IMPORTANCE OF UNREGULATED INFLOW DATASETS

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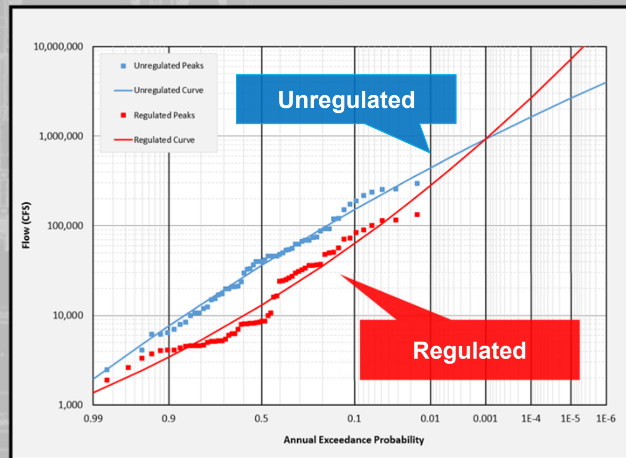

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OVERVIEW

US Army Corps of Engineers
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- Assumptions
- USACE Guidance
- Why is Unregulated Data Important?
- Identification of Appreciable Upstream Regulation
- Development of Unregulated Inflow Dataset
- Development of Stage-Frequency Curve

ASSUMPTIONS

US Army Corps of Engineers
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- USACE Dam Safety Perspective
- Dams with Upstream Regulation

In several of the previous lectures, we've been discussing regulation downstream of a reservoir

In this lecture, I'll focus on the USACE Dam Safety perspective, where the considerations are fitting analytical flow frequency distributions for the inflow to USACE reservoirs that are subject to upstream regulation.

For example, the inflows to Foster Dam, located in the Willamette River Watershed in the state of Oregon, are affected by upstream regulation from Green Peter Dam

TERMINOLOGY

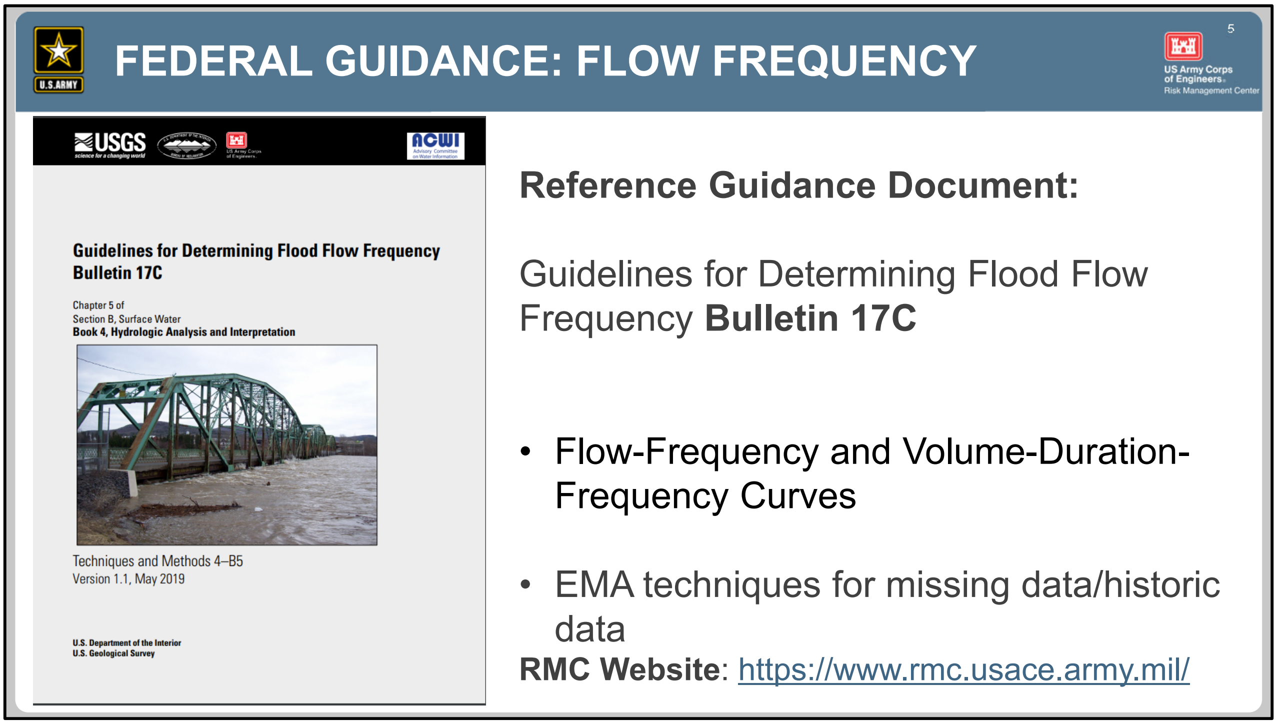
Annual Exceedance Probability (AEP)
Regulated Inflow
Unregulated Inflow
Flow-frequency
Volume-frequency
Annual maximum series
Analytical Distribution
Log-Pearson III (LPIII) Distribution
Plotting Positions
Expected Moments Algorithm (EMA)
Graphical/Empirical Distribution
Convergence Threshold
Stage-frequency

- Annual Exceedance Probability: refers to the probability of a flow/stage/precip depth/etc being equaled or exceeded in a given year.
- **Regulated: Inflow data set that is affected by upstream regulation.**
- **Unregulated: Inflow data set that has no upstream regulation or is not affected by upstream regulation.**
- Flow-Frequency: the frequency with which an instantaneous maximum flow rate is expected to be equaled or exceeded
- Volume-Frequency: the frequency with which a flow over a given duration is expected to be equaled or exceeded. Volume must always be specified with a duration. Typically, volume-frequency is presented using units of flow (i.e. cfs) so that the different durations can be plotted together. (VDF Curves)
- Annual Maximum Series: a data set composed of the maximum flood event in each water year in the period of record
- **Analytical Distribution: A probability distribution developed through the use of statistical parameters, such as mean, skew, and standard deviation**
- **Log-Pearson-III (LPIII) Distribution: The preferred distribution used to describe flow and stage AMS data**
- Plotting Positions: Default is Weibull method, relative ranking
- Expected Moments Algorithm (EMA): Approach used in Bulletin 17C Federal guidance for combining uncertainty from historical data, regional skew, and systematic data.
- **Graphical/Empirical Distribution: A probability distribution developed by selecting flows or stages corresponding to AEP values in an effort to provide a best fit line through the**

historic stage or flow AMS

• **Convergence Threshold: the initial flood magnitude at which the difference between regulated and unregulated flows is negligible.**

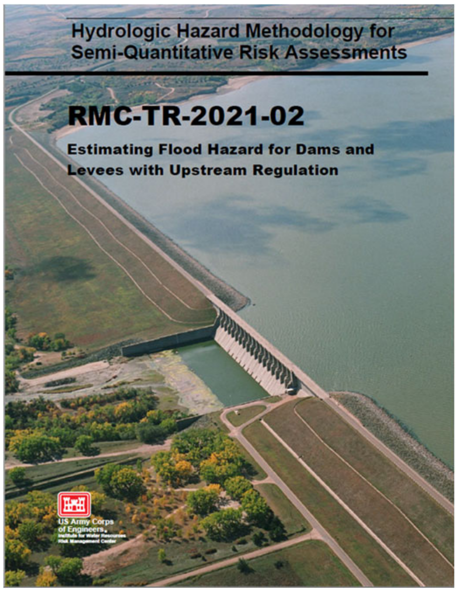
• Stage-Frequency: the frequency with which an instantaneous maximum stage is expected to be equaled or exceeded



Federal Policy requires use of B17C procedures, which fit the Log Pearson Type III analytical distribution to an annual maximum series of unregulated peak flows.

B17C procedures have improved the estimation of confidence limits.

USACE GUIDANCE: UPSTREAM REGULATION



Reference Guidance Document:

Risk Management Center Technical Reference **RMC-TR-2021-02**

“Estimating Flood Hazard for Dams and Levees with Upstream Regulation”

RMC Website: https://www.rmc.usace.army.mil/

A prerequisite for performing flood hazard analysis is obtaining an unregulated inflow period of record dataset.

For more information about how to handle upstream regulation and how to develop an unregulated dataset, please reference Risk Management Center Technical Reference **RMC-TR-2021-02** “Estimating Flood Hazard for Dams and Levees with Upstream Regulation”.

WHY IS UNREGULATED DATA IMPORTANT?

- **Why is it important to treat regulated data sets differently?**
  - Many dams in USACE portfolio have upstream regulation
  - Age of USACE dams is usually less than 100-years
  - **Flow-Frequency Analysis conducted on regulated data can dramatically over or underestimate risk.**
  - Upstream regulation often affects annual maximum series
  - **Federal guidelines require the use of Bulletin 17C**

You might be wondering, why is it important to use unregulated data in flow-frequency analysis?

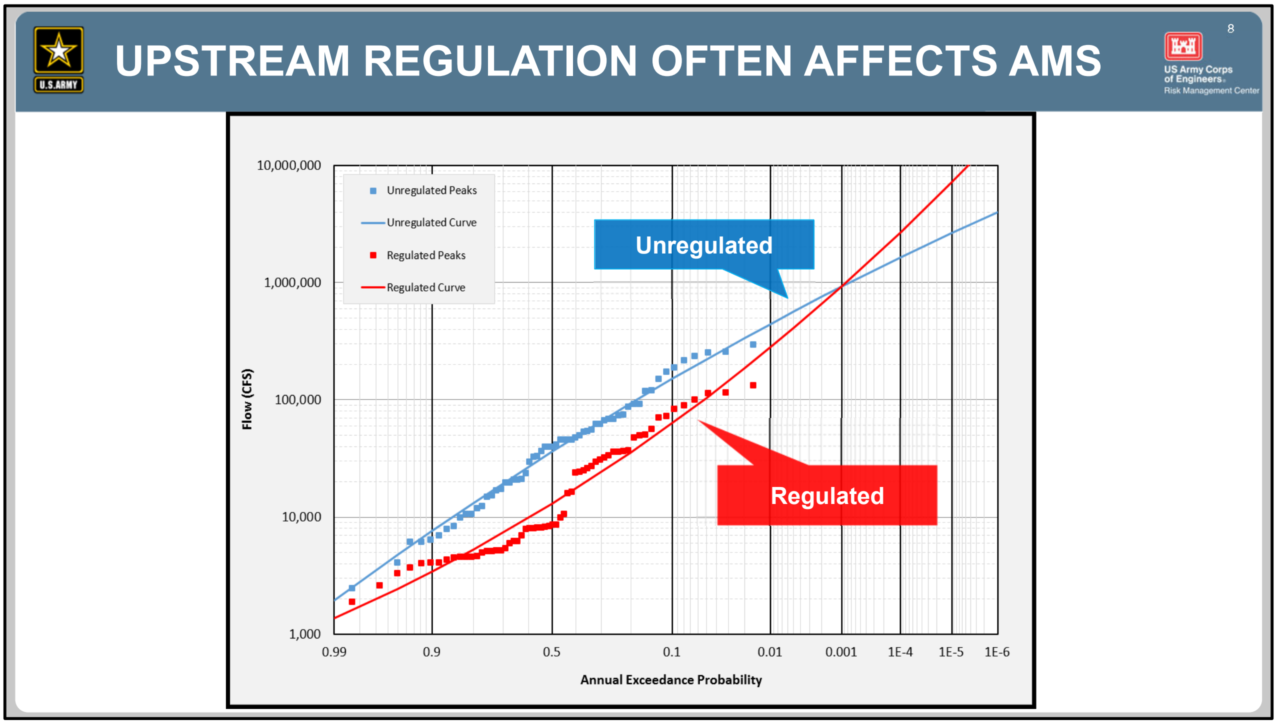
Many locations have upstream regulation which can significantly affect annual maximum flows and volumes.

Many locations also have relatively short record lengths which means that volume frequency curves need to be extrapolated to rare annual exceedance probabilities for risk assessments.

When analytical frequency curves such as Log Pearson Type 3 are fit to regulated data, the impacts of regulation can be dramatic especially for the extrapolated portion of the curve resulting in significant over or underestimation of the risk.

When there is upstream regulation, you will need to assess whether the regulation effects are appreciable, and if the effects are appreciable, perform analysis to remove the effects of regulation from the flow or volume data.

Federal guidelines require the use of Bulletin 17C for flow frequency analysis



An example of appreciable regulation can be seen in the figure. The red series is the annual maximum flow data with upstream regulation and the blue series is the unregulated flow data.

Frequency curves were computed for both annual maximum series, shown as the red and blue curves, respectively.
You can visually see that the blue curve provides a better overall fit to the data and a more credible extrapolation.

The main things to keep in mind are:
•Unregulated flow or volume data should typically be used for frequency analysis. Using regulated data can over- or under-estimate the risk.
•It is important to assess whether upstream regulation has an appreciable effect on the data.
•Unregulated data sets should be developed when regulation effects are significant.
•Regulation can change over time.
•The data needs to be homogenous which means that we should not combine records with significant regulation effects with records of unregulated data.
•As always, Engineering judgment will be required

THREE QUESTIONS TO ANSWER

- 1) Is upstream regulation appreciable at the dam of interest?
- 2) How do I develop an unregulated flow data set?
- 3) How do I ensure the stage frequency curve is relevant to the existing regulated system?

The USACE guidance for Estimating Flood Hazard for dams with upstream regulation is organized to answer these three questions:

1) Is Upstream regulation appreciable at the dam of interest?
2) How to develop unregulated flow data from regulated data.
3) How to ensure that the resulting stage frequency curve is relevant to the existing system

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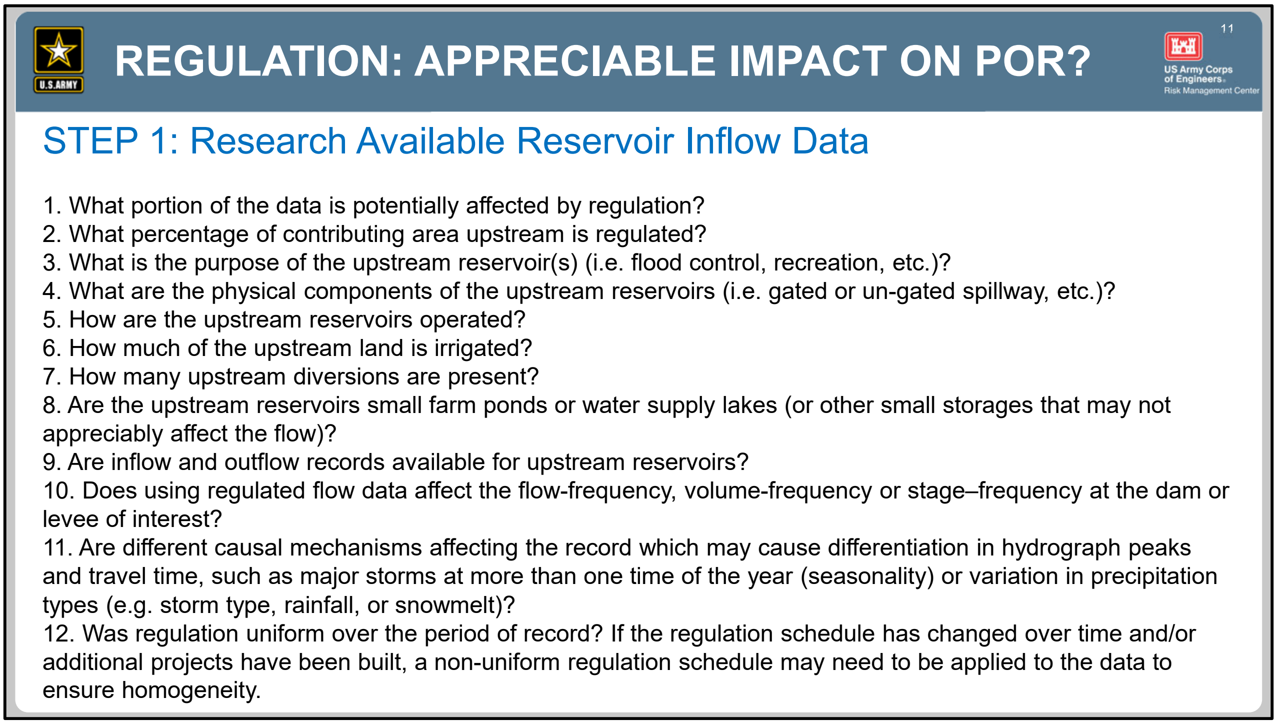
First, we'll discuss how to identify whether the dam of interest experiences appreciable upstream regulation.

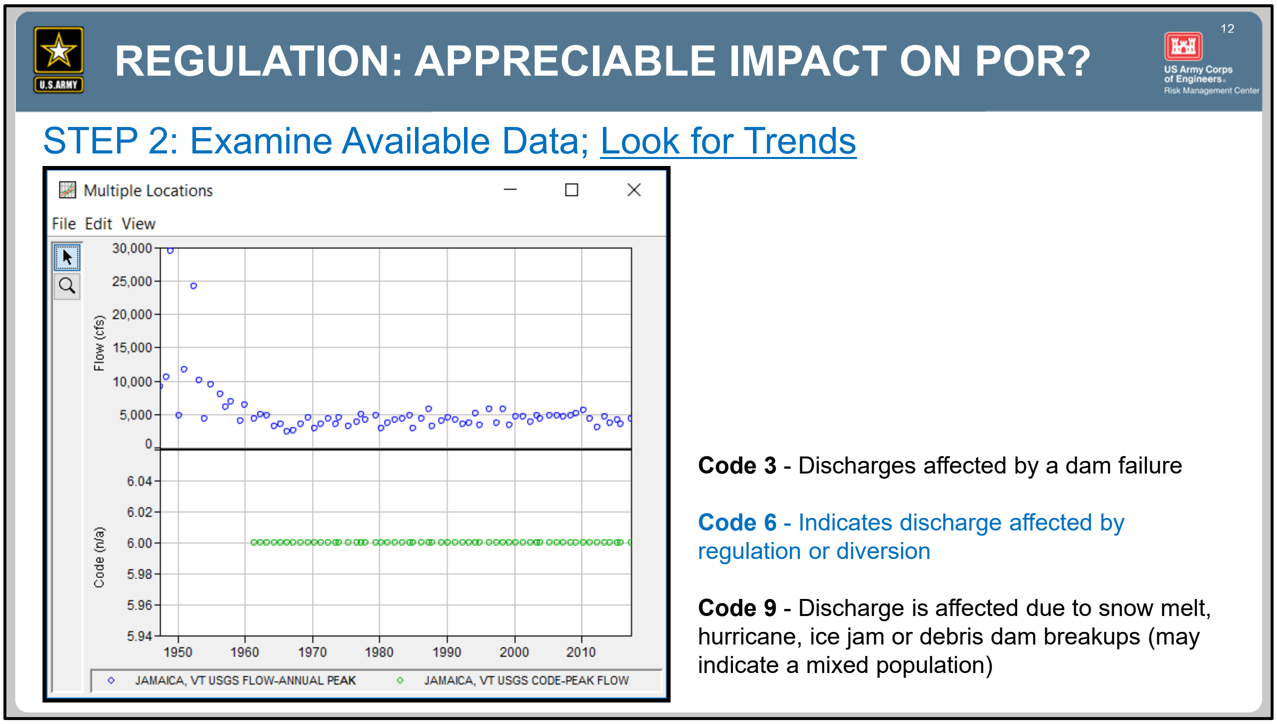


The first step you will want to take when beginning an inflow frequency analysis for a USACE Dam Safety project is to **research the available reservoir inflow data**.

On this slide are some examples of questions you may want to ask yourself when beginning an inflow frequency analysis for a dam.
Investigating these questions can help develop an understanding of the inflow data set and the extent of system regulation.

Examples of Questions to Ask:

- What portion of the reservoir POR was affected by regulation?
- What is the percentage of contributing area upstream affected by regulation?
- What is the purpose of the upstream reservoir(s) (i.e. flood control, recreation, etc.)?
- What are the physical components of the upstream reservoirs (i.e. gated or un-gated spillway, etc.)?



After you have researched the available inflow data, the next step is to **examine the available data for trends.**

When examining the available flood records for a Federal flood risk management project, it is vital to ensure the **homogeneity and consistency**
of the data set while also identifying the **impact of upstream regulation**
prior to development of flow- and volume-frequency curves that will be used to generate a stage-frequency curve.

USGS provides flow codes that indicate external effects that may be impacting the flow measurements
Of particular interest are USGS flow codes 3, 6, and 9 as they indicate potential regulation effects that may need to be removed from the data set:
Code 3: Discharges affected by dam failure
Code 6: Discharge affected by regulation or diversion
Code 9: Discharge affected by snow melt, hurricane, ice jam, or debris dam break ups (Note: this can indicate a mixed population)

In the figure, you can see the annual peak flow vs. time plot displayed as open blue circles
The bottom portion of the plot displays open green circles representing the USGS data code associated with each of the annual peak flows.

Examination of the peak flow dataset displays an appreciable amount of regulation as indicated by the behavior of the data following the construction of an upstream dam in 1961
This trend is corroborated by USGS peak flow code 6, which also begins when the upstream dam was constructed in 1961.

REGULATION: APPRECIABLE IMPACT ON POR?

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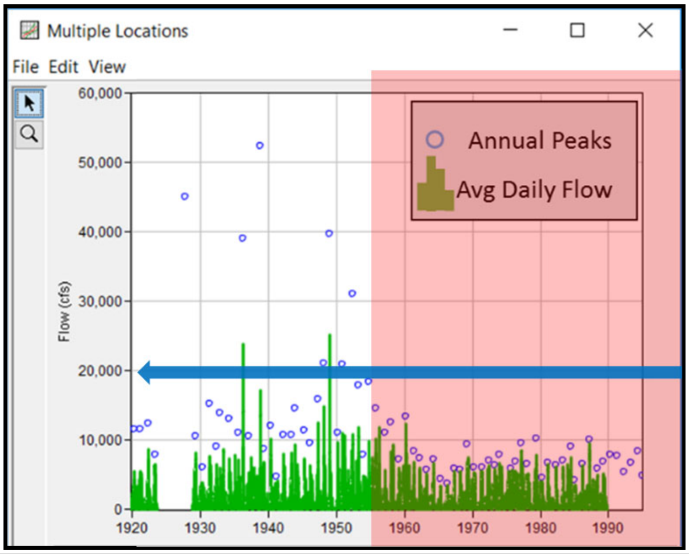
STEP 2: Examine Available Data; Look for Trends



Here is another example of how to examine a reservoir inflow dataset.
This plot displays average daily flows in green, and annual peaks as blue open circles

(click) As you can see, there appears to be a marked change in system behavior starting in the mid 1950's.

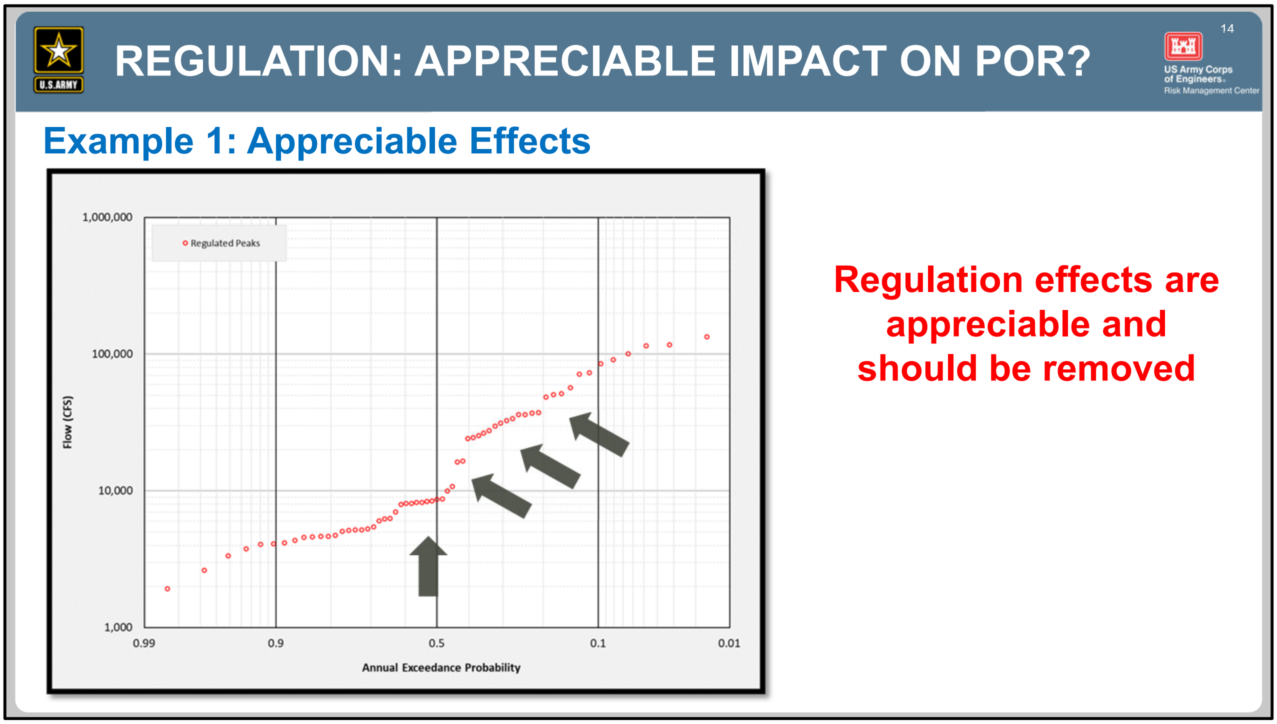
Specifically, notice the lack of large annual peaks in excess of 20,000-cfs after this time period. (click)

This may indicate a change in the upstream system, hinting at a non-homogenous data set.

Also notice the lack of significant differences between annual peak and daily average after the 1950s.

These observations may indicate a change in the upstream system, hinting at a non-homogenous data set.

RMC TR-2021-02 guidance provides suggested methods to parse out the regulated and unregulated portions of the record and develop an acceptable inflow record for use in flow-frequency analysis.



Now I will go through a series of examples to demonstrate how to identify if the upstream regulation is having an appreciable impact on the reservoir inflow dataset.

For all three of the examples, there is one or more dams upstream of our reservoir of interest.

When there is known regulation upstream, but the extent of the impacts are uncertain, further investigation is required.

It may be easiest to observe distinct changes in flow-frequency by plotting the data on a log-normal probability plot using Weibull plotting positions.

(click) Our first example is a dam whose inflow dataset shows an obvious impact from the upstream regulation.

In this example, we can observe the irregular shape of the data,

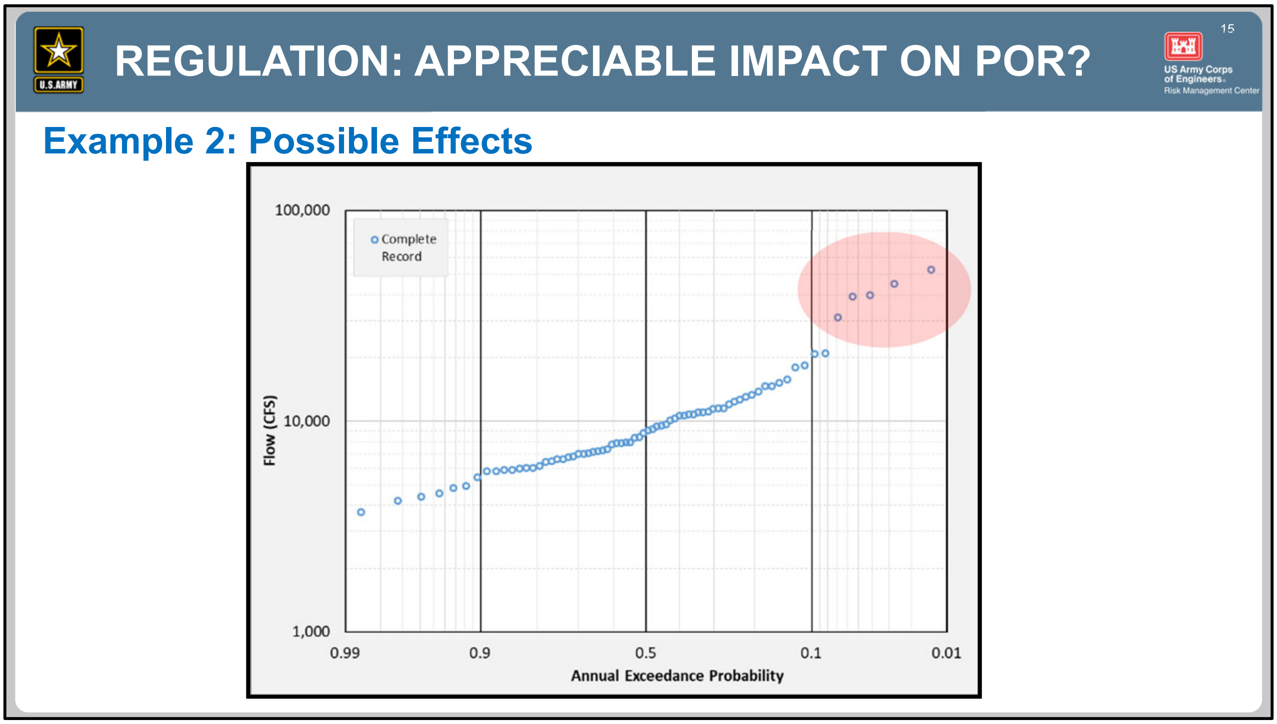
We can see a noticeable flat spot near (click) 8,500-cfs/ 0.5 AEP and (click) marked changes in slope throughout the dataset

If an LPIII distribution was fit to this data, the result will likely be poor and extrapolations to remote AEP may be erroneous.

This is a problem for dam safety studies, when we are often most interested in the remote end of the frequency curves.

(click) In this example, the effects of regulation are appreciable and should be removed.

Examples of how to produce an unregulated inflow data set will be covered in future slides



For example, two, (click) we see a reservoir inflow dataset we know is affected by upstream regulation.
However, when examining the empirical frequency curve, it is not easy to discern whether regulation effects are occurring within this dataset.

(click) There may be regulation effects when flows are greater than 20,000 cfs, or the 5 largest events may be caused by a different run-off mechanism (e.g. rain vs. snowmelt).

If there is a sufficient amount of unregulated data in the record (i.e. 20+ years before and after the upstream dam was in place)
one way to discern whether regulation effects are appreciable is to **separate** the annual maximums into two discrete series:
1) Annual maximums prior to the construction of upstream projects (pre-dam), and
2) Annual maximums after construction of upstream projects (post-dam).

A minimum of 20 years of annual maximum data is recommended within each series to support drawing conclusions regarding regulation effects.
The record length does not need to be the same length for each of the series.

REGULATION: APPRECIABLE IMPACT ON POR?

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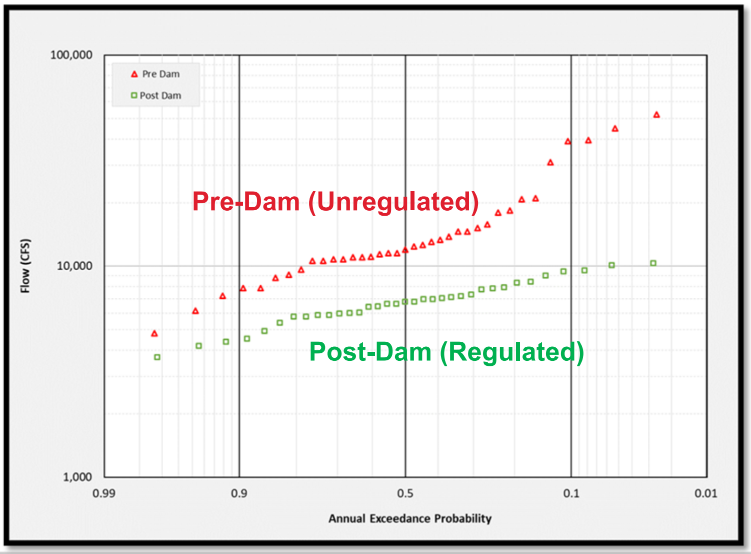
Example 2: Separate Unregulated and Regulated series



In this example, we had sufficient pre and post dam records, so the record has been split into a 37-year pre-upstream dam and 35-year post-upstream dam series to delineate the data based on upstream dam construction.
These records display a noticeable difference in mean, standard deviation, and skew that is likely due to regulation.

Fitting an LPIII distribution to each data set would result in drastically different estimations of flow rates for rare exceedance probabilities

We need to reconcile the differences between the regulated and unregulated series.

How to develop unregulated inflow data sets will be covered in further slides

KOLMOGOROV-SMIRNOV (KS) TEST

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$$D = \sqrt{-\frac{1}{2}\ln\left(\frac{\alpha}{2}\right)}\sqrt{\frac{n+m}{nm}}$$

Alpha (α): Significance Level

Two Samples with sizes n and m

A quick test can be conducted to assess whether the pre-dam and post-dam data sets come from the same population distribution.

The Kolmogorov-Smirnov (**KS) test** is used to compare empirical distribution functions of the two samples.
I'll begin by defining the terms and equations, and then show a few examples of how to compute the KS test.

For sample sizes greater than twelve (12), the **critical KS test value (D)** can be calculated using this Equation which is a function of the significance level (α) and the size of the two samples (n and m).

We can use a **null hypothesis which states that the two samples come from the same population distribution** (i.e. the effects of regulation are negligible).

KOLMOGOROV-SMIRNOV (KS) TEST

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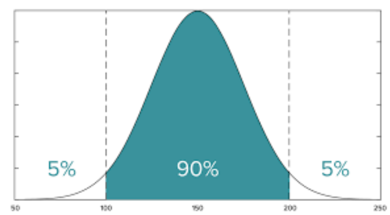
$$D = \sqrt{-\frac{1}{2}\ln\left(\frac{\alpha}{2}\right)}\sqrt{\frac{n+m}{nm}}$$

$$= \sqrt{-\frac{1}{2}\ln\left(\frac{(0.05)}{2}\right)}\sqrt{\frac{n+m}{nm}}$$

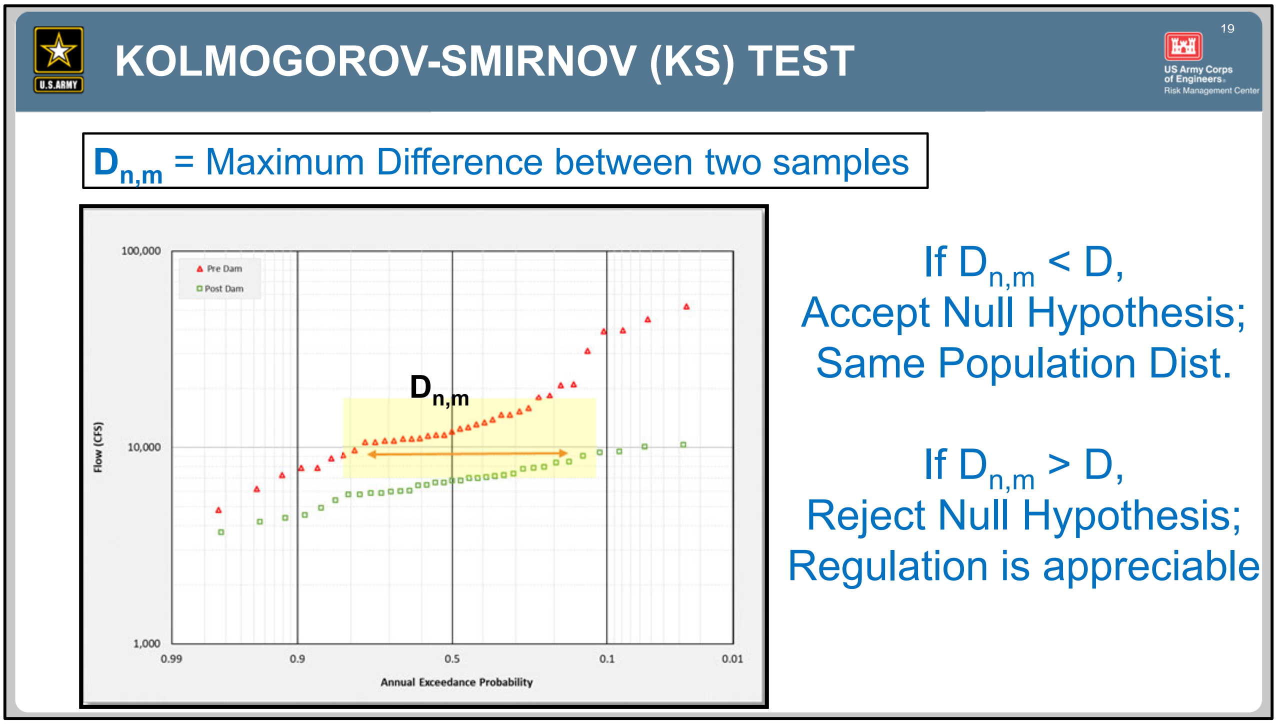
$$= 1.358\sqrt{\frac{n+m}{nm}}$$



The significance level (α) is representative of the level of confidence of the study.

(click) For instance, if a 90% confidence analysis is desired, the significance level selected would be 0.05, representing the 5-percent at the upper and lower ends of a normal distribution that are outside the confidence interval.

(click) Using a significance level of 0.05, the **critical KS test value (D)** equation reduces to: 1.358 SQRT ((n+m)/(nm))



The test statistic $D_{n,m}$ (click) is the maximum difference between the empirical distributions for the two samples
In this example: Greatest horizontal difference between unregulated and regulated data is at a flow value of about 9,000 cfs

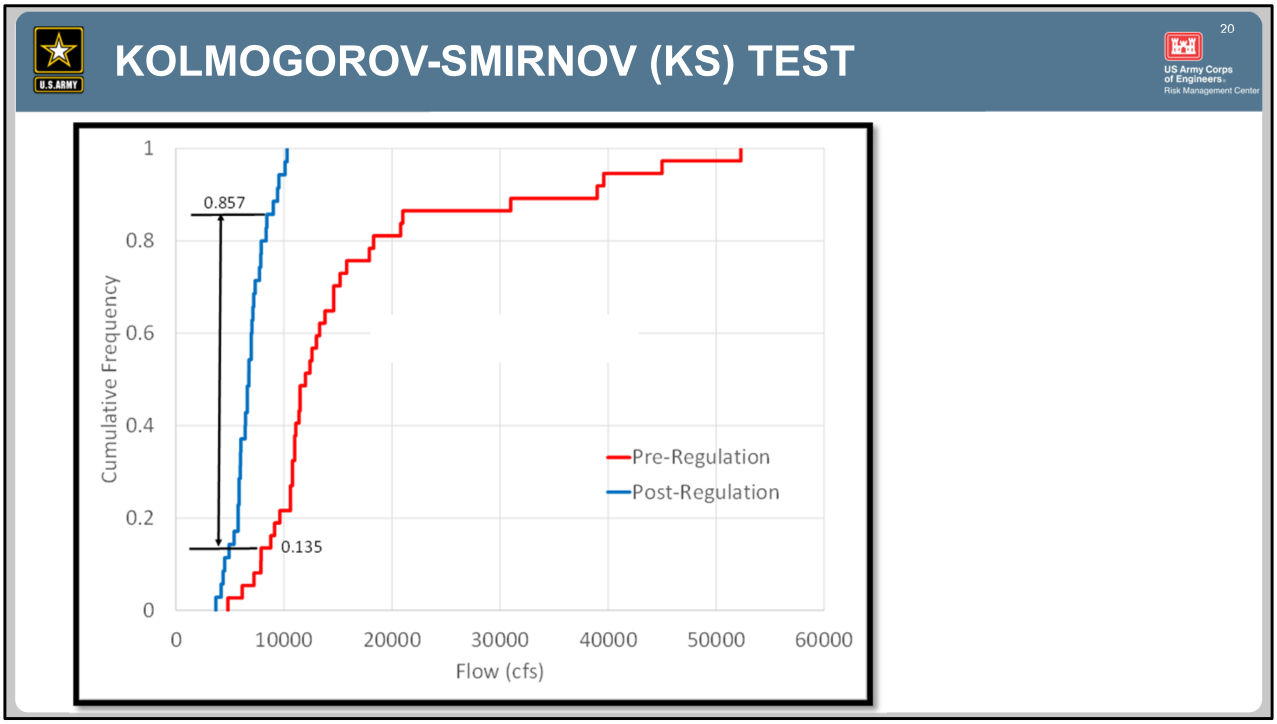
We will investigate the **null hypothesis, which states that the two samples come from the same population distribution** (i.e. the effects of regulation are negligible).

(click) If $D_{n,m}$ < D, then **accept** null hypothesis, which means the two samples **DO** come from the same distribution. This indicates the effects of regulation are not significant and we can neglect the in our analysis.

(click) If $D_{n,m}$ > D, then **reject** null hypothesis, which means the two samples **DO NOT** come from the same distribution – in other words, the effects of regulation are appreciable, and we cannot neglect them.

If we reject the null hypothesis, meaning that the two samples come from different populations, **and we must remove the effects of regulation.**

More to come on future slides on how to accomplish removing the affects of upstream regulation.



The Kolmogorov-Smirnov (**KS) test** is used to compare empirical distribution functions of the two samples.

Each of the two data sets can be converted to a step-wise function plot: flow vs. cumulative frequency plot, as shown in the Figure by sorting the flow data from small to large and assigning probability based on rank

1) First, we flip the chart, so now flow is on the horizontal axis and cumulative freq. is on the vertical axis
2) Convert each of the data sets into a step-wise flow vs. cumulative frequency plot.
    1) Get plotting position by sorting flow data from small to large and assign a probability based on rank (rank/sum of data points).
    2) Then sort from Large to small, and take 1- plotting position
    3) Next, insert intermediate ordinates, and duplicate the flow, so there are steps

STEP WISE FUNCTION EXAMPLE

STEP 1: Compute Cumulative Frequency

	Unregulated =(1-Plotting Position)	Plotting Position	Flow (CFS)
1	0.978	0.022	55,322
2	0.948	0.052	46,400
3	0.917	0.083	39,802
4	0.886	0.114	38,950
5	0.855	0.145	31,580
6	0.824	0.176	22,905
7	0.793	0.207	22,523
8	0.762	0.238	19,640
9	0.731	0.269	18,223
10	0.701	0.299	17,053

STEP 2: Create Step-Wise Function

	Unregulated =(1-Plotting Position)	Flow (CFS)
1	0.978	55,322
1.5	0.948	55,322
2	0.948	46,400
2.5	0.917	46,400
3	0.917	39,802
3.5	0.886	39,802
4	0.886	38,950
4.5	0.855	38,950
5	0.855	31,580
5.5	0.824	31,580

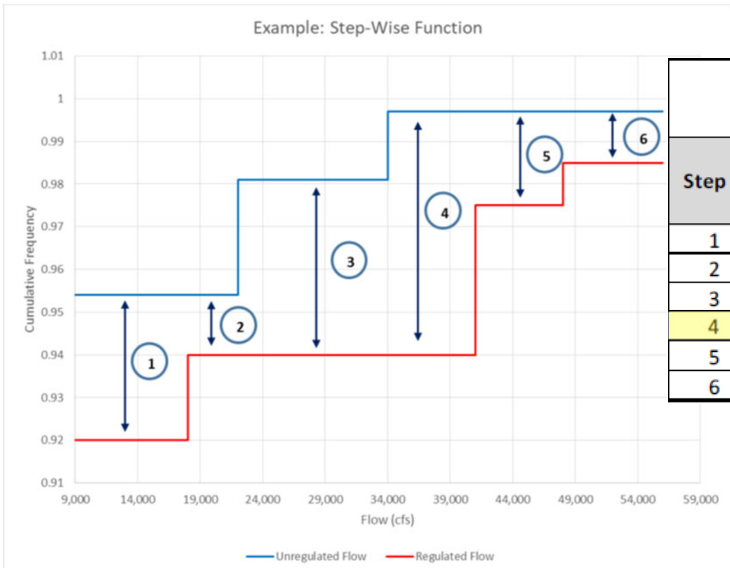
Here is how we develop the step-wise function.

In Step 1, (click) the cumulative frequency is computed by taking 1 minus the plotting position.

In Step 2, (click) a step-wise function is developed by inserting an intermediate ordinate between each ordinate.

To create the step-wise function, (click) the inserted ordinates have the same flow value as the ordinate previous, and have (click) cumulative frequency values the same as the following ordinate

STEP WISE FUNCTION EXAMPLE



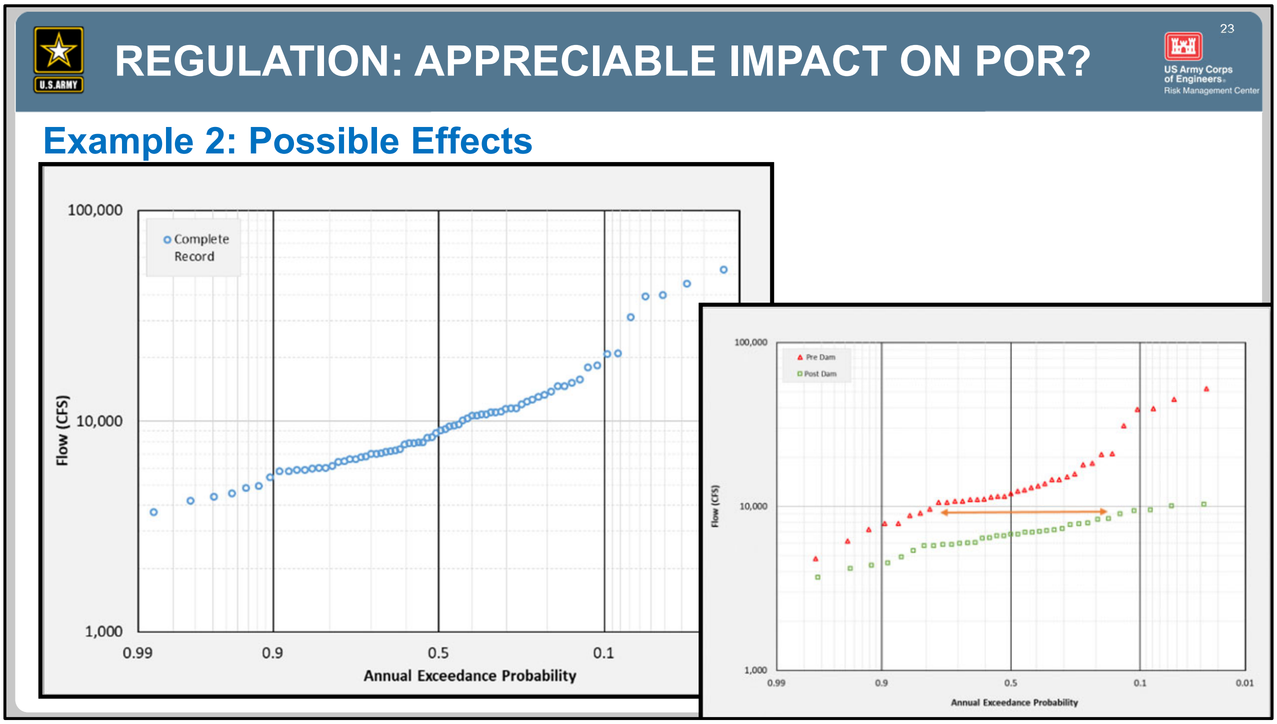
	Blue Curve Unregulated Flow	Red Curve Regulated Flow	
Step #	**Cumulative Frequency**	**Cumulative Frequency**	**AEP (Difference)**
1	0.954	0.92	0.034
2	0.954	0.94	0.014
3	0.981	0.94	0.041
4	0.997	0.94	**0.057**
5	0.997	0.975	0.022
6	0.997	0.985	0.012

Here we will compare the stepwise functions for the unregulated(blue) and regulated(red) data

For the unregulated and regulated data sets shown in the table, we compare the AEP at each step to discover the location of the greatest vertical distance

In this example, the greatest vertical distance between steps can be observed at location number 4 with a difference in AEP of 0.057.

Recall that the location of greatest vertical difference is where we would want to compute the test statistic for the KS test.



Now let's come back to our 2nd example dam.

At this dam, we know there is upstream regulation, and we have separated the pre-upstream dam and post-upstream dam annual maximum series.

Let's use the Kolmogorov-Smirnov (**KS) test** to compare empirical distribution functions of the two samples and determine if they are from the same population.

KOLMOGOROV-SMIRNOV (KS) TEST

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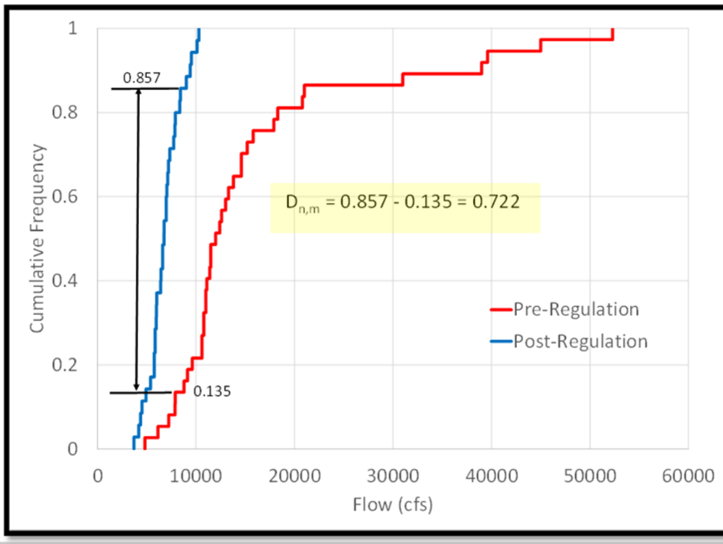
Example 2: Kolmogorov-Smirnov (KS) Test

α = 0.05
n = 37
m = 35

$$D = 1.358\sqrt{\frac{37+35}{1{,}295}} = 0.32$$

$D_{n,m}$ (0.72) > D (0.29)

Effects of Regulation are Significant



Now that we know how to develop a step-wise function, we'll perform the KS test to determine if the regulated and unregulated datasets come from the same population:

In this example, both the unregulated and regulated (pre- and post- dam) datasets were converted to a step-wise flow vs. cumulative frequency plot, as shown in the Figure by sorting the flow data from small to large and assigning probability based on rank

1) We flip the chart, so now **flow** is on the horizontal axis and **cumulative freq.** is on the vertical axis
2) Next, we Convert each of the data sets into a step-wise flow vs. cumulative frequency plot. Recall, we develop the step-wise function by:
    1) Sorting flow data from small to large and assign a probability based on rank (rank/sum of data points)
    2) Then sort from large to small, and take 1- plotting position
    3) Next, insert intermediate ordinates, and duplicate the flow, so there are steps

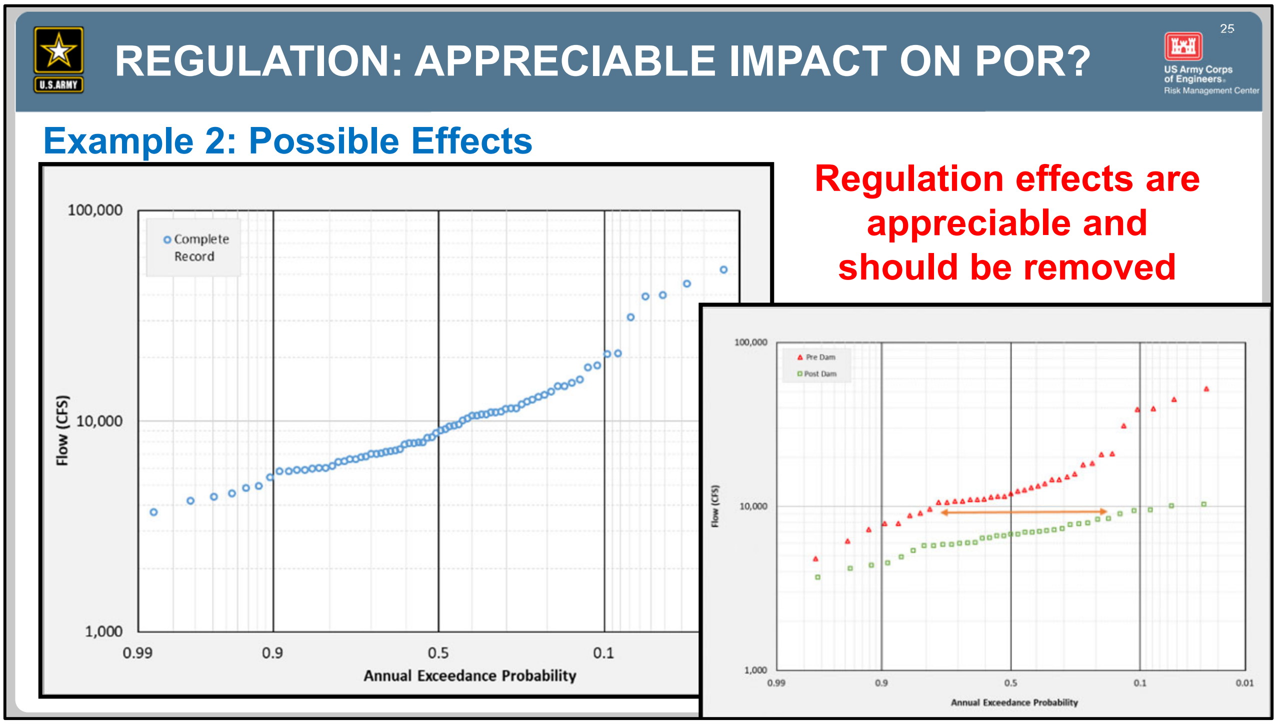
For this example, we'll use (click) significance level of 0.05 for the sample sizes of n=37 pre-dam annual maximums and m=35 post-dam annual maximums.

(click) When we compute the **critical KS test value (D), using a significance level of 0.05 for 90% confidence level, we get a value of 0.32.**

(click) The **test statistic $D_{n,m}$** is the greatest vertical difference in cumulative frequency between the two empirical distributions and was observed at a flow value of approximately 9,000 cfs and computed to have value of (0.857 - 0.135) = 0.722.

The test statistic $D_{n,m}$ (0.72) is greater than the critical KS test value D (0.32) which means that we reject the null hypothesis because there is **evidence to support a conclusion** that the samples come from **different population distributions.**

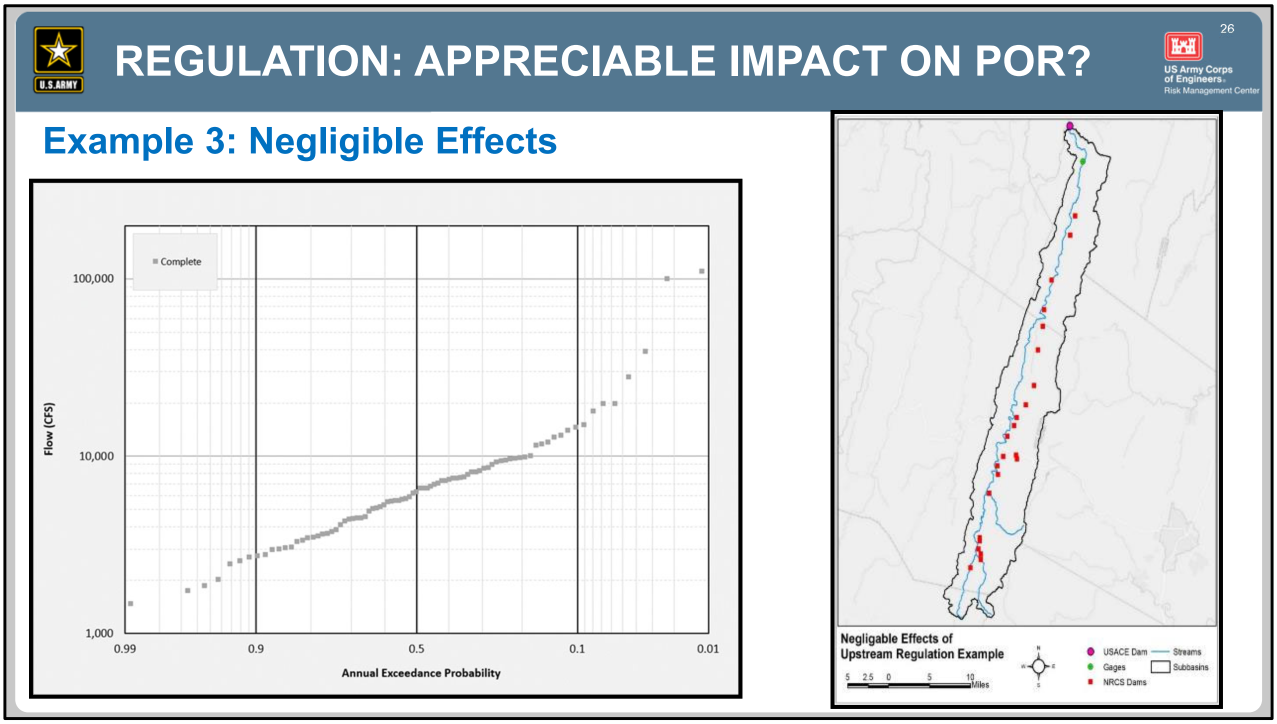
The KS test results support the conclusion that the effects of regulation are significant.



In this example, we found that the null hypothesis was rejected, and indicating that the unregulated pre-upstream dam record and the regulated post-upstream dam record are **NOT** from the same population.

(click) Will need to transform the regulated data to unregulated data

Fitting an LPIII distribution to each data set would result in drastically different estimations of flow rates for rare exceedance probabilities.



Now let's look at a third example. This is example is similar to the last example, because we are unable to visually see the effects of the regulation within the empirical flow-frequency distribution.

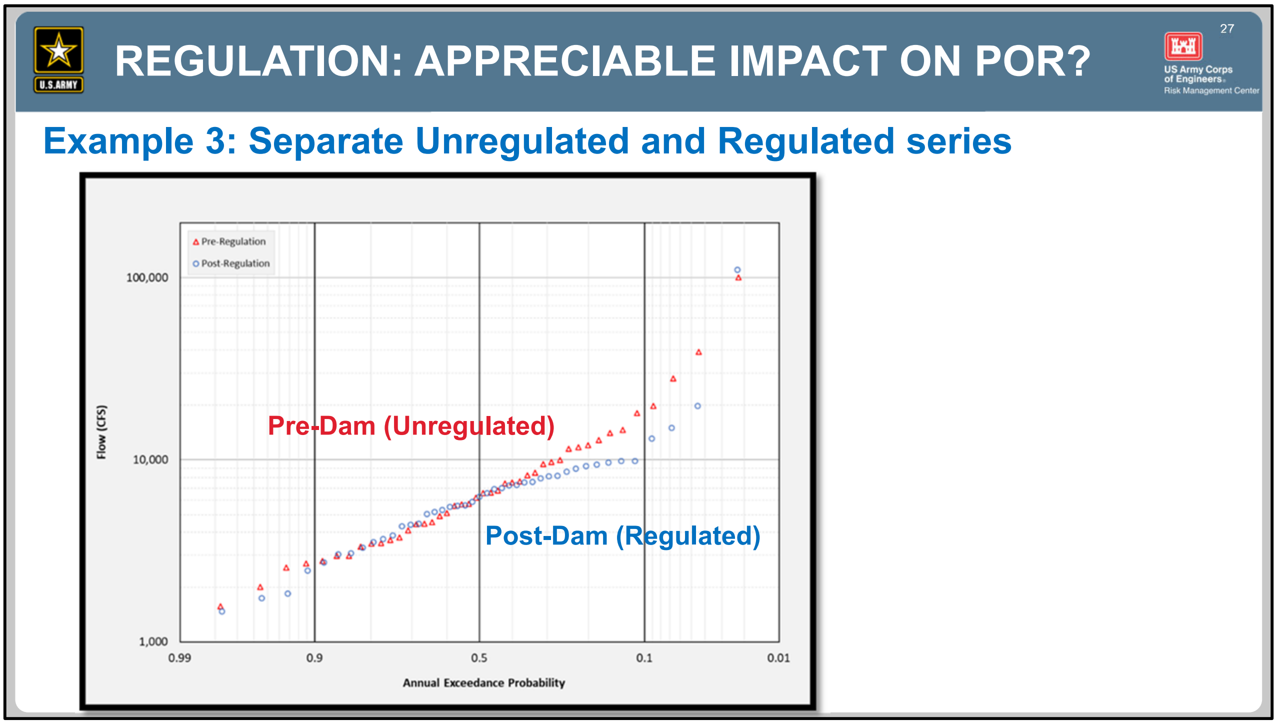
(click) For this dam, we know that there are 23 small flood water detention dams built by the NRCS located in the upstream watershed with storage capacity values ranging from 100-acre ft to approximately 7,000 acre ft (with an average of 1,500 acre-ft) and a total combined detention capacity of 19,870 acre-ft.

Note that NRCS dams are often designed with uncontrolled spillways to pass flood events more extreme than the 1/100 AEP.

Even though we know there are 23 upstream dams, we can't observe any **discernable irregular trends or non-homogenous behavior in the empirical frequency data.**

By visual inspection, it does not appear that regulation effects have an appreciable effect of regulation on the inflow data set,

but <u>further investigation is required.</u>



Since it wasn’t easily discernable whether the known upstream regulation was impacting our inflows at the dam of interest, the annual maximum series for pre-upstream dam construction and post upstream-dam construction were **<u>separated</u>** and **<u>plotted</u>** for further investigation

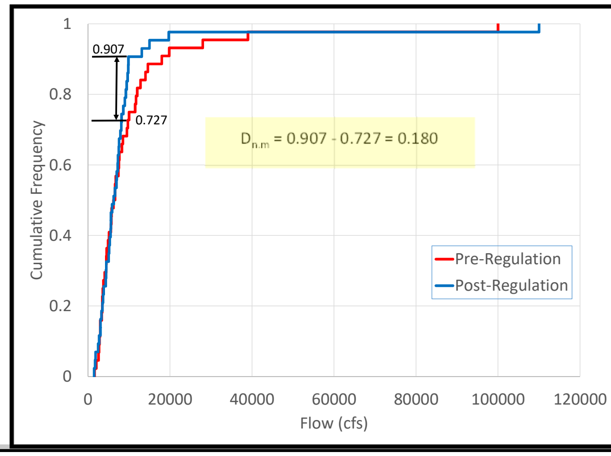
KOLMOGOROV-SMIRNOV (KS) TEST

Example 3: Kolmogorov-Smirnov (KS) Test

α = 0.05
n = 44
m = 43

$$D = \sqrt{-\frac{1}{2}\ln(\frac{0.05}{2})}\sqrt{\frac{44+43}{1,892}} = \mathbf{0.29}$$

$D_{n,m}$ (0.18) < D(0.26)
Effects of Regulation are Negligible



For this third example dam, we again use a two sample Kolmogorov-Smirnov (KS) test to compare the pre-regulation and post-regulation data.

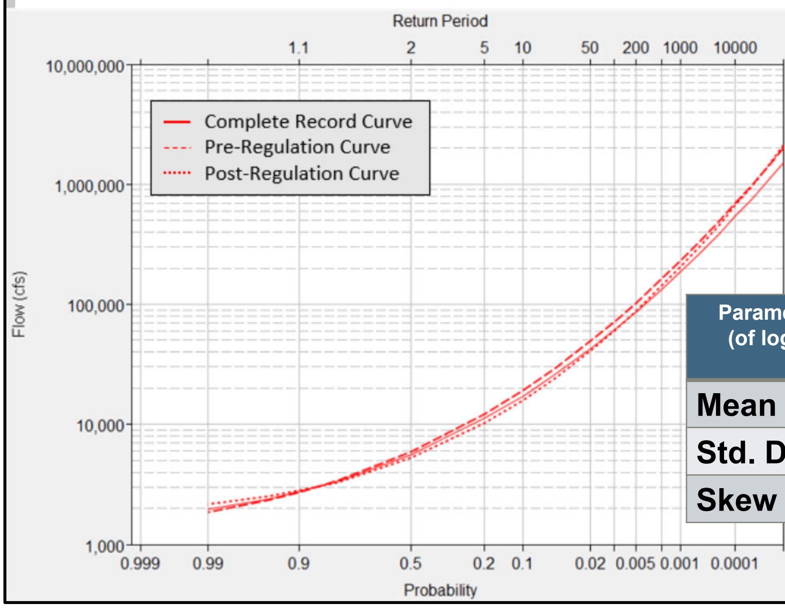
(click) The test statistic Dn,m = 0.18 is shown in the figure at the greatest vertical distance, corresponding to approximately 10,000 cfs.
(click) The critical KS test value (D) is calculated using sample sizes of n=44 and m=43.
(click) and we compute a value of D = 0.29

(click) In this example, the null hypothesis is **not** rejected because Dn,m (0.18) < D(0.29) which means that there is insufficient evidence to support a conclusion that the samples come from different population distributions.

In this example, the KS test supports a conclusion that the effects of regulation are negligible.

In this example, the predominant source of uncertainty is likely due to random sampling error rather than significant regulation effects.
Therefore, the complete record for this example can be treated as homogenous and unregulated for the purposes of an PA/Base Level IES analysis.

REGULATION: APPRECIABLE IMPACT ON POR?



Example 3:

Parameter (of logs)	Complete Record	Pre-Regulation	Post Regulation
Mean	**3.803**	**3.825**	**3.783**
Std. Dev.	**0.324**	**0.343**	**0.314**
Skew	**1.003**	**0.961**	**1.243**

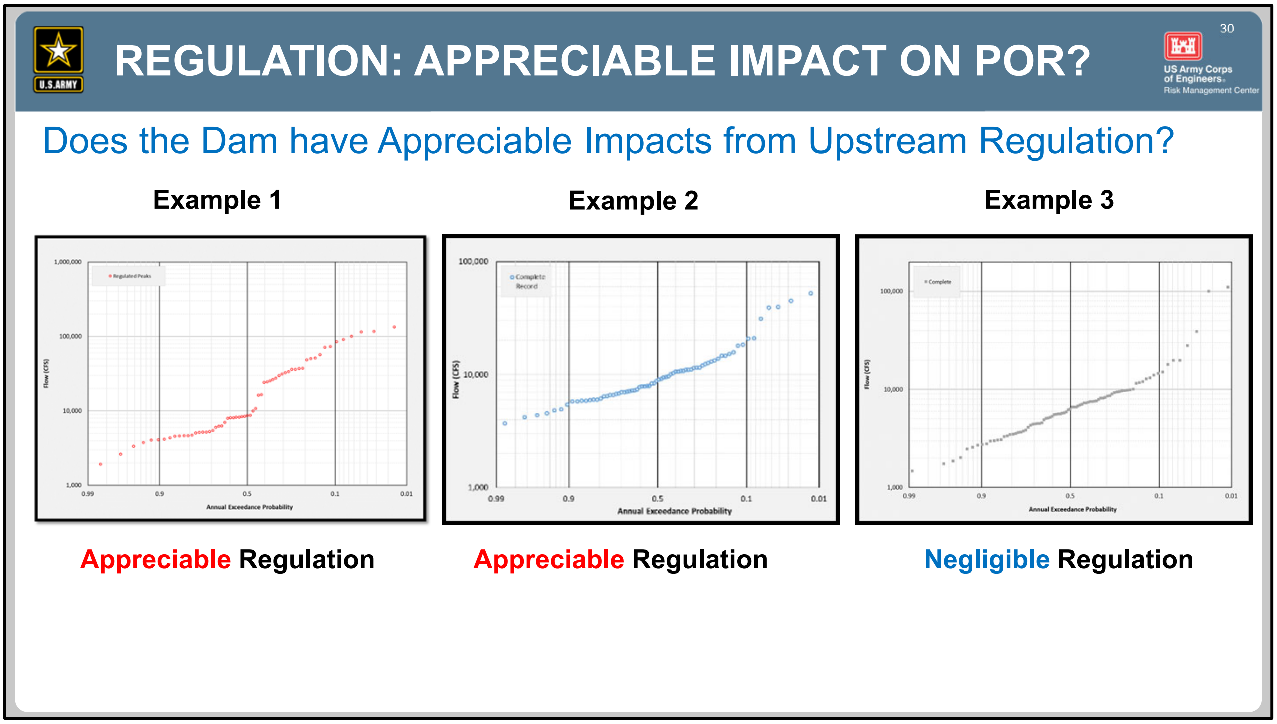
One final check was conducted on our third example dam.

A B17C analysis was run on all three data sets to compare the computed statistics.

As you can see, the mean, standard deviation, and skew were nearly identical for the complete record, as compared to the separated pre-upstream dam and post-upstream dam records.

This displays further confirmation that the effects of upstream regulation are negligible, particularly in the infrequent end of the curve, where we are most interested in for Dam Safety studies, and for input into RMC-RFA software.

Therefore, because the separated and complete records are essentially identical, we can use the complete record without modification.



To Re-Cap the three empirical frequency curves we just examined for dams with upstream regulation.

Example 1 had obvious, visual evidence of upstream regulation. (click)
We must develop an unregulated dataset and remove the impacts of regulation for our analytical flow-frequency analysis.

(click) Example 2 wasn't obvious at first glance, but by separating the pre and post upstream dam inflow datasets and performing the KS test, we were able to determine that we had appreciable impacts from regulation.
(click) We must develop an unregulated dataset and remove the impacts of regulation for our analytical flow-frequency analysis.

(click) Example 3 had 23 upstream dams, so many of us may have expected there to be appreciable impacts from regulation. When we performed the separation of the pre and post upstream dam inflow records and the KS test, we were able to determine that our empirical inflow data is NOT appreciably impacted by regulation
(click) Therefore, we can assume the full dataset is from the same population and use the full record for our flow-frequency analysis without additional manipulation.

OVERVIEW

- Assumptions
- USACE Guidance
- Why is Unregulated Data Important?
- Identification of Appreciable Upstream Regulation
- Development of Unregulated Inflow Dataset
- Development of Stage-Frequency Curve

Thus far, we have discussed how to determine if the regulation from an upstream dam is appreciable.

If the answer is No: Can use data to produce inflow FF curve for the Reservoir of interest without further manipulation

If the answer is Yes: Need to transform data into an unregulated data set

Next, I will show you 3 recommended methods for developing an unregulated inflow dataset for a dam with upstream regulation.

WHEN IS IT ACCEPTABLE TO USE REGULATED?

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- **Fitting LPIII parameters to significantly regulated data is generally not acceptable for RMC-RFA.**
- Suggested Methods in RMC-TR-2021-02 Guidance Document
- Call the PA Help Desk, HEC, or RMC for Guidance

Before we jump in to how we develop an unregulated period of record inflow dataset, lets discuss a question that comes up a lot is "**When is it acceptable to use regulated inflow data for a dam safety study**?"

In general, fitting LPIII parameters to significantly regulated data is **not acceptable** and produces quite different extrapolated results at infrequent AEPs which is unacceptable for Dam Safety studies.

This is because stage-frequency software (RMC-RFA), the software required for USACE Dam Safety Issue Evaluation Studies, currently requires an analytical distribution for inflow-frequency curves.
Regulated flow frequency is often best represented with a graphical-empirical curve, which can not currently be input into RMC-RFA.

There are a few potential methods including a transformation approach and a deterministic approach to informing stage-frequency with regulated inflow data.

In general, when the effects of upstream regulation are significant and development of an unregulated flow frequency curve is not feasible, contact the PA Help Desk, HEC, or RMC for guidance.

DEVELOP UNREGULATED INFLOW DATASET

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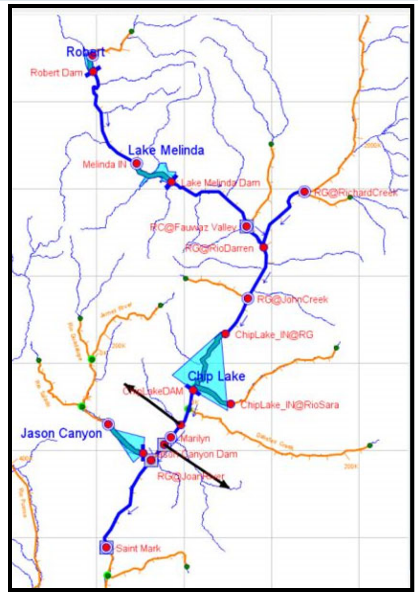
Method 1: Use Existing Models

- HEC-ResSim
- HEC-HMS
- HEC-RAS
- RiverWare
- HEC-WAT
- Etc.



Now I will show you 3 methods for developing an unregulated inflow period of record dataset for a reservoir with significant regulation affects from an upstream dam.

These 3 methods for developing unregulated inflow datasets are in order of preference.

Method 1 is to obtain an unregulated data set by running the period of record reservoir inflows through a reservoir routing model **with and without reservoirs** using **an existing, calibrated model**.
Examples of reservoir routing software are : ResSim, HMS, RAS, Riverware, HEC-WAT, etc.

These models may already be developed and calibrated for the purpose of determining annual savings based on Federal flood risk reduction projects.

B17C analysis can be conducted to fit a frequency distribution to the resulting unregulated dataset to inform the development of a stage-frequency curve.

DEVELOP UNREGULATED INFLOW DATASET

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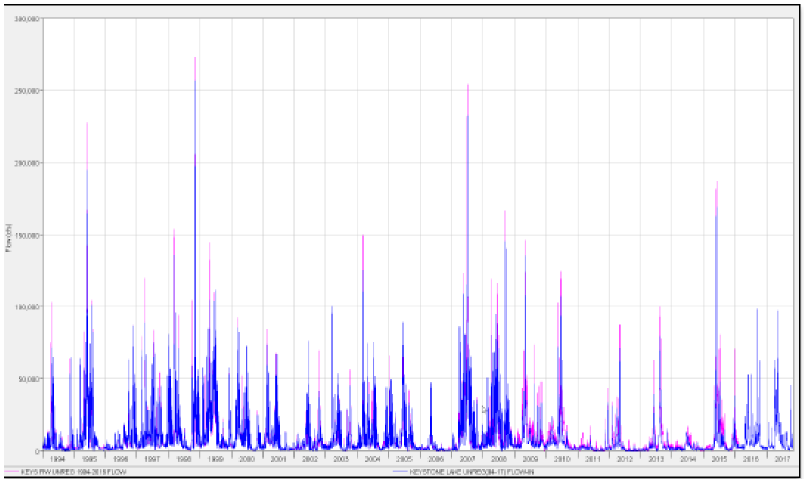
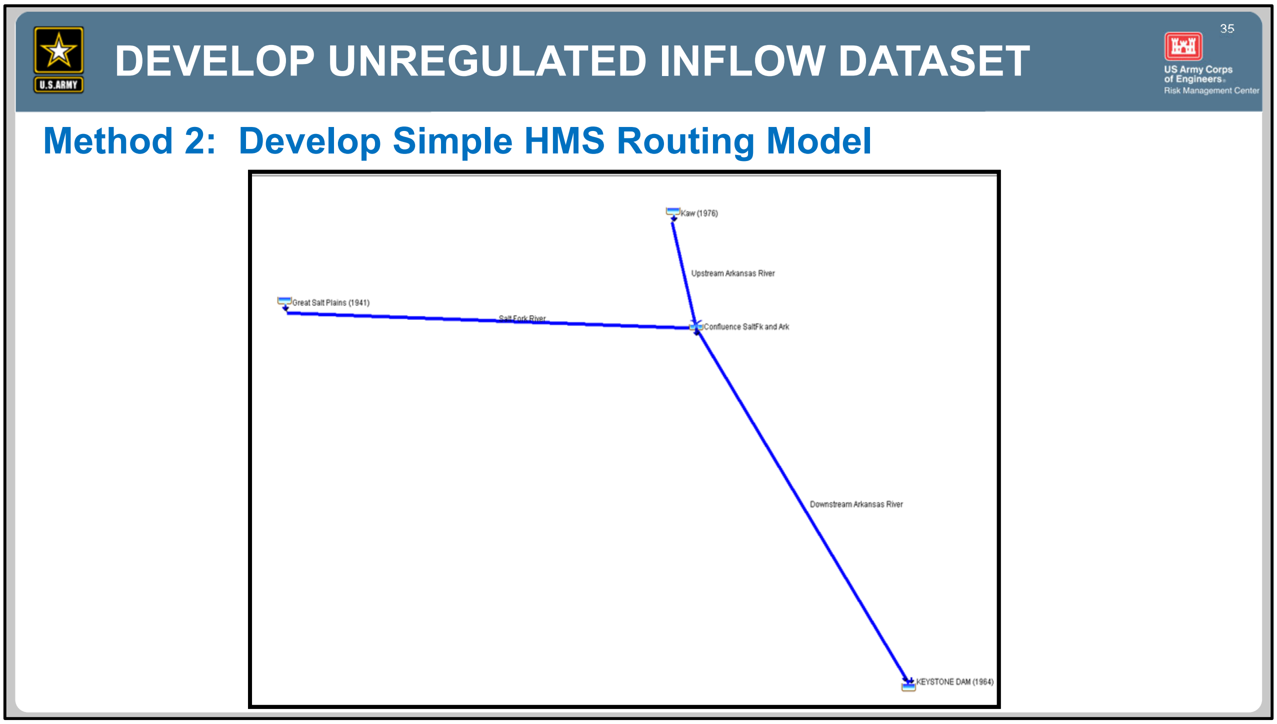
Method 1: Use Existing Models



Shown here is a dataset for Keystone dam in Oklahoma.

The unregulated data is displayed in blue and the unregulated data is shown in red.

This data was developed in an existing district Riverware model.



The second method for developing an unregulated dataset can be used if there is not an existing model for the system.

Some districts have developed simple spreadsheet models as an analog to a routing model.

Rather than using a spreadsheet approach, it is recommended that a **simple HEC-HMS routing model** be developed to create an unregulated inflow data set.

Perform B17C analysis on the unregulated data set to develop the stage-frequency curve for the critical duration.

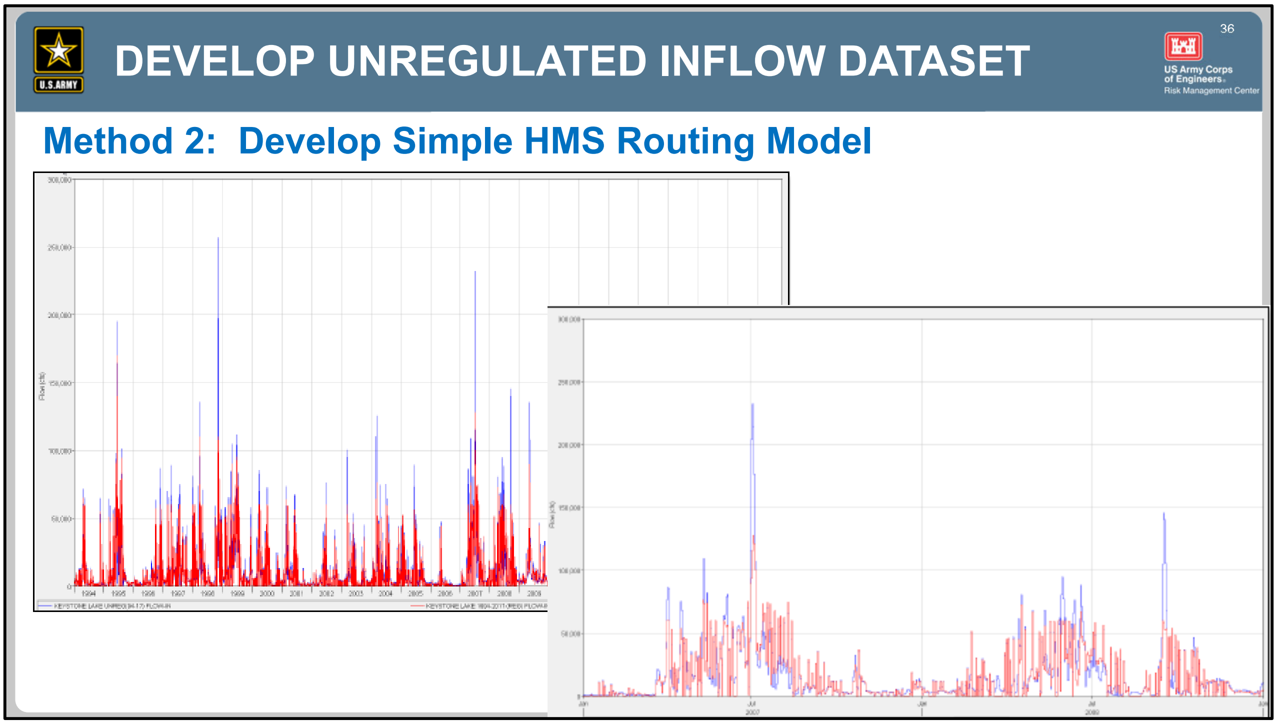
In this figure, we can see a simple HMS model for Keystone Dam built in 1964. The two upstream dams are Great Salt Plains Dam completed in 1941, and Kaw dam completed in 1976.

To develop the unregulated inflow dataset for Keystone dam, we simply removed the two upstream reservoir elements in HMS, and routed the upstream and local flows down to Keystone for the period of record.

The HEC-HMS model can be as simple as source elements representing upstream regulating reservoirs, routing reaches, and a reservoir element to represent the project in question.

Muskingum-Cunge 8-point cross sections or routing parameters from other **existing calibrated routing models** (i.e. HEC-HMS, HEC-RAS, HEC-ResSim, etc.) could be used to define routing parameters.

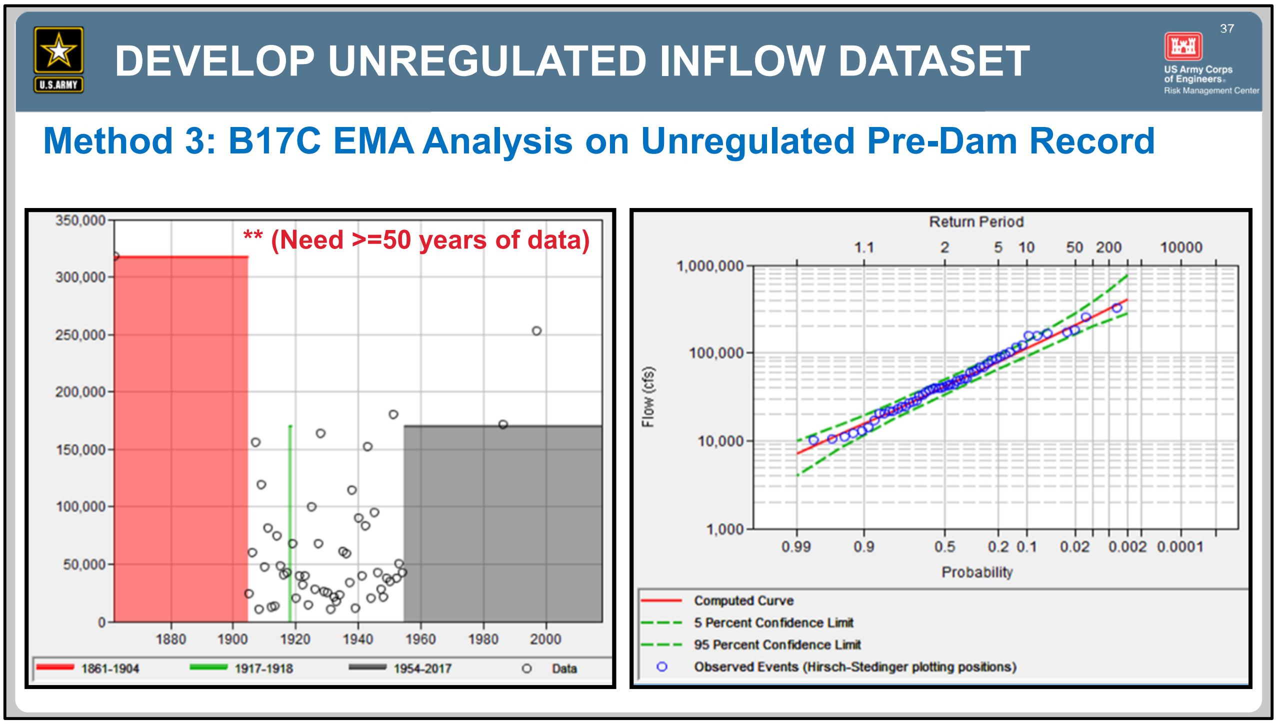
***** It is always advisable to examine the resulting flow-frequency distribution curves to determine if the LPIII analytical curve has a good fit to the unregulated inflow series.**



Here we can see the regulated inflow dataset in red, and the modeled unregulated inflow dataset resulting from our simple HMS model routing.
The figure on the left is the full dataset, and the figure on the right is zoomed in on two years of record.
Steps:

- Develop Simple HMS routing model
- Route observed upstream dam outflows
- Subtract from Dam inflow → Local Area Inflows

- Run HMS with Upstream dam inflows (without reservoirs)
- Add to Local Area Inflows → prelim Unreg data set
- Data clean up: Assume negatives are zero inflows
- Perform B17C → Unregulated Analytical Flow Freq. Curve



The third method is the least preferable but may be the only reasonable option for developing an unregulated inflow dataset for a dam **if no other models are available for use.**

Method 3 is to Perform Bulletin 17C expected moments algorithm (EMA) analysis on the unregulated Pre-upstream Dam record

*** If you have an acceptably long (click) **(at least 50-years of equivalent record),** homogenous, and independent and identically (IID) distributed record **prior to upstream regulation**, this method may be effective.

***A drawback of this method is **a reduction in the quantity of the data** used to inform the flow frequency curve.

Short record lengths **may not support credible extrapolation of the flow frequency curve.**

Example:

- Total POR from 1862 to 2017
- Upstream regulation began in 1955
- Systematic data began in 1904, historic flood in 1862

- Used systematic data from 1904 – 1954
- Point estimate for 1862 flood

- Perception threshold 1862 – 1904: reasonable to assume larger events would have been recorded
- Perception threshold 1955 – 2017 (Cover the regulated period)
- Through modeling: made unregulated estimates of large floods during the regulated period

The resultant LPIII curve can be considered representative of unregulated conditions.

DEVELOP UNREGULATED INFLOW DATASET

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SUMMARY

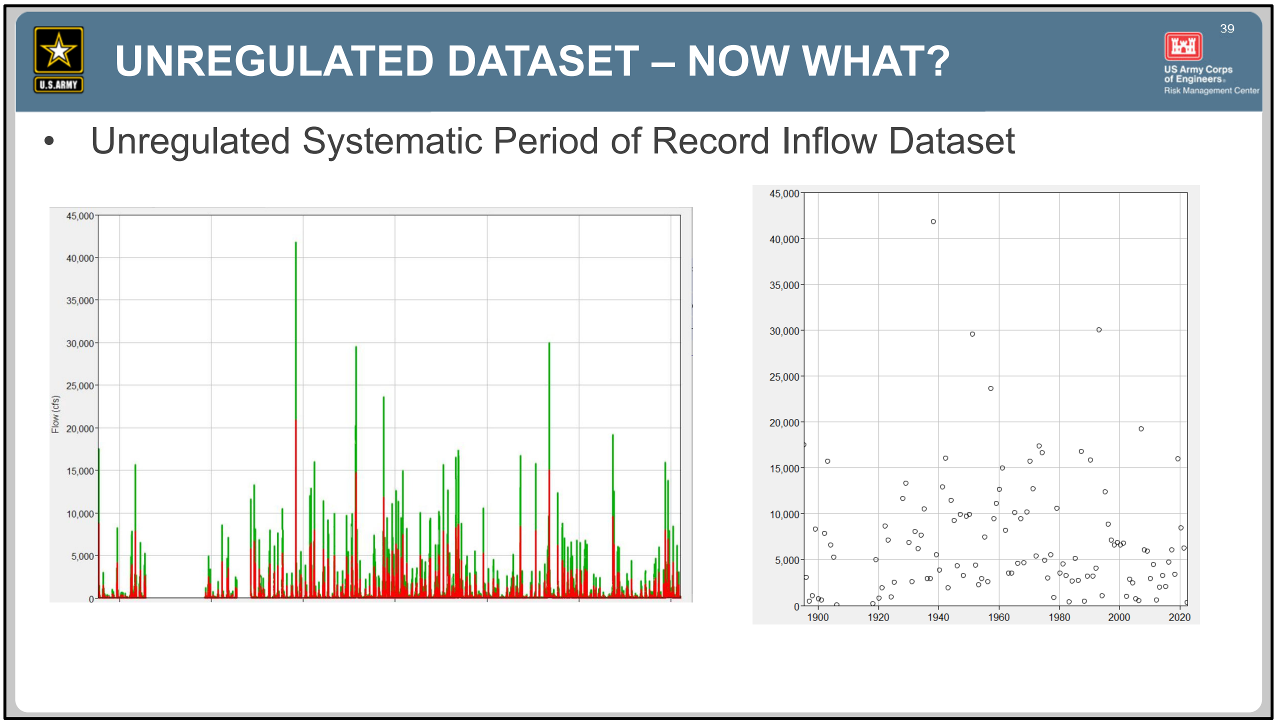
Method 1: Use Existing Models

Method 2: Develop Simple HMS Routing Model

Method 3: B17C EMA Analysis on Unregulated Pre-Dam Record

To re-cap, there are three recommended methods for development of an unregulated inflow dataset for a dam safety project, listed in order of preference:

1) Use **existing reservoir routing models** to route flows with and without upstream dams (preferred method)
2) Develop a **simple HMS** model to route flows with and without upstream dams
3) Perform **Bulletin 17C analysis on unregulated pre-dam record** (if at least 50 years)



Okay – so we've spent several slides explaining how to develop an unregulated dataset, now what do we do with it?

Here is an example for another dam.
On this project, we've used an HMS model to develop a regulated and unregulated period of record dataset

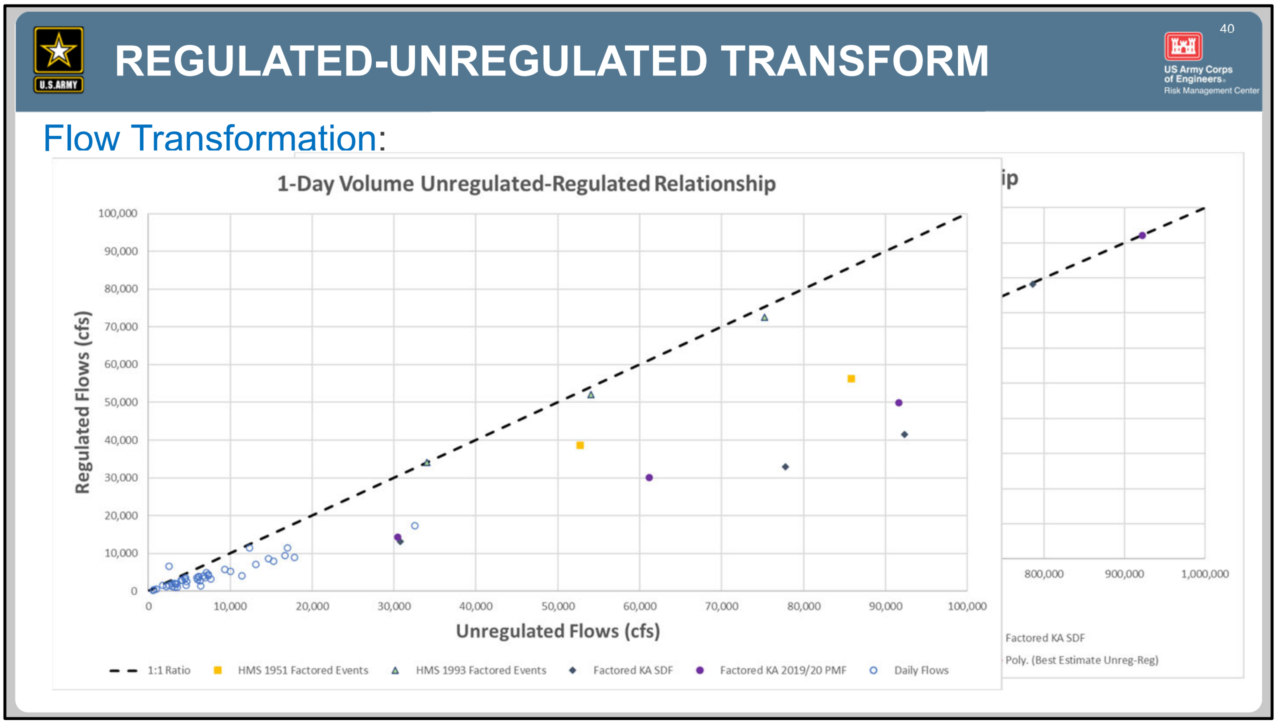
(click) We now have an unregulated **systematic dataset**, that can be entered into HEC-SSP or RMC-Bestfit to perform an inflow volume frequency analysis.

In addition to the systematic data shown here, there are a few historic floods in the basin.

1 that occurred prior to the upstream regulation and 3 the occurred during the period of upstream regulation.

Because it's important to include as much hydrologic data possible in flow-frequency analysis, we will want to transform the regulated floods to unregulated so we can include all these historic flood events in the frequency analysis.

In the next few slides, I'll show you how to do so.



If you have identified significant regulation in your basin, you will likely need to develop a flow transformation relationship to assist in the development of the chronology plot for HEC-SSP or RMC-BestFit.

In other words, you may need to transform some large regulated events to unregulated in the POR.

In this figure, we can see a regulated-unregulated flow transform relationship for a dam with a 1-day critical duration.

I'll begin by describing the elements of the transform relationship:

A black line is plotted along the 1:1 line, where regulated and unregulated flows are equal.

In this example, a HEC-RES Sim model was used to develop an unregulated and regulated daily flows for the period of record.

Because the critical duration for this dam was 1-day, a regulated-unregulated inflow volume transform relationship was developed for the 1-day volumes
1-day Regulated inflow volume is shown on the y axis
1-day Unregulated inflow volume is on the x-axis

The blue points less than ~35,000 cfs Unregulated/20,000 regulated were the observed daily points.

The other points (yellow, green, purple, grey) were developed by scaling up large storms observed in the basin and the PMF until a point was reached called the convergence threshold, where regulated flows are assumed to be equivalent to unregulated flows.

In other words, the convergence threshold is the point at which the upstream dam is filling and spilling, and no longer contributing effects of upstream regulation.
I'll discuss this more in a few slides.

(click) Now I'll zoom out a little so you can see the big picture. Now I'm looking out to 1 Million CFS on both axis.

The red line represents the adopted transform relationship to be used when transforming regulated flow volumes to unregulated flow volumes, or vice versa.

You can also see that this dam reaches the convergence threshold around 390,000 cfs.

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REGULATED-UNREGULATED TRANSFORM

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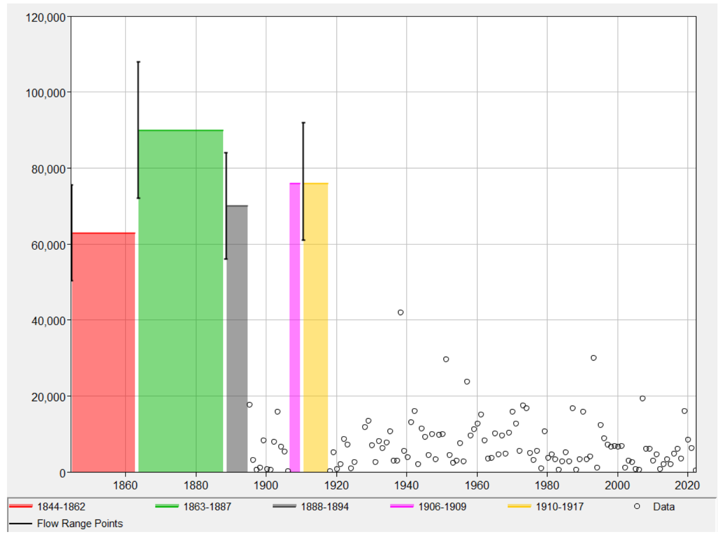
Water Year	1-day Unregulated flow (cfs)	1-day Regulated Flow (cfs)
1844	63,000	---
1863		45,000
1888		35,000
1910		38,000



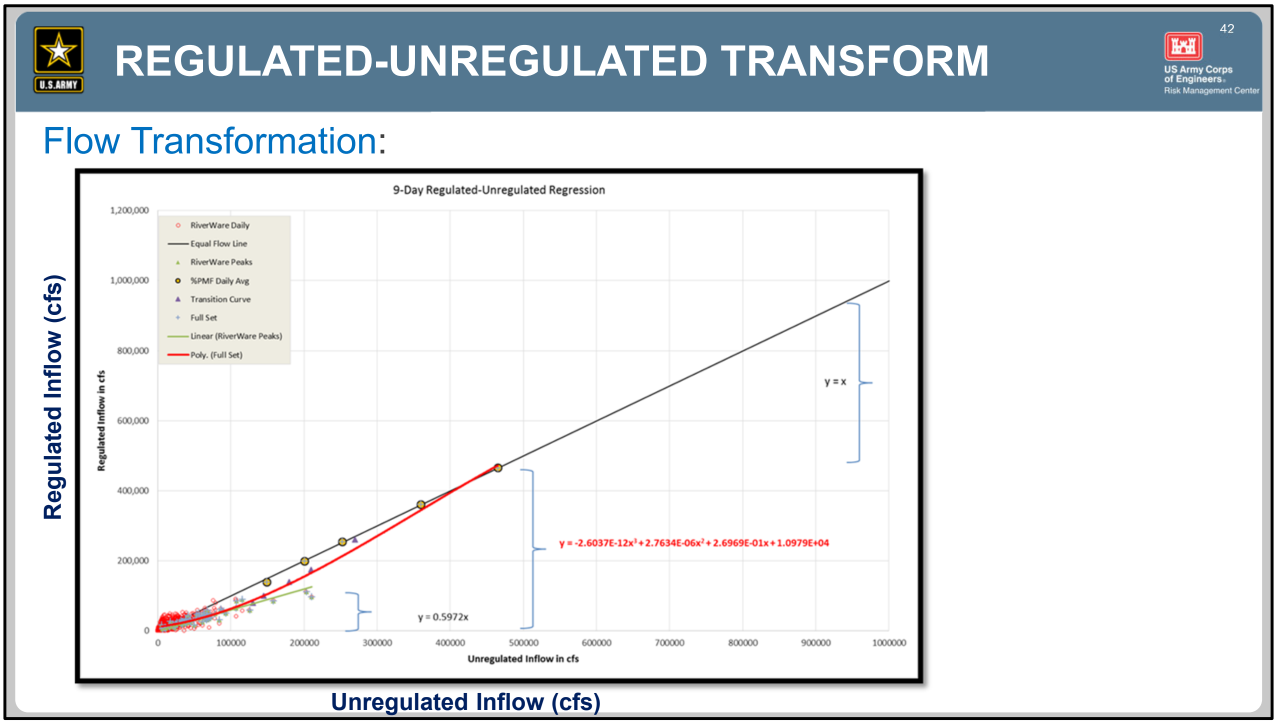
For this example – the 1844 flood occurred prior to the upstream dam being built, so the flow was already considered an unregulated inflow.

The 1863, 1888, and 1910 floods occurred after the upstream dam was constructed, so they were considered regulated historic inflows.

In order to use these floods with our flow-frequency analysis, we need to use the regulated-unregulated flow transform relationship for the critical duration to transform the regulated flows to unregulated flows.

(click) Here you can see the estimated unregulated flows for the 3 events that have occurred since the construction of the upstream dam

(click) Here you can see how I've added the unregulated estimates for the historic floods to my chronology plot in HEC-SSP.



Here is an additional flow transformation example for Keysone Dam in Oklahoma.

In this figure, we can see a regulated-unregulated flow transform relationship for a dam with a 9-day critical duration.

You can see there are similar elements in this flow-transform relationship.

A black line is plotted along the 1:1 line, where regulated and unregulated flows are equal. The flow at which the two converge is called the convergence threshold.

In this example, a Riverware model was used to develop an unregulated and regulated daily flows for the period of record.

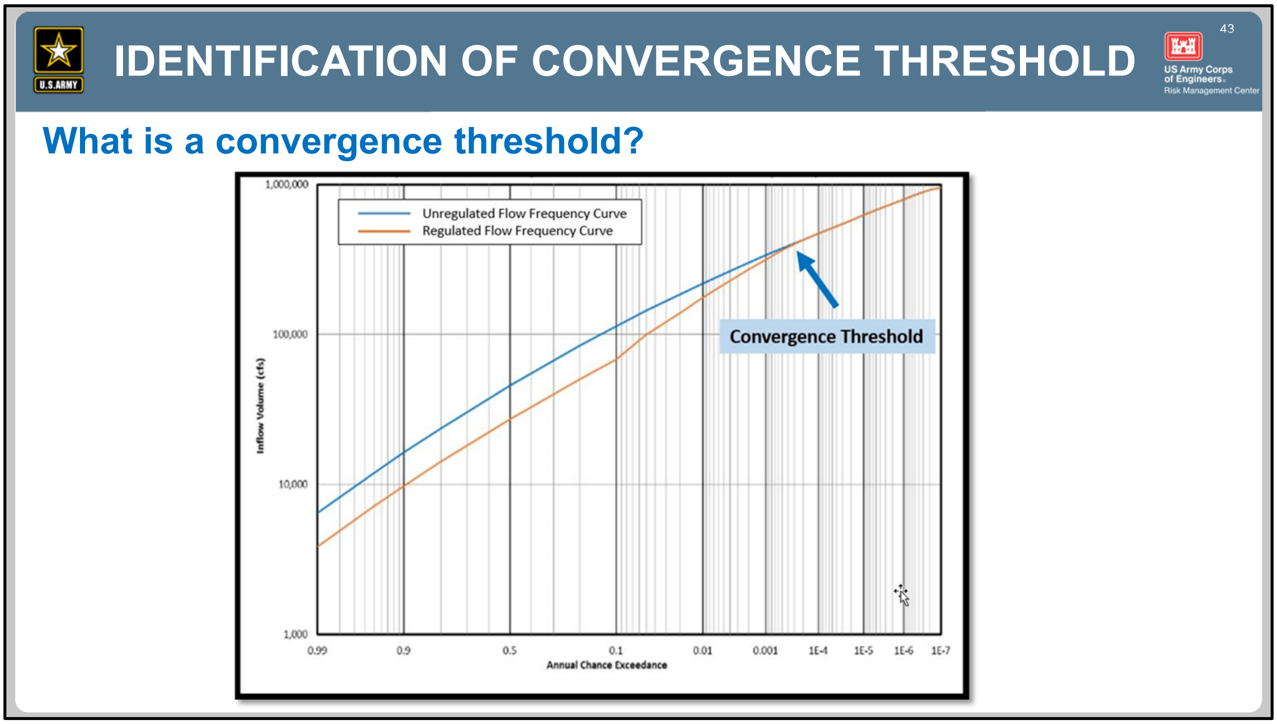
Because the critical duration for this dam was 9-days, a regulated-unregulated inflow volume transform relationship was developed for the 9-day volumes
9-day Regulated inflow volume is shown on the y axis
9-day Unregulated inflow volume is on the x-axis

The points less than ~100,000 cfs were the observed daily points.
The yellow circles were developed by scaling up large storms like the PMF until a point was reached called the convergence threshold, where regulated flows are assumed to be equivalent to unregulated flows.

In other words, it’s the point at which the upstream dam is filling and spilling, and no longer contributing effects of upstream regulation.

The red line represents the adopted transform relationship to be used when transforming regulated flow volumes to unregulated flow volumes, or vice versa.

Notice that for regulated or unregulated flow values greater than about 500,000 cfs, the regulated and unregulated flows are assumed to be equal.



I've mentioned a convergence threshold a few times in this presentation, and you may be wondering What is a convergence threshold?

The ***convergence threshold*** is defined as the initial flood magnitude at which the **difference between regulated and unregulated flows is negligible**.

IDENTIFICATION OF CONVERGENCE THRESHOLD

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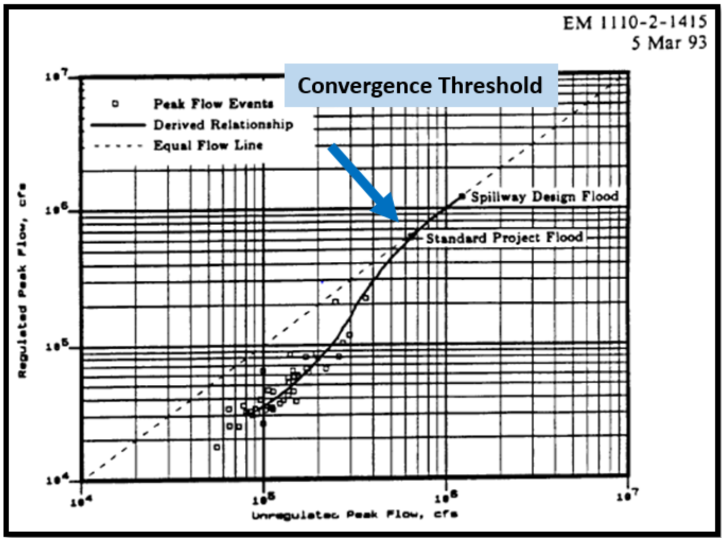
Significance of the Convergence Threshold



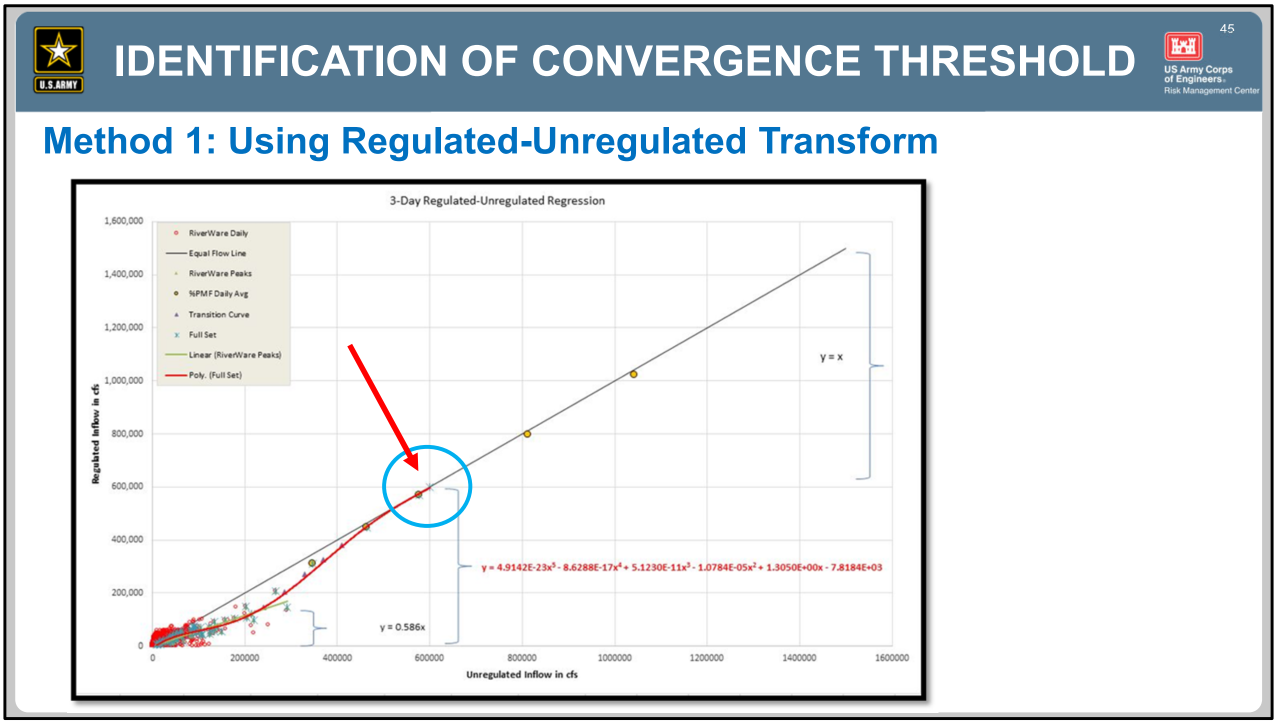
Let's talk about the significance of a convergence threshold?

When you have identified the convergence threshold, **you can make the assumption that the affects of regulation are negligible**
for less frequent AEPs.

When developing the stage freq. curve using an unregulated flow frequency curve, can assume that the upper end of the curve beyond the convergence threshold are **applicable to the existing regulated system**.

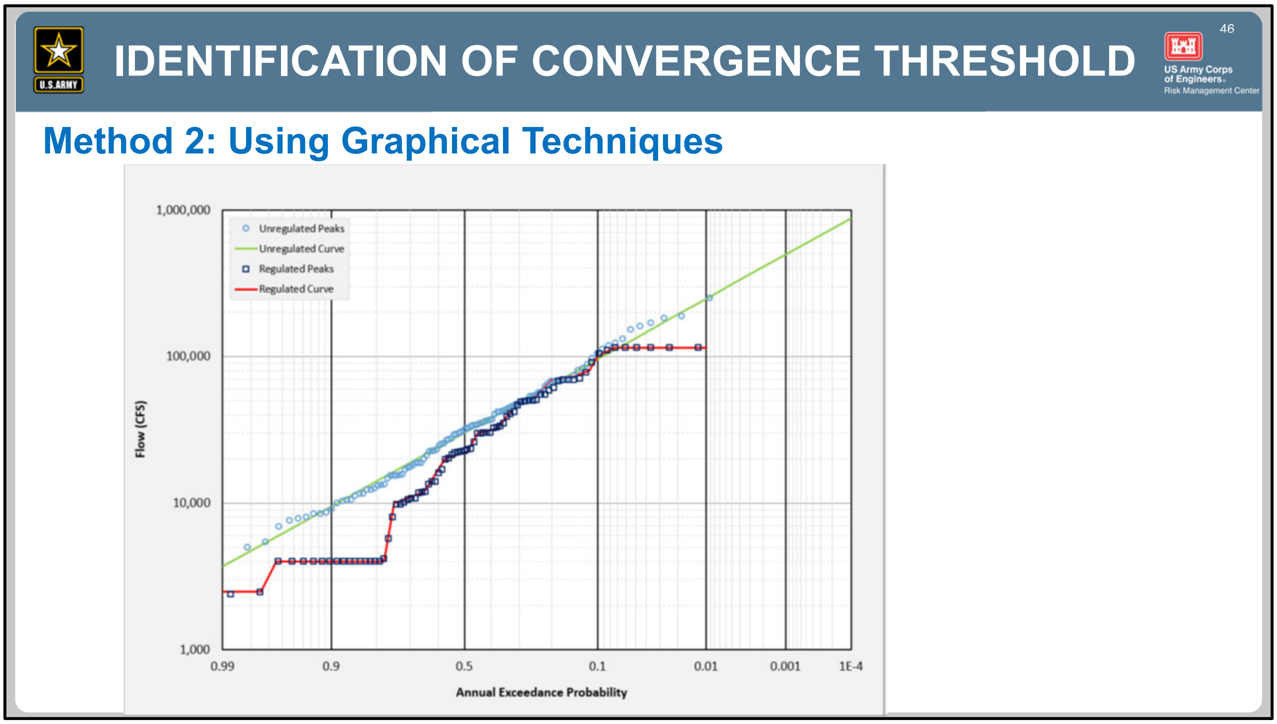
This figure from EM 1110-2-1415 provides an example of a convergence threshold in the context of a flow frequency curve.

In this example, the regulated and unregulated flow frequency curves converge for exceedance probabilities less frequent than approximately **1/4,000 AEP.** In this example, the effects of regulation can be considered negligible for extreme flood events with an AEP less than 1 in 4,000.



How do you identify a convergence threshold?

The first method is to develop a regulated-unregulated transform. Plot the observed data and scale up observed floods and PMF to route through a hydrologic routing model.



For Method 2 – graphical techniques can be used to identify a convergence threshold. We've see this figure from Folsom Dam elsewhere in this course, however it is being used on this slide for **example only**.

This figure displays both the regulated and unregulated annual maximum series inflows for a system with appreciable regulation.

An LPIII analytical distribution was fit to the unregulated annual maximum series and a graphical/empirical flow-frequency distribution was fit to a regulated annual maximum series.
**Note that the regulated empirical flow-frequency distribution does not extend past the observed data.

(**click**) **Two synthetic events**, one representing a **1/200 AEP** and another representing a **1/500 AEP** ("Balanced Hydrographs" in the figure) have been routed through the upstream projects. By routing large events through a reservoir routing model and plotting them with the regulated annual maximum dataset, the trend of the regulated distribution at more infrequent AEP can be observed and a convergence threshold can be estimated.

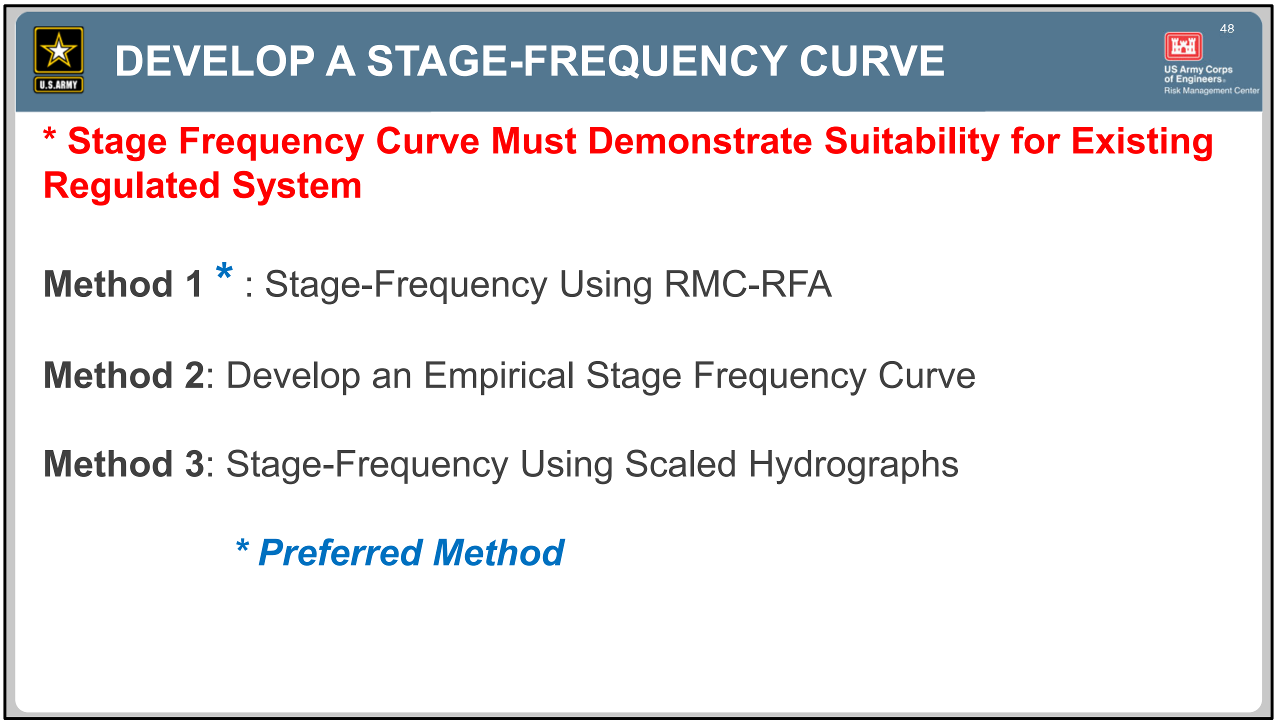
The plotted points for the routed 1/200 and 1/500 AEP synthetic flood events display an upward trend and suggest that a convergence threshold for regulated and unregulated flows may be assumed near **<u>1/1,000 AEP</u>**.

From this example, the green critical duration analytical curve fit to the unregulated peak flows could be input into a stochastic model such as RMC-RFA to develop a stage-frequency curve.
The stage-frequency curve would likely require additional evaluation at frequencies **more frequent than 1/1,000 AEP** to ensure that the full curve is applicable to the regulated system.

OVERVIEW

- Assumptions
- USACE Guidance
- Why is Unregulated Data Important?
- Identification of Appreciable Upstream Regulation
- Development of Unregulated Inflow Dataset
- Identification of Convergence Threshold
- Development of Stage-Frequency Curve

Now let's discuss how we develop a stage-frequency curve for USACE dam or levee safety projects with upstream regulation



A stage-frequency hazard curve that will be used to assess **dam safety risk** for a Base Level Issue Evaluation Study level used for USACE Risk Assessment **must demonstrate an ability to describe the existing regulated system**.

USACE Dam Safety Program requires the use of a Monte Carlo analysis using RMC-RFA to produce stage-frequency curves.

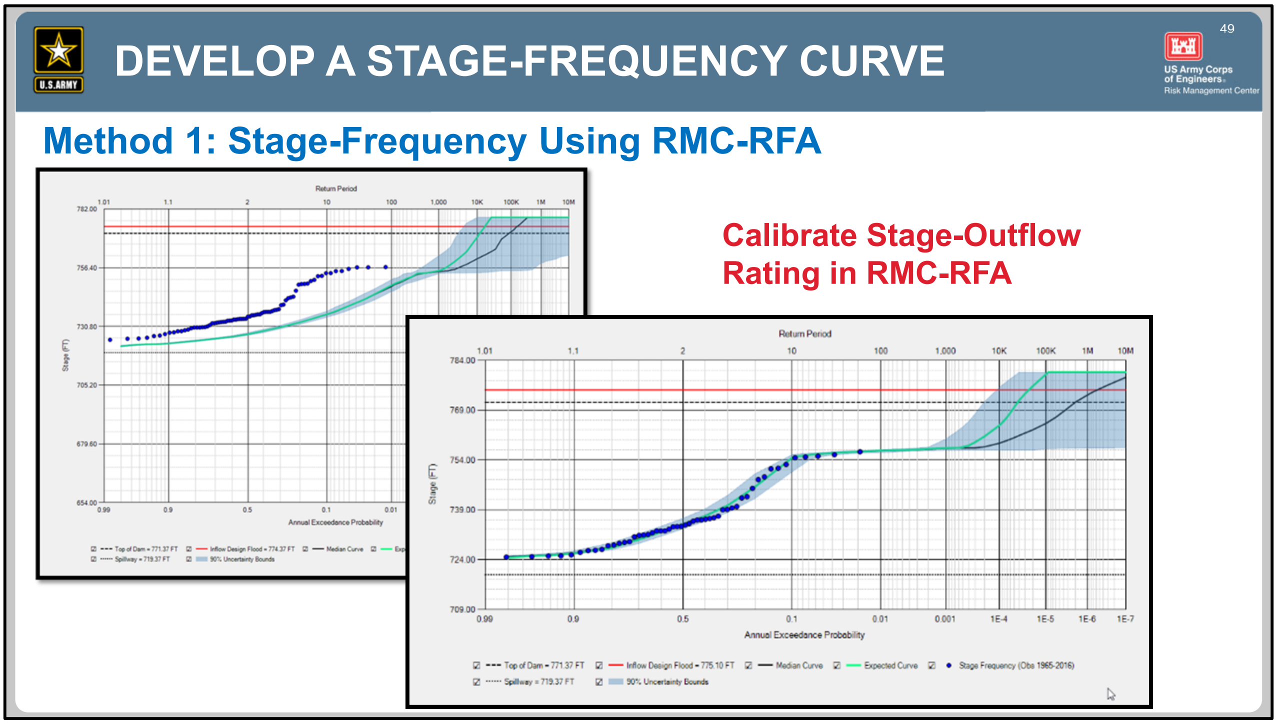
For studies other than Dam and levee safety risk assessment, **another robust method of stage-frequency analysis** is the use of a stochastic HEC-WAT Monte Carlo analysis.

Method 1 is Preferred

Method 2 must be blended with analytical stage freq. curve from RMC-RFA

Two most common Methods will be 1 and 2.

Method 3 will be reserved for rare cases.

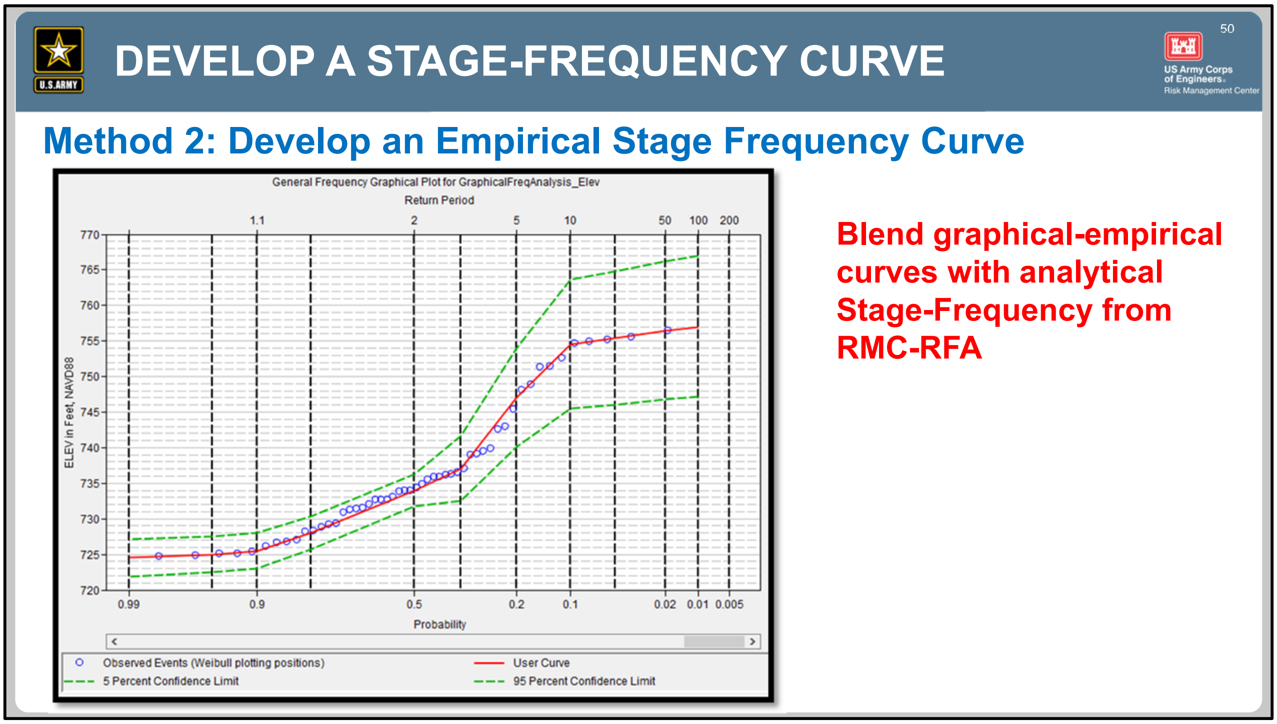


**** Method 1 is the Preferred Method ****

Method 1 includes development of stage-frequency curves using a Monte Carlo approach.

For RMC Dam Safety Issue Evaluation Studies, RMC-RFA software is the required software to produce stage-frequency curves.

- Check for consistency with the convergence threshold in the FF curve and Stage-Freq Curve: regulation effects can be considered negligible at less frequent AEP's
- Calibrate to observed stage events by making adjustments to the best-estimate stage-outflow curve to match the regulated observed peak stages
    - Look at initial analytical curve on left, and the calibrated curve on the right

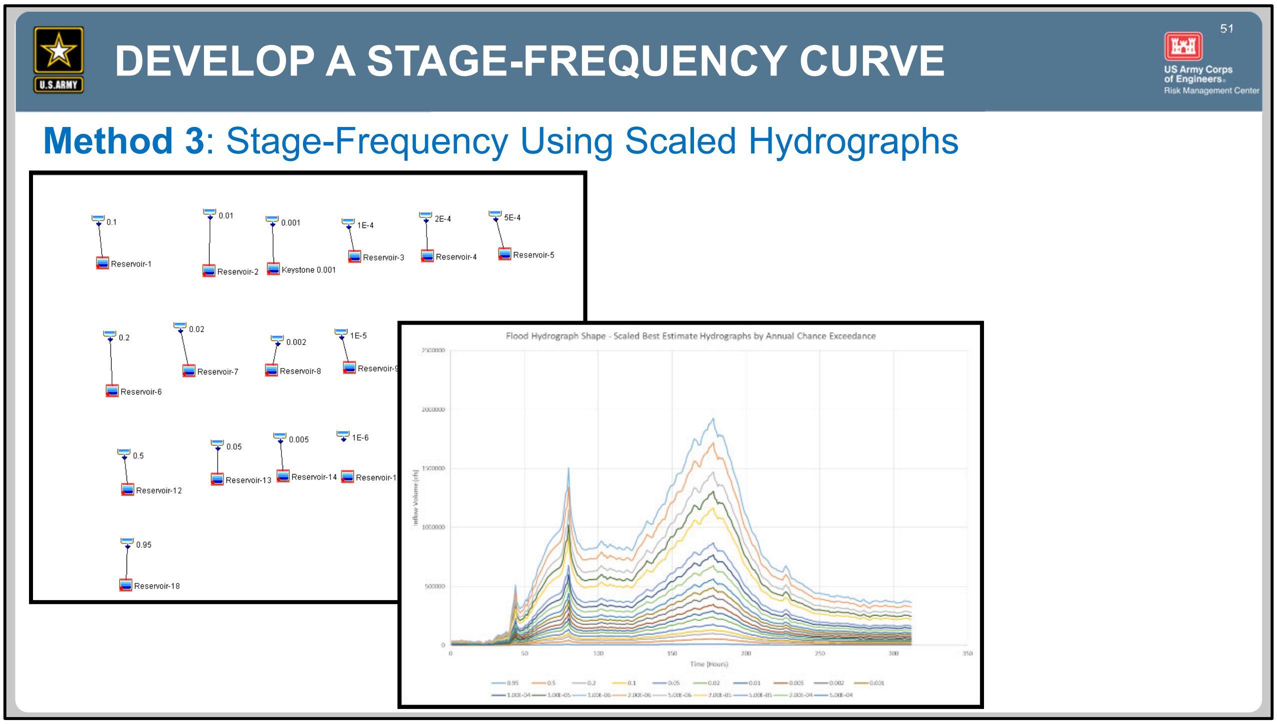


In some cases, Calibration of the reservoir model stage-discharge rating curve is not feasible using RMC-RFA. If this occurs, a graphical-empirical curve can be developed using HEC-SSP.

The resulting empirical stage frequency curve typically provides a good characterization for current regulated conditions within the range of the observed stages.

** Note: Empirical stage freq. curves can't be extrapolated past the observed record

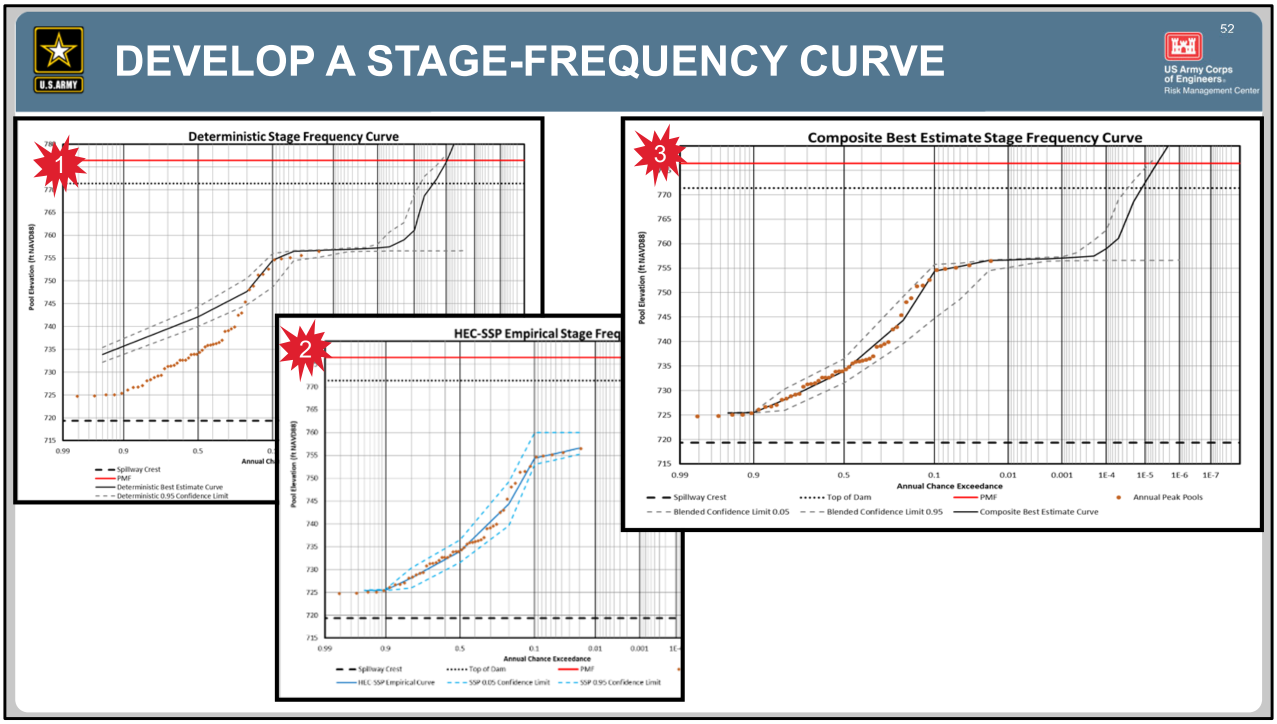
For RMC Dam Safety Studies, these graphical-empirical curves covering the range of observed regulated flows **must be blended with an analytical stage-frequency curve developed in RMC-RFA**



Method 3 involves routing scaled frequency hydrographs through a reservoir routing model. I call this the deterministic method because we are not using a monte carlo approach to develop an analytical stage-frequency curve.

Be aware that it would be VERY Rare to use method #3, and in general will not be used for a Dam Safety Flood Hazard analysis.

Steps:
Perform Unregulated flow-frequency analysis
Transform flow frequency curve from regulated to regulated
Scale each best estimate and confidence limit flow volume to a volume-normalized representative hydrograph for each AEP of interest
Route them through simple HMS model
Plot peak stages, assuming the AEP matches the peak stage



Here we can see an example of how we might blend a deterministic stage-frequency curve developed using HEC-HMS with an empirical frequency curve developed using HEC-SSP.

Upper left #1 is output of deterministic model
Lower right #2 is empirical stage freq curve from HEC-SSP
Upper right #3 is the composite curve which is the blending of the analytical and empirical curves
Engineering judgment used to **blend** confidence limits.

Pro: Produces results that are acceptable for use with the existing regulated system
Con: Deterministic approach can be tedious

Unregulated flow data set is transformed into regulated data set and routed through HMS model.

Individual hydrographs for EACH expected curve and EACH 0.05 Confidence Limit and 0.095 Confidence Limit for EVERY AEP selected.

DEVELOP A STAGE-FREQUENCY CURVE

Method 1 * : **Stage-Frequency Using RMC-RFA**

Method 2: Develop an Empirical Stage Frequency Curve

Method 3: Stage-Frequency Using Scaled Hydrographs

**** Preferred Method***

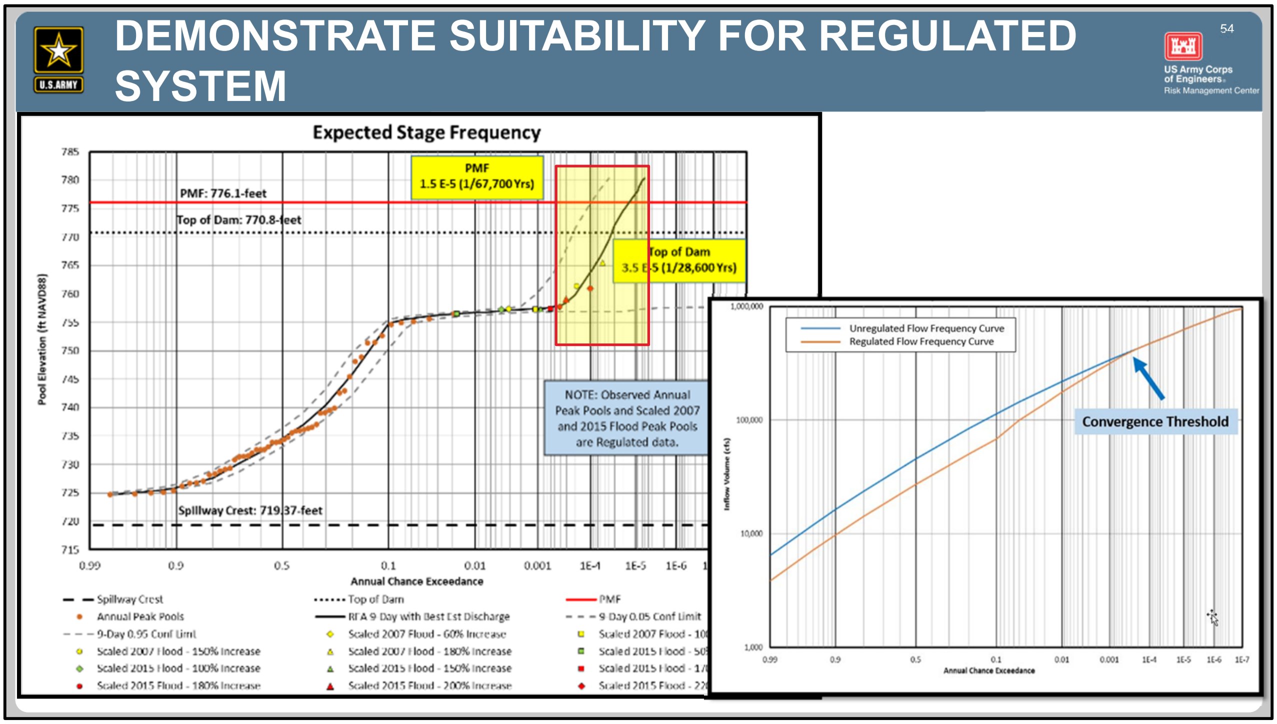
To Re-Cap,

There are three recommended methods for development of stage-frequency curves for USACE Dam Safety studies used for risk analysis:

1) Monte Carlo approach using RMC-RFA

2) Develop a graphical-empirical curve with uncertainty and blend it with the analytical RMC-RFA curve

3) Use a deterministic method. This is rare.



Stage-Frequency curves used for USACE Risk Assessment **must demonstrate an ability to describe the existing regulated system**.

A recommended approach to further **demonstrate that the stage-frequency curve is applicable to a regulated system** is plotting observed peak historic high pools and/or modeled peak stages.

In this figure, we see a stage-frequency curve that was developed using the USACE Dam Safety standard approach, using RMC-RFA.
The empirical stage-frequency curve is plotted as orange points, the black solid curve represents the expected stage-frequency curve, and the dashed grey lines represent the 90% confidence interval.

RMC-RFA requires an analytical volume-frequency curve as an input, and for this analysis we used the standard USACE Dam Safety method, using an **unregulated flow-frequency curve** and calibration of the discharge relationship in RMC-RFA to better approximate the observed portion of the record.

To demonstrate that this stage-frequency curve is reasonable to use for the existing regulated system, several hydrographs scaled to frequency inflow volumes were routed through the hydrologic model to develop peak stages.

The unregulated flow-frequency curve was converted to regulated flows using the regulated-unregulated transform relationship. (click)

Hydrographs were developed using historic event patterns, then scaled to regulated inflow volumes that were transformed using the regulated-unregulated transform relationship.

The scaled hydrographs were routed through an HEC-ResSim model, and resultant peak stages were plotted here as green, yellow, and red points.

You can see that the scaled events demonstrate close similarity to the adopted stage-frequency curve, supporting the assumption that this stage-frequency curve is applicable to the current regulated system.

Additionally, these results support the suitability of the regulated-unregulated convergence threshold selected for this project with an exceedance probability of about 1/4,000 years.

Recall that we make the assumption that unregulated flow frequency is reasonable to use for the development of our stage-frequency curves for AEP's less frequent than the convergence threshold. (click)

In this figure, results should show consistency between empirical stage-frequency estimates (orange points), stochastically simulated stage-frequency curves (RMC-RFA results), and deterministically derived stage-frequency estimates (green, yellow, red points).

Because the regulated peak stage results demonstrate close similarity to the adopted stage-frequency curve, this supports the assumption that this stage-frequency curve is applicable to the current regulated system.

CONCLUSIONS

- **Bulletin 17C procedures -** USACE Dam and Levee Safety Studies
- Unregulated dataset **required**
- Identify: Appreciable upstream regulation
- Develop: Unregulated inflow dataset
- Develop: Unregulated analytical flow-frequency
- Develop: Stage Frequency curve
- ***Engineering judgment is required***

In conclusion – Bulletin 17C methods should generally be used for USACE Dam and Levee Safety Studies

Unregulated inflow datasets are required for development of analytical flow-frequency using Bulletin 17C methods.

We reviewed how to identify if the reservoir of interest is appreciably affected by upstream regulation,

If the reservoir is impacted by upstream regulation,
we discussed how to develop an unregulated inflow dataset.
We discussed how to develop an analytical flow-frequency analysis on unregulated inflow datasets
And we discussed how to develop stage-frequency curves using unregulated analytical inflow volume-frequency curves,
and demonstrate the suitability of the stage-frequency curve for the existing regulated system.

Remember that engineering judgment is required on these analyses and if you run into questions – please reach out to HEC and the RMC for guidance.

QUESTIONS ??

US Army Corps of Engineers
Risk Management Center

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