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Water Loss in Concrete-Lined versus Earthen Irrigation Canals in Andijan, Uzbekistan: A Field-Based Seepage Assessment and Estimate of Potential Water Savings from Canal Lining

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ABSTRACT

This study quantified seepage losses in twelve irrigation canal segments in the Andijan region of Uzbekistan, six concrete-lined and six earthen using the inflow–outflow method. Field measurements indicated a mean seepage rate of 0.92 ± 0.33 $m^3\ s^{-1}$ per 100 m of canal (mean ± standard error) for concrete-lined segments, compared with 12.51 ± 2.99 $m^3\ s^{-1}$ per 100 m for earthen segments a statistically significant and approximately 13.6-fold difference (Welch's $t(5) = 3.85$, $p = 0.011$; Mann–Whitney $U = 36$, $p = 0.002$). These results indicate that lining earthen canals with concrete could reduce seepage losses by approximately 93% in this region. Both cross-sectional area and the magnitude of velocity change along a canal reach were positively associated with seepage. Field-measured rates diverged substantially from estimates produced by the Davis–Wilson empirical formula, suggesting that this widely used formula requires region-specific recalibration before it can be applied reliably to Central Asian canal systems. These findings support prioritizing concrete lining as a practical, evidence-based intervention for reducing conveyance losses and improving irrigation efficiency in this water-stressed agricultural region.

INTRODUCTION

Most irrigation canals worldwide remain unlined. Because soil is a porous medium, large volumes of water seep downward through it and are lost during conveyance rather than reaching the intended fields. Seepage — the gradual movement of water through porous materials such as soil or rock — is the leading contributor to water loss in irrigation networks (Syed and Shuqi), and it creates a persistent gap between the volume of water allocated for irrigation and the volume that actually reaches farmland.

Estimates of seepage loss vary widely by region but are consistently large. Barkhordari et al. report that seepage accounts for approximately 90% of water losses in Australia's earthen irrigation network and over 40% of losses in the Middle Rio Grande Conservancy District, United States. Kulkarni and Nagarajan and

Lund et al. estimate that conveyance losses worldwide range from 20% to 70% of total canal flow, while Barkhordari et al. separately report seepage losses of roughly 55% from canal networks supplying farmland in Spain.

Among post-Soviet Central Asian countries, Uzbekistan — together with Turkmenistan — is classified in the most severe water-stress category (Wang et al.). As a major agricultural producer of water-intensive crops such as rice and cotton, Uzbekistan depends heavily on surface-water irrigation, and this reliance, combined with inefficient water use, has contributed to substantial depletion of rivers and groundwater. The country has no major water source of its own: irrigation water comes primarily from the Amudarya and Sirdarya rivers, both of which originate outside its borders (Gofurov et al.). The Soviet-era canal network, built at large scale but with variable construction quality, continues to suffer from seepage, bank erosion, siltation, and structural degradation — problems with substantial economic and environmental consequences, including reduced agricultural yields, land salinization, and ecosystem disruption (Khalimov).

Andijan, located in the Fergana Valley, is considered a comparatively well-managed region of Uzbekistan in terms of water infrastructure. As of 2026, 91–92% of the region's population has access to a centralized drinking-water supply, following extensive pipeline construction and well repair (JSC “Uzsuvta’minot”). Canal infrastructure, however, remains a persistent challenge. Of the region's 10,552 km of canal network — the ninth-longest in the country — only 353 km is concrete-lined, while 8,399 km remains earthen, making Andijan the sixth-longest network of soil-covered canals nationally (World Bank). This scale of unlined infrastructure represents a substantial opportunity for improvement, and quantifying seepage losses is a necessary first step toward prioritizing renovation.

Seepage cannot be eliminated entirely, but it can be substantially reduced by lining canals with a low-hydraulic-conductivity material such as concrete (Khalimov). The consequences of inaction are considerable. Makhmudov et al. estimate that failure of Uzbekistan's water-facility resource base could cause approximately $1 billion in economic damage, and the World Bank reports that 65–70% of the water sector's budget is spent on pumping electricity, of which an estimated 40% is lost to seepage before reaching its destination. Seepage-driven salinization further compounds the ecological cost of water loss.

Despite the scale of this problem, empirical data on seepage rates in Andijan's unlined canals are limited, and no study has directly compared seepage in concrete-lined and earthen canals within the region. This study addresses that gap using the inflow–outflow method to quantify and compare water loss across concrete-lined and earthen canal segments in the Andijan region, Fergana Valley.

METHODS

Study Area and Site Selection

Twelve canal segments across sites in the Andijan region — including Asaka, Shahrixon, Izboskan, Oltinkol, Qorgontepa, and Pakhtaabad — were selected for field measurement (Figure 1), with one or two segments sampled per site. Six segments were concrete-lined and six were earthen. Only segments with visually uniform channel geometry were selected, to avoid the additional measurement uncertainty introduced by irregular cross-sections.

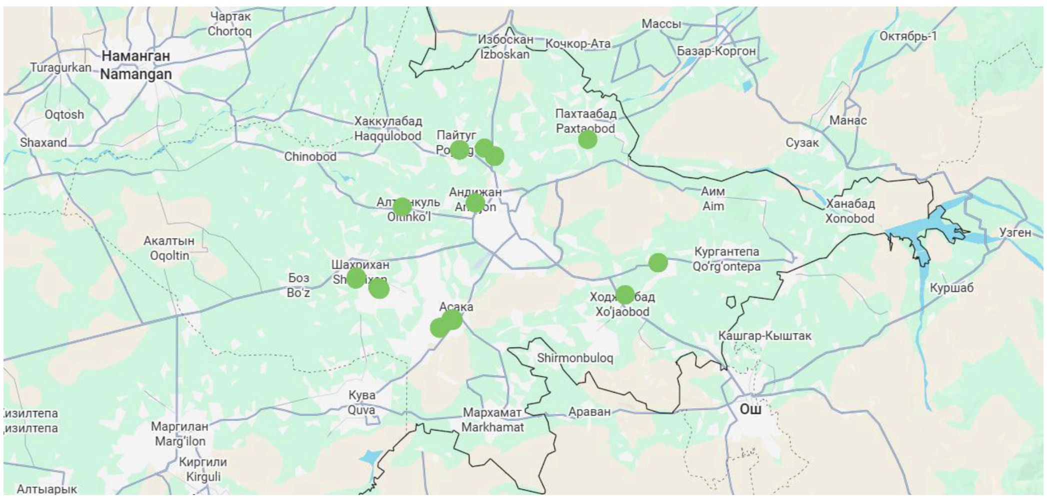

Figure 1: Geographic distribution of the twelve canal segments surveyed in the Andijan region. Green markers indicate individual study sites; six concrete-lined and six earthen segments were sampled across these locations. Segment-level identifiers and cross-referenced site names are given in Table 1.

Field Measurement Procedure

Water discharge was calculated at two points along each canal segment — spaced 100 m apart for eight segments and 120 m apart for the remaining four (Table 1) — using the area–velocity method, in which discharge is the product of cross-sectional area and mean flow velocity.

Cross-sectional area was estimated as (2/3) × width × depth, where depth was measured from the canal centre using a weighted line and rope, and surface width was measured with a tape. This formula approximates a parabolic channel cross-section and was used because the canal base width could not be measured directly; it introduces a systematic uncertainty relative to canals with a more trapezoidal true profile (see Measurement Uncertainty, below).

Flow velocity was measured using the float method: a floating object was released into the canal and timed over a fixed 20 m distance, with velocity calculated as distance divided by time. Because floats travel fastest at the water surface and velocity decreases with depth (Syed and Shuqi), ten trials were conducted at each measurement point, and the resulting surface velocity was multiplied by an empirical correction factor of 0.8 to approximate the cross-sectionally averaged velocity.

The difference between the initial and final velocity measured at the two points of a given segment ($\Delta V = V_i - V_f$) reflects the net loss of flow along that reach. Multiplying ΔV by the cross-sectional area gives the seepage discharge lost over that specific reach, in $m^3\ s^{-1}$. Evaporation was not measured separately and is excluded from this calculation; based on Syed and Shuqi, seepage is estimated to account for 85–95% of total conveyance loss in canals of this type, so this omission is expected to have a modest but non-zero effect on the reported values (see Measurement Uncertainty and Limitations and Future Work, below).

The empirical Davis–Wilson formula (Akkuzu) was also applied to each segment, using standard coefficients of 1 for concrete-lined canals and 4 for earthen canals, to provide an independent estimate for comparison with the field-measured rates (see Comparison with the Davis–Wilson Empirical Formula, below). This formula was developed and calibrated using data from Iran, Egypt, India, and Pakistan (Syed and Shuqi) and, to our knowledge, has not previously been calibrated for conditions in Uzbekistan.

Unit Correction and Normalization

In the original field calculations, the seepage discharge for each segment (area × ΔV, in $m^3\ s^{-1}$) was multiplied a second time by the reach length. Because area × ΔV already represents the rate of water loss integrated over the full measured reach, this additional multiplication is not dimensionally valid: it produces a quantity with units of $m^4\ s^{-1}$ rather than a physically meaningful seepage rate, and it inflated the reported values by a factor equal to the reach length (100 or 120). This error is the most likely explanation for the unusually large seepage magnitudes noted during review.

All seepage values reported in this manuscript have been recalculated without that additional multiplication. Because two- and four-segment subsets were measured over 120 m rather than 100 m reaches, all values are further normalized to a common 100 m basis (multiplied by 100/L, where L is the measured reach length in metres) so that segments of different reach length are directly comparable. Seepage rates throughout this manuscript are therefore reported in $m^3\ s^{-1}$ per 100 m of canal. Because this correction was applied uniformly across every segment, the relative comparison between concrete and earthen canals — the central finding of this study — is essentially unchanged from the original analysis (see Seepage Rates by Canal Type, below).

For the comparison with the Davis–Wilson empirical formula (see Comparison with the Davis–Wilson Empirical Formula, below), the same normalization was applied to the empirical estimates, on the assumption that they were originally computed over the same reach length as the corresponding field measurement. This assumption could not be independently verified against the formula's underlying inputs and is noted as a limitation below.

Measurement Uncertainty

Several sources of measurement uncertainty affect the reported seepage rates, and their relative importance differs between canal types. Width and depth measurements (tape and weighted line) are subject to a small reading uncertainty, estimated at approximately ±5%. The (2/3) × width × depth area approximation introduces a larger, systematic uncertainty of roughly ±10–15%, because it assumes a parabolic cross-section and cannot capture the true (unmeasured) base width of each canal. Float-method velocity measurements carry an estimated uncertainty of ±10–15%, reflecting both the empirical 0.8 correction factor, which is itself an approximation (Syed and Shuqi), and human reaction-time error in timing the float over 20 m; averaging ten trials at each point reduces, but does not eliminate, this source of error.

These uncertainties combine differently for discharge and for ΔV. Combining an area uncertainty of ±15% with a velocity uncertainty of ±10% in quadrature gives a combined discharge uncertainty on the order of ±18–20% at a single point. However, ΔV is a difference between two independently uncertain velocity measurements, so its absolute uncertainty (rather than its relative uncertainty) is approximately fixed by the underlying measurement precision, on the order of ±0.05–0.10 $m\ s^{-1}$ for velocities in the observed range (0.5–1.4 $m\ s^{-1}$). Because concrete-lined segments had very small ΔV values (0.00–0.03 $m\ s^{-1}$), this absolute uncertainty is large relative to the measured signal — plausibly exceeding 100% in relative terms for some segments — while for earthen segments, where ΔV ranged from 0.20 to 0.44 $m\ s^{-1}$, the same absolute uncertainty represents a comparatively smaller relative error (roughly 25–50%). This asymmetry is a plausible explanation for anomalous results such as the zero ΔV recorded for one concrete segment (see Anomalous Segments, below), and it means that the absolute seepage values reported for concrete-lined canals should be interpreted as an upper bound on precision, even though the qualitative and statistical comparison between canal types is robust to this uncertainty.

These figures are order-of-magnitude estimates based on standard practice for the instruments used, rather than uncertainties propagated from repeated independent measurements at each point, which were not recorded in the original field data. We recommend that future studies in this region record repeated, independent area and velocity measurements at each point so that per-segment uncertainty can be propagated rigorously.

Statistical Analysis

Seepage rates ($m^3\ s^{-1}$ per 100 m) were summarized for each canal type as the mean and standard deviation across the six replicate segments. Because the two groups have unequal variances and a small sample size ($n = 6$ per group), the difference in means was tested using Welch's t-test, which does not assume equal variance. As a robustness check against the small sample size and the right-skewed distribution of the earthen-canal values, the comparison was repeated using the Mann–Whitney U test, a non-parametric test that does not assume normality. A significance threshold of $\alpha = 0.05$ was used for both tests.

RESULTS

Seepage Rates by Canal Type

Table 1 reports the corrected, length-normalized seepage rate for each of the twelve canal segments (see Unit Correction and Normalization, above), together with the cross-sectional area and velocity change from which each rate was derived, and the specific site corresponding to each segment (Figure 1).

Segment	Site (Fig. 1)	Lining	Reach L (m)	Area (m^2)	ΔV (m/s)	Seepage(m^3/s per 100 m)
C1	Shaxrixon soy canal, Asaka	Concrete	100	28.58	0.02	0.57
C2	Shaxrixon soy canal, Shahrixon	Concrete	100	24.00	0.01	0.24
C3	Farg'ona canal, Izboskan	Concrete	100	35.83	0.00	0.00
C4	Shaxrixon soy canal, Asaka	Concrete	120	58.33	0.03	1.46
C5	Andijansoy canal, Qorgontepa	Concrete	100	106.67	0.01	1.07
C6	Andijan canal, Izboskan	Concrete	100	72.53	0.03	2.18
E1	Farg'ona canal, Shahrixon	Earthen	120	126.00	0.20	21.00
E2	Asaka tashlanmasi, Oltinkol	Earthen	120	38.88	0.21	6.80
E3	Farg'ona canal, Izboskan	Earthen	100	65.12	0.21	13.68
E4	Qara Daryo, Andijan	Earthen	120	7.10	0.44	2.60
E5	Pakhtaabad canal, Pakhtaabad	Earthen	100	48.60	0.22	10.69
E6	Andijan region (Fig. 1)	Earthen	120	58.00	0.42	20.30

Table 1: Seepage rate by canal segment, corrected for the unit error described under Unit Correction and Normalization and normalized to a 100 m reach basis. ΔV is the measured decrease in flow velocity between the upstream and downstream measurement points.

Across all twelve segments, earthen canals consistently lost more water than concrete-lined canals. Concrete-lined segments ranged from 0.00 to 2.18 $m^3 s^{-1}$ per 100 m (mean = 0.92, SD = 0.81), while earthen segments ranged from 2.60 to 21.00 $m^3 s^{-1}$ per 100 m (mean = 12.51, SD = 7.32) (Table 2). Notably, the lowest earthen value (2.60, segment E4) still exceeded the highest concrete value (2.18, segment C6): every earthen segment in this sample lost more water than every concrete-lined segment.

Canal type	n	Mean (m^3/s per 100 m)	SD	SEM	Min	Max
Concrete-lined	6	0.92	0.81	0.33	0.00	2.18
Earthen	6	12.51	7.32	2.99	2.60	21.00

Table 2: Summary statistics for seepage rate ($m^3 s^{-1}$ per 100 m of canal) by canal lining type, based on the six replicate segments of each type in Table 1.

The mean seepage rate for earthen canals was approximately 13.6 times higher than for concrete-lined canals, corresponding to an estimated potential water saving of approximately 93% if earthen canals were converted to concrete lining. This difference was statistically significant under both a parametric and a non-parametric test: Welch's t-test, which accounts for the unequal variance between groups, gave $t(5) = 3.85$, $p = 0.011$; the Mann–Whitney U test, used as a robustness check given the small sample size and the skew in the earthen-canal distribution, gave $U = 36$, $p = 0.002$, reflecting the complete separation between the two groups (Figure 2).

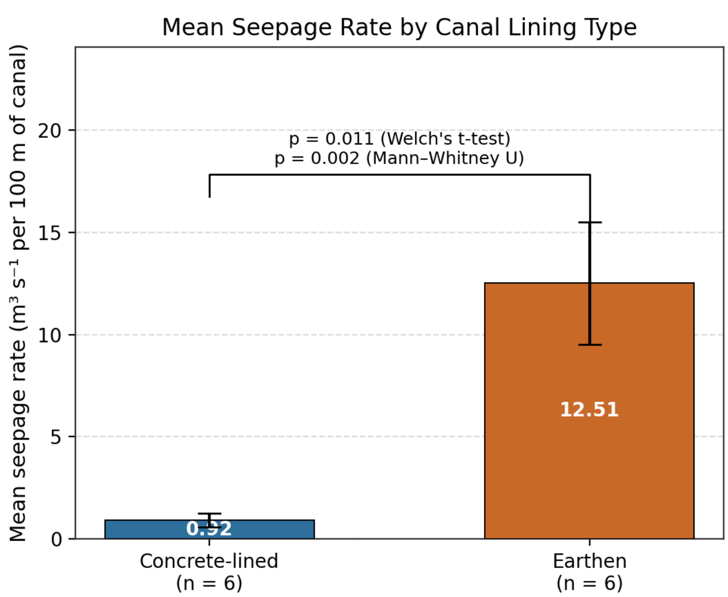

Figure 2: Mean seepage rate (m^3 s^{-1} per 100 m of canal) for concrete-lined and earthen canal segments. Error bars show the standard error of the mean (n = 6 per group); reported p-values are from Welch's t-test and the Mann–Whitney U test.

Velocity Change Across Segments

The change in velocity measured between the two ends of each canal reach (ΔV) was consistently small for concrete-lined segments (0.00–0.03 m s^{-1}) and consistently larger for earthen segments (0.20–0.44 m s^{-1}), with no overlap between the two groups (Figure 3). Because seepage discharge is calculated as the product of ΔV and cross-sectional area, this near-categorical separation in ΔV is the principal driver of the difference in seepage rate reported above.

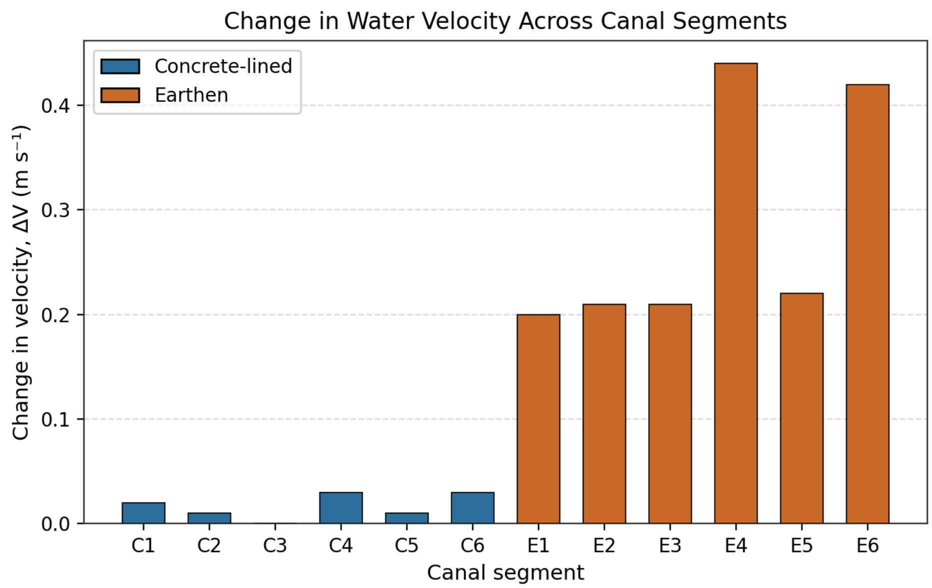

Figure 3: Change in water velocity (ΔV) measured between the upstream and downstream ends of each of the twelve canal segments, grouped by lining type.

Seepage Rate and Cross-Sectional Area

Seepage rate also varied with the cross-sectional area of each canal segment, particularly among earthen segments, where larger cross-sections were generally associated with higher seepage (Figure 4). This pattern is consistent with a larger water-contact surface area allowing more seepage into the surrounding soil. The relationship was less pronounced among concrete-lined segments, where ΔV — and therefore calculated seepage — remained small regardless of cross-sectional area, consistent with concrete's low hydraulic conductivity limiting the influence of channel size on total loss.

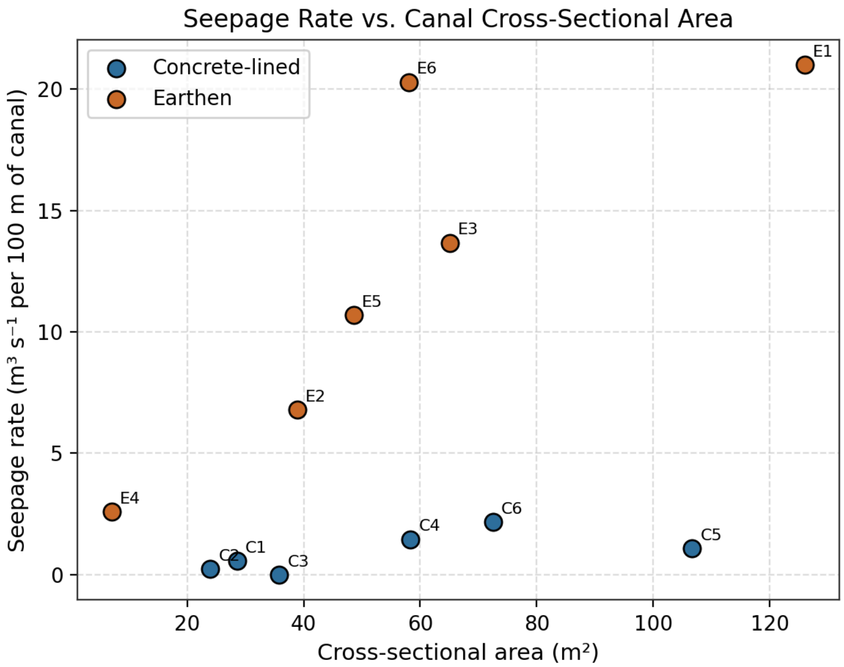

Figure 4: Seepage rate (m^3 s^{-1} per 100 m) plotted against cross-sectional area for each canal segment, grouped by lining type. Labels correspond to the segment identifiers in Table 1.

Comparison with the Davis–Wilson Empirical Formula

Seepage rates estimated using the Davis–Wilson empirical formula (Akkuzu), applied with standard coefficients for concrete and earthen canals, were higher than the corresponding field-measured rates for every segment in this study (Figure 5). The discrepancy was proportionally larger for concrete-lined segments, where the empirical formula overestimated field-measured seepage by roughly two orders of magnitude, than for earthen segments, where the empirical and field estimates differed by a smaller, though still substantial, margin. This pattern is consistent with the formula's calibration coefficients having been developed for canal systems in Iran, Egypt, India, and Pakistan (Syed and Shuqi) rather than for the soil, construction, and maintenance conditions typical of Uzbekistan.

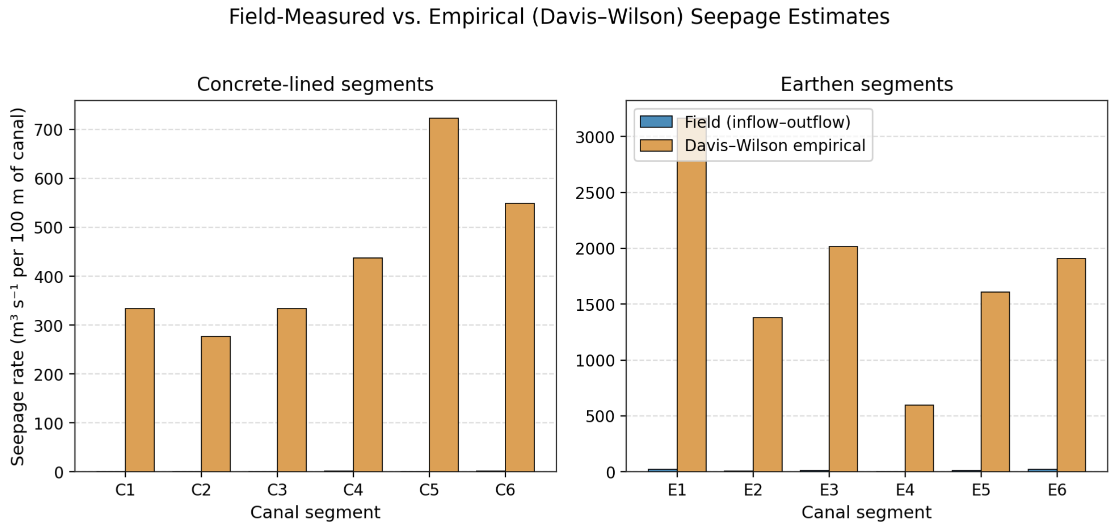

Figure 5: Field-measured seepage rate compared with the Davis–Wilson empirical estimate for each canal segment, grouped by lining type. Both series are expressed on the same normalized 100 m reach basis; the empirical values assume the same reach length as the corresponding field measurement (see Limitations and Future Work, below).

DISCUSSION

Concrete versus Earthen Canal Performance

The results provide clear, statistically supported evidence that concrete lining substantially reduces seepage loss relative to earthen canals in the Andijan region. The near-complete separation between the two groups — every earthen segment lost more water than every concrete-lined segment — together with a significant result under both a parametric and a non-parametric test, suggests that this difference reflects a genuine effect of lining material rather than sampling variability. The magnitude of the effect, an approximately 13.6-fold difference in mean seepage rate, is broadly consistent with the wide range of seepage reductions reported for canal lining elsewhere (Barkhordari et al.; Kulkarni and Nagarajan), while representing a substantially larger relative benefit than the loss reductions reported at the lower end of that range.

The velocity-change data indicate that this difference is driven almost entirely by ΔV rather than by systematic differences in canal size between the two groups: concrete and earthen segments were sampled with broadly overlapping cross-sectional areas (Table 1), yet ΔV showed essentially no overlap between types. This supports the interpretation that lining material, rather than a confound such as canal size, is the principal determinant of the observed difference in seepage.

Anomalous Segments

Two segments departed from the overall pattern and warrant closer interpretation. Concrete segment C3 recorded a ΔV of exactly 0.00 m s^{-1}, implying zero seepage. This is not physically plausible: even well-constructed concrete linings have a non-zero seepage coefficient (Syed and Shuqi), and evaporation alone — excluded from this analysis but unavoidable in an open canal — would be expected to produce some measurable velocity decrease. As discussed under Measurement Uncertainty, the absolute measurement uncertainty in ΔV is large relative to the very small ΔV values typical of concrete segments, and a true ΔV close to the detection limit of the float method is a more plausible explanation than genuinely zero seepage.

Earthen segment E4 (Qara Daryo, Andijan) showed the opposite pattern: it had the largest ΔV of any segment (0.44 m s^{-1}) but, because of its small cross-sectional area (7.10 m^2, less than a fifth of the next-smallest earthen segment), it recorded the lowest seepage rate among the earthen segments. This illustrates that ΔV and cross-sectional area both need to be considered jointly, rather than ΔV alone, when interpreting or predicting seepage: a high velocity loss in a narrow channel can still correspond to a modest absolute discharge loss.

Field-Measured versus Empirical Estimates

The systematic overestimation of seepage by the Davis–Wilson formula, particularly for concrete-lined segments, suggests that its default coefficients are not well calibrated for the canal materials and construction standards found in Andijan. Because the formula was developed using data from South and West Asian irrigation systems (Syed and Shuqi), differences in concrete quality, joint sealing, and canal age between those settings and Uzbekistan's Soviet-era infrastructure (Khalimov) offer a plausible explanation for the discrepancy. This reinforces the value of locally measured seepage data, of the kind produced by this study, for water-management decisions in the region: applying an uncalibrated empirical formula in place of field measurement risks materially overestimating the seepage benefit of canal lining, or misallocating rehabilitation resources across canal segments.

Implications for Water Management

For a water-stressed agricultural region such as Andijan, an estimated 93% reduction in seepage loss from converting earthen canals to concrete lining represents a substantial and actionable opportunity. With only 353 of the region's 10,552 km of canal network currently concrete-lined (World Bank), even a targeted lining program focused on the highest-loss or highest-priority segments could plausibly return a large share of currently seeping water to productive agricultural use, while reducing the pumping-energy losses and salinization risks associated with seepage (World Bank). The finding that seepage scales with both ΔV and cross-sectional area suggests that larger earthen canals, in particular, may offer the greatest absolute water savings per unit length lined, and could be a reasonable basis for prioritizing which segments to line first, pending confirmation in a larger sample.

Implications for Field Practice

Several practical lessons emerged during data collection that are relevant to future seepage studies in Andijan or elsewhere in Uzbekistan. First, some candidate canal segments identified from maps were difficult to locate or access in the field. Researchers planning similar studies should scout candidate sites in person, or with recent satellite imagery, before finalizing a sampling plan. Second, irregular canal geometry made it impossible to measure cross-sectional area reliably at some locations, reinforcing the importance of selecting segments with uniform, well-defined channel shape. Third, bridges introduced a measurement bias: the reduced cross-sectional area beneath a bridge locally accelerates flow, which can distort velocity readings if measurements are taken too close to a bridge; sites well away from bridges or similar structures are preferable for velocity measurement, although a bridge can still be a practical vantage point for measuring depth. Finally, because the water surface can contain multiple wavefronts moving at different speeds, float-method measurements should be taken from a single, consistent stream of flow at both the upstream and downstream points of a given reach to avoid introducing spurious variability into ΔV.

Limitations and Future Work

Sample size. With six replicate segments per canal type, the statistical comparison above is based on a small sample. Although the effect size was large enough to produce a statistically significant result by both parametric and non-parametric tests, a larger sample spanning more sites and canal ages would allow more precise estimation of the mean seepage rate for each canal type, and would support subgroup analyses (for example, by canal age, maintenance history, or soil type) that are not possible with the present data.

Seasonal and hydrological variability. Measurements were taken at a single point in time and do not capture seasonal variation in flow, groundwater table depth, or soil moisture, all of which can influence seepage rates. Seepage is generally expected to vary with the water level in the canal and with the moisture content of the surrounding soil, so the rates reported here should be interpreted as representative of the sampled conditions rather than as year-round averages.

Soil type and canal condition. Earthen canals in this study were treated as a single category, but soil composition, compaction, and vegetation cover can all affect seepage substantially and were not characterized here. Similarly, the age and maintenance history of the concrete linings sampled — which can affect the presence of cracks or joint failures that increase seepage above the theoretical minimum for intact concrete — were not recorded. Both factors are plausible sources of the variability observed within each canal type (Table 1) and should be documented in future studies.

Measurement uncertainty. As discussed under Measurement Uncertainty, the reported seepage values, particularly for concrete-lined segments with very small ΔV, carry substantial uncertainty relative to the signal being measured. Future studies would benefit from a higher-precision velocity measurement method, such as a current meter or acoustic Doppler velocimeter, which would reduce the timing and surface-correction uncertainties inherent to the float method, along with repeated, independently recorded area and velocity measurements at each point to allow rigorous propagation of uncertainty.

Evaporation. Evaporation was not measured directly and was assumed, following Syed and Shuqi, to represent a minor share (5–15%) of total conveyance loss relative to seepage. This assumption was not verified locally and could vary with canal width, air temperature, and wind exposure; direct measurement of evaporation in future work would allow seepage to be isolated with greater confidence.

Empirical formula comparison. The comparison with the Davis–Wilson formula assumes that the empirical estimates were computed over the same reach length as the corresponding field measurement; this assumption was necessary to normalize the two sets of values onto a common basis but could not be independently verified. A more rigorous comparison would recompute the empirical estimate directly from its underlying hydraulic inputs for each segment, rather than relying on previously reported summary values.

Site photography. Closer, site-level photographs of the sampled canals would strengthen future supplementary material. No such photographs were collected during the original field campaign, and none are available for inclusion here. We recommend that future field studies systematically photograph each measurement site, both to document channel condition and lining quality and to support readers' interpretation of the reported geometry.

CONCLUSION

Seepage is the principal mechanism of water loss in irrigation canals and represents a major, largely preventable inefficiency in water-stressed agricultural regions such as Uzbekistan. This study measured seepage in twelve canal segments in the Andijan region using the inflow–outflow method and found that earthen canals lost water at a mean rate approximately 13.6 times higher than concrete-lined canals (12.51 versus 0.92 m^3 s^{-1} per 100 m), a difference that was statistically significant under both parametric and non-parametric tests. These results indicate that converting earthen canals to concrete lining could reduce seepage losses by approximately 93% in this region, with seepage rate also increasing with cross-sectional area and with the magnitude of velocity loss along a canal reach.

These findings provide new, locally grounded evidence for water-management organizations addressing water scarcity in Andijan and the wider Fergana Valley, and support the prioritization of concrete lining, particularly for larger earthen canals, as a practical intervention for improving irrigation efficiency and water conservation. The substantial discrepancy between field-measured seepage and estimates from the Davis–Wilson empirical formula further underscores the importance of locally collected data, rather than uncalibrated empirical formulas, for guiding canal-rehabilitation decisions in this region. Future work with a larger sample, direct evaporation measurement, and higher-precision velocity instrumentation would strengthen and extend these conclusions.

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