.02 to 0.38 cfd. The USBR (1968) classified good canals as having loss rates between 0.03 to 0.10 cfd and poor canals greater than 0.50 cfd, and reported that seasonal variations could reach at much as 59% or 0.34 cfd. Other studies have suggested that seepage losses on lined canals with cracks covering up to 0.01% of the wetted area can equal or exceed unlined canals (Merkley 2007). Rankings of 2 and 3 had loss rates with a greater variance. To expand on this study and improve the level of predictability of the canal lining condition rating system and therefore the seepage loss rates, the following areas could be investigated:

- Seasonal variations and affects of silting;
- Changes in rates from monthly or infrequent use;

- Evaluation of other empirical formulas;
- Construction methods of the original canals concerning sub-soil types.

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APPENDIX A

TEST DIMENSIONS

Table 36. Average starting test dimensions and properties.

Test ID	Test Length (ft)	Width (ft)	Depth (ft)	Cross Sect. Area (ft^2)	Wetted Perimeter (ft)	Hydraulic Radius (ft)
16HC1	3703	13.65	4.25	39.35	17.19	2.29
16HC2	1000	11.81	3.40	27.00	14.43	1.87
BV1	5750	8.53	2.36	14.15	10.17	1.39
BV2	4550	5.27	1.81	6.44	6.77	0.95
DL1-16	4637	11.56	3.53	62.64	14.49	4.32
DL1-20	6768	17.55	4.78	83.64	21.51	3.89
DL2	2552	7.01	2.66	12.46	9.70	1.28
DL3	2500	14.95	4.57	43.25	18.27	2.37
DO1	1500	4.08	1.94	5.29	6.32	0.84
DO2	1500	5.32	2.83	10.26	8.38	1.22
DO3	1500	4.28	1.96	5.59	6.69	0.84
ED1	2080	5.28	2.01	8.44	7.50	1.13
ED2	1729	5.14	1.84	7.55	7.14	1.06
ED3	1235	2.60	1.56	2.69	5.10	0.53
ED4	2450	2.67	1.50	2.87	5.00	0.57
HA1	7300	10.35	2.17	17.83	12.15	1.47
HA2	1890	7.52	3.09	13.75	10.08	1.36
LF1	600	11.20	3.76	28.21	14.57	1.94
LF2	600	10.23	3.50	23.90	13.05	1.83
ME1	9525	7.92	1.98	10.95	9.32	1.18
ME2	2583	9.80	2.08	13.38	10.98	1.22
SJ01	6463	8.23	3.03	15.89	10.75	1.48
SJ04	735	13.83	2.88	24.55	15.30	1.60
SJ05	806	12.93	4.75	37.20	16.67	2.23
SJ06	2603	11.58	3.69	28.35	14.72	1.93
SJ07	2944	16.90	4.08	46.15	19.53	2.36
SJ08	2557	14.65	4.48	44.38	18.21	2.44
SJ09	2426	14.49	4.10	38.57	17.38	2.22
SJ10	880	14.28	4.86	44.44	18.14	2.45
SJ11	2345	16.15	4.47	43.66	18.16	2.40
UN1	600	11.41	4.30	32.56	15.73	2.07
UN2	600	8.18	2.75	14.88	10.65	1.40

Table 37. Average starting test dimensions and properties continued.

Test ID	Canal Wetted Area (ft^2)	Dams Wetted Area (ft^2)	Total Test Wetted Area (ft^2)	% Dam Wetted Area
16HC1	63649	79	63728	0.12%
16HC2	14432	54	14486	0.37%
BV1	58467	28	58496	0.05%
BV2	30815	13	30828	0.04%
DL1-16	67044	125	67169	0.19%
DL1-20	145471	167	145638	0.11%
DL2	24762	25	24787	0.10%
DL3	45669	87	45756	0.19%
DO1	9475	11	9485	0.11%
DO2	12567	21	12588	0.16%
DO3	10032	11	10043	0.11%
ED1	15603	17	15620	0.11%
ED2	12342	15	12357	0.12%
ED3	6295	5	6301	0.09%
ED4	12244	6	12250	0.05%
HA1	88679	36	88715	0.04%
HA2	19052	28	19079	0.14%
LF1	8744	56	8801	0.64%
LF2	7828	48	7876	0.61%
ME1	88737	22	88759	0.02%
ME2	28373	27	28400	0.09%
SJ01	69453	32	69484	0.05%
SJ04	11244	49	11294	0.43%
SJ05	13433	74	13508	0.55%
SJ06	38318	29	38348	0.08%
SJ07	57489	39	57528	0.07%
SJ8	46559	89	46648	0.19%
SJ09	42157	77	42234	0.18%
SJ10	15965	89	16054	0.55%
SJ11	42580	87	42667	0.20%
UN1	9437	65	9502	0.69%
UN2	6388	30	6418	0.46%

Table 38. Canal geometric property change.

Test ID	Change in WP (ft)	Change in Depth (ft)	% Loss Rate Increase
16HC1	0.95	0.67	5.9%
16HC2	0.70	0.50	5.1%
BV1	2.31	1.79	30.8%
BV2	1.86	1.72	42.6%
DL1-16	0.01	0.03	0.1%
DL1-20	0.02	0.03	0.2%
DL2	1.16	0.82	13.6%
DL3	0.28	0.18	1.0%
DO1	1.09	0.82	21.5%
DO2	1.47	1.16	21.5%
DO3	2.43	1.55	58.3%
ED1	0.74	0.66	10.9%
ED2	0.36	0.32	5.9%
ED3	0.59	0.38	13.2%
ED4	1.28	0.84	39.1%
HA1	0.13	0.09	1.1%
HA2	0.64	0.45	6.8%
LF1	0.91	0.65	6.7%
LF2	2.38	1.95	26.7%
SJ01	0.63	0.45	6.3%
SJ04	0.70	0.34	4.8%
SJ05	0.69	0.49	4.3%
SJ06	0.96	0.67	7.0%
SJ07	0.95	0.62	5.2%
SJ09	1.12	0.70	6.9%
SJ10	0.25	0.18	1.4%
SJ11	0.25	0.17	1.4%
UN1	1.24	0.88	8.5%
UN2	1.14	0.80	12.0%

APPENDIX B

LOSS RATE POWER FUNCTIONS AND GRAPHS

Table 39. Power functions for test loss rates.

Test ID	Power equation	R^2 Value	24hr Loss (x = 1) (ft^3/ft^2/day)
16HC1	$y = 0.3025x^{-0.154}$	0.9928	0.30
16HC2	$y = 0.2289x^{-0.191}$	0.9896	0.23
BV1	$y = 1.3601x^{-0.191}$	0.9916	1.36
BV2	$y = 1.5917x^{-0.19}$	0.9614	1.59
DL1-16	$y = 0.0249x^{-0.382}$	0.9985	0.02
DL1-20	$y = 0.0193x^{-0.407}$	0.7876	0.02
DL2	$y = 0.6159x^{-0.601}$	0.9868	0.62
DL3	$y = 0.0687x^{-0.376}$	0.9285	0.07
DO1	$y = 0.37x^{-0.317}$	0.9766	0.37
DO2	$y = 0.5785x^{-0.514}$	0.9837	0.58
DO3	$y = 0.6688x^{-0.302}$	0.9929	0.67
ED1	$y = 2.4802x^{-0.307}$	0.9911	2.48
ED2	$y = 1.0354x^{-0.421}$	0.9934	1.04
ED3	$y = 0.7952x^{-0.324}$	0.9971	0.80
ED4	$y = 2.2199x^{-0.247}$	1.0000	2.22
HA1	$y = 0.0795x^{-0.337}$	0.9658	0.08
HA2	$y = 0.3319x^{-0.043}$	0.4055	0.33
LF1	$y = 0.3095x^{-0.005}$	0.2948	0.31
LF2	$y = 1.3945x^{-0.404}$	0.9949	1.40
SJ01	$y = 0.336x^{-0.184}$	0.9865	0.34
SJ04	$y = 0.1746x^{-0.149}$	0.9571	0.18
SJ05	$y = 0.1844x^{-0.367}$	0.9585	0.18
SJ06	$y = 0.3216x^{-0.186}$	0.9955	0.32
SJ07	$y = 0.2958x^{-0.139}$	0.973	0.30
SJ08	$y = 0.3787x^{-0.36}$	0.9534	0.38
SJ09	$y = 0.3485x^{-0.231}$	0.9709	0.35
SJ10	$y = 0.0916x^{-0.233}$	0.9944	0.09
SJ11	$y = 0.0795x^{-0.052}$	0.8666	0.08
SJ15	$y = 0.0234x^{-1}$	1.0000	0.02
UN1	$y = 0.4563x^{-0.146}$	0.9993	0.46
UN2	$y = 0.4085x^{-0.308}$	0.9989	0.41

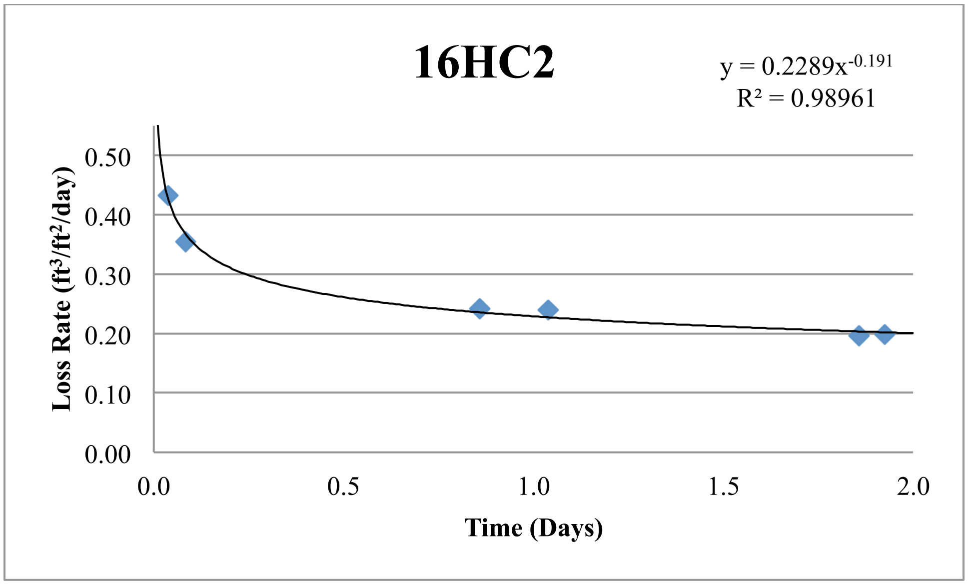

Figure 25. Test 16HC2 loss rates fitted with power function.

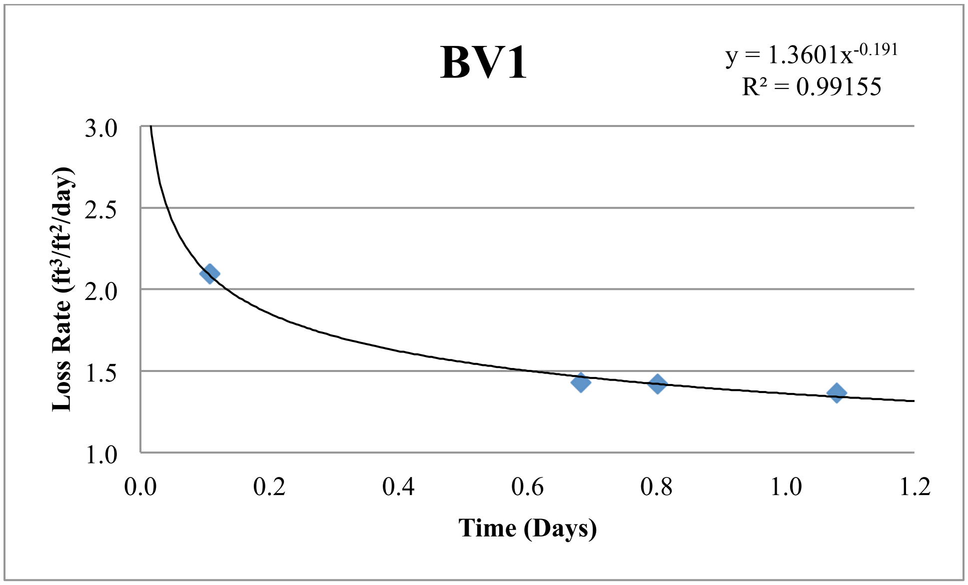

Figure 26. Test BV1 loss rates fitted with power function.

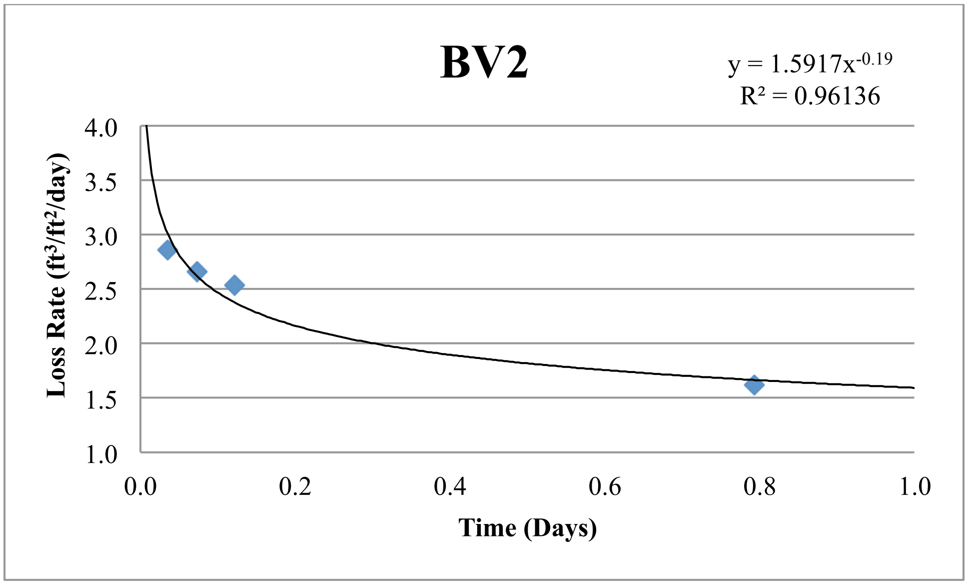

Figure 27. Test BV2 loss rates fitted with power function.

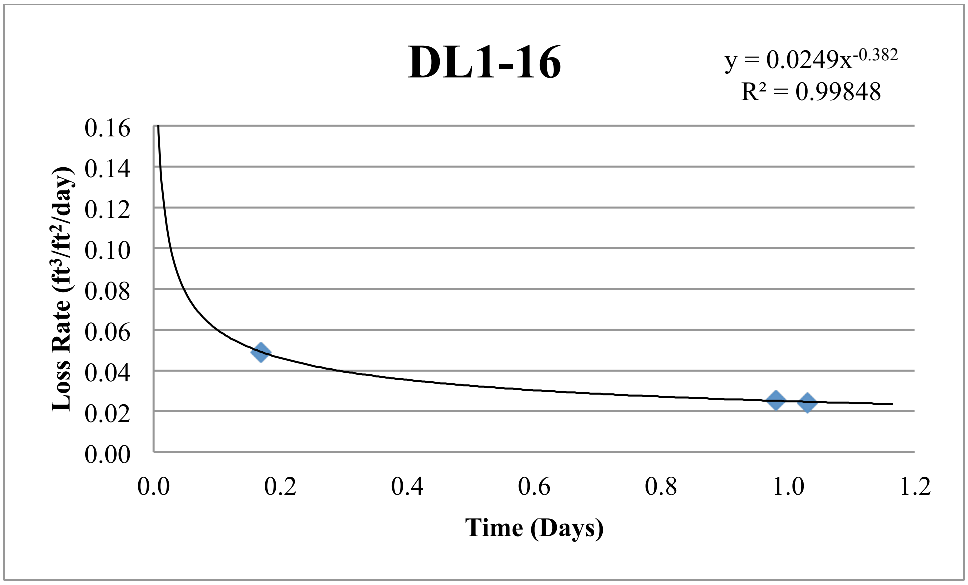

Figure 28. Test DL1-16 loss rates fitted with power function.

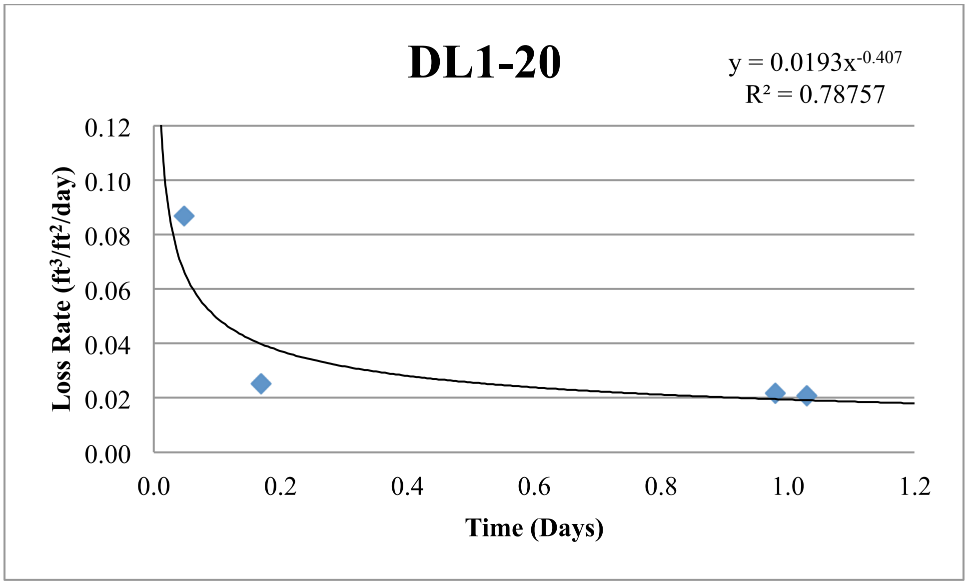

Figure 29. Test DL1-20 loss rates fitted with power function.

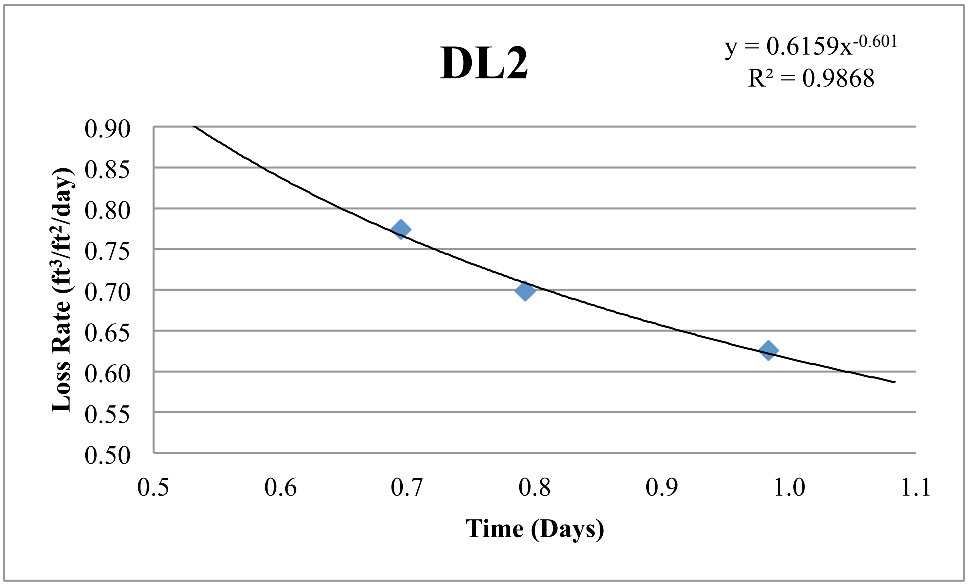

Figure 30. Test DL2 loss rates fitted with power function.

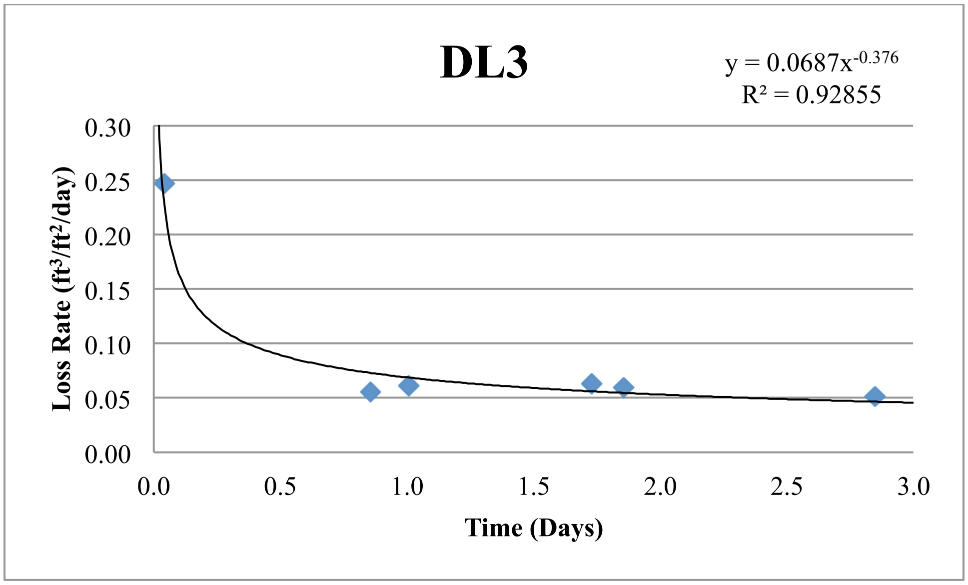

Figure 31. Test DL3 loss rates fitted with power function.

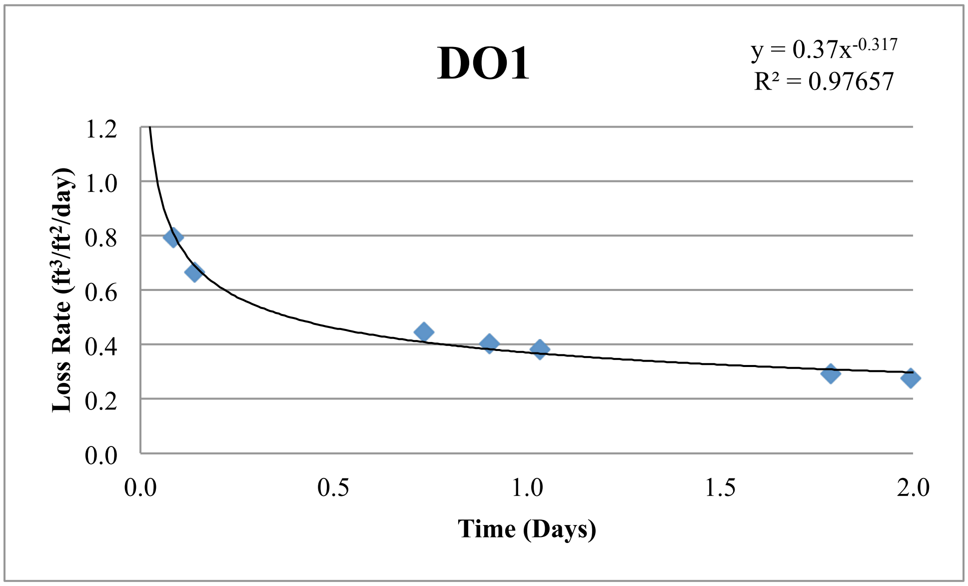

Figure 32. Test DO1 loss rates fitted with power function.

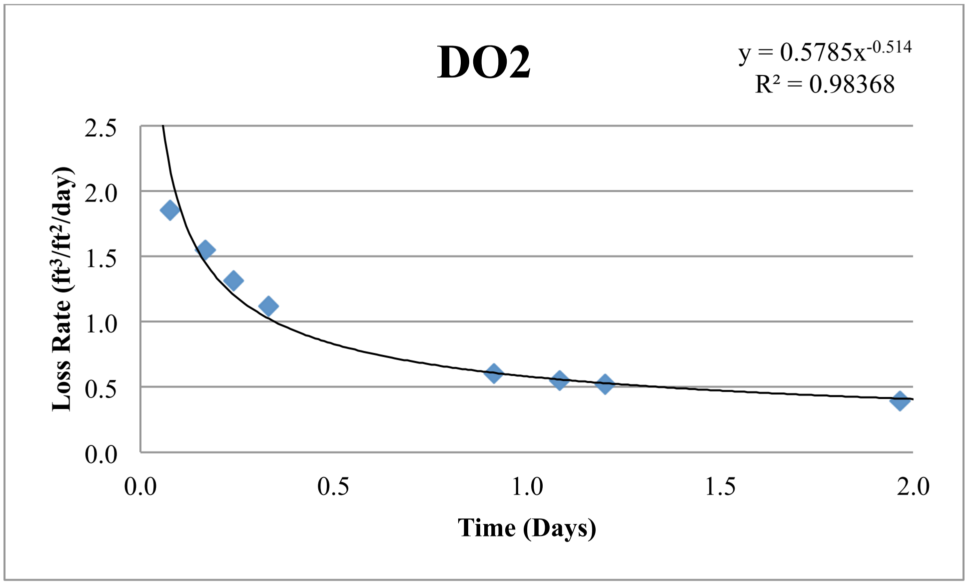

Figure 33. Test DO2 loss rates fitted with power function.

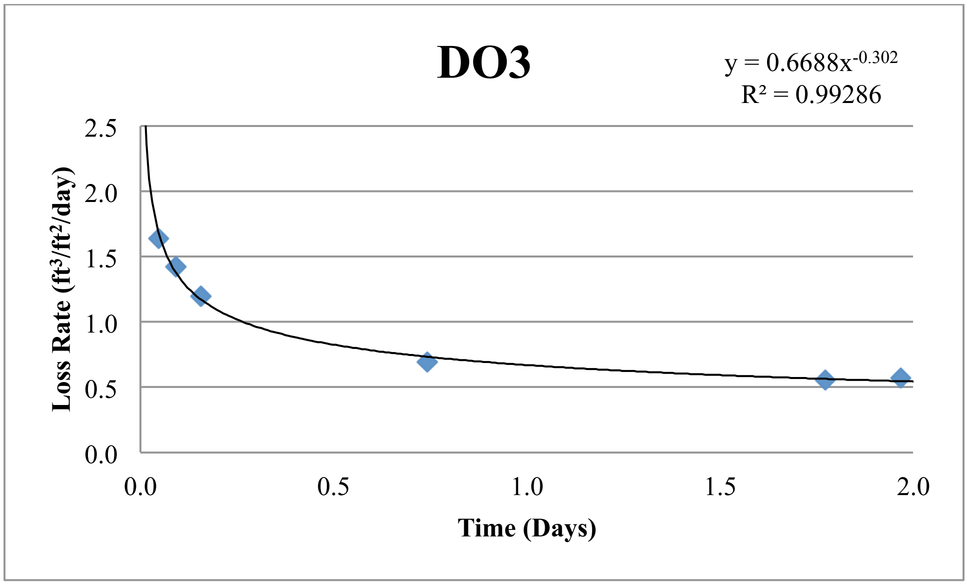

Figure 34. Test DO3 loss rates fitted with power function.

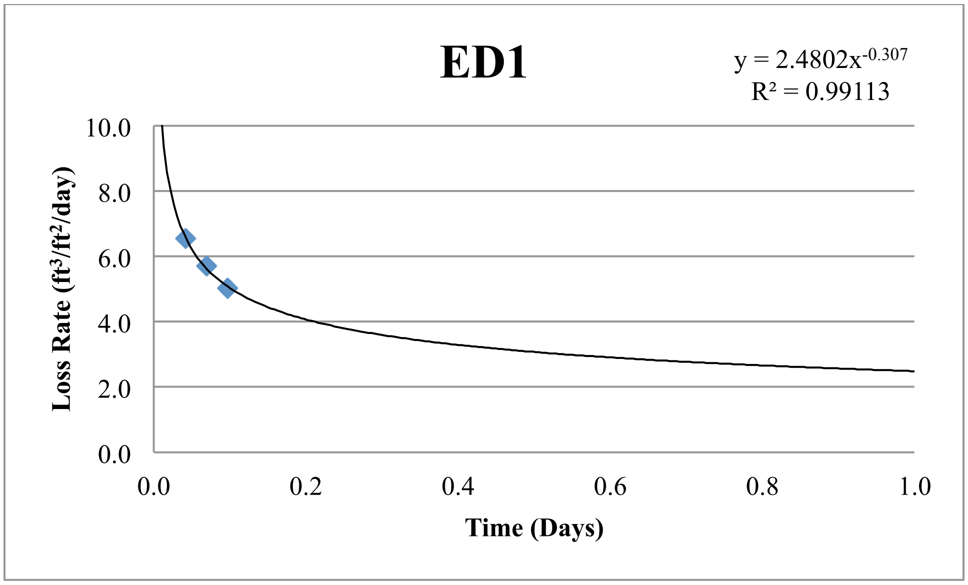

Figure 35. Test ED1 loss rates fitted with power function.

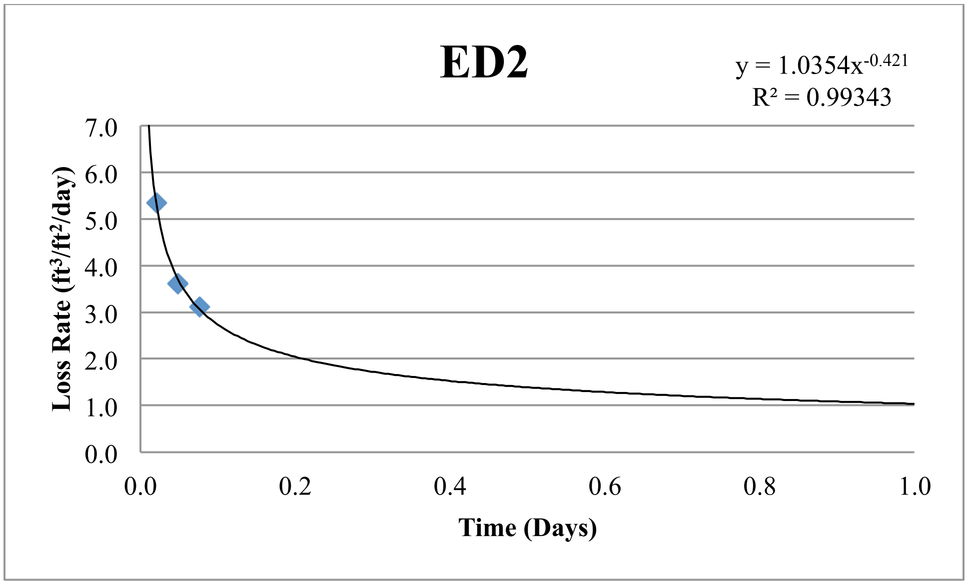

Figure 36. Test ED2 loss rates fitted with power function.

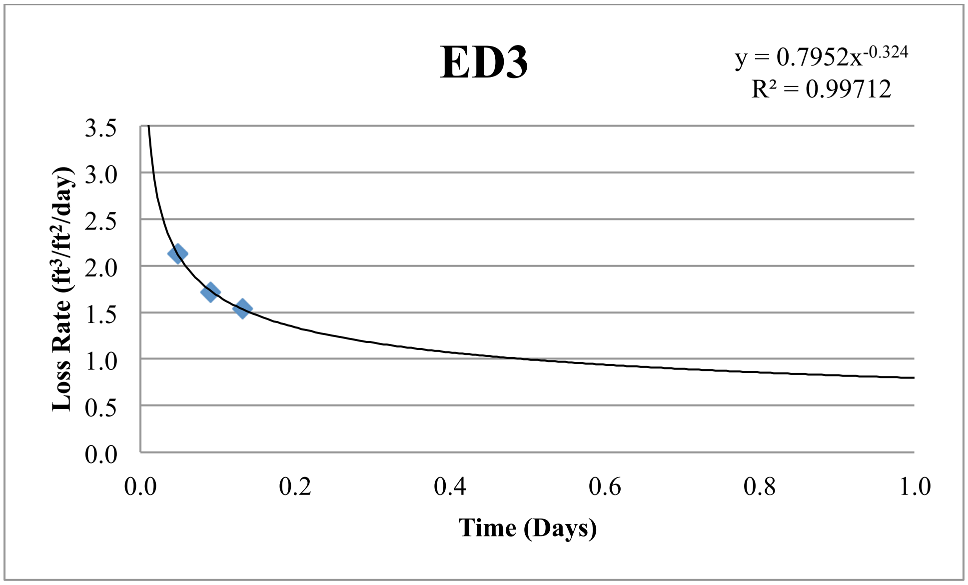

Figure 37. Test ED3 loss rates fitted with power function.

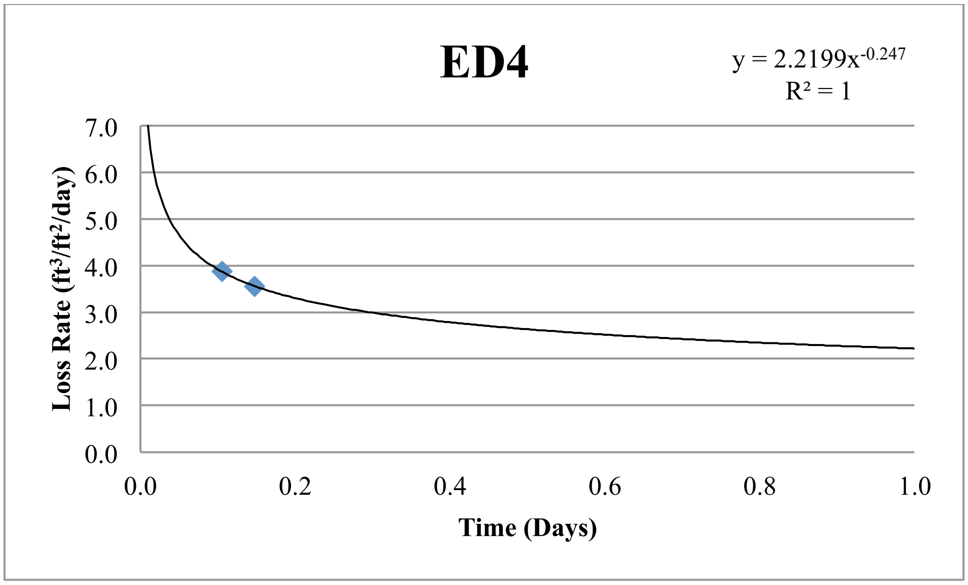

Figure 38. Test ED4 loss rates fitted with power function.

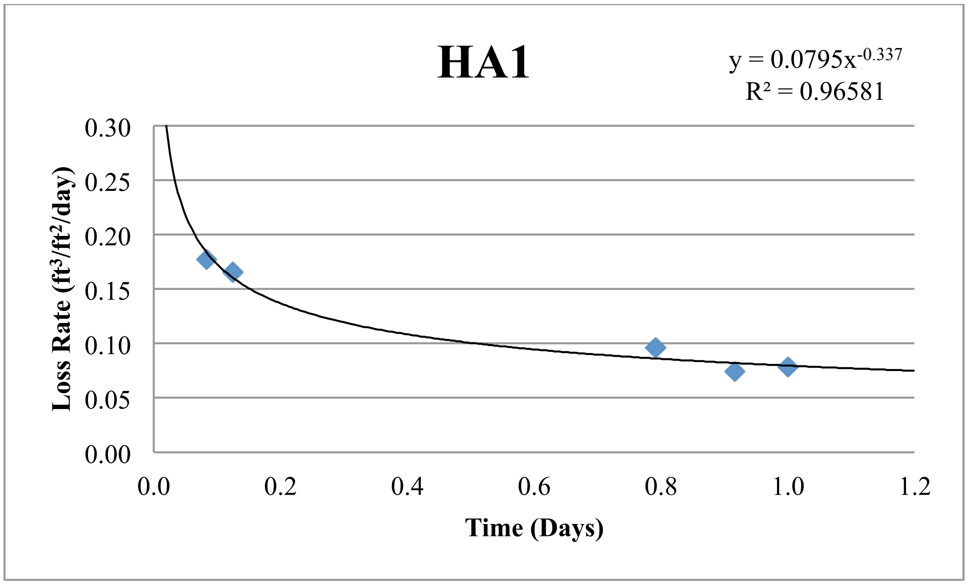

Figure 39. Test HA1 loss rates fitted with power function.

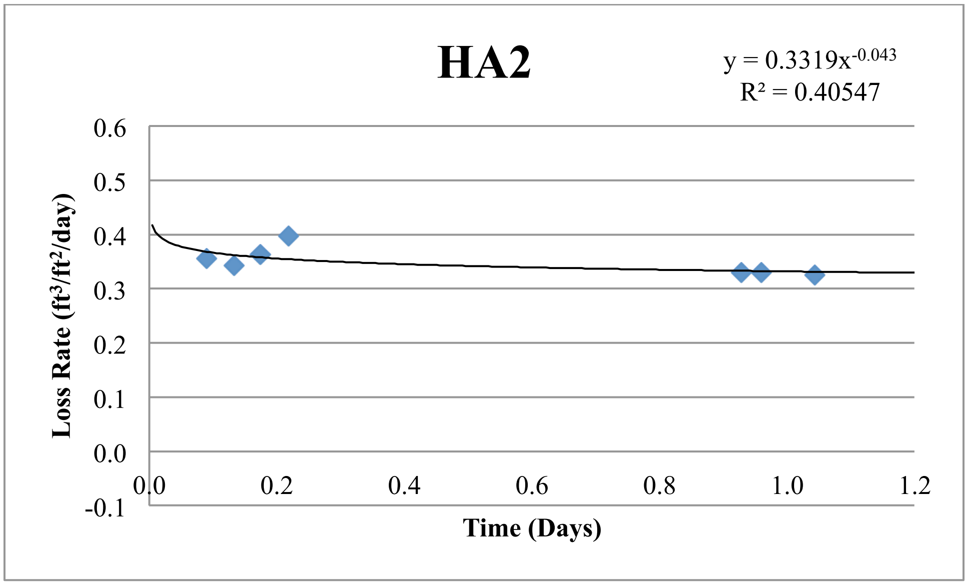

Figure 40. Test HA2 loss rates fitted with power function.

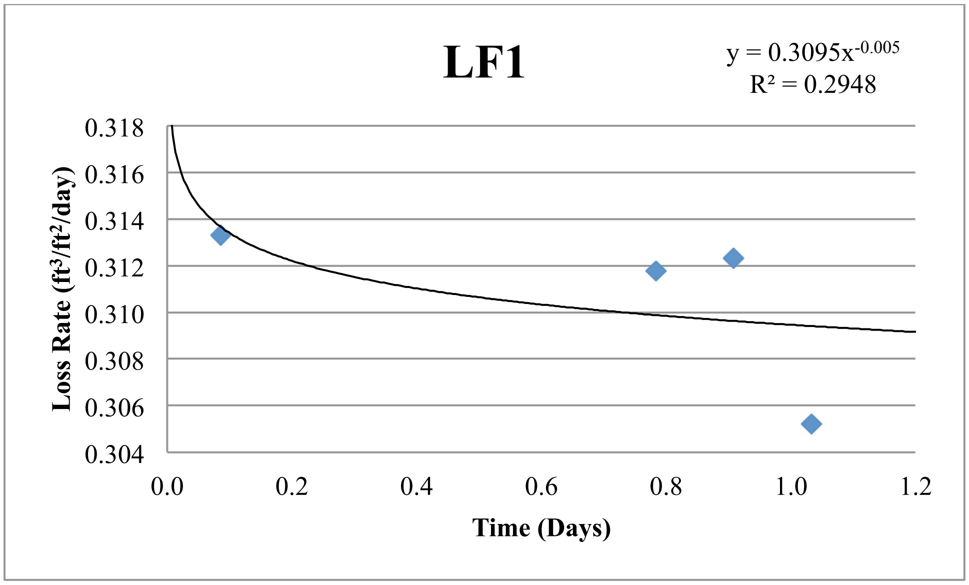

Figure 41. Test LF1 loss rates fitted with power function.

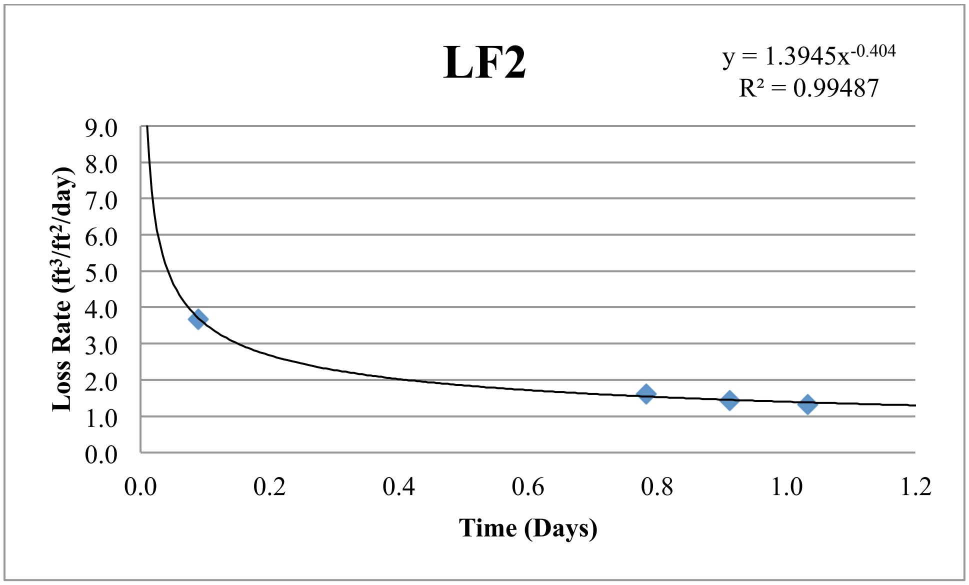

Figure 42. Test LF2 loss rates fitted with power function.

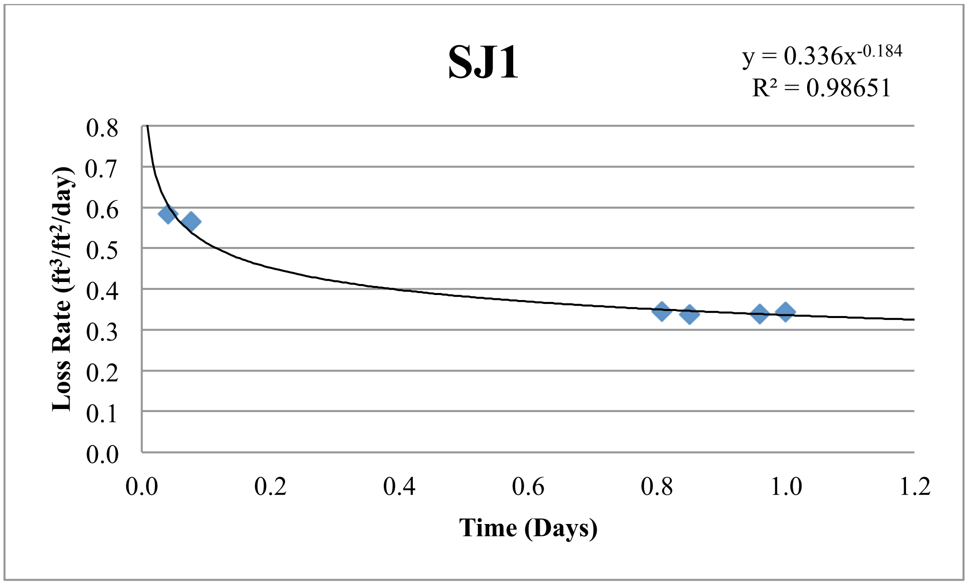

Figure 43. Test SJ1 loss rates fitted with power function.

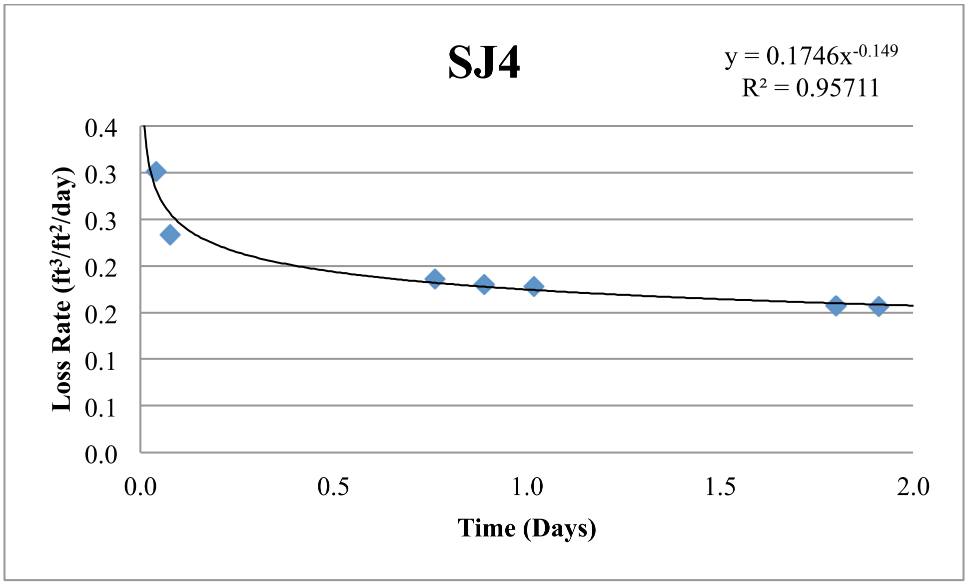

Figure 44. Test SJ4 loss rates fitted with power function.

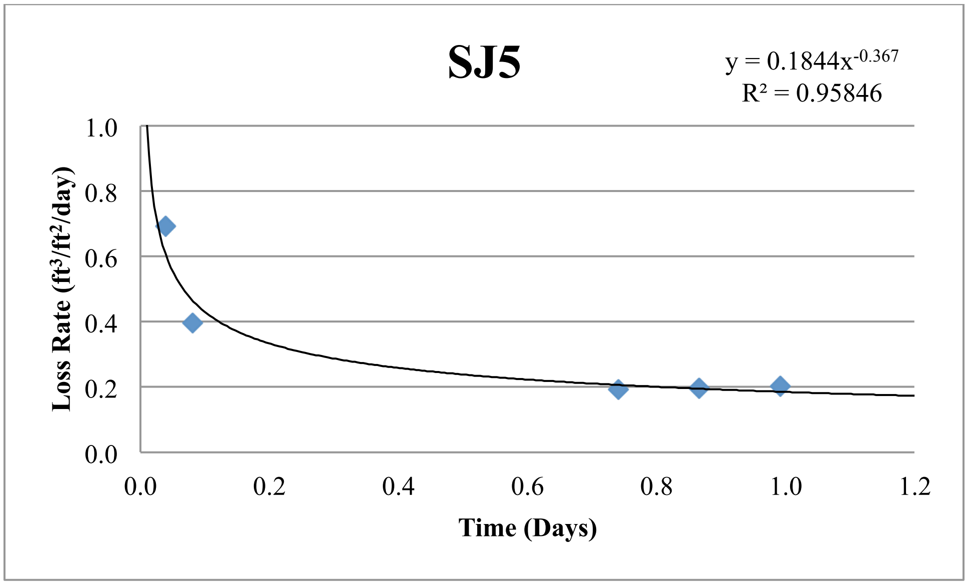

Figure 45. Test SJ5 loss rates fitted with power function.

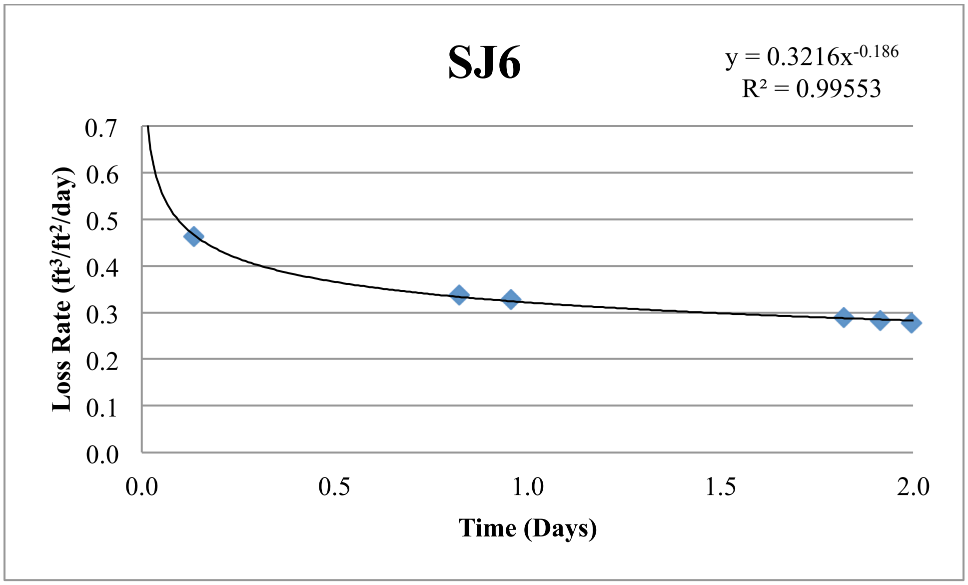

Figure 46. Test SJ6 loss rates fitted with power function.

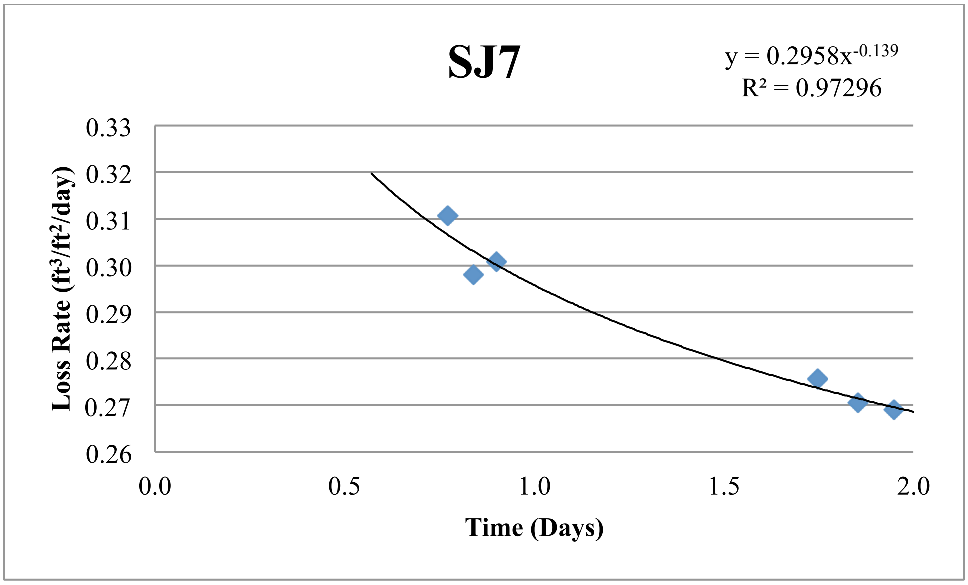

Figure 47. Test SJ7 loss rates fitted with power function.

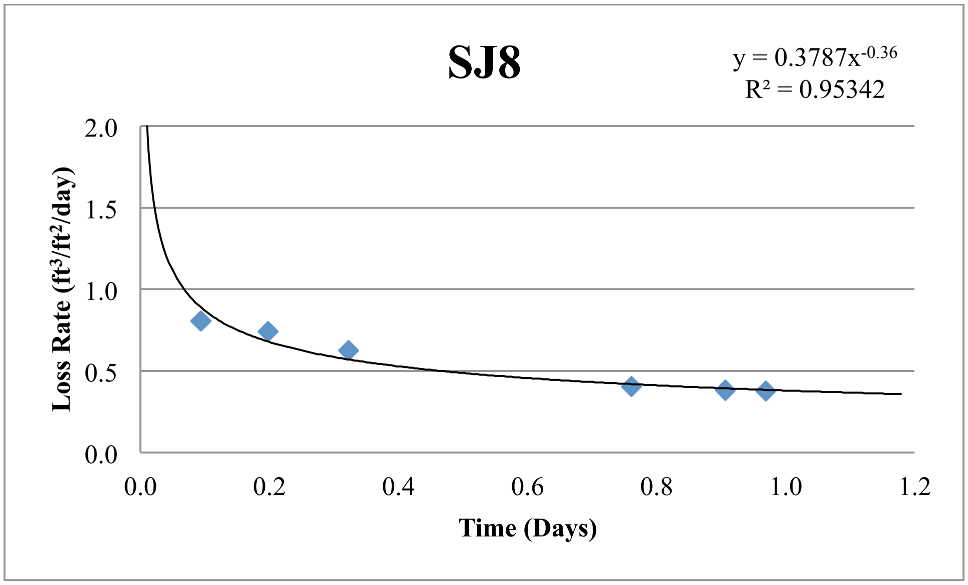

Figure 48. Test SJ8 loss rates fitted with power function.

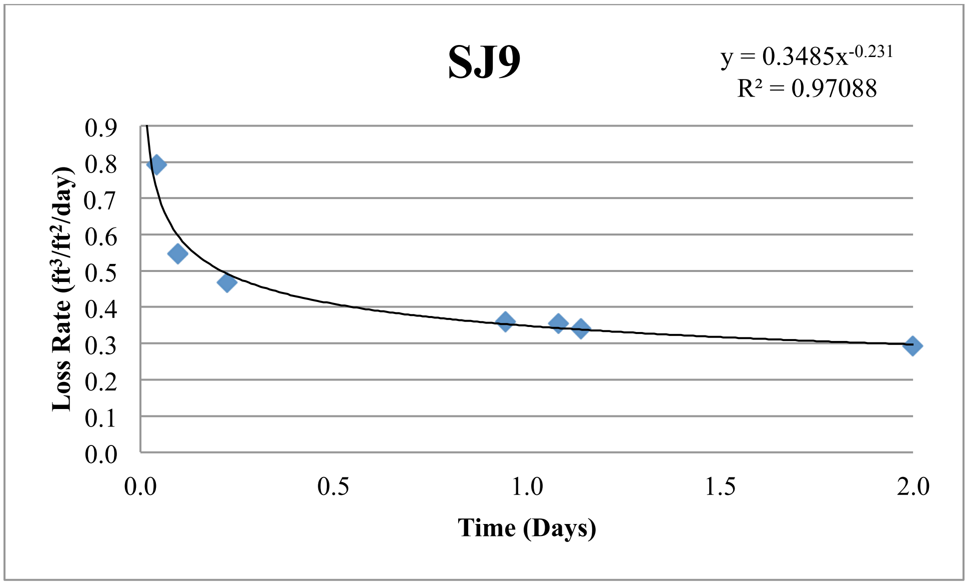

Figure 49. Test SJ9 loss rates fitted with power function.

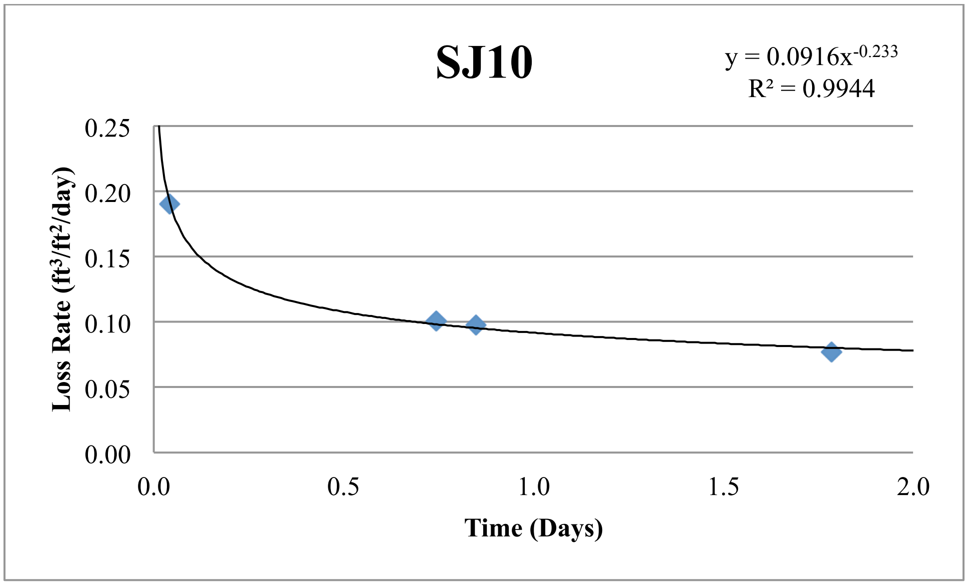

Figure 50. Test SJ10 loss rates fitted with power function.

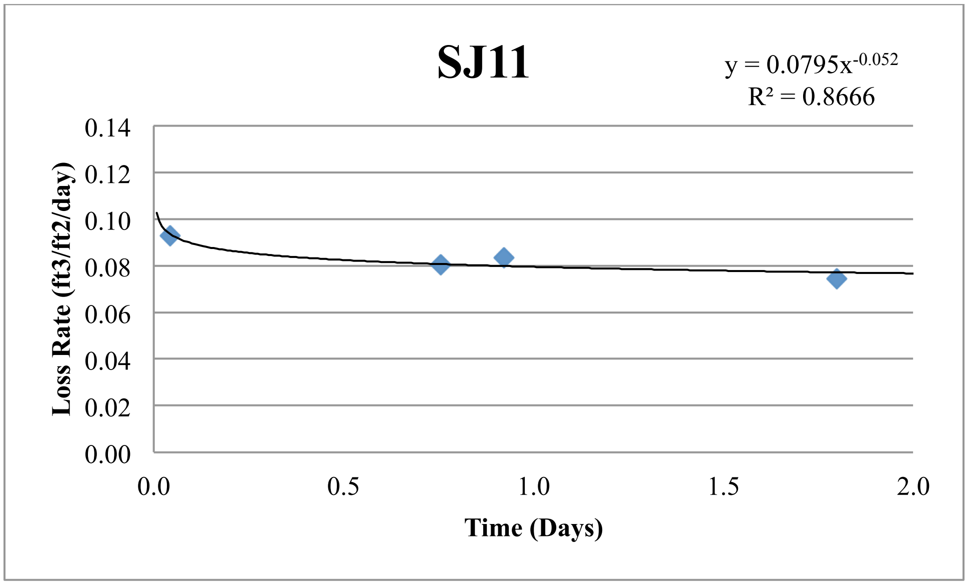

Figure 51. Test SJ11 loss rates fitted with power function.

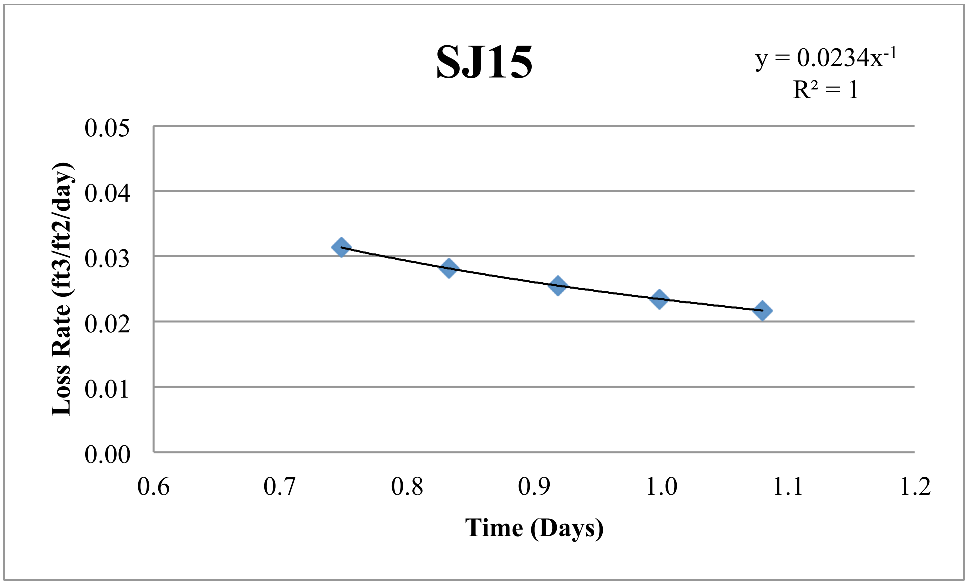

Figure 52. Test SJ15 loss rates fitted with power function.

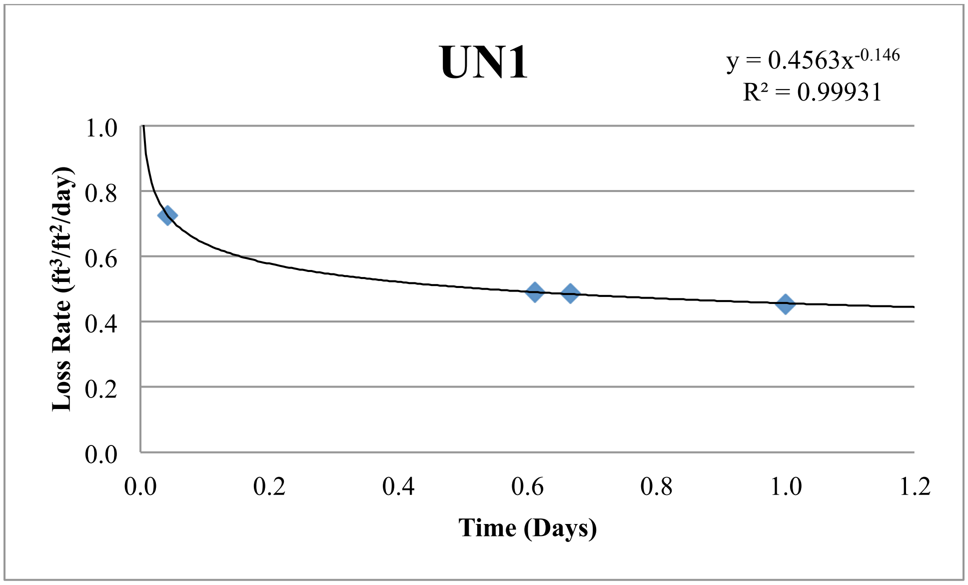

Figure 53. Test UN1 loss rates fitted with power function.

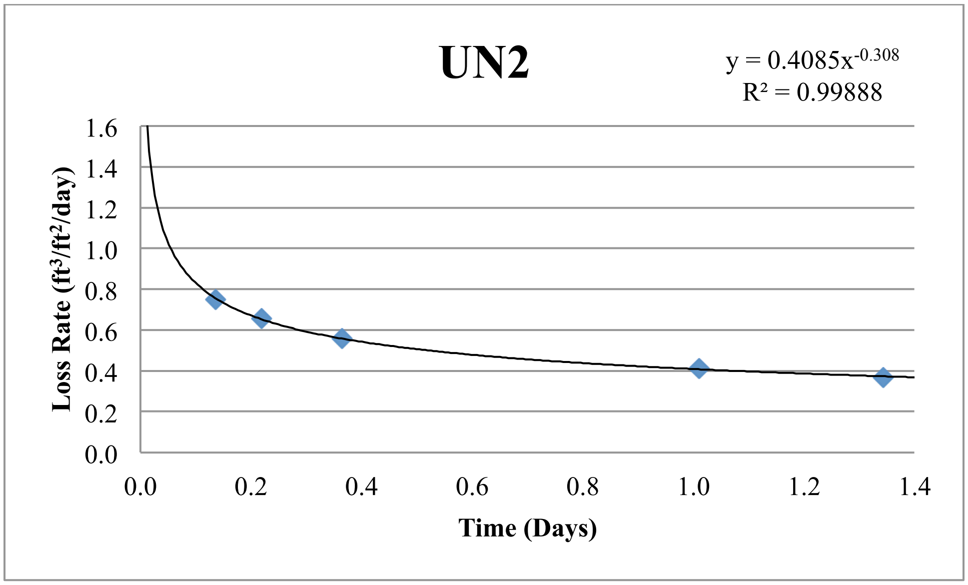

Figure 54. Test UN2 loss rates fitted with power function.

APPENDIX C

ETO SUMMARY TABLES

Table 40. ETo rates and percentages of loss.

Test ID	Avg. Test ETo Rate		ETo 0.8 Adjusted Rate		ETo 0.6 Adjusted Rate	
	(ft/day)	(ft^3/ft^2/day)	(ft^3/ft^2/day)	% of Loss	(ft^3/ft^2/day)	% of Loss
16HC1	0.015	0.012	0.010	3.1%	0.007	2.4%
16HC2	0.012	0.010	0.008	3.3%	0.006	2.5%
BV1	0.008	0.006	0.005	0.4%	0.004	0.3%
BV2	0.012	0.009	0.008	0.5%	0.006	0.4%
DL1-16	0.008	0.007	0.005	22.7%	0.004	17.1%
DL1-20	0.008	0.007	0.005	28.2%	0.004	21.1%
DL2	0.009	0.006	0.005	0.8%	0.004	0.6%
DL3	0.004	0.003	0.003	4.0%	0.002	3.0%
DO1	0.021	0.014	0.011	3.0%	0.008	2.2%
DO2	0.021	0.013	0.011	1.9%	0.008	1.4%
DO3	0.021	0.014	0.011	1.6%	0.008	1.2%
ED1	0.007	0.005	0.004	0.2%	0.003	0.1%
ED2	0.007	0.005	0.004	0.4%	0.003	0.3%
ED3	0.005	0.002	0.002	0.2%	0.001	0.2%
ED4	0.005	0.002	0.002	0.1%	0.001	0.1%
HA1	0.003	0.002	0.002	2.1%	0.001	1.6%
HA2	0.011	0.008	0.006	1.9%	0.005	1.5%
LF1	0.014	0.011	0.008	2.7%	0.006	2.0%
LF2	0.014	0.011	0.009	0.6%	0.006	0.5%
ME1	0.014	0.012	0.009	4.4%	0.007	3.3%
ME2	0.014	0.012	0.010	5.4%	0.007	4.1%
SJ01	0.012	0.009	0.007	2.1%	0.005	1.6%
SJ04	0.013	0.012	0.010	5.5%	0.007	4.1%
SJ05	0.013	0.010	0.008	4.5%	0.006	3.4%
SJ06	0.004	0.003	0.003	0.8%	0.002	0.6%
SJ07	0.004	0.004	0.003	1.0%	0.002	0.7%
SJ08	0.009	0.015	0.007	8.2%	0.005	6.2%
SJ09	0.019	0.008	0.012	3.2%	0.009	2.4%
SJ10	0.009	0.007	0.006	1.8%	0.005	1.3%
SJ11	0.009	0.008	0.006	6.3%	0.004	4.7%
UN1	0.021	0.015	0.012	2.7%	0.009	2.0%
UN2	0.021	0.016	0.013	3.1%	0.010	2.4%

Table 41. ETo adjusted loss rates (ft^3/ft^2/day).

Test ID	Revised Loss Rates	Revised Loss Rates adjusted by		
		Avg ETo	0.8 ETo	0.6 ETo
16HC1	0.303	0.291	0.293	0.295
16HC2	0.229	0.219	0.221	0.223
BV1	1.360	1.354	1.355	1.356
BV2	1.592	1.582	1.584	1.586
DL1-16	0.025	0.018	0.020	0.021
DL1-20	0.019	0.012	0.014	0.015
DL2	0.616	0.610	0.611	0.612
DL3	0.069	0.065	0.066	0.067
DO1	0.370	0.356	0.359	0.362
DO2	0.579	0.565	0.568	0.570
DO3	0.669	0.655	0.658	0.661
ED1	2.480	2.476	2.476	2.477
ED2	1.035	1.031	1.032	1.033
ED3	0.795	0.793	0.793	0.794
ED4	2.220	2.217	2.218	2.218
HA1	0.080	0.077	0.078	0.078
HA2	0.332	0.324	0.325	0.327
LF1	0.310	0.299	0.301	0.303
LF2	1.395	1.384	1.386	1.388
ME1	0.214	0.202	0.205	0.207
ME2	0.180	0.168	0.170	0.173
SJ01	0.336	0.327	0.329	0.331
SJ04	0.175	0.163	0.165	0.167
SJ05	0.184	0.174	0.176	0.178
SJ06	0.322	0.318	0.319	0.320
SJ07	0.296	0.292	0.293	0.294
SJ08	0.379	0.364	0.367	0.370
SJ09	0.349	0.341	0.342	0.344
SJ10	0.092	0.084	0.086	0.087
SJ11	0.080	0.071	0.073	0.075
UN1	0.456	0.441	0.444	0.447
UN2	0.409	0.392	0.396	0.399

APPENDIX D

CANAL CONDITION RATING TABLES

Table 42. New lined canal condition scores and Davis-Wilson calibrated C-values.

Test ID	Crack Frequency (1-3)	Crack Size (1-3)	Rating (2-6)	Ranking (1-3)	Calibrated C-Values
16HC1	2	1	3	1	8.6
16HC2	2	1	3	1	7.0
BV1	2	3	5	3	47.3
BV2	3	3	6	3	60.4
DL1-16	1	2	3	1	0.8
DL1-20	1	2	3	1	0.5
DL2	2	2	4	2	20.6
DL3	2	3	5	3	1.9
ED1	3	3	6	3	91.0
ED2	3	3	6	3	39.1
ED3	3	1	4	2	31.7
ED4	3	1	4	2	89.8
HA1	2	1	3	1	2.8
HA2	3	2	5	3	10.5
LF1	1	1	2	1	9.2
LF2	1	3	4	2	42.5
ME1	1	2	3	1	7.9
ME2	2	1	3	1	6.5
SJ01	1	2	3	1	10.7
SJ04	1	1	2	1	5.7
SJ05	1	1	2	1	5.1
SJ06	1	1	2	1	9.6
SJ07	1	1	2	1	8.6
SJ08	2	1	3	1	10.6
UN1	3	1	4	2	13.0
UN2	3	1	4	2	13.5
*CCWID11	1	1	2	1	NA
*CCWID1-Lat.26	2	1	3	1	NA
*CCWID1-Lat.26-1in	2	1	3	1	NA
*HCWC&ID1-Lat 4M	1	1	2	1	NA
*HCWC&ID6-Lat.C	1	2	3	1	NA
*HWC&ID6-Lat.B5	1	2	3	1	NA