USING AN ADCP TO DETERMINE CANAL SEEPAGE LOSSES IN THE MIDDLE RIO GRANDE CONSERVANCY DISTRICT

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ABSTRACT

Seepage from earthen irrigation canals represents substantial water loss in irrigation districts. Historically, the determination of canal seepage was accomplished using the inflow-outflow method with propeller and electromagnetic type flow meters. This method was difficult, time consuming, and limited by measurement device accuracy. In recent years, advances in technology have lead to the widespread use of Acoustic Doppler Current Profilers (ADCP) for discharge measurements in streams and rivers. Even though ADCP use has become widespread for stream discharges, studies to determine canal seepage using this new technology are limited. Using an ADCP, extensive field measurements were conducted in the Middle Rio Grande Conservancy District. This paper describes the ADCP measurement protocol used to measure irrigation canal seepage and presents predictive equations for determining canal seepage based on flow rate and canal geometry.

INTRODUCTION

According to an Interagency Task Force, the average off-farm water conveyance efficiency for irrigation in the United States is 78% (ITF, 1979) and conveyance loses account for 104 million cubic meters per day (Herschy and Fairbridge, 1998). This seepage represents ten times the daily U.S. domestic water use (Herschy and Fairbridge, 1998). In the Lower Rio Grande Valley, canal seepage accounts for 30-36% of the total diverted water (Fipps, 2001). The major factors that affect seepage rates in irrigation canals are soil permeability, canal length, length and shape of wetted perimeter, water depth, depth to the groundwater table, and presence of other constraints such as wells, drains, and impermeable soil layers (Akbar, 2005; Alam and Bhutta, 2004; Swamee et al. 2000). Some less significant factors include sediment load and size distribution, age of the canal, presence of aquatic plants, viscosity, and salinity of the canal water (Akbar, 2005; Alam and Bhutta, 2004; Swamee et al. 2000).

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Determining canal seepage is usually a difficult undertaking. Fluctuations in canal levels as well as groundwater levels can lead to variations throughout a year and within an irrigation season. Additionally, the amount lost to seepage often falls within the discharge measurement errors of traditional methods.

Overall, the inflow-outflow method has been the preferred method for determining seepage (Alam and Bhutta, 2004; Skogerboe et al. 1999), but is limited by measurement accuracy, time required for measurement, and canal depth and discharge fluctuations. Through the use of an Acoustic Doppler Current Profiler (ADCP) the limitations of the inflow- outflow method can be addressed resulting in high quality, replicable, and efficient measurements of canal seepage.

ADCPs allow for rapid flow rate and velocity measurements in rivers and other open channels (Shields and Rigby, 2005). An ADCP measures the Doppler shift of acoustic signals that are reflected by suspended particles in the water (Rennie and Rainville, 2006; Shields and Rigby, 2005). In recent years the ADCP has become the standard for measuring river discharges as well as velocity distribution (Rennie and Rainville, 2008; Mueller et al. 2007) and ADCP measurements have been shown to be more accurate and as reliable as traditional measurement.

One of the primary advantages of an ADCP is the speed and detail in which data can be collected (Carr and Rehmann, 2007). The amount of data that can be collected about velocity characteristics for a given measurement location greatly exceeds traditional methods and techniques, such as propeller or electromagnetic meters (Carr and Rehmann, 2007; Shields and Rigby, 2005). A significant benefit of the ADCP over traditional meters is that no intrusion into a water body is required, which decreases the risk to operators and increases the overall usefulness of the device (Nystrom et al. 2007).

To date ADCPs have not been extensively used for determining canal seepage although they have found widespread implementation for measuring streamflow. This paper presents the use of an ADCP in the Middle Rio Grande Valley to determine canal seepage rates.

Middle Rio Grande Conservancy District

The Middle Rio Grande Conservancy District (MRGCD) was formed in 1925 in response to flooding and the deterioration of previously constructed irrigation works. The district stretches over a distance of approximately 193 kilometers in the Middle Rio Grande Valley in Central New Mexico with 25,000 ha of irrigated agriculture. Water is conveyed in the MRGCD by gravity flow through primarily earthen canals whose total length exceeds 2,400 kilometers.

Only limited measurements of canal seepage have been previously conducted in the Middle Rio Grande Valley and no equations have been developed to predict seepage loss. Because canal seepage losses can represent a significant portion of diverted water and the MRGCD is focused on improving efficiency, a measurement study was conducted to determine canal seepage rates throughout the MRGCD. Through the availability of an ADCP, this study provided the unique opportunity to apply advanced technology in determining irrigation canal seepage rates under normal operating conditions.

MATERIAL AND METHODS

The ADCP model used for this study was the Teledyne RD Instrument StreamPro. The StreamPro is designed to make moving boat discharge measurements in flow depths from 2.36 cm to 2 meters (AuBuchon et al. 2008; Rehmel, 2006) and has a 2,000-kHz frequency with a small four beam transducer head. The processing software provides velocity profile data over an entire cross section (Figure 1).

The inflow-outflow method using an ADCP was chosen for the determination of canal seepage rates in the Middle Rio Grande Valley. This method was selected because it allows for measurement during normal operating conditions, it is a non-intrusive measurement technique, and previous studies have established this as the preferred method in determining canal seepage (Alam and Bhutta, 2004; Skogerboe et al. 1999). The inflow-outflow method is based on creating a water balance in an irrigation canal where inflow and outflow are measured a certain distance apart. These measurements were taken while ensuring that no water is being diverted of introduced into the measurement reach. The use of an ADCP in tandem with pressure transducers ensured that measurement errors associated with fluctuations in water level were addressed. Coordination with water managers was essential to guarantee that inflow-outflow measured sections had no withdrawals through headgates during the measurement period. A previous study conducted by the MRGCD determined that open water evaporation from the canal system was negligible and therefore evaporation was not incorporated into the analysis of the canal seepage water balance determination.

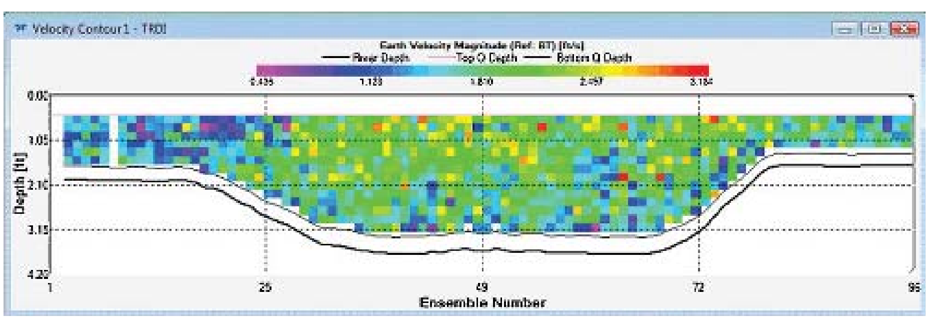

Figure 1. Velocity Profile Measured by ADCP in the Middle Rio Grande Conservancy District (MRGCD)

MEASUREMENT PROTOCOL

The measurement protocol used for the collection of canal seepage data followed the standard USGS ADCP data collection method (Oberg 2005; Simpson, 2001; Morlock 1996). A bank-operated rope and pulley system was deployed and used to move the StreamPro across the channel and back for each transect measurement (Figure 2). Bank-operated pulley setups allow for a more uniform pull, reduced boat motion, and consistent edge measurements.

Figure 2. Bank-operated rope and pulley system with operator and ADCP

All data were collected using the ADCP water mode 12 (WM 12). This is a general purpose mode recommended by the manufacturer (RD Instruments) for high-resolution flow measurements in rivers, streams, and other bodies of water.

In order to verify that storage in the canal was not changing, pressure transducers and temporary staff gages were used during inflow and outflow measurements to monitor water level fluctuations. The pressure transducers used were HOBO brand data loggers manufactured by Onset Incorporated. This data made it possible to determine the exact fluctuation in canal water level.

Once the initial setup and edge data collection was complete, four transects were collected using the USGS ADCP measurement guidelines (Oberg 2005; Rehmel, 2004; Simpson, 2001; Morlock 1996). If the standard deviation between the measurements exceeded 5% of the average, four more transects were collected following the standard USGS protocol. Measurements were conducted on three main canals, three lateral canals, and three acequia (tertiary) canals at three separate times during the irrigation season totaling 25 seepage measurements. The time span of the study was from June11th to October 23rd 2008 with an early, middle, and late season measurement conducted for each canal to address seasonal variability.

The measurements were taken at the upstream inflow and downstream outflow along a significant distance of canal. For each canal, a measurement site was established where a significant length of canal was available for inflow and outflow measurements without water diversions or additions to the flow. To ensure that all irrigation had ceased on the canal, all of the headgates along the canal were checked to see if they were closed. The distance between upstream and downstream measurements was made as long as possible to ensure that a measurable amount of canal seepage could be detected. In most cases this distance exceeded 3.2 kilometers (Table 1). GPS coordinates were taken at both the upstream and downstream measurement locations so that the exact distance between the two stations could be determined using Geographical Information System (GIS) software and maps were created for each canal section measured.

RESULTS

The data collected and subsequent analysis resulted in a database that contained the following information for each seepage measurement location: maximum change in water level, percent change in flow depth, upstream flow rate, downstream flow rate, canal length over which seepage was measured, total change in flow rate across the measured distance, upstream wetted perimeter, upstream flow area, maximum depth upstream, upstream top width, upstream average flow velocity, and percent loss of the inflow rate per mile. The upstream data were chosen for the database so that predictive seepage equations could be applied to upstream channel characteristics. Upstream channel characteristics are well defined for automated measurement sites throughout the MRGCD, and upstream characteristics are also required for determining seepage in the DSS used for scheduled water delivery (Oad et al. 2009). Table 1 displays the database developed from the measurement matrix. Two measurements were removed because of water deliveries from the canal: the Albuquerque Main Canal on 8/20/2008 and on the New Belen Acequia on 7/2/2008. This resulted in a total of 25 seepage measurements.

From the collected data it was determined that main canals exhibited the least amount of seepage with an average seepage rate of 0.64% per kilometer. Lateral canals and Acequia canals exhibited similar seepage rates with an average rate of 1.93% per kilometer and 1.84 % per kilometer, respectively. It was also found that no statistically significant difference in seepage rates existed throughout the season for the nine study canals as the variation fell within the standard deviation. The seepage loss rates obtained resemble results obtained by Fipps (2001) for canal seepage in the Lower Rio Grande Valley. The results also correspond well with a study in a Utah irrigation district that found seepage rates of 2% per kilometer (Napan et al. 2009). The suspected reasons for lower seepage rates in main canals include sedimentation, groundwater and maintenance. The main canals in the MRGCD are all directly connected to the Rio Grande and receive significant fine sediment loads. As water is conveyed down the main canals the sediment eventually settles out in the main canals reducing sediment load in lateral and acequia canals. The settling out in main canals results in soil pores being clogged with finer silt and clay sediment, thereby reducing overall seepage. Another reason for reduced seepage in main canals is the close proximity to the river and subsequent groundwater. Since the main canals originate at the Rio Grande they are not elevated above the river and could be connected to groundwater. Such close proximity to the groundwater would result in a small or negligible gradient for seepage from canal bottoms and to groundwater. Finally, the main canals in the MRGCD receive the most attention when it comes to maintenance and dredging. The main canal shapes in the MRGCD most closely represent the optimized canal sections for minimized seepage presented by (Swamee et al. 2000) and the continued maintenance of these main canals results in a more efficient canal shape and optimized water conveyance.

Table 1 shows the collected seepage data displaying canal name, measurement data, maximum change in water level, upstream and downstream flowrates, canal length over which seepage was measured, total change in flowrate, upstream wetted perimeter, upstream flow area, upstream maximum depth, upstream top width, upstream average flow velocity, and % loss per km.

Table 1.

Canal	US Flowrate (m^3/s)	DS Flowrate (m^3/s)	Length (km)	Total Change (m^3/s)	US Wetted Perimeter (m)	US Flow Area (m^2)	US Max Depth (m)	US Top Width (m)	US Average Flow Velocity (m/s)	Percent Loss per km
Main Canals										
Belen Highline	6.29	6.22	7.04	0.08	16.86	106.09	1.01	15.74	0.70	0.17
Belen Highline	6.54	6.39	7.04	0.15	14.59	127.90	1.09	13.69	0.55	0.32
Belen Highline	4.50	4.21	7.04	0.29	13.80	105.43	1.06	12.28	0.46	0.91
Socorro Main	6.46	6.23	4.44	0.23	10.75	105.72	1.56	8.67	0.68	0.81
Socorro Main	4.57	4.43	4.44	0.14	9.20	78.64	1.08	8.27	0.63	0.67
Socorro Main	3.95	3.85	4.44	0.10	9.65	80.86	1.13	8.78	0.54	0.58
Albuquerque Main	3.98	3.91	2.65	0.07	9.20	72.73	1.35	7.99	0.60	0.70
Albuquerque Main	2.95	2.88	2.65	0.08	8.53	55.28	0.96	7.93	0.59	0.97
Lateral Canals										
New Belen Acequia	1.01	0.95	3.36	0.07	7.07	26.03	0.72	6.49	0.42	1.91
New Belen Acequia	0.81	0.75	4.38	0.06	7.35	20.15	0.36	7.10	0.44	1.81
Bernalillo Acequia	0.80	0.71	5.90	0.09	5.91	32.04	1.06	4.71	0.28	1.84
Bernalillo Acequia	0.78	0.69	5.90	0.09	5.54	34.03	1.07	4.88	0.26	1.95
Bernalillo Acequia	0.84	0.76	5.90	0.09	5.63	32.57	0.92	4.89	0.28	1.75
Barr Main Canal	1.46	1.22	6.72	0.24	6.20	33.39	0.71	5.51	0.46	2.43
Barr Main Canal	1.66	1.40	6.72	0.26	6.70	35.00	0.68	6.12	0.50	2.33
Barr Main Canal	1.43	1.29	6.72	0.14	6.56	34.13	0.66	5.89	0.44	1.44
Acequia or Branch Canals										
Peralta Acequia	0.57	0.51	5.87	0.06	5.40	14.64	0.48	4.89	0.44	1.79
Peralta Acequia	0.76	0.68	5.87	0.07	5.87	24.99	0.76	3.83	0.34	1.65
Peralta Acequia	0.55	0.50	5.87	0.05	5.69	19.45	0.63	4.22	0.31	1.54
Sili Main	0.47	0.41	5.73	0.06	5.50	19.51	0.48	5.05	0.25	2.21
Sili Main	0.58	0.51	5.73	0.07	5.07	21.34	0.54	4.62	0.28	2.15
Sili Main	0.64	0.58	5.73	0.06	5.14	23.09	0.57	4.49	0.28	1.67
Williams Lateral	0.61	0.58	2.87	0.03	3.50	12.75	0.68	2.89	0.55	1.88
Williams Lateral	0.67	0.63	2.87	0.04	3.57	13.94	0.67	3.10	0.55	1.94
Williams Lateral	0.69	0.66	2.87	0.03	3.47	14.74	0.72	2.90	0.53	1.71

Further analysis of the data showed that trends in canal seepage rate existed for upstream flow rate, and the three canal geometry properties of upstream wetted perimeter, upstream flow area, and upstream top width. The data showed that as canal inflow rate decreased the seepage increased. For the wetted perimeter, flow area, and top width data, the seepage increased as these values decreased. In order to develop predictive equations, the characteristics of the upstream cross section were related to the percent loss per mile.

<u>Correlation between Seepage Loss and Flow Rate</u>

Analyzing the data for seepage rate versus upstream flow rate exhibited an exponential trend (Figure 3). This relationship exhibited a coefficient of determination (r^2) of 0.80 and is displayed in Figure 3 as well as Equation 1.

$$S = 2.34e^{-0.28Q} \qquad \text{Equation 1}$$

Where S= percent seepage loss per kilometer (%)
Q = inflow discharge (m^3/s)

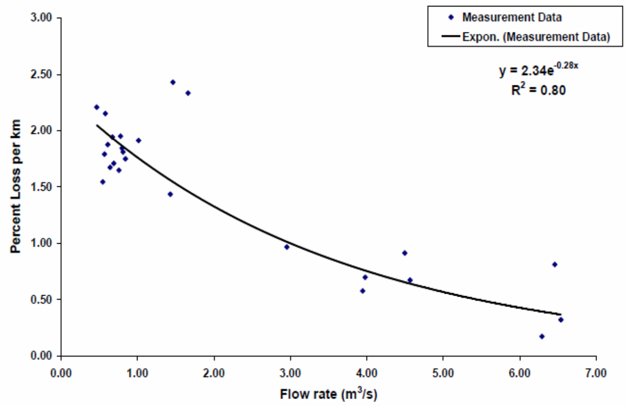

Figure 3. Relationship between upstream flow rate and percent loss per km

<u>Correlation between Seepage Loss and Canal Geometry</u>

In addition to analyzing the inflow rate versus seepage loss, geometric properties of the inflow canal were plotted against the seepage rate. The three geometric properties that exhibited the most significant predictive equations were wetted perimeter, flow area, and channel top width. The data for seepage rate versus upstream wetted perimeter exhibited an exponential trend (Figure 4). The exponential relationship developed exhibited a coefficient of determination (r^2) of 0.79 and is displayed in Figure 4 as well as Equation 2.

$$S = 4.54e^{-0.17P} \qquad \text{Equation 2}$$

Where S = percent seepage loss per kilometer (%)
P = wetted perimeter (m)

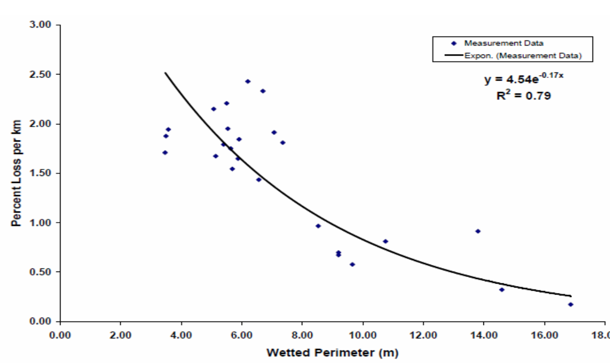

Figure 4. Relationship between wetted perimeter and percent loss per km

The data for seepage rate versus upstream flow area also exhibited an exponential trend (Figure 5). The exponential relationship developed exhibited a coefficient of determination (r^2) of 0.76 and is displayed in Figure 5 as well as Equation 3.

$$S = 2.70e^{-0.18A} \qquad \text{Equation 3}$$

Where S = percent seepage loss per kilometer (%)
A = inflow area (m^2)

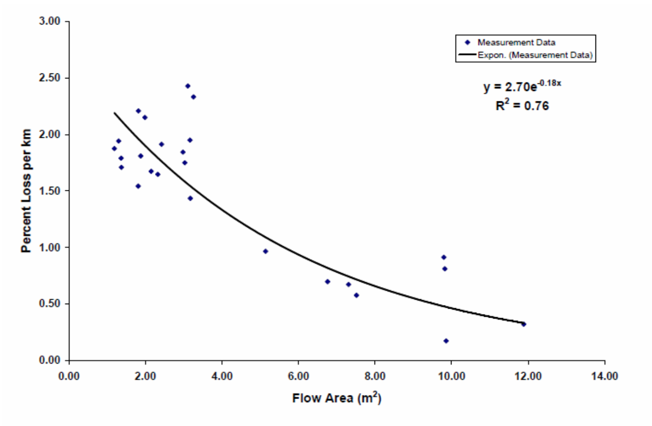

Figure 5. Relationship between flow area and percent loss per km

The data for seepage rate versus upstream top width also exhibited an exponential trend (Figure 6). The exponential relationship exhibited a coefficient of determination (r^2) of 0.78 and is displayed in Figure 6 as well as Equation 4.

$$S = 4.10e^{-0.18T} \qquad \text{Equation 4}$$

Where S = percent seepage loss per kilometer (%)
T = top width (m)

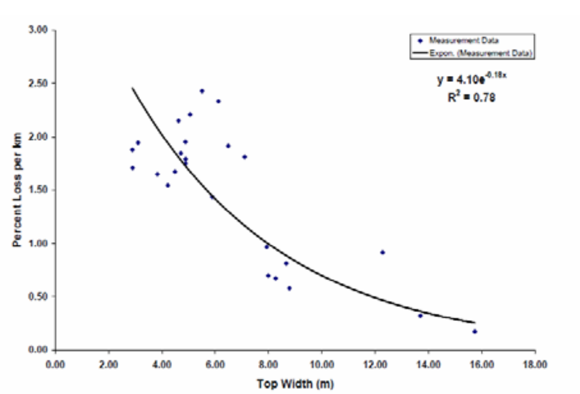

Figure 6. Relationship between top width and percent loss per km

Although the equation for top width is a function of velocity and cross sectional area it will be useful to the MRGCD as ditch-riders and water managers will be able to predict seepage using only the top width of a canal.

These equations present the opportunity to predict canal seepage losses based on the four easily measured parameters of inflow rate, wetted perimeter, flow area, and top width. These equations should only be applied to similar systems and to canals that are comparable in size to the ones measured during this study. The developed equations display r^2 values similar to other published studies. A study by (Hotchkiss et al. 2001) in Nebraska was able to develop predictive canal seepage equations with coefficients of determination of 0.64 and 0.77. Another study in Australia by (Akbar, 2005) developed numerous predictive seepage equations with coefficients of determination ranging between 0.40 and 0.93. Through the development of the equations for the MRGCD, district managers are able to predict seepage. Using the developed seepage equations the total seepage in the MRGCD for 2008 was calculated to be 72,000 acre-feet which is 20% of the total diversion. A similar seepage rate of 15% of the total diversion was found in an Alberta irrigation district (Iqbal et al. 2002).

DISCUSSION AND CONCLUSION

The completed study to examine canal seepage in the MRGCD provides the framework for using technology in the form of an ADCP to determine canal seepage in an irrigation district. ADCPs offer the benefit of reducing measurement error, measurement time, offer high resolution data collection, are non intrusive, and allow for the collection of canal seepage data during normal canal operation. Coupled with a pressure transducer to ensure that canal fluctuations are limited, the presented methodology offers the opportunity to determine canal seepage quickly, accurately, and efficiently.

The developed equations only apply to the Middle Rio Grande Valley or to irrigation systems that are geologically and hydrologically similar. Although the data collected to develop the equations showed no significant seasonal variation there is the possibility that seepage varies from year to year and further investigation is necessary. The two most useful equations to the MRGCD will most likely be Equations 1 and 4 which relate canal inflow and top width to seepage loss rate, respectively. The variables of canal inflow and canal top width are easily obtainable and require minimal effort for data collection. The MRGCD utilizes a network of automated measurement stations (Gensler et al. 2009) which will aid in determining canal inflow, which can then directly be related to a canal seepage rate. Determining the canal top width will be straightforward because many bridges exist across canals allowing ditch-riders and water masters to measure the canal top width to estimate canal seepage.

Using diversion records obtained from the automated measurement network, the MRGCD will also be able to quantify the aquifer recharge from the canal system in the Middle Rio Grande Valley. The length of each canal as well as the inflow for said canal is well defined and the developed equations will allow for calculation of canal seepage rate. The benefit to the MRGCD will be proving the amount of water that the canal system recharges to the regional aquifer. The city of Albuquerque and several smaller communities pump from the regional aquifer, and it is believed that aquifer levels are maintained through the seepage from the Rio Grande and MRGCD irrigation canals. Quantifying the amount of seepage that occurs from the MRGCD canals indicates the benefit that the canal network has on the local aquifer and aids the MRGCD in water rights litigation. Application of the developed equations may help to determine areas where canal maintenance or lining would have the greatest benefit in water saving.

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REFERENCES

Akbar, S., 2005. Measurement of losses from on-farm channels and drains. Cooperative research centre for sustainable rice production. Yanco Agric. Institute. Yanco.

Alam, M.M., Bhutta, M.N., 2004. Comparative evaluation of canal seepage investigation techniques. Agric. Water Manage. 66, 65-76.

AuBuchon, J., Benoit, V., Donnelly, C, Devergie, S., 2008. ADCP field tests comparison: utilizing RD Instruments StreamPro ADCP. Bureau of Reclamation. Technical Services Division, Albuquerque, New Mexico. River Analysis Group.

Carr, M.D. and C.R. Rehmann. 2007. Measuring the Dispersion Coefficient with Acoustic Doppler Current Profilers. J. of Hyd. Eng. 133, 977-982.

Fipps, G., 2001. Potential water savings in irrigated agriculture for the Rio Grande Planning region (Region M). Rio Grande Regional Water Plan. Final Report. December.

Gensler, D. Oad, R. Kinzli, K., 2009. Irrigation system modernization: a case study of the Middle Rio Grande valley." ASCE J. of Irrig. and Drain. 135(2).

Herschy, R.W., Fairbridge, R.W., eds., 1998. Encyclopedia of water resources, Kluwer Academic, Dordrecht, The Netherlands. 442, 777–778.

Hotchkisss, R.H., Wingert, C.B., Kelly W.E.. 2001. Determining irrigation canal seepage with electrical resistivity. ASCE J. of Irrig and Drain. 127, 20-26.

Interagency Task Force (ITF)., 1979. Irrigation water use and management. U.S. EPA Interagency Task Force Rep., U.S. Department of Agriculture, Washington, D.C.

Iqbal, Z., Maclean, R.T., Taylor, B.D., Hecker, F.J., and D.R. Bennett. 2002. Seepage losses in irrigation canals in southern Alberta. Canadian Biosystems Engineering. 44, 22-27.

Morlock, S.E., 1996. Evaluation of acoustic Doppler current profiler measurements of river discharge. U.S. Geological Survey Water Resources Investigation Rep. 95-4218, Denver.

Mueller, D.S., Abad, J.D., García, C.M.,Gartner, J.W., García, M.H., Oberg, K.A., 2007. Errors in acoustic Doppler profiler velocity measurements caused by flow disturbance. J. of Hyd. Eng. 133, 1411-1420.

Napan, K.M., Merkley, G.P., Neale, C.M.U. 2009. Seepage Evaluations in Cache Valley Irrigation Canals. Proc. Fifth International Conference on Irrigation and Drainage. USCID, Salt Lake City, UT.

Nystrom, E.A., Rehmann, C.R., Ober, K.A.., 2007. Evaluation of mean velocity and turbulence measurements with ADCPs. J. of Hyd. Eng. 133, 1310-1318.

Oad, R., Garcia, L., Kinzli, K., Patterson, D., Shafike, N., 2009. Decision support systems for efficient irrigation in the Middle Rio Grande valley. ASCE J. of Irrig. and Drain. 135. 177-185.

Oberg, K.A., Morlock, S.E., Caldwell, W. S., 2005. Quality assurance plan for discharge measurements using acoustic Doppler current profilers. Scientific Investigations Rep. 2005-5183, U.S. Geological Survey, Denver.

Rehmel, M.S., 2006. Field Evaluation of Shallow-Water Acoustic Doppler Current Profiler Discharge Measurements. World Environmental and Water Resource Congress. ASCE Conference Proceedings, 200, 162.

Rennie, C.D., Rainville, F., 2008. Improving precision in the reference velocity of ADCP measurements using a Kalman filter with GPS and bottom track. J. of Hyd. Eng. 134, 1257-1266

Rennie, C.D., Rainville, F., 2006. Case study of GPS differential correction strategies: influence on ADCP velocity and discharge estimates. J .of Hyd. Eng. 132, 225-234.

Shields, F.D. Jr., J.R. Rigby., 2005. River habitat quality from river velocities measured using acoustic Doppler current profiler. Environ. Manage. 36, 565-575.

Simpson, M.R., 2001. Discharge Measurements Using a Broad-Band Acoustic Doppler Current Profiler: Sacramento, CA, United States Geological Survey, pp. 123.

Skogerboe, G.V., Aslam, M., Khan, M.A., Mehmood, K., Mehmood, S., Khan, A.H., 1999. Inflow-outflow channel losses and canal lining cost-effectiveness in the Fordwah

Eastern Sadiqia Project. Report No. R-85. International Water Management Institute, Lahore, June. pp. 3-8.

Swamee, P.K., Mishra, G.C., B.R. Chahar., 2000. Design of minimum seepage loss canal sections. ASCE J.of Irrig. and Drain. 126, 28-32.