Case Studies Evaluating the New Reservoir Volume Reduction Tool in HEC-HMS

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Abstract

Dams and reservoirs disrupt the natural transport of sediment in streams by creating large backwater areas with low velocities that allow sediment to settle to the bottom of the reservoir. Over time, sediment deposition reduces the storage volume and surface area of the reservoir, which can have a detrimental effect on the reservoirs authorized purposes. Accurately predicting sediment deposition can aid in estimating sedimentation impacts and planning future resources. For previous reservoir sedimentation studies, the U.S. Army Corps of Engineers (USACE) Kansas City District (NWK) has calculated volume change using tools such as Microsoft Excel and ArcGIS. However, these tools can be labor intensive and require the use of large, cumbersome datasets. The Hydrologic Engineering Center's Hydrologic Modeling System (HEC-HMS) versions 4.9 and 4.10 added a new reservoir volume reduction tool, which allows for more efficient calculation of reservoir volume change. The new features were tested at three reservoirs in the state of Kansas (Tuttle Creek, Kanopolis, and Perry), which have experienced significant sediment deposition since project construction.

Introduction

The three reservoirs analyzed in this study are located within the Kansas River Watershed and are managed by the U.S. Army Corps of Engineers (USACE). The major tributaries into the reservoirs are the Smoky Hill River (Kanopolis), the Big Blue River (Tuttle Creek), and the Delaware River (Perry). Figure 1 shows the location of the three reservoirs, along with their upstream watersheds. Authorized purposes of the reservoirs include flood control, irrigation, recreation, fish and wildlife, navigation support, and water quality.

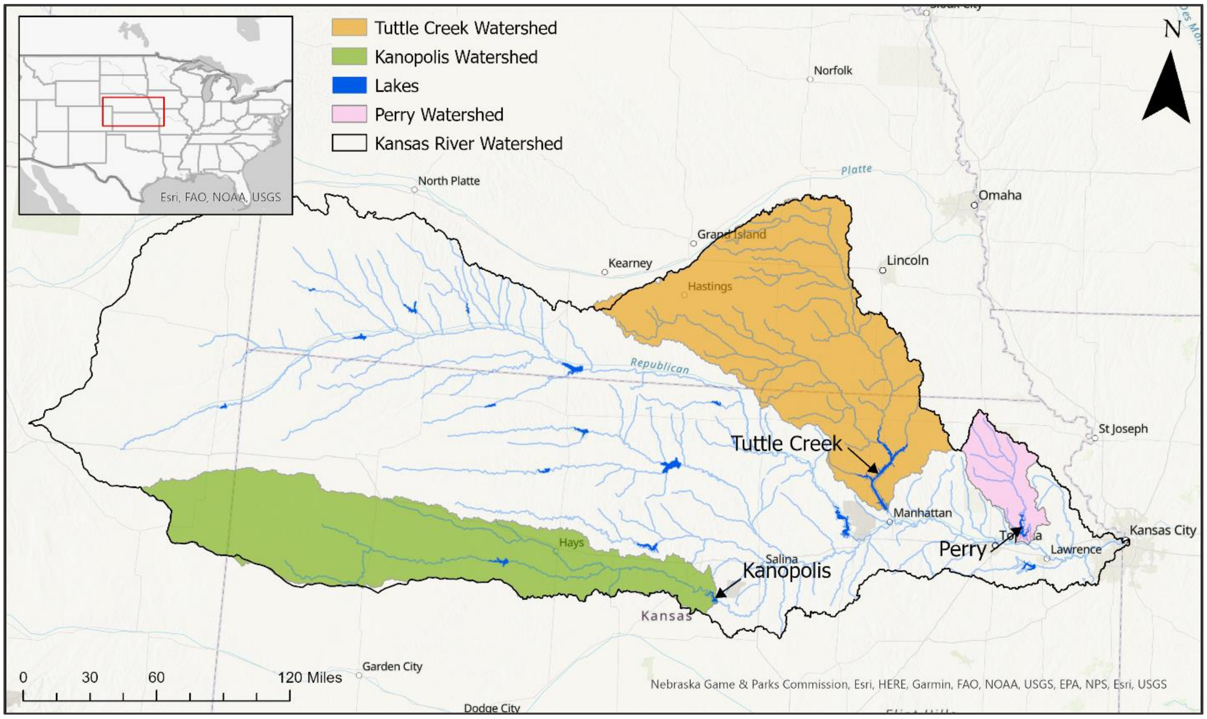

Figure 1. Location and upstream watersheds of case study reservoirs

Reservoir releases are typically made through gates located near the bottom of each reservoir, and USACE manages outflows to prevent downstream discharge from exceeding specified flow targets. The reservoirs analyzed in this case study can generally be divided into two main pools: the multipurpose pool (MPP) and the flood control pool (FCP). The FCP is utilized to store flood waters to mitigate flooding downstream of the dam, while the MPP is the typical operating level of the reservoir and is used for purposes such as water supply and recreation.

Since dam construction, large amounts of sediment have deposited in both the MPP and FCP of all three reservoirs. Bathymetric surveys show that Kanopolis has lost approximately 36% of its original MPP volume, Tuttle Creek 39%, and Perry 18%. The volume of sediment deposition in the FCP has been less than in the MPP, and the FCP deposits are generally denser than MPP deposits, as discussed later in this report. Table 1 gives a summary of information for each reservoir.

Table 1. Summary of reservoir information and sedimentation

Parameter	Perry	Tuttle Creek	Kanopolis
Original MPP Storage (ac-ft)	243,220	424,312	73,200
Current MPP Storage* (ac-ft)	200,004	257,014	48,378
Original FCP Storage (ac-ft)	521,880	1,942,705	373,891
Current FCP Storage* (ac-ft)	515,520	1,884,312	365,143
MPP Deposition (ac-ft)	43,216	167,298	24,822
FCP Deposition (ac-ft)	6,360	58,393	8,748
Upstream USGS gauges	06890100	06882510, 06884400, 06885500	06864500

*Current storage volume estimates based on survey datasets from 2007-2010

Estimations of both existing and future sediment deposition were made for all three reservoirs as part of the Kansas River Watershed Study (USACE, 2023). Various tools were employed during the study to estimate reservoir deposition, including Microsoft Excel, ArcGIS, and a HEC-RAS sediment model at Tuttle Creek. Data derived during the Kansas River Watershed Study was used as inputs into the HEC-HMS models.

HEC-HMS Reservoir Sedimentation Methods

HEC-HMS predicts reservoir sedimentation by updating reservoir storage-elevation and area-elevation curves based on the incoming sediment load and user specified parameters. HEC-HMS can directly estimate sediment and water inflow into the reservoirs using sub-basins and hydrologic inputs, or sediment and water inflow can be calculated externally from HEC-HMS and inputted as time series.

Once the incoming sediment load into the reservoir has been determined, HEC-HMS estimates the reservoir trapping efficiency to calculate the quantity that deposits and the quantity passed downstream. For clay and silt particles, HEC-HMS defaults to calculating the trapping efficiency based on the computed reservoir detention time, along with the calculated fall velocity of the sediment. For the sand and gravel particles, HEC-HMS defaults to using either the Chen (1975) or Brune (1953) empirical methods for estimating trapping efficiency.

After the mass of sediment deposition has been calculated, HEC-HMS converts mass to volume using bulk density. HEC-HMS will compute bulk density based on the incoming gradation and default densities for clay, silt, and sand; but the user can override the default values using onsite measurements.

Once the volume of sediment deposition has been estimated, HEC-HMS will then distribute the deposition in the reservoir according to elevation and sediment grain size. For the clay and silt particles, HEC-HMS uses the V-shape method, which assumes that all the sediment is deposited at the bottom of the reservoir. For the sand and gravel particles, HEC-HMS has the option to deposit the sediment in the Elongated Taper method, which assumes more sediment deposition higher in the reservoir, tapering to zero deposition at the lowest elevations.

Input Data

Simple HEC-HMS models were created for Kanopolis, Tuttle Creek, and Perry reservoirs using data derived during the Kanas River Watershed Study. Daily sediment inflows were estimated from gauges upstream where USACE and the U.S. Geological Service (USGS) have sporadically collected paired flow/sediment concentration measurements. Sediment load versus flow rating curves were constructed from the suspended sediment concentration measurements, which generally followed a log-linear relationship of the form $Q_s = aQ^b$. Bedload calculations were made during design of Kanopolis and Tuttle Creek dams (USACE, 1952; USACE, 1972). The Tuttle Creek bedload was estimated to be 3.7% (rounded up to 5%) of the total load and the Kanopolis bedload to be 15%. Bedload into Perry Lake was assumed to 5% bedload because of a lack of previous estimates.

Duan's (1983) correction for bias introduced by the log transform was applied to the load rating curve. Figure 2 shows an example sediment rating curve that was created for the Big Blue River upstream of Tuttle Creek near Marysville, KS (06882510). The Barneston measurements (06882000), also shown on Figure 2 , were only used for fitting the lower portion of the rating curve, since this gauge is located further upstream than the Marysville gauge. Near the 1.2-year flow of 9,080 cfs, which is the typical channel forming discharge for Kansas streams (Shelley 2012), the sediment load levels off and becomes nearly constant. This leveling off is likely caused by supply limitations in the upstream watershed. The upper and lower segments of the rating curve were fitted manually to the data.

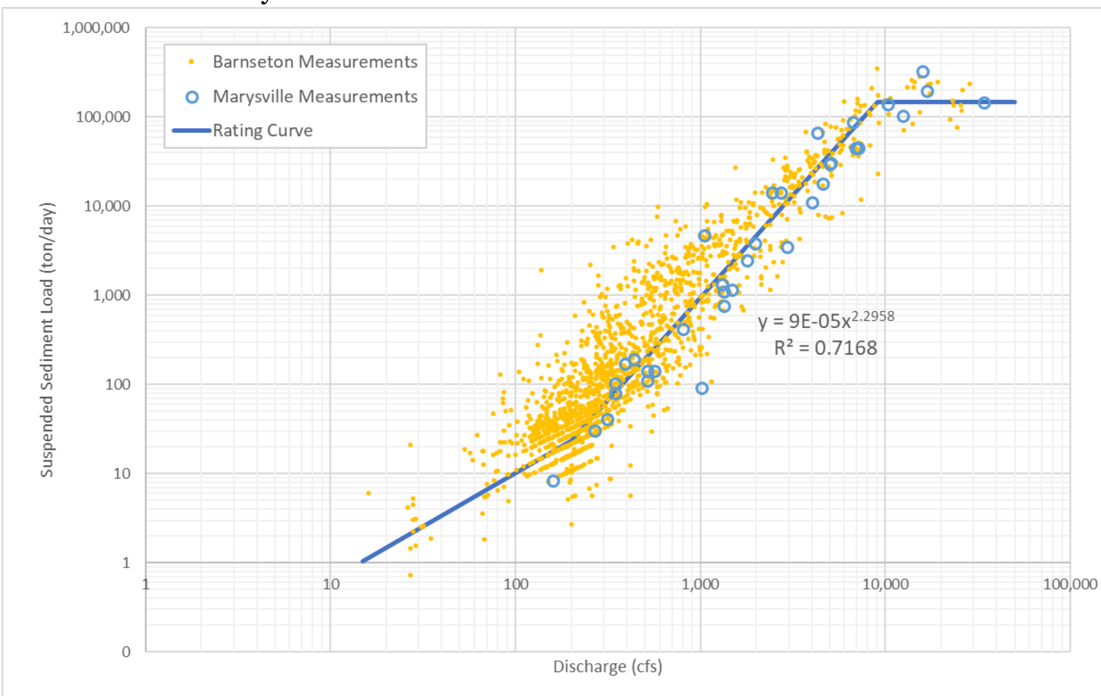

Figure 2. Example sediment rating curve used for computing daily sediment inflow

After sediment rating curves were constructed, they were used to compute a daily sediment load from the daily discharge over the reservoir's period of record. Reservoir daily water inflow and outflow were available from reservoir records, although some adjustments were necessary to maintain water balance.

Sediment grain size measurements were taken simultaneously with the upstream concentration measurements and were used to compute the overall gradation of the sediment inflow (Table 2).

Table 2: Measured sediment gradations of the inflowing sediment

Reservoir	Perry	Tuttle Creek	Kanopolis
Clay	49.2%	47.1%	48.2%
Silt	40.5%	40.8%	28.5%
Sand	10.3%	12.1%	23.3%

The USGS estimated reservoir trapping efficiency from 2008 to 2010 from sediment inflow and outflow measurements (Jurakek, 2011). Calculated trapping efficiency was determined using the Brune curve method (Equation 1), which was compared to the measured trapping efficiency.

$$TE = A[1 - 2e^{-B(\frac{V_{res}}{V_{inflow}})^{0.35}}] \quad (1)$$

Where TE is the reservoir trapping efficiency

V_{res} is the reservoir volume

V_{inflow} is the annual inflow volume

A and B are empirical coefficients

The Brune curve “A” and “B” constants were selected during the KS Watershed Study to best match the measured value. Average annual inflows for the reservoirs and the selected Brune curve constants are shown in Table 3. Only the Tuttle Creek A and B values differ from the default values in HEC-HMS.

Table 3. Average annual inflow and Brune Curve coeficients

Reservoir	Measured Trapping Efficiency	Average Annual Inflow (ac-ft)	Brune A	Brune B	Brune Trapping Efficiency
Perry	NA	187,572	97	6.42	96.8%
Tuttle Creek	98.0%	1,558,785	100	7.71	96.7%
Kanopolis	95.6%	139,271	97	6.42	94.6%

Sediment bulk density measurements have been collected within the reservoirs at various locations. However, bulk density can also be estimated from the inflow gradation measurements using Equation 2. In the final models, the bulk density was adjusted to better calibrate the model (see Table 4).

$$\gamma_c = \frac{1.0}{\left(\left(\frac{F}{\gamma}\right)_{clay} + \left(\frac{F}{\gamma}\right)_{silt} + \left(\frac{F}{\gamma}\right)_{sand}\right)} \qquad (2)$$

where γ_c is the composite bulk density

F is the fraction of clay, silt, or sand

γ for clay, silt and sand is assumed to be 30 pcf, 65 pcf, and 93 pcf respectively.

Model Creation

The setup of the HEC-HMS models was fairly simple, with only three elements (an inflow element, a reservoir element, and an outflow element), as shown in Figure 3. The inflow element respresents the inflow into the reservoir for both water and sediment. Daily time series of the sediment load and water inflow were created from the datasets discussed previously. The incoming sediment gradation was inputted into HEC-HMS as a paired dataset and was initially taken from the sediment concentration measurements.

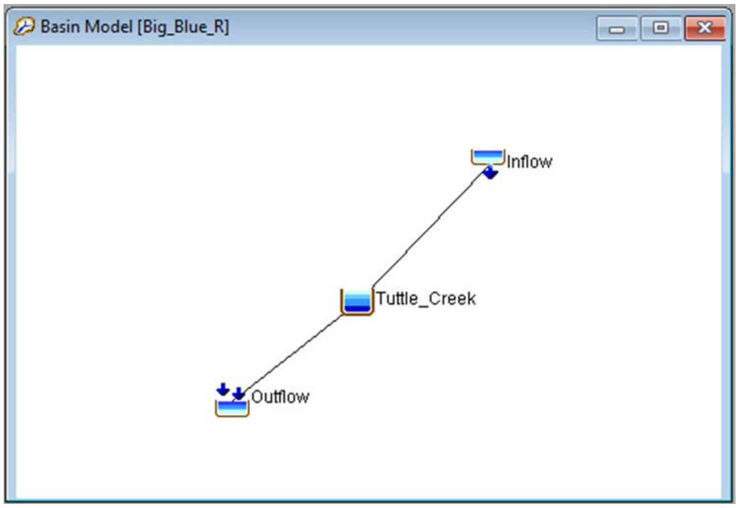

Figure 3. A simple HEC-HMS model for Tuttle Creek used to calculate reservoir volume reduction

The reservoir element represents the main body of the reservoir and was where reservoir parameters were entered. Initial elevation-area and elevation-storage curves were entered into HEC-HMS and were obtained from surveyed datasets. Trapping efficiency information from Table 3 was also entered into the reservoir element for use in the Brune method. The Chen trapping efficiency method was tested, but it did not produce significantly different results. A specified release was used for reservoir outflow. Meteorological data was not needed in the model since gauged data was used as model inputs.

The time step for the models was 12 hours, although the Tuttle Creek model was tested at a smaller timestep to determine sensitivity. Results showed that using the smaller timestep resulted in at most a 1.3% decrease in volume change for any given elevation within the lake. Depending on the precision needed, the 12-hour timestep is likely accurate enough for most studies but should always be tested.

Initial Model Results and Calibration

Results from the HEC-HMS simulations were compared to surveyed volume change over roughly 10-year intervals. The earliest reservoir surveys were collected along fixed range lines with relatively wide spacing. For these, surveyors generally used land-based methods within the FCP and boat-based methods within the MPP. Total volume was calculated from the measured cross-sectional area.

The latest surveys have been collected along more densely spaced lines using single beam sonar within the MPP and Lidar within the FCP. Surfaces were created from the survey data using ArcGIS software, from which the total storage volume was computed. Differences in survey methods, equipment, and storage volume calculations add uncertainty to the measured volume change, which should be considered when comparing to modeled results.

The initial comparison of the measured and modeled volume change showed that the HEC-HMS models consistently underpredicted total deposition and deposited the sediment at too low of elevation in the reservoir. Also, the overall trapping efficiency in HEC-HMS was much lower than the value measured by the USGS. Based on these results, it was concluded that the trapping efficiency method HEC-HMS employs for silts and clays was passing too much sediment downstream, possibly because HEC-HMS cannot currently account for reservoir shape. Another possibility is that the flocculation of the fine particles may be causing them to deposit sooner in the reservoir.

Although the method HMS currently employs for fines underpredicted reservoir trapping efficiency, the Brune methodology was found to accurately predict trapping efficiency during the Kansas Watershed Study (USACE, 2023), as shown in Table 3. Because HMS currently does not allow for the Brune method to be applied to the fine particles, the program was overridden by shifting all the incoming load into the sand grain class, which also allowed the elongated taper deposition method to be applied to all the sediment.

Figure 4 compares the volume change from 1972 to 2009 at Tuttle Creek. The volume change predicted using the measured gradation and default trapping efficiency in HMS resulted in a significant underprediction in the total deposition. Also, the sediment deposits too low in the reservoir. Shifting all the incoming sediment to sand to force the program to use the Brune method for all the sediment (along with selecting the elongated taper method) produced much better results. However, this did result in some underprediction at lower elevations. To better match the lower elevations, some of the sediment was shifted back to the fine grain classes to allow it to deposit lower in the reservoir. The methodology using mostly sand (with some sediment remaining as fines) will be the methodology presented through the rest of this report.

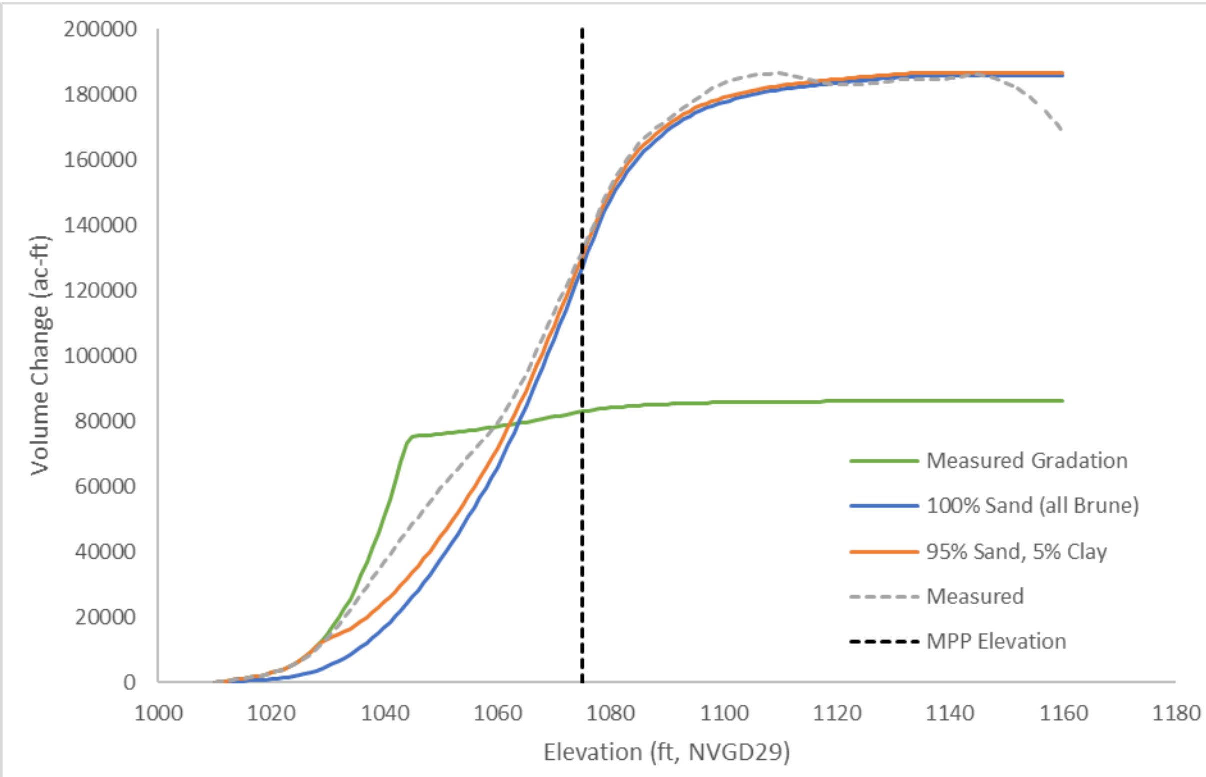

Figure 4: Measured and modeled volume change at Tuttle Creek (1972 to 2009)

The incoming load and sediment density were modified to account for the shifts in gradation (essentially, the sediment density in HMS was set to the measured bulk density). The bulk density was also adjusted slightly as a calibration parameter (see Table 4). Calibration for Kanopolis resulted in a bulk density that was 14% higher than the measured bulk density, which could be due to insufficient measurements, errors in the measured bulk density, or the calculated sediment load being low.

Table 4. Sediment bulk density from direct measurements and incoming gradation estimates

Reservoir	Measured MPP (lb/ft^3)	Measured FCP (lb/ft^3)	Measured Overall (lb/ft^3)	Equation 1 Overall (lb/ft^3)	Calibrated Overall (lb/ft^3)
Perry	39.4	-	-	42.1	42.1
Tuttle Creek	40.7	62.9	46.4	43.0	48.0
Kanopolis	38.7	53.8	43.9	43.8	50.0

Calibrated Model Results

Figure 5 shows the cumulative volume change versus elevation within Tuttle Creek for five different survey periods. Generally, the modeled volume change matches well with the measured change, although there are some inconsistencies. As discussed previously, differences in survey methods and volume calculation can likely explain many of the discrepancies, such as the large error in the 1972-2000 period above elevation 1075 ft. The 2020 bathymetric survey was only collected up to the MPP elevation, which is why it does not go as high as the other surveys. Also, the model still consistently underpredicts deposition in the lower elevations of the reservoir.

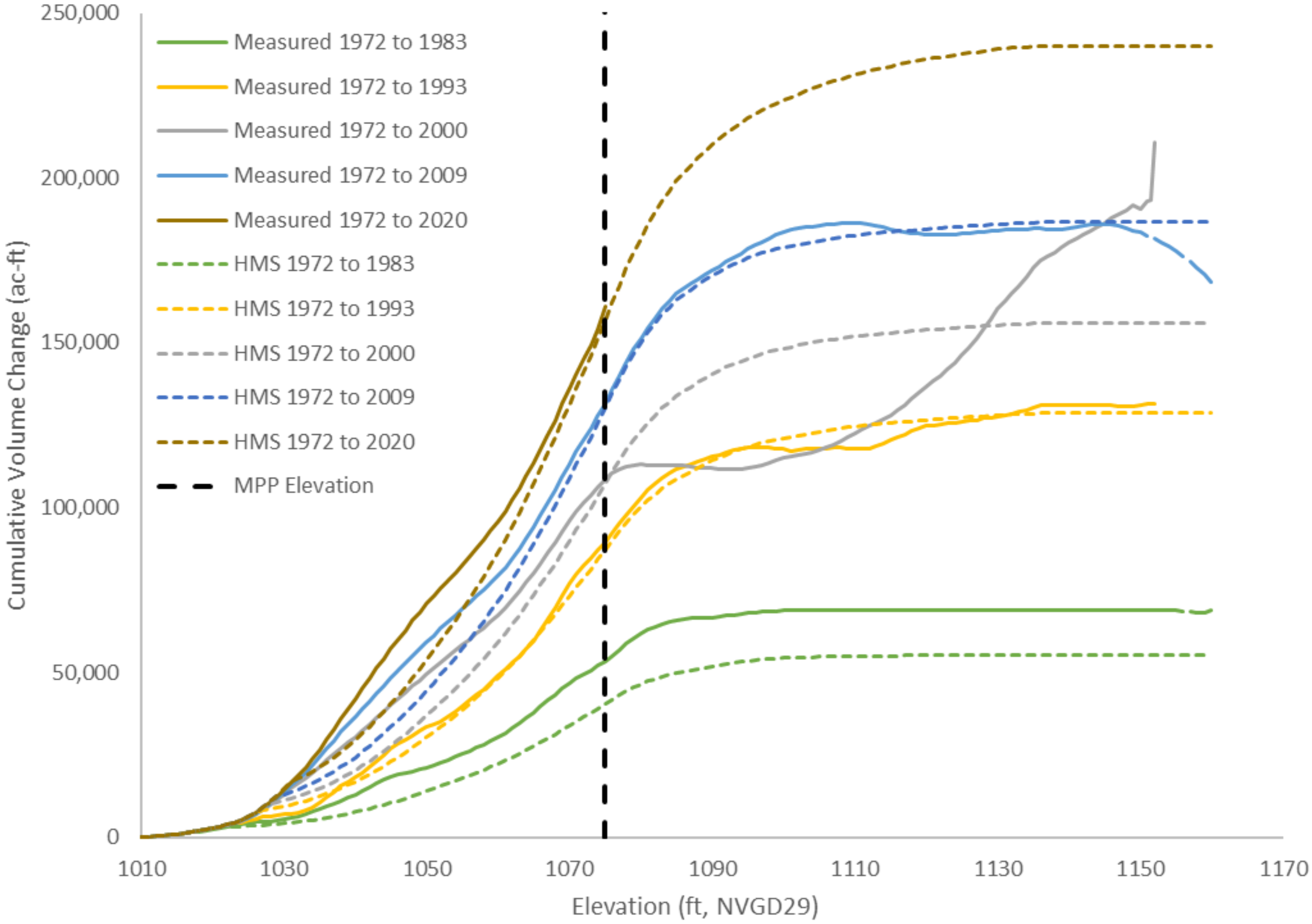

Figure 5. Tuttle Creek measured and modeled cummulative volume change relative to the 1972 survey

Figure 6 shows the measured and modeled pool elevation over the simulation period at Tuttle Creek, along with the modeled pool elevation without including the effects of sedimentation. The modeled and measured pool elevation agree well with each other when including sedimentation, but if sediment is not included in the model, over time the model significantly underpredicts pool elevation. At the end of the simulation, the modeled pool elevation is one foot too high when including sediment, but nine feet low without sediment.

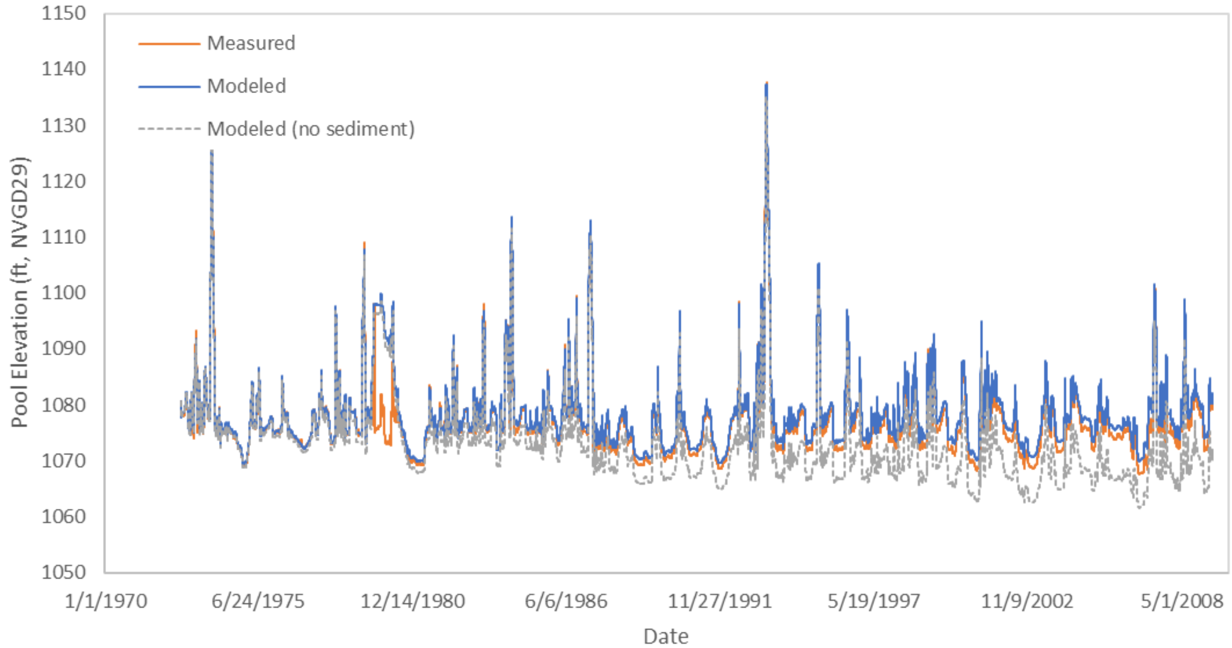

Figure 6. Measured and modeled pool elevation at Tuttle Creek

Figure 7 shows the cumulative volume change for both the measured and modeled data at Kanopolis, with both datasets agreeing relatively well with each other. The calibrated gradation was 10% clay and 90% sand. At the highest elevations, there were large jumps in the measured volume change, which is likely caused by survey discrepancies, and not actual volume change.

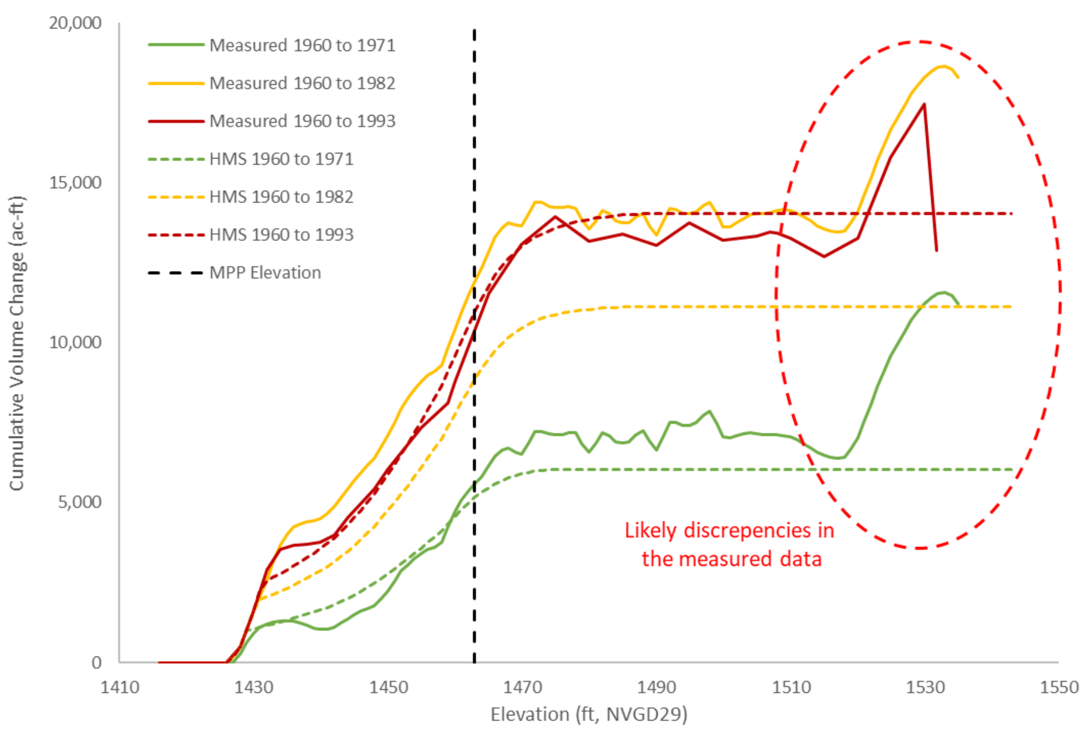

Figure 7: Kanopolis measured and modeled cumulative volume change relative to the 1960 survey

Because the 2007 and 2017 surveys at Kanopolis were collected using different methods, the volume change from 2007 to 2017 was plotted separately (Figure 8).

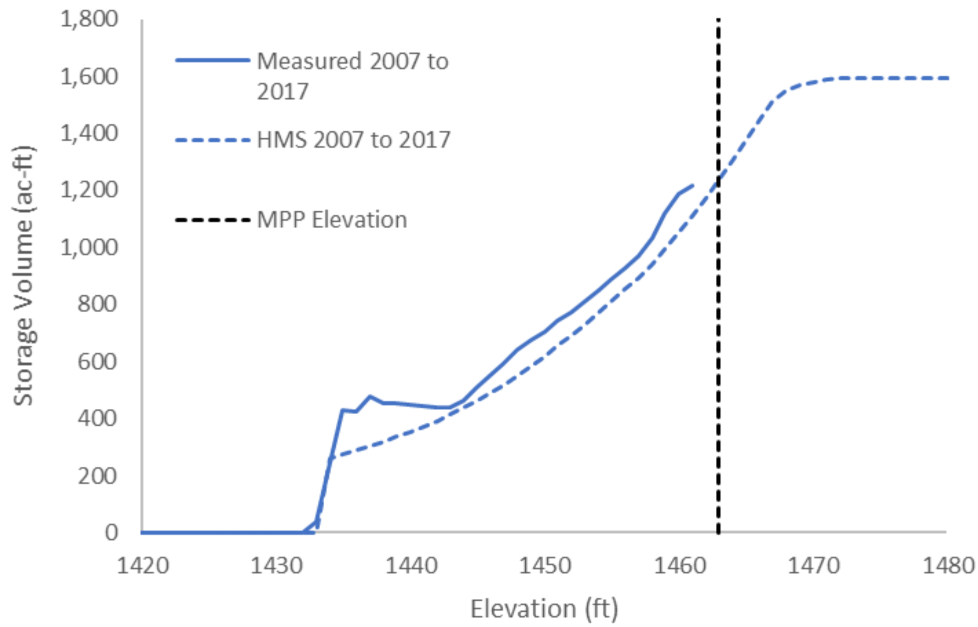

Figure 8: Kanopolis measured and modeled cumulative volume change 2007-2017

Figure 9 gives the measured and modeled cumulative volume change at Perry from 1979 to 1989. The incoming gradation was calibrated to be 8% clay and 92% sand. Compared to the measured data, the model underpredicts deposition.

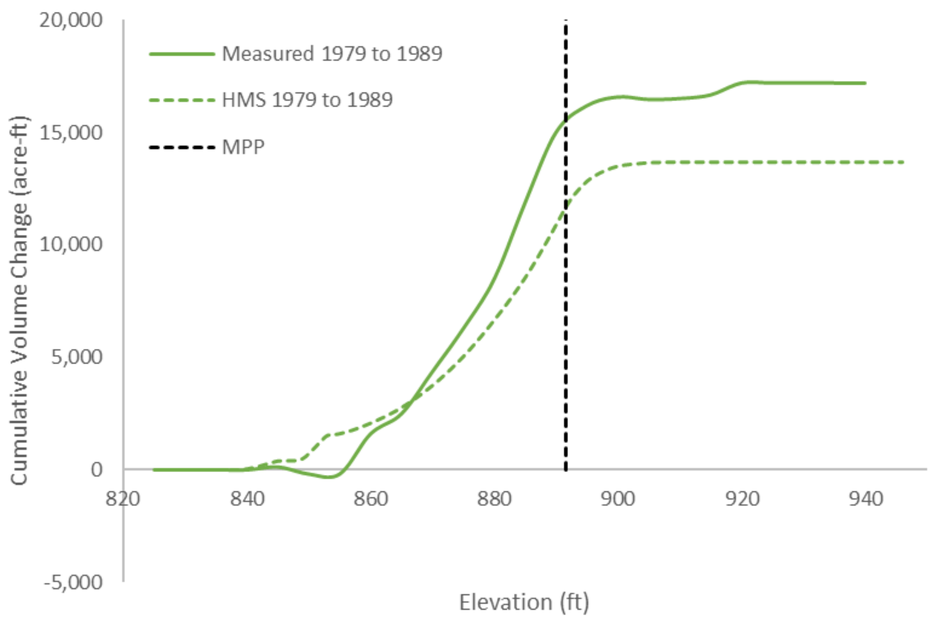

Figure 9: Perry measured and modeled cummulative volume change relative to the 1979 survey

Perry's modeled volume change over the 2000-2009 and 2009-2021 periods more closely matches with the measured data as shown in Figure 10. Once again, the 2001-2009 measured deposition is unreliable above the MPP.

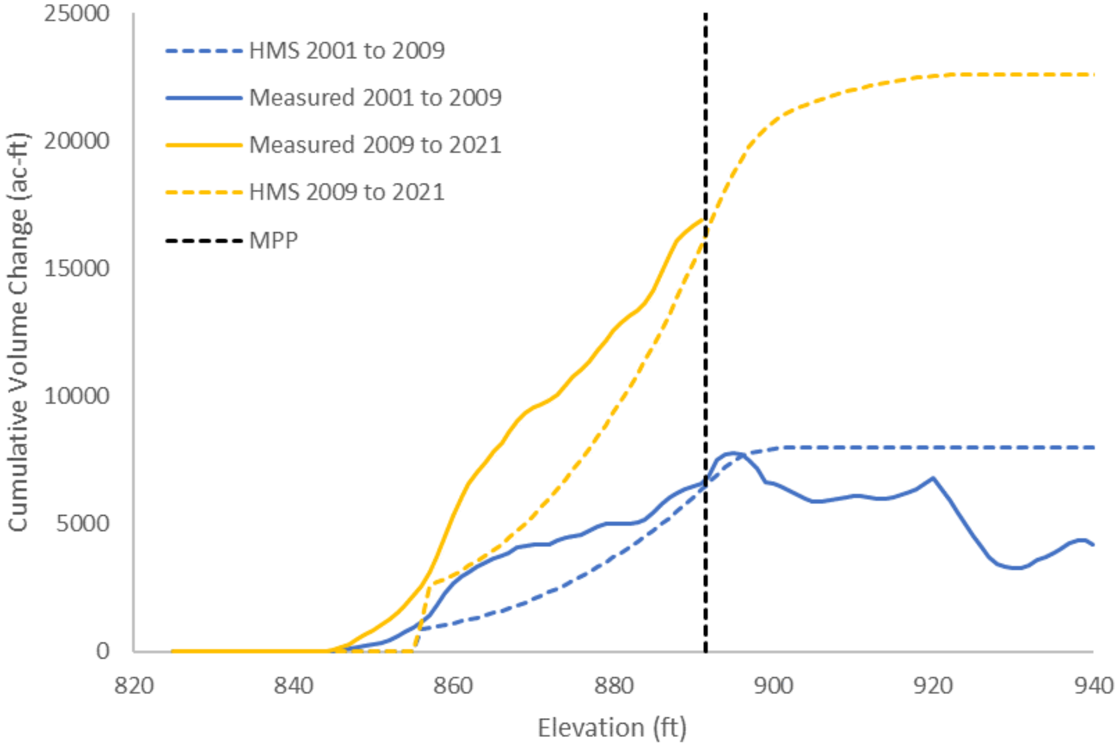

Figure 10: Cumulative volume change from 2001 to 2021 at Perry

Future Without Project and HEC-RAS Comparison

During the Kansas River Watershed Study, the future without project (FWOP) condition was estimated for the period between 2024 and 2124. The FWOP estimates were made using Microsoft Excel and ArcGIS, with a 1D HEC-RAS sediment model being used at Tuttle Creek to verify the methodology. The HEC-RAS sediment model was a 1D quasi-unsteady model that was calibrated to the 2009 to 2020 survey period. The Tuttle Creek HEC-HMS model was simulated over the FWOP period, and results were compared to the HEC-RAS output. Figure 11 shows the total cumulative volume change by elevation from 2024 to 2124, with the HEC-RAS and HEC-HMS results agreeing well with each other.

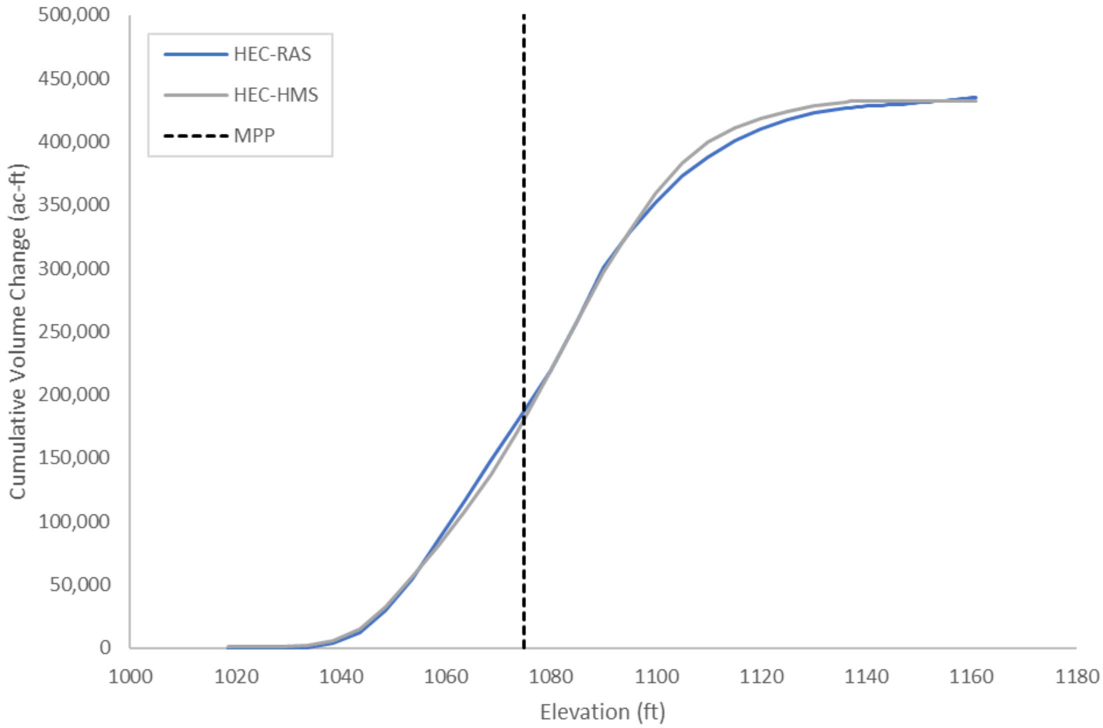

Figure 11: Projected FWOP volume change by elevation from 2024 to 2124

Conclusions

The new HEC-HMS reservoir volume reduction tool was evaluated to assess its ability to predict sediment deposition within three reservoirs in the Kansas River Watershed. Using the measured gradation for the incoming sediment load resulted in predictions for total sediment deposition that were biased low, which was possibly caused by HEC-HMS not being able to account for flocculation or reservoir shape. Shifting all the incoming gradation into the sand range to force the program to use the Brune methodology resulted in a much better agreement with the measured volume change. However, the default densities in HEC-HMS had to be adjusted to compensate for the shift in gradation. After the shift, the model would underpredict deposition at lower elevation in the reservoir, so a small percentage of sediment was shifted back to the fine gradations, which improved results further. The large amounts of calibration data allowed for the fine tuning of the models to match the observed volume change. If calibration data is not available, setting all the incoming sediment load to sand so the program only uses the Brune methodology will likely produce the best results. As indicated in Figure 4, this still produced good results for Tuttle Creek. However, as with any empirical method, the Brune methodology may not be applicable to every reservoir, so calibrating to measured data if available will produce the best results.

Comparing the HEC-HMS model results for Tuttle Creek to results from a 1D HEC-RAS model showed good agreement between the models, which indicates that HEC-HMS compares well with more established modeling methods. However, even after calibration to measured data, the HEC-HMS model underpredicted deposition in the lower elevations of the reservoir, as seen in Figure 5. Based on current limitations in HEC-HMS, HEC-RAS should be used if accurate modeling is needed across the full range of reservoir elevations, if the longitudinal volume change in the reservoir is needed, if accurate outflow concentrations from the dam are needed, or if sediment removal alternatives such as reservoir flushing must be modeled.

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