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Uncertainty of canal seepage losses estimated using flowing water balance with acoustic Doppler devices

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SUMMARY

Seepage losses from unlined irrigation canals amount to a large fraction of the total volume of water diverted for agricultural use, posing problems to both water conservation and water quality. Quantifying these losses and identifying areas where they are most prominent are crucial for determining the severity of seepage-related complications and for assessing the potential benefits of seepage reduction technologies and materials. A relatively easy and inexpensive way to estimate losses over an extensive segment of a canal is the flowing water balance, or inflow–outflow, method. Such estimates, however, have long been considered fraught with ambiguity due both to measurement error and to spatial and temporal variability. This paper presents a water balance analysis that evaluates uncertainty in 60 tests on two typical earthen irrigation canals. Monte Carlo simulation is used to account for a number of different sources of uncertainty. Issues of errors in acoustic Doppler flow measurement, in water level readings, and in evaporation estimates are considered. Storage change and canal wetted perimeter area, affected by variability in the canal prism, as well as lagged vs. simultaneous measurements of discharge at the inflow and outflow ends also are addressed. Mean estimated seepage loss rates for the tested canal reaches ranged from about -0.005 (gain) to $0.110\ \mathrm{m^3\,s^{-1}}$ per hectare of canal wetted perimeter (or -0.043 to $0.95\ \mathrm{m\,d^{-1}}$) with estimated probability distributions revealing substantial uncertainty. Across the tests, the average coefficient of variation was about 240% and the average 90th inter-percentile range was $0.143\ \mathrm{m^3\,s^{-1}}$ per hectare ($1.24\ \mathrm{m\,d^{-1}}$). Sensitivity analysis indicates that while the predominant influence on seepage uncertainty is error in measured discharge at the upstream and downstream ends of the canal test reach, the magnitude and uncertainty of storage change due to unsteady flow also is a significant influence. Recommendations are presented for conducting field water balance tests to recognize and reduce uncertainty in canal seepage estimates.

1. Introduction

Millions of kilometers of earthen canals traverse vast landscapes of irrigated regions to deliver the water that supports the world's most productive agriculture. Along the course of these canals, substantial portions of water often seep through the channel perimeter into the surrounding groundwater. Sharma (1975) estimated that irrigation canals and laterals in New Delhi lose 45% of the total diverted flow rate before water reaches agricultural fields. Similarly, Yussuff et al. (1994) and Tanji and Kielen (2002) estimated that seepage losses in semi-arid regions can account for 20–50% of the total flow volume in unlined earthen canals. USGS (1990) suggests that 17% of the water that was conveyed for irrigation in 1985 in the United States was lost to evaporation or seepage to groundwater, and Fipps (2005) estimated that conveyance efficiency from the point of diversion to the field in canals in the Lower Rio Grande Valley in Texas was 69.7%. A recent study by Kinzli et al. (2010), in which acoustic Doppler equipment was implemented to measure canal flow rates, found that earthen canals in the Middle Rio Grande Valley of New Mexico can lose more than 40% of the diverted water volume to seepage. Despite the variety of estimates, it is clear that significant volumes of water diverted for irrigation purposes never reach agricultural fields due to seepage.

Seepage from irrigation canals poses several problems to agricultural water management: (1) diminished water delivered to agricultural fields to meet evapotranspiration and salt leaching demands; (2) contribution to higher groundwater table elevations which often lead to salinity and waterlogging, with resulting crop yield depression, under cropped fields and non-beneficial water consumption under naturally-vegetated fields; (3) reduction in

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Nomenclature

ADCP	acoustic Doppler current profiler
ADV	acoustic Doppler velocimeter
A_P	canal wetter perimeter area
A_{WS}	canal free-water water surface area
CC	Catlin Canal
C_i	hydraulic geometry coefficient for variable i determined from at-a-cross-section regression
$\widehat{C}_i$	component of hydraulic geometry coefficient for variable i predicted by the "along-the-canal" deterministic trend equation for that location
C'_i	random "along-the-canal" component associated with predicting hydraulic geometry coefficient for variable i
C_{P1}, C_{P2}, C_{P3}	fitted "at-a-cross-section" regression coefficients for P using survey data
C_{T1}, C_{T2}, C_{T3}	fitted "at-a-cross-section" regression coefficients for T_w using survey data
CV	coefficient of variation
EL_{PT}	relative elevation of a pressure transducer
h	canal flow depth
H	canal stage
H_{DS}	canal stage measured at the downstream boundary of the canal test reach
H_{US}	canal stage measured at the upstream boundary of the canal test reach
IR	interpercentile range
LARV	Lower Arkansas River Valley
L_j	length of subreach j along the canal test reach
P	wetted canal perimeter area
p_{abs}	absolute water pressure
p_{baro}	barometric pressure
p_{gage}	gage water pressure
PDF	probability distribution function
Q_D	diverted outflow rate from the canal test reach
Q_{DS}	flow rate through the downstream cross section of the canal test reach
$Q'_{DS,1}$	flow rate at the downstream boundary of the canal test reach at time t_1 estimated using Q vs. H relationship (during "unmeasured" time period Δt_B)
$Q'_{DS,2}$	flow rate at the downstream boundary of the canal test reach at time t_2 estimated using Q vs. H relationship (during "unmeasured" time period Δt_B)
$Q_{DS,3-4}$	measured flow rate at the downstream boundary of the canal test reach during unmeasured time period Δt_B
Q_E	rate of evaporation from the water surface along the canal test reach
Q_p	rate of precipitation through the water surface along the canal reach
Q_S	seepage rate from the canal test reach
Q_{US}	flow rate through the upstream cross section of the canal test reach
$Q_{US,1-2}$	measured flow rate at the upstream boundary of the canal test reach between t_1 and t_2 during unmeasured time period Δt_A
$Q'_{US,3}$	flow rate at the upstream boundary of the canal test reach at time t_3 estimated using Q vs. H relationship (during "unmeasured" time period Δt_A)
$Q'_{US,4}$	flow rate at the upstream boundary of the canal test reach at time t_4 estimated using Q vs. H relationship (during "unmeasured" time period Δt_A)
RFHC	Rocky Ford Highline Canal
StDev	standard deviation
t_1	time at the start of the Q_{US} measurement
t_2	time at the end of the Q_{US} measurement
t_3	time at the start of the Q_{DS} measurement
t_4	time at the end of the Q_{DS} measurement
TH_{el}	relative canal thalweg elevation
T_w	canal top width at the water surface
$\overline{T}_{w_j}$	average canal top width over subreach j along the canal test reach
x	position along the thalweg axis of the canal test reach
$(\Delta H_{1-4})_{DS_j}$	canal stage change over Δt at the stage measurement location at the downstream end of subreach j along the canal test reach
$(\Delta H_{1-4})_{US_j}$	canal stage change over Δt at the stage measurement location at the upstream end of subreach j along the canal test reach
$\Delta H_{DS,1-3}$	measured stage change at the downstream boundary of the canal test reach between t_1 and t_3
$\Delta H_{DS,2-3}$	measured stage change at the downstream boundary of the canal test reach between t_2 and t_3
$\Delta H_{US,2-3}$	measured stage change at the upstream boundary of the canal test reach between t_2 and t_3
$\Delta H_{US,2-4}$	measured stage change at the upstream boundary of the canal test reach between t_2 and t_4
$\left(\frac{\Delta Q}{\Delta H}\right)_{DS}$	change in flow rate with flow stage at the downstream boundary of the canal test reach, as developed using flow rate and stage data
$\left(\frac{\Delta Q}{\Delta H}\right)_{US}$	change in flow rate with flow stage at the upstream boundary of the canal test reach, as developed using flow rate and stage data
$\frac{\Delta S}{\Delta t}$	rate of change of stored water volume within the canal test reach
Δt	flowing water-balance test duration
Δt_A	"unmeasured" time period for Q_{US}, between t_2 and t_4
Δt_B	"unmeasured" time period for Q_{DS}, between t_1 and t_3
$\varepsilon_{H_{abs}}$	random error associated with measuring p_{abs} for use in estimating H
$\varepsilon_{H_{baro}}$	random error associated with measuring p_{baro} for use in estimating H
$\varepsilon_{H_{SG}}$	random error in manual staff gage readings
ε_P	random error associated with measuring P "at-a-station"
$\varepsilon_{P_{trend}}$	random error in estimating P by projecting a linear trend line
$\varepsilon_{Q'_{DS,1}}$	random error in estimating $Q'_{DS,1}$
$\varepsilon_{Q'_{DS,1}}$	random error in estimating $Q'_{DS,2}$
$\varepsilon_{Q_{DS,3-4}}$	random error in estimating $Q_{DS,3-4}$
$\varepsilon_{Q_{US,1-2}}$	random error in estimating $Q_{US,1-2}$
$\varepsilon_{Q'_{US,3}}$	randomly generated flow rate error for estimation of $Q'_{US,3}$
$\varepsilon_{Q'_{US,4}}$	randomly generated flow rate error for estimation of $Q'_{US,4}$
ε_{TH}	random error associated with estimating TH_{el}
ε_{Tw}	random error in measuring T_w "at-a-station"

water quality as groundwater flows, resulting from canal seepage, pick up and transport salts, selenium, uranium, nutrients, and other constituents from the subsurface environment and into rivers and streams; and (4) larger flow rates diverted from streams to meet field water requirements, leading to less in-stream flow (USGS, 1990; Burkhalter and Gates, 2005; Burt et al., 2010). A major step toward mitigation of these problems in any setting is estimation of the actual seepage losses that are occurring.