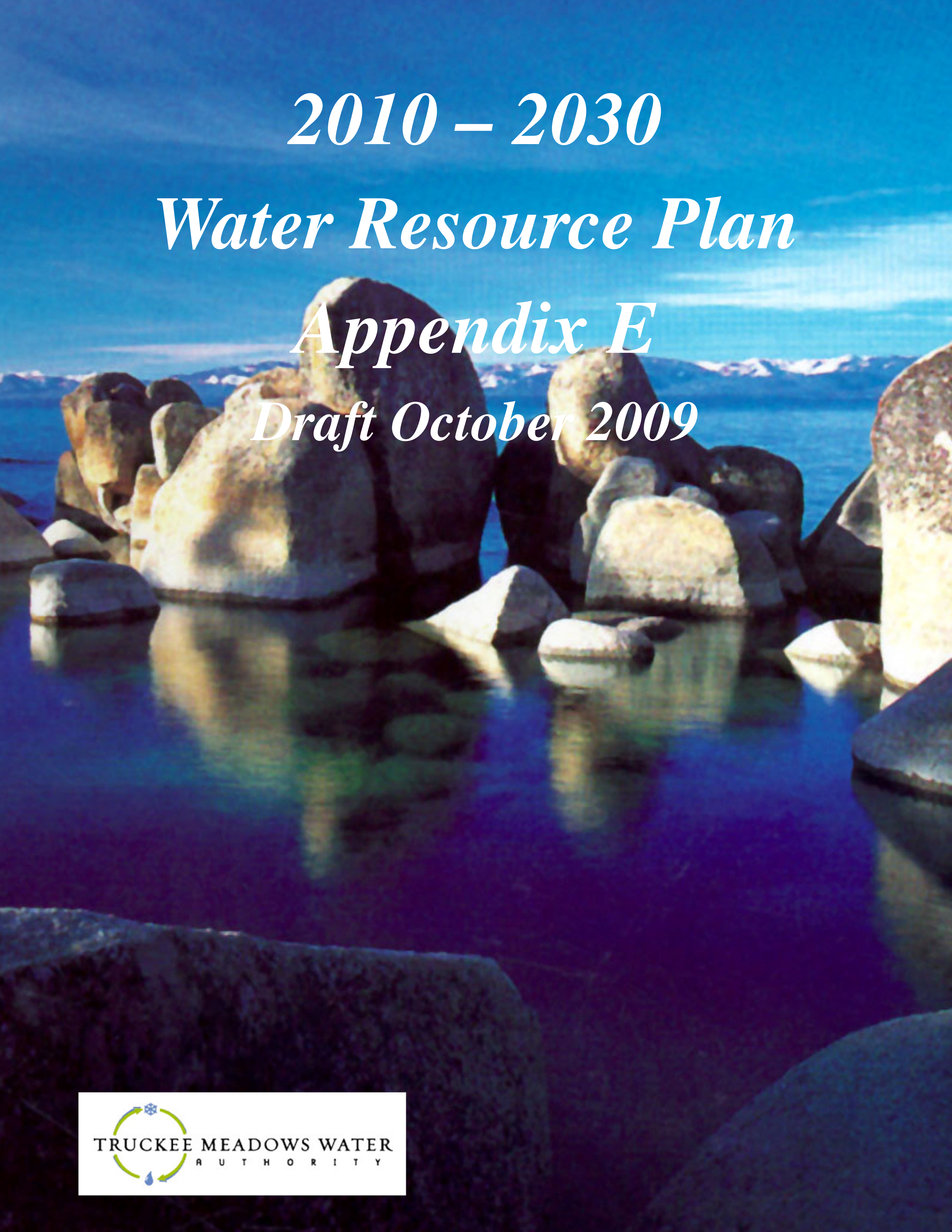
2010 – 2030

Water Resource Plan

Appendix E

Draft October 2009



TRUCKEE MEADOWS WATER AUTHORITY

Appendix E:
Truckee River Contaminate Transport Model

Truckee River Spill Estimates

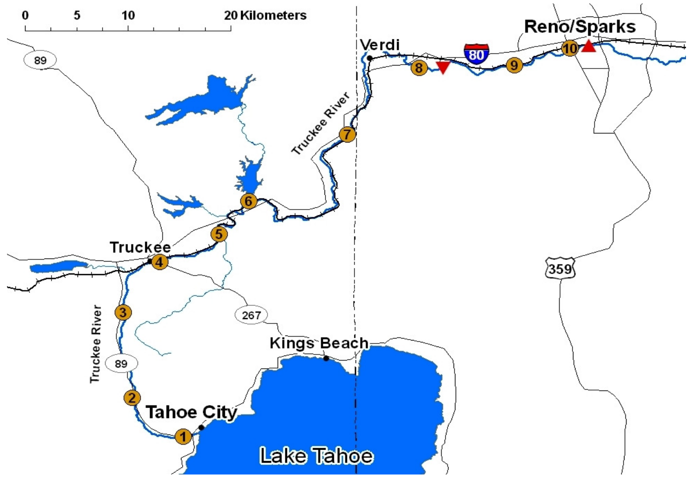
Instructions: Select nearest location of spill, nearest flow at Farad at time of spill, and nearest volume of spill. When unsure, choose closest location downstream, closest higher flow, and/or closest higher volume to get most conservative estimate.

Location of Spill	6 - Truckee River at Boca Bridge, CA	choose location of spill or closest location downstream
Flow at Farad (cfs)[a]	500	choose flow or closest higher flow
Volume of Spill (L)	115000 (train car)	choose volume or closest higher volume
Date of Spill (Month/Day/Year)	5/1/2020	
Time of Spill (hour:minute)	6:00 AM	

	most conservative	**best estimate**	least conservative
Arrival time at Highland (date and time)	5/1/20 1:24 PM	**5/1/20 3:56 PM**	5/1/20 5:30 PM
Peak arrival time at Highland (date and time)	5/1/20 7:50 PM	**5/1/20 8:06 PM**	5/1/20 8:10 PM
Departure time from Highland (date and time)	5/2/20 7:26 AM	**5/2/20 1:28 AM**	5/1/20 10:58 PM
Peak concentration (mg/L)	1549.2	**1021.0**	562.0
Duration at Highland (hr)	18.03	**9.53**	5.47

	most conservative	**best estimate**	least conservative
Arrival time at Orr Ditch (date and time)	5/1/20 4:32 PM	**5/1/20 7:36 PM**	5/1/20 9:26 PM
Peak arrival time at Orr Ditch (date and time)	5/2/20 12:02 AM	**5/2/20 12:18 AM**	5/2/20 12:22 AM
Departure time from Orr Ditch (date and time)	5/2/20 12:32 PM	**5/2/20 6:12 AM**	5/2/20 3:26 AM
Peak concentration (mg/L)	1469.9	**921.7**	498.2
Duration at Orr Ditch (hr)	20.00	**10.60**	6.00

	most conservative	**best estimate**	least conservative
Arrival time at Glendale (date and time)	5/1/20 6:54 PM	**5/1/20 10:12 PM**	5/2/20 12:08 AM
Peak arrival time at Glendale (date and time)	5/2/20 2:44 AM	**5/2/20 3:02 AM**	5/2/20 3:08 AM
Departure time from Glendale (date and time)	5/2/20 3:28 PM	**5/2/20 9:06 AM**	5/2/20 6:16 AM
Peak concentration (mg/L)	1444.9	**894.8**	482.3
Duration at Glendale (hr)	20.57	**10.90**	6.13



[a] See table below for flows simulated in river for this flow scenario

Site name	**simulated flow (cfs)**
Truckee R a Tahoe City CA	212.2
Truckee R at Squaw Creek	212.2
Truckee R nr Truckee CA	213.4
Donner C at HWY 89 nr Truckee CA	*6.0*
Truckee R at Brockway Bridge	219.0
Martis C nr Truckee CA	*4.0*
Truckee R at Glenshire Rd. Bridge	223.2
Prosser C bl Prosser C Dam nr Truckee CA	*100.0*
Little Truckee R bl Boca Dam nr Truckee CA	*115.0*
Truckee R a Boca Bridge nr Truckee CA	437.8
Truckee R a Farad CA	500.0
Truckee R nr Mogul	500.0
Truckee R at West McCarran Bridge	500.0
Truckee R nr Reno	500.0

italics indicate tributary flows

University of Nevada, Reno

Modeling contaminant spills on the upper Truckee River in CA and NV

A thesis submitted in partial fulfillment of the
requirements for the degree of Master of Science in
Hydrologic Sciences

by
Jeremy Rivord

Dr. Laurel Saito/Thesis advisor

August, 2008

ABSTRACT

Originating from Lake Tahoe at Tahoe City, California, the Truckee River follows California Highway 89, then turns and parallels U.S. Interstate 80 and the Union Pacific Railroad into the Reno/Sparks area in Nevada where the river provides 85% of the drinking water to a large population. Traffic along this corridor coupled with its proximity to the river increases the risk of a contaminant spill into the river that could have detrimental effects on the drinking water supplies of the Reno/Sparks area. A one-dimensional solute transport model (OTIS) has been applied to the Truckee River from its headwaters at Lake Tahoe to the Truckee Meadows Water Authority's (TMWA) municipal intakes in Reno. Data collected from Rhodamine WT dye studies on the Truckee River were used to calibrate the model under high and moderate flow scenarios and a theoretical equation for longitudinal dispersion was used to simulate contaminant spills of two sizes from 9 locations under 13 different flow scenarios. Upstream transient storage was not included in the simulations since the inclusion of the storage parameters resulted in the least conservative estimate for arrival times and maximum concentrations. Travel times to the first TMWA intake for a 130,000L spill ranged from 2.8 to 50 hours and maximum simulated concentrations at the intake ranged from 234-5800mg/L. The spill model was most sensitive to the main channel cross-sectional area, which defined downstream advective transport. Model output was influenced by uncertainties in the theoretical equation that estimated longitudinal dispersion. To account for these uncertainties, the estimates of longitudinal dispersion were bracketed by values that were a factor of four greater and less than

the estimated value of dispersion, which resulted in a range of travel times from 1.2-9.4 hours.

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1. INTRODUCTION

There are numerous river systems throughout the American west that share a complex history of resource management. When combined with contemporary environmental policy and the not uncommon situation of over-allocation, water resource management decisions can often be complicated for a particular river. The amount of growth taking place in desert cities like Los Angeles, Las Vegas, and Phoenix require water management plans that account not only for water quantity, but also water quality and ecosystem services (Carle, 2003). The continued increase in development in these and other areas requires extensive resource planning and preparation.

Both the surface and ground water quality within a city are unavoidably impacted by daily urban activities. Additionally, there can be a risk of a catastrophic accident that could spill a large amount of a substance directly into a river, lake, or reservoir, severely impacting the water supply of entire communities. If such a catastrophe were to take place in a river with significant municipal intakes, it would be essential for the water supply managers to know when the spilled contaminant is expected to arrive at the plant's intakes and how long the presence of the contaminant would impact the ability to draw water from the river. Municipal water authorities have emergency response plans that outline the actions to take in the event of an accident, but some do not include an estimate of contaminant travel times in the event of a spill (TRAC, 2005). Having a solute transport model calibrated for a particular system can provide information in the event of a spill—information that can provide an objective means of implementing a response to a river spill.

The Truckee River and its tributaries are the primary water resources for the cities of Reno and Sparks, Nevada, providing approximately 85% of the total water supplied to those areas (Truckee Meadows Water Authority, 2007). Originating from Lake Tahoe at Tahoe City, California, the river flows north along California Highway 89 where it turns and parallels U.S. Interstate 80 and the Union Pacific Railroad into the Reno/Sparks area. Regular traffic on the highway and the rail line, coupled with their proximity to the river and harsh winter conditions, presents a potential water disaster in the event of a contaminant spill. While there is an emergency response plan in the event of a spill for the entire Truckee River corridor (TRAC, 2005), it does not address spill travel times. Thus, the area's drinking water purveyor, the Truckee Meadows Water Authority (TMWA), has a need for predicting the timing, duration, and concentration of spills that might occur on the Truckee River and contaminate the drinking water of the Reno-Sparks area.

2. OBJECTIVES

The primary objective of this study is to develop a solute transport model that can be used by the TMWA to estimate the predicted impacts of a contaminant spill in the Truckee River. The calibrated model will provide travel time estimates from different locations on the river for a conservative constituent in terms of estimated time of first contact, an associated concentration curve, and estimated time for the spill to pass the treatment plants at moderate and high stream flows. It will then be used to provide the same type of information at other flows and spill amounts with a priority on estimating time of arrival.

3. LITERATURE REVIEW

3.1. River spills

The transportation of industrial products poses an inherent risk to water users. Large contaminant spills from transportation accidents have impacted aquatic ecosystems and the water quality of municipal drinking waters (Hume, 2006; GAO, 2006). For example, on August 5, 2005, nine Canadian National rail cars fell off a bridge into the Cheakamus River north of Vancouver, British Columbia, releasing 41,000 liters of sodium hydroxide, ultimately killing more than 500,000 fish in an 18 km section of the river (Canadian Broadcasting Corporation, 2006).

Similarly, in 1991, 70,000 liters of VAPAM liquid, a commonly used agricultural fumigant, were spilled into the upper Sacramento River when several rail cars overturned and spilled near Dunsmuir, CA. The spill degraded into several products that are toxic to humans and aquatic life. Analytes deriving from VAPAM were detected in 6 of 8 spatially distributed sites downstream from the spill 23 days after the spill (del Rosario et al., 1994). At five sites in Shasta Lake 55 km downstream from the spill, Brett et al. (1995) monitored water quality and ecological responses from 12 hours before the plume's arrival through 26 days after the spill. The spill resulted in a huge mortality of benthic life and impacted the ecology around the monitoring sites for the entire 26 days (Brett et al., 1995). Human communities along the river and surrounding Shasta Lake raised concerns regarding the safety of the drinking water, but the quick response time for monitoring solute concentrations assisted officials in managing the accident and verifying when water was safe to drink (del Rosario et al., 1994).

3.2. Tracer studies

Such large-scale spills are not everyday occurrences, but the magnitude of their impacts justifies a comprehensive response plan that considers travel times. To develop predictive plans that address these types of events, it is important to understand the movement and transport of contaminants in a particular water body. Conservative tracer studies have commonly been used to determine the mixing characteristics of stream systems for solute transport (Stream Solute Workshop, 1990). In a tracer experiment, a conservative tracer is injected into the channel and samples are measured at one or more downstream locations. These data can be used to develop plots of observed concentrations and the elapsed travel times, which when graphed are referred to as response curves (figure 1).

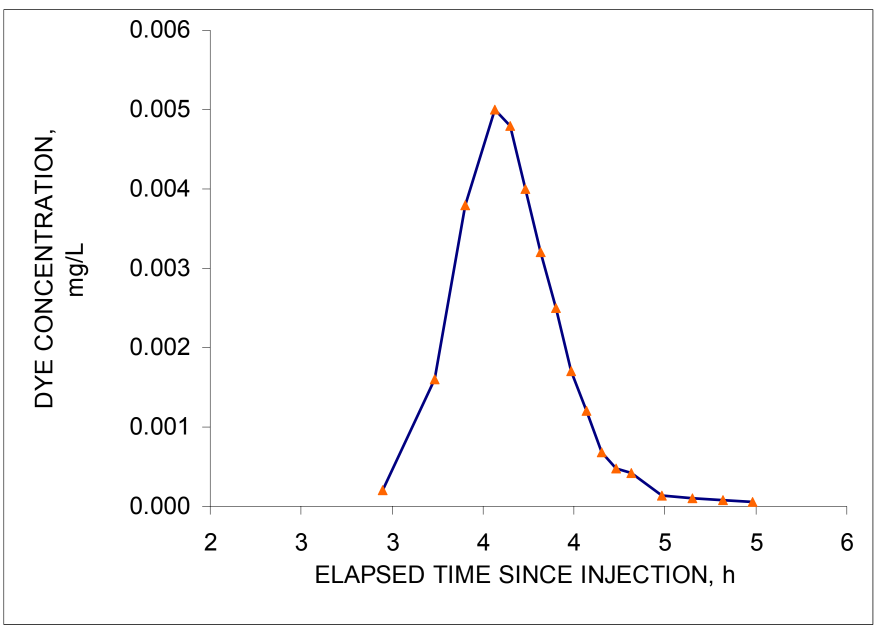

Figure 1. Observed response curve at one river location

3.2.1. Types of tracers

Rhodamine WT dye is a commonly used conservative tracer that is measured with a fluorometer, but other tracers such as chloride and dissolved iron from mine tailings have been successfully used as conservative and non-conservative tracers (Kilpatrick and Wilson, 1989; Stream Solute Workshop, 1990; Broshears et al., 1993; Knust, 2006). From the perspective of regional water managers, tracer studies have been used to provide conservative travel times at varied flow levels in a particular system (Kilpatrick and Wilson, 1989; Bohman, 2000; Crompton and Bohman, 2000; Saito et al., 2002).

3.2.2. Mixing processes

Figure 2. Dye mixing immediately after injection at Old US 40 bridge, June 29, 2006.

Upon an instantaneous "slug injection," mixing of the dye is immediately apparent, with certain regions of the channel advancing downstream faster than others, while some pockets circle behind rocks and within eddies (figure 2). In this sense, the particles of a conservative tracer behave similarly to water particles, mixing in three dimensions. The mixing process of a tracer in the channel moves laterally, vertically, and longitudinally. Vertical dispersion is stronger than lateral dispersion, but both are much more rapid than longitudinal dispersion (Kilpatrick and Wilson, 1989). In models that assume complete vertical and lateral mixing, longitudinal dispersion, or the mixing of particles in the direction of flow, is the primary mechanism that influences a constituent's duration at a specific site.

Longitudinal dispersion is driven by the combined effects of shear and transverse diffusion and is not bounded in the modeled system (Fischer et al., 1979). If given enough time to mix, the presence of a spill will spread up and down the length of the

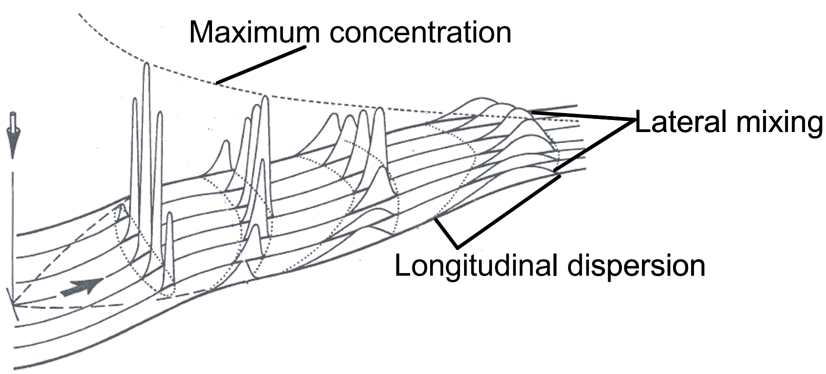

Figure 3. In-channel mixing processes (adapted from Kilpatrick and Wilson, 1989)

channel. Longitudinal dispersion is apparent in figure 3 where the peak concentration decreases and the "length" of the slug increases with distance downstream from an injection point. With greater mixing, the solute impacts a larger volume of the stream at a decreased concentration.

3.3. Mixing models

3.3.1. One-dimensional advection dispersion equation (ADE)

Tracer studies provide valuable data that can be used in the development of various water quality and hydraulic models. Parameters for the one dimensional transport equation, or the advection dispersion equation (ADE), can readily be inferred from data observed in solute tracer experiments. In the one-dimensional ADE, instantaneous and complete cross-sectional mixing is assumed, which implies immediate vertical and lateral dispersion when dye is injected to the channel. The one-dimensional ADE (Fischer et al., 1979) has been extensively used in solute transport and hydraulic studies of streams and rivers:

Equation 1.

$$A\frac{\partial C}{\partial t} + Q\frac{\partial C}{\partial x} = \frac{\partial}{\partial x}(AK\frac{\partial C}{\partial x})$$

where,

C	solute concentration [M/L^3]
Q	volumetric flow rate [L^3/T]
A	stream cross-sectional area [L^2]
K	dispersion coefficient [L^2/T]
t	time [T]
x	downstream distance [L].

Using estimated parameters, the concentration time series can be modeled for a particular stream using the ADE. Output concentrations can be compared alongside observed concentrations as a means of obtaining parameters that produce better model fits. The process of calibrating the parameters within the ADE is repeated until an acceptable fit exists between the modeled and observed concentrations.

3.3.2. ADE with transient storage

Response curves from the one-dimensional ADE model have shown to be inconsistent with response curves in numerous tracer studies (Bencala and Walters, 1983;

Knust, 2006). The response curve of observed tracer data often has an asymmetrical shape compared to the curve predicted by the ADE. In particular, the observed curve has a heavy tail on the descending limb of the curve. A comparison of observed and modeled response curves suggests that a small, but considerable amount of solute mass is removed from the rising limb of the tracer curve and delayed before it is released back into the channel at a later time. It has commonly been hypothesized that this phenomenon was due to a temporary storage mechanism referred to as "dead zones" or transient storage (Fischer et al., 1979; Bencala and Walters, 1983). Such storage zones can occur as eddies, pools, or subsurface flows paths, and can have a significant impact in the prediction of spilled contaminants moving downstream, lengthening the duration of time that a spilled contaminant would be present in the channel.

The transient storage model is the one dimensional ADE modified to account for transport delays from dead zones by simulating storage zones that exhibit a first order mass transfer relationship with the main channel (Bencala and Walters, 1983). The equations are defined as (Bencala and Walters, 1983):

Equation 2.

$$\frac{\partial C}{\partial t} = -\frac{Q}{A}\frac{\partial C}{\partial x} + \frac{1}{A}\frac{\partial}{\partial x}(AK\frac{\partial C}{\partial x}) + \frac{q_L}{A}(C_L - C) + \alpha(C_S - C)$$

Equation 3.

$$\frac{dC_S}{dt} = -\alpha\frac{A}{A_S}(C_S - C),$$

where

q_L lateral volumetric inflow rate $[L^3/T]$

C_L solute concentration in lateral inflow $[M/L^3]$

C_S solute concentration in the storage zone $[M/L^3]$

A_S cross-sectional area of the storage zone $[L^2]$

α stream storage zone coefficient $[T^{-1}]$.

The first three parts on the right hand side of equation 2 are the main channel processes. The first term is advection, the second term models longitudinal dispersion, and the third term models lateral inflow outflow. The final term in equation 2 is the transient storage term, which is a first order mass transfer from the main channel to the storage zone. Equation 3 is an ordinary differential equation, which models the change in solute concentration over time for the storage zone.

3.3.3. OTIS model

The United States Geological Survey (USGS) has developed a FORTRAN based computer model called the One-dimensional Transport with Inflow and Storage (OTIS) model that uses equations 2 and 3 for the simulation of one-dimensional surface water transport. Designed to account for surface water dead zones such as eddies and pools as well as hyporheic flow paths, the storage zone in OTIS is a conceptual storage zone and the parameters that describe it are not easily quantifiable in the field. Due to the presence of temporal and spatial derivatives, the transient storage equation (equation 2) is a partial differential equation and requires numerical solution techniques. The OTIS model employs the Crank-Nicolson method for estimating the transient storage model, which is an implicit technique that is centered in time and space (Runkel and Chapra, 1993).

Within OTIS is a parameter estimation algorithm called OTIS-P. OTIS-P uses the adaptive nonlinear least squares (NLS) technique as described by Dennis et al. (1981). The NLS procedure begins with initial user-defined estimates of A, K, A_s and α, which are then used by the OTIS program. The sum of squared errors is calculated from the simulated and observed concentrations, and an updated parameter set is estimated from a partial derivative-based adaptive algorithm. With the adapted parameter set, the model is executed again. The process continues until convergence, which is attained when either the parameter values or the sum of squared errors are no longer changing relative to a predefined value. Two other undesired convergence types are possible: 1) false convergence occurs when the convergence criteria are set too small or when there is a discontinuity in the derivative being estimated, and 2) singular convergence occurs when there are too many parameters for the model. Both can be addressed by performing additional OTIS-P simulations with an adjusted initial parameter set.

OTIS has been used in numerous scenarios to model in-channel solute mixing and transport, nutrient uptake, trace metal chemical reactions for both steady and unsteady state scenarios for mountain streams and rivers (Runkel, 2000). Runkel et al. (1999) also applied the model to assess potential reactions that could occur with One-dimensional Transport with EQuilibrium chemistry (OTEQ). Recently, OTIS has been used to model transient storage values on larger rivers. Using data from 20 dye injections along with detailed flow measurements, nine portions of seven different rivers in the Willamette Basin in Oregon were modeled using OTIS. The reaches with substantial measured surface water-groundwater flux had higher storage zone parameters, A_s and α, indicating that OTIS is capable of modeling transient storage in systems with higher flow and longer reaches than in previous applications (Laenen and Bencala, 2001). Furthermore, analysis of data from a dye study of a 26 km stretch of the Willamette River attempted to distinguish hyporheic storage from surface storage by sampling water from below the riverbed. In this research, Fernald et al. (2001) concluded that there was no pattern of reach length effect on storage zone parameters.

OTIS has been used previously on the Truckee River. Saito et al. (2002) used OTIS-P to estimate river parameters to calibrate a spill model using dye study data from 1999 (Crompton and Bohman, 2000). However, the model was only able to provide predictions for one flow regime due to limited time available to complete the study. It was suggested that model parameters from a higher flow scenario be modeled to investigate changes in storage and travel times (Saito et al., 2002). Most recently, OTIS was used to estimate potential changes in hyporheic exchange due to restoration efforts at McCarran Ranch on the lower Truckee River (Knust, 2006).

3.3.3.1. OTIS assumptions

As previously defined, the governing equations of the OTIS model are the one-dimensional ADE with an additional derivative to simulate transient storage (Bencala and Walters, 1983). The most important assumption of the OTIS model is that any simulated solute is entirely mixed in the vertical and lateral directions. OTIS is a one-dimensional model and thus, tracer concentrations can only vary in the longitudinal direction. Because of this assumption, the modeled river can be segmented into a series of control volumes over which tracer mass is passed in one direction.

Within each river segment is a main channel portion and a storage zone. The main channel is impacted by the processes of advection, dispersion, lateral inflow and outflow, sorption to streambed, first order decay, and transient storage. The storage zone is not affected by advection, dispersion, or lateral flow, but is subject to sorption and decay.

Reaches in the model are bounded both upstream and downstream by locations where tracer samples were collected. A reach may have many segments (or control volumes), but it is assumed that the four estimated parameters, cross-sectional area (A), dispersion (K), storage zone exchange coefficient (α), and cross-sectional area of the storage zone (A_s), are all constant for an entire reach.

3.4. Longitudinal dispersion

Dispersion has important implications in spill modeling because it affects the amount of time a certain contaminant may be present at a particular site. Crompton and Bohman (2000) found that flow conditions in the Truckee River had a direct impact on travel times and estimated dispersion. The equations governing OTIS are sensitive to changes to the A and K parameters. Therefore, in order to simulate spills, it is necessary to estimate specific values of A and K. Longitudinal dispersion is commonly measured with data obtained from tracer studies (Stream Solute Workshop, 1990; Graf, 1995). Dispersion can be measured by matching data from the tracer study to a simulated concentration modeled with the ADE.

3.4.1. Method of moments

In addition to matching the ADE model, dispersion coefficients can be estimated using a statistical approach referred to as the method of moments. Observed response curves of a common tracer study are shaped similar to the normal distribution in what is sometimes called the "random walk," where dispersing particles from a centered mass have the highest probability to concentrate near the center of mass, and decreasing probability of occurrence with distance from the center of mass. The variance measures the curve's spread from the center of mass. The probability distribution function for the normal distribution p(x) is defined as:

Equation 4.

$$p(x) = \frac{1}{\sqrt{2\pi\sigma}} \exp^{\frac{-(x-\mu)^2}{2\sigma^2}}$$

where μ is the mean, σ is the standard deviation and σ^2 is the variance of the curve.

Slug injections of tracers can be modeled with an equation similar to equation 4. For a dispersion coefficient, K, describing longitudinal mixing and a slug injected mass, M, at time t = 0 at location $x = x_0$, the concentration time series, C(x,t) is modeled as (Fischer et al., 1979):

Equation 5.

$$C(x,t) = \left(M \middle/ \sqrt{4\pi Kt} \right) \exp^{-\left(x^2 / 4Kt\right)}$$

K replaces the statistical variance from equation 4, describing the spread of the tracer from the center of mass. Equation 5 has been used to estimate longitudinal dispersion in tracer studies of various magnitudes (Graf, 1995).

Because, the dispersion of tracers in surface water can be modeled using a derivation of the probability distribution function for the normal distribution, additional statistical methods can be utilized to estimate unknown values in the model. The method of moments is a common procedure for estimating unknown values of mean (μ) and variance (σ^2) in the function that defines the Gaussian distribution (equation 4). Likewise, using the model from equation 5, values of average in-stream velocity, average channel cross-sectional area, and longitudinal dispersion can be estimated by applying the method of moments to tracer data Yotsukura et al., 1970; Chapra, 1997; Lees et al., 2000). The Rth moment of a function, M'_R, is defined as (Fischer et al., 1979):

Equation 6

$$M'_R(C) = \int_{-\infty}^{\infty} C(x,t)x^R dx$$

The zeroth moment is simply the area under the entire concentration curve, or the total tracer mass. Two additional quantities, the temporal location of the centroid, $\bar{t}$ and the variance of the distribution, s^2 are expressed as (Chapra, 1997):

Equation 7

$$\bar{t} = {M'_1}/{M'_2} = \frac{\sum_{i=0}^{n-1}(c_i t_i + c_{i+1} t_{i+1})(t_{i+1} - t_i)}{\sum_{i=0}^{n-1}(c_i + c_{i+1})(t_{i+1} - t_i)} =$$

Equation 8

$$s^2 = {M'_2}/{M'_0} - \bar{t}^2 = \frac{\sum_{i=o}^{n-1}(c_i t_i^2 + c_{i+1} t_{i+1}^2)(t_{i+1} - t_i)}{\sum_{i=0}^{n-1}(c_i + c_{i+1})(t_{i+1} - t_i)} - (\overline{t})^2$$ where i = time step in the sequence

For additional discussion on the application of moment matching techniques see Graf (1995) and Lees et al. (2000).

The temporal mean and variance can then be applied in order to estimate the velocity of the centroid, U (and consequently, A) and the longitudinal dispersion, K for two sample locations. The two equations are described below (Chapra, 1997):

Equation 9

$$U = \frac{x_2 - x_1}{\bar{t}_2 - \bar{t}_1}$$

Equation 10

$$K = \frac{U^2 (s_2^2 - s_1^2)}{2(\bar{t}_2 - \bar{t}_1)}$$

3.4.2. Theoretical equations of longitudinal dispersion

There are also numerous theoretical equations for estimating longitudinal dispersion that have been derived from bulk flow parameters using channel geometry. Longitudinal dispersion is primarily the result of velocity profiles created from the shearing processes around the wetted perimeter. For an average cross-sectional area, Fischer et al. (1979) defines the "longitudinal dispersion coefficient," K in the form of a triple integral that accounts for shearing throughout the main channel.

Theoretical equations have been developed to define longitudinal dispersion using bulk flow parameters and various regression techniques (Liu, 1977; Kashefipour and Falconer, 2002). With the recognition that rivers are generally much wider than they are deep, Fischer et al. (1979) simplified the triple integral in equation 11 through a series of laboratory experiments and dimensional analysis to propose a bulk flow parameter equation for longitudinal dispersion:

Equation 11

$$K = \frac{0.011 U^2 w^2}{h U_*}$$

in which U_* = the shear velocity over the cross-section, commonly estimated as $U_* = \sqrt{g r_h S}$ where g is the acceleration due to gravity, r_h= the hydraulic radius and S= the hydraulic gradient. The variables defining equation 11 consist of measurable river characteristics that are quantifiable using tracer studies and channel geometry. Fischer et al. (1979) found that equation 11 was able to predict dispersion coefficients within a factor of four of observed dispersion coefficients.

Since the proposal of equation 11, numerous studies have built upon the basic equation (Liu, 1977; Seo and Cheong, 1998; Deng et al., 2002; Kashefipour and Falconer, 2002). Seo and Cheong (1998) used dimensional analysis with a nonlinear, one-step Huber regression to derive an equation for dispersion that was based off of 35 measured dispersion values. In non-dimensional form, the relationship is defined as:

Equation 12

$$\frac{K}{hU_*} = 5.915\left(\frac{w}{h}\right)^{0.620}\left(\frac{U}{U_*}\right)^{1.428}$$

The equation was validated to 24 independent dispersion values and then assessed using discrepancy ratios as performance criteria. For predicted values of dispersion, K_p and measured values of dispersion, $K_{m,}$ the discrepancy ratio as defined in Seo and Cheong (1998) is:

Equation 13

$$DiscrepancyRatio = \log\frac{K_p}{K_m}$$

For a discrepancy ratio of zero the predicted dispersion value matches exactly with the measured dispersion value, whereas the prediction is overestimated for a ratio greater than 0 and underestimated for a ratio less than 0. Seo and Cheong (1998) found that equation 12 estimated dispersion values with a range of discrepancy values from -0.6 to 1 and estimated 79% of the dispersion values within a range of -0.3 to 0.3.

Due to the complexities and heterogeneities of river systems, using bulk flow parameters to predict dispersion coefficients within a range of discrepancy ratios smaller than -0.3 to 0.3 is unrealistic. Deng et al. (2002) have proposed a dispersion equation that performs exceptionally well (91% of predictions within the range of -0.3 to 0.3) and in so doing have discussed the potential for further improvements. With the understanding that even observed dispersion values have a range of uncertainty, equations that can estimate dispersion with discrepancy ratios with a range less than -0.3 to 0.3 can only be accomplished with the separation of molecular diffusion from longitudinal dispersion and the inclusion of channel sinuosity and transverse dispersion (i.e., two-dimensions) (Deng et al., 2002). Given the range of uncertainty in dispersion measurements, other studies have used ranges of discrepancy ratios from ± 0.78 to ± 0.30 (Liu, 1977; Chapra, 1997; Deng et al., 2002).

A recent review of different methods for estimating dispersion concluded that several of the reviewed dispersion equations poorly estimated dispersion coefficients measured in the field (Wallis and Mason, 2003). The evaluation of each equation's performance to observed values showed that precision under a range of transport conditions was a difficult task and that equation 11 from Fischer et al. (1979) appears to regularly overpredict dispersion coefficients.

4. STUDY AREA

4.1. General basin description

Originating on the eastern Sierra Nevada mountain slope, the Truckee River flows 190 km through the coniferous Tahoe National Forest, past the town of Truckee, California, into the Truckee Meadows with the cities of Reno and Sparks, Nevada, and to its terminus at Pyramid Lake (figure 4). With headwater altitudes in excess of 3,000 m around Lake Tahoe, the Truckee River watershed drains approximately 8,000 km^2 and contains five major reservoirs. The elevation of the river from its outlet to its terminus decreases more than 700 m giving it an average slope of 0.0038. The geology of the Truckee River basin is composed of Cretaceous- and Tertiary-age plutonic and extrusive igneous rocks. South of the Little Truckee River and east of the town of Truckee, occurrences of Tertiary lacustrine deposits indicate that stream systems were dammed by volcanic units (McGraw et al., 2001). Higher altitudes around Lake Tahoe experience an average annual precipitation of 81 cm, mostly in the form of winter snow and occasional summer thunderstorms. The Truckee Meadows and Pyramid Lake, averaging only about 18 cm each year, experience the influences of the rain shadow effect. The spring snowmelt in the Sierra Nevada creates the highest river flows of the year with lower discharges typically occurring in late July and August.

4.2. Study site descriptions

The 103 km portion of the river that is modeled in this study begins at Lake Tahoe and ends at the USGS Vista gage east of Sparks, Nevada. For the spill model, the river was segmented into three portions as defined by three tracer injection sites with a minimum of three downstream sample sites. Injection sites were chosen to best facilitate a single-slug injection near the center of streamflow. Monitoring sites were chosen according to their accessibility for collection of water and the presence of USGS gaging stations. Sample sites were also chosen to be far enough downstream from the injection site so as to ensure complete lateral mixing (Crompton and Bohman, 2000).

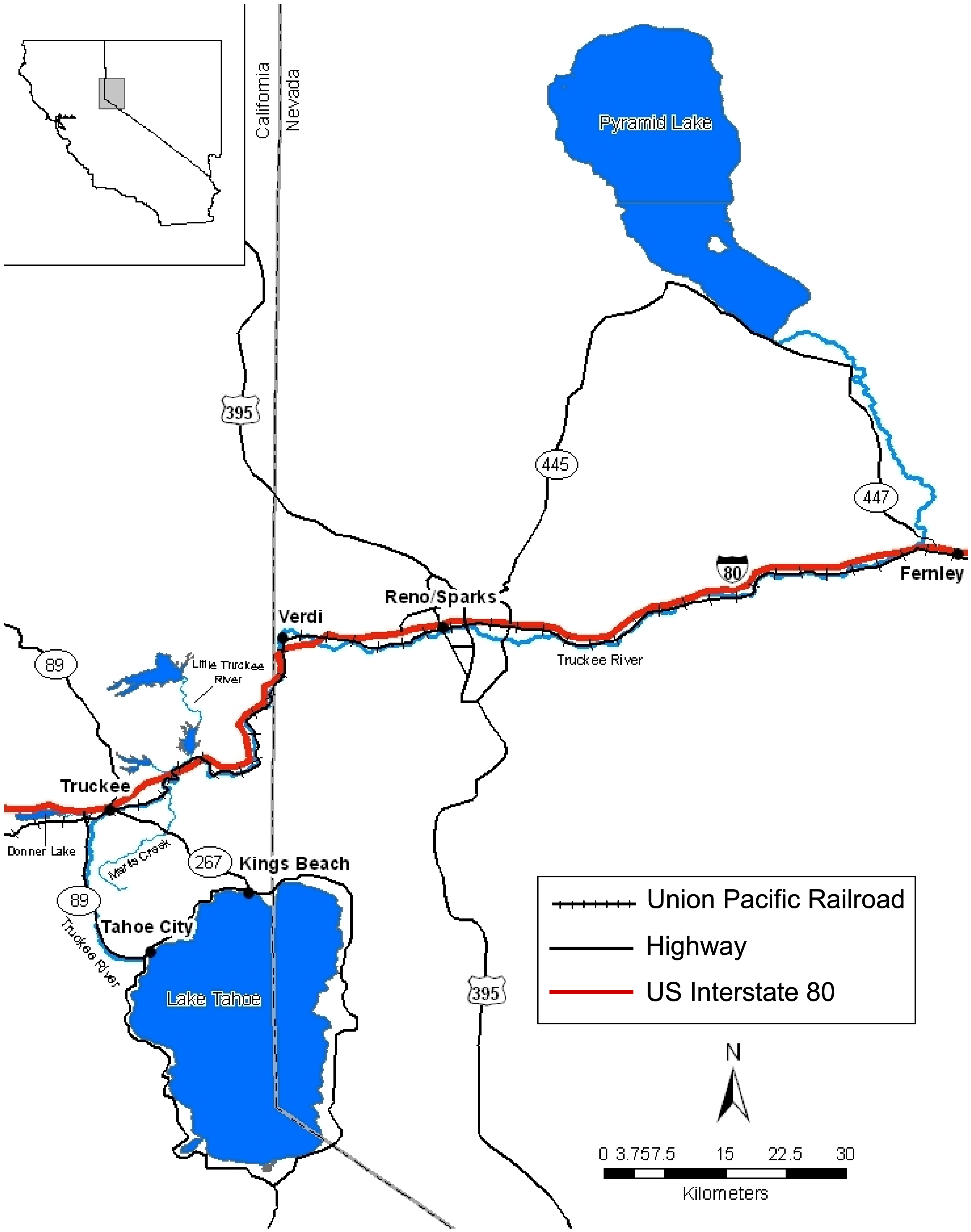

Figure 4. Truckee River watershed

The Upper Reach of the river as defined by this study begins at the injection site from California State Route 89 Bridge in Tahoe City, California and is composed of five downstream observation sites over 32 river km (figure 5, table 1). From the injection site outside of Tahoe City (THC), the Truckee River flows north alongside California State Route 89 for 24 km into the town of Truckee, California. Upstream of the town of Truckee, Donner Creek is the first major tributary to enter the river. The Donner Creek input to the Truckee River is controlled by the dam that is located at the outlet from Donner Lake. It is also in the town of Truckee where US Interstate 80 and the Union Pacific Railroad begin their descent into the Truckee Meadows. East of the town of Truckee, the river makes a northeasterly turn and meets with tributaries Martis Creek, Prosser Creek, and the Little Truckee River, all of which are controlled by reservoirs. Glaciated at least three times, the portion of the Truckee River east of the town of Truckee was a large lake in the last ice age and the fluvial deposits in that region can be associated with glacial outwash (Houghton, 1994). The portion of the Truckee River west of Martis Creek to Boca Bridge (BOC) is composed of unconsolidated sedimentary rocks, which appear to facilitate accretion from groundwater (Fox, 1982; McKenna, 1990). The final sample location for the Upper Reach is immediately downstream from the Little Truckee River tributary at BOC.

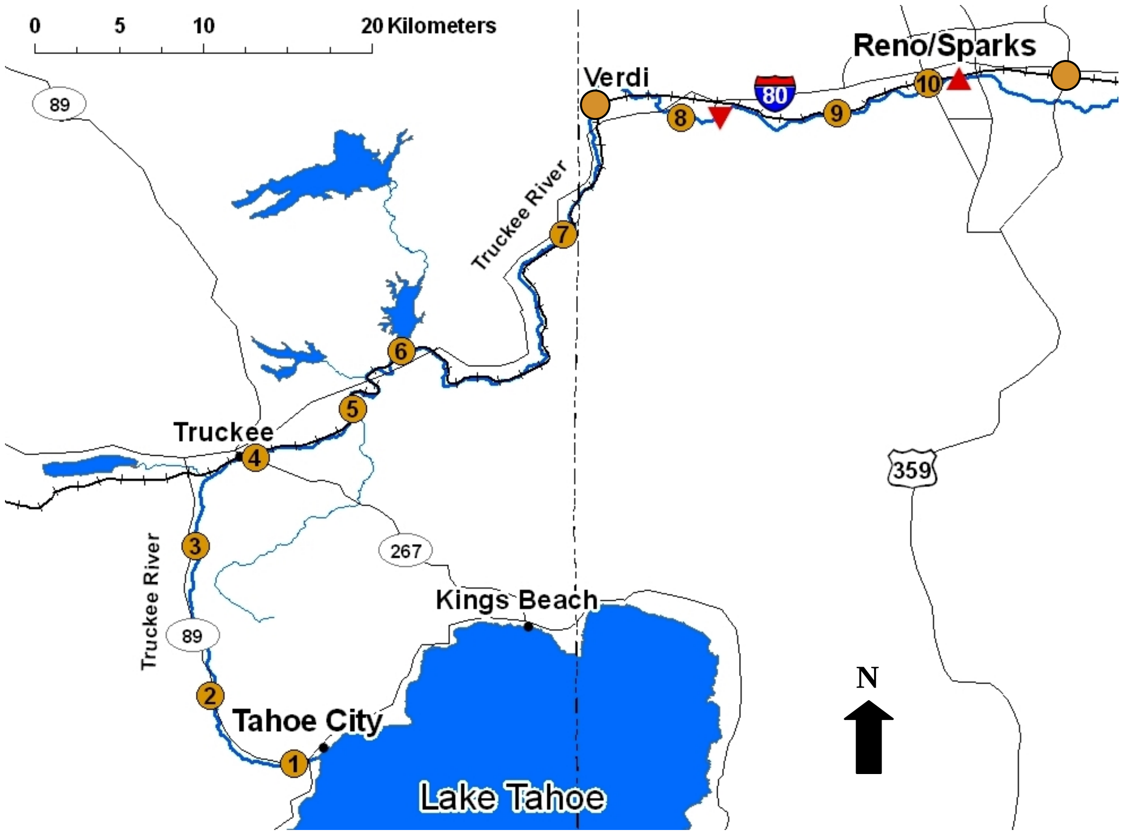

Figure 5. Site map for the two Truckee River tracer studies. Brown circles denote tracer study site numbers described in Table 1. Blank circles are tracer study sample locations that were not included in modeling domain. Red triangles are TMWA water intakes.

Table 1. Reach names, abbreviations and lengths. Red italic indicates TMWA intakes for TMWA's drinking water supply.

#	Site description	Site abbreviation	Distance from Tahoe city dam (km)
1	Tahoe City Dam	THC*	0.03
2	Squaw Creek	SQW	10
3	Truckee R nr Truckee	TRU	20
4	Brockway bridge	BRO	25
5	Glenshire Rd. bridge	GLE*	32
6	Boca Bridge	BOC	40
7	**Truckee R nr Farad**	**FAR**	**55**
	Bridge St., Bridge	VER	69
▼	*Highland ditch (TMWA diversion)*	TMWA #1	73
8	Truckee R nr Mogul	MOG*	77
9 ▼	West McCarran bridge and *Orr ditch (TMWA diversion)*	WMC & TMWA #2	84
10 ▼	Truckee R nr Reno and *Glendale ditch (TMWA diversion)*	REN & TMWA #3	92
	Truckee R at Vista	VIS	103

* tracer study injection sites

The Middle Reach of the spill model covers 44 river km. The Glenshire Road Bridge (GLE), which is a sample site in the Upper Reach, is also the injection site for the Middle Reach of the study with four downstream sample locations. From GLE, the Truckee River enters a steep canyon (average slope of 0.0066) with I-80 adjacent to the river for the next 35 km. There are three hydro-powerplant diversions and returns that regularly divert 10-13 m^3/s along this section of river (Federal Water Master, personal communication). As a result of these diversions, parameterization of the FAR to VER section of the model was not possible for the 1999 dye study and VER is not given a site number in table 1 and figure 5 (see Section 6.2). Thus, the FAR section of the model ends at the MOG site for both 2006 and 1999 dye studies. East of Verdi, Nevada, the river exits the mountains and enters the flatter alluvial valley of Truckee Meadows and the cities of Reno and Sparks. The first of three TMWA municipal diversions, the Highland ditch diversion, which feeds the Chalk Bluff Treatment Plant, occurs about 1 km upstream of the Mogul (MOG) site, which is also the final sample location of the Middle Reach.

The Lower Reach of the spill model begins at MOG with only two downstream sample locations and 25 km of river. The gradient is relatively flat (about 0.0003) and there are numerous agricultural diversions throughout this reach that divert water on a seasonal basis at flows less than 0.5 m^3/s (Federal Water Master, personal communication). It is also in this reach where the final two TMWA treatment diversions are located. The downstream Chalk Bluff treatment plant diversion is at Orr ditch, which is a little more that 6 km downstream from MOG. The Glendale treatment plant is less than 1 km downstream from the USGS Reno gage (REN), which serves as a sample location in the dye study.

5. METHODS

Two rhodamine WT dye tracer studies conducted in 1999 and 2006 by the USGS provide data for calibration of the OTIS model. The studies were conducted under moderate and high flow conditions for the Truckee River. Fifteen river cross sections were surveyed by a consultant in the fall of 2006. The cross sections were used in estimating main channel cross sectional areas and Manning's roughness coefficients to be used in the spill model for a simulated range of streamflow spill scenarios. Additionally, 14 sediment samples were collected and analyzed for size distribution and organic content at each spill model location. In addition to the explanation of field methods, an analysis of the tracer data is included below.

5.1 Field methods

5.1.1 Truckee River rhodamine WT dye tracer studies

There are three dye injection sites used for this study, segmenting the river into three reaches, which are referred to as the Upper, Middle and Lower River Reaches of the tracer studies. Field procedures for conducting travel time dye studies as described in Kilpatrick and Wilson (1989) were followed for both the 1999 and 2006 studies. An instantaneous slug injection of Rhodamine WT dye was made near the center of active flow at each injection site. The amount of dye, time and location of injection, and observed streamflow were recorded for each injection. The amount of dye necessary for each study was calculated using empirical relationships defined in Kilpatrick and Wilson

(1989) so that peak concentrations did not exceed 10 μg/L at sampling sites. Background concentrations were determined on-site using a Turner Designs model 10 fluorometer. When concentrations at the sample site increased from background levels, regular samples were collected at five-minute intervals until concentrations returned to background levels. Samples were stored in a cooler and transported to the USGS laboratory in Carson City, Nevada for analysis with the same fluorometer at a controlled temperature. These concentrations obtained in the USGS lab were used in model calibration.

5.1.1.1 Unit concentration analysis

It is important to note that the injection volumes and sampled streamflows for each study were different and thus, a one-to-one comparison of observed concentrations between studies can be misleading. Methods from Jobson (1996) can be employed to account for diluting effects of different streamflows and tracer recoveries in what is referred to as the unit concentration curve. Unit concentrations, C_u with units of ((mg/L/s)/mg) or simply (s^{-1}) were calculated for the Truckee River tracer data. For Q = observed streamflow in L/s, C_o= observed tracer concentration in mg/L, W_R = mass of tracer recovered in mg, the unit concentration, C_u is defined as (Jobson, 1996):

Equation 14.

$$C_u = 1 \times 10^6 \times \frac{C_0}{W_R} \times Q$$

Figure 6 illustrates the difference between an observed tracer curve for the 1999 Middle Reach tracer study in which there was considerable loss of tracer mass due to a diversion. Thus, the observed concentrations are markedly different from the unit-concentration curves and are included in Appendix A for both tracer studies.

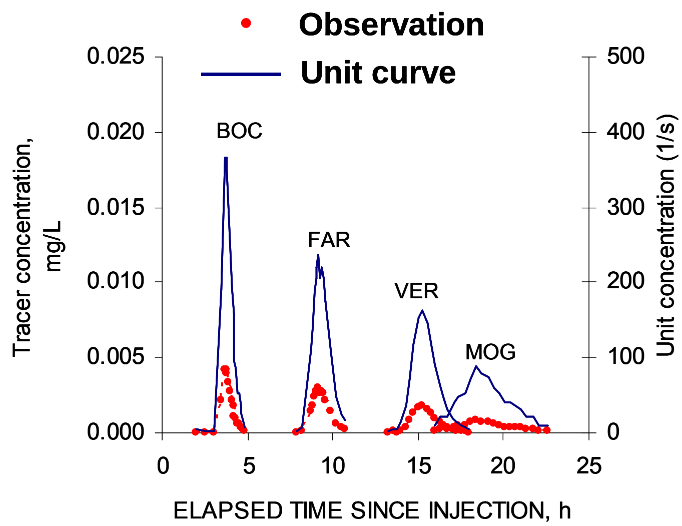

Figure 6. Observed concentration curve and unit-concentration curves for the 1999 Middle Reach

The 2006 tracer studies were conducted at flows larger than the streamflows from the 1999 tracer studies for the Middle and Lower Reaches, and the response curves for the two flow scenarios highlight the change in the travel times with a change in flow. In the Middle and Lower Reaches, the peak concentration arrived at each site sooner for the 2006 high flow scenario than for the 1999 moderate flows (see Appendix A). Assuming constant channel geometry between the years, a greater flow on the same reach should result in a higher velocity. Dispersion is apparent in the consistent decrease of peak concentrations at sites downstream as well as in the lengthened presence of dye that is observed at downstream sites.

5.1.2. Cross-sectional surveys and sediment sampling

In October 2006, 15 cross sections along the Truckee River were surveyed by Brendan Belby of Entrix, Inc. These measured cross sections provided physical characteristics such as channel geometry, water elevation at certain flows, and average slope of the sampling sites that were used in calibrating the model. In addition to the cross-sections, sediment samples were collected from fourteen sites and analyzed for organic matter and particle size distribution. The results of the sediment samples provided sorption and porosity information that was used in supporting the assumption that rhodamine WT acted conservatively. The results from the soil survey indicated that the rhodamine WT dye was unlikely to adsorb. According to the USDA soil classification, 11 out of the 14 sites were composed of very gravelly and sand substrate, with the three other sites classified as loamy sand. All of the sediment samples had a percentage of organic matter that was less than 2.5%.

5.2 Truckee River OTIS modeling

5.2.1. Model setup

Reach lengths and output locations were calculated using river distances from the Lake Tahoe dam in Tahoe City, California as documented by Crompton and Bohman (2000) and Crompton (unpublished data). Additional river locations such as tributaries, diversions, and TMWA intakes are obtained from TMWA's River Recreation map (TMWA, 2008). Diagrams of the three reaches as described by the OTIS model are shown in figure 9. The lengths of the Upper, Middle, and Lower Reaches are noted in figure 9 as well as diversions and returns that are simulated in the spill model.

Primary impacts on the Upper Reach occur only as tributaries. There are several smaller creeks between THC and TRU, but it is the inputs from Donner Creek, Prosser Creek and the Little Truckee River that contribute the largest portion of streamflow to the Truckee River. The Middle Reach is characterized by municipal and agricultural impacts

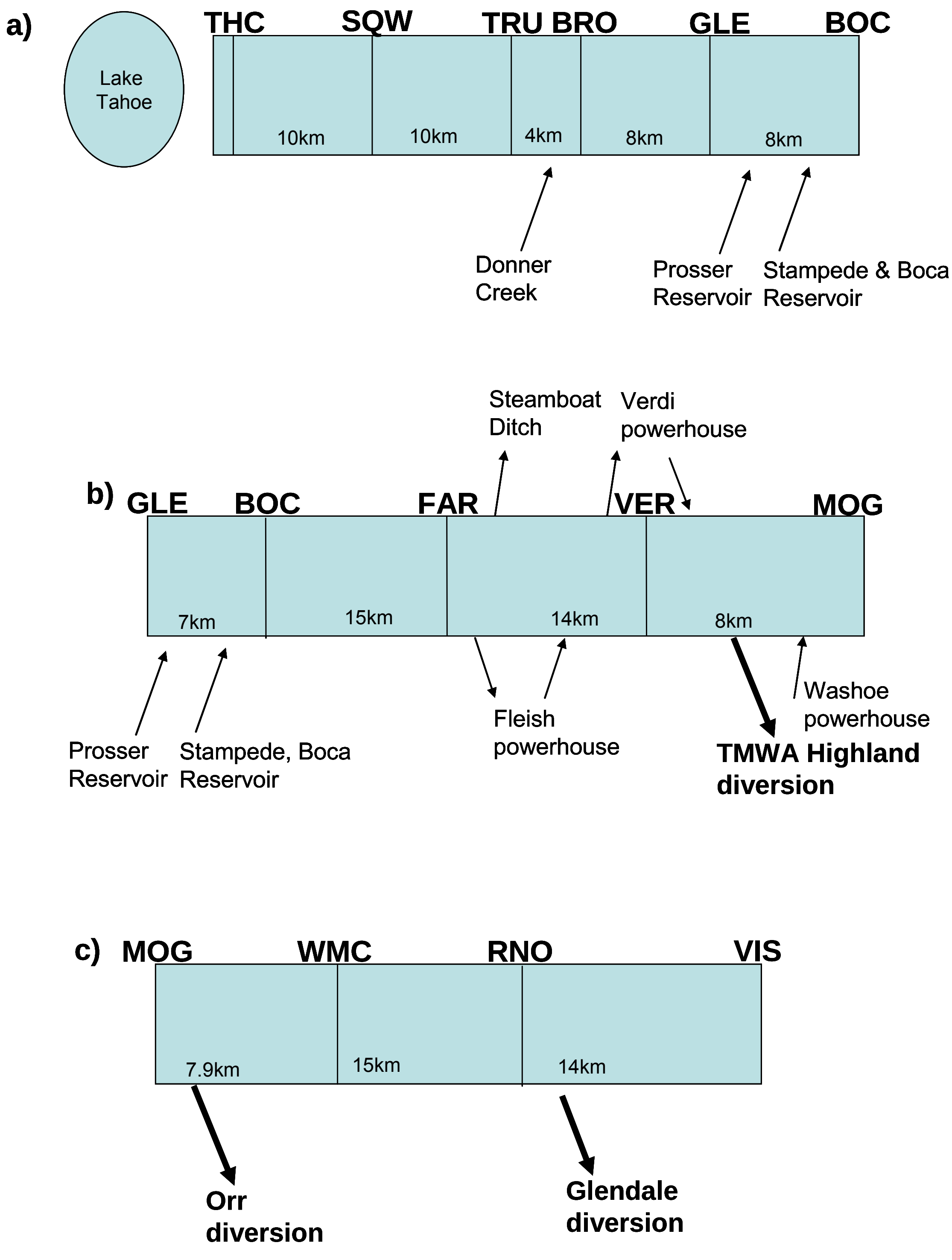

Figure 7.—OTIS model river schematic for the a) Upper, b) Middle, and c) Lower reaches. Refer to Table 1 for site abbreviations. The lengths of the GLE to BOC reaches are slightly different between a) and b) due to the location of dye injection.

at multiple locations. Operating only six months out of the year, agricultural diversions are consumptive and thus do not return water to the main channel. The hydropower diversions, on the other hand, are operational year round and are considered non-consumptive. The Middle Reach has three hydropower diversions and two returns, all of which move 10 m^3/s or more of streamflow (Federal water master, personal communication). The Middle Reach also has the Highland Ditch diversion, which is the first of three TMWA treatment plant intakes. The Washoe powerhouse and the Highland Ditch share the same diversion just upstream of the MOG site. The Lower Reach has several natural tributaries as well as half a dozen agricultural diversions, but only significant inputs or diversion are shown in the river schematic. Orr Ditch and Glendale Ditch, the two remaining TMWA intakes, are located in the Lower River.

5.2.2. Assumptions

Calibrating the Truckee River spill model required several assumptions in addition to those initially presented in Section 3.3.3.1. First, it was assumed that the rhodamine WT (RWT) tracer used in the Truckee River spill model was a conservative tracer. Losses of RWT due to adsorption and photodegredation of the dye have been observed in previous studies (Laenen and Bencala, 2001; Bencala et al., 1983). The tracer studies on the Truckee River were conducted at flows high enough to validate a conservative assumption. Not only are all of the studies performed under predominantly advective environments, but with high flows there is also a low ratio of sediment mass to water, which prohibits loss due to adsorption that has been observed in smaller stream studies (Bencala et al., 1983).

The mass of injected dye recovered at each sampling site in the Truckee River tracer studies was estimated by the method described by Jobson (1996). Assuming steady flow, the estimated mass from a response curve is the multiplicative product of the area under the concentration curve by the observed flow and total duration of observations. Results from the mass recovery analysis as well as observed streamflows are shown in Table 2. Because the area under the concentration curve is multiplied by the observed discharge, uncertainty in discharge measurements influences calculations of mass. Similarly, the volume of dye that is recorded for each injection and the fluorescence measurements have associated measurement errors, which contribute to perceived increases or decreases in mass at sites downstream. Furthermore, there are errors associated with extrapolating discrete measurements to the total mass calculations. All but three of the sites exhibited only minor losses (or gains) of tracer mass that can be attributed to measurement uncertainty.

The VER site in 1999 exhibited an exceptionally large loss of mass. During the agriculture season, Steamboat Ditch removes 1-3 m^3/s of flow that is consumed (i.e. not returned to the Truckee). Additionally, there are three run of river powerplant diversions on the Truckee River between FAR and MOG that are not consumptive but do have a large impact on travel times and mixing processes. During the 1999 tracer study, both the Fleish and Verdi hydro-powerplants were diverting and returning nearly 75% of the dyed water from the river. Because the Verdi powerhouse diverts water upstream of VER and returns it downstream of VER (see figure 9b), observations at VER only recorded about 50 g of dye—about 70% less than what was measured upstream at FAR. Observations at MOG, which is downstream of the Verdi powerhouse return, recorded nearly 140 g of dye—an increase of more than 150% of the VER observations. To account for the large loss of mass in the FAR reach and the large increase in mass for the VER reach, the two reaches were combined in the modeling calibration and scenarios and the observations at VER were not used in calibration. Combining these two reaches into one reach improved the mass balance of the measured dye and diminished the impacts of such large diversions and returns.

Table 2. Observed streamflows and mass recovery calculations for both Truckee River tracer studies

	Date	Site	Flow (cms)	Flow duration	Estimated mass (g)	Tracer recovery ratio from injection, R[1]	Date	Site	Flow (cms)	Flow duration	Estimated mass (g)	Tracer recovery ratio rom injection, R[1]
Upper	22-May-07	Tahoe City injection	1.9	62.0%	825		14-Sep-99	Tahoe City injection	7.6	32.6%	638	
		Squaw Creek	4.0		906	1.1		Squaw Creek [2]	8.0		497	0.78
		Truckee	5.5	58.7%	801	1.0		Truckee	8.1	39.2%	449	0.70
		Brockway bridge	7.5		761	0.92		Brockway bridge [2]	9.1		443	0.70
		Glenshire Rd	7.6		666	0.81		Glenshire Rd	9.8		412	0.65
		Boca Br	18.0	28.9%	582	0.71		Boca Br	16.1	35.2%	250	0.39
Middle	29-Jun-06	Glenshire injection	60.3		1300		20-Sep-99	Glenshire injection [2]	11.2		275	
		Boca bridge	64.0	3.2%	1265	1.0		Boca bridge [2]	17.8	29.9%	204	0.74
		Farad	75.3	4.1%	1346	1.0		Farad	17.8	31.9%	225	0.82
		Verdi [2]	65.1		1225	0.94		Verdi [2]	4.9		54	0.20
		Mogul	61.7	7.4%	1053	0.81		Mogul	14.3	43.6%	138	0.50
Lower	27-Jun-06	Mogul injection	39.4	14.3%	463		25-Aug-99	Mogul injection	15.4	39.3%	663	
		W. McCarran [2]	38.2		486	1.1		McCarran	12.2		431	0.65
		Reno	35.7	14.1%	425	0.92		Reno	11.8	44.1%	453	0.68
		Vista [3]	43.6	12.7%	157	0.34		Vista	13.9	51.2%	359	0.54
	4-May-99	Mogul injection	65.4	6.6%	1918							
		W. McCarran [2]	65.1		1606	0.84						
		Reno	60.3	7.0%	1503	0.78						
		Vista	66.5	6.9%	1268	0.66						

[1] R = (mass injected)/(mass recovered)
[2] flow estimated
[3] complete curve not sampled

There were two additional reaches that exhibited a loss of mass greater than measurement error and uncertainty. BOC on September 14, 1999, lost nearly 40% of the mass observed immediately upstream at GLE. This reach does not have any diversions, but there are two tributaries from reservoirs as well as geology that indicates potential surface-groundwater interactions. The geology of this section of the Truckee River shows Tertiary lacustrine deposits and unconsolidated sedimentary alluvium, which indicate the historic presence of a lake in addition to glacial outwash. Houghton (1994) briefly discusses Truckee Lake that was formed during the last glacial period (Pleistocene epoch) and covered nearly 73 square miles (190 km^2) in area. Increased river sinuosity from alluvial deposits facilitates surface-groundwater interactions in this region. In 1999, the contribution of the two tributaries in this area nearly doubled the streamflow. Driven by this sudden increase in streamflow and subsequently an increase in pressure head, it is possible that the Truckee River is connected to the surrounding aquifer in this area, and the loss of mass along on the GLE section was a result of the loss of dyed river water to the aquifer. In a UNR thesis that used water quality analysis to locate surface-groundwater interactions along the Truckee River, McKenna (1990) found that seasonal groundwater accretion occurred downstream from the region near Martis Creek.

The third site that exhibited a large loss of tracer mass was the VIS site in the 2006 tracer study. The leading edge and peak concentration for the VIS site was missed in the field in 2006, which explains the nearly 70% loss of tracer mass from the injection.

The mass balance in table 2, therefore, substantiates the conservative assumption of rhodamine WT dye. Considering the uncertainty associated with measuring streamflow and initial injection mass, losses of 10% or less between consecutive sites were deemed acceptable. With the exception of the VIS 2006, BOC and VER 1999, the majority of sample sites measured were within the value of 10%.

An additional assumption for the Truckee River spill model concerns the modeled flow regime, which is assumed to be steady, nonuniform flow (i.e. $dQ/dt = 0$; $dQ/dx \neq 0$). The Truckee River is a highly regulated system with flows frequently manipulated at the Lake Tahoe dam as well as at four reservoirs downstream from the town of Truckee. Observation of gage data at the Tahoe City dam and at the three major reservoirs show that operational adjustments only occur once in a day. Alternatively, the longest duration of tracer observed at a particular location was about 8 hours. Because it is uncommon for numerous adjustments to occur at one location over the course of one day, and the tracer studies do not take longer than eight hours, it was assumed that a reservoir operation did not occur during the time that a tracer was collected from the study, and a steady state assumption was reasonable.

Changes in river flow at the spatial scale on the other hand, necessitate a nonuniform flow assumption. As previously discussed, there are four large tributaries to the Truckee River as well as three hydro-electric, run-of-river diversions and returns that at times divert 80% of the instream flow. These impacts undoubtedly influence the travel time and mixing characteristics of the river and therefore need to be simulated. To account for these impacts, tributaries to the Truckee River are modeled in two different fashions. If the tributary has a considerable year-round contribution to the Truckee River, then the change in streamflow due to that tributary is simulated to occur over a distance of 30 m. The tributaries that were modeled in this way were Donner Creek, Martis Creek, Prosser Creek and the Little Truckee River. For smaller tributaries like Squaw Creek and Bronco Creek that contribute comparatively less streamflow on a more seasonal pattern, the change in flow is averaged over the entire reach, rather than a 30 m segment**.** The streamflow values that are used in calibration are presented in Appendix B.

5.2.3. Model input files

5.2.3.1 Params.inp

The integration time step (Δt) used in the Truckee River spill model was set to 0.02 hours (1.2 minutes) to account for the variability in the sample frequencies. Several of the sites were sampled on a 3-minute basis, while others were sampled on a 5-minute time step. In the event that an injection served as a step concentration boundary condition, the time step was set at 0.001 hours (3.6 seconds) in order to simulate the brevity and magnitude of the injected tracer.

Two different types of upstream boundary conditions were needed for model calibration. A continuous concentration boundary condition was used for reaches that had an observation time series at the upstream boundary. For the 6 reaches that only had a tracer injection as an upstream boundary, a step concentration was used as the boundary condition. In this case, the volume of dye injected was converted into a constant concentration sustained over one integration time step. An example of this conversion is described in Appendix C. The concentration estimates that were derived from the injected volumes created simulations that were close in time to the observations, but uncertainty in streamflow and measurement error required minor adjustments of the final concentrations to make the simulated area under the curve match with the observed area under the curve. In most cases, the adjustment was no greater than 1 mg/L. For example, in the case of the 1999 THC injection, a change in 1mg/L for the boundary concentration is a change in 20 mL of solution or 0.23 m^3/sec of flow.

5.2.3.2. Q.inp

The water balance for each reach was set up using the streamflows from the tracer studies along with any necessary tributary or diversion data that was necessary (Appendix C). For most cases, the water balance was reasonable. There were several occasions when the documented streamflow at the downstream boundary varied greatly from what was estimated with the water balance. With such an event, the discrepancy was accounted for by adjusting tributaries, diversions, or groundwater influences. As mentioned in Section 5.2.2, a segment length was set at 30 m.

5.2.4. Calibration

Data from seven conservative tracer tests conducted on the Truckee River in 1999 and 2006/2007 are used in the calibration of the Truckee River spill model (Appendix A). Three tracer studies from 1999 and one study from 2007 were used in the calibration of the model for moderate flow scenarios (flows between 4 m^3/s and 18 m^3/s), while one tracer study from 1999 and two studies from 2006 were used for high flow scenarios (flows between 36 m^3/s and 75 m^3/s). The 1999 moderate flow studies were conducted at a 38% flow duration for the Truckee, whereas the 2006 study in the Middle and Lower Rivers was conducted near a 9% flow duration. The high flow study that was conducted in 1999 took place with flows at 7% duration and the low flow for the 2007 study was at a 50% duration.

The tracer data from each of the studies was analyzed using the method of moments as described in Section 3.4.1. The results from the method of moments were then input as the user-defined initial OTIS-P estimates for main channel cross-sectional area and longitudinal dispersion from which the estimation algorithm begins. After OTIS-P was calibrated for only area and dispersion, the model was again calibrated with OTIS-P for a scenario that modeled transient storage. With both tracer studies calibrated, the values of main channel cross-sectional area from the no-storage parameterization were used to estimate the Manning's roughness coefficient in the geometry model. Then with the parameterized Manning's coefficients for the geometry model, three different theoretical equations for longitudinal dispersion were evaluated. An in-depth explanation of the calibration process follows.

5.2.4.1. Method of moments

Results from the method of moments for the 1999 and 2006/2007 tracer studies are shown in Tables 3 and 4. The most downstream site of each reach does not have a K, U or A value because there are no data downstream from which to calculate these values (see equations 9 and 10). Additionally, injection sites do not have a K value because equation 10 is a function of the temporal variance at both the upstream and downstream sites and injections sites do not have a measurement of variance.

Table 3. Results from method of moments for 1999

1999						
Site	Flow (m^3/sec)	Peak conc. (mg/L)	Mean conc. (mg/L)	Mean Velocity (m/sec)	Average cross sectional area (m^2)	Dispersion (m^2/sec)
THC	7.6	----	----	0.46	16	----
SQW	8.0	0.011	0.0041	0.72	11	33
TRU	8.1	0.0089	0.0029	0.61	13	27
BRO	9.1	0.007	0.0027	0.61	15	35
GLE	9.8	0.0055	0.0021	0.68	14	18
BOC	16.1	0.002	0.00084	----	----	----
GLE inj	10.5	----	----	0.12	88	----
BOC	17.8	0.0042	0.0011	0.76	23	21
FAR	17.8	0.0030	0.0012	0.61	29	40
MOG	14.3	0.00085	0.00041	----	----	----
MOG inj	15.4	----	----	0.67	23	----
WMC	12.2	0.014	0.0055	0.71	17	41
REN	11.8	0.0094	0.0038	0.60	20	41
VIS	13.9	0.0040	0.0017	----	----	----
MOG inj	64.0	----	----	1.4	46	----
WMC	65.0	0.0230	0.0083	1.5	43	65
REN	60.0	0.0150	0.0052	1.5	41	62
VIS	60.0	0.0085	0.0032	----	----	----

Table 4. Results for method of moment for 2006

2006						
Site	Flow (m^3/sec)	Peak conc. (mg/L)	Mean conc. (mg/L)	Mean Velocity (m/sec)	Average cross sectional area (m^2)	Dispersion (m^2/sec)
THC	1.9	----	----	0.23	8	----
SQW	4.0	0.025	0.0073	0.55	7	41
TRU	5.5	0.012	0.0052	0.58	10	9
BRO	7.5	0.0081	0.0037	0.55	14	74
GLE	7.6	0.0064	0.0026	0.58	13	1
BOC	18.0	0.0026	0.0011	-----	----	----
GLE inj	60.3	----	----	1.5	41	----
BOC	64.0	0.018	0.0061	1.6	40	132
FAR	75.3	0.0086	0.0018	1.4	53	265
MOG	61.7	0.0047	0.0015	-----	----	----
MOG inj	39.4	----	----	1.1	35	----
WMC	38.2	0.0090	0.0030	1.1	34	84
REN	35.7	0.0050	0.0016	1.2	30	13
VIS	39.0	----	----	-----	----	----

In comparing mean velocities and cross-sectional areas between years, it is apparent that greater streamflows generally result in greater velocities and areas. Most of the dispersion values estimated with the method of moments are also of the same magnitude measured in literature. Truckee River sites that are not impacted by diversions have dispersion values that range from 1-130 m^2/s. For rivers of similar dimensions and velocities, dispersion values range from 20-160 m^2/s (Kashefipour and Falconer, 2002). It is apparent that the diversions have a significant impact on the estimated variance of the tracer response curves and these values were not used in the initial calibration.

5.2.4.2. OTIS-P calibration

Calibration of the Truckee River spill model was performed with the OTIS-P calibration algorithm. Calibration was executed on a reach-by-reach basis and was performed twice—once for a no storage simulation and once for a storage simulation. OTIS-P requires an initial estimate of each parameter as defined by the model user, which begins the iteration procedure for the NLS algorithm. For the no-storage calibration, average cross-sectional area and dispersion were initially estimated using the method of moments analysis from the tracer data (Tables 3 and 4).

To begin the OTIS-P calibration for the storage simulations, parameterized values of A and D from the no-storage calibration were used as the initial estimates. The user-based estimates of the transient storage parameters were based off of results in the literature. For each reach, the initial values of the storage zone exchange coefficient were defined to be 1.0 X 10^{-6} sec^{-1} (Fernald et al., 2001). The initial values of A_s were estimated from published ratios of the storage zone cross sectional area to the main channel cross sectional area (A_s/A), which is a commonly used metric in assessing a relative amount of transient storage between systems. Laenen and Bencala (2001) assessed several rivers in the Wilamette Basin with a resulting mean ratio of 0.2. This mean value was used as the initial estimate for A_s in the OTIS-P routine.

5.2.4.3. Geometry model

OTIS model calibration for the two tracer studies only provided two parameter sets that were representative of one high and one moderate flow scenario. In order to model contaminant spills under streamflows that are different from the two tracer study flows, it was necessary to develop a method that estimated A and K for additional flows. To do this, the data obtained from the Truckee River cross sectional survey was used with the Excel Solver routine for the Chezy-Manning equation. The spreadsheet model adjusts the elevation of the water surface so that the streamflow as calculated by the Chezy-Manning equation matches the desired streamflow. Assuming that the surveyed channel geometry was characteristic of a particular reach, the geometry model was used to estimate both A and K for tracer study streamflows. It was assumed that the energy gradient for the Chezy-Manning equation was the same as the channel slope for the survey site. Also, it was assumed that the cross-sectional geometry at the survey site was characteristic of the rest of the reach.

The Manning's roughness coefficient (n) was an unmeasured value in the geometry model, and thus it was necessary to perform a calibration that estimated the n for each survey site. The geometry model was sensitive to n, where small changes in n resulted in large changes in the estimated A. Also, the OTIS model is sensitive to A, where small changes in A have a considerable impact on the performance of the model. Because of these sensitivities in OTIS and the geometry model, it was necessary to calibrate the geometry model so that its A was the same as the A estimated by OTIS-P. To accomplish this, the water elevation at the survey site was adjusted until the Chezy-Manning cross-sectional A matched the OTIS-P calibrated A. The elevation was then kept at this value and n was adjusted until the Chezy-Manning estimate of streamflow matched with the observed streamflow. The roughness coefficient was estimated in this manner for each reach and tracer study streamflow, resulting in two coefficients per reach—one for high flows and one for low flows (table 5).

Table 5. Manning's n-values estimated from the calibration of the geometry model using OTIS-P no-storage A values

		LOW Q	HIGH Q
Site	**30% EP flow (cms)**	**If EP > 30%, then n-value =**	**If EP <= 30%, then n-value =**
THC	8.2	0.28	0.12
SQW		0.08	0.06
TRU	9.2	0.08	0.08
BRO		0.09	0.09
GLE		0.10	0.11
BOC	17.8	0.09	0.06
FAR	18.8	0.09	0.08
MOG	21.4	0.09	0.07
WMC		0.03	0.05

5.2.4.4. Selection of dispersion equations

Because K values were unknown for streamflows other than those in the tracer study, a theoretical equation was used to estimate K at other flows for spill scenario simulations. A review of theoretical dispersion equations was performed in order to find equations that could be applied to the Truckee River. Due to its endurance over time and criticism (not to mention its simplicity), equation 11 from Fischer et al. (1979) was estimated and compared to values of dispersion from the tracer studies. Also frequently cited, but more recent and still not too complicated, equation 12 from Seo and Cheong (1998) was also investigated. Other equations reviewed included equations from Kashefipour and Falconer (2002) and Jain et al. (1977), but these equations had issues regarding validity and lack of data required for the estimation.

Fischer et al. (1979) and the Seo and Cheong (1998) equations for longitudinal dispersion were used to calculate K at each site for tracer study streamflows. These coefficients were compared to the OTIS-P no-storage K values and each equation was assessed using the discrepancy ratio (equation 13). As previously discussed in section 3.4.2, theoretical estimates of dispersion coefficients are difficult to match with observed data and thus, a discrepancy ratio within the range of ±0.60 was deemed acceptable for the Truckee River spill model and is within the ranges used or recommended in Fischer et al. (1979) and Chapra (1997). Furthermore, acceptability was assessed by defining a reasonable fit as the proportion of predicted coefficients for which the discrepancy ratio was within the range of ±0.60.

The equation from Seo and Cheong (1998) performed the best with the OTIS-P values. Under moderate flows, the dispersion values as estimated with Seo and Cheong

(1998) had a reasonable fit of 83%, compared to a reasonable fit of 65% for Fischer et al. (1979). Both of the theoretical dispersion equations considered performed poorly for the high flow scenarios, consistently overestimating dispersion coefficients outside the reasonable fit criteria. It is possible that the geometry model overestimates several of the channel properties, which would result in high values of dispersion. As a result, it was decided that no theoretical equation for dispersion would be used in the simulation of high flow spills. Instead, the OTIS-P estimates of dispersion from the high flow scenario would be used in the simulation of spills that occurred at FAR flows greater than 1000 cfs (28 m^3/s).

Using the Seo and Cheong (1998) dispersion equation to estimate dispersion for the 1999 tracer flows, a simulation of a semi-truck spill originating at the TRU site was compared to simulations using the two OTIS-P parameter sets (i.e., no-storage and storage). The 1999 tracer studies occurred over streamflows that were continuous between the three reaches. This continuity of flows over the three reaches facilitated the splicing together of the Upper, Middle, and Lower Reaches to make a complete, continuous Truckee river spill model. The 1999 tracer study flow at FAR was 627 cfs and so the Seo and Cheong (1998) based model was defined by the FAR 600 cfs indexed flow. The injection location of TRU was chosen because it is the most upstream site that is adjacent to Interstate 80 and the train tracks. The most upstream site should highlight the differences in travel times for the three simulations.

5.2.5. OTIS model evaluation

Limited travel time data for the Truckee River prevented a traditional validation of the complete model, but an evaluation of the Upper Reach was possible due to the similarity of streamflows observed for the 2007 and 1999 Upper Reach dye studies. The calibrated OTIS-P parameters were compared across the years in order to evaluate model performance. The no-storage parameters estimated from the 2007 parameterization were used to simulate the transport of the injection volume from 1999 under 1999 flow conditions. The same process was performed with the 1999 parameters to simulate the 2007 injection.

5.2.6 Spill scenario modeling

With the OTIS model and the geometry model calibrated and the Seo and Cheong (1998) dispersion equation chosen, the final step was to model the transport of potential contaminant spills. Using the method previously explained to estimate A and K, two spill simulations were conducted from each of the site locations under 13 possible flow scenarios. For each of these spills the time of arrival and time of departure (as defined by a 5μg/L method detection limit (MDL)) and the maximum simulated concentration and time were recorded at each of the three TMWA.

5.2.6.1. Spill scenario setup

The Truckee River has an emergency response plan, which provides guidance for regional authorities as to who needs to be contacted and what sequence of actions need to occur in the event of a spill (TRAC, 2005). Because of this response plan, a major spill on the river has a good chance of being attended to in a relatively expeditious manner. As a result of the response plan, it was assumed that a train tanker spill would occur over the course of 90 minutes, while the semi-truck spill occurred over 60 minutes, because it was expected that a spill would be contained within this period of time. It was also assumed that both would be best simulated by a simple step function (i.e., the concentration would be constant over the duration of the spill).

The volume of a rail car spill was simulated at 130,000 L and the volume of a dual tanker rig spill from a semi-truck was simulated at 75,000L. These values were obtained from maximum allowable volumes described in the Code of Federal Regulations (49CFR179.13; Holztman, 1997). It was assumed that the density of the spilled contaminant was similar to that of water (i.e., 1000 kg/m^3), which allowed for the fasted transport downstream. The estimated mass from the density calculation was then divided by the spill duration in order to estimate the injection rate. Finally, the mass per unit time was divided by the simulated streamflow in liters. This was the value that defined the upstream boundary condition for a spill that occurs over the spill duration.

5.2.6.2. Streamflow scenario setup

In addition to creating spill scenarios, it was necessary to define various streamflow scenarios. Because the model is assumed to be nonuniform, tributaries to the Truckee River will have different contributions under different conditions. The streamflow scenarios were developed at 8 sites along the Truckee River from USGS streamflow data beginning in October 1, 1996 and going through September 30, 2007. The FAR site was chosen as the index site for flows due to its historical significance in Truckee River operations (Nevada Department of Conservation and Natural Resources, 1997). Streamflow simulations were defined for the seven river locations at 100 cfs flow increments from 100-1000 cfs as well as at 1500, 2000 and 2500 cfs as observed at FAR.

To create a flow scenario, the 10-year record of daily mean flows at FAR was searched to find the dates during which a particular index flow was measured. In order to account for seasonal variability such as spring runoff, late summer baseflows, and winter driving conditions, observation dates were segmented into seasonal quarters according to the water year. Since spills had the highest likelihood of occurring during the winter months under inclement weather conditions, streamflow scenarios focused on January 1-March 31 and April 1-June 30.

Using the dates of observations for an index flow at the FAR site, streamflows at the additional 7 river locations were tabulated for comparison. If there was only one observation of a particular flow, then the flow scenario was defined by the recorded streamflows at the other sites on that date. When there were several observations of one particular flow, similar seasons were grouped, and the winter season observations were averaged for each site with the resulting values defining that scenario. It was assumed that river diversions on the Truckee River would be turned off in the event of a spill and so the flow that is simulated at FAR is also used at the two sites downstream of FAR.

Table 6. Table of simulated stream flows as indexed at FAR

Site name	Potential spill location	Simulated streamflow (cfs)												
Truckee R a Tahoe City CA	THC	0	0	90	174	212	216	47	61	68	60	492	67	865
Squaw Creek	SQW													
Truckee R nr Truckee CA	TRU	12	20	120	198	213	265	218	234	269	284	678	682	1145
Donner C at HWY 89 nr Truckee CA		8	28	32	27	6	39	129	149	137	150	105	397	185
Brockway Bridge	BRO													
Martis C nr Truckee CA		5	7	11	13	4	12	51	46	26	39	22	68	88
Glenshire Rd. Bridge	GLE													
Prosser C bl Prosse C Dam nr Truckee CA		8	42	32	45	100	76	171	136	59	110	96	323	256
Little Truckee R bl Boca Dam nr Truckee CA		69	76	53	70	115	141	1	92	357	250	320	124	606
Truckee R a Boca Bridge nr Truckee CA	BOC	98	194	291	355	469	545	700[a]	729	918	904	1500[a]	1755	2279
		Index streamflow (cfs) at FAR												
Truckee R a Farad CA	FAR	100	200	300	400	500	600	700	800	900	1000	1500	2000	2500
Truckee R nr Mogul	**MOG**	100	200	300	400	500	600	700	800	900	1000	1500	2000	2500
West McCarran Bridge	**WMC**	100	200	300	400	500	600	700	800	900	1000	1500	2000	2500
Truckee R nr Reno	**REN**	100	200	300	400	500	600	700	800	900	1000	1500	2000	2500

yellow box signifies a Truckee River tributary

[a] Streamflow data unavailable for this date at this location. Estimate comes from the FAR index flow value

Once spill scenarios were defined, values of K and A were calculated for each reach using the geometry model. Storage was not simulated in the spill model in part because there was not a method to estimate A_s and α at unstudied streamflows. Because the storage zone is a conceptual zone it is not measurable with survey data and there are no theoretical equations to estimate the two parameters. Also, the initial simulations showed that the OTIS-P storage parameters simulated the least conservative spill in terms of time of arrival and peak concentration.

Using the K and A values estimated with the geometry model, the OTIS model was set up in the Matlab framework to execute all of the 13 streamflow simulations from each of the nine injection locations. The Matlab routine processed the output to obtain the time of arrival, peak, and departure as well as the peak concentration. The arrival and departure times were defined as the times at which the simulated concentration reached a method detection limit of 5 μg/L, respectively, as requested by TMWA water manager, Shawn Stoddard (personal communication). The time series for each spill at each site was also output.

To account for the uncertainty associated with the dispersion calculations, other values of K were used to bracket estimated values. As noted in section 5.2.4.4, a discrepancy ratio of ±0.60 was deemed acceptable for the Truckee River. A discrepancy value of +0.60 is equivalent to $K_p = 4K_m$ and a discrepancy ratio of -0.6 is equivalent to $K_p = K_m/4$. Therefore, spills were simulated for each flow scenario at each location with the estimated value of K divided by four as well as the estimated value of K multiplied by four. These provided upper and lower bounds of travel times. Similar to the previous simulations, time of arrival, peak, and departure as well as the peak concentration were recorded for these simulations.

6. RESULTS

6.1. Calibration results

Visually, the curves from those reaches with the lowest streamflow (2007 Upper, 1999 Middle, and 1999 Lower) have the largest spread about the centroid, but longitudinal dispersion coefficients are largest for the highest flows (figures 10 and 11). The lower flows have a smaller dispersion coefficient, but due to the slower velocities, they are mixed for a longer period of time. Finally, it is important to recognize that the injection volumes for each dye study were different and thus a direct comparison of concentrations is misleading. Note that in 1999, two dye studies were done for the Lower Reach (figures 10c and 10d).

The performance of each of the three models (i.e., OTIS-P no-storage, OTIS-P storage, and Seo and Cheong based dispersion) is varied between each of the studies. For the majority of the model executions, the Seo and Cheong (1998), referred to hereafter as the S&C model, and the OTIS-P no-storage simulations tend to have the largest peak concentrations. The peak concentration for the OTIS-P storage simulation is lower than each of the OTIS-P no-storage simulations. Additionally, the two OTIS-P models are able to recreate the arrival and departure of each curve rather well.

The S&C model is able to locate the modeled curve around the time of the observations (indicating that the cross-sectional area is appropriate), but the spread of the modeled curves is not always well-matched with the observations. In most cases, the

S&C dispersion coefficients are over-estimated, which results in a decrease of the peak concentration as well as an increase in the duration over which the tracer is present. Although the S&C curves do not model the dispersion of the observations as well as the OTIS-P models, the S&C model is the most conservative estimate for arrival time.

The difference in travel time as a result of large change in flow is more pronounced for the Middle and Lower Reaches than it is for the Upper. The 2006 Middle Reach was conducted at 5% exceedence flow and the 1999 Middle Reach was conducted at flows less than 35% exceedence flows. The 2006 Lower Reach was conducted at a 14% exceedence flow, one of the 1999 studies was conducted at flows less than 42% exceedence, and the other 1999 study occurred at 7% exceedence flows. The curves for the 2006 Middle Reach arrive at each of the sample locations earlier than they do for the 1999 tracer study. In fact, in 2006, the tracer has completely left the Middle Reach before it even arrives to the final MOG site in 1999. There is a similar trend in the Lower Reach travel times, as well.

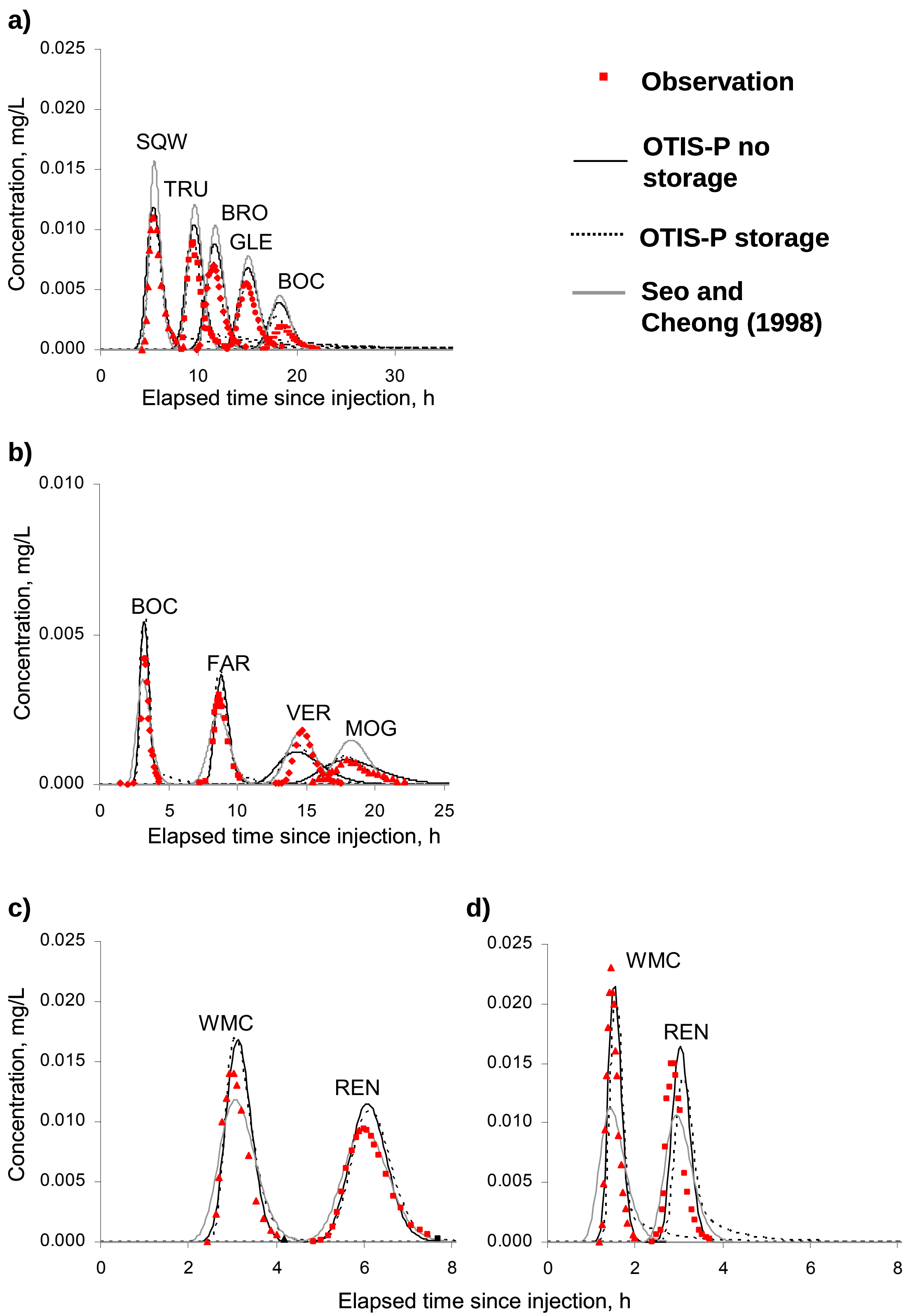

Figure 8. 1999 tracer data and model output for a) Upper, b) Middle c) Lower (low flow) and d) Lower (high flow) reaches

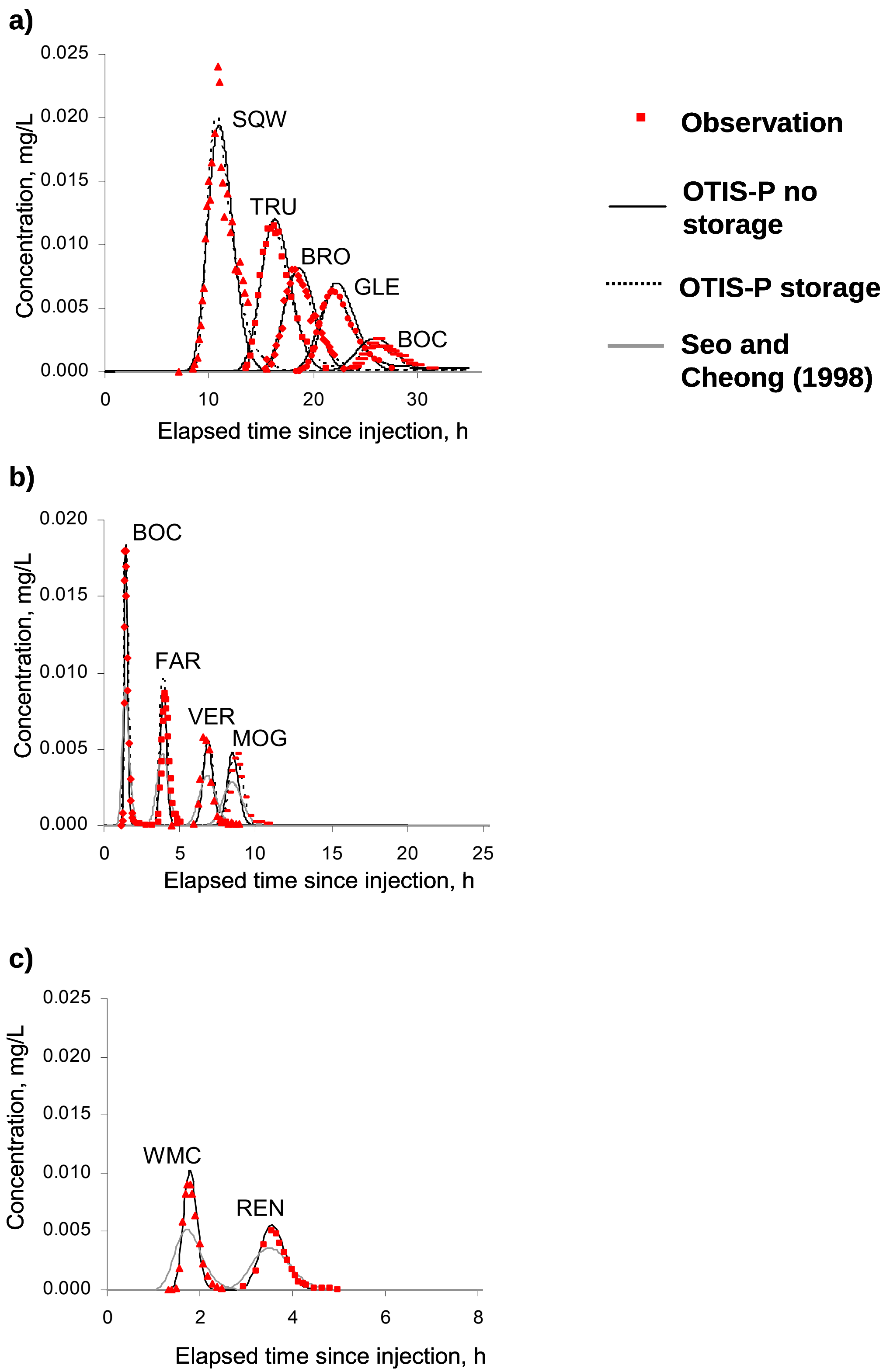

Figure 9. 2006/2007 tracer data and model output for a) Upper, b) Middle and c) Lower Reaches

6.2 OTIS model evaluation results

As described in section 5.2.5, the OTIS-P parameters from each year were evaluated with the tracer data from the opposite year. The results of this evaluation are shown in figures 12 and 13. The 1999 OTIS-P dispersion coefficients are too large to consistently recreate the 2007 observations. It also appears that the main channel areas for the 1999 parameters are too small for the 2007 scenario, most notably in the first two reaches, SQW and TRU (figure 12). The smaller area increases the advective downstream transport and the modeled curves arrive earlier than the observations.

Looking at the streamflows for both years, the 1999 Upper Reach should have larger areas because it was sampled at a 35% exceedence flow, as compared to the lower, 50% exceedence flow for 2007. What occurs in the first two reaches of figure 12 is that the distribution of flow along the reach is impacting downstream transport. In 1999, streamflow gradually increased from 7.5 at THC to 8.0 m^3/s at SQW and ultimately to 16.1 m^3/s at BOC. In 2007 the streamflow began at 1.9 m^3/s at THC, then doubled to 4.0 m^3/s at SQW, finally increasing to 18.3m^3/s at BOC. The incompatibility of A for the early part of the Reach between the two years is a result of two distinct flow scenarios. At the end of the reach though, the differences in flow have been muted. The 1999 OTIS-P model arrives and departs from BOC similar to the tracer curve. For the purpose of the spill model, which is to estimate the arrival times at the downstream location, the 1999 OTIS-P model performs rather well under flows that are similar when averaged over the reach.

In figure 13, the 2007 parameters model output is compared to the 1999 observations. The high peaks and generally skinny spread indicates that the dispersion coefficient from the 2007 OTIS-P parameters is somewhat low for the reach. The areas appear to match well and in the end, a similar result to figure 12 shows that at the BOC site the time of arrival is close to the observations.

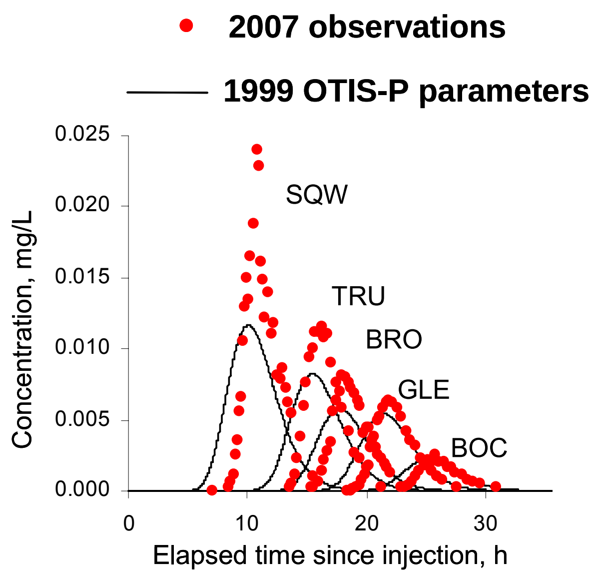

Figure 10. Evaluation of 1999 OTIS-P Upper Reach parameters to 2007 tracer data

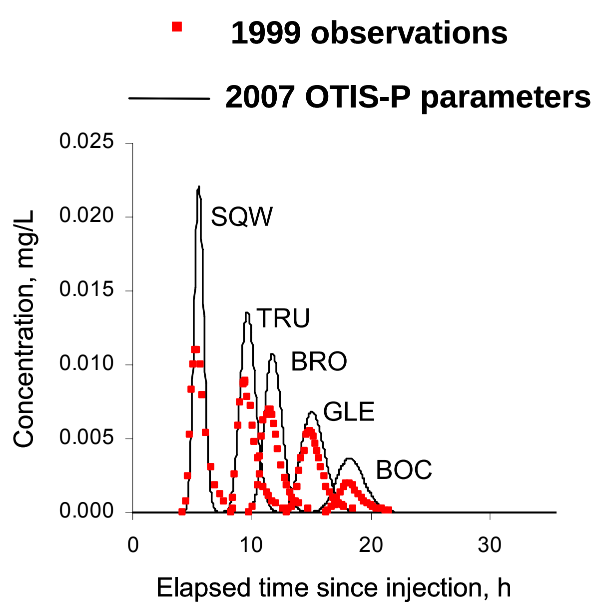

Figure 11. Evaluation of 2007 OTIS-P Upper Reach parameters to 1999 tracer data

6.3 Simulation results

6.3.1. Semi-truck spill simulation under tracer study conditions

The three model simulations of a semi-truck spill occurring at TRU for FAR 600 cfs flows are shown in figure 14. In modeling spills, it is important to estimate the most conservative situation (i.e., the soonest arrival time, the greatest peak concentration, and the latest departure time), but in the event of a spill, TMWA will have a monitoring program in place to verify when the contaminant plume has departed. Therefore, it is most important that the spill model predict arrival times conservatively.

Despite the fact that the S&C modeled curve does not look much like either of the calibrated OTIS-P curves, it is the S&C model that is most conservative for the time of arrival. In the magnified leading edge of figure 14, it is apparent that the S&C model arrives first with respect to the 5 μg/L MDL (17.3 hours after injection), the OTIS-P no storage simulation arrives second (18.3 hours after injection) and the OTIS-P storage simulation arrives last (20.5 hours after injection). For the peak concentration and the arrival time of the peak, the S&C model is the most conservative as well, simulating the largest peak concentration in the earliest time of the three. The OTIS-P storage model is the least conservative for peak concentration and the OTIS-P no-storage model is the least conservative for the arrival time of the peak concentration. The S&C model is the least conservative for the departure time as well as the total duration contaminant present, but such estimates are not as important for our purposes as the arrival time is.

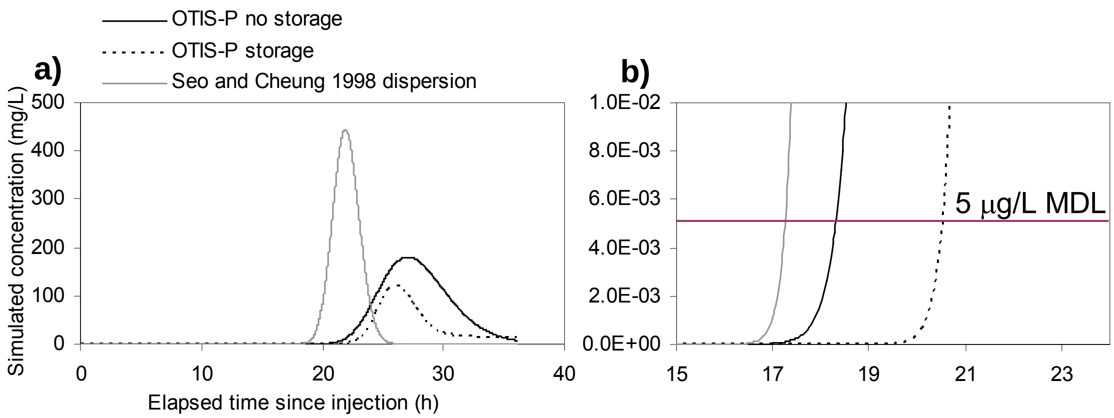

Figure 12. Simulated semi-truck spill occurring at TRU under FAR 600 cfs streamflows

6.3.2. Semi-truck and train spill simulation results for all modeled spills

Since the output that most concerns TMWA is the earliest estimated time of arrival, the time of arrival of the peak concentration and trailing edge are not analyzed in this paper. The following analysis is for the simulation of arrival times to the first TMWA intake at the Highland diversion for a train car spill. Simulated data are available at all three TMWA intakes for peak concentration and the trailing edge as well as for a semi-truck spill, which are presented in Appendix E.

Figure 15 shows the change in estimated travel time to the Highland diversion for a change in modeled streamflow for a train spill occurring at TRU and BOC. The middle, darkest line is the Seo and Cheong (1998) estimated travel times and the lighter toned lines provide upper and lower bounds for travel time as estimated by the factor of four dispersion values. Due to reservoir contributions, the rate of change in travel time for a TRU spill is considerably greater for flows at FAR under 1000 cfs than the rate of change in travel times for a BOC spill. The FAR site is downstream of BOC and both FAR and BOC are downstream of the major reservoirs. The TRU site is in the heart of the Upper Reach, 20 km upstream from the BOC site. Therefore, as the indexed flow at

FAR increases, the travel times from TRU (and the Upper Reach in general) increase due to contributions from the two major reservoirs. Conversely, because there are no major tributaries after the BOC site, the rate of change in travel times for a spill at BOC is smaller than the rate of change in travel times for a spill occurring at TRU.

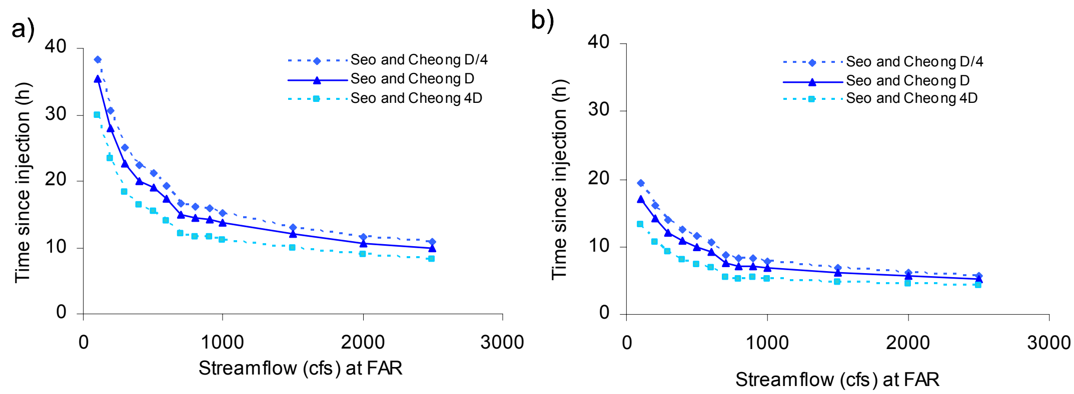

Figure 13. Simulated arrival times after spill to Highland Ditch with respect to streamflow at FAR for train spill occurring at a) TRU and b) BOC

The factor of four criteria for the dispersion coefficeitn provides upper and lower bounds for the estimated travel times. For the simulation that is indexed to FAR streamflows of 100 cfs (FAR 100 cfs), estimated travel time for the TRU spill is over 35 hours to the Highland intake. The upper and lower bounds for the dispersion values provide an 8-hour range of travel times: the earliest arrival occurs 30 hours after the spill and the latest occurs 38 hours after the spill, with the larger dispersion value providing the most conservative travel time.

The range in travel times between the upper and lower bounds for a TRU spill decreases with an increase in streamflow to a range of 2.5 hours for the FAR 2500 cfs simulation. As previously mentioned, the parameter with the strongest influence on simulated travel times in the model is the main-channel cross sectional area as it defines the advective transport downstream. At lower flows, A is small, the velocity is low and the spill has a longer time to mix in the channel, resulting in a larger spread of travel times. With a greater streamflow, there will be a greater dispersion value, but the mixing time will be less, which results in a smaller spread of travel times. A plot of travel time as a function of distance upstream from the Highland diversion shows that the change in travel time is more linear than it is for the streamflow dependent travel times (figure 16).

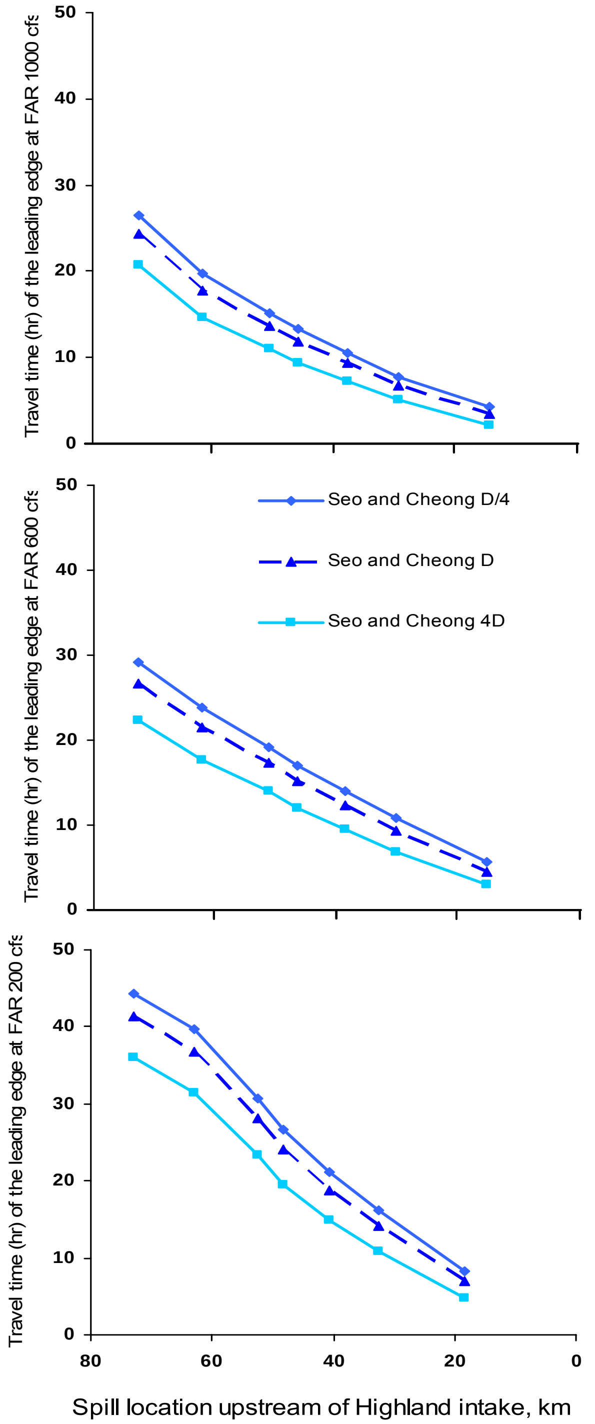

Figure 14. Change in travel time with respect to spill location for three flow scenarios for a train spill

Similar with travel times, the simulated peak concentrations that are modeled using the S&C dispersion value with the two boundary estimates for the dispersion vary largely for lower FAR streamflows. Figure 17 is a plot of simulated peak concentration as a function of streamflow for a train spill occurring at TRU. With the range of dispersion estimates from the factor of four analyses, estimated maximum concentrations range over 7,000 mg/L for the FAR 100 cfs scenario. The range of concentrations decreases rapidly for the first five FAR streamflows (100-500 cfs), after which the rate of change decreases considerably until the FAR 2500 cfs scenario has a concentration range of less than 200 mg/L.

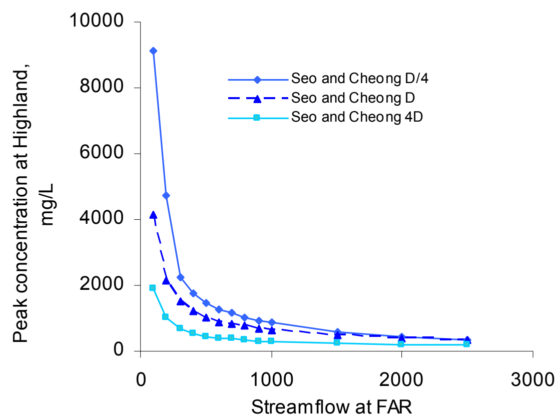

Figure 15. Change in simulated peak concentration simulated at Highland diversion with respect to streamflow for a train spill occurring at TRU

7. DISCUSSION

7.1 Longitudinal dispersion

The dispersion parameters estimated with OTIS-P are acceptable in their magnitudes and simulate the tracer data well. The values of longitudinal dispersion estimated with OTIS-P ranged from 12-96 m^2/s. In research conducted on the Truckee River below the VIS site, Knust (2006) estimated dispersion coefficients for a flow of 15

m^3/s to be around 20 m^2/s. Chapra (1997) presents a list of observed dispersion values along with the hydrogeometric parameters for a range of rivers. The rivers that share similar geometric parameters with the Truckee River have longitudinal dispersion values that range from 8-38 m^2/s. Although still within a factor of three of the Chapra (1997) values, the values of dispersion calculated in the OTIS-P calibration that are outside of the range all occurred in the Upper Reach where the slope is great and the river is characterized more as a mountain stream than at other locations downstream. The Middle and Lower Reaches both had dispersion coefficients that were closer to the range cited from Chapra (1997).

The Seo and Cheong (1998) equation predicted 83% of the dispersion coefficients within a factor of four of the observed dispersion values for the Truckee River (discrepancy ratio ±0.60), which is comparable to discrepancy values discussed in the literature (Hibbs and Gulliver, 1999). Using the equation from Fischer et al. (1979), Chapra (1997) predicted 88% of observed dispersion values within a factor of five (discrepancy ratio ±0.70) and Deng et al. (2002) proposed an equation that predicted 91% of dispersion values that were within a factor of two to the observed values (discrepancy ratio ±0.30). Considering the length of the model reaches and the limited amount of river geometry that was available, a reasonable fit for 83% of the dispersion values is acceptable for the Truckee River spill model. The discrepancy ratios in figure 18 are skewed to the right of the histogram, indicating that the Seo and Cheong (1998) equation was primarily overestimating dispersion coefficients.

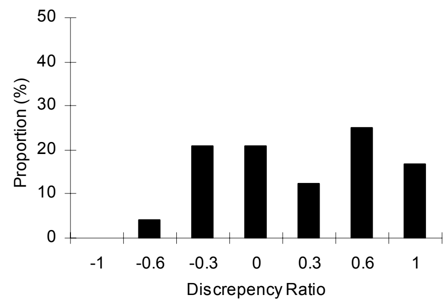

Figure 16. Frequency plot of discrepancy ratios for dispersion values on the Truckee River using the equation from Seo and Cheong (1998)

7.2. Model performance and uncertainty

There are several uncertainties in the modeling process that have the potential to influence the modeled output. In estimating the main channel cross sectional area and the theoretical dispersion coefficient, the spreadsheet geometry model played a large part in impacting downstream transport. As previously discussed, the advective portion of the river and implicitly, the main channel area has an influential role on downstream transport. Although main channel cross-sections were measured at 15 Truckee River locations over 90 km, most of the cross-sections were unknown. The geometry model used one measured cross-section to characterize the geometry for a river segment that is several kilometers long. On a river, certain hydogeometric parameters such as the slope and sinuosity are relatively constant, whereas parameters like the width, depth, and roughness tend to be variable with flow (Jobson, 2001). As a result, changes in channel geometry could change the estimated cross-sectional area and in turn the time of arrival. In order to estimate the fastest downstream transport, it is best for the main channel area to be underestimated for a particular flow. A smaller area would result in travel times that are quicker than what would be observed, providing TMWA with the conservative estimate.

Also linked with the geometry model, as well as being influential to simulated travel times, is the dispersion parameter. Jobson (1996) questions the appropriateness of certain simulation models as well as the application of theoretical estimates of dispersion due to their inability to adequately model the longitudinal mixing processes. Beyond the calibrated dispersion coefficients, several theoretically based longitudinal dispersion equations were investigated to be used in model simulation under flows that did not have tracer data. It was concluded that the equation from Seo and Cheong (1998) was most appropriate. Although the dispersion equation of Seo and Cheong (1998) performed best with the Truckee River tracer data, Wallis and Manson (2003) concluded that Seo and Cheong (1998) had a tendency to overestimate dispersion values. This was observed with the Truckee River dispersion values in figure 18. For the purposes of this project, overestimation of the dispersion coefficient was preferred to underestimation, since an overestimated coefficient provides the conservative choice in the Truckee River spill model in terms of arrival time. Although the equation from Deng et al. (2002) is capable of producing dispersion coefficients that matched better with observed, data were not available to apply that approach. To account for uncertainty in the dispersion coefficient we applied dispersion coefficients that were a factor of four greater and less than that estimated by the Seo and Cheong (1998) equation. This ensured that we would get a conservative estimate of dispersion for arrival, as well as peak concentration.

Uncertainty in streamflow scenarios also had the potential to alter simulated travel times. Streamflows on the Truckee River vary daily as a result of reservoir operations and run of the river diversions and the 13 streamflow scenarios do not account for such variability of streamflow on the Truckee River. In order to simulate lateral inflow from a tributary over a 30 m segment, each of the four major tributaries in the spill model has a flow value from which lateral inflow is calculated (see table 5). The variability that these tributaries can exhibit on a daily and seasonal basis is not accounted for in the streamflow simulations, and consequently in the spill model. The OTIS model has been shown to be sensitive to the lateral inflow parameter, and the inability of the spill model to account for different tributary contributions (and lateral inflow as a result) creates the possibility for uncertainty in travel time estiamtes (Scott et al., 2003). McCarthy (2006) developed a spill model for the Yellowstone River that applied linear regression equations to model downstream transport with instantaneous streamflow data from the USGS internet database. The availability of instantaneous streamflow data addresses the issue of uncertainty in the lateral inflow parameter, but instantaneous streamflow data are not available throughout the modeling domain of the Truckee river spill model.

It was also assumed that the rhodamine WT dye tracer was a conservative tracer, although several studies have shown that rhodamine WT dye decays due to photodegredation and adsorbs to sediment and organic matter (Bencala et al., 1983; Tai and Rathburn, 1988). Using the half life of rhodamine WT dye estimated by Tai and Rathburn (1988), less than 10% of the rhodamine WT tracer had the potential to photodecay over the longest duration that a tracer study occurred. Furthermore, sediment samples taken from each of the Truckee River sample locations showed low levels of organic matter. Finally, the flows in the Truckee River are predominantly advective, which help to move the dye downstream, rather than allowing it to linger and adsorb to the riverbed. It was therefore reasonable to assume that rhodamine WT dye was not likely to adsorb to sediment. The only sites that exhibited a considerable loss of mass occurred in the 1999 Upper Reach and the 1999 moderate flow Middle Reach. The loss of mass in the 1999 Upper Reach occurred specifically along the GLE section where surface-groundwater interactions have been previously observed (McKenna, 1990). There is the potential that dyed water left the GLE segment through a losing groundwater situation, effectively removing injected tracer from the Upper Reach. As noted in section 5.2.2, however, the mass balance for each of the tracer injections was calculated, and it showed that the conservative assumption was applicable for all of the injections.

In conclusion, even though there are several uncertainties present in the Truckee River spill model, the estimates of travel time from both of the spill scenarios provide valuable insight into spill potential along the Truckee River. Uncertainties with estimates of dispersion were addressed by simulating additional spill with dispersion values that are a factor of four greater and less than the estimated value. Also, to account for uncertainty in the streamflow scenarios, travel times for FAR streamflow that are one index value above and one index value below the simulated FAR streamflow can be evaluated. In the event of a spill though, TMWA will act in the most prudent manner possible and even the most robust model will only serve as the initial piece of information from which to assist with decision making.

8. RECOMMENDATIONS FOR FURTHER WORK

To address several of the mentioned uncertainties, recommendations for further work are suggested. As is the case in much of science, more data are needed. The Upper Reach does not have high flow tracer study data. Intentions were to sample the Upper Reach under a high flow, but the winter in 2006-2007 did not create streamflows that were on the order of the 2006 tracer studies. Data from a high flow Upper Reach tracer study could be used to better calibrate both the geometry model and the OTIS model. In terms of having the least amount of response time, Upper Reach high flow tracer data would provide information for the worst case scenario.

For a greater undertaking, it is recommended that an additional tracer study take place for the entire model area of the Truckee River at a low flow scenario. A spill occurring during low flow will greatly increase the instream concentration. In addition, the results of this study show that the largest range of uncertainty in arrival time occurs at the lowest flows. Therefore, calibrating the OTIS model to data collected under low flow conditions would make the Truckee River spill model more robust than it is now.

Also, with any subsequent tracer studies more precise streamflow measurements are needed at sample sites as well as at diversions and tributaries. As discussed, streamflow and main channel cross sectional area are the two most influential parameters of the spill model. Several of the 1999 and 2006-07 streamflows were not actually measured; instead they were estimated using surrounding stream gage data. Similarly, none of the diversions were quantified during the two tracer studies. Calibrating to streamflows that are measured during the tracer studies could help to improve the overall calibration.

Also related to data collection, it is recommended that additional cross sections of the Truckee River be measured. The weakest link in the spill model exists in estimating the main channel cross-sectional area, and measuring additional cross sections could help with the calibration of the geometry and the spill model. Additionally, it may be beneficial to develop a hydrodynamic model of the Truckee River to assist with spill simulations. Several studies have linked unsteady hydrodynamic flow models with solute transport models to investigate the transport of hypothetical spills into a river (Wiley, 1993; Nishikawa et al., 1999) In addition to more rigorously estimating the cross sectional area under different flows, a hydrodynamic model has the capability to utilize the approach employed by McCarthy (2006) that would decrease the uncertainty in travel times as a result of real-time lateral inflow estimates.

A comparison of methods is recommended to determine if other methods used to estimate travel time are more applicable than the approach used in this study. Using tracer data that was collected from two flow durations at the same reach, Kilpatrick and Wilson (1989) developed a method for estimating travel times and downstream peak concentrations for spills occurring at flows that do not have tracer data. The velocity of the leading edge, peak concentration, or trailing edge for both durations is calculated from the data and plotted on log-log paper with respect to streamflow. The two points are connected with a line, which is then used to estimate the velocity (and travel time) at additional, unstudied streamflows. Furthermore, a method is derived from the relationship between the time to peak concentration and the unit peak concentration to provide an estimate of possible peak concentration for a given accident (Kilpatrick and Taylor, 1986). In another approach, Jobson (1996) developed equations using tracer data compiled from 90 different rivers that were based on dimensionless relative streamflow and drainage area to estimate the time to peak, time to arrival, and total duration of contaminant for conditions that do not have available tracer data. These methods of estimating travel time on rivers and streams have been applied to various tracer studies and a comparison of such methods with the Truckee River spill model can highlight the strengths and weaknesses associated with each approach. The uncertainties of the spill model might additionally be clarified through the application of such methods.

There are several recommendations for the general application of spill models. First, it is important for resource managers to have an estimated time of arrival for a spilled contaminant, but the trailing edge is also a parameter of concern, since it defines the total amount of time that the contaminant is present. In the event of a spill, water managers need to turn off the pumps from the river as well as reserve sufficient water supplies to be used for the duration that the river is inaccessible. Having a grasp of the total amount of time that a water processing plant could be shut down as a result of a spill can help water authorities prepare accordingly.

Parameters that have the ability to influence time of departure include the main channel cross-sectional area, the dispersion coefficient as well as upstream transient storage and understanding how these parameters affect the time of departure is necessary for such planning purposes. Estimating main channel cross-sectional area can be improved by surveying river cross-sections and incorporating that data into the model, but the estimation of longitudinal dispersion is dependent both on the resulting survey data and the theoretical equation used. Theoretical estimates of longitudinal dispersion have evolved from early stages with an increase in estimation performance, but still are not able to make precise predictions. Deng et al. (2002) developed an equation that accounted for the effects of river sinuosity on dispersion that performed within a factor of two to observed values of dispersion. The performance of the Deng et al. (2002) equation is better than that attained with Seo and Cheong (1998), but the equation of Deng et al. (2002) is comparatively more complicated, utilizing hydraulic parameters that are not easily measured. The further development of longitudinal dispersion equations should continue to investigate the effects of river sinuosity on dispersion, as well as incorporating the effects of transient storage on dispersion.

An additional recommendation that influences spill modeling has to do with the spill simulation. The spills that occur in the Truckee River spill model are simple, step concentration profiles that spill directly into the path of flow. In reality, a spill occurring as a result of a catastrophic transportation accident would inject a contaminant into the stream as well onto the surrounding terrain. Additional complexities such as the infiltration of contaminants through the stream bank and streambed and the leaching of contaminant between the surface and groundwater present processes that are not considered in most spill models. These processes, though quite complicated, impact the mixing routine in the river and ultimately the travel times of a spilled contaminant.

Investigating the impacts that a potential contaminant spill could have on a river's resources is a worthwhile endeavor and requires further research. The resultant spill model, even with its associated uncertainties, is a valuable tool for local water authorities and public health agencies. Further development of the Truckee River spill model could help to quantify (and hopefully, decrease) the uncertainty in travel time for a spill.

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APPENDIX A— Tabulated tracer data and observed and unitized response curves from the two tracer studies are presented in Appendix A. At several of the sites, the first sample was collected after the dye tracer had arrived or the last sample was collected before the concentrations reached background levels. Estimates of missed observations at Vista (VIS) 2006 are not feasible due to the amount of missing data.

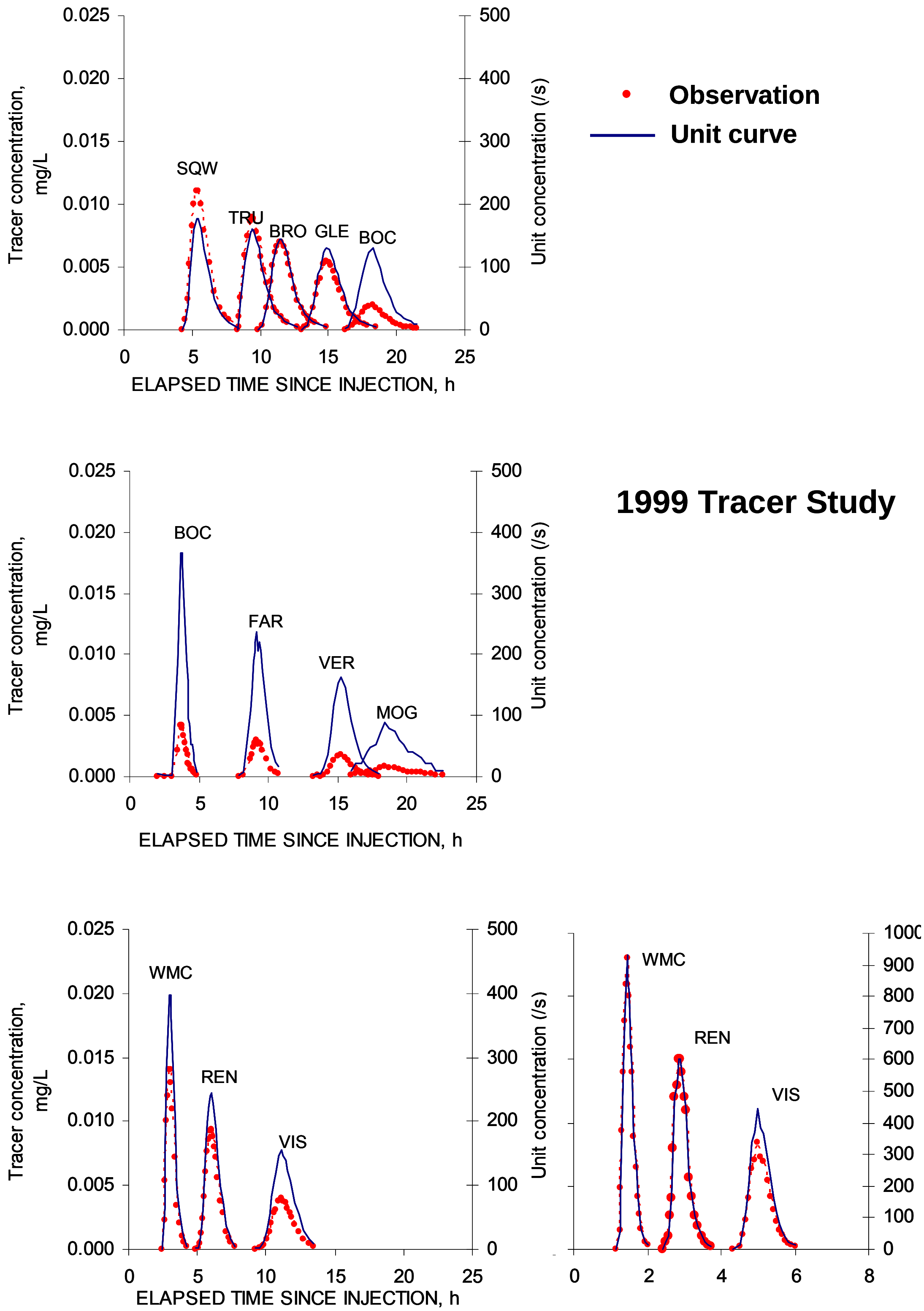

Figure 17. Response curves and unitized response curves for the 1999 tracer studies

Table 7. Tracer data, unit values, and observed streamflow for the 1999 Upper Reach tracer study

1999 Upper Reach														
SQW			TRU			BRO			GLE			BOC		
Q =	8.014	cms	Q =	8.099	cms	Q =	9.061	cms	Q =	9.797629	cms	Q =	16.1406	cms
Time of day	Concer ug/L	C_unit /s	Time of day	Concer ug/L	C_unit /s	Time of day	Concer ug/L	C_unit /s	Time of day	Concentrat ug/L	C_unit /s	Time of day	Concentrat ug/L	C_unit /s
2315	0.03	0	318	0	0	450	0.03	1	759	0.02	0	1115	0.03	2
2330	0.79	13	325	1	18	510	0.38	8	812	0.19	5	1130	0.08	5
2340	2.5	40	335	2.6	47	530	1.8	37	826	0.32	8	1145	0.4	26
2350	5.2	84	355	5.9	106	545	3.8	78	837	0.77	18	1200	0.54	35
2400	8.3	134	405	7.4	134	555	5.1	104	851	1.7	40	1215	0.95	61
10	10	161	417	8.6	155	605	6.2	127	905	2.8	67	1230	1.4	90
20	11	177	421	8.8	159	615	6.6	135	910	3.7	88	1245	1.7	110
30	11	177	427	8.9	161	625	7	143	925	4.1	97	1300	1.9	123
40	10	161	432	8.8	159	635	7	143	935	5.2	124	1315	2	129
55	7.9	127	442	7.8	141	645	6.6	135	943	5.4	128	1330	1.8	116
115	5.4	87	453	7.2	130	655	6	123	953	5.5	131	1345	1.5	97
140	3	48	505	5.8	105	705	5.2	106	1002	5.4	128	1400	1.2	78
200	1.8	29	515	4.8	87	715	4.3	88	1012	5.1	121	1415	0.99	64
221	1.2	19	530	3.7	67	730	3.2	65	1021	4.6	109	1430	0.78	50
241	0.76	12	545	2.6	47	745	2.3	47	1031	4.1	97	1445	0.59	38
324	0.2	3	600	1.7	31	800	1.8	37	1041	3.7	88	1500	0.44	28
			615	1.4	25	815	1.3	27	1051	3.1	74	1515	0.35	23
			630	1.1	20	830	1	20	1106	2.4	57	1530	0.27	17
			646	0.74	13	845	0.73	15	1121	1.7	40	1545	0.24	16
			700	0.6	11	900	0.58	12	1136	1.3	31	1600	0.2	13
			742	0.2	4	948	0.2	4	1151	1	24	1615	0.16	10
									1206	0.78	19	1630	0.14	9
									1221	0.58	14			
									1236	0.5	12			
									1251	0.39	9			
									1330	0.2	5			

Table 8. Tracer data, unit values, and observed streamflow for the 1999 Middle Reach tracer study

1999 Middle Reach										
GLE			FAR			VER			MOG	
Q=	17.75 cms		Q=	17.75 cms		Q=	4.899 cms		Q=	14.30001
Time of day	Concer ug/L	C_unit /s	Time of day	Concer ug/L	C_unit /s	Time of day	Concer ug/L	C_unit /s	Time of day	Concentrat ug/L
100	0.05	4	650	0.03	2	1215	0.03	3	1500	0.10
130	0.02	2	714	0.10	8	1230	0.06	5	1520	0.20
200	0.04	3	744	1.40	110	1245	0.05	5	1540	0.21
230	2.2	192	750	1.80	142	1300	0.15	14	1605	0.40
240	4.2	366	755	2.40	189	1315	0.40	36	1621	0.45
248	4.2	366	800	2.60	205	1330	0.80	72	1643	0.50
250	4	348	805	2.80	221	1345	1.30	118	1701	0.70
255	3.4	296	810	3.00	237	1400	1.70	154	1722	0.85
300	2.8	244	815	2.60	205	1415	1.80	163	1742	0.75
305	2.2	192	821	2.80	221	1430	1.60	145	1804	0.72
310	1.8	157	827	2.60	205	1445	1.30	118	1824	0.58
315	1.1	96	835	2.20	174	1500	1.00	90	1845	0.50
320	1	87	850	1.40	110	1515	0.70	63	1904	0.40
325	0.6	52	913	0.60	47	1530	0.50	45	1922	0.40
330	0.6	52	933	0.30	24	1545	0.35	32	1942	0.35
335	0.4	35	940	0.20	16	1600	0.20	18	2003	0.31
340	0.3	26				1615	0.15	14	2022	0.20
345	0.2	17				1630	0.10	9	2043	0.20
350	0.09	8				1645	0.08	7	2104	0.10
						1700	0.05	5	2133	0.10

Table 9. Tracer data, unit values, and observed streamflow for the 1999 Lower Reach moderate flow tracer study

1999 Lower Reach moderate flow								
WMC			RNO			VIS		
Q =	12.23 cms		Q =	11.81 cms		Q =	13.88 cms	
Time of day	Concer ug/L	C_unit /s	Time of day	Concer ug/L	C_unit /s	Time of day	Concer ug/L	C_unit /s
1040	0.02	1	1307	0.05	1	1728	0.04	2
1052	2.3	65	1317	0.07	2	1745	0.06	2
1057	5.4	153	1327	0.50	13	1800	0.23	9
1102	10	284	1332	1.20	31	1809	0.38	15
1107	12	341	1339	2.40	63	1820	0.78	30
1112	14	397	1346	4.10	107	1830	1.40	54
1117	14	397	1352	6.10	159	1840	2.10	81
1122	13	369	1359	7.60	198	1850	2.80	108
1127	11	312	1405	8.60	224	1900	3.10	120
1137	7.2	204	1410	9.20	240	1910	3.80	147
1147	3.4	96	1415	9.40	245	1920	4.00	155
1157	2	57	1420	9.30	242	1930	3.80	147
1207	1	28	1425	8.80	229	1942	3.60	139
1217	0.62	18	1430	8.00	208	1950	3.20	124
1227	0.2	6	1435	7.20	188	2000	2.80	108
			1445	5.60	146	2010	2.50	97
			1456	4	99.03	2020	1.90	73
			1506	3	72.97	2041	1.40	54
			1521	1	36.49	2100	0.78	30
			1532	1	24.50	2120	0.44	17
			1542	0.62	16	2140	0.25	10
			1557	0.2	5.212			

Table 10. Tracer data, unit values, and observed streamflow for the 1999 Lower Reach high flow tracer study

1999 Lower Reach hi flow								
GLE			FAR			VER		
Q =	65.13	cms	Q =	60.31	cms	Q =	66.54	cms
Time of day	Concer ug/L	C_unit /s	Time of day	Concer ug/L	C_unit /s	Time of day	Concer ug/L	C_unit /s
1010	0.03	1	1124	0	0	1320	0.04	2
1015	1.5	61	1130	0.62	25	1330	0.28	15
1017	4.9	199	1135	1	40	1335	1.2	63
1019	9.4	381	1137	2.7	108	1340	2.3	121
1021	14	568	1139	4.1	165	1345	4	210
1023	18	730	1142	8	321	1350	6.4	336
1025	21	852	1145	12	482	1355	7.1	373
1027	23	933	1148	13	522	1400	8.5	446
1029	21	852	1151	15	602	1405	7.3	383
1031	20	811	1154	15	602	1410	7	367
1033	16	649	1157	14	562	1415	5.4	283
1035	14	568	1200	12	482	1420	4.2	220
1038	8.9	361	1203	11	441	1425	3.1	163
1041	6.5	264	1208	5.7	229	1430	2.2	115
1044	4.2	170	1213	4.2	169	1435	1.5	79
1047	2.8	114	1218	2.7	108	1440	1.1	58
1050	1.6	65	1223	1.8	72	1445	0.7	37
1057	0.6	24	1228	1	40	1450	0.48	25
1100	0.35	14	1233	0.58	23	1455	0.35	18
			1238	0.38	15	1500	0.23	12
			1243	0.23	9			

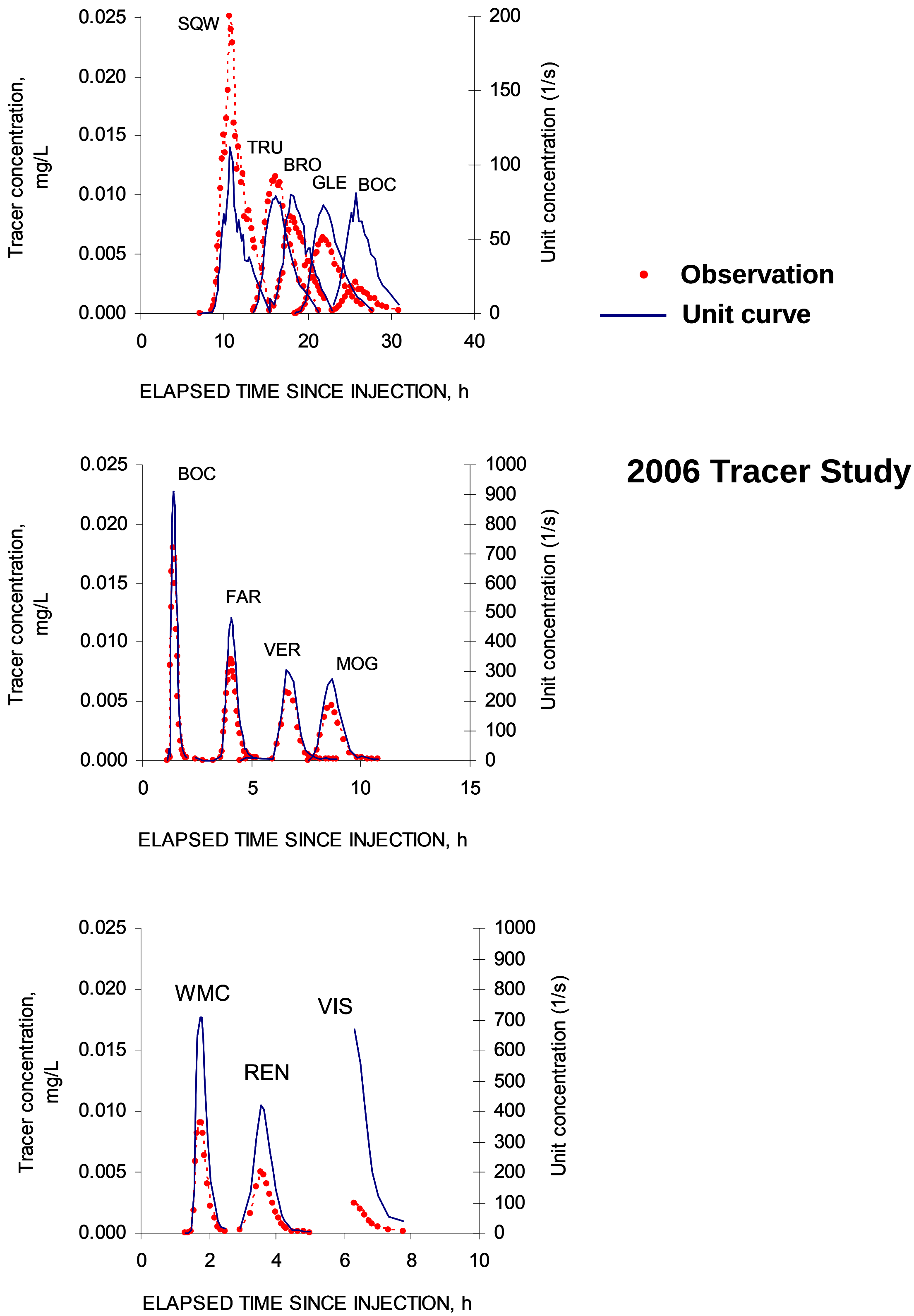

Figure 18. Response curves and unitized response curves for the 2006/2007 tracer studies

Table 11. Tracer data, unit values, and observed streamflow for the 2007 Upper Reach tracer study

2006 Upper Reach														
SQW			TRU			BRO			GLE			BOC		
Q =	4.049	cms	Q =	5.493	cms	Q =	7.532	cms	Q =	7.560598	cms	Q =	18.03783	cms
Time of day	Concer ug/L	C_unit /s	Time of day	Concer ug/L	C_unit /s	Time of day	Concer ug/L	C_unit /s	Time of day	Concentrat mg/L	C_unit /s	Time of day	Concentrat ug/L	C_unit /s
0532	0	0	1205	0.2	1	1355	0.2	2	1655	0	0	2140	0.2	6
0658	0.2	1	1215	0.5	3	1400	1	10	1710	0.05	1	2200	0.4	12
0710	0.6	3	1230	1.2	8	1430	0.6	6	1725	0.1	1	2220	0.6	19
0720	1.1	5	1245	2.3	16	1448	1.4	14	1740	0.2	2	2240	1	31
0730	2.6	12	1300	3.8	26	1500	2.1	21	1755	0.4	5	2300	1.4	43
0740	3.6	16	1315	6	41	1515	2.8	28	1810	0.7	8	2320	1.8	56
0750	5.6	25	1330	7.6	52	1530	3.4	34	1825	1.2	14	2340	2.2	68
0800	6.6	30	1345	9.4	64	1545	5.6	55	1840	1.8	20	2400	2	62
0810	10.5	47	1400	10	69	1600	6.4	63	1855	3	34	0020	2.6	81
0820	13	58	1415	11.2	77	1615	7	69	1910	3.8	43	0040	2	62
0830	15	67	1430	11.2	77	1630	8.1	80	1925	5	57	0100	2	62
0840	13.5	60	1445	11.5	79	1645	8	79	1940	5.2	59	0120	1.7	53
0850	16.5	74	1500	10.8	74	1700	7.6	75	1955	5.8	66	0140	1.6	50
0900	18.8	84	1515	11	75	1715	7.2	71	2010	6.2	70	0200	1.3	40
0910	25.1	112	1530	9	62	1730	6.8	67	2025	6.4	73	0230	1.2	37
0920	24	107	1600	7.6	52	1745	6.4	63	2040	6.2	70	0300	0.8	25
0930	22.8	102	1630	5.8	40	1800	6	59	2105	5.8	66	0330	0.6	19
0940	16.1	72	1700	4.2	29	1815	4	40	2125	5.2	59	0400	0.5	16
0950	14.9	67	1730	2.7	19	1830	4.4	44	2150	4.2	48	0530	0.2	6
1000	12.2	55	1800	2.3	16	1845	4.4	44	2215	3.6	41			
1015	14	63	1830	1.7	12	1900	3.6	36	2240	3.2	36			
1030	11	49	1950	0.2	1	1915	3	30	2305	2.3	26			
1045	11.8	53				1930	2.6	26	2335	1.8	20			
1100	8.1	36				1945	2.3	23	2400	1.4	16			
1115	7.9	35				2000	1.9	19	0025	1	11			
1130	8.6	38				2015	1.6	16	0055	0.8	9			
1145	7.2	32				2030	1.3	13	0210	0.2	2			
1200	6.2	28				2130	0.2	2						
1215	5.5	25												
1400	0.2	1												

Table 12. Tracer data, unit values, and observed streamflow for the 2006 Middle Reach tracer study

2006 Middle Reach										
GLE			FAR			VER			MOG	
Q=	64	cms	Q=	75.32	cms	Q=	65.13	cms	Q=	61.73073
Time of day	Concer ug/L	C_unit /s	Time of day	Concer ug/L	C_unit /s	Time of day	Concer ug/L	C_unit /s	Time of day	Concentrat ug/L
0715	0	0	0830	0.15	8	1035	0.02	1	1340	0
0719	0.8	40	0850	0.04	2	1051	0.18	10	1355	0.3
0721	0.28	14	0920	0.02	1	1202	0.12	6	1405	0.9
0723	8	405	0940	0.24	13	1217	1.4	74	1415	2.1
0725	13	658	0945	0.74	41	1226	3	159	1425	3.6
0727	16	809	0950	2.4	134	1238	5.8	308	1435	4.4
0729	18	911	095230	3.4	190	1248	5.6	298	1445	4.7
0731	18	911	0955	4.2	235	1259	5	266	1453	4
0733	17	860	095730	5.6	313	1311	2.8	149	1503	3.1
0735	15	759	1000	6.8	381	1322	1.6	85	1518	1.8
0738	11	556	100230	7.4	414	1334	0.64	34	1537	0.6
0741	8.8	445	1005	8.2	459	1343	0.44	23	1554	0.2
0744	5.4	273	100730	8.4	470	1353	0.26	14	1609	0.24
0748	3	152	1010	8.6	481	1403	0.2	11	1624	0.16
0752	1.6	81	101230	8.2	459	1415	0.12	6	1638	0.12
0756	0.82	41	1015	7.6	425	1428	0.16	9	1653	0.1
0800	0.5	25	101730	7	392	1438	0.1	5		
0805	0.28	14	1020	5.8	325	1449	0.1	5		
0808	0.2	10	1025	4.2	235	1459	0.08	4		
			1030	3	168					
			1035	2.2	123					
			1040	1.4	78					
			1045	0.74	41.41					
			1050	0.74	41.41					
			1055	0.44	24.62					
			1100	0.32	17.91					
			1110	0.2	11.19					
			1120	0.22	12.31					

Table 13. Tracer data, unit values, and observed streamflow for the 2007 Lower Reach tracer study

2006 Lower Reach								
GLE			FAR			VER		
Q =	38.23	cms	Q =	35.68	cms	Q =	43.61	cms
Time of day	Concer ug/L	C_unit /s	Time of day	Concer ug/L	C_unit /s	Time of day	Concer ug/L	C_unit /s
0820	0.02	2	958	0.2	17	1320	2.4	667
0825	0.01	1	1015	1.6	134	1330	2	556
0830	0.1	8	1025	3.8	319	1338	1.5	417
0835	1.8	142	1035	5	420	1346	1	278
0839	5.8	456	1040	4.8	403	1352	0.72	200
0842	8.2	645	1045	4	336	1402	0.44	122
0845	9	708	1050	3.2	269	1420	0.2	56
0848	9	708	1055	2.5	210	1447	0.14	39
0851	8.2	645	1100	1.7	143			
0855	6.4	503	1105	1.2	101			
0900	4	315	1110	0.68	57			
0906	2.2	173	1115	0.48	40			
0912	1.2	94	1120	0.42	35			
0918	0.52	41	1130	0.14	12			
0924	0.26	20	1140	0.1	8			
0930	0.18	14	1150	0.08	7			
			1200	0.06	5			

APPENDIX B—Streamflow summary for 1999 and 2006 tracer studies. Streamflow data are from Crompton and Bohman (2000) and Crompton (2008). In the event that measurements were not made during the dye studies, data from nearby gaging stations and diverted flows provided by the Federal Water Master were used to estimate the flow within the reach. The daily mean flows for several of the larger tributaries were obtained from the USGS database and used in the calibration.

Table 14. Streamflows used in OTIS-P model calibration

			Flow (m^3/sec)					
			2006			1999		
Number	Site	Distance from Tahoe city dam (km)	and Bohman flow(2000)	USGS database	Federal water master	and Bohman flow(2000)	USGS database	Federal water master
1	THC	0.03	1.9			7.6		
2	SQW	9.9	4.0			8.0		
3	TRU	20	5.5			8.1		
	Donner Creek	23		2.4			0.9	
4	BRO	25	7.5			9.1		
5	GLE	32	7.6			9.8		
	Prosser Creek	36		0.9			3.4	
	Little Truckee River	39		10.3			3.8	
6	BOC	40	18.0			16.1		
7	FAR	55		20.9			17.7	
5	GLE inj	32	60.3			11.2		
	Prosser Creek	36		5.2			3.4	
	Little Truckee River	39		3.2			3.2	
6	BOC	40	64.0			17.8		
7	FAR	55	75.3			17.8		
	Steamboat ditch	62			-1.0			-2
	Verdi diversion	65			-11.3			-11
	VER	69	60.9			4.9		
	Verdi return	70			11.3			11
	Highland Chalk Bluff	73			-13.7			-2
	Washoe return	76			11.4			0
8	MOG	77	61.7			61.7		14
9	WMC	84	61.0					
8	MOG inj	77	39.4			15.4		
9	WMC	84	38.2			12.2		
10	REN	92	35.7			11.8		
	Glendale TMWA diversion	93						
	VIS	103	43.6			13.9		

APPENDIX C—Sample conversion of a volume of dye injected to a concentration injected

To convert a volume of dye injected to a concentration, the mass of dye is derived from the volume injected, which is then divided by the volumetric flow rate, then divided by the integration time step (0.001 hr). The mass of dye injected is calculated by multiplying the volume of dye solution injected by 0.20 (20% dye solution) and then by 1.25, the specific gravity of RWT. A sample calculation is provided below for the injection volume at Tahoe City in 1999. The same calculations are performed on the other 5 injection sites.

Volume of 20% rhodamine dye injected at Tahoe City, 1999: 2.55 L

Reported discharge: 7.56 m^3/sec = 7560 L/sec

Mass of dye = 2.55L * 1000mL/L * 0.20g dye/mL solution* 1000mg/g *1.25 = 637500mg

Injected concentration for 3.6sec: [(637500mg) / (7560L/sec)] / 3.6sec = 23.42mg/L

APPENDIX D—Further explanation of OTIS model setup of input files

Params.inp

Within the parameter file, the time step record type defines the integration time step (Δt) that is used in the Crank-Nicolson algorithm to estimate the time derivative, $dC/dt = (C_i^{j+1} - C_i^j)/ \Delta t$. The Crank-Nicolson method is unconditionally stable, which means that the solution will not fluctuate as the time step is increased (Runkel, 1998).

River reach lengths and print locations are defined in the parameter file. The parameter input file also contains three of the model parameters for each reach: the dispersion coefficient (D), cross-sectional area of the storage zone (A_s), and storage zone exchange coefficient (α). These are the values that are adjusted in the calibration process as a means of matching observed tracer data. Finally, upstream boundary conditions are included at the end of the params.inp file.

q.inp

The flow file contains the flow rate at the upstream boundary, the reach specific values of lateral flow (i.e. diversions, tributaries, groundwater interaction), as well as the main channel cross-sectional area (A). In OTIS, lateral flow (QLATIN and QLATOUT) is a reach averaged value, with units of [L^3/T-L]. That is, the change in flow is constant over the length of that change and so, two types of lateral flow were considered; lateral flow from tributaries and diversions, which occur over short distances and lateral flow such as ground water losses, which occur over longer distances. For example, for a tributary that contributes 3m^3/sec the lateral inflow value for that reach is divided by one segment length, where as a 3m^3/sec inflow from groundwater is averaged over an entire reach (in some cases, over 100 segments). This method is employed because tributaries and diversions require a proportional impact to the mixing process

Execution

With the three input files properly setup, the OTIS model is executed and, if successful, two output files are created: echo.out and solute.out. The echo file is a record of the values that were read from the three input files. If there is an error, it is recorded in the echo file. The solute.out file has the simulated time series of main channel and storage zone concentrations.

APPENDIX E—Travel time curves for semi-truck spill

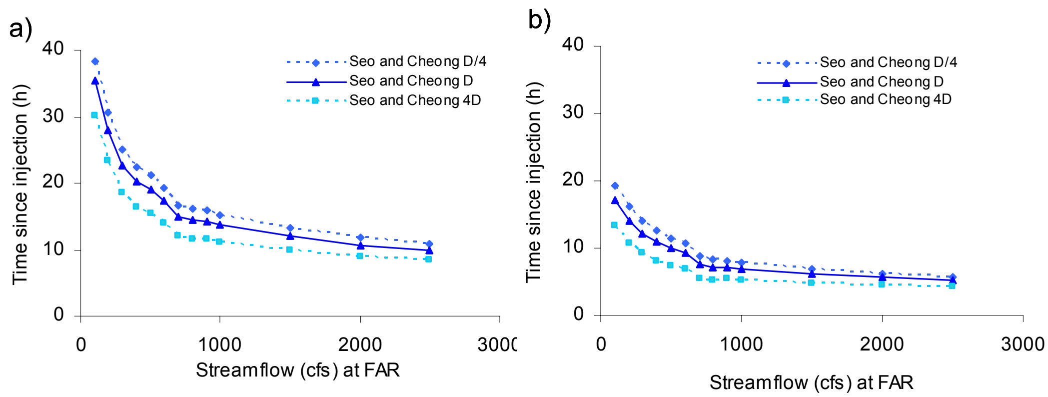

Figure 19. Simulated arrival times after spill to Highland Ditch with respect to streamflow at FAR for semi-truck spill occurring at a) TRU and b) BOC

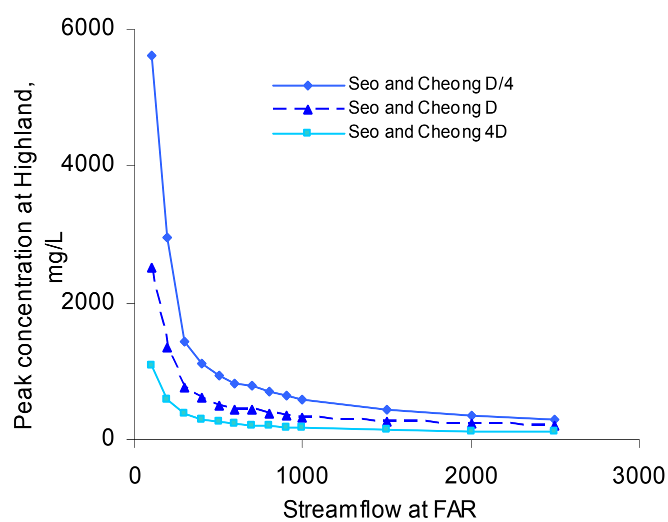

Figure 20. Change in simulated peak concentration simulated at Highland diversion with respect to streamflow for a semi-truck spill occurring at TRU

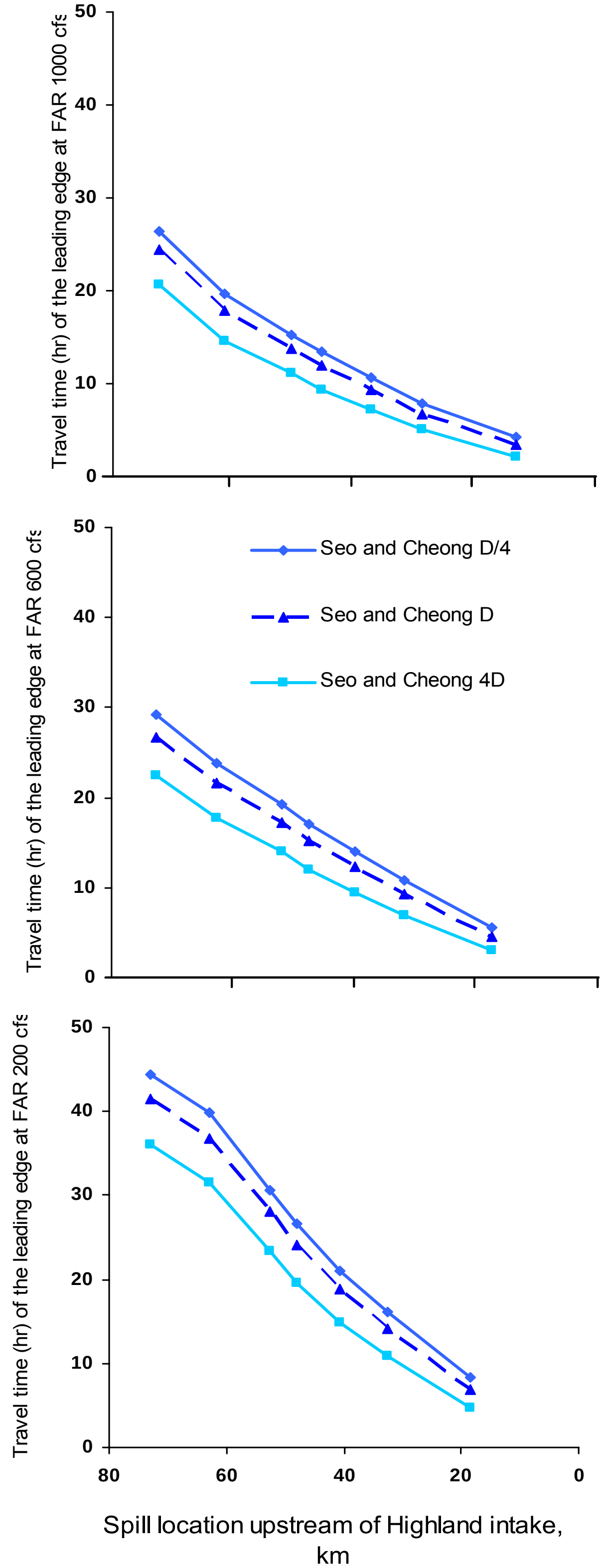

Figure 21. Change in travel time with respect to spill location for three flow scenarios for a semi-truck spill