NEGOTIATING HYDROLOGIC UNCERTAINTY IN LONG TERM RESERVOIR SEDIMENT MODELS: SIMULATING ARGHANDAB RESERVOIR DEPOSITION WITH HEC-RAS

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Abstract: Water stored in the Arghandab Reservoir, in northeastern Afghanistan, supports subsistence agriculture in the Arghandab valley. The reservoir's contributing watershed is mountainous and mostly unvegetated, contributing unusually high sediment concentrations. Since its 1952 closure, sediment has filled about 45% of the reservoir volume. Lost reservoir capacity makes meeting downstream demand during low flow years difficult. The HEC-RAS sediment model was constructed and calibrated with a systematic, three step calibration process, targeting: 1) total volume, 2) longitudinal distribution and 3) gradation of sediment deposits. The calibrated model predicted reservoir stage-volume curves for four scenarios, including current conditions and three spillway raises. However, hydrologic uncertainty complicated prediction.

Gage flow records in this region are discontinuous, making hydrologic modeling challenging. Truncated time-series introduce uncertainty in sediment delivery and deposition simulations over standard, 50-year "project" time scales, longer simulations predicting reservoir lifespan. Therefore, stochastic scenarios of future hydrology included unobserved, low probability (1% to 0.1%) synthetic time series to quantify the uncertainty on long term (200 year) reservoir lifespan analyses associated with a brief measured flow record. This paper describes a systematic, three-stage method to calibrate 1D reservoir models, and an approach to hydrologic uncertainty in long-term sediment studies with short flow records.

Keywords: Sediment Modeling, Reservoir sedimentation, hydrologic uncertainty, sediment calibration, HEC-RAS

INTRODUCTION

The Arghandab River, and the irrigation systems built around it, made agriculture possible in arid southern Afghanistan, and are responsible for most of the region's economy (CID, 2008). The river supports subsistence agriculture in the Arghandab valley with water from mountain snow. Snow-melt hydrology is episodic, so converting it into reliable irrigation requires storage. The Arghandab reservoir, impounded by Dala -am, the second largest in Afghanistan, storing the episodic snow-melt regime and releasing predictable flows required for agriculture and irrigation. However, the mountainous, unvegetated watershed delivers unusually high sediment loads, filling 45% of the reservoir's capacity since the dam closure in 1952. As reservoirs fill with sediment, water storage is reduced and they lose the capacity to buffer communities against either floods or droughts. Storage lost to sediment increases the risk that water demand in dry years will not be met, which could have devastating social impacts on downstream agricultural communities.

The U.S. Army Corps of Engineers Omaha District and Hydrologic Engineering Center built hydrologic, hydraulic, and sediment models of this system to estimate the reservoir lifecycle and predict sedimentation effects on future drought vulnerability. The models also evaluated three spillway raise proposals and the influence these would have on reservoir life and future drought

risk on these estimates. The sediment modeling encountered two obstacles common in reservoir sediment transport modeling, equifinality and hydrologic uncertainty. The study documented approaches to:

1. Negotiate equifinality with a three-stage process of sediment calibration.
2. Quantify hydrologic uncertainty with stochastic analysis featuring hybrid time series including historical and synthetic hydrology.

These approaches to these common problems could inform and improve similar future work.

THREE-STAGE SEDIMENT CALIBRATION PROCESS

"Equifinality" - multiple parameter combinations can produce the same calibration results -is a challenge for any multi-parameter modeling problem (Beven, 1993; Pappenberger et al., 2005). Calibrating models with multiple, sensitive, uncertain parameters introduces non-unique solutions. Multiple parameter combinations can produce the same model result, reducing the confidence in the calibration and increasing the uncertainty of predictive results. Ordering free parameters by sensitivity and confidence can isolate the most important parameters (Ruark, 2011; USACE, 2014), those that are both sensitive and uncertain, but sediment models still often require multi-parameter calibration. Because sediment data are usually rare, sediment load magnitude and gradation are usually mostly uncertain. This is true in Western systems, but especially in regions of conflict like Afghanistan.

Evaluating a model against multiple, independent, calibration time windows (i.e. calibration-validation, though the terminology and methodology are controversial) is the classical approach to mitigate equifinality (e.g. Shelley and Gibson, 2015). However, in the absence of multiple calibration time-series, comparing results to several different prototype measurements over a single calibration window can help modelers negotiate non-unique calibration problems, converging on more robust models.

In an analogy of the n-equation solution to n-variable problems of more elegant mathematical systems, numerical calibration can mitigate equifinality with a multi-stage calibration approach, evaluating a multi- parameter calibration against multiple prototype measurements. In this case, two sensitive and uncertain parameters were estimated in a three-step calibration process.

Sediment calibration should always follow hydraulic calibration (HEC, 1993; Thomas and Cheng, 2007; e.g. Shelley and Gibson, 2014). Sediment models depend on good hydraulic calibration, as sediment results are highly sensitive to hydraulic parameters like bed roughness. Hydraulic calibration could be considered an additional stage to calibrate a third uncertain parameter (n-value). When possible the hydraulic calibration should be followed by a robustness analysis to test numerical stability, (HEC, 1993; Thomas and Cheng, 2007) though fundamentally non-equilibrium problems, like reservoir deposition, make the robustness concept difficult to apply.

After hydraulic calibration, the sediment calibration Arghandab Reservoir for the progressed through three stages, calibrating two free parameters by comparing model results to three

prototype measurements over a single calibration window (Table 1).

Table 1 Uncertain/sensitive model parameters and the prototype measurements used to estimate them.

Estimated Parameters	Evaluation Measurements
1. Load Magnitude	1. Total sediment volume
2. Load Gradation	2. Longitudinal sediment distribution
	3. Longitudinal bed gradation trend

1. Total Sediment Volume: Calibrating Load Magnitude

Most reservoir sediment models specify boundary sediment loads with flow-load rating curves. Even when the data to develop flow-load curves are available, scatter around a selected curve often span one- to-two orders of magnitude, making the flow load relationship a common calibration variable.

Mort et al. (1973) measured transects of the reservoir along historical, as-built cross sections, in 1971. A few years later data series end because of regional conflicts. These measurements created a 19-year calibration window that aligned with continuous upstream flow and reservoir stage data.

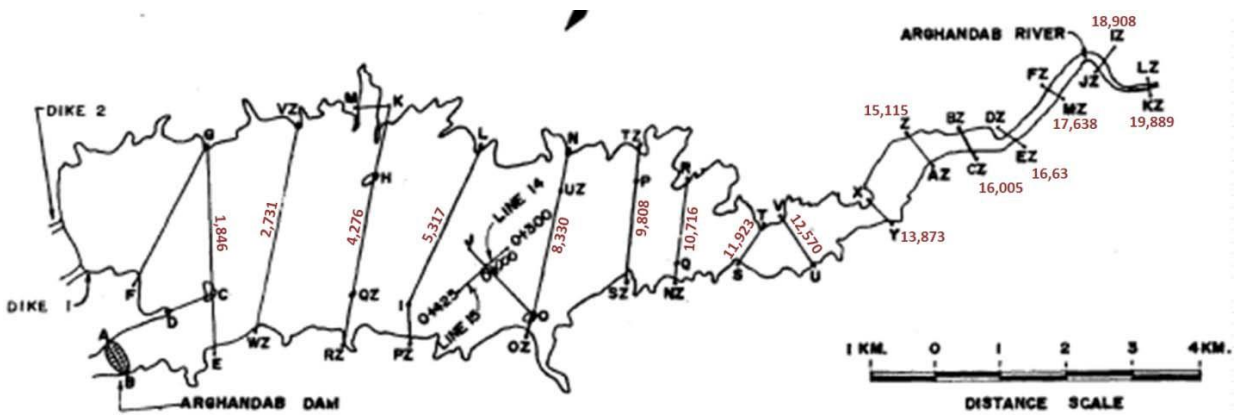

Figure 1 HEC-RAS cross section stations (red numbers) associated with the corresponding Mort et al. (1973) transects.

An as-built HEC-RAS model was constructed with the 1952 cross sections and run over the calibration period. Sediment volume change results were compared to the 89 million m3 deposition computed from the Mort et al. (1973) transects. The flow-load curve was adjusted until the model reproduced the total observed deposition volume. Results were compared to a few available load measurements and other regional flow-load curves.

2. Longitudinal Sediment Distribution: Calibrating Load Gradation

Most sediment transport models require sediment boundary conditions by grain class. Therefore, two uncertain parameters are wrapped up in the sediment load boundary: magnitude and

gradation. While load magnitude data are rare and noisy, load gradation data are usually even more uncertain, based on fewer and more erratic measurements.

In depositional environments however, load gradation can be calibrated to the longitudinal distribution of the deposits. Reservoirs sort sediment longitudinally by gradation and models use fall velocity to simulate that sorting relatively precisely (relative to the uncertainty in other transport algorithms). Therefore, once the total load is established with the flow-load curve, the gradational distribution of the inflowing loads can be adjusted to fit the longitudinal trend.

In the Arghandab model, load gradations were adjusted until the Arghandab HEC-RAS model re-created volume change at each location (Figure 2). This step sometimes requires feedback with the total volume analysis (Section 3.1), because moving mass to finer grain classes (e.g. clay or very fine silt) to induce deep pool deposition with trap efficiencies <100%, can reduce the total sediment mass deposited, requiring adjustments to the magnitude of inflowing loads. However the modeled trap efficiency and sediment releases through the dam should be checked against actual reservoir release concentrations, to verify that the estimated fine components are justified.

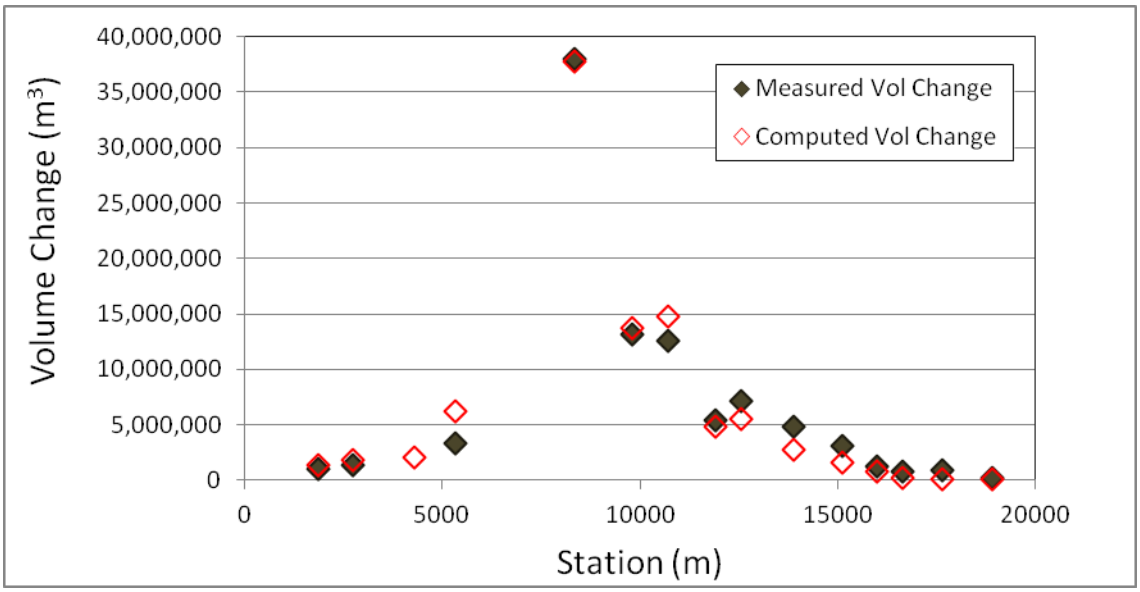

Figure 2 Computed and measured longitudinal volume change. Bed change at each cross section in the Arghandab reservoir between 1952 and 1971. The gradation of the upstream load boundary was adjusted to fit the computed result to the measurements.

3. Gradational Trend: Check and Update Load Gradations

Finally, the calibration was checked against bed gradations and updated accordingly. This could be considered a single-time-series analogy "verification," but verification terminology is controversial (Oreskes et al., 1994; Rykiel, 1996; Gibson, 2013), and production level models do not simply "fail" verification, but use the new data to update parameterization to produce the best final model possible.

Gradations were extracted from HEC-RAS calibration results and compared to a handful of 1973

bed gradations (Figure 3). Both the model and prototype gradation data must be interpreted carefully in this comparison. Computing gradational evolution results from active layer sediment models (like HEC- RAS) can be challenging. Cover layer gradations in HEC-RAS are a function of layer thickness, which are sometimes confounded by non-linear mixing dynamics. Especially detailed, multi-layer Lagrangian mixing methods like the Thomas and Copland methods (Exner 5 and 7 respectively in version 4.1) in HEC-RAS (which are required to develop and maintain the armor layers in the upper reach of the model), often reset cover gradations, making the surficial gradations at any time step stochastic, evolving non- monotonically.

Therefore, "computed gradations" were extracted from "total mass change" results, which develop more consistently. Because reservoir deposition is mainly monotonic, gradations can be computed from the depositional mass. This approach integrates vertical gradations in the deposit, extracting finer model gradations than the surficial prototype samples. As a reservoir delta progrades, finer material deposits deep in the reservoir, at the toe of the delta. Later, coarser deltaic deposits cover these deep, fine, materials. Reservoir sediment samples tend to collect the coarser, surface materials. The Arghandab model produced this result as the measured total-deposit gradations were coarser than the computed deposits (Figure 3).

Despite these complexities in comparing computed gradations of the active layer against surficial measurements, the comparison provided an independent evaluation of the model to mitigate equifinality uncertainty. Calibrating the model against three observations increased confidence and mitigated uncertainty in predictive results.

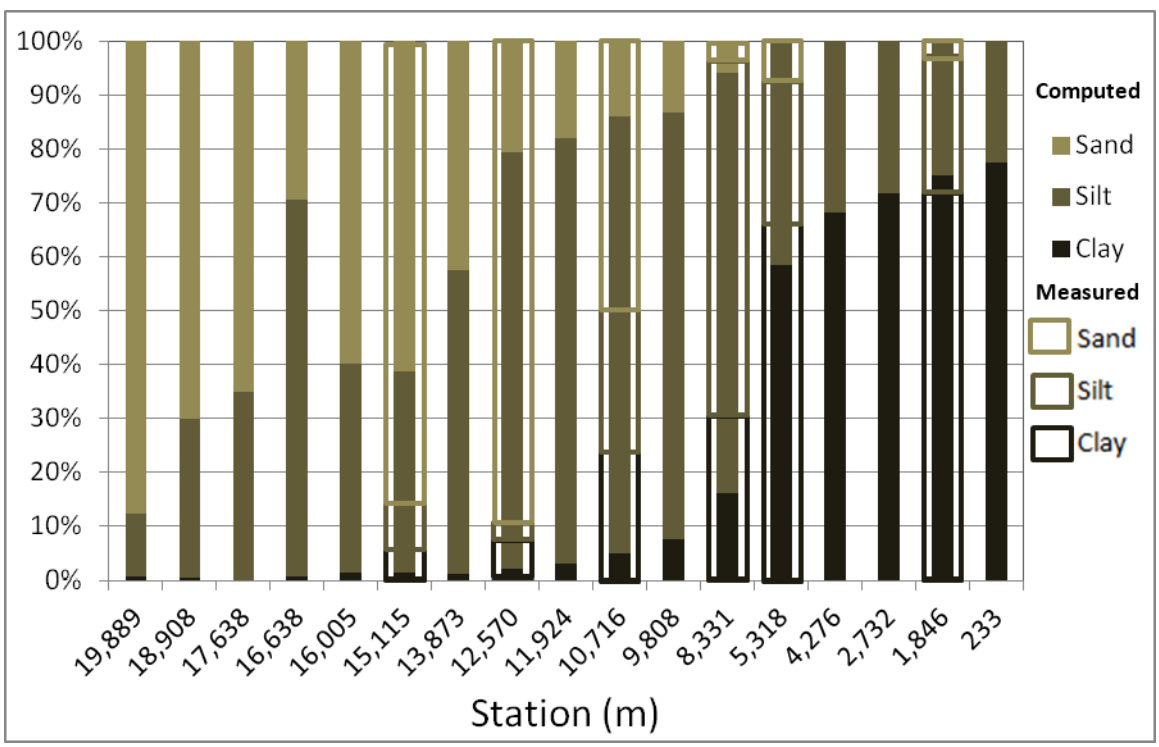

Figure 3 Computed and measured bed gradations for the 1952-1971 calibration of Arghandab reservoir deposition. Computed, vertically integrated, deposits are finer than the surficial measurements, as expected, but the trend "validates" load gradation calibration.

QUANTIFYING PREDICTIVE HYDROLOGIC UNCERTAINTY FOR SEDIMENT MODELS

Most reservoirs operate based on upstream and downstream flow gages, which provide good historic flow data for sediment models. Therefore sediment parameter uncertainty, confounded by limited data and scatter when data are available, usually overshadows historic flow uncertainty. However, when sediment analyses move from historic to predictive simulations, hydrologic uncertainty can dominate in a well-calibrated reservoir sediment model. Sediment transport is a non-linear function of flow, making projected deposition, reservoir life cycle, and future drought or flood protection heavily dependent on the flows in the following decades, particularly the frequency and timing of large events.

Historically, predictive sediment models have either ignored hydrologic uncertainty, by simply repeating historical records, or collapsed historical records into "representative years," sometimes augmented with probabilistic flows, that are repeated for every year of the simulation.

These approaches have limitations, however. Reservoir life cycles depend largely on the unknown time- series of future hydrology, so a repeated time-series will only predict the future (or even simulate a probable future) if it does not over or under predict flood frequency. Repeating the historical record can be particularly problematic in a system like Arghandab, where the regional history left a hydrologic record of only 28 years, and anecdotal evidence suggests that the ungaged records include much larger flows than those included in the measured time-series (Needham, 2006). Additionally, bed response to large events depends on their timing, sequence, and temporal relation to other events. A 1% event, five years into a simulation, may affect the system very differently than the same event in year 45.

Synthetic hydrographs of future conditions were developed to quantify hydrologic uncertainty in the Arghandab study. These stochastic hydrologic time-series were developed from a combination of 1) historical annual flow series and 2) synthetic flow years.

The HEC Statistical Software Package (HEC-SSP) (Brunner and Fleming, 2010) ordered the historic annual time-series and associated each with an exceedance probability based on peak seven-day flow volumes with a Log-Pearson III distribution (Figure 4). Each historical annual flow record was assigned a range of probabilities surrounding its plotting position. The ordered peaks had an "S-shaped" alignment, however, so the right half of the data (larger than average flows) had a prominent negative skew. Negative skew makes the log normal distribution (i.e. LPIII with zero skew) over predict high flows, so historical flow series were scaled to align with the flow at the corresponding position on the flow-frequency curve. For example, the 1954 flow record was assigned probabilities between 0.33 and 0.365 (based on where it plotted on the flow-frequency curve) and high flows were multiplied by a scaling factor of 0.94 to bring the seven-day volume in line with the log normal distribution.

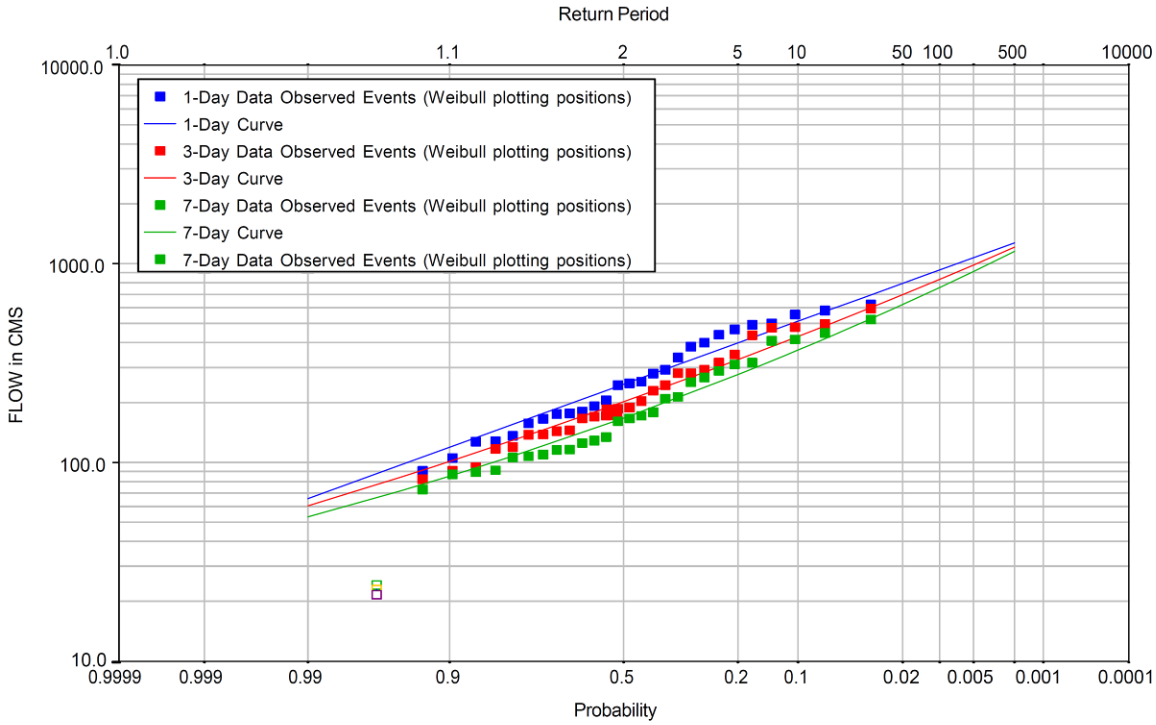

Figure 4 Volume frequency analysis for the gage upstream of Arghandab Reservoir (September 1951 to Mar 1979).

When using plotting positions, a 6% exceedance probability is assigned to the largest historical flow. Rarer events (5%, 2%, 1%, 0.5%, and 0.1%), were constructed by scaling a regularly shaped, single peak, historic "model" hydrograph (Water Year 1965) into synthetic, low-frequency flood events. The flood season flows of the model hydrograph were scaled by the ratio of the peak flow (computed in a separate HEC- SSP analysis) to the 1965 peak (Figure 5). Twenty, 50-year, synthetic flow series (1,000 total flow years) sampled these historic and synthetic annual time-series (Figure 6) with a random number generator, including nine 1% events, two 0.5% (200 year) events, and one 0.1% (1,000 year) event.

The HEC-RAS sediment model (with estimated contemporary bathymetry) simulated 50-year futures including a no-action alternative and three proposed spillway raises, by repeating the historic time-series and each of the twenty stochastic time-series for each of the four alternatives. Final bed elevation profiles for the three alternatives and no-action condition with the repeated historic record are plotted in Figure 7. However, the stochastic hydrologic analysis made it possible to compute and communicate the potential range of results hydrologic variability could produce. In Figure 8, the 50-year reservoir storage volume computed from the analyses in Figure 7 are plotted with results from the stochastic simulations, placing the repeated historic time-series results in the context of its hydrologic uncertainty.

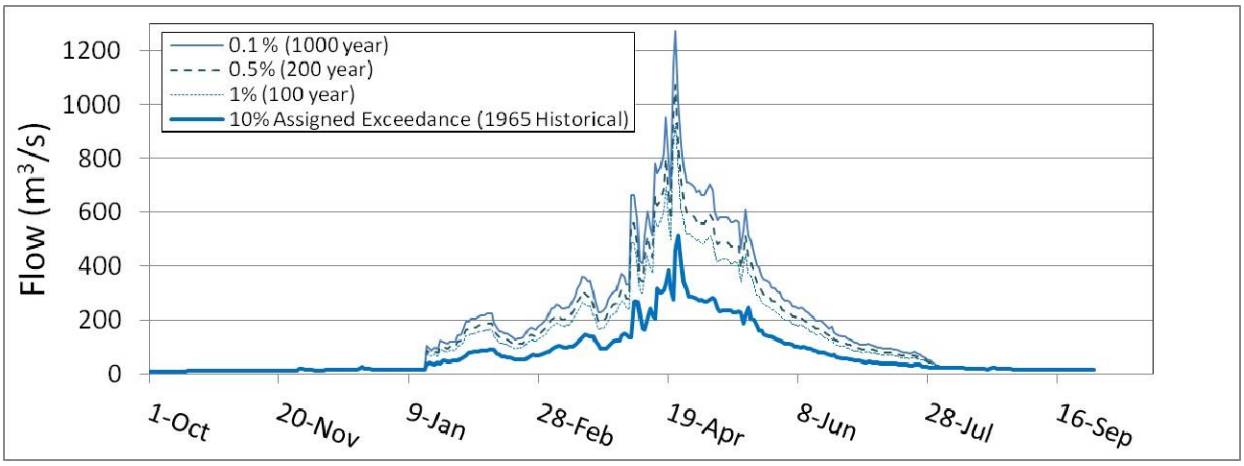

Figure 5 Synthetic annual flow series, low probability flows, larger than those observed during the 32 year flow record, constructed by scaling the 1965 event to the 7-day probabilistic volumes computed by HEC-SSP.

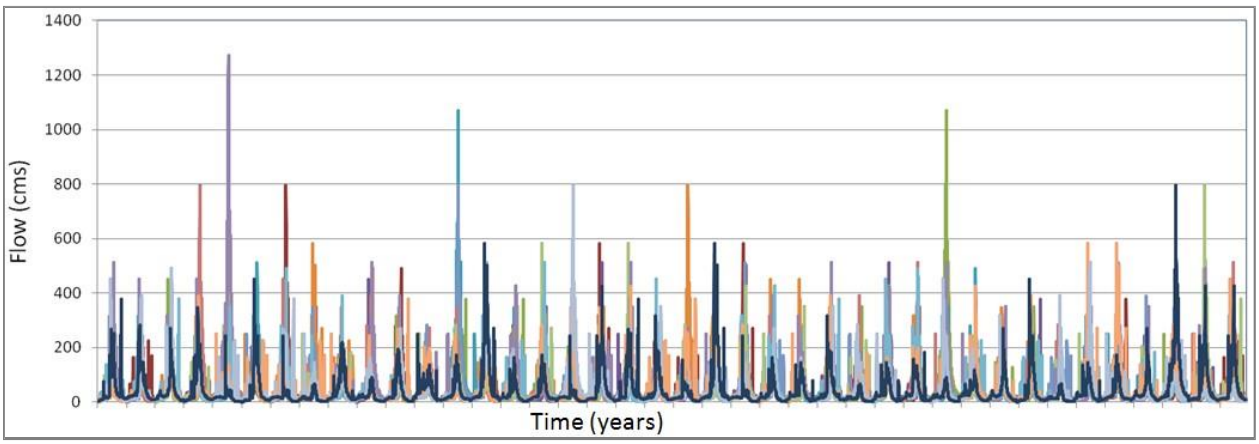

Figure 6 Twenty synthetic flow series used to quantify hydrologic uncertainty.

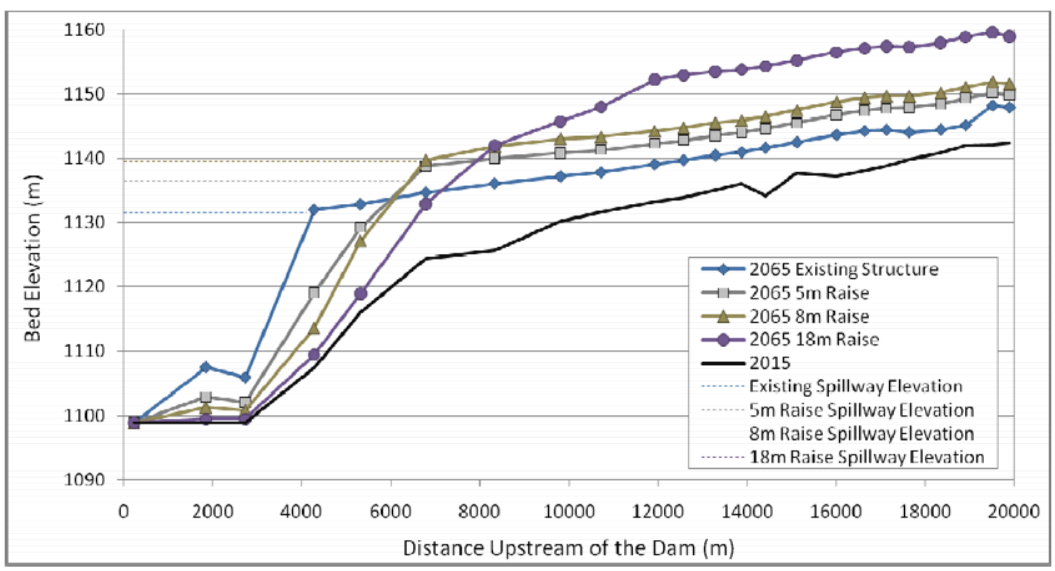

Figure 7 Predicted 2065 reservoir bed elevation (thalweg) for the existing structure and three alternatives, plotted with the initial (2015) profile.

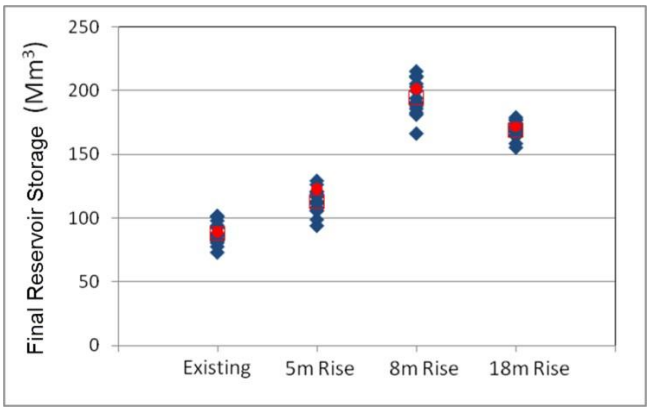

Figure 8 The final water volume (in 2065) beneath the original spillway elevation (1135.4 m) for the predictive simulation (red dot •), simulations based on random 50-year hydrologies (blue diamonds □) and the average of the random simulations (red square□).

RECENT DEVELOPMENTS

Customized code generated stochastic hydrologic time-series in this study. Since then, HEC has developed unsteady sediment transport capabilities in HEC-RAS (Gibson and Boyd, 2014; Shelley et al., 2015) and automated time-series sampling in the HEC-WAT (Dunn and Baker, 2010). Combining these capabilities automate sediment model hydrologic uncertainty analyses, like the one described above.

HEC-WAT creates time-series from historic and synthetic annual time-series like those depicted in Figures 5 and 6, and automatically launches HEC-RAS sediment simulations with each realization automatically. These developments will simplify hydrologic uncertainty for sediment models.

CONCLUSIONS

The uncertainty surrounding sediment models can reduce their utility and is sometimes cited as a reason to forgo modeling that could add value by reducing uncertainty. Good calibration against multiple time-series, or in their absence, against multiple measurements, can reduce model uncertainty to acceptable levels. However, the uncertainty associated with sediment transport model results is a fundamental characteristic of the analysis. Providing results with explicit uncertainty analyses puts results in the context of the project risk portfolio and provides the range of probable outcomes.

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