A PRACTITIONER'S FIELD GUIDE TO GUESSING IN THE DARK

HOW I LEARNED TO STOP WORRYING AND LOVE UNCERTAINTY

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INTRODUCTION

The field of dam safety relies heavily upon the practice of hydrology, both in the design of new structures and in the evaluation and regulation of existing ones. This critical science is often assumed by the general public to be a precise and reliable technique capable of producing a single value response to any question. Those of us who practice in this field realize this is not the case. Uncertainty is the ghost haunting our mansion, and it stands behind us in everything we do. This public confidence in a very uncertain practice places a burden on us. To bear it and do right for the public, we need a solid knowledge of the tools at our disposal, their strengths and weaknesses, and especially when to trust and when to doubt them.

Current practice seems to indicate a lack of attention to these fundamental issues. This inattention can lead to ill-founded assumptions on the part of practitioners and confusion on the part of the public they serve.

Our tools fall into two main categories: Probabilistic and deterministic. The two are distinct in their development, application, and purpose. A practitioner must know when and how to apply each.

TOOLS - PROBABILISTIC

Probabilistic analysis strives to determine the magnitudes of the events a project will endure during its service life. Two methods are commonly employed for this task.

STATISTICAL

The Statistical method uses observations of a river system at a point to predict future behaviors. In theory, with an adequate record a good estimate can be made of the likelihood of occurrence of various values. The stream gage record is a sample of a population, and the tools of statistics allow us to derive properties of the entire population. Confidence in our analysis rests on several assumptions:

1) The sample size is large enough to adequately represent the population;
2) The population is homogeneous;
3) The population is time invariant;
4) We can derive a Probability Distribution Function (PDF) to fit the behavior of the sample;
5) We can extend this PDF to predict the behavior of the population.

It takes little meditation on any of these to cause some degree of concern. However, if it is the best we have we must use it with our best judgment.

Let us examine the assumptions then. The sample size is always too small. The population is all the peak annual discharges that have, or will have occurred at a given point on a stream and our record is only a small sample of that. However, if we are modest in the time period of concern, we can have some degree of confidence. And that degree is wholly dependent upon the ratio of the record length to the period of concern.

The population may or may not be homogeneous. Few streams in this nation are truly unaffected by natural or man-made changes. Many of those changes, however, upon reflection may be determined to be inconsequential. Others can sometimes be addressed by adjusting the record in careful and well-documented ways. Then there is a lot we just don't understand, especially about the events which cause the flows.

No one believes the population is truly time invariant. Current theories about climate change are not even necessary to come to this conclusion. The cyclic nature of climate conditions has been recognized for generations. Again, however, we can only use what we do have with great care and judgment. Here again, sample size is vital. A longer record has a better chance of including extremes in both cyclic directions, giving more confidence than a shorter record including only a high or low period.

Then we must consider the PDF. There is no scientific logic, theory, or technique that tells us how to construct a mathematical function to describe the distribution of annual peak discharges or volumes. All we know about the population is that it is bounded by zero on the low end, unbounded on the upper, and skewed to the low end (i.e. there are more lower values than higher ones.) It is necessary to select, by trial and error, a mathematical function that will best describe a population by simply seeking one which looks best. This problem is exacerbated by the fact that different functions can give different results, leading to irresolvable conflicts.

In 1964 a committee of federal agencies was formed to resolve the matter. Their efforts resulted in what is now known as Bulletin 17-B. The PDF selected was the Pearson type III to be applied to the logarithms of the values. Its adoption by federal agencies virtually mandated its use by all sectors. The log Pearson III is usually supplemented by the Weibull method, in which the logs of the values are ranked and their individual probabilities are computed from their positions within the ranked set. The two curves are then plotted together on probability paper. The log Pearson III method also gives the means to compute a confidence envelope. The 95% confidence level is commonly used, meaning we have 95% confidence that the true value lies between the two boundaries, usually plotted as dashed lines on the combined curve.

This analysis produces credible and reproducible results, but it must be remembered that it contains no representation of the physical realities of the basin. Its validity rests entirely upon the assumptions listed above, and is highly dependent upon the sample size.

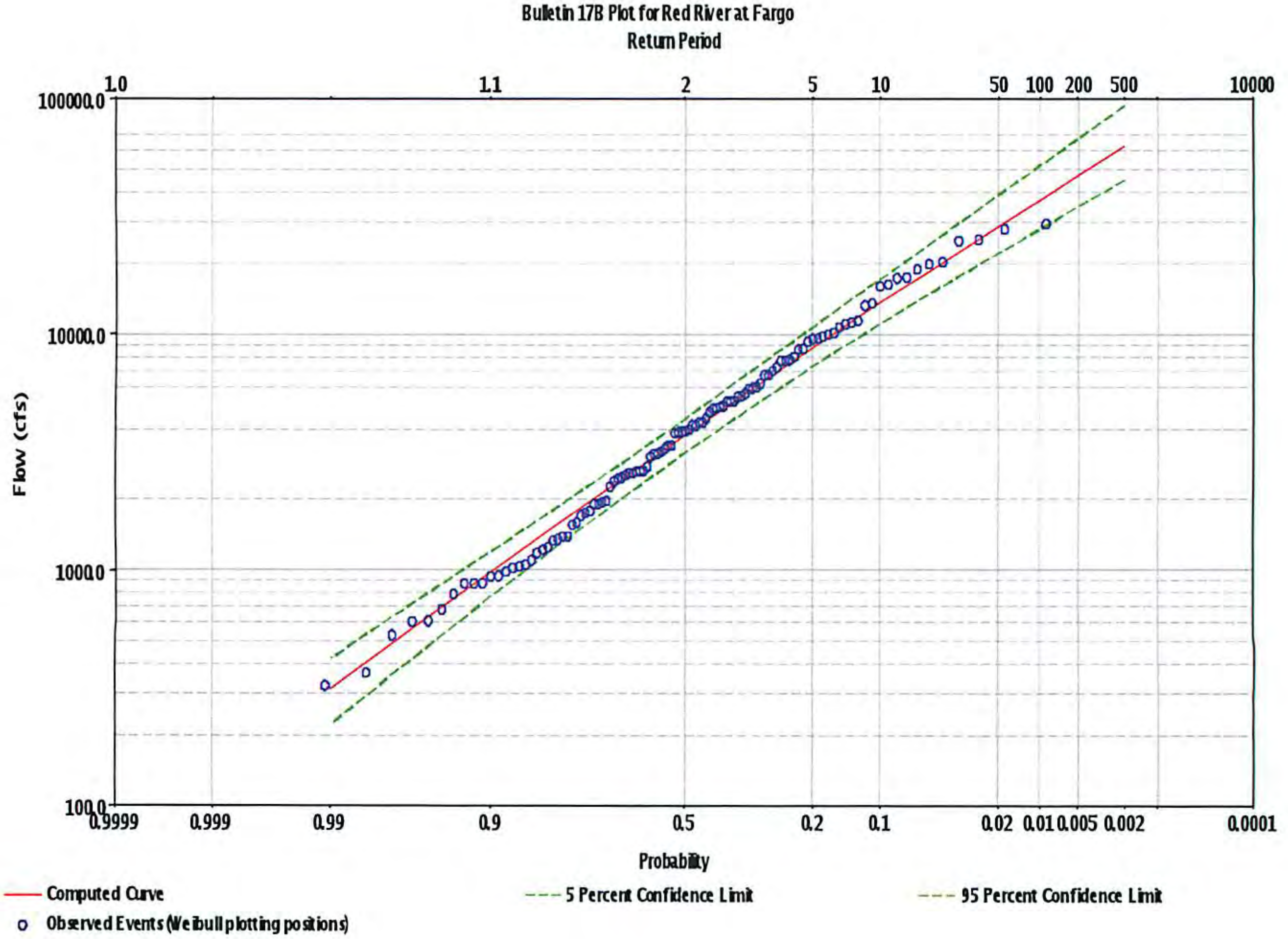

FIGURE 1:

Flow Frequency Curve Red River at Fargo, N. Dak.

(The example in Figure 1 is constructed by applying a standardized program to the record of stream gage on the Red River in eastern North Dakota with more than 100 years of record. The "official" curve at that site, which is used for flood plain management and other matters, differs somewhat.)

All this is very useful as long as a stream gage is present at or near the point of interest. What if there is none? This concern is far from hypothetical. In fact there is rarely a useable stream gage nearby. Other methods must be sought.

NUMERICAL MODELING

The other principal method of analyzing the probabilistic hydrology of a basin is by formulating a mathematical model that incorporates the basin's properties. Contributing drainage area, infiltration parameters, timing properties, slopes, channel conditions and so forth are used to generate runoff, while timing and sometimes other factors are used to select and parameterize a synthetic unit hydrograph. There are numerous packaged models available to use for this purpose: HEC-HMS; HEC-1; TR-20, etc.

These models are extremely versatile. They enable the practitioner to formulate a mathematical representation of the basin of interest which can be used to test the effect of a project on the basin as a whole, test various project configurations, and test a given project under various conditions. The model can be tested against known recorded events, or events measured on similar basins. For these reasons, this method is often verified by comparison to a statistical analysis to enhance reliability.

They require a high degree of judgment, however. Each of the components – infiltration, timing, unit hydrograph, basin configurations, rainfall distribution, all require assumptions. Furthermore, antecedent conditions, which can be extremely influential, must be selected.

The probabilistic element is introduced in the selection of the model stimulus: Precipitation.

Precipitation depths for various return periods, areas and durations are published. In the past, NOAA's Technical Paper 40 was the principal source for these values. Currently NOAA is in the process of replacing TP-40 with Atlas 14, based upon a much denser data set and enhanced in other ways as well. Atlas 14 is available in some parts of the nation, however in the remainder, TP-40 is still used. Valuable as it has been in the past, TP-40 is based on a very sparse data set.

To apply this method a practitioner assembles the data representing his basin and selects a precipitation distribution of appropriate probability and duration scaled to the response time of the basin. The rainfall temporal distribution must be assumed and there are several appropriate methods to do this. The result is a discharge hydrograph that can be used to resolve the questions arising in design or evaluation. However its reliability rests entirely upon the judgment of the practitioner. Even the assurance of the admittedly small sample of the statistical method is missing here.

This may be a rather long and redundant recitation of standard procedures, but certain factors bear illustration. Both these methods are dependent on the judgment of the practitioner. Both require a high degree of reliance on recorded data, either precipitation or stream flow, which must be assumed to be time invariant.

If we are concerned about life and safety issues, these techniques, because of their inherent uncertainty, are clearly unacceptable. In legal and ethical realms, risk is equivalent to liability. In economic terms, however, risk is equivalent to opportunity. Economic decisions are inherently gambles, and there exist techniques within this field to quantify risk and incorporate it in the decision-making process. These decisions, in the sphere of dam safety include project siting, primary outlet works sizing, O&M cost planning, and whether the project should be constructed at all. In the realm of evaluating existing structures, they influence operation and maintenance practices and the need for improvements.

Statistical methods provide competent and reliable tools for quantifying the long-term costs and benefits of a project. This is true, however, only as long as the analysis remains within the approximate time span of the record. In most cases this is, or can reasonably be extrapolated to, one century. This equates to a one percent chance probability, and contains most of the implications of an economic decision.

Economic decision-making, however, does not apply to the design of features that may endanger life and safety. Costs and benefits have no bearing on these matters. The only question is how to avoid these risks. For these decisions, we need to identify the worst possible challenge that could be presented to the project. In hydrologic terms, this is the Probable Maximum Flood.

TOOLS - DETERMINISTIC

The other main type of hydrologic analysis is the Extreme Event approach. While the statistical methods are probabilistic, the extreme event method is inherently deterministic.

Probable Maximum Floods (PMF) result from Probable Maximum Precipitation (PMP). The latter is defined as "the theoretically greatest depth of precipitation for a given duration that is physically possible over a particular drainage area at a certain time of year," (American Meteorological Society 1959). In consideration of our limited knowledge of the complicated processes and interrelationships in storms, PMP values are identified as estimates.

Values for the PMP are given in a number of documents produced by the NWS. Hydrometeorological Report #51, 52, and 53 cover most of the continental US east of the 105th meridian (see Figure 2), with site-specific studies available in certain areas, including one recently completed by the State of

Nebraska, which is not shown on this map. West of the 105th, different orographic and coastal effects must be included.

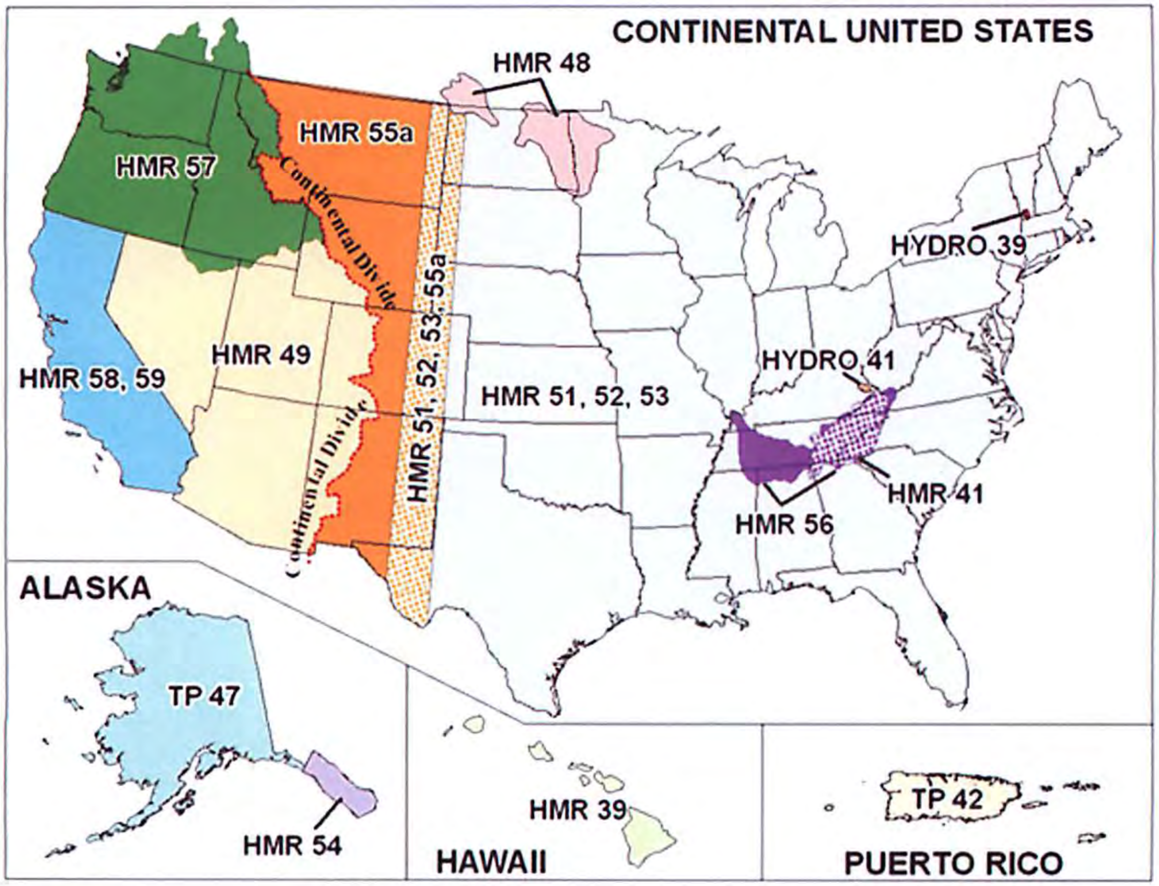

FIGURE 2

NWS Hydrometeorological Reports

The values given in these documents result from a process of maximizing precipitation producing parameters in recorded historical storms of extreme violence. For this reason they are not probabilistic, and are not dependent upon a sample size. It can always be argued that better estimates can be made, but any shortcomings are not attributable to insufficient record. In a sense, determining an extreme value is conceptually simpler than determining a probabilistic one because the extreme value need not meet expectations based on observations.

The PMF, which results from a PMP, is not so clearly defined: " . . . the steps followed by hydrometeorologists in arriving at the answers supplied to engineers for hydrological design purposes" (WHO 1973). This definition leads to answers deemed adequate by competent meteorologists and engineers and judged as meeting the requirements of a design criterion. Thus considerable latitude is give to those involved in the development of a PMF. In exercising this latitude, however, the practitioner must take deeply to heart the obligation of "competent meteorologists and engineers" and their task of judging whether the requirements of a design criterion are met.

The purpose of extreme value hydrology is to identify the most severe conditions that a particular basin can experience. If failure of a dam on that basin would threaten life and safety then the dam must be able to survive that event. This survival can be either by passing or retaining the PMF. The volumes involved are usually so large that retention is not reasonable. But damages caused by passage of the event are attributable to the occurrence of the event, not the existence of the dam. Incremental Hazard Analysis can also be useful in such cases.

APPLICATION

This then is the process: A dam site is selected and basic features are designed. Design standards, often based on statistical methods are used to size features such as capacity and freeboard for the principal outlet. Then, if it is a high or medium hazard site, it is evaluated against a Probable Maximum Flood or some fraction thereof. The emergency spillway capacity and top of dam freeboard are designed to allow the dam to survive this event. Costs for the resulting structure are combined with the expected O&M costs over the structure's service life and compared economically against the benefits over its service life, using the statistical techniques discussed above to project the recurrence of different magnitudes of floods. If the benefits exceed the cost, the project is feasible. Some projects are constructed even if not feasible, but a solid assessment of true costs of a safe structure is necessary nevertheless. And it must be built in such a manner as not to endanger life and safety.

Evaluation of existing structures is more difficult, since many structures pre-date this approach and development downstream frequently creates a high hazard condition that did not exist at the time of construction. In such cases, the use of fractions of the PMF, if used with caution and a clear understanding of the issues, can offer a path to adequate and reasonable regulation. Incremental hazard analysis also may be useful. Whatever the case, these structures call for extreme wisdom and judgment on the part of decision makers. Decision makers seldom have a good working understanding of hydrology; therefore they must rely on technical practitioners to advise them. A solid knowledge of the risk on the part of the practitioner, then, is vital to service of the public.

COMMON ERRORS IN APPLICATION

The principal thesis of this paper is that each of these two techniques, while both valid and useful, has a different basis, technology, limitations. Probabilistic methods are valid and useful in making economic decisions as long as the analysis period does not exceed about 100 years. Extreme event techniques are necessary in designing features to prevent failure of the structure with consequent threats to life and property. When used together, they are effective in designing and evaluating safe dams. There are two trends current today which confuse this distinction.

At times we hear of attempts to define the probability of the PMF. This is a profound misuse of the entire concept of extreme event hydrology. The PMF is derived from deterministic analysis. There is no probabilistic element at all. It is an attempt to define the ultimate end of the probability curve. No rationale exists for assigning it a return period.

The other error is in attempting to project extreme events from a Weibull/log Pearson curve. To illustrate the potential dangers in extending a probability curve too far beyond its record consider the following hypothesis: Occasionally in performing a log-Pearson analysis, the record contains points that simply will not fit the PDF. Bulletin 17-B gives guidance to identify these points as outliers, and how to deal with them. The guidance is to discard them. But this action acknowledges that these points do not belong to the sample population. However, they are real and valid points, generated by the same watershed as all the others. If they do not belong to the sample population under analysis, then what population do they represent? The hypothesis is that they are members of a population of events so rare that we very seldom record them. If we had an extremely long record, however, this population could plot as a line with a much steeper slope than the log-Pearson line with which we are familiar. The upper terminus of this line would be the PMF.

The community in which the Figure 1 gage is located is considering flood protection at the 500-year level. A log-Pearson curve simply does not give us these values, and no other method will either because of the limitations on the record. The log Pearson line shows the most likely value for the 100-year discharge is 37,239 cfs. The 95%confidence band, however, is 28,000 to 52,000 cfs. Even with a 100-year plus record, the confidence band is nearly 65% of the most likely value. A wide band, but for planning purposes the economic implications can be addressed.

It is clearly insufficient, however, for the complete design of a structure whose failure could endanger life and safety.

Extending the same curve gives a 500 yr. discharge of 62,638.0. The 95% confidence band, however, extends from 45,299.5 to 93,069.1 (Decimal points included for amusement). The band is nearly 48,000 cfs wide. Confidence that risks are quantified at this level is simply not present. Basing a design on such a projection is highly quantitative ignorance and a conscientious practitioner should attempt to dispel it, not contribute to it.

It could be argued that to ensure safety, the upper confidence limit value should be used. But what this wide confidence interval really tells us is that we simply know too little about the system to have any confidence in the statistical method at all in this domain, especially in consideration of the two-population hypothesis described above. Furthermore, what real value is there in knowing the probability of such a rare event?

A careful practitioner, then, should use whatever probabilistic methods he can do determine configuration of features that are economic in nature. For dam safety matters, he needs to turn to extreme event techniques (either PMF or some fraction thereof). This is the best we can do, and that knowledge makes the uncertainty inherent in our field of practice tolerable, even fun.