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Scour and Extreme Events: Focusing on the Issues.

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ABSTRACT

Future changes in precipitation, flood flow, and sea-level rise will potentially affect transportation systems, including scour at bridges. Research to better understand these climate causes are reasonable and valid; requiring thoughtful consideration of any effects. However, in doing so, there is a difference between correlation and causation in how such changes or events will affect scour. Some recent literature describes a relationship between extreme events/climate change and increased scour risks. Such arguments (perhaps inadvertently) lack causality or else constitutes logical fallacies (e.g., appeals to authorities, unrepresentative samples, single cause, hasty generalizations, etc.). Paraphrasing some examples demonstrating our concerns: increases in peak flow will result in deeper scour depth; increasing future flows dictates using a design scour exceedance probability greater than the 1 percent frequency; or a Q_{100} flood event occurring at a bridge means the bridge has experienced scour failure, so more events will result in more failures. Besides weak causation, another concern is a lack of focus on other reasonable outcomes from change. Current scour prediction equations and methods essentially recognize total hydraulic loads on streambeds decrease with increased water depths. So, rather than focusing on increases in peaks of flood events, the scour impact might focus on how climate change flow reductions may lower tailwater and perhaps induce vertical instability; can temperature changes lead to geotechnical alteration of soil and streambed characteristics; or that the changes may manifest in the duration or number of occurrences of flood events, etc. A final concern is making such assertions without providing any supporting citations (or else citing other literature that, in turn, make unsupported assertions).

While acknowledging the potential for engaging in our own logical fallacies, FHWA research seeks to begin to better characterize a wider focus with a goal to help researchers and practitioners understand and mitigate effects of future changes on scour.

INTRODUCTION

As of 2019, within the United States of America (U.S.), the U.S. Department of Transportation (USDOT), Federal Highway Administration (FHWA) has oversight for approximately 616,000 publicly owned highway bridges, of which about 83 percent (or about 508,000) span waterways. To illustrate, Figure 1 depicts many of those highway bridges within the conterminous U.S. (i.e., excluding, for clarity only, Alaska, Hawaii, Puerto Rico, and U.S. territories).

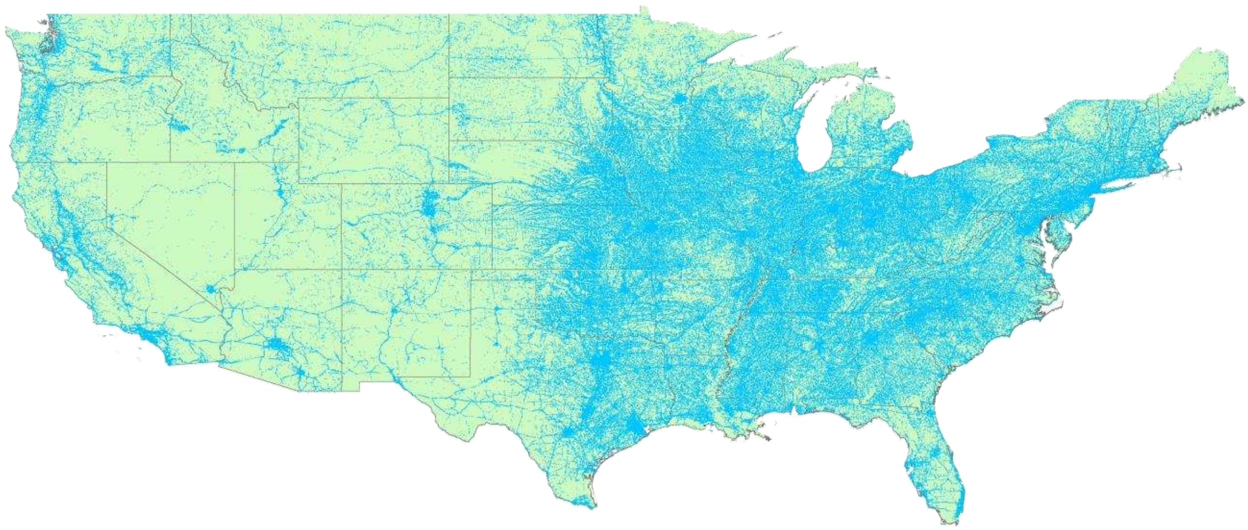

Figure 1. Highway Bridges in the conterminous USA.

A reasonable question and research topic would consider how any potential future changes in precipitation, riverine flow, storm surges, and sea-level rise will potentially affect transportation systems; including scour at those over 508,000 bridges. As governing FHWA statute[1] variously groups such concepts of climate change and extreme weather events using the term "*extreme events*[2]," this paper will adopt such terminology. So, again, how would the transportation community consider such extreme events in regards to scour?

Fortunately, the scientific method provides a framework that (1) a better understanding of these climate *causes* are reasonable and valid; but (2) also requiring thoughtful consideration of any *effects*. For example, increases in sea level (cause) may place some coastal highways at increased risk from more frequent flooding (effect). These causative frameworks apply to scour at bridges. However, when doing so, researchers need to recognize there is a difference between *correlation* and *causation* in considering how such changes or events will affect scour. Unfortunately, perhaps not understanding the historical evolution of scour research or scour physics and approaches that form knowledge and practice, some recent literature appears to potential confuse correlation and causation. This paper attempts to provide some thoughts about how these apply to extreme events and scour at bridges.

BACKGROUND

A historical review of how the international scientific and engineering community scour research reveals how the body of knowledge and understanding of the topic has steadily improved since 1875 when Mr. N.A. Beleyubsky considered scour while designing a bridge over the Volga River in the city of Syzran, Russia (Andreyev 1960). Mr. Beleyubsky postulating *"Scour ceases*

[1] The FHWA operates under the statutory authority of Title 23 (Highways) of the United States Code (U.S.C.).

[2] See 23 U.S.C. § 119(d)(2)(B), 23 U.S.C. § 133(b)(9), and 23 U.S.C. § 503(b)(3)(B)(viii) for situations and context that statute applies the "extreme event" term.

after the underbridge area is increased to the extent that the underbridge velocity becomes equal to the channels 'actual' velocity" (Andreyev 1960). Likewise, Dr. Emmett.V. Richardson[3] provided an excellent history of scour research and programmatic efforts in his 1996 paper *"Historical Development of Bridge Scour Research and Evaluation."* (Richardson, 1996). In his paper, Dr. Richardson related how the efforts by G.S. Morrison (1893), H. Engles (1894), J.R. Freeman (1929), C. Keutner (1932), T. Ishihar (1942) and others contributed to the evolution of various aspects of scour (Richardson, 1996). Dr. Richardson's paper describes an international effort, relating research in places such as Europe, India, Japan, Egypt, as well as the U.S. However, Dr. Richardson noted that *"Bridge scour research prior to 1949 was not systematic, and much of it was single purpose research or reports of a scour problem experienced at a bridge."* Dr. Richardson attributes the year 1949 as representing the beginning of efforts by Dr. Emmett M. Laursen (*Iowa Institute for Hydraulic Research*) to begin such systematic scour research within the U.S. (Richardson, 1996). Beginning in 1949, the U.S. Bureau of Public Roads[4] (BPR) also recognized potential issues related to stream instability and scour at bridges:

- Beginning in 1949, BPR began funding some of Dr. Laursen's seminal bridge scour research (Laursen 1951, 1952, 1956).
- In 1951, the BPR addressed the need to consider both bridge scour and stream stability in Hydraulic Information Circular Number 2, "Special Problems in Drainage" (BPR, 1951).
- The 1962 failure of the Interstate Highway System 29 (I-29) bridge over the Big Sioux River in South Dakota revealed that (1) scour could adversely affect even new, major structures and (2) discharge alone is not a predictor of how scour forms.
- The 1973 FHWA report *"A Statistical Summary of the Cause and Cost of Bridge Failures"* attempted to consider (1) what constitutes bridge failure and (2) provided an estimated that nearly 60% of bridge failures (in a sample of 383 bridges) had a hydraulic related component (including stream instability and bridge scour) (Chang, 1973).

Clearly, FHWA and transportation community recognized a need for scour research. However, various physical and political conditions and diverse and varying areas within the U.S. played major factors in not consistently applying research insights to bridges.

Why? Quite simply, the FHWA lacked the authority to consider scour at bridges in anything more than in a research context, or as an ancillary to floodplain requirements.

FHWA Authorities & Directions

The FHWA began to obtain such authority over such bridges when the U.S. Congress passed and President Johnson signed the "*Federal-Aid Highway Act of 1968"* (Public Law 90-495 1968) and in 1971, FHWA promulgated statutory requirements within 23 Code of Federal Regulations

[3] The FHWA acknowledges Dr. Everett V. Richardson (1924-2013) for his leading role in scour research and deployment, including assisting in development of the FHWA Scour Program.
[4] The BPR was the precursor to the FHWA.

(CFR) – Highways, *National Bridge Inspection Standards* (NBIS) (FHWA 1971)[5]. However, the NBIS did not yet include or consider scour (Krolak 2016).

The April 5, 1987 scour induced collapse of New York's I-90 Schoharie Creek Bridge resulted in 10 fatalities and disrupted a major Interstate route. The National Transportation Safety Board (NTSB) summarized *"Contributing to the accident [was] ... **inadequate oversight by** ... the **Federal Highway Administration**[6] ... "* (NTSB 1988). Subsequent scour related bridge failures reinforced the need for FHWA oversight of scour (NTSB 1990).

Most notably, for the purposes of this paper, the FHWA initiated response after the Schoharie failure directed that *"... each State should evaluate the risk of its bridges being subjected to similar damage during floods on the order of a 100 to 500 year return period or more* (FHWA 1987).

As previously related by one of the authors (Krolak, 2016), the introduction of these 100-year and 500-year flow events, as a means to determine design scour and check scour values, were ***not*** a result of any scour research studies that suggested these two flood events were prone to any worse scour formation.[7] Rather, the rationale for using 100-year and 500-year events appears to have been: (1) availability of such specific flow estimates through U.S. Geologic Survey (USGS) regression equations for those return periods; (2) potential availability as a consequence of National Flood Insurance Program floodplain mapping; and (3) they are greater return periods than most all typical hydraulic bridge design standards (Davis 2001, Krolak 2016).

Regardless, the FHWA Scour Program incorporated these 100-year and 500-year discharges into various Technical Advisories (TAs), such as TA 5140.20 (FHWA 189) and TA 5140.23 (1991). The American Association of State Highway and Transportation Officials (AASHTO) incorporated them into national applicable bridge standards, such as the AASHTO LRFD Bridge Design Specifications (AASHTO 2017). To illustrate, assessing a bridge as scour critical essentially links the stability of the structure to the evaluated Q_{100} event.

SOME THOUGHTS ON THE PHYSICS OF SCOUR

If the use the 100-year and 500-year discharges[8] as a standard within the FHWA Scour Program was more of quest for expediency than some probabilistic framework, what would be their role when considering the physics of scour? In other words, is it reasonable to assume that there is a direct relationship between increased discharges and increased scour formation?

For insights on this, the FHWA NBIS regulation defines scour as *"**Erosion** of streambed or bank material **due to flowing water**; often considered as being localized around piers and abutments*

[5] The FHWA has updated this regulation over the years to consider, among other issues, scour (FHWA 1978, 1988, 2004). The current NBIS regulation is cited as 23 CFR 650 subpart C.
[6] ***Bold*** emphasis from the authors.
[7] In 1969, Dr. Laursen proposed a probabilistic framework that may have formed such a basis of considering appropriate discharges (Laursen 1969).
[8] e.g., 1 percent and 0.2 percent annual exceedance probabilities.

of bridges." [23 CFR § 650.305 (Definitions)]. Likely, Dr. Laursen, Dr. Richardson and other scour researchers would recognize key terms in this language being ***erosion*** and ***flowing water***.

However, they would also recognize that flowing water (discharge) was only a ***surrogate***[9] for the actual ***forces and loads*** that erode the streambed and bank materials and result in scour. For example, in 1952 Dr. Laursen wrote *"Scour can be defined as the enlargement of a flow section by the removal of material composing the boundary through the action of the fluid in motion. Implicit in this definition is the fact that the* ***moving fluid exerts forces*** *on the particles composing the boundary, causing their movement."* (Laursen 1952).

Also implicit is that discharge (and basic hydraulic principles) allowed determination of more precise surrogates, such as velocity and depth. As a result, many scour equations apply velocity and depths in an attempt to describe the actual pressure, tractive, shearing, drag, hydrostatic and other forces (and other phenomena[10]) that erode the streambed and result in scour. The FHWA recommended scour equations in HEC-18 reflect this approach (FHWA 2012)[11].

In turn, from a Newtonian perspective, having velocity and depth allows derivation of even more focused, "lower level" surrogates such as energy and momentum. Likewise, having that information enables derivation of potential forces and loads themselves. Additionally, given advances in technology that allows use of temporal coupled, three-dimensional hydraulic models (such as computational fluid dynamic (CFD) approaches), we can increase the fidelity and precision of the physics of such surrogates. In other words, we can focus on velocities, depths, energy, momentum, and forces to an extent that Dr. Laursen and our predecessors could only dream of!

We hypothesize that (1) each surrogate has an associated uncertainty, (2) moving from a "higher level" to "lower level" surrogate should also reflect a reduction of that uncertainty, and (3) not necessarily a one-to-one mapping, that is, there may be some trends[12] in the relationship that have a reversal branch.

Intuitively, Hydraulic Engineers know this; the velocity profile would vary as a function of depth. Consider two streams having the "same" velocity, but one having shallow water and the other deeper waters. We would expect higher forces/loads on the shallower streambed. Deeper depths would be associated with reduced forces/loads. As Dr. Laursen wrote *"The rate of scour will decrease as the flow section is enlarged."* (Laursen 1952). In their 2012 research report "Pier Scour in Clear-Water Conditions with Non-Uniform Bed Materials," Dr. Junke Guo (et. al) describe these relationships; focusing on *"scour mechanisms in terms of pressure gradient*

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[9] In this paper, the authors use the term "surrogate" to indicate an indirect constituent that leads to an effect. We add some numerical qualifier to represent some level between the effect and that indirect constituent. In our usage, the "lower" the number, the closer that constituent can be said to directly influence that effect.
[10] e.g., sediment transport capacity and supply, soil strength, type, and thickness, etc.
[11] Furthermore, the FHWA purposely developed the equations to provide conservative scour estimates. This conservatism is a common criticism by practitioners when applying those equations in design or analyses.
[12]Not included in uncertainties, which do not have trends.

through the flow-structure interaction, the flow-sediment interaction, and the sediment-structure interaction" (Guo 2012).

Figure 2 attempts to depict this hypothesis as related to approaches to describe hydraulic aspects of scour formation; with Loads, Energy (& Momentum); Velocity & Depth; Discharge, and Rainfall representing fifth order (Rainfall) to first order (Loads) surrogates. For example, as a fifth order surrogate, rainfall has a great deal of uncertainty as a means to adequately apply to scour because of the assumptions needed in the hydrologic and hydraulic derivation of the discharge at a specific location.

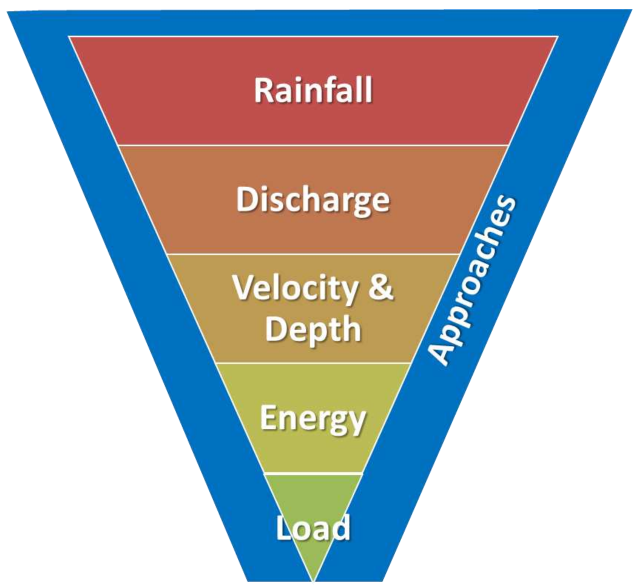

Figure 2. Constituents of Scour Formation.

In other words, these surrogates implicitly recognize (1) every bridge is more or less unique; (2) the same discharge and/or flow frequency will likely result in different scour estimates at any two bridges; and (3) future research and technological advances should allow better characterization of potential scour.

SCOUR IN THE (NON-HYDRAULIC) LITERATURE

However, during this same period, various academic, professional, and governmental literature began to posit the hypothesis that extreme events would result in increased number of scour related bridge failures. At best, such studies essentially assumed that (1) as a result of extreme events, future discharges would increase in peak quantities, frequencies, and number of occurrences. These studies then would (2) look at some small sample of bridge failures and/or assume the Q_{100} represents a scour induced bridge failure (pointing to various FHWA NBIS regulations or AASHTO specifications). They would then conclude that (3) the U.S. should expect increased numbers of scour induced bridge failures.

However, they did not typically provide any causation between (1), (2), and (3). Rather (at best) making a case of some correlation of the three. The (1973) Chang study of bridge failures represents an example of how a small sample (383 bridges) cannot be assumed to represent an entire population; with even Chang noting some of his conclusions consisted of *"a certain amount of speculation…"* (Chang 1973). Other examples in the literature attempts to use "condition" information within the NBIS National Bridge Inventory (NBI) to support their conclusions on extreme events and scour. However, the NBI ***does not have data*** that allows such conclusions. Rather, the NBI may have information that describes a bridge as "scour critical" or describing the "waterway adequacy", etc. However, such designations do not support the (typical) assumption that if the Q_{100} event occurs, then that bridge has failed; or more precisely, failed as a result of scour.

At worst, the literature would cite some other literature; ofttimes reframing the findings and not recognizing that cited literature has not itself demonstrated causation.

In engaging in such approaches, such literature (perhaps inadvertently) does not align with the scientific method vis-à-vis lacking causality or else engaging in logical fallacies (e.g., appeals to authorities, unrepresentative samples, single cause, hasty generalizations, etc.). Commonalities of such literature also include unstated assumptions, not addressing or neglecting physics of scour, and assuming the context of the change applies to the entire population of bridges.

Sadly, the FHWA is guilty of such practices as well; for example, over the years, those 383 bridge failures in Dr. Chang's 1973 report somehow morphed into the FHWA stating *"The most common cause of bridge failures stems from floods. The scouring of bridge foundations is the most common cause of flood damage to bridges."* and ultimately leading to FHWA and others sometimes stating that *"60% of bridge failures are scour related"* (FHWA 1973, FHWA 1991). The FHWA is unaware of any robust studies that have substantiated such a percentage nor have been able to apply a study of some small samples of failures to the entire population of bridges with any stochastic and causal robustness.

A Few Examples

To protect both innocent and guilty alike, perhaps we should focus on a few examples from U.S. Federal Government literature within the last decade.

The 2013 U.S. General Accounting Office (GAO) report *"Climate Change – Future Federal Adaptation Efforts Could Better Support Local Infrastructure Decision Makers"* stated that *"... storm surges are projected*[13] *to … 'scour' bridges by eroding riverbeds and exposing bridge foundations …"* (GAO 2013). Unfortunately, this report (and the literature cited to substantiate this statement) did not provide any supporting evidence, rather describing anecdotal situations and extending those nationally (GAO 2013).

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[13] Climate scientists often use the term "projected" to refer to applying global climate models and approaches to assess future conditions.

The 2017 U.S. Environmental Protection Agency (EPA) report *"Multi-Model Framework for Quantitative Sectoral Impacts Analysis - A Technical Report for the Fourth National Climate Assessment"* describes *"Currently, most bridge failures caused by extreme events are due to scour, where swiftly moving water removes sediment from around bridge structural supports, weakening or destroying their foundations. Increased flooding and long-term river flow changes caused by climate change are expected to increase the frequency of bridge scour, further stressing the aging U.S. transportation system."* (EPA 2017). The first sentence (indirectly) refers to the "most bridge failures" fallacy discussed above as applying to the entire population of U.S. bridges over waterways. The second sentence is a statement without any citation at all.

The 2018 Fourth National Climate Assessment stated *"… Increases in rainfall intensity can accelerate bridge foundation erosion and compromise the integrity and stability of scour-critical bridges. …"* (USGCRP 2018). However, both this report and the literature cited to substantiate these types of statements did not provide any supporting evidence. Rather they cited earlier studies described above or studies using the NBI and engaging in correlation that high discharges at a bridge indicates the bridge has failed, etc. Additionally, they cited a fifth order surrogate (rainfall) to describe scour physics.

A THOUGHT EXERCISE

The FHWA engaged in a small research activity designed to consider two null hypotheses:

H_0 : Q_{100} event = Bridge Scour Failure ?

H_0 : Q_{100} event = Directly Related to Scour Formation ?

In our methodology, we obtained U.S. Geological Survey (USGS) data of 27,748 streamflow gaging stations with annual peak flow records within the conterminous U.S. (Figure 3) (USGS 2019).

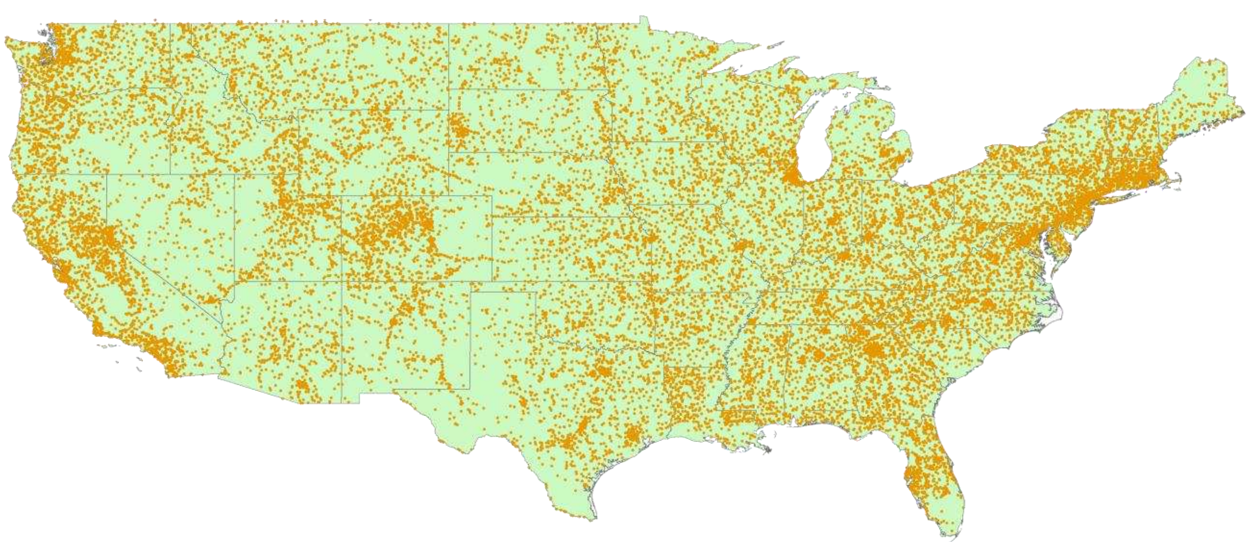

Figure 3. 27,748 USGS Gaging Stations in the Conterminous U.S.

Using those records, we applied the log-Pearson type III "method of moments" to determine flow events at those stations that equaled or exceeded the 1% annual exceedance probability (i.e., Q_{100} or greater). Being an annual series, the analyses did not capture any partial duration series data. So, we did not obtain ALL events equal or greater than the Q_{100}, just the annual maximums. We were also able to obtain the date of each event and estimate the approximate return period.

This resulted in 5,367 USGS gaging stations having one or more events greater than the Q_{100} (Figure 4). Those 5,367 appear to provide reasonable geographical representation within the U.S. – covering each of the 48 conterminous States.

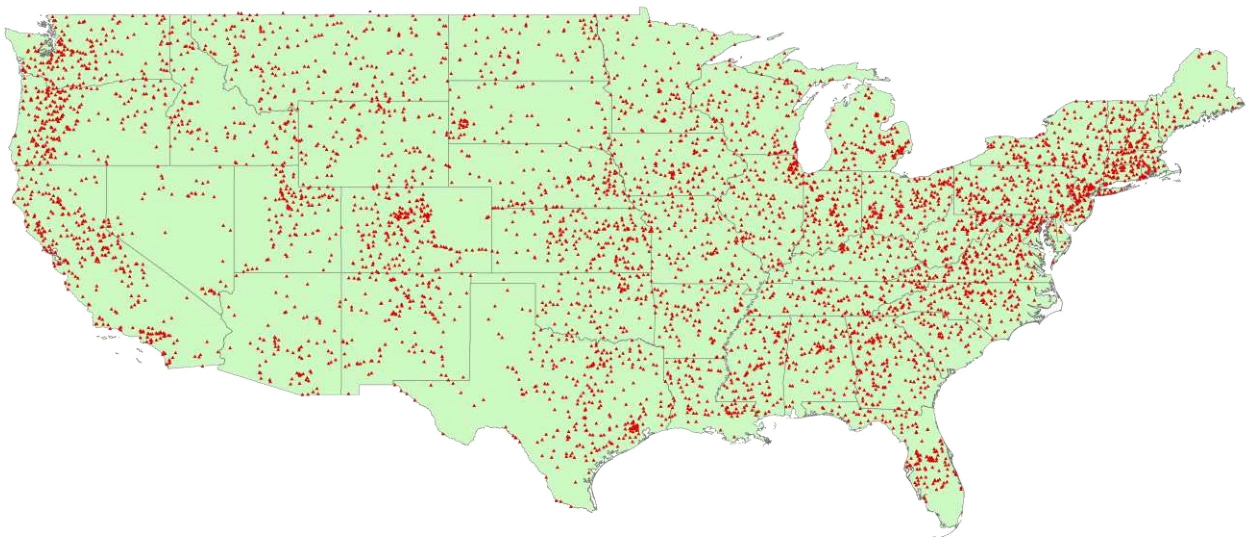

Figure 4. USGS Gaging Stations with one or more flow events greater than the Q_{100}.

Before the next step, we returned to the NBI information that comprised Figure 1. Recall this was about 508,000 bridges over water. These included 21,279 scour critical bridges (Figure 5).

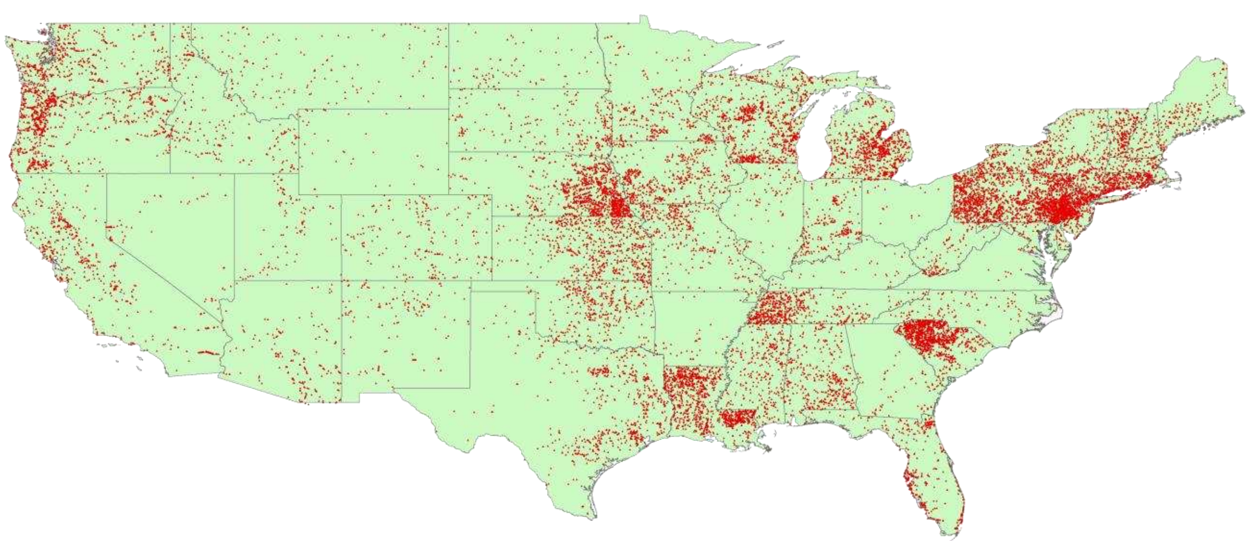

Figure 5. "Scour Critical" bridges reported in the 2019 NBI.

Our next step performed a geographical information system (GIS) analyses of those 5,367 stations and the various NBI bridge information.

We assumed that proximity of a bridge within some radius of those stations would allow consideration of whether such bridges might be affected by those events. In other words, how would proximity "correlate" with potential bridge failure from those events?

The GIS analysis revealed that (a surprising) 344,281 bridges were within a 10-mile radius of those 5,367 stations. That was over half (56%) of ALL bridges in the NBI. Concerned that we had overly broadened the proximity, we reduced the proximity to a 2-mile radius.

Reducing that proximity radius yielded 43,566 bridges within a 2-mile radius of those 5,367 stations. In regards to the scour critical status, that also resulted in 1,640 scour critical bridges within a 2-mile radius of those 5,367 stations.

However, the FHWA does not know of 43,566 bridge failures that have occurred in the U.S. That seems to reject any hypothesis that such events indicate scour failures at bridges. Likewise, if the NBI data represents any correlation that equates conditions (i.e., scour criticality) to bridge failure, then the FHWA would expect some evidence that some portion of those 1,640 bridges have failed, at least some as a result from flood events greater than the Q_{100}. However, a preliminary review of those bridges does not (as yet) support that hypothesis either.

Thoughts on Thought Exercises

So, this thought exercise does not seem to support a hypothesis that the Q_{100} event correlates with scour failure or justify attempts to correlate NBI condition data to similar failure.

The exercise does not reject the hypothesis that these events may correlate to scour formation. The analyses do provide specific dates that could be reviewed to assess potential effects on a bridge (e.g., review of bridge owner records or media accounts). Likewise, having such dates allows the possibility to use the NBI to see if there may have been changes in conditions or costs before and after such events by looking at those specific bridge funding NBI records over a several year period.

Of course, very good arguments could be made that the analysis misses those remaining 19,639 scour critical bridges or has other flaws and issues in the methodology and execution compared to other literature.

CONCLUSIONS

The authors believe that considering extreme events to transportation is both prudent and consistent with principles of asset management and insights of scour researchers and practitioners. We do not believe that the research community has done an adequate job in incorporating such considerations in a defensible manner. Given the implications of extreme events on the U.S. transportation system, "getting this right" is imperative.

We believe that we are at a stage, such as prior to 1949, when such research is not yet systematic or focused. Drs. Laursen, Richardson, Chang, and others performed incredibly important scour research within the limits of technology available to apply underlying physics or hydraulics and scour. Today, advancement in technology allows researchers to move past those limits. We are gratified to see some researchers doing so.

We are also extremely aware that when living in glass houses, one should be careful of tossing around stones. So, the authors may have engaged in logical fallacies and applied inadequate scientific methods ourselves. We offer our apologies for any errors or omissions.

Finally, we suggest that there are a wide range of interesting and useful research topics to address scour and these extreme events in a meaningful way with useful research outcomes that would advance the transportation community. We propose some potential examples:

- What would a more thorough review of flood events and reports of damage using NBI temporal data reveal?
- Given the increasing number of bridge locations analyzed using two-dimensional and three-dimensional hydraulic models, can we simulate a variety of boundary conditions (including varying discharge and water surface) and use the results to analyze load conditions at specific bridge substructure elements to see if patterns emerge?
- Can we formulate any improved approaches than using discharge as a surrogate to express the design scour probability, perhaps applying "fragility curve" concepts to scour?
- Climate science understands that extreme events do not always equate to higher rainfall and runoff quantities; some portions of the U.S. may see reductions in such quantities.
    - So how may such reductions lower tailwater and perhaps induce vertical instability in channels;
    - If main river stems have decreased flows, what are risks to bridges on upstream tributaries, such as what occurred during the 1962 Big Sioux River failure?
- Can temperature changes lead to geotechnical alteration of soil and streambed characteristics?
- What changes may manifest in the duration or number of occurrences of flood events, etc.

We look forward to seeing the research community respond to these and other important ideas and concepts.

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