Extreme Hydrologic Events Monitoring

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U.S. Department of the Interior
U.S. Geological Survey

Mission Statement

"The USGS serves the Nation by providing reliable scientific information to describe and understand the Earth; minimize loss of life and property from natural disasters; manage water, biological, energy, and mineral resources; and enhance and protect our quality of life."

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Extreme Hydrologic Events

- Extreme hydrologic events are the outliers in streamflow conditions, occur infrequently but require the majority of planning and preparation.

- Extreme hydrologic events increase risks to life and property and their impact can be felt by a community for years after the flood waters have receded or the drought has ended.

Agenda

- Today we'll be talking about:
  - Prerequisites
    - Uses of streamflow information
    - How streamgage network is funded and how that impacts *where* streamgages are located
    - What a streamgage is and how it works
  - What the current streamgage network in Kansas looks like
  - How the USGS streamgage network supports flood management in Kansas
  - How the USGS supports drought planning and mitigation

Presenter:
Craig Painter

  - Extreme events and sediment transport

Presenter:
Ariele Kramer

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Prerequisites

- Uses of streamgage data
  - Water supply and allocations
  - Engineering design of bridges, roads, culverts, reservoirs, and treatment facilities
  - Flood warning and flood planning
  - Water-quality monitoring and studies
  - Aquatic wildlife assessment
  - Reservoir operations, hydroelectric dam production, navigation
  - Recreational use by fisherman and paddlers

Prerequisites

- Types of streamgages:
  - Stage only, full discharge, crest stage gage, water quality
- They all measure “stage”
  - Other terms “gage height” or “elevation”
- Discharge is the main product for many streamgages but not all
- High flow data can also be assessed with non-realtime data from crest stage gages
- At some streamgages we have water-quality data, very rarely do we have locations with water quality data and not have stage and discharge data

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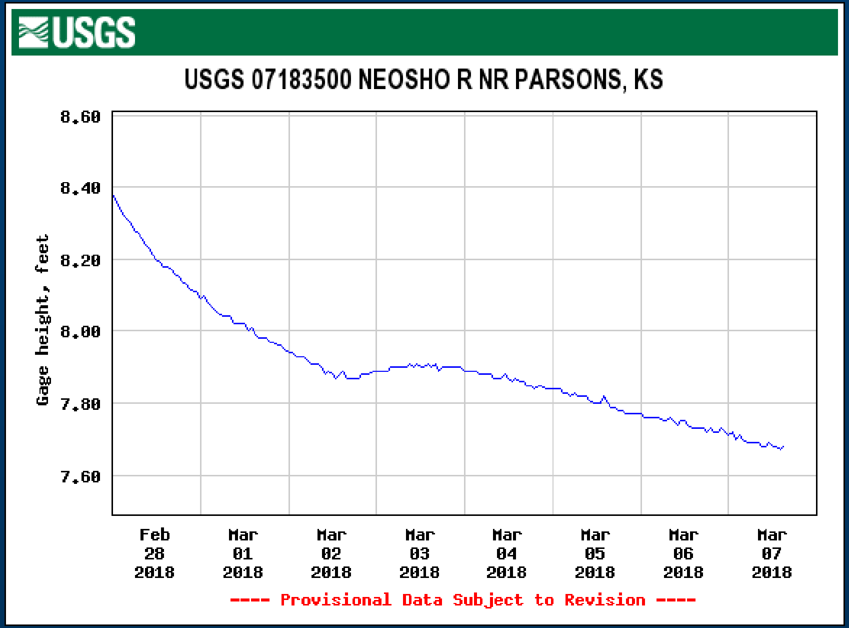
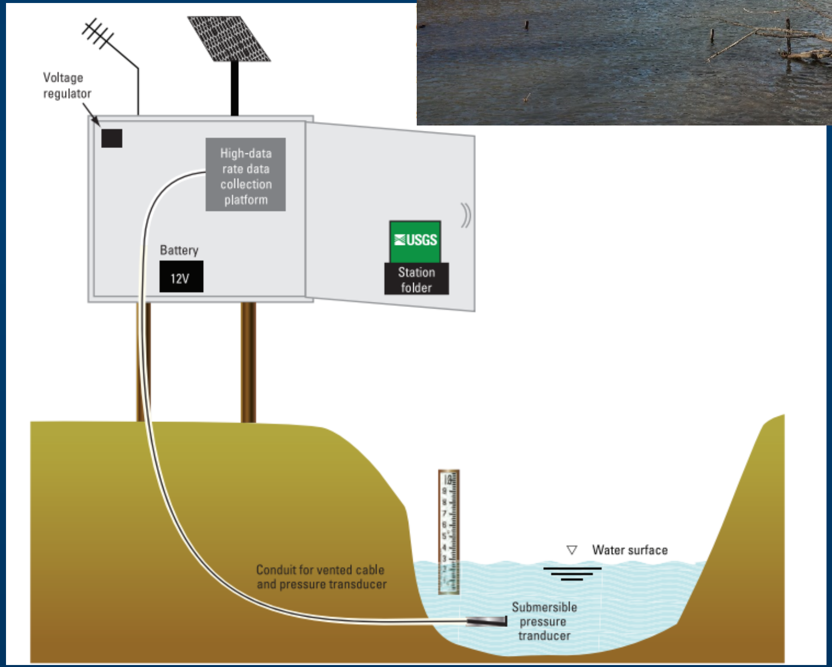
Streamgages

A continuous record of stream elevation is the foundation for all streamflow data.



Gage height (also referred to as stage) is recorded in local datum.

Streamgages: – Pressure Transducer (Bubbler)



Gas line running into stream

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Streamgages – Radar

No moving parts to break down, but are subject to bias from water-surface disturbances. Data can be accurately interpreted after disturbance has ceased.

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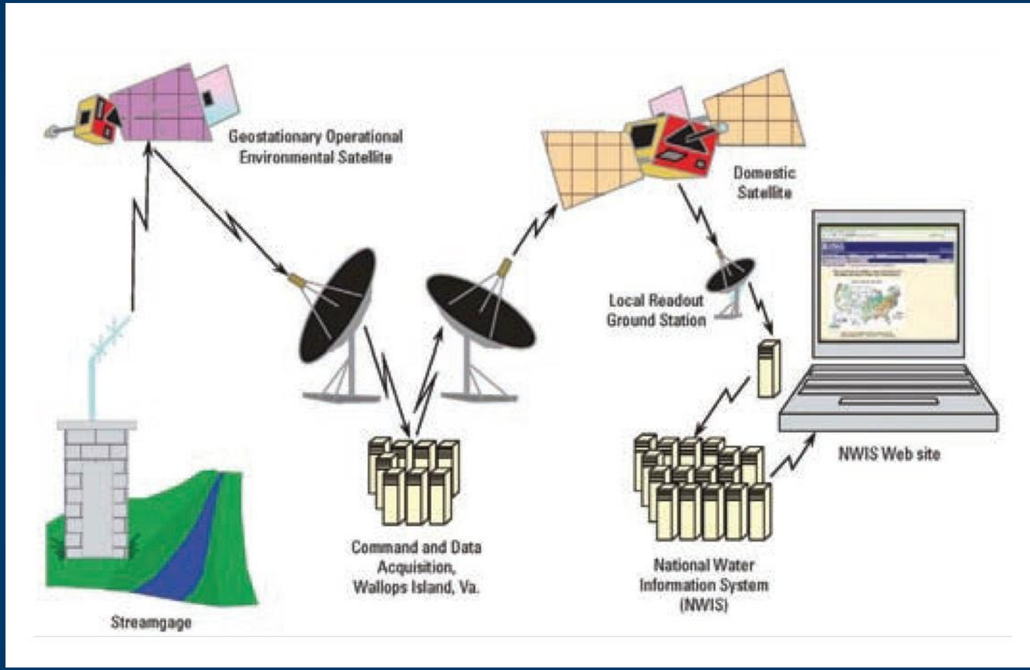
Streamgages – Data Retrieval

Streamgage data is sent out to geostationary (GOES) satellites, which then broadcast the signal back down to ground readout stations.



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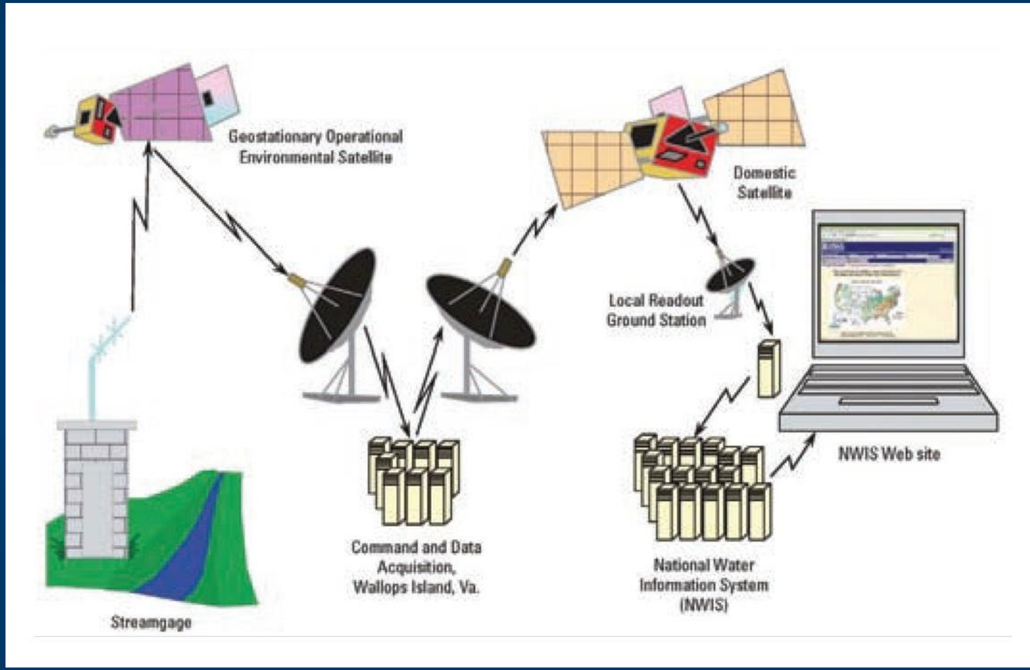
Streamgages – Data Retrieval

NOAA and US Army Corps of Engineers are able to directly retrieve transmissions and ingest into their respective systems and feed the forecast and reservoir routing models.



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Streamgages – Non-traditional methods

Data transmission can also be done via cellular modems, iridium modems, or a few other options.

Stage/Q doesn't always work. For sites where stage/q relation is invalid we must bring in more data to approximate the streamflow.

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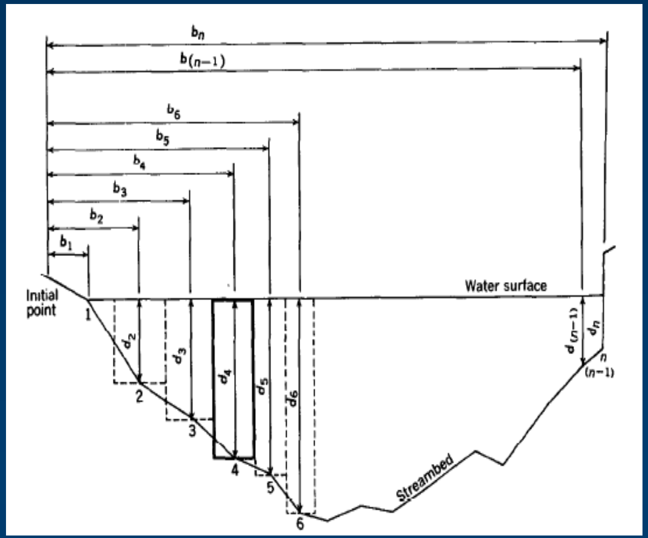
Streamflow (Discharge) Measurements



Q=V×A

Discharge (velocity x width x depth), is calculated for 25 to 35 sections across the stream. These are summed to provide the total discharge of the stream at the time of measurement. Measurements are made in cubic feet per second (cfs)

1 cfs = 7.5 gallons per second

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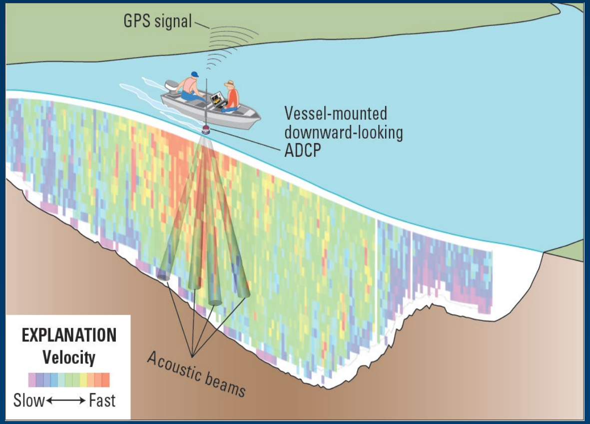
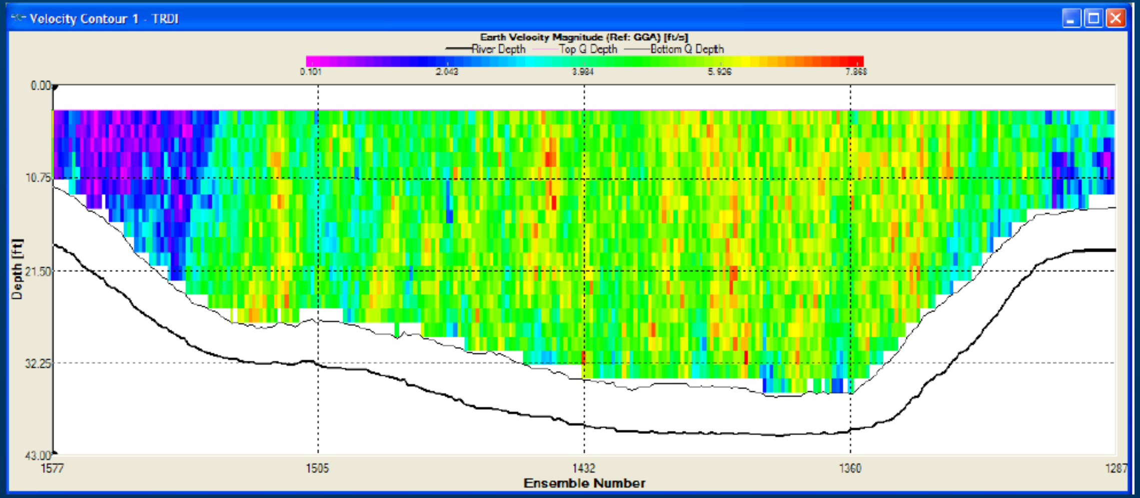
Streamflow (Discharge) Measurements





Other measuring devices use hundreds to thousands of data points on 3-dimensional velocity, width, and depth to compute discharge from a single cross section.

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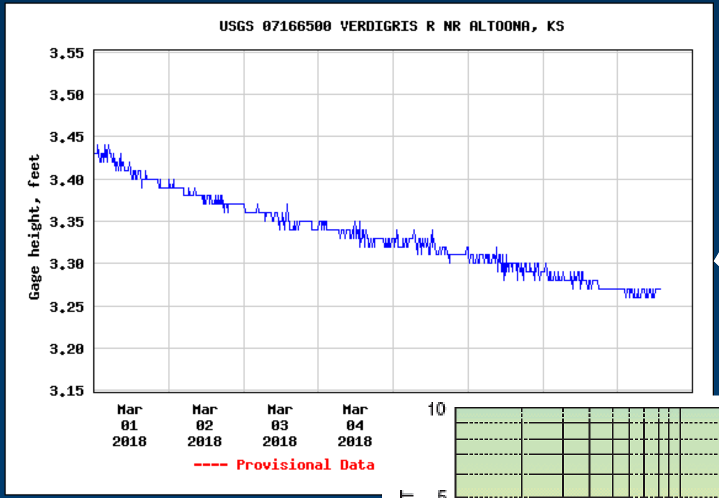
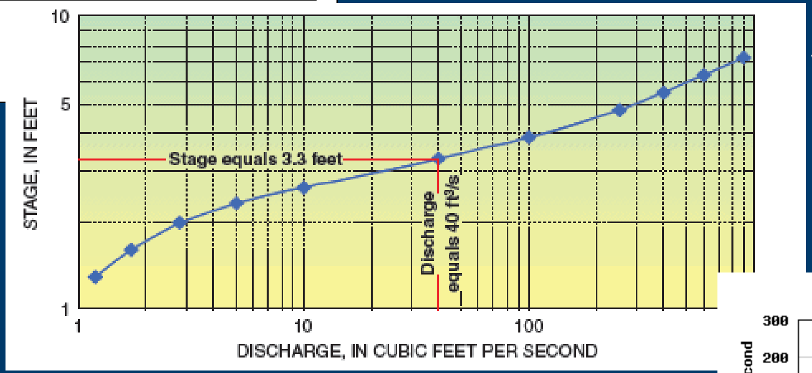
Relating elevation to streamflow

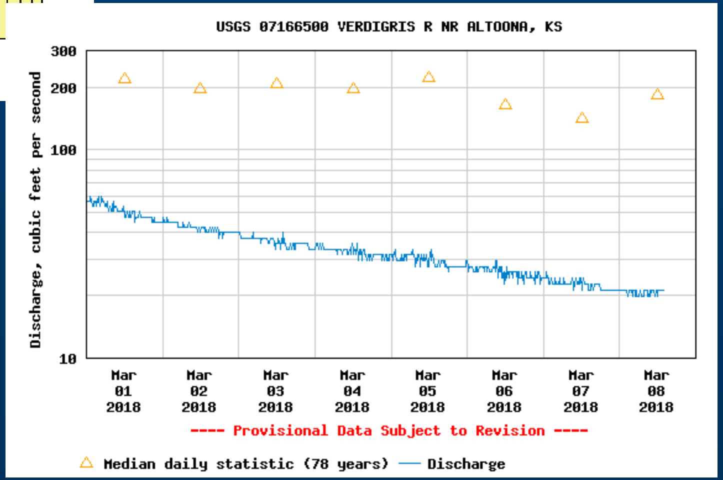


Raw stream elevation data collected by the streamgage.



Compiled with onsite streamflow measurements covering the entire range of stage.

To produce the record of streamflow.



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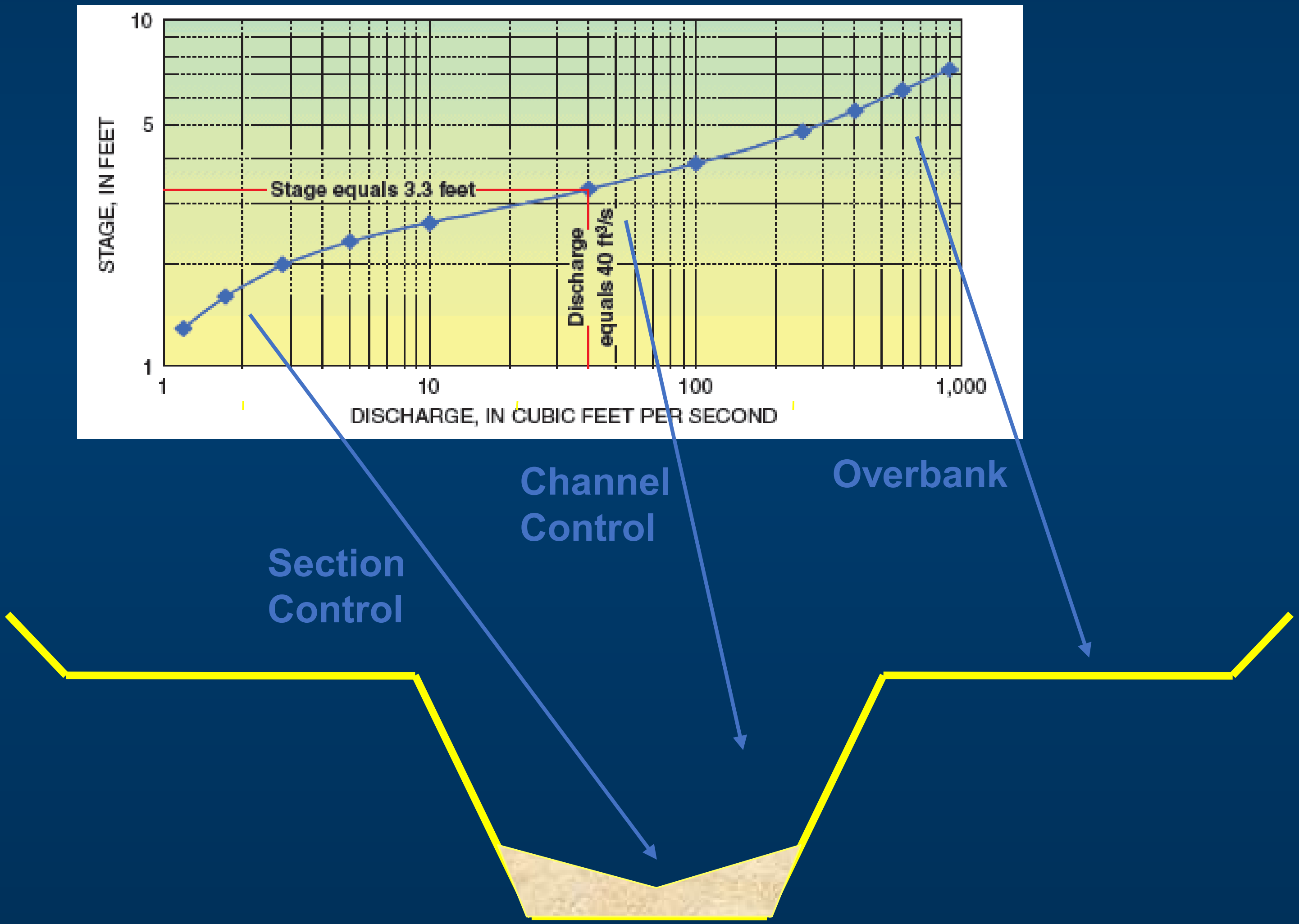
Breakdown of a stage-discharge rating



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Breakdown of a stage-discharge rating

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Breakdown of a stage-discharge rating

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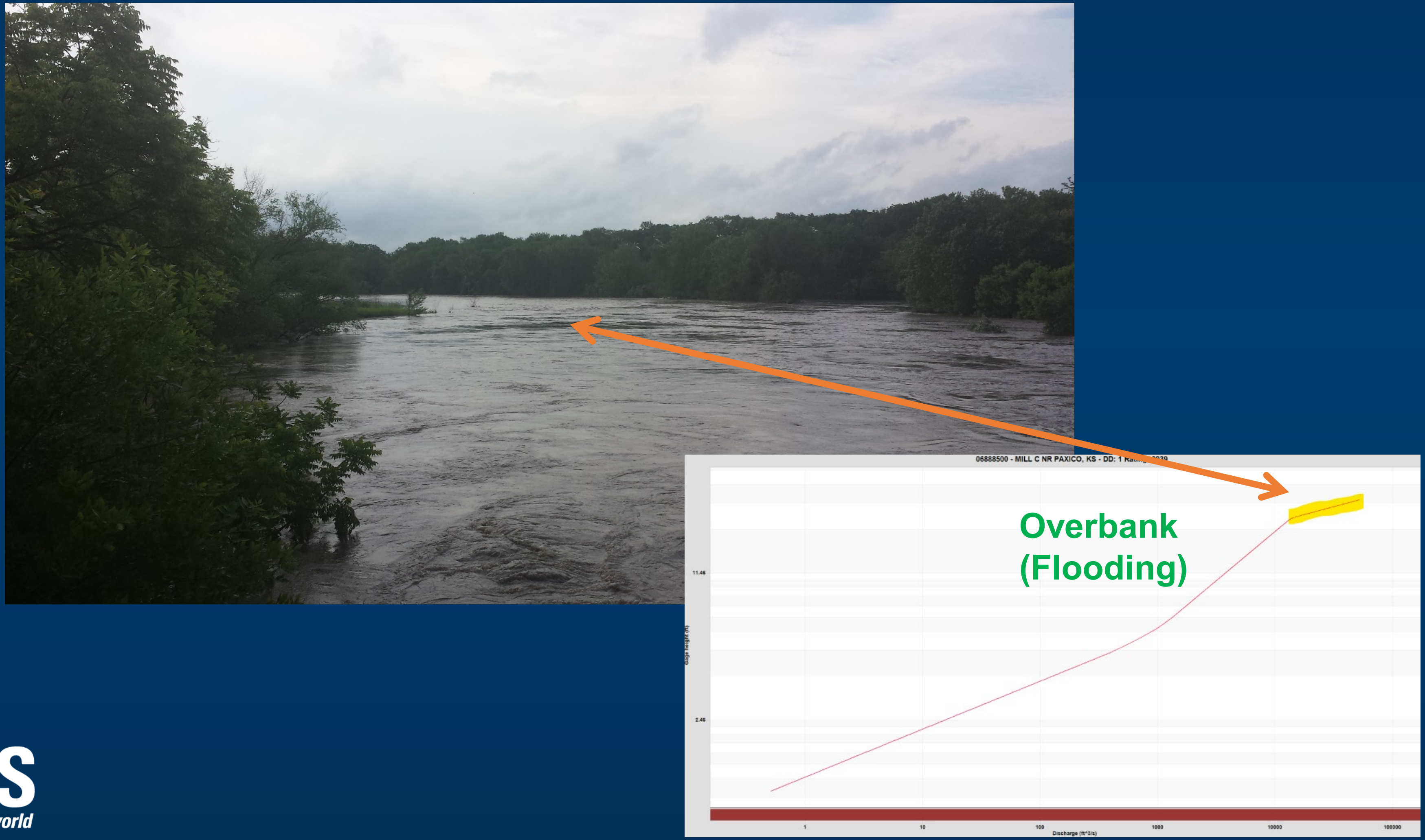
Breakdown of a stage-discharge rating



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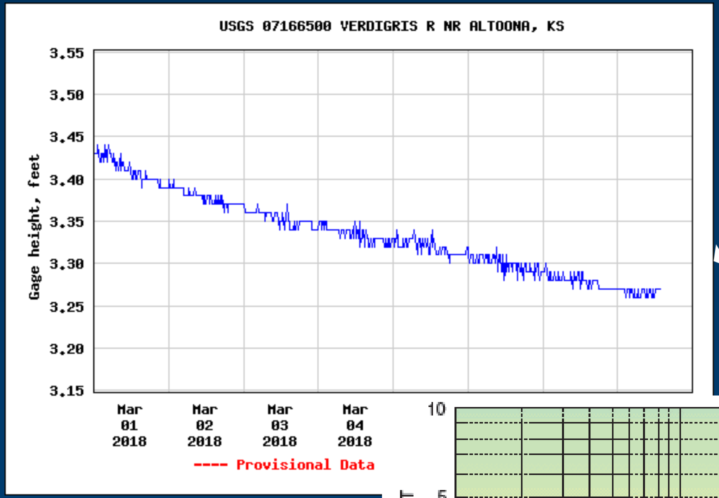
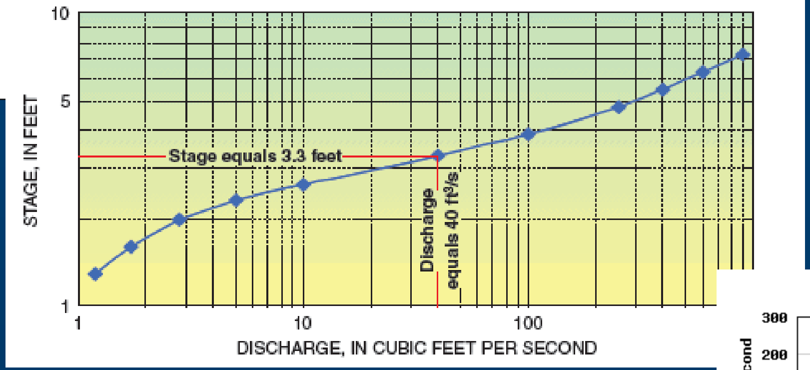
Relating elevation to streamflow

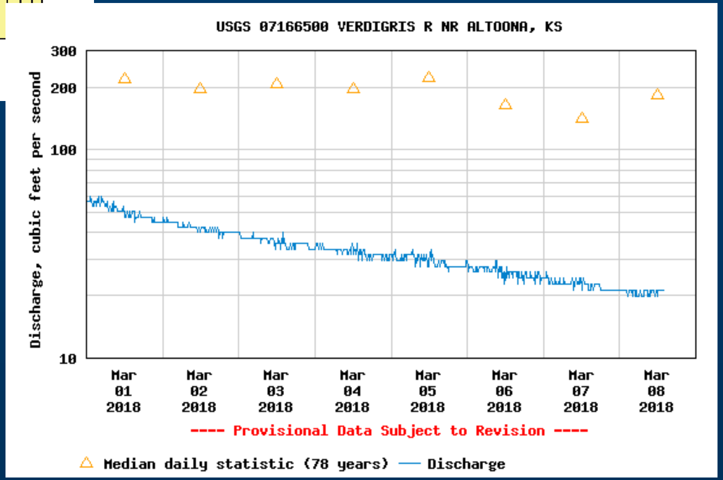


Continuous record of stage.



Streamflow measurements at a range of stages and channel conditions.

To produce the record of streamflow.



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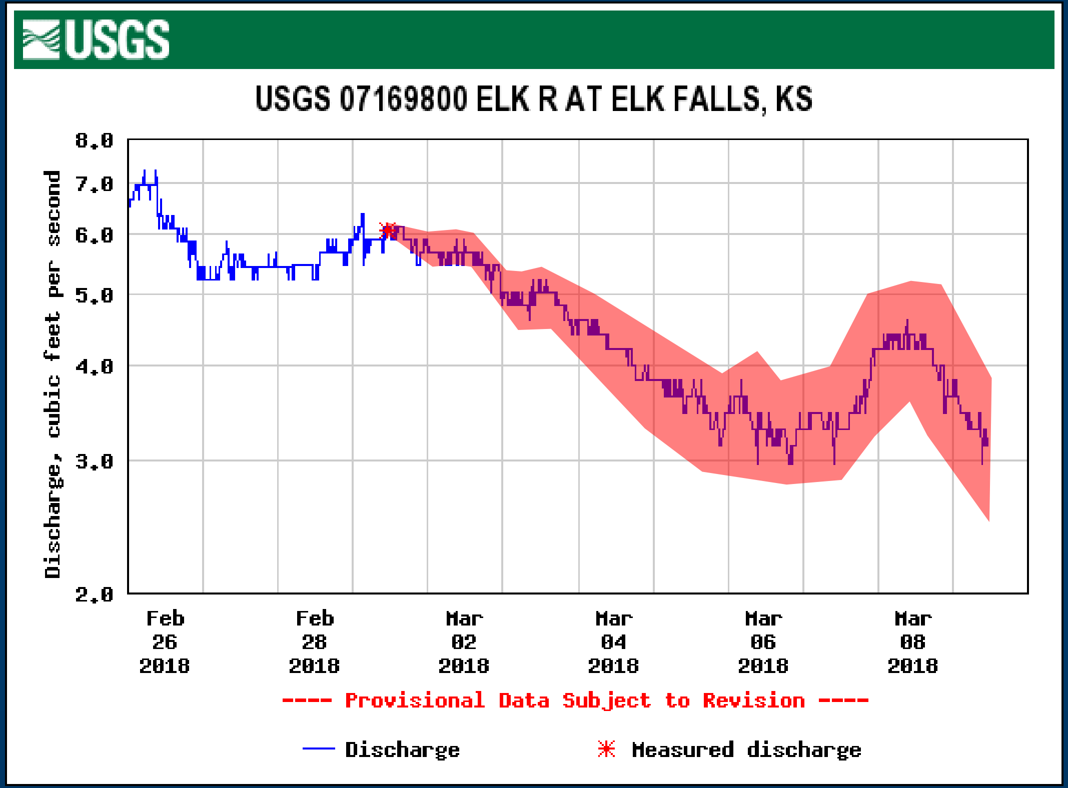
Potential error grows with time since last measurement



Due to the possibility of naturally changing conditions in the stream, or stage sensor reporting a reading in error, measurements are made on a routine basis and in response to identified needs for the site.

Verdigris R at Independence

An extreme example of changes to a rating at low flow.

October 18, 2011
Stage: 2.17 feet (gage datum)
Discharge: 18.9 cfs

September 16, 2015
Stage: 2.00 feet (gage datum)
Discharge: 47 cfs

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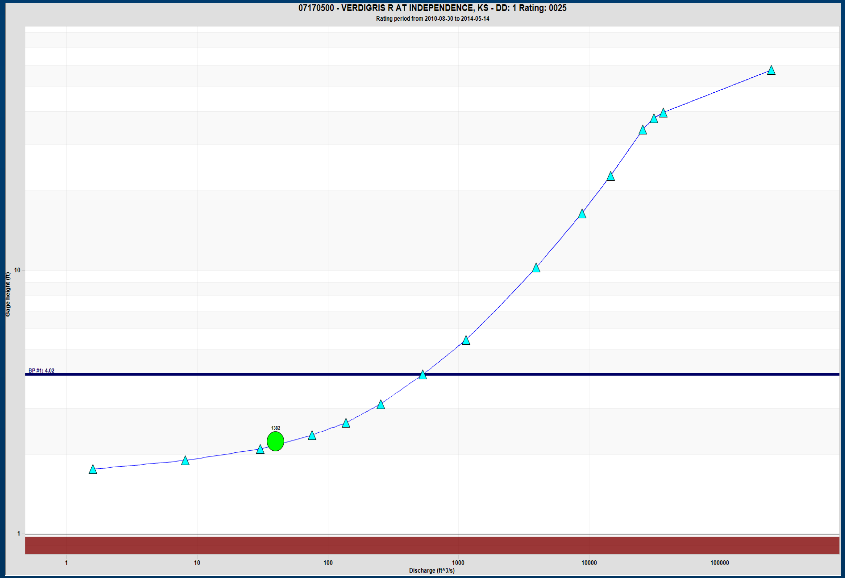
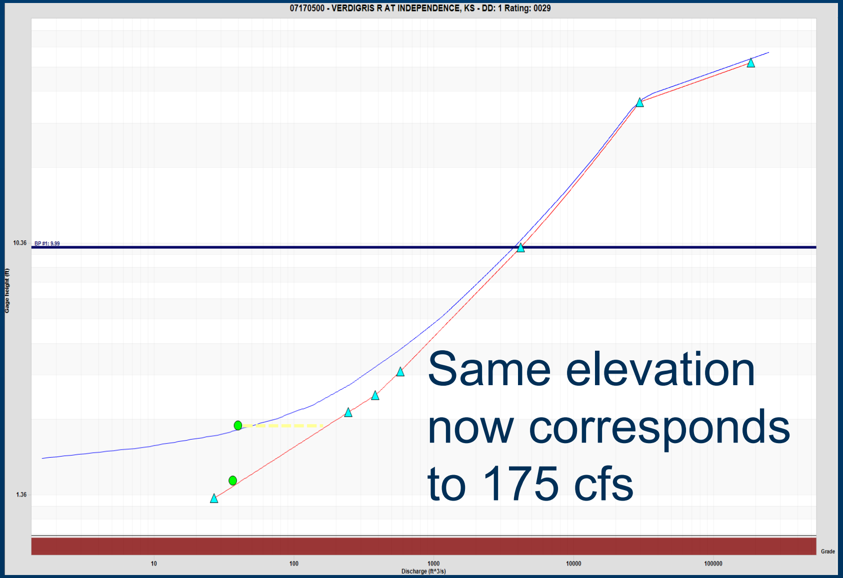
Verdigris R at Independence

An extreme example of changes to a rating at low flow.

September 8, 2011
Stage: 2.25 feet (gage datum)
Discharge: 39.6 cfs

January 30, 2018
Stage: 1.50 feet (gage datum)
Discharge: 36.5 cfs





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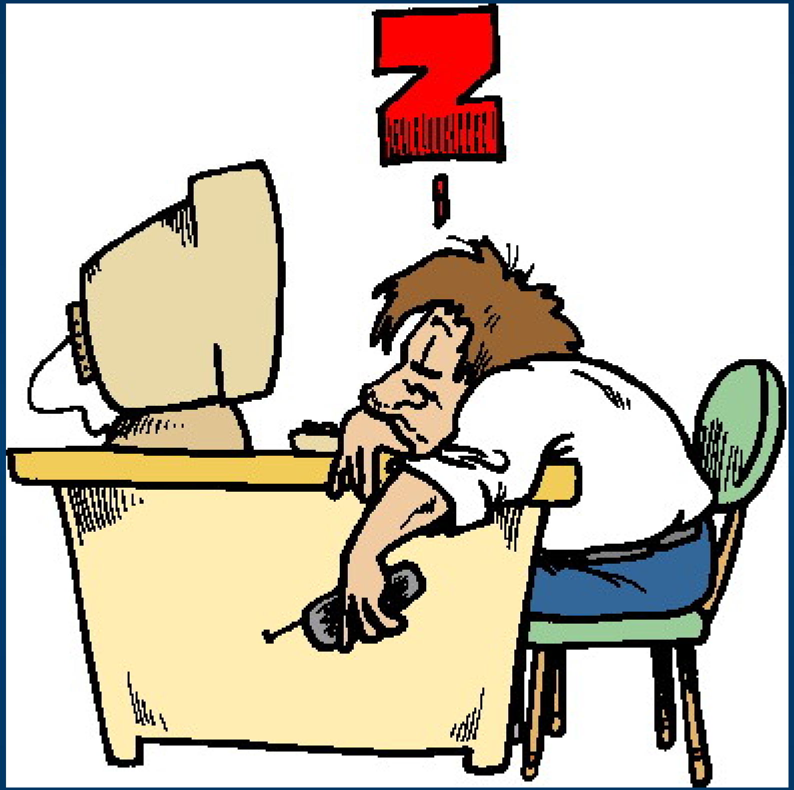

Enough with the background information, let's talk extreme events!

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Extreme Events in Kansas

Come in three general flavors:

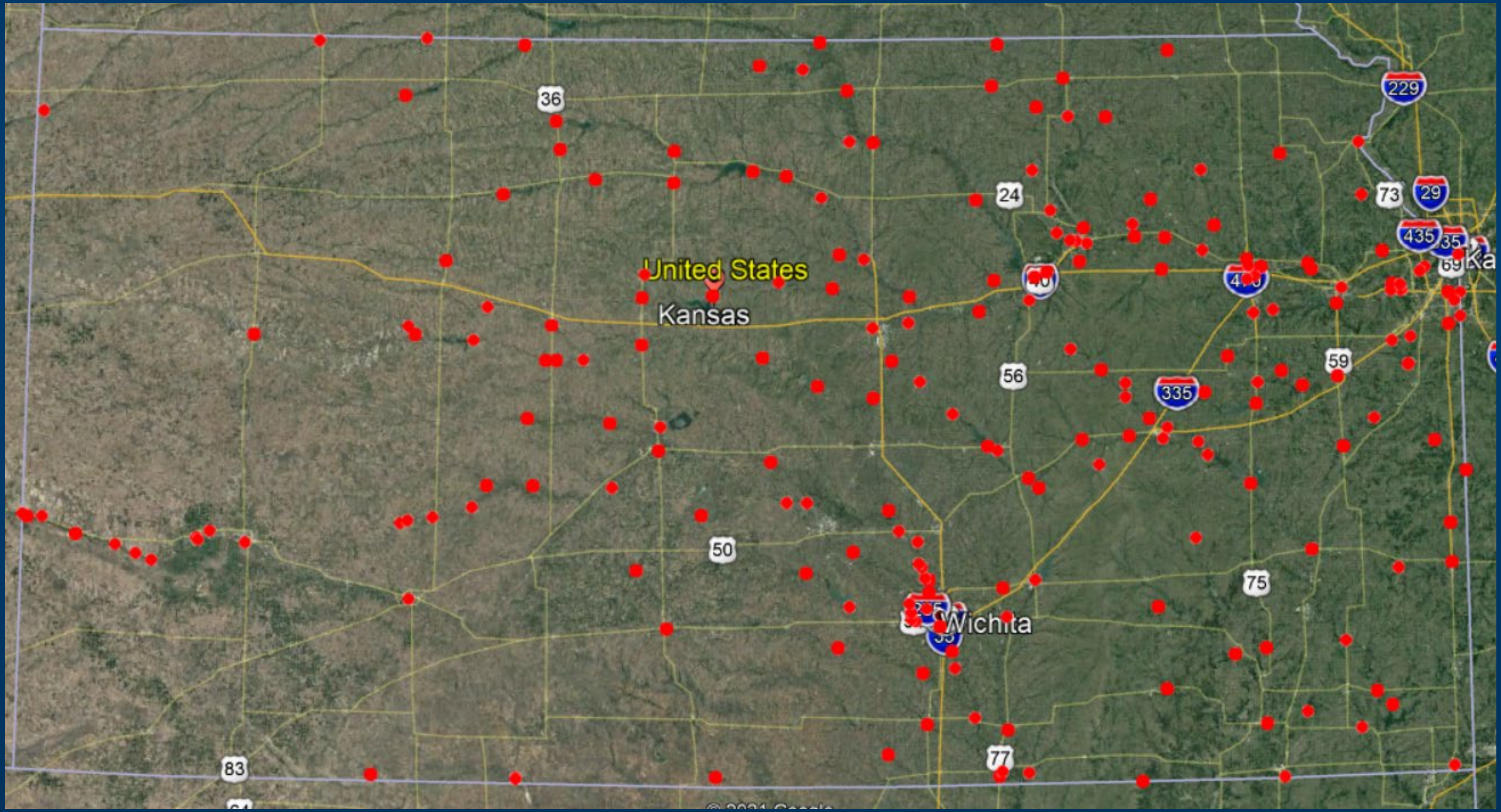
1. Flooding
   - Not as predictable in Kansas as it is in other areas of the country. The main drivers for flooding in many areas are snow melt or hurricane.
   - Flooding in Kansas is generally caused by either highly convective storms dropping a large amount of precipitation in a small area over a short amount of time or persistent rainfall over a large area lasting for several weeks.
2. Drought
   - Can be predicted several months in advance with confirmation coming in the form of continued monitoring throughout a drought event.
3. Water-quality events
   - Can either be related to an extreme in the streamflow conditions (flood or drought) or can occur independently.

Extreme Events in Kansas

Flooding

All streamgages measure stage, not all streamgages have a discharge that is associated with that stage data.

Currently there are 217 USGS streamgages in Kansas.



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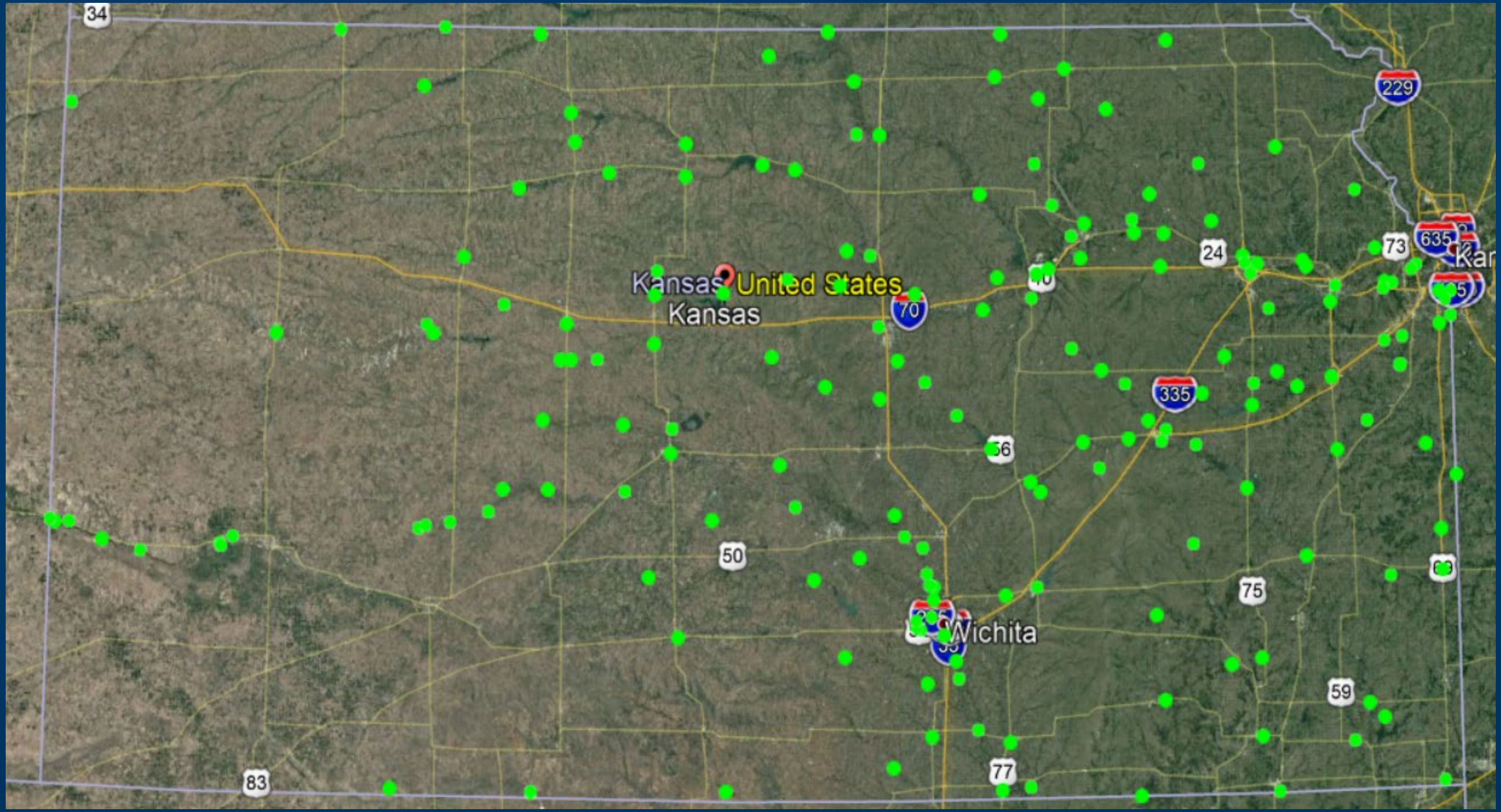
Extreme Events in Kansas

Flooding

All streamgages measure stage, not all streamgages have a discharge that is associated with that stage data.

Of those 217 streamgages, 187 are full hydrograph discharge gages. Meaning that streamflow is calculated at those sites making them useful for forecasting reservoir operations, and peak flow studies.



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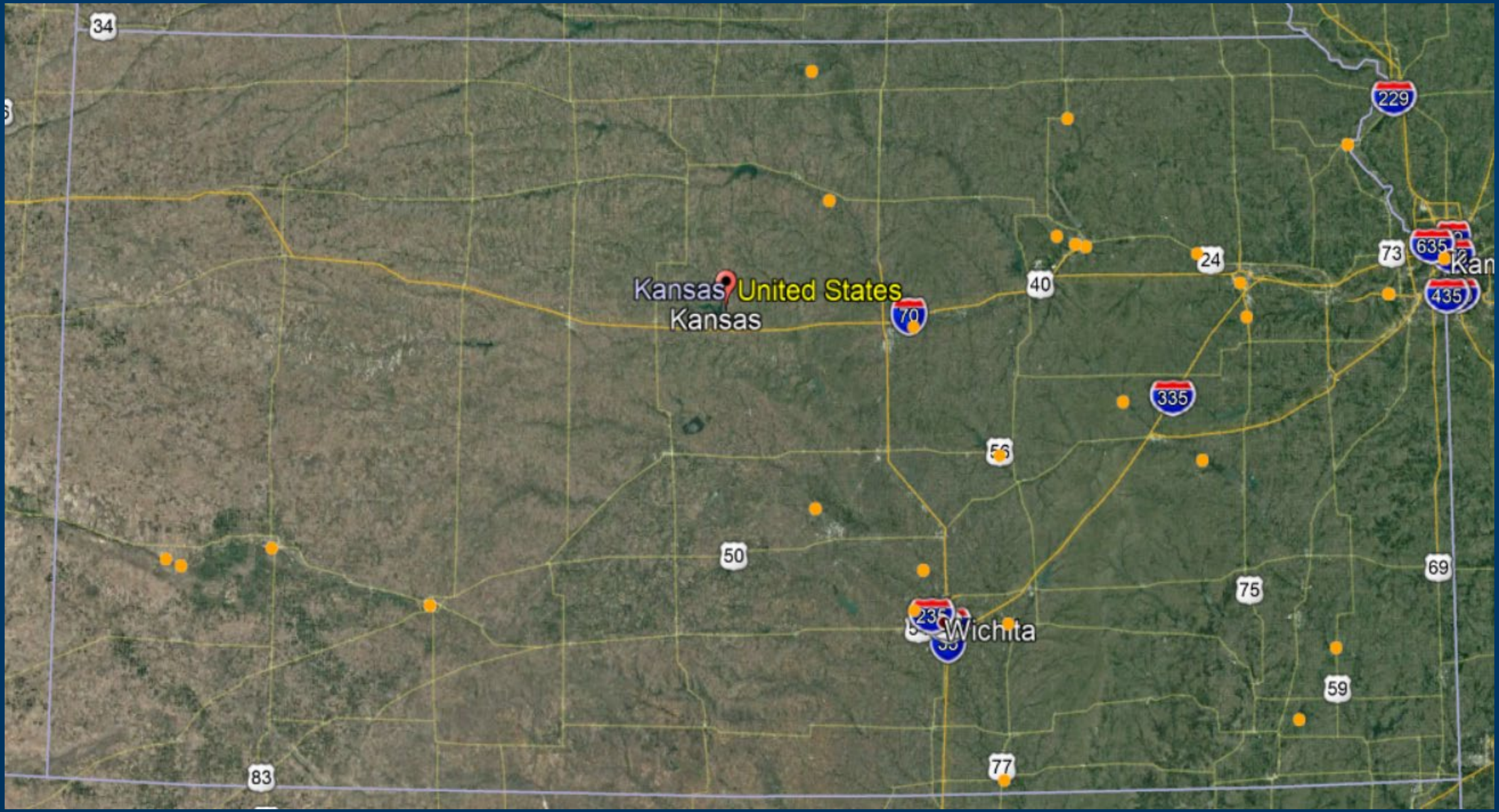
Extreme Events in Kansas

Flooding

All streamgages measure stage, not all streamgages have a discharge that is associated with that stage data.

30 of the streamgages are stage only, which do not have streamflow data calculated at the site. These sites typically have municipal partners using the data for levee/pump operations and flood warning.



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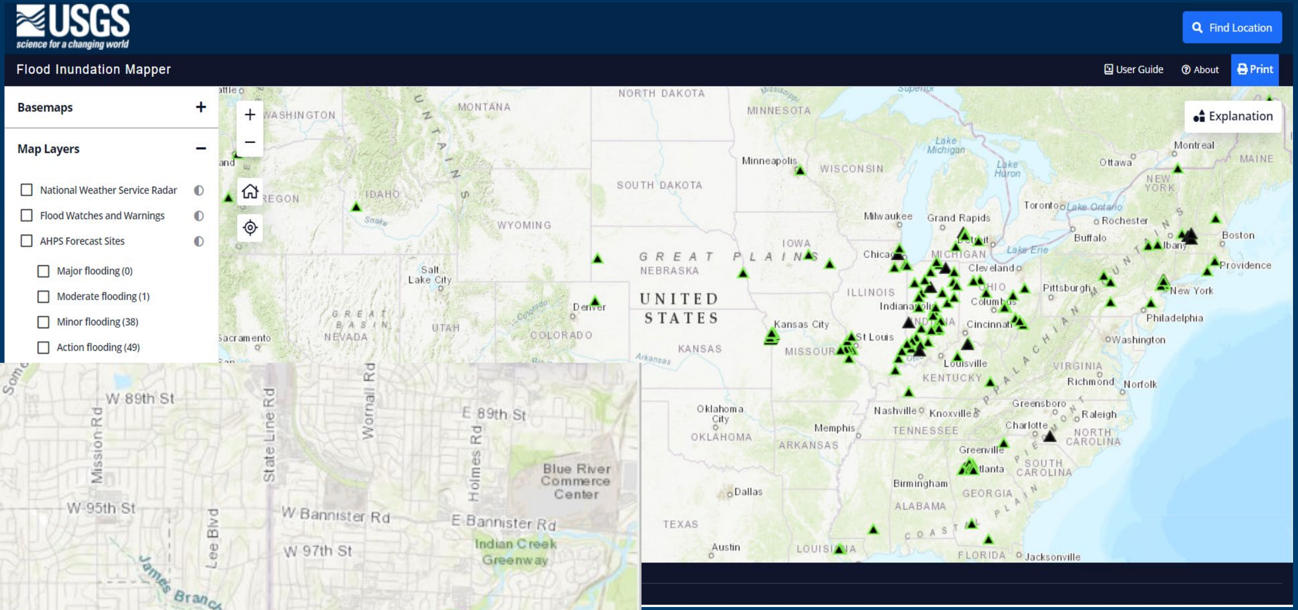
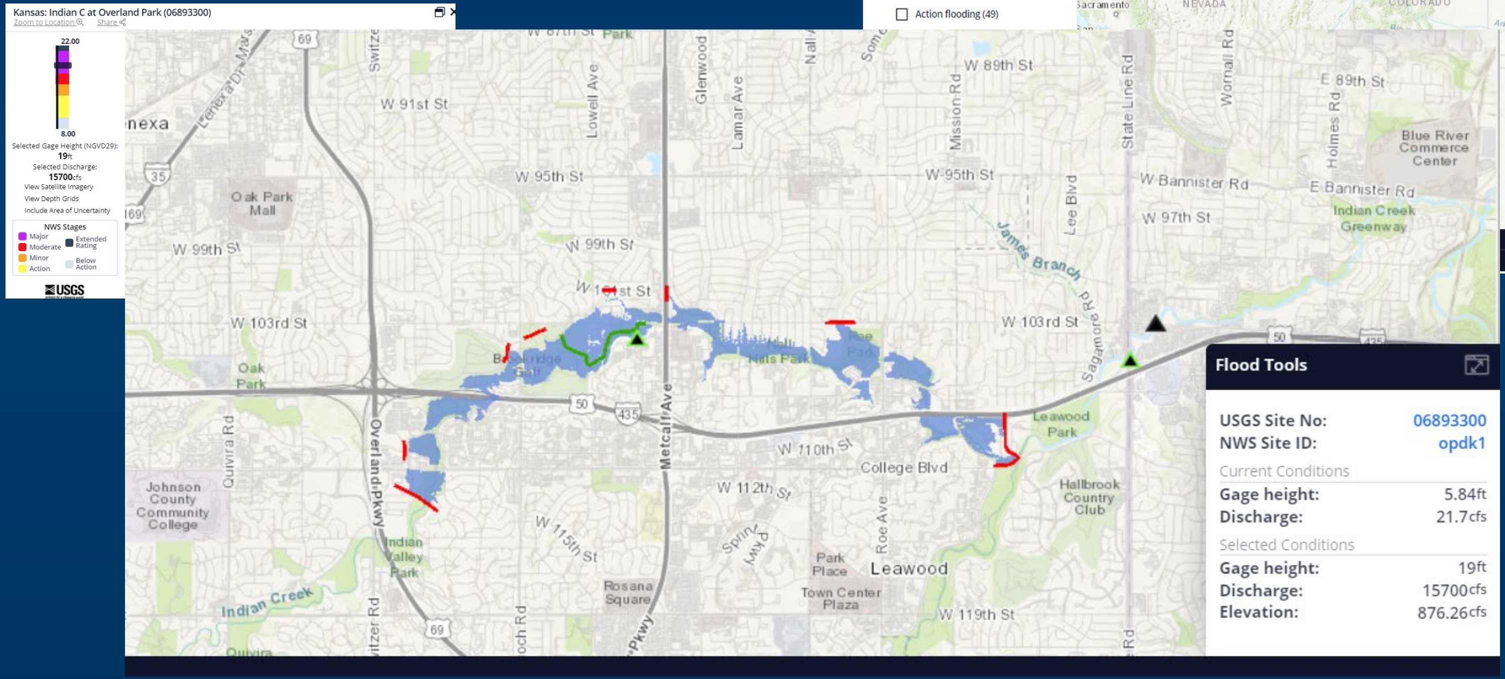
Extreme Events in Kansas

Flooding

What does USGS do with this information?





Flood inundation mapping. Interactive maps that are tied to streamgage data showing the extent of flood waters.

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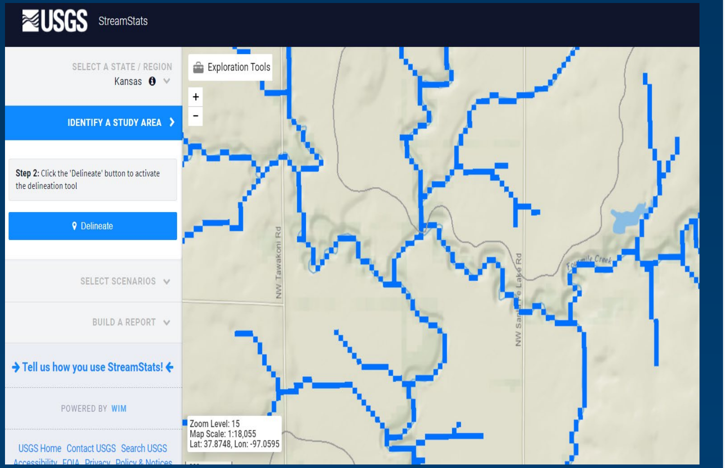
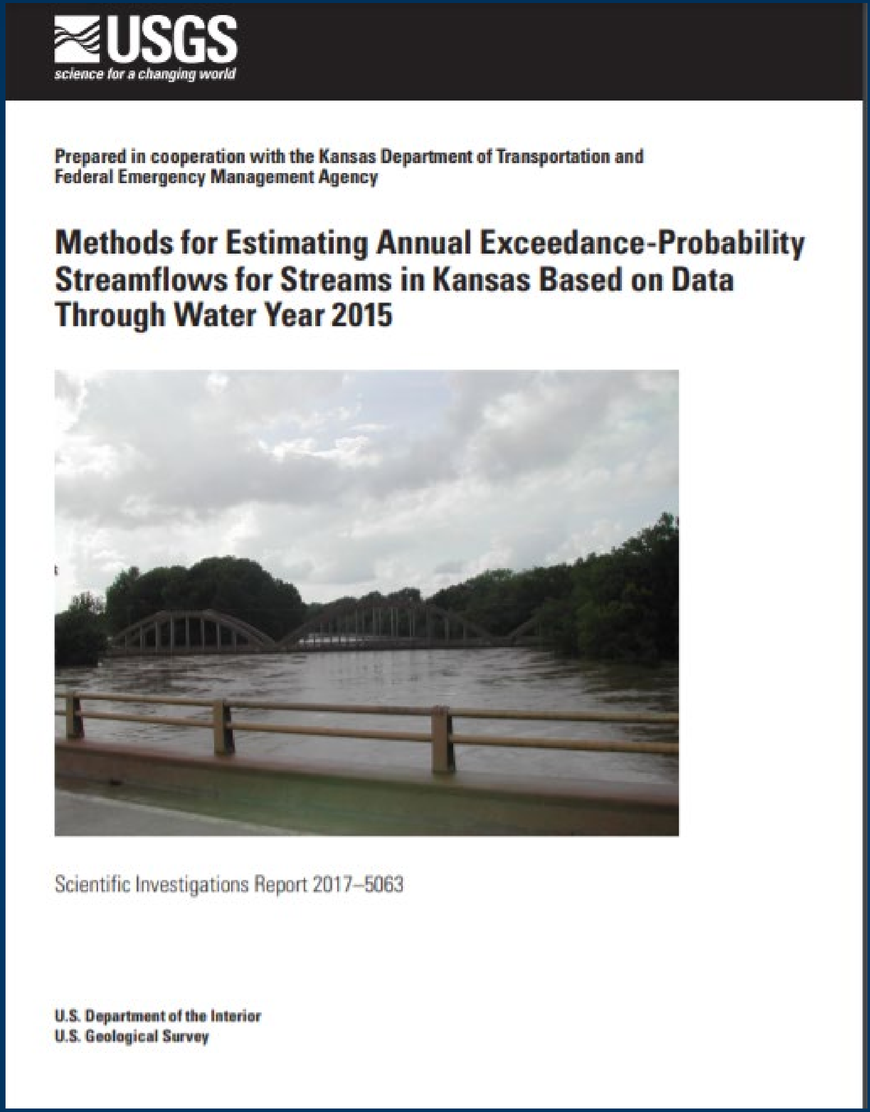
Extreme Events in Kansas

Flooding

What does USGS do with this information?



Studies on flood recurrence, which are used for assessing flood risk at ungaged locations. The streamstats web application has made this more user friendly than ever before.



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Prepared in cooperation with the Kansas Department of Transportation and Federal Emergency Management Agency

Methods for Estimating Annual Exceedance-Probability Streamflows for Streams in Kansas Based on Data Through Water Year 2015

Scientific Investigations Report 2017–5063

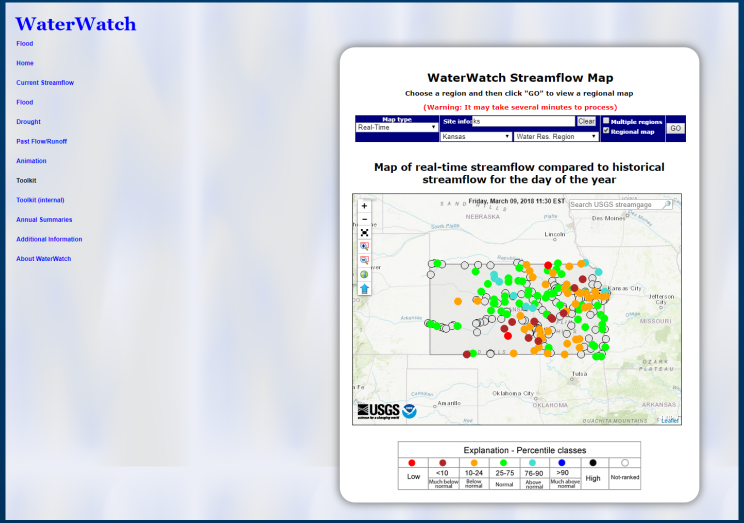
U.S. Department of the Interior
U.S. Geological Survey

Extreme Events in Kansas

Flooding

What does USGS do with this information?

Most importantly the USGS provides streamflow and flooding information to the public and other management agencies.



USGS products include:

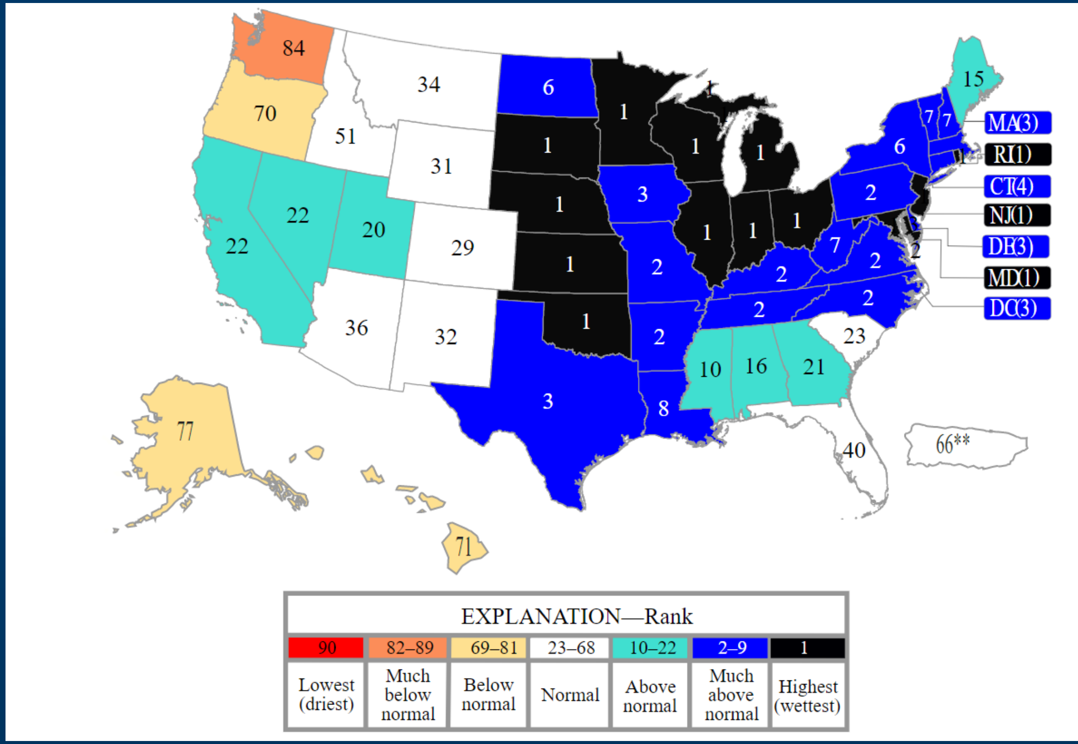
- WaterWatch
  - A web application that provides a wide array of streamflow statistics computed on the fly providing context to the information available.
- WaterAlert
  - A SMS messaging system where users can set thresholds of interest and receive automated alerts when those thresholds are exceeded at the streamgage.

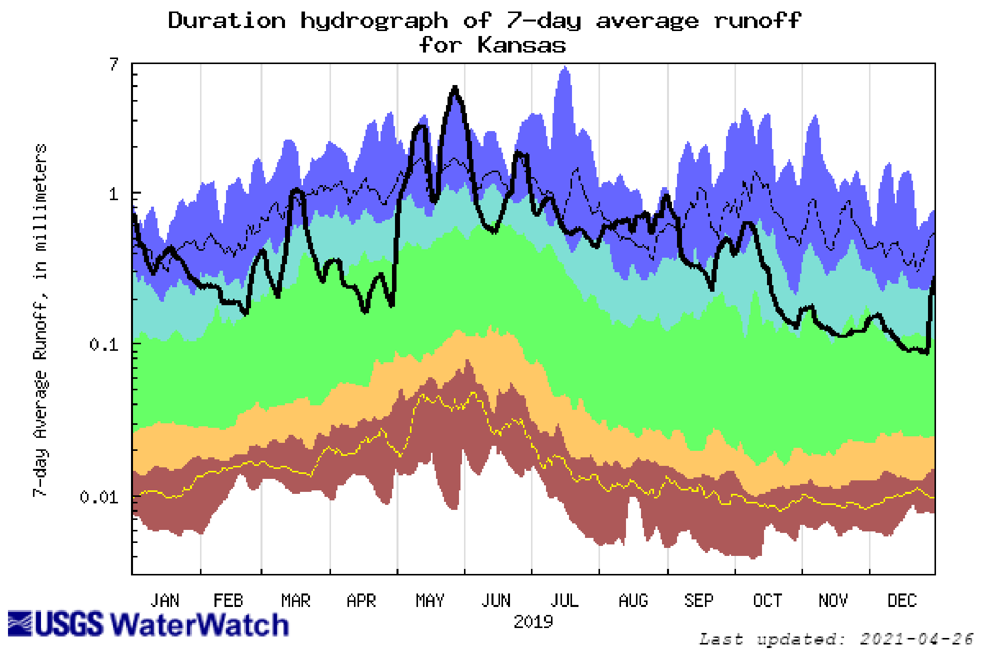
Extreme Events in Kansas

Flooding

Major flood events in Kansas

2019 – Statewide





A well mitigated flood.

High soil moisture preceded the spring rains.

Persistent rainfall throughout the spring.

Reservoir water levels were high for several months.

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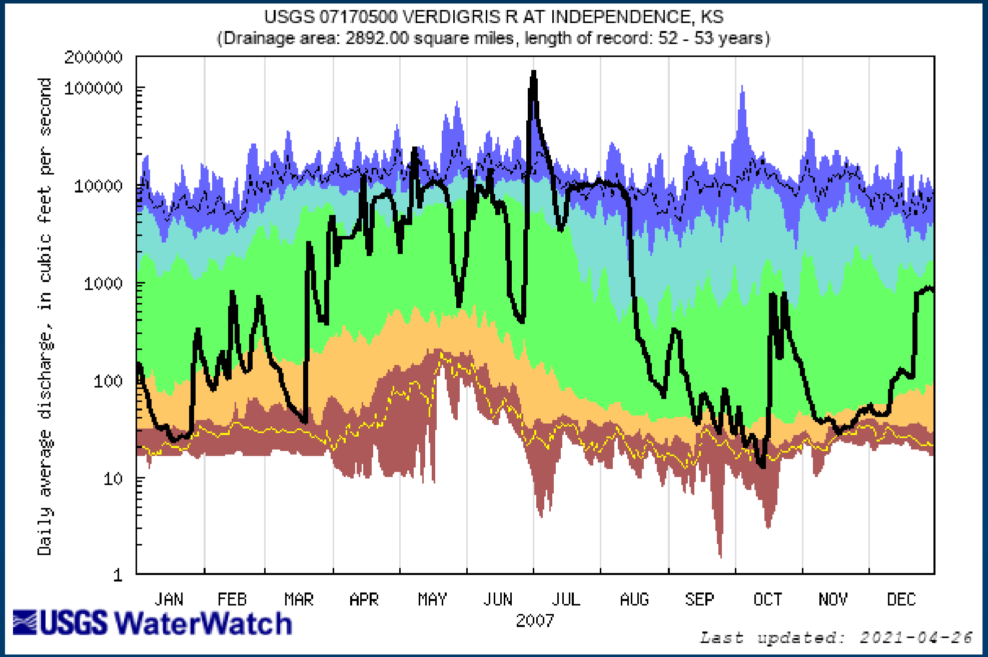
Extreme Events in Kansas

Flooding

Major flood events in Kansas

2007 – Southeast Kansas



Widespread flash flooding.

Remnants of a tropical storm dumped as much as 17 inches of rain over 2 days. Rivers throughout Southeast Kansas overtopped levees, closed major highways, caused incredible damage.

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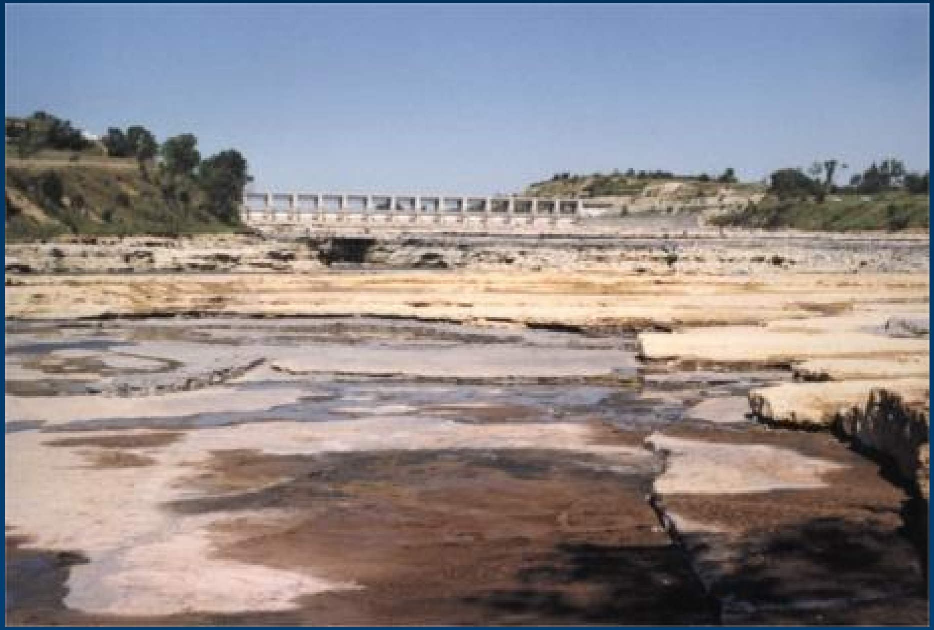
Extreme Events in Kansas

Flooding

Major flood events in Kansas
1993 – Statewide



Rainfall that would not stop.

Much like the 2019 year, persistent rainfall throughout the spring and summer led to the flooding of 1993.

High soil moisture and rising reservoir levels preceded the flood.

A knockout rainfall event in July of 1993 fell while rivers and reservoirs were already high.

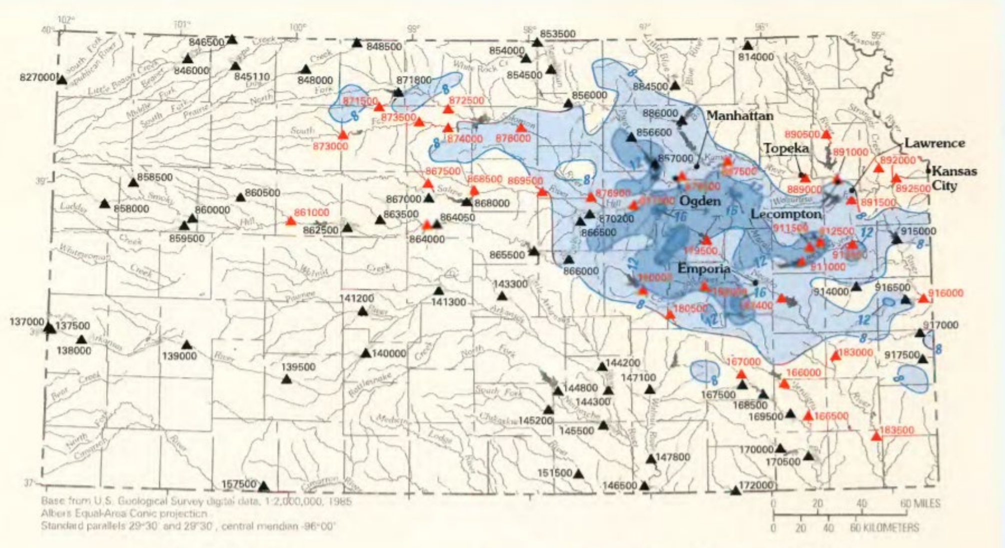
Extreme Events in Kansas

Flooding

Major flood events in Kansas

1951 – Statewide

Photo courtesy of Kansas State Historical Society



Juracek, Perry, and Putnam 2001

A large-scale flash flood.

*Weather data to analyze this event is not equal to the data available for later flood events.

Flood event was prior to many of the mitigation efforts put in place soon after such as flood control reservoirs and levees.

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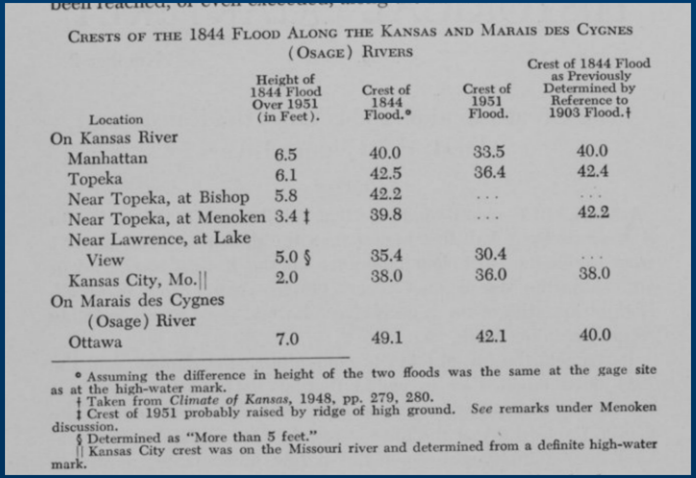
Extreme Events in Kansas

Flooding

Other notable events

- Halloween Flood of 1998 – Wichita, KS
- The Great Flood of 1903
    - Spotty data is available for this flood.
- The Big Water of 1844
    - Thought to be the greatest flood on record.



CRESTS OF THE 1844 FLOOD ALONG THE KANSAS AND MARAIS DES CYGNES (OSAGE) RIVERS

Location	Height of 1844 Flood Over 1951 (in Feet).	Crest of 1844 Flood.*	Crest of 1951 Flood.	Crest of 1844 Flood as Previously Determined by Reference to 1903 Flood.†
On Kansas River				
Manhattan	6.5	40.0	33.5	40.0
Topeka	6.1	42.5	36.4	42.4
Near Topeka, at Bishop	5.8	42.2	. . .	. . .
Near Topeka, at Menoken	3.4 ‡	39.8	. . .	42.2
Near Lawrence, at Lake View	5.0 §	35.4	30.4	. . .
Kansas City, Mo.‖	2.0	38.0	36.0	38.0
On Marais des Cygnes (Osage) River				
Ottawa	7.0	49.1	42.1	40.0

* Assuming the difference in height of the two floods was the same at the gage site as at the high-water mark.
† Taken from *Climate of Kansas*, 1948, pp. 279, 280.
‡ Crest of 1951 probably raised by ridge of high ground. *See* remarks under Menoken discussion.
§ Determined as "More than 5 feet."
‖ Kansas City crest was on the Missouri river and determined from a definite high-water mark.

(Courtesy of Kansas State Historical Society)

North Topeka during height of 1903 flood (photograph courtesy of the Kansas State Historical Society, Topeka).

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Extreme Events in Kansas

Flooding

Comparison

1951 – Few flood control measures in place.
1993 – Flood control comes from levees and reservoirs; real-time data and forecasting are in their infancy.
2019 – Real-time data is now an expectation rather than a commodity. Streamflow forecasting has become highly reliable based off the availability of current streamflow combined with forecast weather.

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Extreme Events in Kansas

Flooding

What is the streamgage network doing well at?

Data used for reservoir operations. US Army Corps of Engineers has been a long-standing partner with the KSWSC and the federal reservoirs have streamgages used for inflow and outflow.

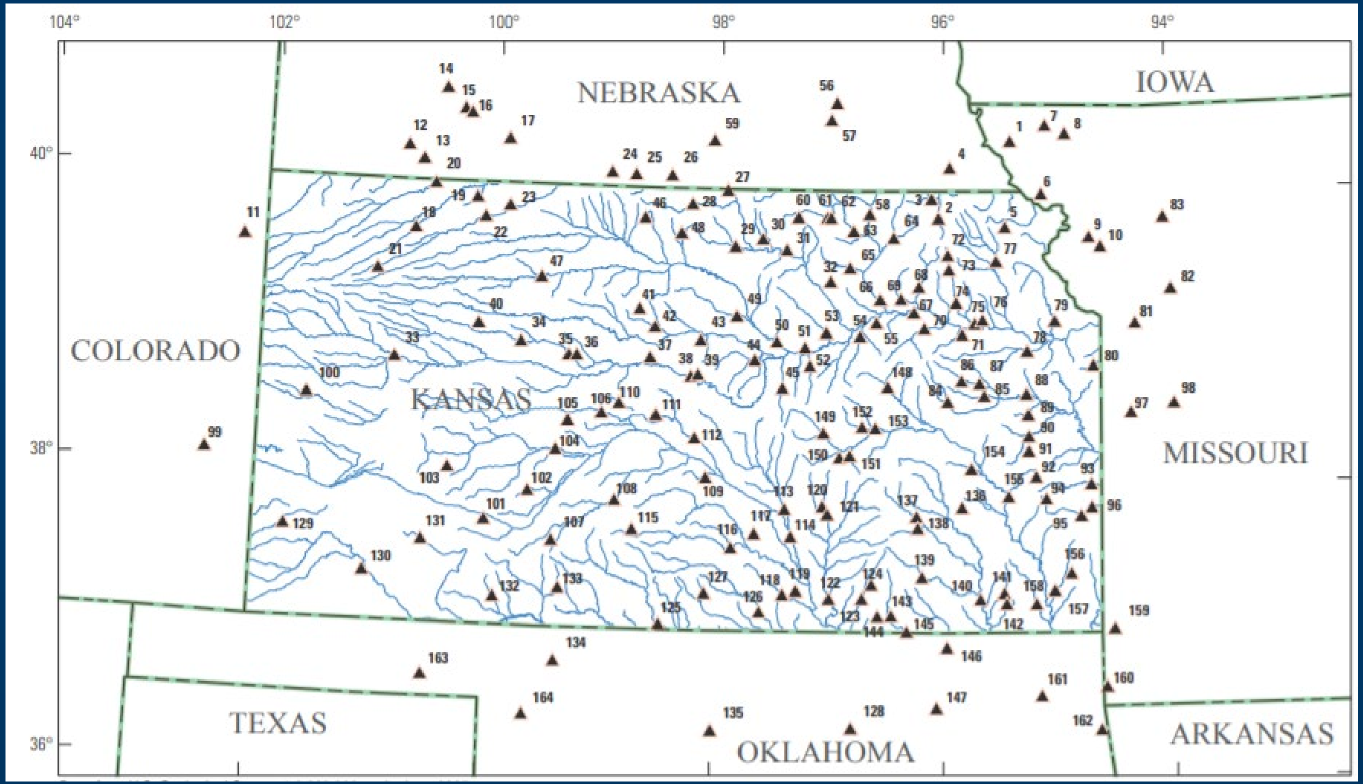
A robust network for forecasting in the locations of heavy population and industry.

Extreme Events in Kansas

Flooding

What flooding aspects could see improvement in the USGS streamgage network?

We have holes in our data where we lack local partnerships. In particular, the western part of the state lacks sites which are useful for flood recurrence studies as most sites in that region currently in operation are subject to regulated flows or diversions for irrigation.



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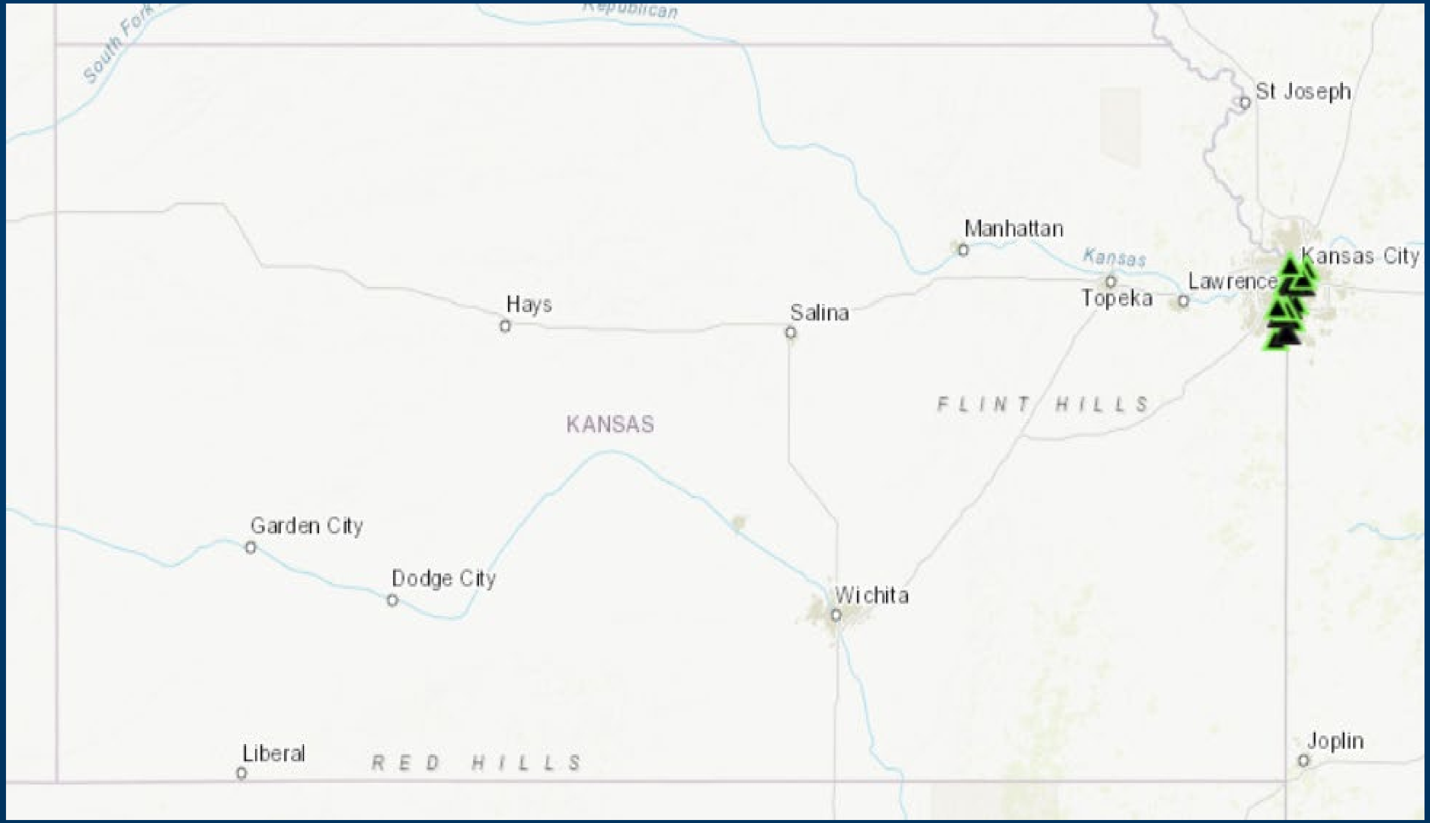
Extreme Events in Kansas

Flooding

What flooding aspects could see improvement in the USGS streamgage network?

Flood inundation mapping. Currently only one FIM study in Kansas is available through the USGS FIM library, another FIM study was published prior to the USGS FIM library.



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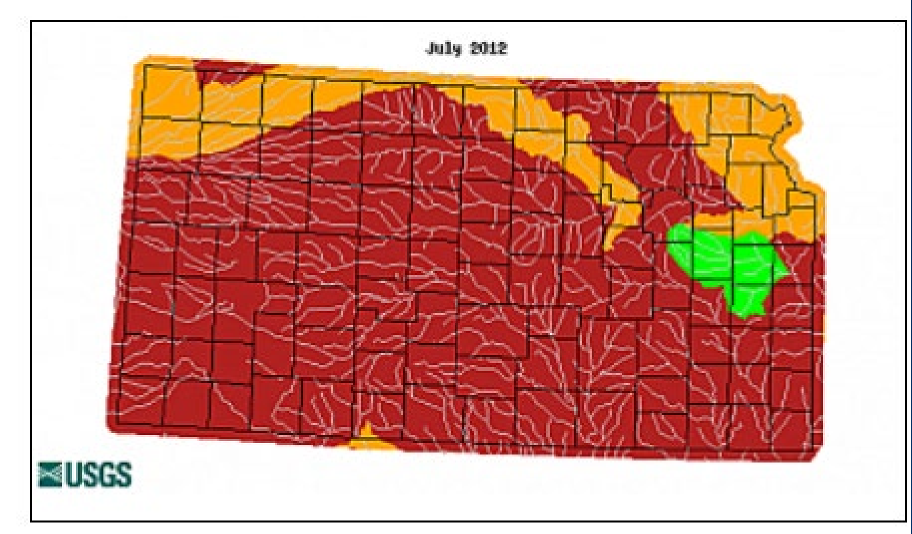
Extreme Events in Kansas

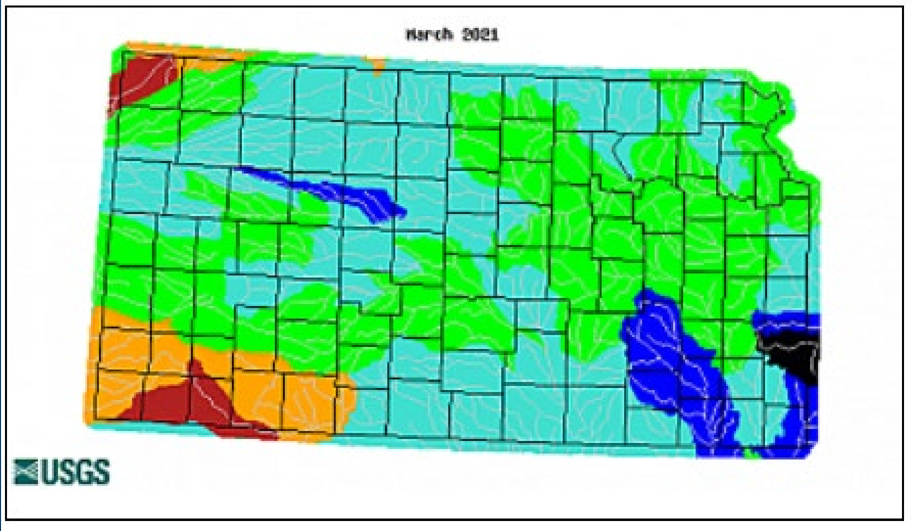
Drought

Droughts are… complicated

No single measure can determine presence or absence of a drought.

Streamflow is *part* of the equation. USGS partners with other organizations in support of drought monitoring.
During local droughts, USGS performs studies of seepage to determine what factors are driving loss of streamflow.





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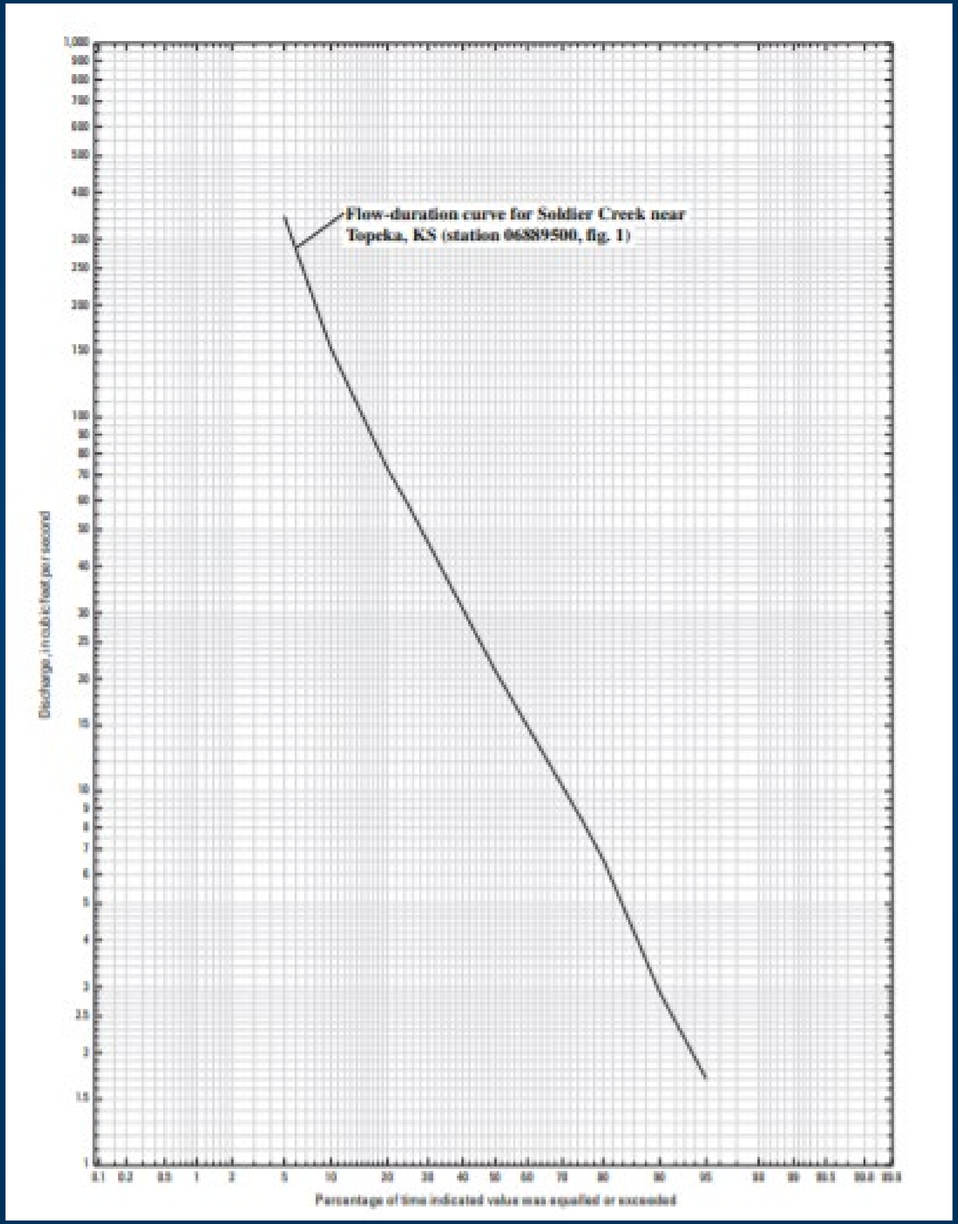
Extreme Events in Kansas

Drought

Regression studies of streamflow data

Used to plan for droughts

Streamflow statistics are an indication of what can be expected during extreme droughts.
Regression methods allow for this information to be used at locations where no streamflow data exists.



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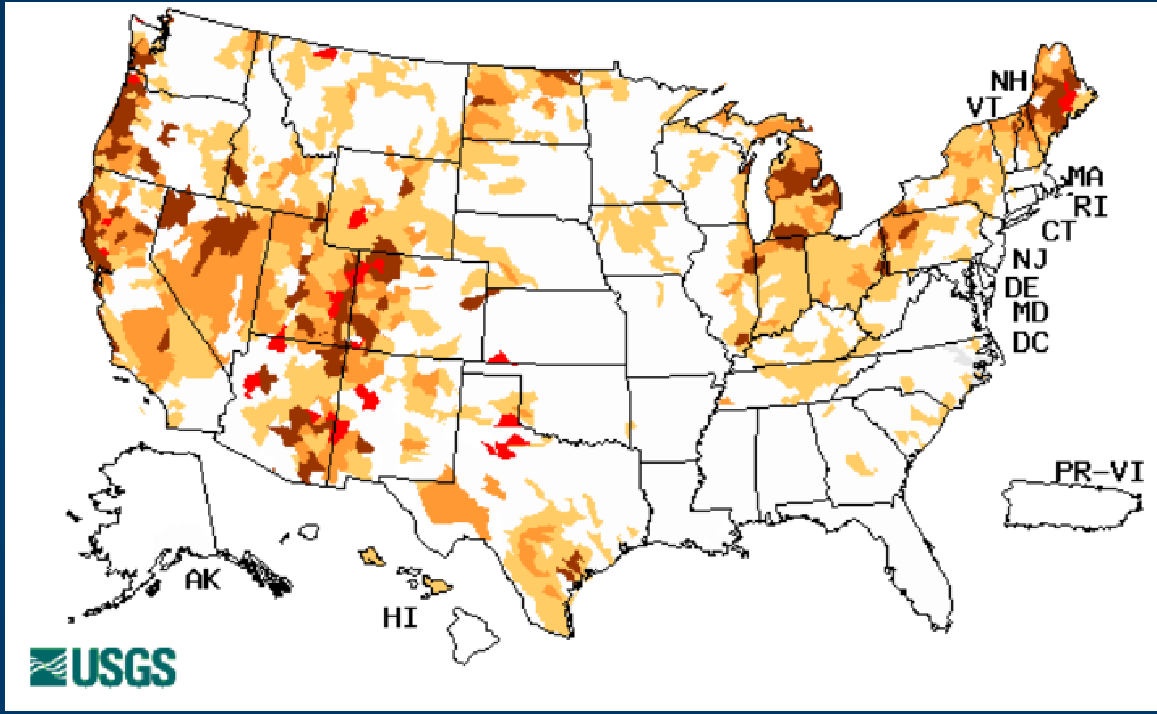
Drought

What does the USGS streamgage network do well for droughts?

Data for water supply managers

The State of Kansas was the first organization to partner with USGS anywhere in the nation in support of streamflow information. This data has been used for water supply managers at the state dating back to 1895. Many of the streamgages in the network support this function.



USGS Drought Watch

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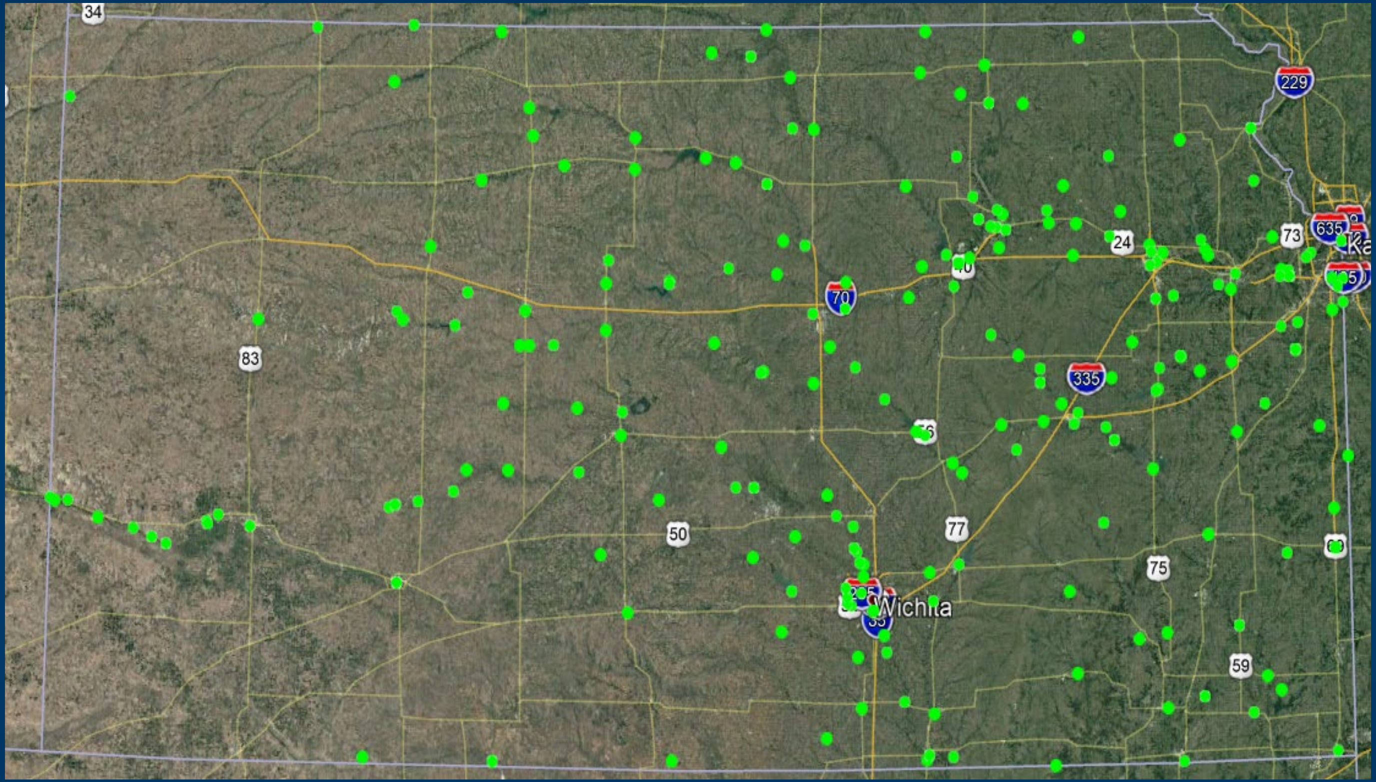
Extreme Events in Kansas

Drought

What gaps in drought data exist in the USGS streamgage network?

Non-irrigation affected streamgaging sites especially in Western Kansas.

Climatological studies require data which is unaffected by direct human interference with the streamflow. The number of sites representing natural conditions is shrinking.



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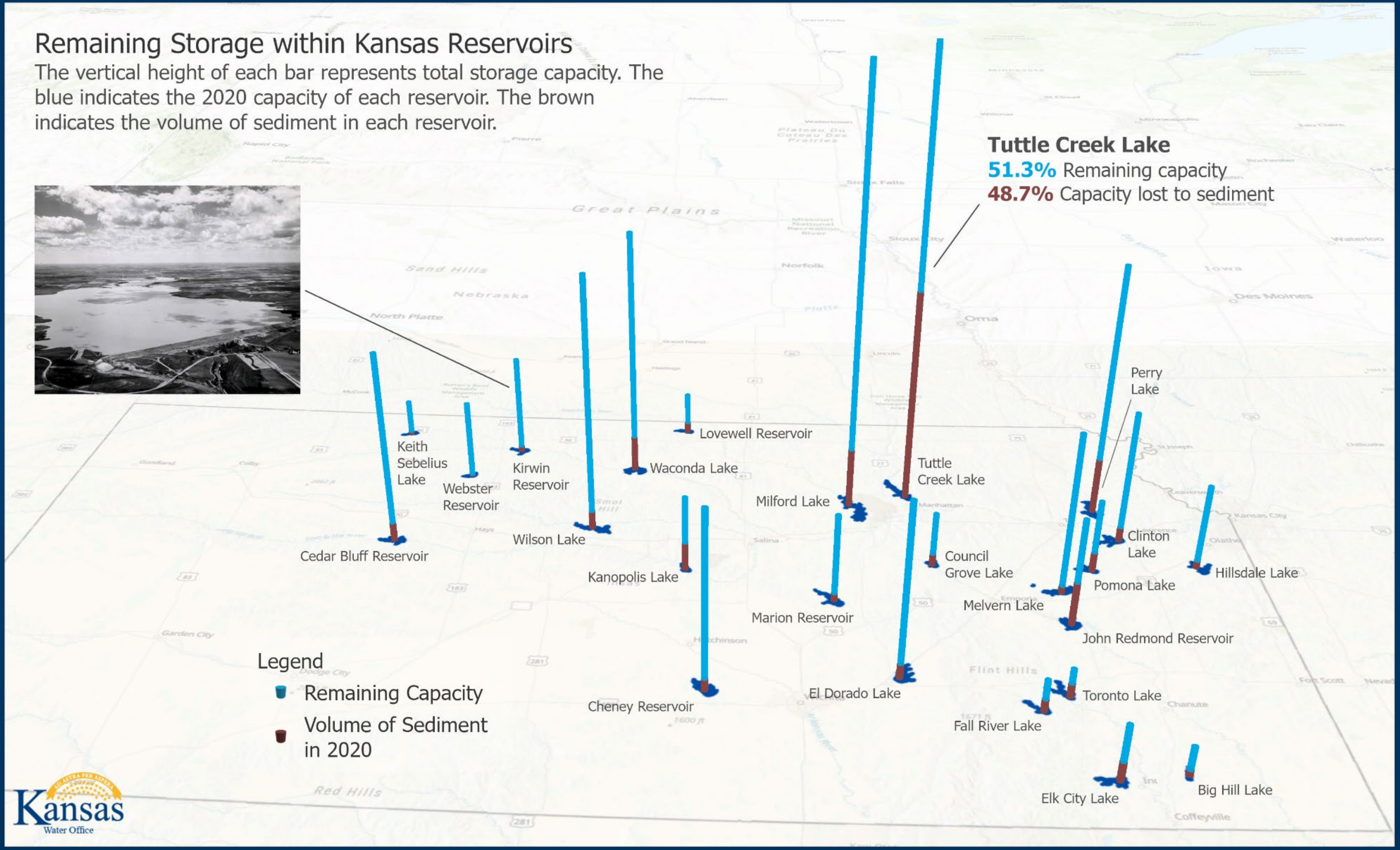
Suspended Sediment

- Sediment is a primary aquatic impairment in the United States, including Kansas.
- Reasons for concern:
  - Decreases storage capacity, flood control, and water supply
  - Impacts to recreation
  - Negative impacts to wildlife habitats
  - Degrades water quality: increased costs for water treatment, strains on phytoplankton communities and aquatic macrophytes, increased nutrient transport
- Mitigation solutions can be costly and time consuming

Sedimentation of Federal Reservoirs

- Federal reservoirs are important for water supply and flood control
- Sedimentation → reducing storage space
- Highlighted USGS sediment studies
  - Kanopolis and Tuttle Creek Lakes
  - Clinton Lake
  - Cheney Reservoir
  - John Redmond Reservoir
  - Other small impoundments



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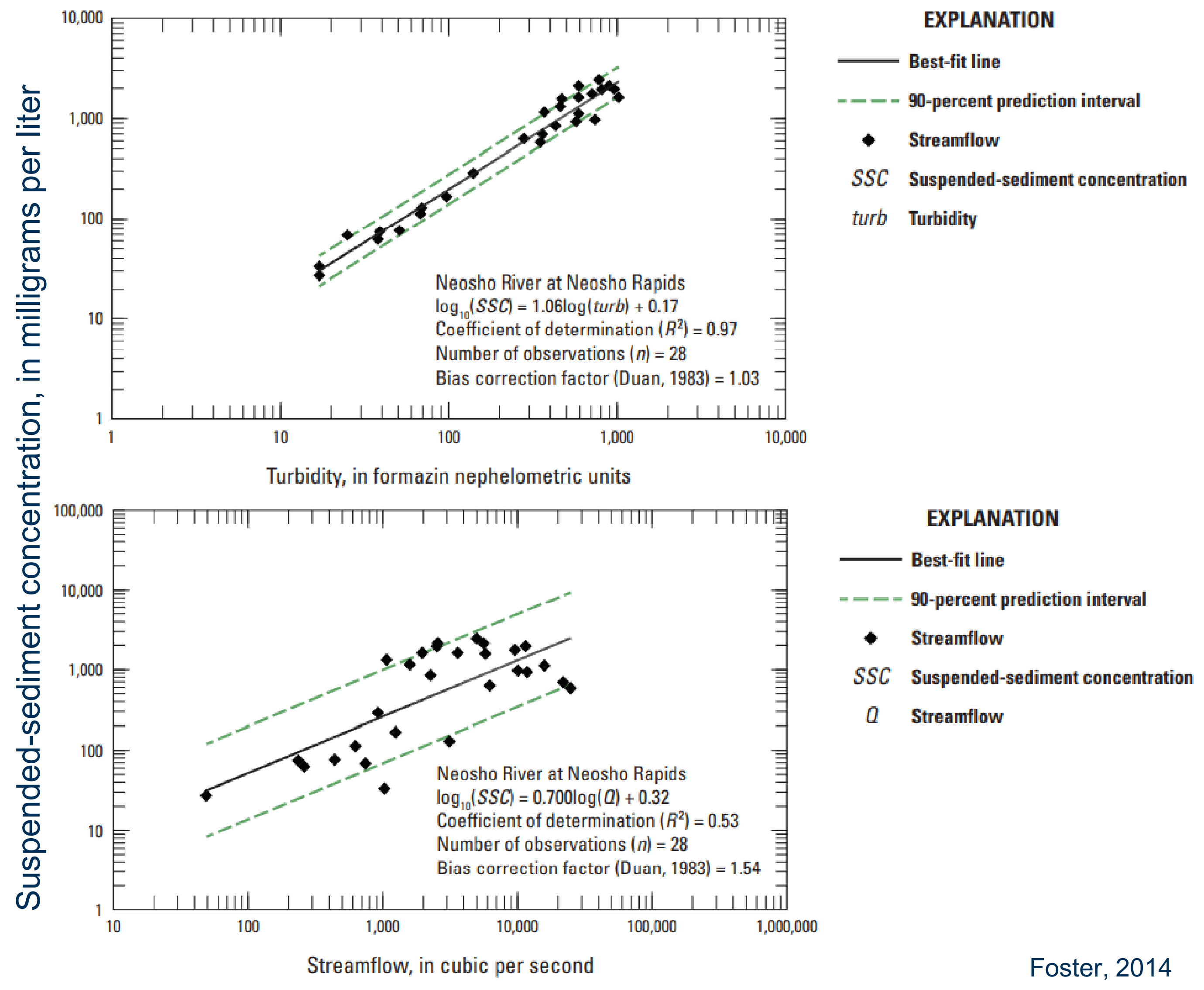
How is suspended sediment measured?

- Suspended-sediment concentration is a discretely measured constituent, not directly measured in real time.
- Turbidity is often used as a surrogate for suspended-sediment concentration since it is an indicator of sediment and other solid material transported in streams.
- Streamflow is also sometimes used as a surrogate for suspended-sediment concentration but usually explains significantly less variance (much lower R^2 values)



Foster, 2014

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Extreme events and sedimentation

- Extreme events have many definitions sometimes making it difficult to directly compare studies
  - Extreme precipitation events
  - Extreme streamflow events
  - Extreme sediment transport events
- The USGS studies included have similar yet slightly different approaches to describing sedimentation as it relates to extreme events

Kanopolis and Tuttle Creek Lakes: 2008–10

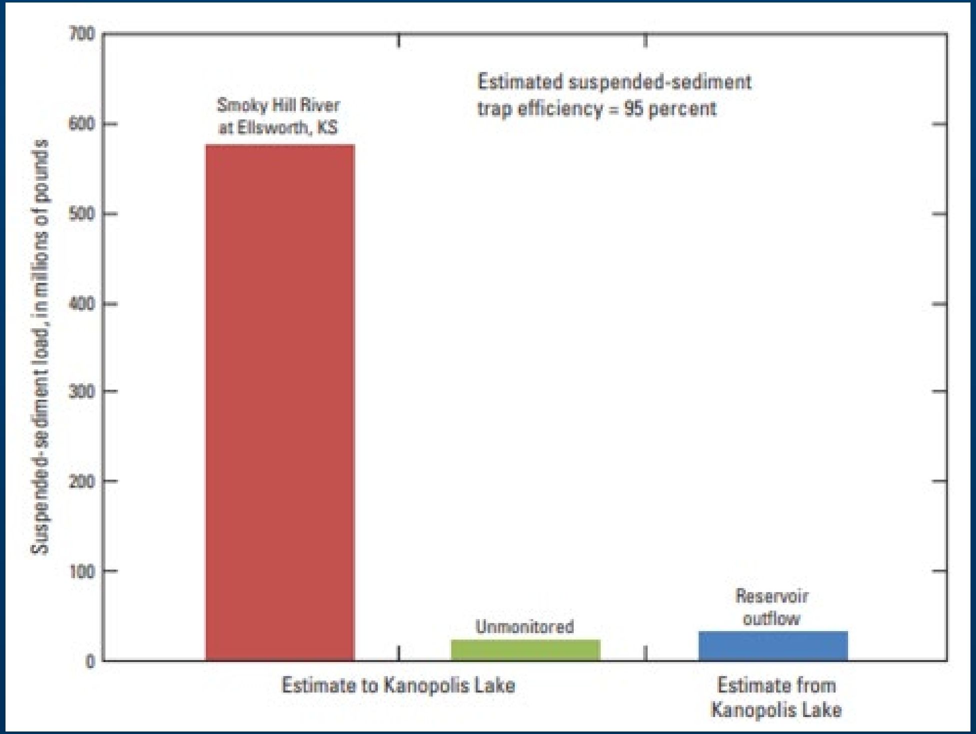
For both reservoirs, most of the inflow suspended-sediment load was delivered during short-term, high-discharge periods.

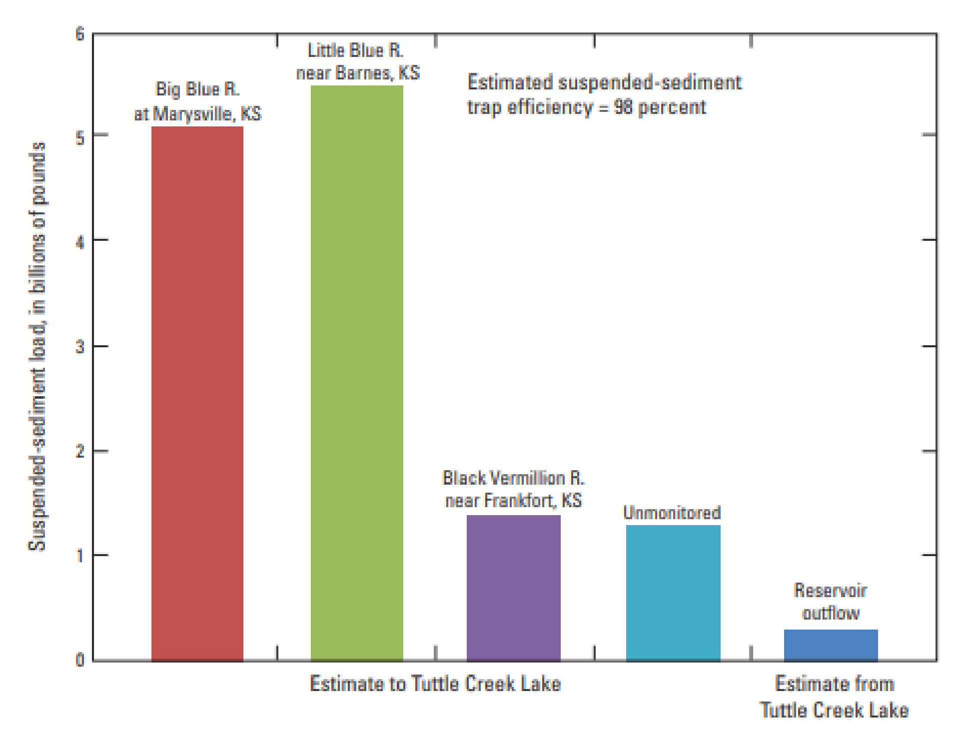
Kanopolis Lake

- Ellsworth streamgage (upstream)
  - 7 storm events → 88% of total suspended-sediment load
    - 48% of total discharge, in 12% of the analysis period

Tuttle Creek Lake

- Barnes streamgage (upstream)
  - 14 storm events → 94% of total suspended-sediment load
    - 72% of total discharge, in 30% of analysis period





Juracek, 2011

Clinton Lake: 2010–12

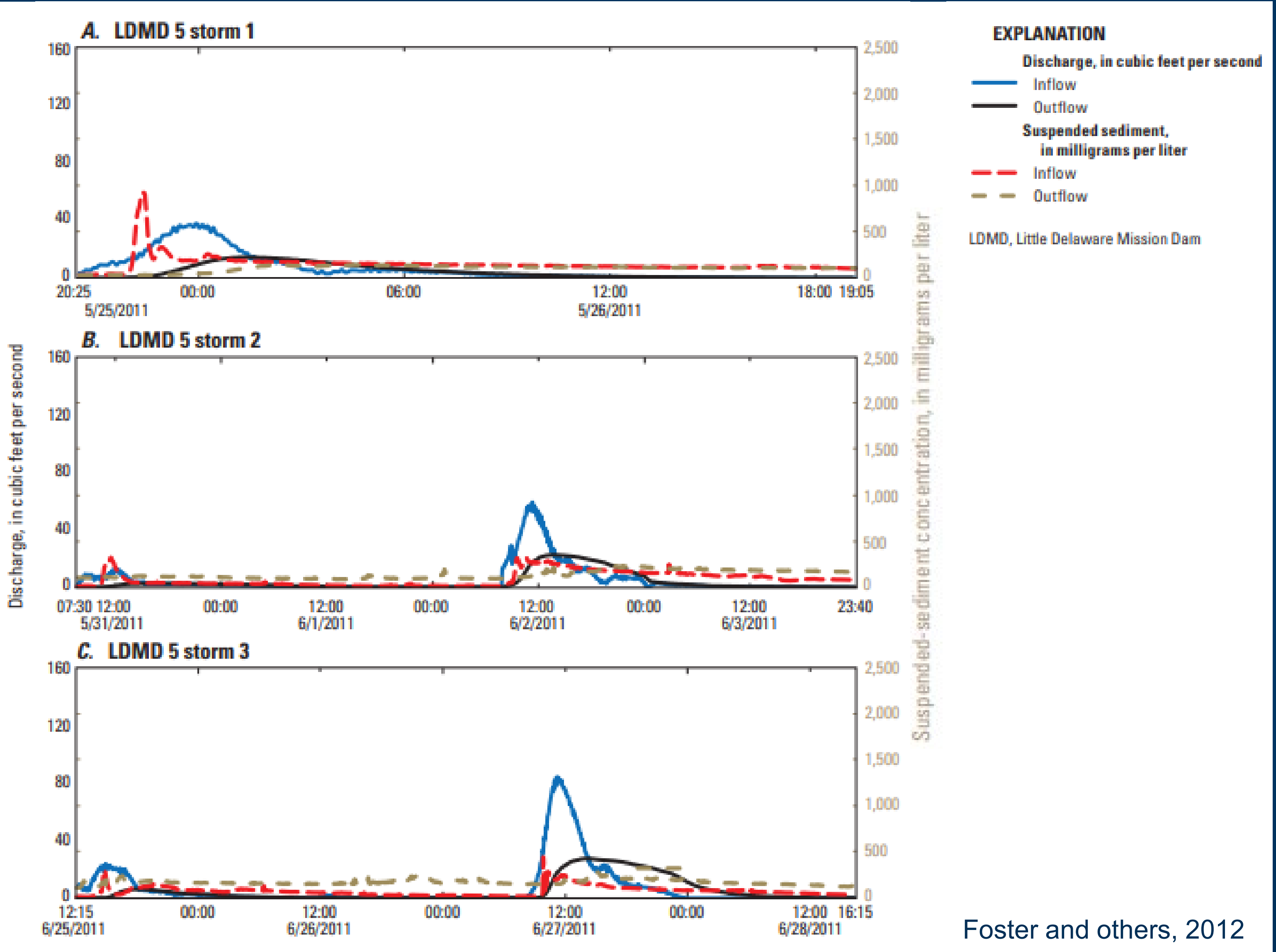
Most of the inflow suspended-sediment load was delivered during short-term, high-discharge periods.

- Trapping efficiency: 97%
- 7 storm events → 91% of total suspended-sediment load
  - 47% of total discharge, in 4% of the analysis period
- The largest stormflow (7 days) accounted for about 33% of the total suspended-sediment load
  - 16% of total discharge, in <1% of the analysis period
- Study completed during drought conditions

Juracek, 2013

Small impoundments study: 2009–11

- In <0.1% of the record period:
  - Atchison County Lake: 24% of total suspended-sediment load
  - Banner Creek Lake: 38% of total suspended-sediment load
  - Centralia Lake: 32% of total suspended-sediment load
- Seasonality and preceding conditions had influence on size of sediment loads when comparing similarly sized events



Foster and others, 2012

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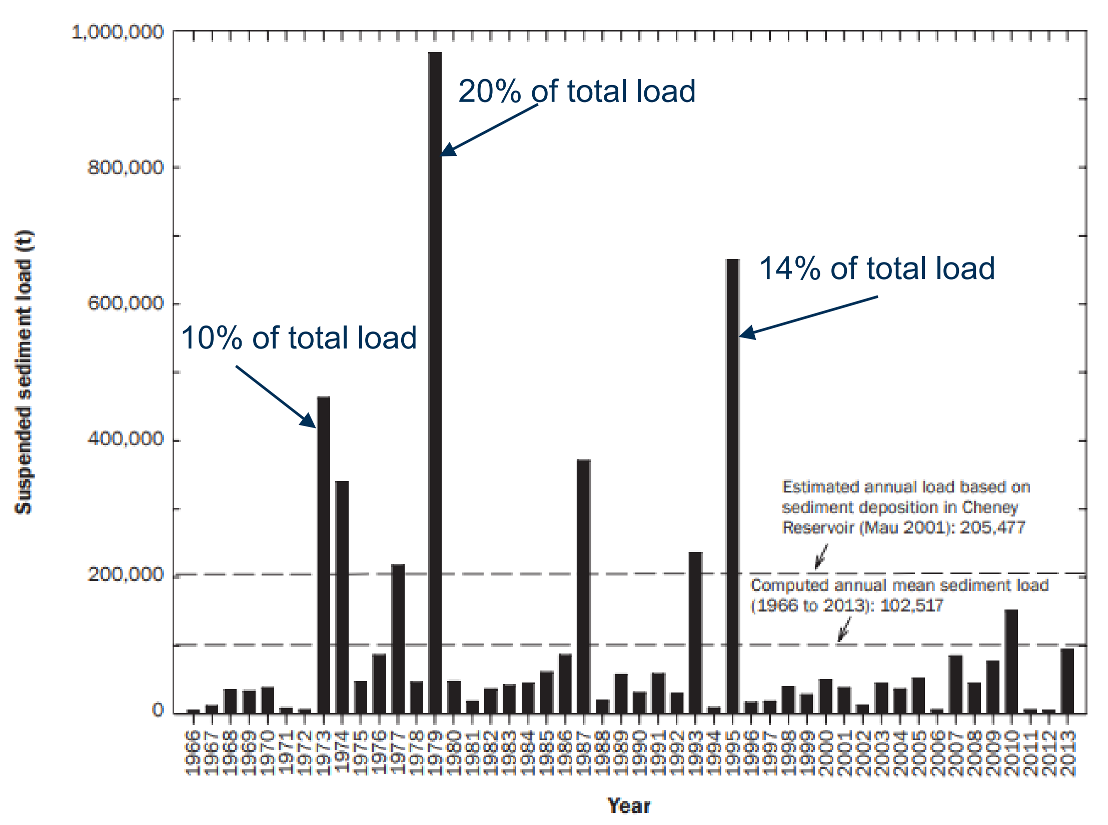
Cheney Reservoir

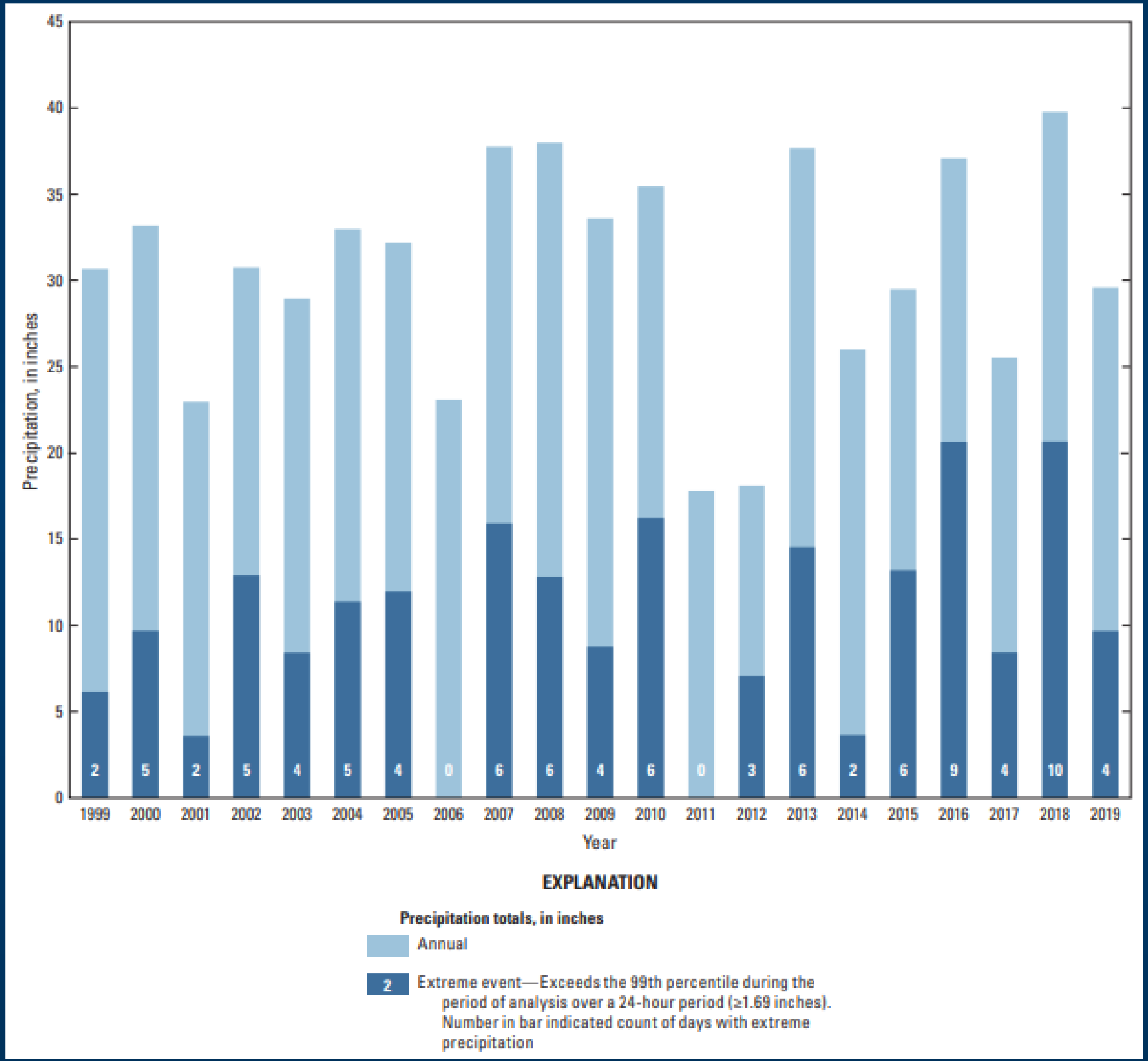
- Computed using streamflow as the explanatory variable
- 41% of all sediment during the 48-year study period occurred during 5 storm events spanning only 8 24-hour periods
- 60% of total sediment load occurred during 5 years with extreme flow events



Stone and others, 2015

Cheney Reservoir

- Extreme events (defined as days with >1.69 in. of precipitation) accounted for up to 56% of the total annual precipitation
- During this same analysis period, 55% of the total suspended-sediment load was transported during top 1% of loading days (76 days).
- 22% of the total sediment load was transported in the top 10 loading days



Kramer and others, 2021

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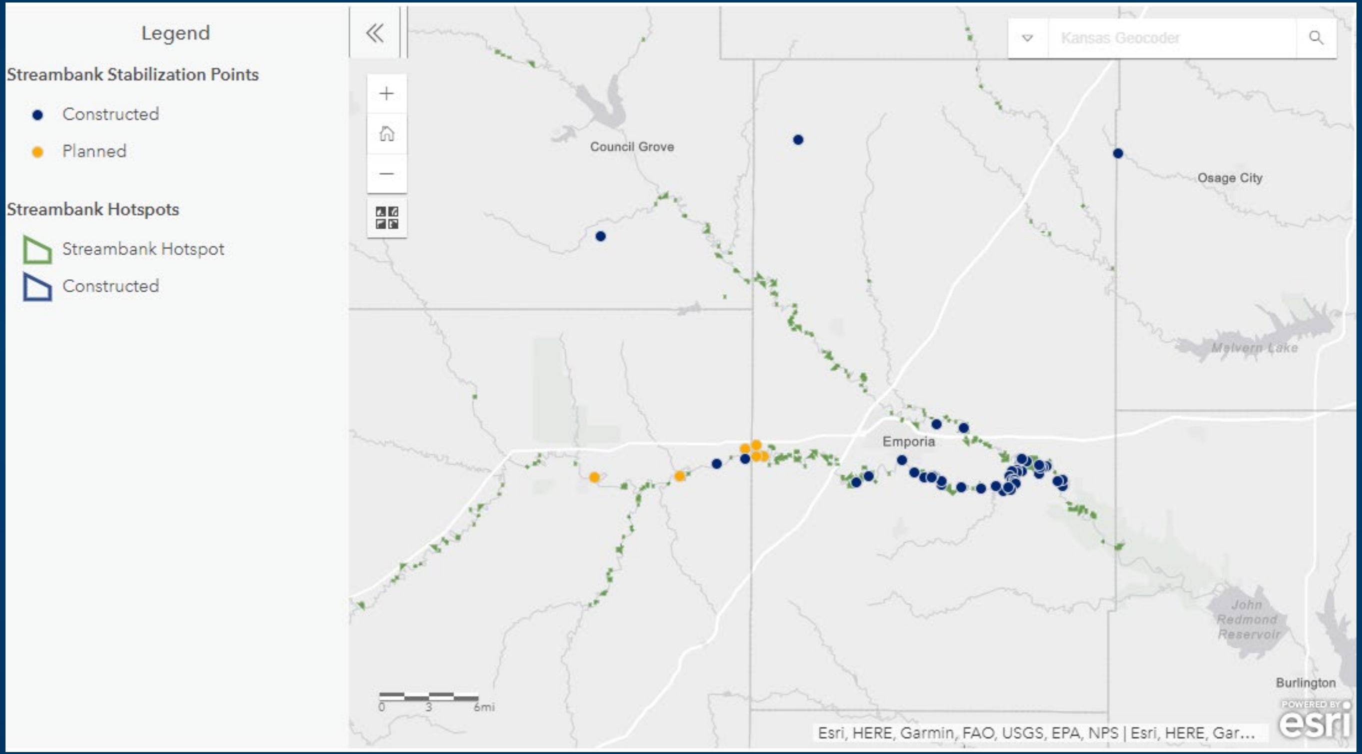
John Redmond Reservoir and drainage basin

- Cottonwood and Neosho Rivers flow into John Redmond Reservoir which, by 2019, had an estimated conservation pool loss of 42%
- Streambank stabilization projects have been implemented primarily along the Cottonwood River but also in the Neosho River
- Dredging operation in 2016 removed 3 million cubic yards of sediment from John Redmond Reservoir



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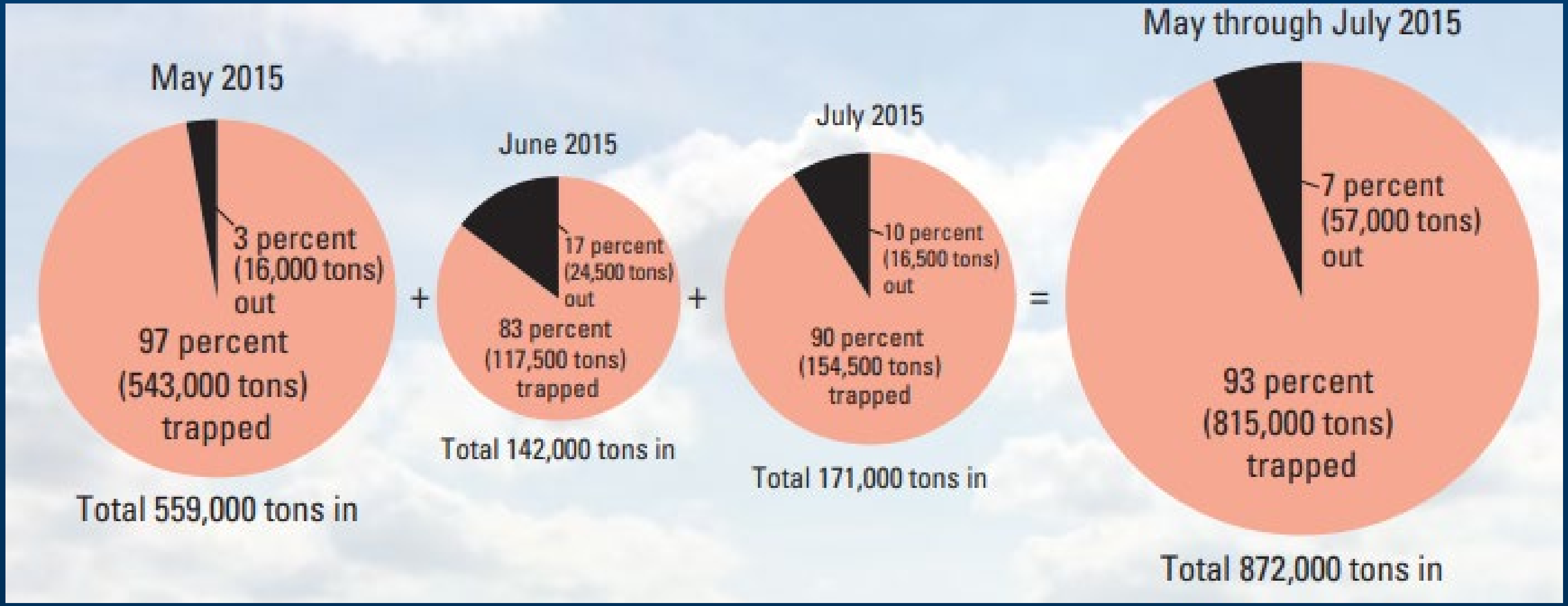
John Redmond Reservoir and drainage basin

- Storm events during May–July 2015 exceeded the designed annual sedimentation rate in May alone
- The total sediment retained in John Redmond Reservoir during these 3 months was 1.6% of the conservation-pool storage capacity of the reservoir
- Dredging effectively removed sediment, but extreme events move a considerable amount of sediment in a very short period of time.



Foster and King, 2016

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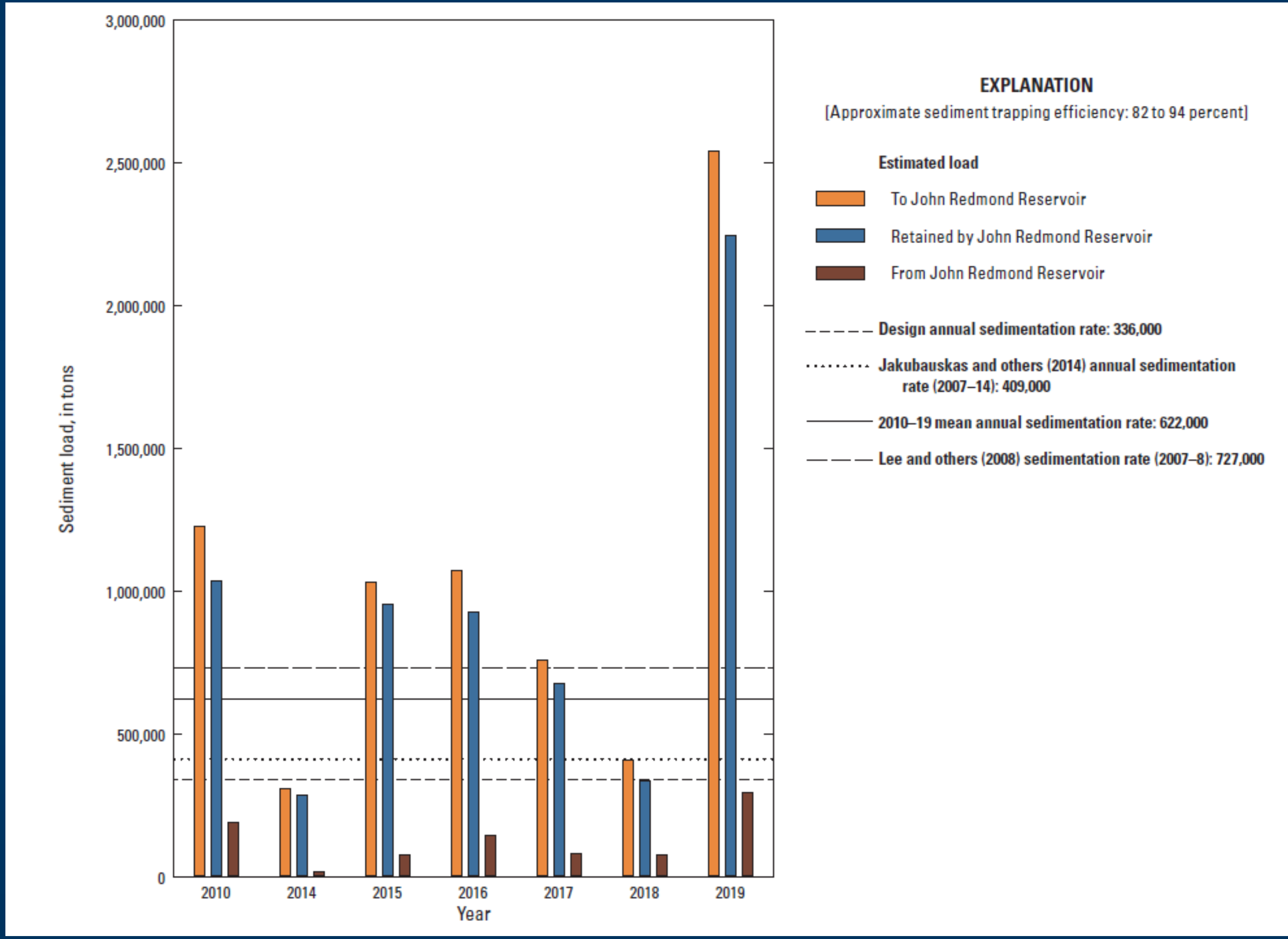
John Redmond Reservoir and drainage basin

- John Redmond Reservoir annual trapping efficiency during 2009–19: 82–94%
- During high flows and flooding in 2019, an estimated 2.2 million tons of sediment were trapped in the reservoir (about 17% of the remaining space as reported in 2007)
- Suspended-sediment loads transported during flows greater than the National Weather Service Flood Action Stage (0.1–5% of the analysis period) comprised about 56% of the total load



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Preliminary Results

What does this mean and what can we do?

- Extreme episodic events → increased sediment transport
- Possible sediment reduction strategies
  - Reservoir outflow management (Lee and Foster, 2013)
    - Operating with shorter residence times and around normal operating capacity as opposed to higher flood pool levels → up to 3% reduction of sediment trapping
    - A 3% reduction in John Redmond Reservoir during the 2009–19 analysis period would have equaled about 14% of the total sediment removed as part of the $20 million dredging operation
  - Agriculture BMPs
  - Streambank stabilization projects
  - Dredging

Type	Description
Prevention Techniques	
Erosion control in basin	Land surface methods include contour farming, conservation tillage, grassed waterways, and terraces. In-channel methods include grade control structures and bank stabilization
Sediment bypass	Use of a channel or tunnel to bypass sediment-laden flows around the reservoir during high-flow conditions
Sluicing	The movement of sediment-laden flows through a reservoir as quickly as possible during flood events to reduce deposition
Density current venting	Passage of sediment-laden density currents through a reservoir along the lakebed is enabled by low-level outlets through which the currents are released. Alternatively, density currents can be routed up and over a dam using a curtain wall
Removal Techniques	
Dredging	Removal of deposited sediment from a reservoir using a hydraulic or mechanical dredge
Dry excavation	Following the draining of a reservoir, the deposited sediment is removed using conventional excavation equipment
Flushing	Drawdown of the reservoir to temporarily establish flow conditions that will resuspend deposited sediment and remove it through low-level outlets

Morris and Fan, 1998; Annandale, 2013; Juracek, 2014

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What does this mean and what can we do?

- Continued investigation of how and when sedimentation occurs and its relation to sediment reduction strategies with the understanding that sedimentation rate is largely driven by high flows.
- Continued water-quality and streamflow data collection and analysis enhances our ability to understand sedimentation processes and develop effective sediment management strategies.

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