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Re-evaluation Application of the Training Range Environmental Evaluation and Characterization System (TREECS™) to Small Arms Firing Ranges, Fort Leonard Wood, MO

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PURPOSE: This U.S. Army Corps of Engineers (USACE) Technical Note (TN) documents a re-evaluation application of the Training Range Environmental Evaluation and Characterization System (TREECS™) to small arms firing ranges (SAFRs) located at Fort Leonard Wood (FLW), MO. The TREECS™ was applied previously at FLW to demonstrate and evaluate the capability to predict stream concentrations of lead that is transported off-range and into the receiving stream, Falls Hollow. The present application was conducted to further validate the model against more recently observed lead concentrations in Falls Hollow and to better understand the sensitivity of various model inputs. This TN documents the results of this re-evaluation application.

BACKGROUND: The TREECS™ was previously applied to SAFRs 20–22 at FLW and the downstream receiving stream, Falls Hollow, to simulate the fate of lead. That application, which was documented by Dortch (2013), was conducted using only one observed grab sample value of lead. This sample was collected from the stream at the Falls Hollow highway bridge, about 3.2 km downstream of the ranges, and measured total lead concentration in the water column of 0.027 mg/L (27 parts per billion, ppb). There were no measurements conducted for the stream benthic sediment concentrations of lead. Subsequently, the U.S. Geological Survey (USGS) collected stream benthic sediment samples in Falls Hollow during the summer of 2014 and analyzed these samples for total and dissolved pore-water lead concentrations. The present application of TREECS™ to this site was conducted to re-evaluate the model given the 2014 sediment lead sample results.

Additionally, the USGS measured stream total suspended sediment (TSS) during four storm events in 2013 and 2014. The average TSS concentration for these four events was 63 mg/L. The long-term, average TSS concentration is not known (which is required by the model) but it is suspected to be lower than 63 mg/L due to long periods of low flows when TSS concentrations are lower.

Contaminant concentrations in streams resulting from land loadings within the watershed can be highly transient, varying with watershed rainfall and runoff. Thus, water column contaminant concentrations vary widely with rainfall and resulting stream flow. However, contaminant concentrations in stream benthic sediments change much more slowly; therefore, the benthic sediments provide a history of past land loadings and a clearer understanding of the level of stream contamination. This application was conducted and compared with the 2014 measured stream benthic lead concentrations to re-evaluate the ability of the TREECS™ models to predict long-term stream lead concentrations downstream of SAFRs and to evaluate the sensitivity of various model inputs.

MODEL INPUTS: The model inputs are described for the original application (Dortch 2013) and are not repeated except where changes were made. In the original application, range firing rates recorded between 1999 and 2012 were used to set input firing rates (where the annual average of the rates for 1999–2012 was assumed to apply for the entire period 1940–2012). This rate was approximately 2.5 million total (for all munitions types) rounds per year. It was later determined that firing ranges 20–22 were not operational as far back as 1940. Range 21 was Range 34 and was used as far back as the 1940's but may have had much less use than assumed. Ranges 20 and 21 were built, and subsequently rebuilt, in July 1964, and Range 22 was added in July 1986. The range operational inputs were modified for the present application such that range use in the area of interest (AOI) started in 1965 with recent annual average rates reported for Ranges 20 and 21 applied for 1965–1987. In 1987, the average annual rates were increased to include the recent average annual rates for Range 22. The recent average annual firing rates for all three ranges were applied from 1987 to the end of the simulation in 2024 (60 year duration). The end result of this input change was that there was less cumulative loading of lead to the range AOI than in the previous application (Dortch 2013). These inputs are summarized as 1,856,350 and 2,432,569 rounds fired per year into the AOI for years 1965–1986 and years 1987 to the end of the simulation (2024), respectively. This translates into a lead loading into the AOI of 6,538 and 7,724 kg/year for 1965–1986 and 1987–2024, respectively.

There were two modifications to inputs for the TREECS™ Tier 2 soil model. The annual average soil moisture content was changed from 29% to 19%. This change was made to reflect a more accurate estimate of the long-term average soil moisture based on more recent improvements to the hydrology model within the TREECS™ Hydro-Geo-Characteristics Toolkit (HGCT). The second change was to reduce the AOI soil erosion rate by half from 0.003 to 0.0015 m/yr. This reduction was made to reflect the fact that about half of the silty loam soils on the ranges probably do not move off-range due to larger particle sizes of sands and some silt. It was assumed that half of the silt and all of the clay is transported off-range into Falls Hollow resulting in halving the previous erosion rate.

Several of the inputs for the Contaminant Model for Streams (CMS) were changed from those used in the original application. The USGS flow gage on Falls Hollow has been in operation for a longer time since the first study; thus, there is now a longer flow record for determining the average annual flow rate as required by the model. Based on the longer record, the input for average annual flow rate was increased from 3.0E6 m^3/yr to 3.13E6 m^3/yr. Although the recent USGS measurements for TSS were made during storm events, these data tended to support a higher value for annual average TSS concentration. Therefore, the input for average annual TSS was increased from 9 to 20 mg/L.

The sediment-water partitioning distribution coefficients (K_d) for benthic and suspended sediments are two important model inputs. The values in the original application were 500,000 and 40,000 L/kg for suspended (TSS) and benthic sediments, respectively. Values for K_d for metals can vary widely from site to site, within a site over time, and for varying sediment concentrations; thus, these inputs are highly uncertain. For this reason, these two inputs were treated as uncertain, and the Monte Carlo Sensitivity and Uncertainty (S/U) module was used within TREECS™ to provide the upper and lower 95% confidence bounds on model output resulting from this uncertainty. The baseline simulation was developed using improved K_d estimates of 100,000 and 12,000 L/kg, respectively, for suspended and benthic sediments. These improved estimates were based on other modeling. For the uncertainty analysis, these K_d values were assumed to vary uniformly between 3,000 and 350,000 L/kg for suspended sediments and between 3,000 and 1,000,000 L/kg for benthic sediments. The Monte Carlo simulation was run for 70 iterations which was enough to reach repeatable results due to the Latin Hypercube sampling methodology within the S/U module.

The final change for the CMS inputs was the settling rate of TSS. The previous value of 1 m/day was reduced to 0.25 m/day to reflect the slower rate for finer sediments.

MODEL RESULTS: It is important to note that the model was not calibrated to fit the observed data, rather the inputs described in the previous section were applied using the best available information and judgement as if there were no observations, similar to what would be done when forecasting future concentrations to support range vulnerability assessments. This approach provided a much fairer assessment of the model's capabilities to forecast.

Model results for Falls Hollow using the input changes described above are shown in Figure 1 for water column total (particulate and dissolved) concentration and in Figure 2 for benthic sediment total concentration. The computed concentrations are located at the Falls Hollow highway bridge. The measured water column concentration was collected in January 2012 at the bridge. The measured sediment concentrations were collected in 2014 at two stations, upper Falls Hollow and Outfall #21, which is at the bridge. The upper Falls Hollow station is only about 300 m upstream of the bridge, which is close enough to lump with the data from Outfall #21. Thus, all the measured sediment lead data from both stations were averaged and plotted in Figure 2 along with the range of these measured data. The model's upper and lower 95% confidence bounds due to uncertainty in K_d are also shown in Figures 1 and 2.

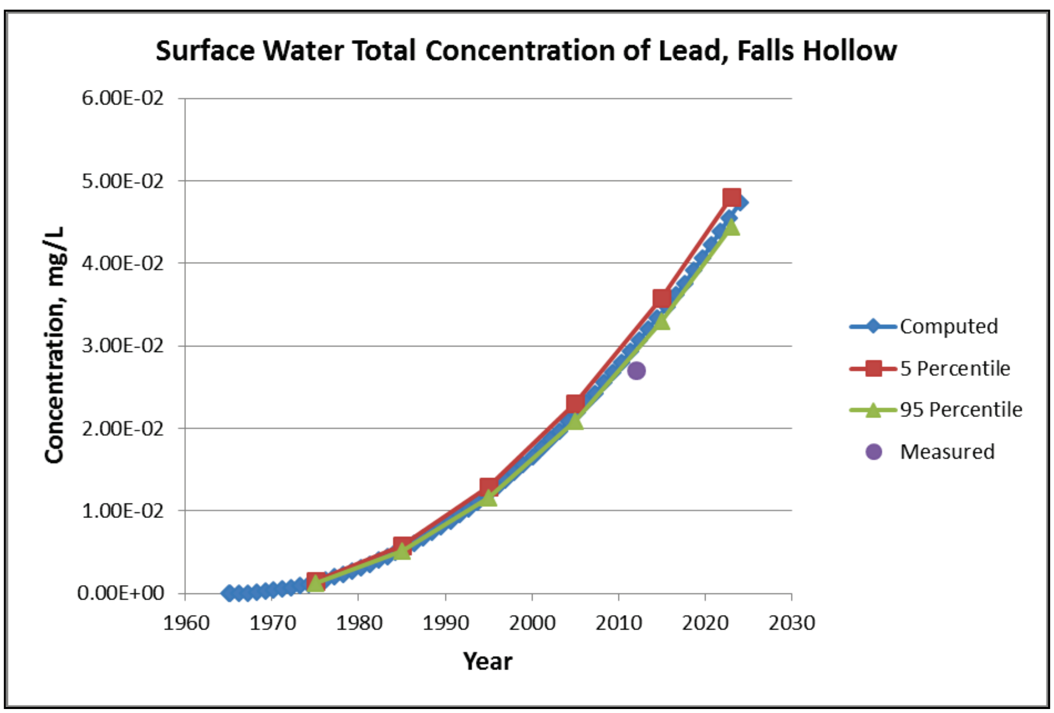

Figure 1. Computed and measured lead total concentration in water at Falls Hollow Bridge with upper and lower 95% confidence bounds for uncertainty in K_d.

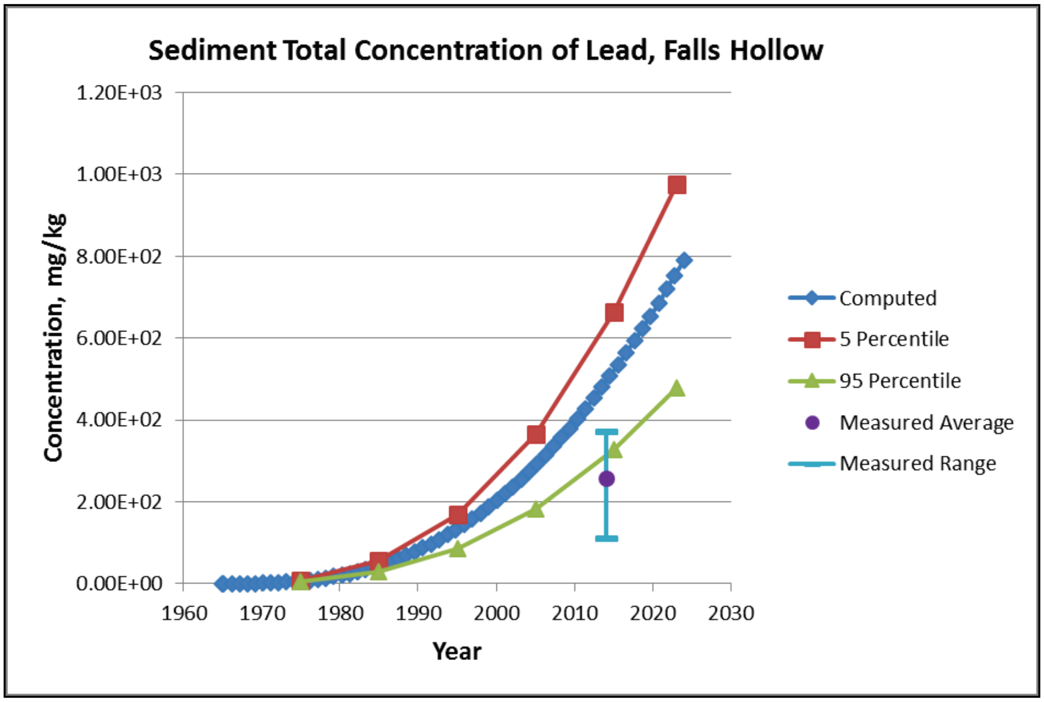

Figure 2. Computed and measured lead total concentration in benthic sediment in Falls Hollow with upper and lower 95% confidence bounds for uncertainty in K_d.

The computed and measured water column concentrations are quite close (Figure 1) and there is little variation in confidence bounds due to uncertainty in K_d because these concentrations are total (i.e., particulate and dissolved) where K_d affects the distribution between dissolved and particulate concentrations. The confidence bounds are quite wide when examining water dissolved lead concentrations as shown in Figure 3. The wider variation in the confidence bounds for water dissolved lead concentration is caused by the variation in suspended sediment K_d values. Although it may be remarkable how well the model agrees with the observed water column lead concentration, it is noted that measured stream contaminant concentrations can vary widely depending on stream water flow rate and recent rainfall history as mentioned previously.

The computed sediment lead total concentration in 2014 is greater than (almost double) the measured mean concentration (490 versus 258 mg/kg), although the lower confidence bound of the model does capture the measured upper limit concentrations. The reason for the over-predicted sediment concentration could be due to over-estimation of the suspended sediment K_d value. As explained in the next section, benthic sediment lead concentrations are highly sensitive to the suspended sediment K_d value, and there is much uncertainty in suspended sediment K_d. A value of 25,000 L/kg, rather than 100,000 L/kg, for suspended sediment K_d results in a benthic sediment lead concentration approximately equal to the mean measured concentration in 2014 with little to no change in computed water column total lead concentration. Also, there could be over-estimation of the firing rates prior to 1999. Receiving water concentrations are directly and linearly related to the specified firing rates. There were probably periods with relatively high firing rates prior to 1999, such as the 1960s due to the Vietnam War. However, most likely there were also periods when firing rates were lower.

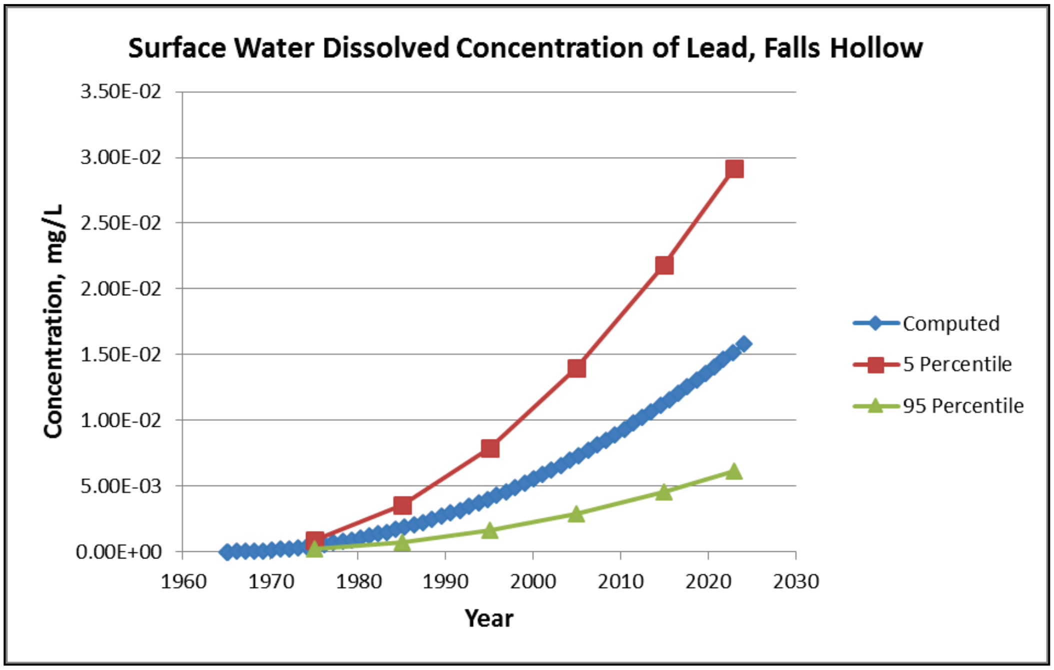

Figure 3. Computed dissolved lead concentration in water at Falls Hollow Bridge with upper and lower 95% confidence bounds for uncertainty in K_d.

DISCUSSION: Model predictions could be improved with improved estimates of suspended sediment K_d. There are no concurrent measurements of total and dissolved lead concentration in the water column for estimating suspended sediment K_d values. The USGS measurements of benthic lead during 2014 included both total and dissolved pore-water concentration. However, all of the pore-water concentrations were below the detection limit of 0.1 mg/L. Therefore, it was not possible to determine benthic sediment K_d values, with the exception that benthic sediment K_d is not expected to be less than about 3,000 L/kg since the pore-water lead concentration did not exceed 0.1 mg/L.

Most of the variability in computed benthic lead concentration is due to variation in the suspended sediment K_d value; thus, model sediment lead concentrations are far more sensitive to suspended sediment K_d than benthic sediment K_d. Variations in benthic K_d values has an almost negligible effect on benthic lead total concentrations for this application, whereas variations in suspended sediment K_d values explained 74 % of the variation in computed sediment lead concentration. In contrast, applying the full range of benthic K_d values used in the Monte Carlo simulation causes only an 8% change in benthic total lead concentration. Decreasing the suspended sediment K_d value has the effect of decreasing the computed benthic sediment lead concentration. The reason for this decrease is due to distributing more lead to dissolved concentrations in the water column, allowing more lead to be flushed out of the system with less benthic deposition of particulate lead. Therefore, site-specific measurement of suspended sediment K_d values would substantially improve the accuracy of computed benthic sediment concentrations of lead.

Computed sediment lead concentrations decrease with lower TSS concentration, but the effect is not nearly as great as that associated with varying suspended sediment K_d values. For example, halving the TSS concentration results in only a 3% decrease in benthic lead concentration.

There are other inputs that affect computed lead concentrations, such as the input parameters that affect solid lead dissolution rates, which include lead solubility and initial solid lead particle size from bullet fragments. The latter input has an almost linear and inverse relationship to computed sediment lead concentration. Doubling the size from 1,000 microns to 2,000 microns approximately halves the computed sediment concentration in 2014, resulting in a concentration that is fairly close to the measured concentration. However, these inputs were set using best available information, so changing or varying these values is not appropriate for forecast modeling, which is a major impetus for TREECS™ applications, unless varying the fragment size is done within the context of S/U simulations.

The AOI surface soil K_d value also affects receiving stream concentrations via retardation of transport from the AOI soils. However, this input was found to have a relatively minor effect on stream lead concentrations. For example, increasing the specified soil K_d value an order of magnitude from 597 to 5,000 L/kg had the effect of decreasing computed benthic sediment lead total concentration from 490 to 456 mg/kg in 2014, or only 7%. Also, there is reasonably fair confidence in the originally specified soil K_d value of 597 L/kg.

As stated previously, the specified value of suspended sediment K_d can be set to yield exactly the same benthic sediment concentration of lead as measured, while producing about the same computed total concentration of lead as measured for the water column (see Figure 1). However, the question is whether or not a *calibrated* suspended sediment K_d value would yield the correct dissolved lead concentration in the water column. Since there are no dissolved lead concentrations available for the water column, this question cannot be answered for this study application.

CONCLUSIONS AND RECOMMENDATIONS: A re-evaluation application of TREECS™ was conducted for lead in Falls Hollow, downstream of the FLW SAFRs using additional observed data for benthic sediment lead concentrations. For this application, the predicted and observed water column total lead concentrations were 31 and 26 ppb, respectively, during 2012. The predicted benthic sediment total lead concentration was about double that observed in 2014 (490 versus 258 mg/kg). Although the error in predicted sediment concentration may seem large, this error should be considered within the context of the requirement of this application, which was to start the model farther back in time (1965) to predict concentrations in 2012 and 2014 with a rough estimate of firing rates over that period. Such a long-term application is necessary to approximate the temporal build-up of lead mass in firing range soils. Receiving stream concentrations of lead, and any constituent, are proportional to the amount of constituent mass that has accumulated in the source soils, thus the reason the modeled stream concentrations increase over time. This proportionality is a result of fundamental mass balance. However, the steepness of the curves in the above figures is questionable in absence of observed concentrations over long periods of time. There can be processes not accounted for in the model, such as soil accretion with constituent burial that could render the constituent less available to runoff, resulting in a flattening of receiving stream concentrations.

Predicted sediment lead concentration was found to be highly sensitive to the suspended sediment K_d value, which has a high level of uncertainty. Improved estimates for suspended sediment K_d would yield more accurate model predictions.

Future data collection efforts for metals at any site should include concurrent sampling and measurement of total and dissolved metal concentrations in the water column and total and dissolved, pore-water metal concentrations in benthic sediments. These measurements provide information for determining K_d values. The detection limit for the dissolved metal concentration should be on the order of micrograms per liter, rather than milligrams per liter, to facilitate estimating K_d values. Finally, it would be very beneficial to have stream water column and benthic sediment measurements of metals over time, such as every five years, to provide a firmer basis for model evaluation with improved confidence in model predictions.

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Dortch, M. S. 2013. *Application of TREECS™ to small arms firing ranges at Fort Leonard Wood, MO.* ERDC TN-EQT-13-2. Vicksburg, MS: U.S. Army Engineer Research and Development Center.