

# Incorporating Temperature into Seepage Loss Estimates for the Truckee Canal

Science and Technology Program Research and Development Office Final Report No. ST-2022-1765-01



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# **Mission Statements**

The U.S. Department of the Interior protects and manages the Nation's natural resources and cultural heritage; provides scientific and other information about those resources; and honors its trust responsibilities or special commitments to American Indians, Alaska Natives, and affiliated Island Communities.

The mission of the Bureau of Reclamation is to manage, develop, and protect water and related resources in an environmentally and economically sound manner in the interest of the American public.

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Final Report No. ST-2022-1765-01

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# **Peer Review**

Bureau of Reclamation Research and Development Office Science and Technology Program

Final Report No. ST-2022-1765-01

Incorporating Temperature into Seepage Loss Estimates for the Truckee Canal

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# **Executive Summary**

Quantifying seepage losses from unlined irrigation canals is necessary to improve water use and conservation. The use of heat as a tracer is widely used in quantifying seepage rates across the sediment-water interface. In this study, field observations and two-dimensional numerical models were used to simulate seepage losses during the 2018 and 2019 irrigation season in the Truckee Canal system. Nineteen transects were instrumented with temperature probes and stage recording devices for inverse modeling to derive seepage flux and volumetric losses over the 39 km length of canal. The numerical models for each transect were calibrated and validated using the two-year dataset. Soil zones and observation data were used in each numerical model to help guide calibration of vertical and lateral heat and fluid fluxes. Model simulations were used to derive multivariable regression equations that consider stage, temperature, and hydraulic gradient. The results demonstrate the value of long-term datasets that illustrate the seasonality of groundwater levels, siltation, stage, and temperature on seepage rates. Seepage rates estimated by the numerical models range from 0.16 to 4.6 m3 d-1 m-1. Total annual volumetric losses estimated for 2018 and 2019 were 1.6 x 10-2 to 1.2 x 10-2 km3, respectively. The seepage losses estimated by this study account for 32% to 41% of the inflow volumes. Regression models were able to reproduce seepage timeseries simulated by the numerical models reasonably well. In arid environments, water diverted into irrigation canals may be influenced by seasonal variations in temperature sufficient to influence the water accounting of conveyed surface flows.

# Report

A manuscript containing pertinent data and results pertaining to the subject project has been published by the Journal of Hydrology. The non-type set version of the final manuscript is included as Appendix A.

Link to the journal article https://www.sciencedirect.com/science/article/pii/S0022169423000598?dgcid=author

Link to data release and model archive https://www.sciencebase.gov/catalog/item/61c35f21d34e2ca389dadc64

# Appendix A

# Incorporating temperature into seepage loss estimates for a large unlined irrigation canal

#### 2 3

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## 7 Abstract

- 8 Quantifying seepage losses from unlined irrigation canals is necessary to improve water use and
- 9 conservation. The use of heat as a tracer is widely used in quantifying seepage rates across the
- sediment-water interface. In this study, field observations and two-dimensional numerical
- 11 models were used to simulate seepage losses during the 2018 and 2019 irrigation season in the
- 12 Truckee Canal system. Nineteen transects were instrumented with temperature probes and stage
- recording devices for inverse modeling to derive seepage flux and volumetric losses over the 39
- 14 km length of canal. The numerical models for each transect were calibrated and validated using
- the two-year dataset. Soil zones and observation data were used in each numerical model to help
- 16 guide calibration of vertical and lateral heat and fluid fluxes. Model simulations were used to
- 17 derive multivariable regression equations that consider stage, temperature, and hydraulic
- 18 gradient. The results demonstrate the value of long-term datasets that illustrate the seasonality of
- 19 groundwater levels, siltation, stage, and temperature on seepage rates. Seepage rates estimated by
- 20 the numerical models range from 0.16 to 4.6  $m^3 d^{-1} m^{-1}$ . Total annual volumetric losses estimated
- for 2018 and 2019 were  $1.6 \ge 10^{-2}$  to  $1.2 \ge 10^{-2}$  km<sup>3</sup>, respectively. The seepage losses estimated
- by this study account for 32% to 41% of the inflow volumes. Regression models were able to
- reproduce seepage time-series simulated by the numerical models reasonably well. In arid
- environments, water diverted into irrigation canals may be influenced by seasonal variations in
- temperature sufficient to influence the water accounting of conveyed surface flows.

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# 27 Highlights

- Seepage responses to changes in stage, temperature, and groundwater elevations were
   simulated using VS2DHI
  - Sediment temperature data are helpful in developing and testing seepage conceptual models
- Continuous long-term sediment data were used to validate seepage models
- Temperature effect on seepage rates and volumetric loss are substantial
- Real-time seepage monitoring is possible with coupled field and modeling approaches

# 35 **1.0 Introduction**

- 36 In the United States, agricultural irrigation is a major use of ground and surface water,
- accounting for 42 percent of the Nation's total freshwater withdrawals (*Dieter et al.*, 2018). In
- arid environments, the reliance on irrigation from surface water within watersheds that are highly

susceptible to climate variability poses major challenges in managing water resources (USGCRP, 39 2017). Given these challenges, irrigation canals are important for inter-basin transfer of surface 40 41 water to agricultural areas and reservoirs within watersheds that are water-limited and may not receive sustainable water naturally. Water scarcity is driving the need to improve understanding 42 of flows and fluxes within agricultural areas to improve sustainability and efficiency of water 43 44 resources (Steduto et al, 2012). Climate change is contributing to already mounting pressures to conserve water resources to maintain economic and environmental benefits (Sterle et al., 2019). 45 Irrigation canals used for conveyance of water for agriculture represent an evolving 46 challenge for managers. There is a general recognition that improvements in conveyance 47 48 efficiency are needed to better manage water resources (Lindenbach et al., 2021). Seepage losses 49 from unlined canals can represent substantial inefficiencies in surface water conveyance, accounting for 15 to 50 percent of the total diverted volume (Van der Leen et al, 1990; Kacimov, 50 51 1992; Sharma and Chawla, 1979), requiring more water to be diverted to meet irrigation 52 demand. The volume of water diverted for agriculture can result in substantial declines in 53 streamflow that may result in water quality and ecosystems impacts (*Wurtsbaugh et al.*, 2017; 54 Scanlon et al., 2007; Chen et al., 2003; Scoppettone et al., 1986). Improvements in conveyance 55 efficiency are a critical resource management objective to conserve water and ensure farmers 56 receive their permitted water allocations.

57 Canal maintenance and lining projects are a means to increase conveyance efficiency and 58 reduce seepage but may have unintended consequences. Seepage contributes to aquifer recharge 59 that can be recovered for further agriculture or domestic use. As such, in some communities 60 there is a reliance on recharge from canals for domestic water use or for continued agricultural 61 use by groundwater pumping (*Arumí et al.*, 2009; *Fernald and Guldan*, 2006). Recharge from

irrigation canals can also provide water quality benefits and restore depleted aquifers (*Thodal* 62 and Tumbusch, 2006; Pohll et. al., 2001). Aquifer recharge from irrigation canals is often 63 64 included as an important component within regional studies given the spatial extent of canal networks and quantity of water supplied (Arumí et al., 2009; Maurer, 2002; Pohll et al., 2001). 65 66 Irrigation canals can also serve important secondary purposes to provide ecosystem services 67 (Carlson et al., 2019; Fleming et al, 2014), reduce flood peaks during spring runoff (Fernald and Guldan, 2006), and restore declines in aquifer storage for managed aquifer recharge (Niswonger 68 et al., 2017). Agricultural water is multifunctional, and plays a critical role in rural community 69 70 livelihood, cultural heritage, and identity. Water management decisions may need to consider a more diverse set of integrated benefits canals provide (Groenfeldt, 2006). 71

72 Canal seepage losses are governed by hydraulic properties of sediments, canal geometry, stage, and the hydraulic gradient between surface flows with the underlying aquifer (Bouwer, 73 74 1965; *Robinson and Roher*, 1959). The presence of low permeability sediments at the base of 75 and beneath the canals influences the rates and direction of seepage (*Wachyan and Uston*, 1987; 76 Yao et al., 2012). Other factors that influence rates are sediment temperatures, periods of 77 operation (wet-dry cycles), and canal maintenance removing vegetation and fine sediments to 78 improve conveyance (Naranjo and Smith, 2016). In the presence of near surface clogging, 79 seepage can become drastically reduced. Settling of fine sediments can be mediated by both 80 physical and biotic factors leading to seasonably variable seepage rates (*Rosenberry et al.*, 2021; Naranjo and Smith, 2016). 81

Quantifying the rate and locations of seepage can be challenging due to spatial variations
of canal characteristics and temporal variability of operations. Traditional direct methods such as
ponding methods, seepage meters, and inflow-outflow measurements have been used widely

(Batlle-Aguilar and Cook, 2012; Alam and Bhutta, 2004; Robinson and Rohwer, 1959; Warnick, 85 1951). These approaches are generally considered suitable for many systems but have practical 86 87 limitations. Ponding methods require controlled measurements of stage decline between sections of a diked reach, causing disruptions to water operations. Seepage meters have been used for 88 89 several decades and are an efficient method to obtain discrete seepage measurements at multiple 90 locations for both losing and gaining sections of canals. Drawbacks include the need for multiple deployments to obtain seepage rates during different stage conditions and may be challenging or 91 92 impractical in unwadable conditions or in canals with high stage variability (Rosenberry et al, 93 2020). Seepage losses made from inflow-outflow or differential discharge measurements are reliable when losses are greater than discharge measurement uncertainty and canal flow is 94 maintained at steady state conditions. Acoustic doppler current profilers (ADCP) are better 95 suited for discharge as measurement uncertainty is reduced (Martin and Gates, 2014; Kinzli et 96 97 al., 2010;). Surface geophysical methods can be a viable indirect tool for mapping long sections 98 of canals to identify potentially high seepage rates. Hobza and Andersen, (2010) used resistivity surveys on 84 km of canals in Nebraska to determine contrasting lithologies to a depth of 8 m 99 below land surface to better understand spatial variations in seepage. Additional field 100 101 observations such as sediment descriptions, electrical conductivity logs, and seepage meters are combined with electrical conductivity (inverse of resistivity) to estimate seepage loss (Hobza and 102 103 Andersen, 2010; Hotchiss et al, 2001;). A key limitation to traditional approaches is the inability 104 to account for variations of losses during canal operations and over the duration of the entire 105 irrigation season.

Heat as a tracer has been widely used for estimated fluxes between surface water and
groundwater at variable time and spatial scales (e.g., *Schilling et al.*, 2019, *Rau et al.*, 2014;

108	Constantz et al., 2008; Andersen, 2006; Stonestrom and Constantz, 2003). This approach can
109	also be used to quantify the effects of scour and siltation on seepage rates by evaluating the
110	changes in thermal gradients over time (Naranjo and Smith, 2016; Tonina et al., 2014). In
111	addition to seepage estimates, identifying large-scale sections of a canal where groundwater
112	discharge is present can also be made from distributed fiber-optic temperature sensing (Selker et
113	al., 2006; Briggs et al., 2011 and Sebok et al., 2013). Recent advancements in processing
114	programs are available to automate processing of temperature time-series and calculate vertical
115	seepage flux, such as Ex-stream (Swanson and Cardenas, 2011) and VFLUX (Gordon et al.,
116	2012). Integrating temperature observations into fully coupled surface and groundwater models
117	provide insight in hydrogeological constraints (Brookfield et al., 2009; Engeler et. al., 2011).
118	Continuous observations of sediment temperatures can be used to estimate early infiltration rates,
119	or in the case of lateral canals, periods of flow and no-flow, and variations in flux caused by
120	stage conditions (Karan et al., 2014). The heat as a tracer approach for canal seepage estimation
121	can provide seepage or loss rates during managed canal operation, through embankment
122	sediments, and during periods of hydraulic disconnection with the aquifer (Naranjo and Smith,
123	2016; Hobza and Andersen, 2010; Shanafield et al., 2010; Mihevc et al., 2002). The
124	consideration of seasonal effects, such as episodic deposition and erosion, water table
125	fluctuations, sediment clogging, and temperature effects, are becoming increasingly important in
126	quantifying seepage rates but rarely are considered (Rosenberry et al., 2021).
127	Our primary objective in this study was to use field data and numerical seepage models to
128	quantify the spatial and temporal variability of seepage rates during operation of the Truckee
129	Canal, Nevada. In this project, we measured subsurface temperatures, canal stage and
130	groundwater levels to calibrate and validate parameters used in the numerical seepage models

during a two-year period of canal operations. Multivariable regression models were developed
from numerical models to provide seepage equations to be applied with field data for future
canal operations.

#### 134 **2.0 Study Area**

The Truckee Canal (TC) conveys water from the Derby Dam on the Truckee River to 135 Lahontan Reservoir within the Carson River basin (Figure 1). The construction of the TC 136 occurred in 1903 and was the first U.S. Bureau of Reclamation (Reclamation) project in the 137 United States (Townley, 1977). The TC is roughly trapezoidal in geometry and is operated and 138 managed in three major reaches: Derby reach (16 km), Fernley reach (18 km), and Lahontan 139 reach (16 km). Approximately 42 km of the canal is unlined with earthen embankments and is 140 gaged by the U.S Geological Survey (USGS) at two locations, the Truckee Canal at Wadsworth 141 (USGS 10351650), Nevada and at the Truckee Canal near Hazen, Nevada (USGS 10351400) 142 (USGS, 2018). 143

144 During the last century, diversions into the TC and other upstream diversions have 145 reduced streamflow downgradient of Derby Dam resulting in reduced inflows into Pyramid Lake 146 inhabited by the endemic and endangered fish Cui-ui (*Chasmistes cujus*) and federally threatened Lahontan Cutthroat Trout (Oncorhynchus clarkii henshawi; Scoppettone et al., 1986). Since 147 148 1997 several Operating Criteria and Procedures (OCAP) for the Newlands Reclamation Project 149 have been established to regulate the timing and amount of water that can be diverted out of the Truckee River to serve water rights, minimize the use of Truckee River, and maximize the use of 150 151 the Carson River (OCAP, 1997). The Truckee River Operating Agreement (TROA) coordinates the operation of upstream reservoirs and provide additional storage to benefit instream flows, 152

reduce the declining water levels of Pyramid Lake, and improve water quality in the Lower
Truckee River (*TROA*, 2008).

The TC was originally designed to convey up to 43  $m^3s^{-1}$ ; however, in recent decades of 155 operation the canal has rarely conveyed more than 21 m<sup>3</sup>s<sup>-1</sup>. In 2008, a section of the Fernley 156 reach breached causing flooding and property damage. Since this failure, the TC has been 157 operated under reduced flows to limit risk of future failure with a maximum flow of 10 m<sup>3</sup>s<sup>-1</sup> 158 (*Reclamation*, 2015b). During 2018 and 2019, an average inflow of approximately 2 m<sup>3</sup>s<sup>-1</sup> was 159 measured at the USGS gage at Wadsworth (USGS 10351650 Truckee River at Wadsworth, NV). 160 Gate structures within the Fernley and Lahontan reaches are used to release water to a series of 161 lateral ditches. For sections of the TC upgradient of gate structures, stage can widely fluctuate. 162 During the 2018 and 2019 irrigation seasons (April to November), 3.4 x 10<sup>-2</sup> km<sup>3</sup> (27,570 acre-ft) 163 and 2.4 x 10<sup>-2</sup> km<sup>3</sup> (19,422 acre-ft), respectively, flowed past the USGS gage at Wadsworth and 164 into the canal system. 165

Water diverted to the TC flows through varying geological features of volcanic rocks,
paleolake bed sediments, and alluvial fan deposits. The Derby reach of the TC is founded on
volcanic bedrock and overlying alluvium and lakebed sediments are present downgradient of the
USGS gage at Wadsworth and throughout the Fernley and Lahontan reaches (*Reclamation*,
2015b; 2015c). Lakebed sediments consist of a horizontally bedded sequence of clay, silt, and
sand with claystone and siltstone deposits formed by paleo Lake Lahontan (*Benson*, 1981).

The climate where the TC is located is considered arid and lies in the rain shadow of the Sierra Nevada where the average annual precipitation is 119 mm, most of which occurs in the surrounding mountains during the winter (*Moffet et al.*, 2019; *Thodal and Tumbusch*, 2006). Daily high temperatures during summer months are warm, normally ranging from 27°C to 32°C

and can exceed 38°C (*Moffet et al.*, 2019). Average monthly air temperatures Fernley area range
from 3.1 °C to 20 °C.

### 178 **2.1 The Derby Reach**

The Derby reach is 16 km in length with 6 km of discontinuous concrete lined sections. 179 Flows are controlled in this section by Derby Dam and through gated spillways that return water 180 to the Truckee River. In this reach, the TC intersects numerous narrow ephemeral drainages that 181 once flowed to the southern slope of the Truckee River canyon. The TC was excavated into an 182 existing hillslope with the sediment material used to construct the left embankment (facing 183 184 downstream). The left embankment ranges in height from 1.5 to 15.0 m (*Reclamation*, 2015a). Boreholes drilled for geological investigations encountered groundwater at a depth greater than 185 3.0 m below the base of the TC while the TC was dry. Five seepage sites in the Derby reach were 186 187 selected to be collocated with seeps identified along the left outer embankment. The presence of 188 seeps on the outer embankment are expressed as visible flowing or ponded water. Seepage Sites 189 1-3 were selected in 2018, and Sites 0.5 and 2.5 were added in 2019 (Figure 1). The upstream-190 most site within this reach, Site 0.5 was located 2.7 km downstream of Derby Dam. At the end of 191 the reach, Site 3 was located 0.26 km from the USGS gage at Wadsworth. The average bottom 192 width of seepage sites on the Derby reach was 5.4 m with an average of embankment slope 193 (vertical to horizontal) of 1:2.5.

194 **2.2 The Fernley Reach** 

The Fernley reach is 18 km and trends southeast through gently sloping terrain along the edge of the City of Fernley. Several seepage and geologic investigations have been done in this reach to address water resource and safety concerns (*Reclamation*, 2015b; *Shanafield et al.* 2014; *Mihevc et. al.*, 2002; *Pohll et al.*, 2001; *Van Denburgh and Arteaga*, 1985). The TC in the Fernley reach has been breached at least nine times with the most recent occurring in 2008

(*Reclamation*, 2015b). Improvements to the sections of canal where historic breaches occurred 200 widened the TC, stabilized the banks, and fine sediments were placed at the bottom of the TC to 201 202 reduce seepage rates. Flows entering this reach are measured at the USGS Wadsworth gage and there are nine lateral canals with three gate structures or checks that control the canal stage for 203 diversions into lateral ditches. There were eight seepage sites selected in this reach at an average 204 205 distance interval of 2.2 km co-located with seeps and located up-gradient of gate structures. Seepage Sites 4-9 were selected in 2018 and 3.5 and 9.5 were added in 2019 (figure 1). Site 6 206 207 was located near a monitoring well that was included in the monitoring effort. The average bottom width of seepage sites in the Fernley reach was 4.3 m with an average vertical to 208 209 horizontal side slope of 1:3.4.

210 2.3 The Lahontan Reach

211 The Lahontan reach is 16 km and trends southeast to southwest, mostly across gently 212 sloping terrain to the terminus of Lahontan Reservoir in the Carson River Basin. Flows in this reach are measured at the USGS gage near Hazen (USGS 10351400) near a gate structure that 213 214 controls flow into Lahontan Reservoir and a lateral canal. Canal sediments and embankment 215 materials consist of a heterogenous mixture of sandy silts and silty sand derived from lakebed 216 sediments excavated during canal construction (Reclamation, 2015c). The TC also flows through 217 sections of alluvial and volcanic deposits with loamy sand through cobble-size sediments. 218 Groundwater was encountered approximately 5.0 m below the base of the TC perched above layers of low-permeable lakebed sediments and volcanic rock while the canal was dry 219 220 (Reclamation, 2015c). There were 6 seepage sites selected in this reach at an average distance interval of 1.9 km co-located with seeps and located up-gradient of gate structures (Figure 1). 221 222 The last seepage site, Site 15 was located 250 m down gradient of the USGS gage near Hazen.

The average bottom width of sites on the Lahontan reach was 6.3 m with an average of verticalto horizontal side slope of 1:3.0.

### 225 **3.0 Methods**

### 226 **3.1 Field Methods**

Equipment deployed at each seepage site was used to characterize vertical and lateral 227 228 seepage by focusing sensor placement near the sediment-water interface at the bottom and sides 229 of the canal. Two temperature probes (Naranjo and Turcotte, 2015) were installed in the bottom 230 of the channel at each transect (Figure 2). Each probe contained temperature sensors spaced at 0, 10, 20, 50, 75, and 100 cm beneath the sediment-water interface at the canal invert. A 2.54 cm 231 232 diameter Polyvinyl Chloride (PVC) piezometer was driven 2-3 m below the ground surface along the left bank in the canal access road. Only one piezometer was installed given access to 233 download data from the right side of the canal during operations was impractical. A screen 234 length of 10 cm was located 5 cm from the bottom of the piezometers to monitor the potential for 235 236 rising water tables. However, given the depth to water and side slope of embankment material, 237 piezometers driven with hand tools were not able to reach the groundwater table. Three to four temperature sensors (Ibcods Type Z; Alpha Mach, Inc.) were strung inside the piezometer at 238 evenly spaced depths ranging from 10 to 40 cm apart. The upper most temperature sensor (Ibcod, 239 240 Type G, Alpha Mach, Inc.) was placed 10-20 cm below the surface to measure land surface temperatures. Temperature data were recorded at one-hour intervals and retrieved from the 241 loggers monthly. Prior to deployment of equipment, the temperature sensors were independently 242 243 calibrated in a water-bath utilizing a 5-point linear regression to validate raw temperature readings. Accuracy of the sensors after calibration is within 0.1°C (Naranjo and Turcotte, 2015). 244 Canal stage is monitored by Truckee-Carson Irrigation District and Reclamation at 12 245

seepage sites along the TC. The remaining 7 sites were instrumented with pressure transducers

(TD-Divers, Van Essen Instruments) deployed near the canal bottom to capture the low-flow 247 stage but close enough to the edge of water to manually measure stage at monthly intervals. 248 249 Stage as discussed herein, is defined as the head (or height) of water above the bottom of the canal. Stage was recorded every hour and manual water-level measurements taken monthly were 250 251 used to verify and correct pressure transducer-derived water-level measurements (Sauer and 252 Turnipseed, 2010). The accuracy of the pressure transducer measurements is  $\pm 2.0$  cm, with a resolution of 0.2 cm. The temperature readings have an accuracy of  $\pm 0.2$  °C and a resolution of 253 0.01 °C. 254

The TC is generally considered hydraulically disconnected from the saturated aquifer and is characterized as a losing system. However, groundwater may mound above low-permeable lakebed sediments and contribute to perched aquifers with recharge from the TC. To measure the influence of changing water levels on seepage rates, pressure transducers and temperature sensors were installed in existing monitoring wells at Site 2 and Site 6. During the deployment of sensors in April 2018, the wells were dry.

Elevation data for each cross section, monitoring well, bank piezometer, and temperature 261 262 probe were obtained through RTK GNSS survey techniques (Rydlund and Densmore, 2012). Soil 263 cores (3.2 cm diameter) were collected from the bottom of the channel to a depth of 61 cm to provide visual descriptions of the soil profile and to identify confining or low permeable deposits 264 near the surface. Thermal conductivity was measured monthly along the saturated embankment 265 266 sediments using a handheld thermal conductivity probe (KD2 Pro, Decagon). Observations taken from bottom sediments were not possible while the canal was in operation. Values obtained from 267 discrete measurements were used to set the range in values of thermal conductivity at saturation 268 for model calibration. 269

#### 270 **3.2 Numerical Methods**

- Seepage was numerically simulated for each of the 19 transects using the variably
  saturated two-dimensional hydraulic model (VS2DHI, *Hsieh et al.*, 2000; *Healy and Ronan*,
  1996). VS2DHI is a finite difference model that uses the Richard's equation for variably
  saturated flow and the energy transport equation to simulate the change in thermal storage as a
  function of thermal conduction, dispersion, and convection (*Healy and Ronan*, 1996).
  Groundwater flow simulated by the model accounts for temperature dependency of viscosity
  within the hydraulic conductivity term (*Healy and Ronan*, 1996),
- 278  $K = \rho g k / \mu (T)$  (1)

279 Where  $\rho$  is density, in kg/m<sup>3</sup>; g is the acceleration of gravity, in m/s<sup>2</sup>; k is the intrinsic 280 permeability, in m<sup>2</sup>; and  $\mu$  is viscosity in ns/m<sup>2</sup> as a function of temperature, T. Viscosity is 281 calculated empirically (*Kipp*, 1987),

282  $\mu(T) = 2.4 \times 10^5 \times 10^{[247.8/(T+133.16)]}$ (2)

Two-dimensional (2D) seepage models were created for each transect by defining the 283 cross-sectional representation of the canal, soils, initial conditions, boundary conditions, and 284 locations of observations in the graphical processor VS2DHI (Hsieh et al., 2000; Figure 2). Soil 285 286 thermal and hydraulic properties were defined by soil zone polygons (Figure 2b). The sediments near the sediment-water interface with the greatest variations in temperature and were 287 represented by three zones (zone 1-3). Soil zone 4 was used to describe subsurface properties 288 important for simulating lateral flow away from the canal. Soil zone 5 was used at transects 289 where borehole data indicated volcanic or lakebed sediments were present (not shown in Figure 290 2, see Naranjo et al., 2023 and Supplemental data Figure SI.1). The 2D conceptual model 291 assumes the bottom canal sediments are represented by a uniform clogging layer (Naranjo and 292

Smith, 2016). However, the parameter estimation calibration technique (PEST ++, Welter et al., 293 294 2015) could confirm the presence or absence of surface clogging layers by matching near surface 295 temperature observations (0.10 to 0.20 cm depths) that are very sensitive to soil hydraulic conductivity. As such, low amplitude temperature signals measured near the surface would be 296 indicative of heat conduction due to low permeable sediments whereas high amplitude signals 297 298 would be indicative of heat advection due to high permeable sediments. The two temperature probes were used to estimate parameters in zones 1, 2, and 4 (Figure 2b). The near surface, canal 299 300 embankment materials were defined by soil zone 3 and assumed to represent both sides of the canal. Ten temperature observations were used to calibrate the models for estimation of vertical 301 seepage (zones 1, 2, and 4). Three to four temperature observations collected in the embankment 302 sediments were used to calibrate each model for estimation of lateral seepage (zone 3). A 303 304 variable temperature boundary condition representing soil temperatures were specified at the upper boundary of the model. Stage and temperature measured at the sediment-water interface (0 305 306 cm depth) along the wetted perimeter were specified as a variable head and temperatures boundary condition. Lateral vertical boundary conditions were defined as no-flow and positioned 307 away from influence on subsurface flow. At Sites 2 and 6, groundwater levels measured in 308 309 monitoring wells were used to define the bottom and both lateral boundaries.

The 2D seepage models were defined by the surveyed cross-section that included bottom width, side-slope, and embankment sediments. The model grids were refined near the canal boundary and temperature observations. Grid spacing between 0.01 and 3.0 m was used in the horizontal direction and between 0.01 and 1 m in the vertical direction with coarser grid spacing further away from the observations and wetted perimeter. The width and depth of the model domain varied for each model to avoid boundary condition edge effects on the simulations. The

316 models extent in the horizontal and vertical direction varied between 80 and 200 m, and 15 and 317 40 m, respectively. The vertical sides of the models were specified as no flow boundaries. The 318 lower horizontal boundary of the model was specified as gravity drainage. In transects where the 319 canal was hydraulically connected to groundwater, the lateral and bottom horizontal boundary 320 conditions was specified as variable head boundary condition.

Initial conditions specified for each model were initial moisture content and sediment temperatures. The initial moisture contents among the different cross-sectional models were assumed to range between 0.05 to  $0.15 \text{ m}^3/\text{m}^3$  for the zones near the sediment-water interface. The initial temperature for each model was based on interpolation of the observed temperature measurements at the start of the simulation for the entire model domain.

326 **3.3 Model Calibration** 

327 The parameter-estimation model, PEST++ (Welter et al., 2015) was used to calibrate each transect model by adjusting hydraulic and thermal properties to match observed 328 329 temperatures. PEST ++ is an independent, object-oriented parameter estimation code that 330 executes the VS2DHI model and adjusts the parameters using the Gauss-Marquardt-Levenberg optimization algorithm by comparing the simulated temperatures to the observed through a 331 weighted least-squares objective function. PEST++ allows the use of observation and time 332 varying weights to give greater importance to data points or specific behaviors in the data such as 333 daily fluctuations of temperature. Temperatures near the daily minimum and maximum were 334 given a weight of 1 to emphasize amplitude variations. All other temperatures were given zero 335 weight. Focusing on the amplitude variations, yield model simulations that are more 336 representative of field data and directly relate to the hydraulic and thermal properties of the soils 337 338 (Naranjo and Smith, 2016). Arrays of time varying weights were created using the first

observation (0.0 m) in the center of canal with Series SEE (v1.12; *Halford et al.*, 2012) using the
Period Function.

341 Soil property values that were not estimated were assigned based on values reported in 342 Carsel and Parrish (1988) for general soil textural classifications provided in VS2DHI. Parameters such as saturated hydraulic conductivity, thermal conductivity, porosity, and heat 343 344 capacity are among the most sensitive to temperature simulations (Naranjo and Smith, 2016). However, the saturated hydraulic conductivity predominantly influences seepage rates (Lapham, 345 346 1989; Constantz, 2008; Naranjo and Smith, 2016). The parameter values and ranges used in PEST++ are provided in Table 1. The estimated parameters in each transect model were 347 348 saturated hydraulic conductivity in the horizontal direction  $(K_h)$ , thermal conductivity at saturation (Kts), and volumetric heat capacity of sediments (Cs). The ratio of the saturated 349 hydraulic conductivity in the vertical to horizontal direction (anisotropy) was assumed to be 0.1 350 for canal sediments and 0.01 for subsurface lakebed and volcanic sediments. 351

Performance of each model was evaluated during calibration and validation periods. 352 Model calibration was based on 2,500 hours of sediment temperature and stage data measured 353 354 after the canal stage was relatively stable and seasonal variability in canal water temperature ranged between 10°C and 25°C (May to August). The model parameters determined during 355 356 calibration were then validated by evaluating each model's performance for the irrigation season 357 (March to November) into the subsequent year. Model performance was measured by the Root Mean Square Error (RMSE) between observed and simulated temperatures for each sensor 358 359 location separately and for all observations. Differences between observed and simulated 360 temperatures RMSE were examined within the validation period to determine whether recalibration was necessary for the following year. Validation RMSE values that are different 361

from calibration RMSE values of more than 1.0 °C are typically caused by changes in hydraulic 362 and thermal properties due to siltation or scour (Naranjo and Smith, 2016). Siltation reduces 363 infiltration by reducing the porosity and hydraulic conductivity, thereby dampening the 364 amplitude of the temperature signal imparted by canal seepage beneath the surface. Scour events 365 366 can rapidly remove deposited silt layers and decrease the thermal gradients (Sebok et al., 2015). 367 This effect is distinguishable by the similarity in temperature in observations with respect to depth within a profile (*Tonina et al.*, 2014; *DeWeese et al*, 2017). Thus, using observational data 368 369 for model validation can provide insight into potentially time-varying hydraulic and thermal 370 properties (Naranjo and Smith, 2016). Increases in model RMSE calculated for all observations between calibration and validation periods to a maximum of 0.5°C were considered acceptable. 371

Seepage loss regressions for the TC need to account for the range in stage conditions 372 during normal operations of the canal. Additional transect models (herein defined as *max stage*) 373 374 were developed to simulate seepage losses at the maximum operational stage. Numerical model 375 seepage predictions for 2018, 2019, and max stage were then used to develop regressions models that would account for range in temperature and stage conditions. For each transect model, a new 376 377 boundary condition was developed by increasing the observed stage by a factor until the average 378 stage condition was at the maximum operational stage of the canal. By using a factor, the daily and seasonal variation in stage was preserved. The temperature boundary condition within the 379 canal was assumed to be consistent with daily and seasonal variation observed at 0.0 m depth 380 during 2018 or 2019 for each transect model. 381

### 382 **4.0 Results**

The numerical models were used to simulate seepage losses along transects during operation of the Truckee Canal during the 2018 and 2019 irrigation seasons (Naranjo *et al.*,

2022). Multivariable regression equations were then developed from numerical models for each
transect. The numerical model output and regression model are presented as total seepage flux in
vertical and lateral directions across the wetted canal surface. The results described in this
section demonstrate the use of temperature and stage observations to calibrate numerical models.
For brevity, a transect model from each reach is discussed. The reader is referred to Naranjo *et al.*, (2023) for further description of models, observation data, and calibration results.

391

### 4.1 Numerical Model Performance

The calculated overall RMSE for all observations at each transect for the calibration and 392 393 validation periods are summarized in Table 2. During the calibration period (typically May to August; see Naranjo et al. 2023 for simulation periods), the models performed reasonably well 394 with overall RMSE values ranging from  $0.34^{\circ}$ C to  $0.76^{\circ}$ C. During the validation periods for 395 396 2018 and 2019 (March to November), the overall RMSE values ranged from 0.33° to 0.99°C. At Site 3, the overall RMSE computed for the 2018 validation period was substantially greater than 397 398 the 0.5 °C criteria and required re-calibration with temperature data from 2019. The re-calibrated 399 2019 model performed reasonably well with an overall RMSE of 0.76  $^{\circ}$ C, a difference of 0.14  $^{\circ}$ C 400 compared to the calibration results of 2018. Re-calibration of the model was done manually by 401 reducing K<sub>h</sub> until simulated temperatures in 2019 were within agreement with observation data 402 and the RMSE was within the threshold of 0.5 °C of the 2018 calibration model. The changes in K<sub>h</sub> at this transect were likely caused by localized siltation as other transect models were not 403 affected. 404

Stage measured at Site 1 varied from 0.2 m to 1.4 m with large variations occurring
during the initial 1,500 hrs and final 100 hrs of operation (Figure 3). Seasonal temperature
variations observed at 0.1 m varied from 5.4 to 25.5 °C during the remainder of 2018 (March to

November; Naranjo et al, 2022). Model simulations match the daily amplitudes in the shallow observations near the sediment-water interface as well as the seasonal variation in heat transport in the deeper observations (overall RMSE =  $0.63^{\circ}$ C). During the early validation period (0 to 200 hrs.), the model underestimates the large variations in thermal patterns at all depths as flow in the canal starts and during initially dry soil.

413 The canal stage was significantly more variable at transects located upgradient of the gate structures used to divert water to lateral canals. Additionally, transects at these locations also 414 415 recorded higher stages during water delivery to the laterals. Figure 4 shows the stage conditions at Site 8 in the Fernley reach where the stage varied from 1.8 to 2.7 m during 2018 (March to 416 417 November). Seasonal variation in temperatures observed at 0.1 m depth was 4.1 to 26.4 °C. At this transect, the daily temperature variations at 0.10 m depth were dampened compared to Site 1 418 with approximately 1.0 °C in variation. Overall, the model simulates the general behavior during 419 420 the May to August calibration 2018 period (overall RMSE =  $0.40 \,^{\circ}$ C) with greater deviation 421 from the observations occurring during the April to November 2018 validation period (4,500-5,000 hrs) at the 0.75 and 1.0m depths (overall RMSE =  $0.62 \circ C$ ). 422

The stage at Site 14 varied from 0.4 to 1.7 m during April to November 2018 as water was delivered to a lateral canal (Figure 5). During this period, temperature at 0.10 m varied seasonally from 2.7 to 26.4 °C. Larger daily variations were observed during calibration with the amplitude variations at 0.5 m. The model simulates and captures the general behavior during the calibration period (overall RMSE = 0.49 °C) with greater deviation from the observations occurring during the validation period (2,760 to 5,400 hrs) at the 0.75 and 1.0 m depths (overall RMSE = 0.52 °C).

430

431	At Sites 1, and 14, there are clear links between simulated seepage flux and observed
432	sediment temperature (Figure 6). While it is apparent that variations in canal stage affect
433	seepage, when stage is relatively constant the seasonal fluxes are influenced by temperature. The
434	seasonal effect of temperature can be observed at Site 1 with notable differences in seepage
435	behavior from 2018 and 2019 (Figure 6b). During 3/30/2018 to 7/2/2018, stage and simulated
436	flux rapidly varied between 0.2 to 1.5 m and 0.7 to 4.4 $m^3d^{-1}m^{-1}$ , respectively (Figure 6b). During
437	2019, the seasonal change in simulated flux corresponds to changes in observed temperature.
438	During 5/1/2019 to 8/15/2019, an average stage of 1.0 m was observed with a doubling (2.4 to
439	4.4 $m^3 d^{-1}m^{-1}$ ) of the simulated flux along with observed temperature (10 to 25°C). In months
440	following the peak in temperature (August 2019), the simulated flux decreased from 4.2 to 2.0
441	$m^{3}d^{-1}m^{-1}$ along with decreases in temperature from 26.0 to 5.0 °C while stage was nearly
442	constant at 1.2 m. At Site 8 in the Fernley reach, canal stage fluctuated between two contrasting
443	hydraulic properties of soil zone 2 ( $K_h = 0.15 \text{ mhr}^{-1}$ ) and soil zone 3 ( $K_h = 0.26 \text{ mhr}^{-1}$ ; see
444	Naranjo et al., 2022 Figure SI.1 and Table 1) which resulted in rapidly changing seepage
445	behavior (Figure 6d). At Site 8, lateral seepage through the embankment material is the dominant
446	direction of flow. At Site 14 within the Lahontan reach, the seasonal change in stage during
447	operations of the canal in 2018 and 2019 obscures the influence of temperature (Figure 6e, f). In
448	2018, seepage rates corresponded to the sediment temperature increase until the annual
449	maximum temperature of $26^{\circ}$ C on 7/16/2018, then declines to 13.6 on 10/12/2018. In 2019,
450	seepage rates were responding to rapid changes in canal stage and temperature seasonal
451	temperature declines.

### 454 **4.2 Seepage Flux and Volume Estimates**

The seepage flux and volumetric loss per unit length of canal estimated for each transect during the modeling period of 2018 and 2019 are shown in Table 3. Seepage flux estimated along the transects ranged from 0.2 to  $4.6 \text{ m}^3 \text{d}^{-1}\text{m}^{-1}$  with an average across all transects of 1.5 m<sup>3</sup>d<sup>-1</sup>m<sup>-1</sup>. Site 15 was located down gradient of a gate structure controlling nearly all the flow measured at the USGS gage at Hazen (USGS 10351400). An average of 0.2 m of canal stage was observed at this location. During the period of monitoring, the canal was dry for both years downgradient of Site 15.

462 The seepage flux estimated for each transect model was used to compute volumetric loss for each reach (Table 4). Because seepage estimates could not be made for the entire 16 km 463 Lahontan reach to Lahontan Reservoir, the volumetric losses were estimated for 10.3 km to the 464 465 USGS gage at Hazen (Site 14). The seepage fluxes per unit length of canal were assumed to represent the segment of canal between transects and summed over each reach. The total 466 volumetric losses for the 2018 and 2019 irrigation periods were  $1.6 \times 10^{-2} \text{ km}^3$  (12,737 acre-ft) 467 and  $1.2 \times 10^{-2} \text{ km}^3$  (9,497 acre-ft), respectively. Averaged over the 38.3 km distance from Derby 468 469 Dam to the USGS gage at Hazen, the overall volumetric loss per unit length of canal was 4.2 x 10<sup>-4</sup> km<sup>3</sup> km<sup>-1</sup> (474 acre-ft mi<sup>-1</sup>) and 3.0 x10<sup>-4</sup> km<sup>3</sup> km<sup>-1</sup> (351 acre-ft mi<sup>-1</sup>) during 2018 and 2019 470 471 monitoring period, respectively. The seepage losses represent 32% to 41% of the inflow volume 472 measured at the USGS gage at Wadsworth (USGS 10351650).

473 **4.3 Multivariable Regression** 

474 Regression equations that include stage and temperature to estimate seepage losses are
475 necessary to account for seasonal variability. The relationship between stage and sediment
476 temperature at the sediment-water interface (0.0m), and seepage loss for the range of conditions
477 observed in 2018, 2019 and for the maximum stage models are shown in Figure 7. Seepage rates

were grouped by sediment temperatures, low (<10 °C), moderate (10 to 20 °C) and high (>20 478 °C). At Site 1, the simulated flux at 2.0 m stage for sediment temperatures  $< 10^{\circ}$ C was 4.0 m<sup>3</sup>d<sup>-</sup> 479  $^{1}$ m<sup>-1</sup>. For sediment temperatures >20°C, the same stage condition would result in 38% increase in 480 losses of 5.5 m<sup>3</sup>d<sup>-1</sup>m<sup>-1</sup>. For the same change in temperature and stage condition, the increase in 481 simulated seepage flux would be 23% (2.4 to 3.0  $\text{m}^3\text{d}^{-1}\text{m}^{-1}$ ) and 44% (4.7 to 6.8  $\text{m}^3\text{d}^{-1}\text{m}^{-1}$ ) at Site 482 483 8 and Site 14, respectively. Canal temperature increases from Derby to Lahontan. At Site 1, temperatures were in the low, moderate, and high ranges 13%, 54%, and 32% of time, 484 respectively. For comparison, sediment temperatures were warmer 40.4 km further down the 485 canal at Site 14 with temperatures in the low, moderate, and high ranges 10%, 49%, and 41% 486 percent of the time, respectively. 487

Seepage flux derived from multivariable regression equations using observations of 488 temperature, stage, and VS2DHI estimated seepage flux for each transect on the TC are 489 490 summarized in Table 5. Regressions developed with stage and temperature have statistically 491 significant p-values (p < 0.001). In the Derby reach the multi-regression equations explain more than 81% of the variability in seepage (p < 0.001). For the Fernley reach, correlations between 492 estimates were much more variable with a range of  $R^2$  between 0.62 to 0.95 (p<0.001). There 493 494 were limited groundwater wells within the vicinity of the TC to account for fluctuating groundwater levels on seepage rates. At Site 6, the multi-regression equation needed to account 495 496 for the effect of changing groundwater elevations on seepage flux. Using stage and groundwater level data, the horizontal hydraulic gradient between the canal and an existing monitoring well a 497 498 distance of 8.7 m from the edge of the canal was included in the multi-regression equation. Including the horizontal gradient in the regression equation improved the correlation  $R^2$  from 499

500 0.53 to 0.85. In the Lahontan reach, the multi-regressions with stage and temperature explain 501 more than 95% of the variability in seepage (p < 0.001).

Time-series comparison between seepage fluxes estimated by VS2DHI and multiregression for Site 1, Site 8, and Site 14 are shown in Figure 8. Overall, the regression models match reasonably well to the seasonal and daily seepage estimates from VS2DHI at Site 1 and Site 14. However, at Site 8, the multi-regression equation matched the seasonal variation but did not replicate the large daily variations caused by stage fluctuations and lateral losses into embankment soils. As such, the regression equations describing fluxes at Site 8 had the highest error between losses estimated with VS2DHI ( $R^2 = 0.62$ ; p<0.001; RMSE = 0.29 m<sup>3</sup>d<sup>-1</sup>m<sup>-1</sup>).

The effects of groundwater elevation and temperature on seepage rates were influential at 509 510 the Fernley reach Site 6. Figure 9 shows the variations in groundwater elevation in response to recharge from canal seepage and subsequent declines likely due to groundwater pumping. 511 During the period between April to July, stage in the canal remained relatively constant with 0.8 512 m of variation. During the early wetting up period (April to May), the average seepage rates were 513 1.8 m<sup>3</sup>d<sup>-1</sup>m<sup>-1</sup>. The seepage rates decreased to a minimum of 0.8 m<sup>3</sup>d<sup>-1</sup>m<sup>-1</sup> during a period when 514 groundwater elevations reached the bottom elevation of the canal. The rapid variations in 515 groundwater elevations could be attributed to groundwater pumping. The overall increasing trend 516 in seepage is attributed to the effect of temperature, resulting in a 213% increase in rates. The 517 518 groundwater elevation decreased below the screen interval of the well for the remaining period beyond June 5, 2018. 519

520 5.0 Discussion

### 521 **5.1 Operational Seepage Monitoring**

The purpose of this study was to use field data and numerical seepage models to quantify 522 the spatial and temporal variability of seepage rates during canal operations. Seepage models 523 524 were used to derive regression equations based on stage and temperature, with one transect model including hydraulic gradient. The numerical models provide estimates of seepage flux 525 526 and volumetric loss per unit length of canal accounting for variations in hydraulic and thermal properties of canal sediments. To utilize the seepage information gained from the numerical 527 models, the regressions equations provide seepage estimates that can be made from future 528 observations of canal stage and temperature. Regression equations are necessary because canal 529 seepage will vary from year to year depending on water availability and canal operations. 530 Regression equations were derived the numerical models estimates for the full range of canal 531 532 stage and seasonal variation in temperatures. The existing monitoring infrastructure in the TC provide unique opportunities for automating seepage estimates during canal operations. The use 533 534 of sediment temperatures for estimating fluid flux is advantageous because temperature-based 535 estimates are sensitive to changes in infiltration caused by siltation, erosion, and streambed clogging. Schmidt et. al., (2014) demonstrated the use sediment temperatures along with 536 analytical equations for automated vertical fluid flux estimation and provided workflow for 537 538 translating field data to online accessible fluid rates. This study uses similar datasets to develop seepage relationships for total flux (vertical and lateral) as well as account for hydraulic 539 540 connectivity to groundwater. Results of this study highlight the importance of temperature in seasonal variations in seepage flux and volumetric losses. Seepage rates are influenced by the 541 temperature dependent viscosity of water (e.g., Rosenberry et. al., 2021; Constantz, 2008; Ronan 542 543 et al., 1998; Constantz et al., 1994; Jaynes, 1990; Levy et al., 1989; Robinson and Rohwer,

1959). As reported by Constantz et al., (1994), the hydraulic conductivity doubles within an 544 increase in temperatures from  $0.0^{\circ}$ C to  $25^{\circ}$ C and for typical diurnal variations of  $10^{\circ}$ C from a 545 546 mean of 15°C, an increase of 30% in seepage rates would be expected. In the modeling approach applied on the TC, we observed variations between 4.0 to 26.0 °C in temperature and seepage 547 548 rates seasonally varied with temperatures. From a practical standpoint, future implementation of 549 the regression equations can be applied given that stage and temperature are actively being measured. This would involve a separate regression of temperature measured at the sediment-550 551 water interface (0.0 m) with canal water temperature measured with existing sensors to input the 552 sediment temperature in the seepage equations.

Regression equations provide a simple and effective tool in seepage estimation (Salmasi 553 and Abraham, 2020; Hosseinzadeh et al., 2020). The regression equations based on numerical 554 seepage models account for differences in soil hydraulic and thermal properties governing 555 556 vertical and lateral seepage with site specific information for each transect. Additional 557 groundwater data are needed to refine the seepage estimates along the canal where water table fluctuation influenced seepage rates. Prior to this study, the Truckee Canal was assumed to be 558 559 hydraulically disconnected from the shallow aquifer (Epstein et al, 2007; Shanafield et al. 2014). 560 The findings presented from this study indicate the canal and shallow aquifer may transition between being hydraulically connected and disconnected within an irrigation season along 561 562 sections of canal. Given the distance between transects, it is uncertain to what spatial and temporal extent groundwater levels may influence seepage. Further work is needed to examine 563 564 the implications of these transitions in hydraulic connectivity to reach scale volumetric losses.

565 **5.2 Previous Seepage Investigations on the Truckee Canal** 

Previous seepage investigations on the TC focused on annual volumetric losses using 566 inflow-outflow, heat as a tracer, ponding experiments, and modeling at varying spatial and 567 temporal scales (Van Denburgh et al., 1973; Mihevc et al., 2002; Shanafield et al., 2014). To 568 guide comparisons among different methods, seepage loss for the 27 km reach between the 569 USGS gages at Wadsworth and Hazen are discussed. Seepage losses estimated for this length of 570 the Fernley and Lahontan reaches were similar during 2018 and 2019 with annual rates of 1.1 x 571  $10^{-2}$  km<sup>3</sup> yr<sup>-1</sup> (8,889 acre-ftyr<sup>-1</sup>) and 1.0 x  $10^{-2}$  km<sup>3</sup> yr<sup>-1</sup> (7,992 acre-ft yr<sup>-1</sup>), respectively (Table 4). 572 Seepage losses as a percentage of inflows during 2018 and 2019 at Wadsworth were 32% and 573 574 41%, respectively. Seepage losses estimated by inflow-outflow measurements between the gages were done as a part of a 1970s reconnaissance study for the Truckee River Basin (Van Denburgh 575 et al., 1973; Van Denburgh and Arteaga, 1985). Accounting for diversions, Van Dengburgh and 576 Arteaga, (1985) estimated  $3.0 \times 10^{-2} \text{ km}^3 \text{yr}^{-1}$  (24,000 acre-ft yr<sup>-1</sup>) for the period of 1968 to 1978. 577 During this period, inflows to the USGS gage at Wadsworth averaged 0.25 km<sup>3</sup>yr<sup>-1</sup> and as a 578 percentage, seepage losses for this section were 22% of the inflow volume. Nowlin (1987) 579 estimated seepage rates from 1979 to 1980 for the same length of canal, an average of  $3.0 \times 10^{-2}$ 580 km<sup>3</sup>yr<sup>-1</sup> (24,000 acre-ft yr<sup>-1</sup>). With inflows at the USGS gage Wadsworth measured at 0.23 581 km<sup>3</sup>yr<sup>-1</sup>, the seepage loss represented 13% of the inflow volume. Annual seepage estimates were 582 made by Pohll et al., (2001) using a 20-year inflow period (1969 to 1995) to refine a regional 583 groundwater flow model of the Fernley area. A developed regression based on measured annual 584 average inflow volume predicted seepage rates to range between  $1.6 \times 10^{-2}$  to  $4.9 \times 10^{-2}$  km<sup>3</sup>yr<sup>-1</sup> 585 (13,352 to 40,057 acre-ft yr<sup>-1</sup>). An investigation by *Mihevc et al.*, (2002) along a 11 km section 586 of the Fernley reach was approached using heat as a tracer. Quantified along two-dimensional 587 transects at 6 study sites, the seepage rates ranged from  $1.0 \times 10^{-4}$  to  $8.5 \times 10^{-3} \text{ km}^3 \text{yr}^{-1}$ . With an 588

589	inflow volume of 0.15 km <sup>3</sup> yr <sup>-1</sup> , the seepage estimates were 3.3 x $10^{-2}$ km <sup>3</sup> yr <sup>-1</sup> (26,954 acre-ft yr <sup>-1</sup> )
590	<sup>1</sup> ) or 22% of the inflow ( <i>Mihevc et al.</i> , 2002). <i>Shanafield et.al.</i> , (2014) applied the diffusion wave
591	approach on a 6.4 km section of the Fernley reach and found seepage flux estimates to be
592	consistent with Mihevc et al., (2002) at transect sites. Applying the Shanafield et al., (2014)
593	regression with the average inflow during 2018 and 2019 of 1.9 m <sup>3</sup> s <sup>-1</sup> inflow results in an
594	estimated seepage loss is $1.5 \times 10^{-2} \text{ km}^3 \text{yr}^{-1}$ (12,480 acre-ft yr <sup>-1</sup> ) or about 53% of the average
595	inflow. Volumetric losses estimated by Reclamation during the 2018 and 2019 irrigation seasons
596	by inflow-outflow from USGS gages, measured diversions, and unmetered estimates of lateral
597	diversions were 1.4 x $10^{-2}$ km <sup>3</sup> yr <sup>-1</sup> (11,698 acre-ft) and 1.2 x $10^{-2}$ km <sup>3</sup> yr <sup>-1</sup> (9,744 acre-ft) or 45%
598	and 50% of the inflows at Wadsworth (Reclamation, 2019; 2020). Differences in volumetric
599	seepage loss reported for the TC can be attributed to differences in methodology, assumptions,
600	timeframe, inflow rates, and changes in canal operations. For example, during the Mihevc et al.,
601	(2002) study, inflow at Wadsworth were 78% lower than what was observed in 2018. This
602	difference in inflow may contribute to the 67% reduction in estimated seepage losses for the
603	Wadsworth to Hazen reach. Results of our study provide new information for the Derby and
604	Lahontan reaches where seepage has not been studied and identified a section of canal where
605	groundwater may influence rates within the Fernley reach. In previous studies, the influence of
606	groundwater on seepage rates were not accounted for.

607

### 5.3 Management Considerations

For water managers, planning accurate conveyance of water in canals involves making
predictions of seepage losses. This investigation provides insights into the influence of
temperature on seepage rates that could be used to improve canal operations and improve
conveyance efficiency. For example, canal operations could be optimized during seasonally
cooler temperatures to reduce seepage losses. Hydraulic connectivity between canal flow and

groundwater were shown to seasonally vary in the presence of water level fluctuations and
declines. In these conditions, spatial and temporal data are needed to identify reaches where the
water table may influence seasonal seepage rates.

616 Considerations for reduction of seepage losses through engineering approaches are effective means of reducing losses. Understanding where high seepage occurs, minimizing losses 617 618 and improvements to conveyance can be accomplished by canal lining (Reclamation, 1976). Low-cost options such as compacted earth lining can be an effective means to reducing rates of 619 620 seepage. Burt et al., (2010) reported 86 to 90% reduction in seepage losses when the sides and 621 bottom of the canal were treated by compaction and measured by ponded infiltration test. 622 Numerical modeling by *El-Molla and El-Molla*, (2021) estimated 99.8% seepage reduction 623 through compaction. Combining compaction with clay lining can also prove effective in reducing seepage rates (Yao et. al, 2012). The use of synthetic and concrete materials may be 624 625 successful for reductions of seepage but can be costly and deteriorate over time (Han et al., 626 2021). Reductions of seepage through lining improves conveyance but can also have unintended impacts on water levels and domestic use (Meijer et al., 2006). Compacted earth lining along 627 628 embankment could be a viable low-cost option to reduce seepage losses where coarse bank 629 sediments are contributing to high lateral seepage.

Managing water resources in arid environments is complicated but critical for the sustainability of water use in the western United States. This study quantified seepage losses in a large irrigation canal using two-dimensional numerical models calibrated with field data. The model simulations were used to develop regression equations to be applied in managing and forecasting water deliveries. The numerical models demonstrate the need to account for temperature effects on canal conveyance. Regression equations compare reasonably well with

numerical models and can be easily applied within the framework of existing stage and
temperature monitoring. In the presence of contrasting hydraulic properties of embankment
sediments, simple regression equations may be problematic in predicting seepage with
substantial variations in stage.

#### 640 **6.0 Conclusions**

This study shows that estimates of seepage rates and volumetric losses over an irrigation 641 season are improved by inclusion of the dependence of temperature, variations in stage and 642 connectivity to groundwater. The field data and numerical models were used to derive hydraulic 643 thermal properties of canal sediments represented by soil zones to estimate vertical and lateral 644 seepage rates. Transects with high seepage can be managed through embankment compaction or 645 lining. The numerical models used for each transect were derived from parsimony, accounting 646 for near surface siltation and the groundwater table data where available. Segregating the 647 648 modelling approach into calibration and validation periods allowed confirmation of estimated parameters and recalibration of a transect affected by siltation. During canal operations, lateral 649 650 seepage rates can fluctuate widely through embankment materials with high contrast in hydraulic 651 conductivity.

The numerical models demonstrate the importance of accounting for seasonal temperature changes on seepage rates and seasonal volume estimates. More than half the time of operation, the TC exhibits shallow sediment temperatures within the 10 to 25 °C. During these periods, seepage rates can increase by nearly 50% over periods of operation when temperatures are below 10°C. This case study integrated field data and models to provide simple relationships to be implemented with field data collected from the canal for routine operations. Applying the regression models with canal operations data can provide real-time estimates of seepage rates for

improved accounting of water conveyance. Periodic updating of regressions maybe necessary if
hydraulic or thermal properties of canal sediments change substantially from validated seepage
models. The use of heat as a groundwater tracer continues to be a reliable approach for
quantifying seepage rates and this approach would be valid for developing and updating
regression equations. Further refinements of transect-scale seepage rates to reach-scale
volumetric losses can be made using ground-based geophysics (*Lindenbach et al.*, 2021).
Efficient use of surface water diverted from the Truckee River for irrigation will be

beneficial for farmers and the lower Truckee River system to Pyramid Lake. The data collected
from this study will help improve forecasts of water deliveries and guide canal modifications
such as canal lining.

669 7.0 Acknowledgements

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- Figure 1. a) Location of study area and seepage sites used to develop seepage estimates and b) Flow intothe Truckee Canal measured at the USGS Truckee Canal gage at Wadsworth
- 1039 Figure 2. a) Photograph of the Truckee Canal in the Fernley Reach with location of piezometer and
- 1040 temperature probes, and b) conceptual model of the canal hydraulically disconnected from groundwater
- 1041 showing upper boundary conditions, soil zones and temperature sensors. No-flow boundary conditions
- 1042 were applied along the vertical boundary placed 50 to 70 m away from the center of the canal. A gravity
- 1043 drainage boundary was specified 15 m along the lower boundary of the model. Temperature probe sensor
- spacing were 0.0, 0.10, 0.20, 0.50, 0.75 and 1 m below ground surface. Sensor spacing in piezometer was
- 1045 variable based on total depth.
- Table 1. Summary of hydraulic and thermal parameters as input into PEST to calibrate the VS2DHItransect models.

- Table 2. Summary of the overall Root Mean Square Error (RMSE) in units of degree Celsius for thecalibration and validation periods.
- 1050 Figure 3. Timeseries of (a) measured canal stage and (b-f) comparison between simulated and observed
- sediment temperatures during the calibration period (5/31/2018 to 9/12/2018) and the validation periods
- during 2018 irrigation season (3/30/2018 to 11/9/2018) on the Truckee Canal Site 1 Derby Reach.
- 1053 Figure 4. Timeseries of (a) measured canal stage and (b-f) comparison between simulated and observed
- sediment temperatures during the calibration period (5/1/2018 to 8/13/2018) and the validation periods
- during 2018 irrigation season (4/20/2018 to 11/15/2018) on the Truckee Canal Site 8 Fernley Reach.
- Figure 5. Timeseries of (a) measured canal stage and (b-f) comparison between simulated and observed
  sediment temperatures during the calibration period (5/1/2018 to 8/13/2018) and the validation periods
  during 2018 irrigation season (4/20/2018 to 11/21/2018) on the Truckee Canal Site 14 Lahontan Reach.
- 1059 Figure 6. Temperature measured at sediment water interface (0 m; *upper panel*), estimated seepage loss,
- and measured stage (*lower panel*) at Derby reach Site 1 (a,b), Fernley reach Site 8 (c-d) and Lahontan
- 1061 reach Site 14 (e-f) during the model period of irrigation season 2018-2019.
- Table 3. Seepage estimates for sites simulated on the Derby, Fernley and Lahontan reaches during 2018and 2019.
- 1064 Table 4. Volumetric loss estimates for each reach on the Truckee Canal during 2018 and 2019.
- Figure 7. Relationship between stage and seepage flux for temperature less than 10°C, 10 to 20°C, and greater than 20°C at a) Derby reach Site 1, b) Fernley reach Site 8 and c) Lahontan reach Site 14. Linear
- 1067 fit through seepage fluxes less than 10°C and greater than 20°C denoted by black dashed line.
- 1068 Table 5. Multivariable regression equations for seepage flux along the Derby, Fernley, and Lahontan
- 1069 transects. Units of flux (*Flux*), temperature (*temp*) and stage are  $m^3d^{-1}m^{-1}$ , °C, and m, respectively. The
- 1070 range in temperature and stage correspond to the conditions the equations are applicable. At Site 6,the
- 1071 horizontal gradient (*hgrad*) between canal and aquifer was included in regression equation. Root mean
- square error (RMSE) in units of  $m^3d^{-1}m^{-1}$  computed between fluxes estimated by regression and numerical
- 1073 models. Regression equations were significant at p < 0.001.
- 1074 Figure 8 Timeseries comparison between seepage flux estimated by numerical model VS2DH and
- 1075 multivariable regression (MR) for irrigation season 2018 and 2019 at a) Derby Reach Site 1, b) Fernley
- 1076 reach Site 8, and c) Lahontan Reach Site 14. Scatter plots on right panel correspond to 2018, 2019, max
- 1077 *stage* models and linear fit of 1:1. Refer to Table 5 for regressions equations and correlations ( $\mathbb{R}^2$ ).
- 1078 Figure 9. a) Variations in canal stage and groundwater elevation relative to canal bottom, b) sediment
- temperature at 0.0m, and c) seepage flux for based on VS2DHI and multivariable regression (MR)
- 1080 equation with stage, temperature, and horizontal hydraulic gradient at Fernley Reach Site 6 during
- 1081 irrigation period 2018.
- 1082



National Hydrograph Dataset, 2021. USGS National Map, 2018. Universal Transverse Mercator, Zone 11N, North American Datum of 1983.















• Less than 10C • 10 to 20C • Greater than 20C





Parameter Description	Symbol	Units	Values	Source
Saturated horizontal hydraulic conductivity	K <sub>h</sub>	mhr⁻¹	1.0 x 10 <sup>-4</sup> - 10	Estimated
Vertical to horizontal anisotropy	K <sub>z</sub> /K <sub>h</sub>	-	0.1; 0.01	Stonestrom and Constantz, (2003)
Specific storage	$S_{s}$	m <sup>-1</sup>	$1.0 \times 10^{-4}$	Stonestrom and Constantz, (2003)
Porosity	n	m <sup>3</sup> m <sup>-3</sup>	0.4	Carsel and Parrish (1988)
van Genuthen Alpha	α	$m^{-1}$	7.5	Carsel and Parrish (1988)
van Genuthen Beta	β	-	1.89	Carsel and Parrish (1988)
Longitudinal dispersivity	αL	m	0.01	Stonestrom and Constantz, (2003)
Transverse dispersivity	αT	m	0.01	Stonestrom and Constantz, (2003)
Volumetric heat capacity of solids	Cs	J m <sup>-3</sup> °C <sup>-1</sup>	1.0 x 10 <sup>6</sup> to 1.3 x 10 <sup>6</sup>	Estimated
Thermal conductivity of sediments at residual moisture content	K <sub>tr</sub>	W m <sup>-1</sup> °C <sup>-1</sup>	1.0	Stonestrom and Constantz, (2003)
Thermal conductivity of saturated sediments	K <sub>ts</sub>	W m <sup>-1</sup> °C <sup>-1</sup>	0.5 to 2.7	Estimated
Volumetric heat capacity of water	C <sub>w</sub>	Jm <sup>-3</sup> °C <sup>-1</sup>	4.2 x 10 <sup>6</sup>	Stonestrom and Constantz, (2003)

Table 1. Summary of hydraulic and thermal parameters as input into PEST to calibrate the VS2DHI transect models.

Table 2. Summary of the overall Root Mean Square Error (RMSE) in units of degree Celsius for the calibration and validation periods.

TransectRMSE (°C)RMSE (°C)Derby ReachSite 0.5 $0.55$ $0.55$ Site 1 $0.64$ $0.63$ $0.49$ Site 2 $0.76$ $0.75$ $0.80$ Site 2.5 $0.67$ $ 0.72$ Site 3 $0.62$ $0.97$ $0.76$ Fernley ReachSite 3.5 $0.36$ $-$ Site 3.5 $0.36$ $ 0.33$ Site 4 $0.53$ $0.51$ $0.51$ Site 5 $0.73$ $0.88$ $0.89$ Site 6 $0.68$ $0.75$ $0.55$ Site 7 $0.51$ $0.65$ $0.74$ Site 8 $0.40$ $0.62$ $0.88$		Calibration	2018 2019	
Derby Reach           Site 0.5         0.55         0.55           Site 1         0.64         0.63         0.49           Site 2         0.76         0.75         0.80           Site 2.5         0.67         -         0.72           Site 3         0.62         0.97         0.76           Eernley Reach         0.33         0.51         0.51           Site 3.5         0.36         -         0.33           Site 4         0.53         0.51         0.51           Site 5         0.73         0.88         0.89           Site 6         0.68         0.75         0.55           Site 7         0.51         0.65         0.74           Site 8         0.40         0.62         0.88           Site 9         0.34         0.55         0.74	Transect	RMSE (°C)	RMS	E (°C)
Site 0.5 $0.55$ $ 0.55$ Site 1 $0.64$ $0.63$ $0.49$ Site 2 $0.76$ $0.75$ $0.80$ Site 2.5 $0.67$ $ 0.72$ Site 3 $0.62$ $0.97$ $0.76$ Fernley ReachSite 3.5 $0.36$ $-$ Site 3.5 $0.36$ $ 0.33$ Site 4 $0.53$ $0.51$ $0.51$ Site 5 $0.73$ $0.88$ $0.89$ Site 6 $0.68$ $0.75$ $0.55$ Site 7 $0.51$ $0.65$ $0.76$ Site 8 $0.40$ $0.62$ $0.88$ Site 9 $0.34$ $0.55$ $0.71$		Derby Reach	า	
Site 1       0.64       0.63       0.49         Site 2       0.76       0.75       0.80         Site 2.5       0.67       -       0.72         Site 3       0.62       0.97       0.76         Fernley Reach         Site 3.5       0.36       -       0.33         Site 4       0.53       0.51       0.51         Site 5       0.73       0.88       0.89         Site 6       0.68       0.75       0.55         Site 7       0.51       0.65       0.76         Site 8       0.40       0.62       0.88	Site 0.5	0.55	-	0.55
Site 2       0.76       0.75       0.80         Site 2.5       0.67       -       0.72         Site 3       0.62       0.97       0.76         Site 3       0.62       0.97       0.76         Fernley Reach       -       0.33         Site 3.5       0.36       -       0.33         Site 4       0.53       0.51       0.51         Site 5       0.73       0.88       0.89         Site 6       0.68       0.75       0.55         Site 7       0.51       0.65       0.76         Site 8       0.40       0.62       0.88         Site 9       0.34       0.55       0.71	Site 1	0.64	0.63	0.49
Site 2.5       0.67       -       0.72         Site 3       0.62       0.97       0.76         Fernley Reach         Site 3.5       0.36       -       0.33         Site 3.5       0.36       0.51       0.51         Site 4       0.53       0.51       0.51         Site 5       0.73       0.88       0.89         Site 6       0.68       0.75       0.55         Site 7       0.51       0.65       0.76         Site 8       0.40       0.62       0.88         Site 9       0.34       0.55       0.71	Site 2	0.76	0.75	0.80
Site 3         0.62         0.97         0.76           Fernley Reach           Site 3.5         0.36         -         0.33           Site 3.5         0.36         0.51         0.51           Site 4         0.53         0.51         0.51           Site 5         0.73         0.88         0.89           Site 6         0.68         0.75         0.55           Site 7         0.51         0.65         0.76           Site 8         0.40         0.62         0.88           Site 9         0.34         0.55         0.71	Site 2.5	0.67	-	0.72
Fernley Reach           Site 3.5         0.36         -         0.33           Site 4         0.53         0.51         0.51           Site 5         0.73         0.88         0.89           Site 6         0.68         0.75         0.55           Site 7         0.51         0.65         0.76           Site 8         0.40         0.62         0.88           Site 9         0.34         0.55         0.71	Site 3	0.62	0.97	0.76
Site 3.5       0.36       -       0.33         Site 4       0.53       0.51       0.51         Site 5       0.73       0.88       0.89         Site 6       0.68       0.75       0.55         Site 7       0.51       0.65       0.76         Site 8       0.40       0.62       0.88         Site 9       0.34       0.55       0.71		Fernley Reac	h	
Site 4       0.53       0.51       0.51         Site 5       0.73       0.88       0.89         Site 6       0.68       0.75       0.55         Site 7       0.51       0.65       0.76         Site 8       0.40       0.62       0.88         Site 9       0.34       0.55       0.71	Site 3.5	0.36	-	0.33
Site 5         0.73         0.88         0.89           Site 6         0.68         0.75         0.55           Site 7         0.51         0.65         0.76           Site 8         0.40         0.62         0.88           Site 9         0.34         0.55         0.71	Site 4	0.53	0.51	0.51
Site 6         0.68         0.75         0.55           Site 7         0.51         0.65         0.76           Site 8         0.40         0.62         0.88           Site 9         0.34         0.55         0.71	Site 5	0.73	0.88	0.89
Site 7         0.51         0.65         0.76           Site 8         0.40         0.62         0.88           Site 9         0.34         0.55         0.71	Site 6	0.68	0.75	0.55
Site 8 0.40 0.62 0.88	Site 7	0.51	0.65	0.76
	Site 8	0.40	0.62	0.88
JIC 9 0.34 0.35 0.71	Site 9	0.34	0.55	0.71
Site 9.5 0.43 - 0.50	Site 9.5	0.43	-	0.50
Lahontan Reach	L	ahontan Rea	ch	
Site 10 0.60 0.59 0.87	Site 10	0.60	0.59	0.87
Site 11 0.54 0.59 0.84	Site 11	0.54	0.59	0.84
Site 12 0.58 0.48 0.57	Site 12	0.58	0.48	0.57
Site 13 0.45 0.52 0.84	Site 13	0.45	0.52	0.84
Site 14 0.49 0.52 0.58	Site 14	0.49	0.52	0.58
Site 15 0.45 0.99 0.67	Site 15	0.45	0.99	0.67

Table 3. Seepage estimates for sites simulated on the Derby, Fernley and Lahontan reaches during 2018 and 2019.

			Average				Aver	age		
		Distance	Wetted	Average	Dura	tion	Seepag	ge Flux	Volume	tric Loss
		from Derby	Perimeter	Stage	2018	2019	2018	2019	2018	2019
Canal Reach	Transect	Dam (km)	(m)	(m)	(day	/s)	(m³d <sup>-:</sup>	<sup>1</sup> m <sup>-1</sup> )	(km³	km <sup>⁻¹</sup> )
Derby	Site 0.5	2.7	15.0	1.0	-	240	-	1.0	-	2.4 x 10 <sup>-4</sup>
Derby	Site 1	4.0	9.1	0.9	224	209	2.8	3.3	6.3 x 10 <sup>-4</sup>	6.8 x 10 <sup>-4</sup>
Derby	Site 2	5.7	11.6	1.2	230	210	0.2	0.2	3.7 x 10 <sup>-5</sup>	3.4 x 10 <sup>-5</sup>
Derby	Site 2.5	14.1	9.2	1.1	-	236	-	0.2	-	4.1 x 10 <sup>-5</sup>
Derby	Site 3	14.8	9.7	1.2	226	198	2.1	0.6	4.8 x 10 <sup>-4</sup>	1.2 x 10 <sup>-4</sup>
Fernley	Site 3.5	16.8	16.7	2.0	-	236	-	0.2	-	4.7 x 10 <sup>-5</sup>
Fernley	Site 4	17.6	23.9	2.8	213	205	0.3	0.3	7.0 x 10 <sup>-5</sup>	6.6 x 10 <sup>-5</sup>
Fernley	Site 5	20.9	30.1	3.1	220	231	2.3	2.1	5.1 x 10 <sup>-4</sup>	4.7 x 10 <sup>-4</sup>
Fernley	Site 6	22.8	14.7	2.3	212	230	2.3	2.0	4.9 x 10 <sup>-4</sup>	4.6 x 10 <sup>-4</sup>
Fernley	Site 7	27.1	10.8	1.1	209	202	0.8	0.8	1.7 x 10 <sup>-4</sup>	$1.6 \times 10^{-4}$
Fernley	Site 8	30.3	15.7	2.1	209	207	3.1	3.1	6.6 x 10 <sup>-4</sup>	6.4 x 10 <sup>-4</sup>
Fernley	Site 9	31.5	19.5	2.5	210	209	1.9	1.8	$4.0 \times 10^{-4}$	$3.8 \times 10^{-4}$
Fernley	Site 9.5	32.2	14.0	0.8	-	245	-	0.2	-	4.9 x 10 <sup>-5</sup>
Lahontan	Site 10	35.2	22.6	2.5	216	200	1.9	1.8	4.1 x 10 <sup>-4</sup>	3.6 x 10 <sup>-4</sup>
Lahontan	Site 11	37.4	11.5	1.2	215	199	1.0	1.0	2.1 x 10 <sup>-4</sup>	1.9 x 10 <sup>-4</sup>
Lahontan	Site 12	39.2	22.2	2.4	216	215	1.0	1.2	2.2 x 10 <sup>-4</sup>	2.6 x 10 <sup>-4</sup>
Lahontan	Site 13	42.0	14.3	1.4	223	211	0.6	0.6	1.3 x 10 <sup>-4</sup>	1.3 x 10 <sup>-4</sup>
Lahontan	Site 14	44.4	15.7	2.0	215	213	4.3	4.6	9.2 x 10 <sup>-4</sup>	$9.8 \times 10^{-4}$
Lahontan	Site 15	44.7	7.3	0.2	225	150	0.3	0.3	6.7 x 10 <sup>-5</sup>	4.5 x 10 <sup>-5</sup>

		Volumetri	ic Loss (km <sup>3</sup> )
Reach	Distance (km)	2018	2019
Derby	10.0	4.8 x 10 <sup>-3</sup>	1.8 x 10 <sup>-3</sup>
Fernley	18.0	7.0 x 10 <sup>-3</sup>	5.8 x 10 <sup>-3</sup>
Lahontan	10.3	3.9 x 10 <sup>-3</sup>	$4.0 \times 10^{-3}$
total	39	1.6 x 10 <sup>-2</sup>	1.2 x 10 <sup>-2</sup>

Table 4. Volumetric loss estimates for each reach on the Truckee Canal during 2018 and 2019.

Table 5. Multivariable regression equations for seepage flux along the Derby, Fernley, and Lahontan transects. Units of flux (*Flux*), temperature (*temp*) and stage are  $m^3d^{-1}m^{-1}$ , °C, and m, respectively. The range in temperature and stage correspond to the conditions the equations are applicable. At Site 6, the horizontal gradient (*hgrad*) between canal and aquifer was included in regression equation. Root mean square error (RMSE) in units of  $m^3d^{-1}m^{-1}$  computed between fluxes estimated by regression and numerical models. Regression equations were significant at p <0.001.

Temp (°C) Stage (n		e (m)					
Transect	Min	Max	Min	Max	Equation	R <sup>2</sup>	RMSE
					Derby Reach		
Site 0.5	4.5	24.3	0.3	2.8	Flux = 0.036 (temp) + 0.57 (stage) - 0.10	0.98	0.07
Site 1	4.8	25.5	0.2	2.6	Flux = 0.094 (temp) + 1.70 (stage) - 0.13	0.97	0.24
Site 2	4.3	25.3	0.4	2.7	Flux = 0.001 (temp) + 0.13 (stage) + 0.02	0.92	0.03
Site 2.5	3.1	25.3	0.5	2.5	Flux = -0.001 (temp) + 0.13 (stage) + 0.05	0.81	0.04
Site 3	4.9	23.8	0.5	2.6	Flux = 0.013 (temp) + 0.28 (stage) + 0.07	0.96	0.03
Site 3.5	5.5	23.7	0.8	2.5	Flux = 0.004 (temp) + 0.08 (stage) - 0.05	0.99	0.004
					Fernley Reach		
Site 4	5.4	24.4	0.4	2.4	Flux = -1e-4 (temp) + 0.10 (stage) + 0.23	0.85	0.03
Site 5	4.0	25.4	0.6	2.5	Flux = 0.055 (temp) + 2.11 (stage) - 2.64	0.95	0.16
Site 6	4.3	24.9	0.6	1.8	Flux = 0.031 (temp) + 1.03 (stage) + 3.90 (hgrad) - 1.52	0.85	0.27
Site 7	4.1	26.4	0.6	2.3	Flux = 0.008 (temp) + 1.03 (stage) - 0.50	0.91	0.15
Site 8	4.1	26.4	1.6	2.7	Flux = 0.043 (temp) + 2.16 (stage) - 2.29	0.62	0.29
Site 9	3.3	25.9	1.6	2.5	Flux = 0.025 (temp) + 0.65 (stage) - 0.09	0.71	0.10
Site 9.5	5.3	25.7	0.0	2.8	Flux = 0.007 (temp) + 0.72 (stage) - 0.42	0.95	0.16
					Lahontan Reach		
Site 10	4.6	26.1	0.9	2.6	Flux = 0.055 (temp) + 1.40 (stage) - 0.95	0.99	0.08
Site 11	4.3	26.7	0.8	2.5	Flux = 0.029 (temp) + 1.11 (stage) - 0.99	0.98	0.07
Site 12	3.9	24.6	0.6	2.5	Flux = 0.031 (temp) + 1.15 (stage) - 1.0	0.95	0.13
Site 13	3.1	26.5	0.8	2.7	Flux = 0.013 (temp) + 0.37 (stage) - 0.20	0.96	0.03
Site 14	2.7	26.4	0.4	2.3	Flux = 0.111 (temp) + 1.77 (stage) - 0.62	0.98	0.15
Site 15	1.8	26.6	0.1	8.4	Flux = -2e-4 (temp) + 0.13 (stage) + 0.10	0.97	0.08



Figure SI-1. Conceptual models showing soil zones used to develop seepage estimates for the Truckee Canal.

Derby Reach								
	e "	Kh	Cs	K <sub>ts</sub>				
Transect	Soil Zone	(m hr <sup>-</sup> 1)	(J m⁻³ °C⁻¹)	(W m <sup>-1</sup> °C <sup>-1</sup> )				
Site 0.5	Zone 1	0.013	741,000	0.1				
	Zone 2	0.032	5,230,000	2.7				
	Zone 3	0.091	2,710,000	1.4				
	Zone 4	0.032	3,000,000	2.6				
Site 1.0	Zone 1	0.036	823,900	0.8				
	Zone 2	0.059	969,300	0.2				
	Zone 3	0.001	1,567,000	0.2				
	Zone 4	0.150	3,593,000	0.2				
Site 2.0	Zone 1	0.000	1,449,000	0.9				
	Zone 2	0.003	3,600,000	2.1				
	Zone 3	0.004	2,256,000	2.3				
	Zone 4	0.005	2,975,000	1.2				
Site 2.5	Zone 1	0.015	778,800	0.8				
	Zone 2	0.068	1,060,000	1.1				
	Zone 3	0.010	1,454,000	2.5				
	Zone 4	0.016	1,882,000	0.6				
Site 3.0	Zone 1	0.014	574,300	2.7				
	Zone 2	0.073	500,000	2.6				
	Zone 3	0.015	1,727,000	1.5				
	Zone 4	0.053	3,000,000	2.7				
Site 3.0								
(recalibrated)	Zone 1	0.014	574,300	2.7				
	Zone 2	0.007	500,000	2.6				
	Zone 3	0.002	1,727,000	1.5				
	Zone 4	0.020	1,100,000	1.0				
Site 3.5	Zone 1	0.000	500,000	1.3				
	Zone 2	0.001	2,880,000	2.6				
	Zone 3	0.260	2,670,000	1.3				
	Zone 4	0.000	831,300	1.2				

Table SI-S1. Final estimated hydraulic and thermal properties for each soil zone.

Fernley Reach						
	Soil	K <sub>h</sub> (m.hr⁻	Cs	K <sub>ts</sub>		
Transect	Zone	(,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,	(J m⁻³ °C⁻¹)	(W m <sup>-1</sup> °C <sup>-1</sup> )		
Site 4.0	Zone 1	0.024	3,000,000	0.6		
	Zone 2	0.057	1,722,000	0.6		
	Zone 3	0.003	2,968,000	1.4		
	Zone 4	0.004	2,523,000	1.4		
Site 5	Zone 1	0.014	3,000,000	1.4		
	Zone 2	0.014	1,386,000	1.4		
	Zone 3	0.071	5,549,000	1.1		
	Zone 4	0.072	1,100,000	1.4		
Site 6	Zone 1	0.050	1,100,000	1.0		
	Zone 2	0.060	1,100,000	1.0		
	Zone 3	0.200	1,100,000	1.0		
	Zone 4	0.040	1,100,000	1.0		
Site 7	Zone 1	0.083	506,300	2.0		
	Zone 2	0.042	822,900	0.7		
	Zone 3	0.397	2,016,000	0.8		
	Zone 4	0.011	500,000	0.6		
Site 8	Zone 1	0.091	3,000,000	1.6		
	Zone 2	0.151	505,300	2.0		
	Zone 3	0.260	500,800	2.0		
	Zone 4	0.031	1,173,000	0.9		
Site 9	Zone 1	0.273	2,062,000	2.0		
	Zone 2	0.034	958,400	2.0		
	Zone 3	0.002	1,112,000	2.0		
	Zone 4	0.031	2,584,000	0.8		
Site 9.5	Zone 1	0.005	2,889,000	1.3		
	Zone 2	0.102	500,000	2.7		
	Zone 3	0.071	1,326,000	1.2		
	Zone 4	0.270	500,000	1.6		
	Zone 5	0.001	3,000,000	0.7		

Lahontan Reach				
	Soil	K <sub>h</sub> (m hr⁻	Cs	K <sub>ts</sub>
Transect	Zone	1)	(J m⁻³ °C⁻¹)	(W m⁻¹ °C⁻¹)
Site 10	Zone 1	0.001	874,500	1.4
	Zone 2	0.035	532,000	2.0
	Zone 3	0.015	529,000	2.0
	Zone 4	0.001	1,033,000	2.0
Site 11	Zone 1	0.009	500,000	2.0
	Zone 2	0.014	500,000	1.6
	Zone 3	0.017	1,513,000	2.0
	Zone 4	5.000	500,000	1.9
Site 12	Zone 1	0.009	2,919,000	1.0
	Zone 2	0.033	762,400	2.0
	Zone 3	2.182	1,491,000	0.9
Site 13	Zone 1	0.007	2,236,000	1.4
	Zone 2	0.010	2,953,000	1.4
	Zone 3	0.005	3,000,000	1.3
	Zone 4	0.077	563,400	0.9
Site 14	Zone 1	0.099	500,000	2.0
	Zone 2	0.009	2,260,000	1.1
	Zone 3	0.146	2,937,000	2.0
Site 15	Zone 1	0.002	515,500	1.2
	Zone 2	0.010	500,000	1.0
	Zone 3	5.000	500,000	0.6