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EVALUATING THE IMPACTS OF UNCERTAINTY IN GEOMORPHIC CHANNEL- CHANGES ON PREDICTING MERCURY TRANSPORT AND FATE IN THE CARSON RIVER SYSTEM, NEVADA

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ABSTRACT

The Carson River is one of the most mercury-contaminated fluvial systems in North America. Most of its mercury is affiliated with channel bank material and floodplain deposits, with the movement of mercury through this system being highly dependent on bank erosion and sediment transport processes. Mercury transport is simulated using three computer models: RIVMOD, WASP5, and MERC4. Model improvements include the addition of a bank package that accounts for flow history. The rates at which river stages are rising or falling will, in turn, impart time-dependant and vertically variable MeHg concentrations within the channel banks along the Carson River. Also, Lahontan Reservoir's geomorphic characteristics have been refined along with the explicit tracking of a temporally and spatially varying colloidal fraction. The augmented and refined modeling approach results in more accurate and realistic simulation of mercury transport and fate. An extensive uncertainty analysis, involving characterizing the co-variance of two calibration parameters used to define bank erosion and overbank deposition, will define the degree of expected variation in model predictions relative to limitations posed by available field data.

Keywords: Monte Carlo, mercury modeling, Carson River, Lahontan Reservoir

1. INTRODUCTION

The United States Environmental Protection Agency (US EPA) designated the Carson River as part of a Superfund site in 1991 due to contamination by mercury. It is estimated that approximately 6.36 x 10^6 kg (7,000 tons) of residual mercury is now distributed throughout the river's bank sediments and floodplain deposits (Miller et al, 1998; Smith and Tingley, 1998). It has also been found that more than 95% of the mercury transported

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in the Carson River is affiliated with particulate matter (Bonzongo et al., 1996). During January 1997 a rare, high magnitude flood generated significant geomorphic change and resulted in an estimated 1.81×10^8 kg (200,000 tons) of sediment and 1,360 kg (3,000 lbs.) of mercury to be transported downstream into Lahontan Reservoir (Hoffman and Taylor, 1998). These quantities far exceed the amount of sediment and mercury transported in the decade prior to the flood. Consequently, any useful model of mercury transport in the Carson River system requires an accurate simulation of bank erosion and floodplain sedimentation mechanisms during extreme flood events. The January 1997 flood is the largest recorded event on the Carson River (1911 to present) and provides a unique opportunity to assess sediment cycling and mercury transport as a result of a rare-magnitude event. Modeling procedures use data collected by Miller et al. (1999) on channel widening and overbank deposition as a result of the 1997 flood as well as mercury data collected by the University of Nevada, Reno (UNR) and the United States Geological Survey (USGS) before, during and after the flood.

2. SITE DESCRIPTION

The Carson River flows eastward out of the Sierra Nevada Mountains just to the south of the Lake Tahoe Basin. Figure 1 shows a map of the Carson River with several reference locations marked. The section of the Carson River under investigation extends from the USGS gaging station near Carson City, Nevada (CCG, point 0 in Figure 1 detail) downstream through Lahontan Reservoir. The river's delta is located approximately 80 km from CCG and is located approximately 10 km below the Fort Churchill gaging station (FCH). Miller et al. (1999) conducted an extensive survey of the Carson River in the early spring following the 1997 flood. Both bank erosion and overbank deposition were evaluated using geomorphic techniques of aerial photography (taken in 1991 and 1997) and floodplain mapping. Data were discretized into ten river reaches (refer to Figure 1) defined by valley slope and floodplain width. For a complete discussion on techniques and results of the geomorphic survey read Miller et al. (1999).

Flow in the Carson River is typical of most semi-arid fluvial systems in that it is highly variable. Flow is predominately from snowmelt in the Sierra Nevada with peak discharge generally occurring in the spring with a sustained moderately high hydrograph. Catastrophic floods, such as the January 1997 flood, however, are generated with rain-on-snow events that can occur during the winter months. Peak mean daily discharge during the 1997 flood was estimated at 630 m^3/s. For comparison, the designated 100-year event occurred in 1986 with a peak discharge of 470 m^3/s. In contrast, the summer and fall months are dominated by low flows and these flows can cease all together during extended periods of drought.

International Journal of Soil, Sediment and Water, vol 1, no 1, 2008

3. MODELING PROCEDURES

3.1 Model Description

Three computer models (RIVMOD, WASP5 and MERC4) were used to simulate the transport of sediment and mercury in the Carson River. RIVMOD (Hosseinipour and Martin, 1990) is a U.S. EPA 1-dimensional hydrodynamic and sediment transport routine that simultaneously solves standard fluid equations of continuity and momentum. Finite difference equations are solved by the Newton-Raphson method to determine fluid velocity and depth given unsteady flow conditions. WASP5 (Ambrose et al., 1991) is the U.S. EPA

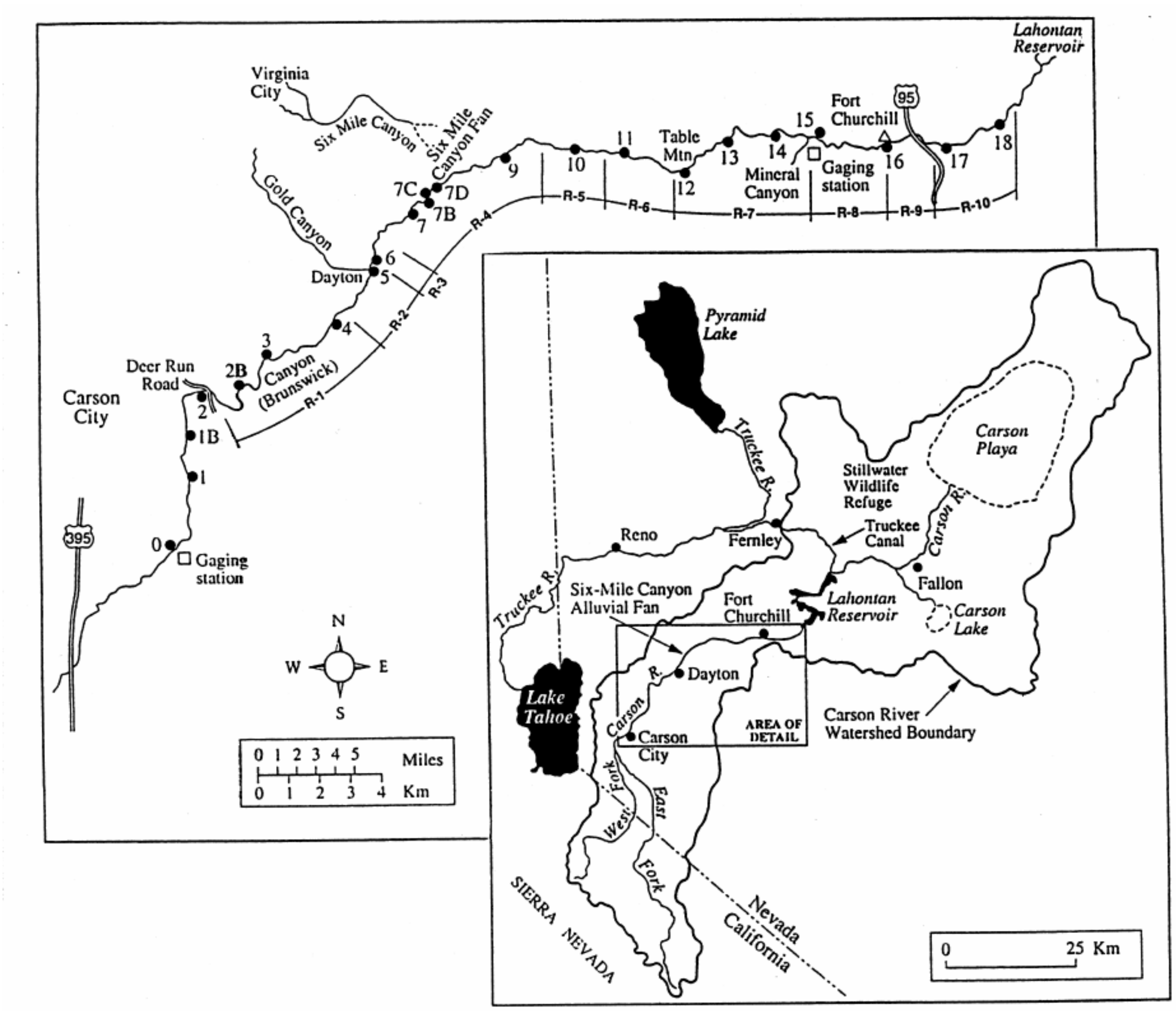


Figure 1. The Carson River – Lahontan Reservoir system with the detail showing the ten river reaches used by Miller *et al*. (1999) for geomorphic analysis.

Water Quality Analysis Simulation Program-5 that was developed to simulate the transport and transformation of various water body constituents. Mass balance equations account for all material entering and leaving model segments through direct and diffuse loading, advective and dispersive transport, and any physical or chemical transformation. MERC4 (Martin, 1992) is a subroutine contained within WASP5. It was developed to specifically compute mercury speciation and kinetic transformation. MERC4 is capable of simulating up to four mercury species and three distinct solid types. Five state variables are modeled in this study: inorganic mercury (Hg^{2+}), methylmercury (MeHg), washload, coarse suspended sediment (CSS) and bedload. Elemental mercury (Hg0), while very toxic, is highly volatile with only very low concentrations detected in the surface waters of the Carson River (Bonzongo et al., 1996) and so was excluded from analysis.

Washload constitutes the smallest fraction (diameter< 0.063 mm) and is considered uniformly distributed from the riverbed to the water surface. Concentrations of CSS (diameter> 0.063 mm) are greatest near the riverbed and diminish upward toward the water surface. This is a direct reflection of the exchange of bed material into suspension and visa-versa (Meade, 1990). Bedload is the third type of solid modeled. It is defined as coarse material that travels by rolling, skipping and/or sliding along the riverbed. In addition to these three sediment fractions, the colloidal material (diameter less than 0.002 mm) was assumed to occupy a fraction of the washload. Colloids represent fine material that will not settle despite a decrease in stream velocities either on the river's floodplain or within the reservoir. The colloidal upstream boundary condition at the CCG was set to 11% of the total washload based on site data. The modeled fraction of colloidal material was then allowed to vary downstream such that when washload was deposited the fraction of colloids increased. The colloidal fraction increases to 100% of the fine material following sedimentation in the reservoir's delta region.

RIVMOD, WASP5 and MERC4 were originally chosen, linked and modified by Warwick and Heim (1995) and Heim and Warwick (1997) with further modification by Carroll et al. (2000) and Carroll et al. (2004). It is acknowledged an updated WASP7 and mercury module exist, however dynamic linking of WASP5 with RIVMOD as well as extensive code modifications to WASP5 done by previous studies prohibit its use. An attempt has been made to briefly summarize modeling procedures, however one is encouraged to refer to these previous studies for a complete discussion on model development.

The Carson River - Lahontan Reservoir model contains 307 water column segments starting at the CCG and ending at Lahontan Dam. The river is defined as segments 1 through 203 with segment spacing equal to 0.5 km. Reservoir segments (204 to 307) encompass the entire reservoir during peak capacity and are discretized smaller (0.25 km) to improve numeric stability during summer and fall drawdowns. All water column segments contain a corresponding bed segment for sediment and mercury exchange, but only river segments contain a representative bank element (described in the section Methylation in Bank Segments) for a total of 817 modeled segments. Carroll et al. (2004) modeled daily flows from 1991 to 1997 to simulate estimated erosion by Miller et al. (1999). Carroll et al. (2004) found no significant geomorphic change occurred during the drought years of 1991, 1992 and 1993. Therefore, this study will only focus only on daily

International Journal of Soil, Sediment and Water, vol 1, no 1, 2008

flows beginning October 1, 1993 and extend through the 1998 water year to include University of Nevada, Reno (UNR) and USGS data collected near FCH in the model's analysis (refer to Figure 2).

3.2 Previous Modifications to RIVMOD

Early alterations to RIVMOD include a revision of the simple rectangular channel geometry to a more complex shape (Warwick and Heim, 1995). Past research along the Carson River considered cross sectional geometry spatially variable but temporally fixed (Carroll *et al.,* 2000). Subsequent modifications allowed dynamic width adjustment in which the modeled mass eroded was used to update channel width every timestep by assuming the entire vertical face of the bank was susceptible to erosion (Carroll *et al.,* 2004). The divided channel approach was also applied to the momentum equation contained within the RIVMOD numeric code to estimate floodplain depths and velocities during overbank flows (Carroll *et al.,* 2004).

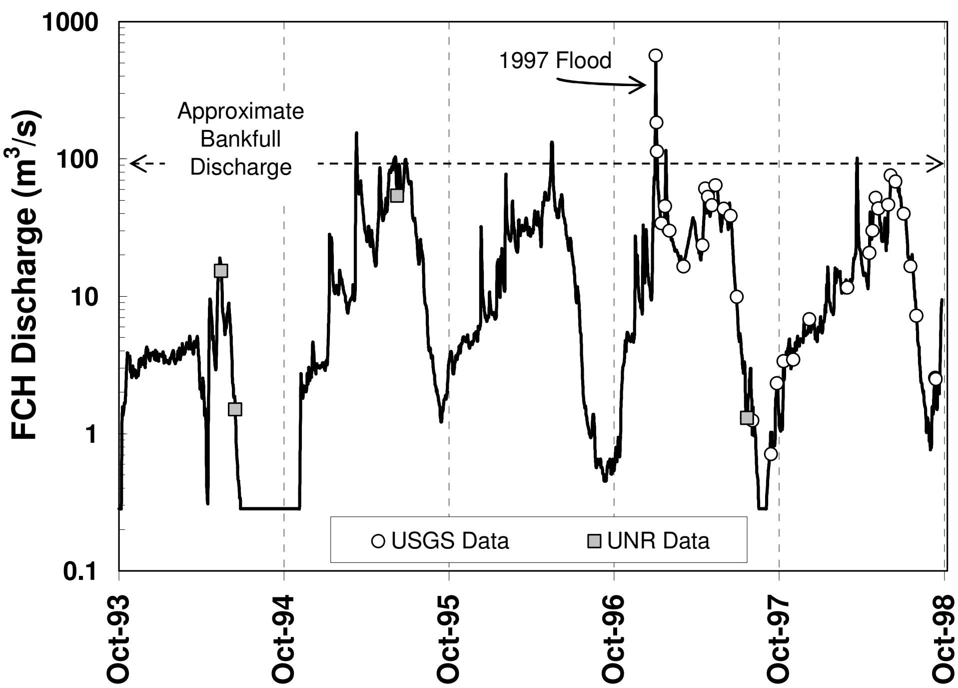


Figure 2. Modeled discharge at the Fort Churchill gage, with water column sampling dates marked. (UNR = collected by the University of Nevada, Reno; USGS = collected by the United States Geological Survey).

3.3 Modeling Bank Erosion and Overbank Deposition

Carroll *et al.*, (2004) developed an empirical relationship in WASP to describe bank erosion during in-channel flows as well as during over-bank flows. These relationships assume the rate of erosion is proportional to the shear stress applied to the bank (Darby and Thorne, 1996) and is indirectly related the average velocity, or square-root of the channel bottom slope. Using Manning's wide channel relationship Carroll et al. (2004) developed the following relationship for bank erosion,

$$MER = \frac{\psi_1 \rho_s \gamma_w n^2 D^{2/3} v^2 L_s}{S_0^{1/2}} + \frac{\psi_2 \rho_s \gamma_w n^2 (D-h) v^2 L_s}{h^{1/3} S_0^{1/2}} \quad (1)$$

Where *MER* is the total bank mass eroded (kg) γ_w is the specific weight of water ($kg/m^2/s^2$), *h* is the height of the vertical bank face along the river's edge (*m*), *D* is the water depth starting at the vertical face of the channel bank (*m*), S_f is the friction slope, *v* is the water velocity (*m/s*), *n* is Manning's coefficient, L_S is the segment length (*m*), and ψ_1 and ψ_2 are constants of proportionality ($m^2\ s/kg$). The first term on the right-hand-side of equation 1 was used to model mass eroded from the banks when river discharge was below bank-full, while both terms on the right-hand-side of equation 1 were used to model mass eroded during over-bank discharge. Carroll et al. (2004) calibrated ψ_1 using measured water column concentrations of washload material at FCH when flows were below bankfull discharge and calibrated ψ_2 such that total modeled mass eroded (*MER*) from the banks fell within the range presented by Miller et al. (1999). It is only possible to match observed values by allowing significantly more erosion to occur when flows surpass bankfull discharge than when flows are confined to the main channel. Carroll et al. (2004) modeled results show that nearly 87% of bank mass eroded in a 6-year time span occurred during the single 1997 flood event. These results agreed with Miller et al. (1999) who attributed all geomorphic change along the Carson River from 1991-1997 to this single high-magnitude event. Verification of this approach showed the model fell within the 95% confidence interval of the observed mean channel width increase in seven of the ten reaches (reaches shown in Figure 1 detail), with trends well predicted in two of the remaining three reaches.

Overbank deposition was modeled using separate, but related, approaches for CSS and washload (Carroll et al., 2004). CSS was modeled by coupling analytical approaches presented by Thomann and Mueller (1987) and Walling and He (1997) in order to relate the amount of sediment deposited to the distance from the main channel. With no calibration, modeled values of CSS deposition on the floodplain agreed quite well with observed values by matching observed values in five out of ten reaches (Carroll et al., 2004).

Carroll et al. (2004) modeled washload deposition using a functional relationship developed for the model WEPP (Foster et al., 1995) that relates the rate of washload deposition to the difference between the actual concentration of sediment in the water column and the theoretical transport capacity (Johnson et al., 2000). The rate of washload deposition R_s^w ($kg/s/m^2$) is given by,

$$R_s^w = \frac{\overline{\beta} V_s^w}{q_f}\left(G_{main}^w - T_c\right) \quad (2)$$

International Journal of Soil, Sediment and Water, vol 1, no 1, 2008

where V_s^w is the average fall velocity for washload material (m/s) and q_f (m^2/s) is the discharge per unit width on the floodplain. Using Stoke's Law and assuming an average washload particle diameter of 0.033 mm (non-colloidal washload 0.002 mm to 0.63 mm), V_s^w equals 0.001 m/s. G_{main}^w is the water column non-colloidal washload (kg/s/m) in the main channel and T_c is the transport capacity (kg/m/s). β is a dimensionless turbulence coefficient and is assumed to decay exponentially with distance from the channel across the floodplain. To estimate T_c, a modified form of the model applied by Johnson et al. (2000) was used (Carroll et al., 2004),

$$T_c = \psi_3 q^2 S_0^{1.66} \tag{3}$$

where ψ_3 is a calibration constant (kg s/m^5) adjusted to match washload water column concentrations at FCH during overbank flows. These functions were able to predict washload concentrations at FCH, but over predicted washload deposited on the floodplain for most modeled reaches and over predicted total washload deposited by a factor of 2.7 (Carroll *et al*., 2004). Carroll *et al*. (2004) calibration of ψ_1, ψ_2, and ψ_3 to model bank erosion and overbank deposition was maintained in this study.

3.4 Modeling Lahontan Reservoir

Lahontan Reservoir consists of three distinct basins with water from the Carson River entering the south basin and moving northward through the middle basin and into the north basin (refer to Figure 1). The north basin terminates at Lahontan Dam with inputs from the Truckee Canal occurring at the north side of the dam. Lahontan Reservoir is almost 30 km in length when filled to maximum capacity. Past modeling of the Carson River-Lahontan Reservoir system used 0.5 km model segment lengths throughout the study site, but allowed for a finer discretization of segments (0.25 km) in the region of the reservoir delta. Rediscretization of the entire reservoir into 0.25 km segments was done to improve model stability during the drought of 1994 when drawdown in the reservoir allowed the delta to migrate into the north basin. Model stability was similarly improved by smoothing reservoir channel bottom slopes. Detailed cross sections of each modeled segment in the reservoir were developed using an updated United States Bureau of Reclamation (USBR) bathymetry map. Reservoir segments were redefined using these cross sections and the geometric definitions required by the modified RIVMOD (Carroll et al., 2004). Groundwater inflows/outflows were added to the reservoir to force modeled reservoir stages to match observed values. In particular, this was important to match massive drawdown in the reservoir during the drought of 1994 and allowed for accurate movement of the delta region which is important in simulating sediment and mercury deposition.

3.5 Modeling Mercury Transport

Boundary conditions, initial conditions, methylation - demethylation rates, particle reaction coefficients and the diffusion from bottom sediments are discussed in detail by Carroll et al. (2000). Carroll et al. (2000) developed a relationship describing river bank Hg concentrations ($[Hg^{2+}]_{bank}$) as a function of channel bed slope (S_0) (equation 4a) in which λ_1 (µg/kg) was adjusted to match observed pre-1997 flood water column concentrations along the Carson River. To accommodate a newly developed bank package where the concentration of MeHg would be computed as time varying based upon bank moisture history, a spatially variable (simple linear function) inorganic mercury bank concentration was imposed as shown in equation 4b,

$$[Hg^{2+}]_{bank} = \frac{\lambda_1}{S_0^{0.5}} \qquad [Hg^{2+}]_{\max} = \frac{\lambda_1}{S_0^{0.5}} \tag{4a}$$

$$[Hg^{2+}]_{bank} = [Hg^{2+}]_{bot} + \frac{\left([Hg^{2+}]_{\max} - [Hg^{2+}]_{bot}\right)D}{2h} \tag{4b}$$

where $[Hg^{2+}]_{max}$ = maximum inorganic bank mercury concentration ($\mu g/Kg$), $[Hg^{2+}]_{bot}$ = measured channel bottom inorganic mercury concentration ($\mu g/Kg$) based on data collected by Miller and Lechler (1998) and described by (Carroll et al., 2000), D is water depth beginning at the vertical face of the bank (m) and h = the vertical height of the bank (m). The factor of two in the denominator of equation 4b accounts for banks on both sides of the river. It is also assumed that banks related to the low flow inner channel as well as the low to medium flow transition slope (roughly flow depths less than 1 m) have Hg^{2+} bank concentrations similar to channel bottom sediments. For this study, the calibration of λ_1 was accomplished using Hg^{2+} water column data collected during flow conditions just below bankfull (June 10, 1995).

3.6 Methylation in the Bank Sediments

Laboratory experiments conducted by Dr. Mark Hines (University of Massachusetts, Lowell) demonstrated that methylation activity was nonexistent when the bank soils were dry but quickly became significant after approximately four days of soil saturation (http://biogeochemistry.uml.edu/pages/Hg.html). To implement these findings, the newly developed bank package tracks the depth of vertical bank that has been saturated for four or more days, computes the average Hg^{2+} concentration in the saturated bank sediments (equation 4b), and then computes a MeHg bank concentration based on the computed amount of Hg^{2+} and the methylation-demethylation ratio. Rapid increases in flow will actually cause a "dilution" of in-stream MeHg concentrations since the bank concentrations will not increase by the time of significant erosion. On the other hand, if flow rises more gradually such that a majority of the bank remains saturated for four or more days, then the concentration of MeHg in the banks will be substantial as will be the potential mass loading rate into the river due to bank erosion and possibly bank diffusion. No calibration was performed using MeHg bank concentrations to match water column concentrations.

International Journal of Soil, Sediment and Water, vol 1, no 1, 2008

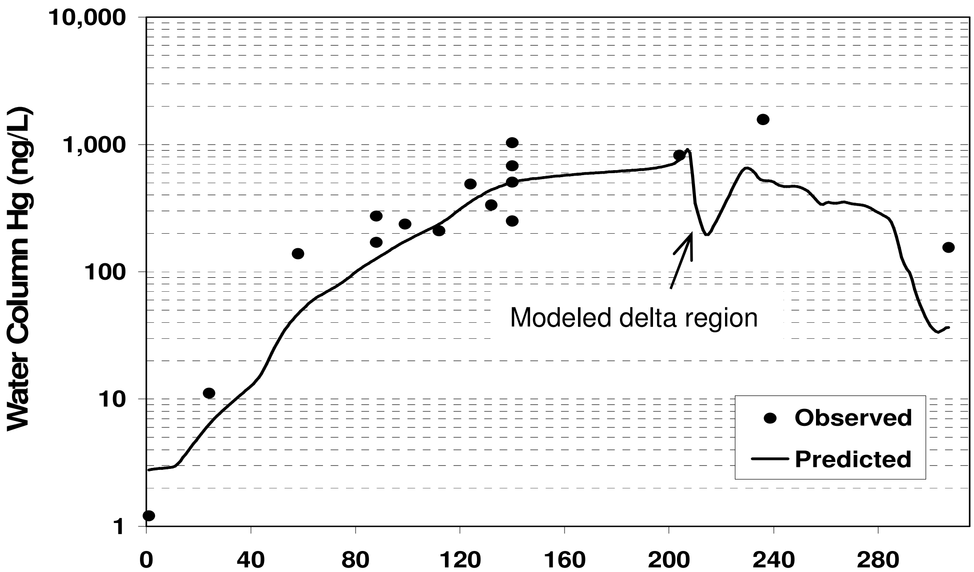
3.7 Uncertainty Analysis

Carroll and Warwick (2001) performed the first comprehensive uncertainty analysis of the Carson River mercury transport model. Specifically, uncertainty in the methylation-demethylation ratio and the diffusion rate of mercury from channel bottom sediments were evaluated in the river channel from the CCG to the FCH region. This study used a similar approach to uncertainty, but focused only on impacts of geomorphic change on mercury transport while incorporating channel widening and dynamic bank methylation rates into the analysis. The Monte Carlo simulation was employed using the computing power of the Desert Research Institute's Advanced Computing in Environmental Sciences (ACES) program. This is a sophisticated research grid among the three University and Community College System of Nevada campuses. Grid computing power comes from a SGI Altix 3700 from Silicon Graphics with the shared –memory high performance supercomputer boasting 40 Intel Itanium2 CPUs, 80 GB of RAM and 3 TB of disk space and the Linux kernel. Five hundred simulations were run on ACES (taking three months computing time) simultaneously adjusting the parameters λ_1 and ψ_1. Results were then ranked to establish the 80% confidence interval of Hg and MeHg water column concentrations across the modeled domain and over the entire course of the simulation.

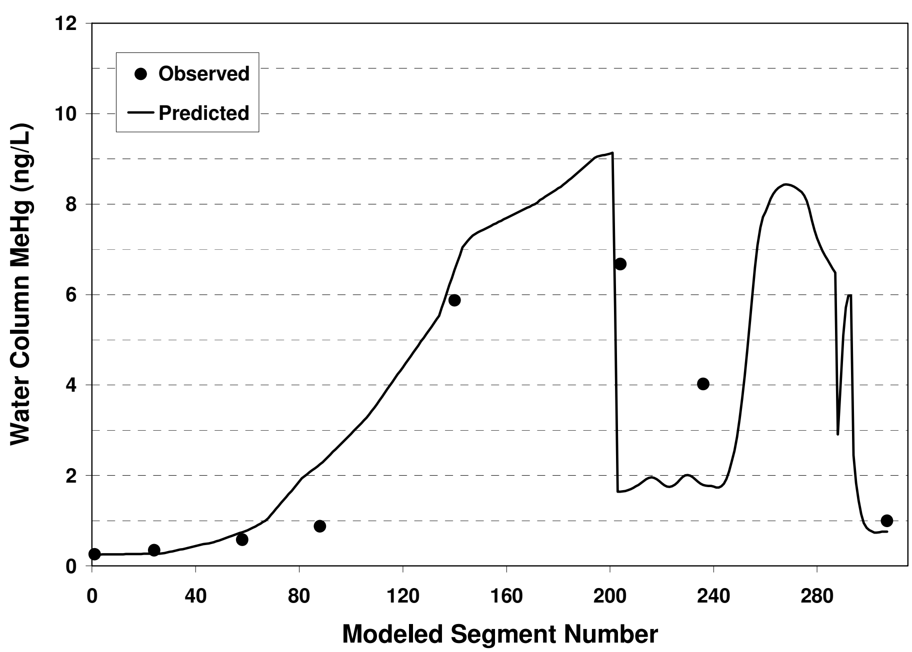
4. RESULTS AND DISCUSSION

Hg water column concentrations measured June 1995 were calibrated using a λ_1 value equal to 6,000 μg/kg. This value is approximately double that presented by Carroll et al. (2000), which is explained by the relationships between equation 4a used by Carroll et al. (2000) and equations 4b used herein. Figure 3a shows that while water column Hg^{2+} concentrations are slightly over-predicted in the upper river reaches, river Hg^{2+} concentrations at FCH (segment 140) and the river's delta region were well predicted. No calibration was attempted to match Hg^{2+} reservoir concentrations. Figure 3a suggests that the model may either over-estimate the importance of the over-bank flow event earlier in 1995 (refer to Figure 2) and its ability to transport Hg^{2+} into the reservoir, or has not moved the pulse of Hg^{2+} through the reservoir quickly enough. Verification of λ_1 used pre- and post-1997 flood data collected by UNR (refer to Figure 2 for sampling dates and flow regimes). Excellent results suggest equation 4b is fairly robust and capable of modeling systematic trends seen in mercury water column concentrations. No calibration was attempted to match MeHg water column data. Modeled MeHg water column concentrations for June 10, 1995 are compared to observed values in Figure 3b. Given no calibration, modeled results show excellent correlation with observed concentrations. Similar to Hg^{2+} results, MeHg concentrations in the reservoir show a large pulse of MeHg. Lack of data in the reservoir prevents judgment on the existence of this pulse.

The Monte Carlo simulation was conducted running 500 realizations with confidence intervals calculated from ranked results. λ_1 was varied ±33% from its calibrated value to assess uncertainty in Hg^{2+} and MeHg bank concentrations and their subsequent impact on water column concentrations due to bank erosion and bank diffusion processes. A triangle distribution was used with a mean (maximum probability of occurring) equal to the



(a)



(b)

Figure 3: Water column mercury concentrations collected June 10, 1995 along the Carson River and Lahontan Reservoir, (a) Calibration of λ_1 (Hg^{2+} bank concentrations) to best match observed Hg^{2+} water column concentrations, (b) comparison of modeled and observed MeHg with no calibration.

calibrated value (6,000 μg/kg) and the upper and lower bounds set to a probability of zero. On the other hand, a half-triangle distribution was used to define ψ_2 with maximum probability set to the calibrated value (8,000 $m^2 \cdot s/kg$) and 4,000 $m^2 \cdot s/kg$ set to zero probability. This lower bound was established by matching the minimum estimated total mass eroded (*MER*) by Miller et al. (1999). Maximum values of each probability distribution function (*PDF*) were computed such that the area under each *PDF* equaled 1.0. Note that *MER*, as determined by ψ_2 and the amount of fine material deposited on the floodplain, as defined by the transport capacity (ψ_3), are indirectly related to each other. The relationship between these variables was developed (equation 5) by adjusting ψ_3 to match the highest observed washload concentration (2,250 mg/L at 514 m^3/s) given different values for ψ_2. The resultant strong correlation ($r^2 = 0.99$) allows for excellent auto-calibration during the Monte Carlo simulation.

$$\Psi_3 = 1.96\times10^6 - 13.694(\Psi_2 - 40{,}000) \quad (5)$$

Setting the maximum limit of the ψ_2 distribution to the original calibrated value excludes the upper bound of *MER* as defined by Miller et al. (1999). This was done because Carroll et al. (2004) found the model over predicted washload deposition on the floodplain (i.e. transport capacity (ψ_3.) was too small). To bias the Monte Carlo realizations toward less over-bank deposition, it was necessary, according to equation 5, to bias the model toward less bank erosion (i.e. smaller values of ψ_2.).

Figure 4 shows that the resultant 80% confidence interval for expected variation due to bank erosion near FCH does not encapsulate all available data. Marked in Figure 4 are data collected during a flash flood event in Mineral Canyon (refer to Figure 1). Elevated Hg^{2+} and MeHg concentrations in the Carson River during this event are not related to modeled processes in the Carson River and, while shown in Figure 4, are excluded from analysis. Figure 4a shows bank erosion processes dominate Hg^{2+} inputs during spring melt (and rain-on-snow events) with peak Hg^{2+} concentrations occurring during over-bank discharge events. Hg^{2+} data collected prior to, and during, the 1997 flood fall within the estimated bounds.

Unlike inorganic mercury, modeled MeHg in the river's water column appears dominated by diffusion and not necessarily bank erosion processes. This is evident during the drought of 1994 when MeHg experiences its highest water column concentrations (Figure 4b) and the greatest range in the 80% confidence interval. The large range in uncertainty modeled in 1994 is a reflection of uncertainty in λ_1, the associated MeHg bank concentrations and resultant bank diffusion since significant bank erosion does not occur before or during 1994. In contrast, the second largest range in MeHg uncertainty occurs during the first over-bank flow event in 1995. This demonstrates that while diffusion appears more important, bank erosion is still a viable mechanism for MeHg loading to the river with significant impacts on MeHg water column concentrations. The 1997 flood event, which is so important to loading of Hg^{2+}, actually dilutes MeHg due to the flashy nature of the flood and the lag in peak MeHg bank concentrations relative to bank erosion.

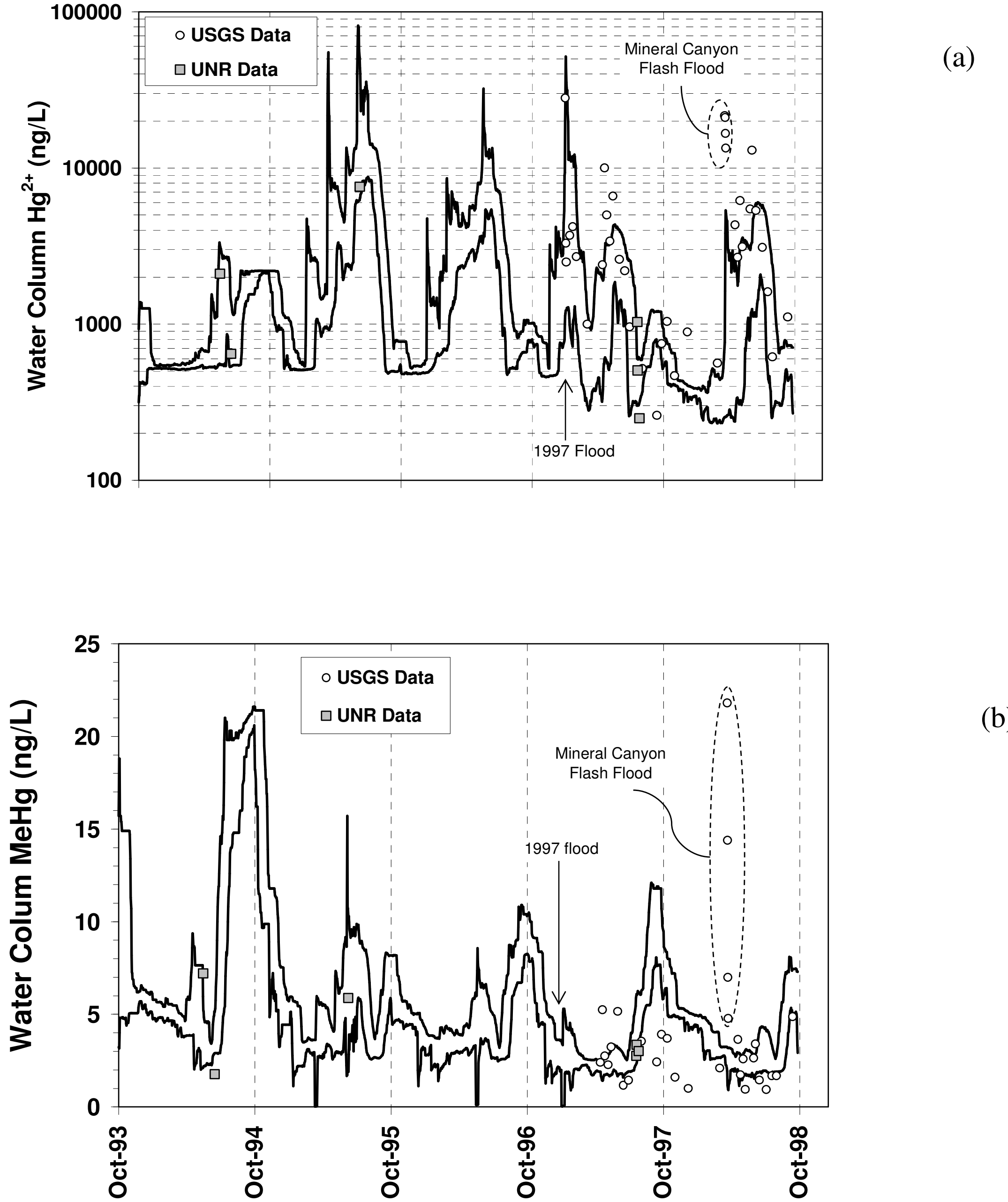


Figure 4: 80% confidence intervals given uncertainty related to geomorphic change near FCH for (a) Hg^{2+} and, (b) MeHg. Model results compared to data collected by UNR and the USGS.

International Journal of Soil, Sediment and Water, vol 1, no 1, 2008

However, modeled MeHg uncertainty decreases over time such that MeHg loading via bank erosion or bank diffusion diminishes with each successive over-bank flow event as a result of increased channel widths.

System-wide upper 80% bounds of uncertainty due to bank erosion processes are presented in Figure 5. The 1997 flood occurred on day 1193 in the simulation and model segment 304 represents the furthest upstream extent of Lahontan Reservoir. Settling of contaminated sediment at the reservoir delta causes a rapid decrease in mercury concentrations (Hg^{2+} and MeHg) and allows quick delineation of the delta region. During the drought of 1994 the reservoir (day 350 to 400) reverted back to river-status as it was nearly drained. Hg^{2+} and MeHg concentrations were relatively high throughout the reservoir during the drought since water column velocities remained high and sedimentation was limited. MeHg concentrations throughout the system were highest during the drought of 1994 with diffusion dominated loading (Figure 5b). MeHg concentrations during the 1997 flood were much lower as the result of dilution.

System-wide Hg^{2+} results (Figure 5a) agree, in part, with those presented for FCH in Figure 5a, such that erosion is important during 1995 when flows first go over bank, and to a lesser degree in 1996. However, system-wide, the 1997 flood appears the dominate Hg^{2+} loading event into the reservoir and not 1995 as suggested by FCH results. During the 1997 flood the Hg^{2+} upper 80% confidence interval is significantly elevated throughout most of the system, including the reservoir where velocities remained high despite the reservoir reaching its maximum capacity. The discrepancy between FCH results and system-wide results has to do with the very shallow channel bottom slope (S_0) defined at FCH and its indirect relationship to MER defined by equation 1. The FCH site, marked in Figure 5a, shows a significant dip in Hg^{2+} concentrations during the 1997 flood relative to steeper river segments above and below its location. A similar dip is not evident in 1995 during peak flows. FCH illustrates that segments with shallow river bottom slopes place greater emphasis on earlier over-bank flow events than steeper river segments.

5. CONCLUSIONS

In summary, uncertainty related to modeled geomorphic processes of bank erosion and over bank deposition describe observed variation in Hg^{2+} water column concentrations prior to and during the 1997 flood. The model places relatively greater uncertainty in modeled behavior on earlier over-bank discharge events than later events. This is most evident in river reaches that have shallow channel slopes, which experience the greatest increases in channel widths during the earliest modeled over-bank flow events. Despite this limitation, the model is able to capture all of the measured variation in the Hg^{2+} concentrations during the 1997 flood arguably the largest Hg^{2+} loading event ever recorded in the Carson system. However, a change in the system appears to occur during the 1997 flood that is not adequately modeled since uncertainty in modeled parameters alone cannot explain Hg^{2+} variation following the flood.

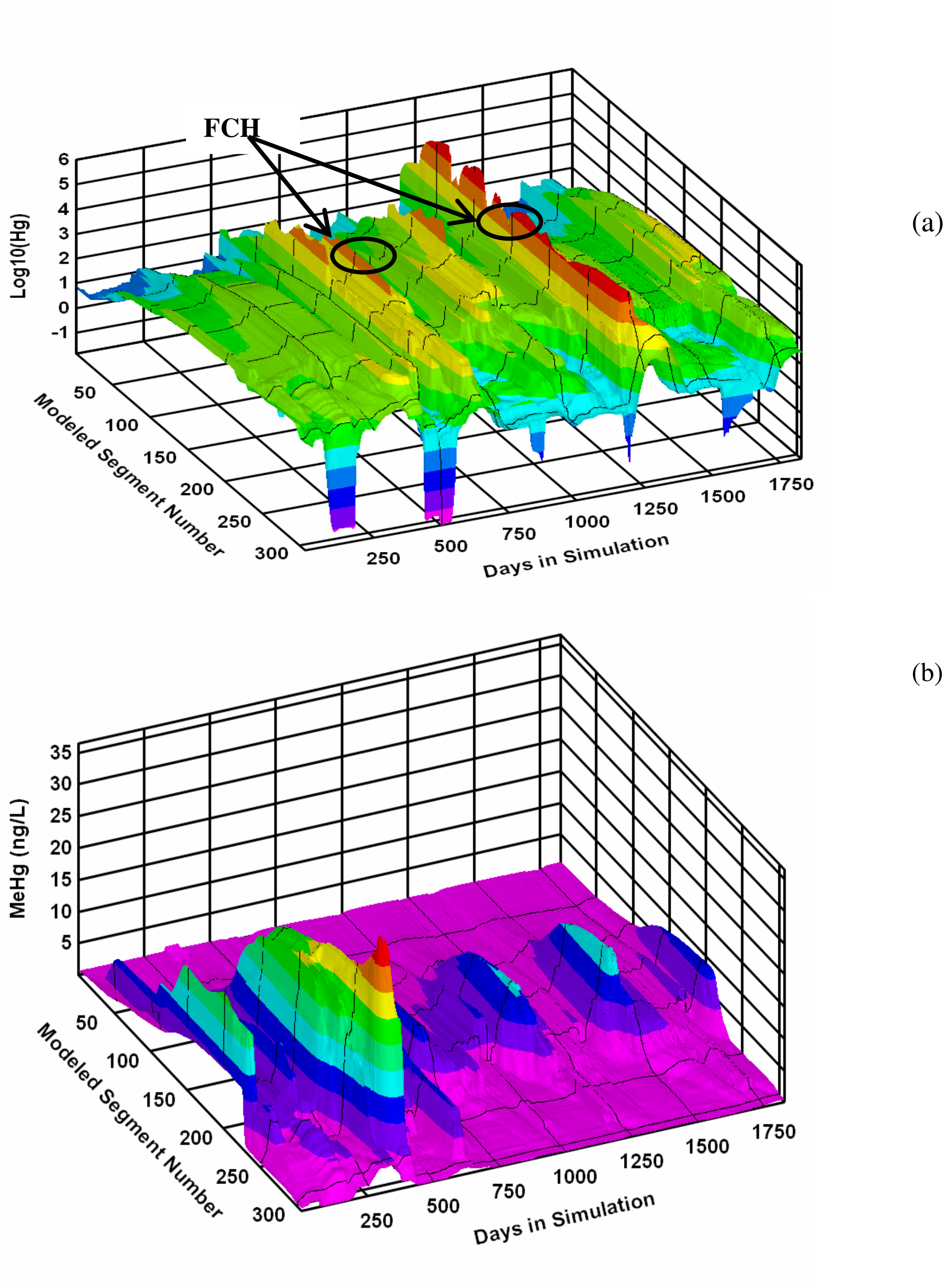


Figure 5: Upper 80% confidence interval for entire model domain over entire simulation given uncertainty in geomorphic changes to the river channel. (a) Hg^{2+}, (b) MeHg. Note that Hg^{2+} is plotted in log10-units.

International Journal of Soil, Sediment and Water, vol 1, no 1, 2008

MeHg loading appears dominated by diffusion as opposed to geomorphic changes to the river channel. Diffusion from river banks is indirectly included in the uncertainty analysis via the amount of Hg^{2+} (and subsequent MeHg) in the river banks. Bank diffusion appears as an important mechanism for MeHg loading as evidenced by the large amount of MeHg uncertainty in during the drought of 1994. However, its influence diminishes with time because of increased channel widths and the resultant decrease in river depths. Uncertainty in geomorphic channel change, including Hg^{2+} and MeHg bank concentrations, are not enough to capture observed variation in MeHg water column concentrations at FCH. Future work will need to include uncertainty in diffusion rates as well as methylation and demethylation rates to encompass all observed variability.

6. ACKNOWLEDGMENTS

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