MODEL REVIEW REPORT

HEC-FDA MODEL VERSION 1.4

1. PURPOSE. The purpose of this report is to document the review process and findings of the Hydrologic Engineering Center – Flood Damage Analysis (HEC-FDA) version 1.4 model review. It is enclosed with the following attachments: HEC-FDA Version 1.4 Model Review Plan and Memorandum dated May 9th, 2013 (attachment a), Model Documentation provided by the proponent to the reviewers on July 29th, 2013 (attachment b) and a Dr. Checks Report detailing the final status of all reviewer comments (attachment c). In addition to the enclosures listed above several additional documents are available electronically, these include the HEC-FDA version 1.4: release notes, user's manual, user's manual appendices, readme file, installation package and a document detailing changes to the electronically available documentation since the certification of HEC-FDA version 1.2.5a.

2. REFERENCES AND GUIDANCE. The review was conducted in accordance with the HEC-FDA Version 1.4 Model Review Plan dated May 9th, 2013 (attachment a) and guidance established by Engineering Circular (EC) 1105-2-412, titled "Assuring the Quality of Planning Models" dated 31 March 2011.

Several additional pieces of guidance governing the use of graphical frequency curves were also useful as background information, driving the computations made within the model. They include Engineering Technical Letter (ETL) 1110-2-537, titled "Uncertainty Estimates for Non-analytic Frequency Curves", dated 31 October 1997; Engineering Regulation (ER) 1105-2-101, titled "Risk Analysis for Flood Damage Reduction Studies", titled 3 January 2006; and Bulletin 17-B of the US Interagency Advisory Committee on Water Data, titled "Guidelines for Determining Flood Flow Frequency", dated 1982.

3. BACKGROUND. HEC-FDA was developed through collaborative research between the Institute for Water Resources (IWR) and the Hydrologic Engineering Center (HEC). It is a planning tool used to inform the plan formulation process through the evaluation flood damages and risks associated with flood risk management plans. Since its initial release in 2000 it has become widely used throughout the US Army Corps of Engineers and other water resource entities.

As a well established model with multiple previously certified versions and over a decade of wide spread use HEC-FDA has been exposed to numerous formal and informal reviews. Consequently, its capabilities and limitation are well understood by users and developers. Version 1.2.4 of HEC-FDA was certified in March 2009; and Version 1.2.5a was certified in June 2011. Version 1.4 incorporates updates and enhancements, resulting from HEC's continuous process of identifying and implementing improvements to the program.

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HEC-FDA version 1.4 is the last version using the Galaxy platform, which is obsolete and difficult to support in contemporary versions of Windows. HEC-FDA version 2.0 is currently under development. It uses the same computational libraries as FDA 1.4, but with a Java-based interface. Computational and interface components in HEC-FDA 1.4 were re-organized and refined, in order to prepare for a seamless replacement of the interface components. This has resulted in more robust performance than previous versions of the model (i.e. fewer frustrating "glitches"). These internal improvements are listed in the electronically available release notes. However, they have little or no impact on models outputs and results.

HEC-FDA version 1.4 incorporates one important computation improvement, wholly unrelated to the internal improvements noted above. Previous versions of the model (e.g. version 1.2.5a) use a method to compute uncertainty about graphical discharge or stage frequency curves (graphical frequency curves), which produces inconsistent and counter intuitive results under a specific and limited set of circumstances.[1] Version 1.4 replaces this computation algorithm with a different more reliable method.

Changes to the computation of uncertainty about graphical frequency curves, referenced above, represent the most significant change to HEC-FDA's function as a planning model. A more description of these changes is provided in the Graphical Frequency Curve section below.

4. CERTIFICATION DOCUMENTATION. The following documentation was reviewed as part of this review: (1) copy of the software and example datasets; (2) revised user's manual and summary of significant revisions; (3) a white paper titled, "Estimating Uncertainty due to Sampling Error for a Graphical Frequency Curve," describing the desirability of the so called, "less simple" method; (4) updated certification report, showing changes to the prior certification report; (5) description of the testing plan, with testing results available to reviewers upon request; (6) a description of standard Hydrologic Engineering Center (HEC) documentation and software quality assurance/quality control (QA/QC) processes. The white paper and updated certification report are included within attachment b. The other documents are available upon request.

5. REVIEWERS CHARGE. The HEC-FDA model's high degree of complexity is partially offset by its long history of use, successful formal reviews, and previously certified versions; however, there is a considerable risk associated with the importance of the model's outputs in the decision making process. The model's outputs often play a critical role in the evaluation and selection of flood risk management alternatives; and in the NFIP Levee System Evaluation process. Accordingly, a level four review was recommended and approved, with the model review plan.

Reviewers were charged with the following specific questions in the section five of the model review plan: (1) Are quality control procedures adequate regarding the internal improvements, i.e., based on the provided quality control documentation, do the reviewers concur that the code

[1] In a limited number of instances, in previous versions of the model uncertainty about the graphical frequency curve was found to be positively, rather than negatively, correlated with the equivalent length of record.

changes were properly tested and likely cause no inadvertent differences in results? (2) Do the reviewers agree with the replacement of the version 1.2.5 Ordered Statistics method with the version 1.4 Less Simple Ordered Statistics method? If not, would they support replacement with the version 1.4 Simple method? (3) Are the updates to documentation clear and complete?

Responses to the general model review topics and specific charge questions listed above are discussed in the Findings section below.

6. REVIEW TEAM MEMBERS. The model review team consisted of two internal reviewers, one external reviewer, and the model review lead. The reviewer's qualifications are discussed below.

Craig Loftin a hydrologist from the Fort Worth district and Brian Maestri and economist from the New Orleans district were selected as internal reviewers. Mr. Loftin and Maestri are regarded as flood risk management subject matter experts within the USACE. As a result both are expert users of the HEC-FDA program. Mr. Loftin was selected, in part, for his extensive knowledge and experience in the development of graphical frequency curves for flood risk management projects. Mr. Maestri, as an expert in flood risk management economics, has expertise in identifying the impact that hydrologic assumptions have on HEC-FDA outputs, and ultimately planning decisions. He also possesses deep knowledge of the models capabilities and limitations.

Dr. Jery Stedinger provided external review. Dr. Stedinger is a Professor of Civil and Environmental Engineering at Cornell University. In addition to being an internationally recognized expert in the fields of hydrological statistics and risk analysis he has held advisory positions with the USACE, USGS, Bureau of Reclamation and other federal agencies. In 2005 he spent his sabbatical at the HEC as the Leo R. Beard Visiting Scholar. During this time he developed expert level knowledge of the HEC-FDA program.

John Kucharski of the Sacramento district managed the review as the model review lead. John is regional technical specialist in flood risk management economics and certified flood risk management reviewer. As such he processes knowledge of the HEC-FDA models capabilities and limitations.

The following individuals were also engaged in the review process: Eric Thaut, Deputy Director of the FRM-PCX, provided oversight of the review and is responsible for the final PCX recommendation on model certification based on the review findings. Jeremy LaDart, from the Office of Water Project Review, served as the headquarters subject matter expert. Comment responses were submitted by Dr. Beth Faber and Bob Carl, at the HEC in Davis, CA.

7. GRAPHICAL FREQUENCY CURVES. Changes to the computation of uncertainty about graphical discharge or stage frequency curves represent the most significant change to HEC-FDA version 1.4. Consequently, this was a major focus of the review, as reflected in the specific charge questions listed in section five of this report. The general method for computing uncertainty about the graphical frequency curve, in all versions of HEC-FDA; issues associated with the computation algorithms used in version 1.2.5a; and changes incorporated in version 1.4 are discussed below.

Techniques for the estimation of the uncertainty in graphical flood flow frequencies are established in Engineering Technical Letter 1110-2-537 (ETL 1110-2-537), titled "Uncertainty Estimates for Non-analytic Frequency Curves," dated 31 October 1997. The guidance applies to "all HQUSACE elements and USACE commands where estimates of uncertainty about non-analytic frequency curves are required." Accordingly, the general methods used to estimate uncertainty about graphical frequency curves have a long history of frequent application within the USACE water resources community. All versions of HEC-FDA incorporate the general methods described below. More specific methods, unique to various versions of the HEC-FDA software, are labeled as such.

The *order statistics* (or *ordered events*) method described in ETL 1110-2-537 recognizes that the historical record can be used inform the probability of stages or flows associated with given flood frequency events. The method also uses that historical record, or an artificial facsimile of it, to estimate the uncertainty in those probabilities. The weakness of this ordered events approach is that it can only be used to compute uncertainty in the probability of flows or stages (for a given flood frequency event) within the range of the historical events. In other words, uncertainty in the probability of flows or stages that are larger than those found in the historical record cannot be estimated directly using the order statistics approach. This restriction is pertinent since it is often the rare events (e.g. those that are larger than any found in historical record) that are the most relevant to the analysis and decision-making.

The development of a computationally sufficient graphical frequency curve includes the estimation of less frequent events and flows than are found in the historical record. As is noted above, the ordered events approach is incapable of producing estimates for events larger than those found in the historical record. Similarly, estimates of the uncertainty in the flow or stage produced by any given event is also restricted to the range of stages and flows observed in the historical record, using the methods described in ETL 1110-2-537. Accordingly, an extrapolation of the ordered statistics approach is necessary to estimate uncertainty in flows or stages about less frequent events. Past versions of the model, including 1.2.5a, approximated uncertainty beyond the bounds of the historical record using an equation referred to as the "simple method" in the model review documentation." Unfortunately this method has the undesirable quality of being relatively unresponsive to changes in the slope of the frequency curve, generated by the historical record. As a result uncertainty is overestimated in flat portions of the curve and underestimated in steep portions of the curve, when using the simple method.[2] Due to this undesirable quality, a different method is incorporated into version 1.4. The so-called "less simple method" method estimates uncertainty with a simplification of the order statistics approach (using a first-order Taylor Series expansion). The estimate of variance that results from this approach produces a near exact match

[2] A "flat" portion of the curve is a portion of the curve where a wide range of probabilities of occurrence (on the horizontal axis) are assigned to similar flows or stages (on the vertical axis); conversely a "steep" portion of the curve is an area of the curve where events with similar probabilities of occurrence are associated with dissimilar flows or stages. In other words, the "flatness" or "steepness" of various parts of the frequency curve is determined by comparing how quickly the stage or flow increases in one part, relative to another.

to the variance estimated using the order statistics approach, and therefore is more responsive to changes in the slope of the frequency curve.[3] Due to this similarity in computed variance, in version 1.4 the "less simple approach" is used to estimate uncertainty about the entire graphical frequency curve, rather than only for those flows or stages in excess of those observed within the historical record.[4]

The methods described above produce approximated flow or stage variances, but not the full uncertainty distributions, associated with events on the infrequent end of the graphical frequency curve. Consequently, the approximated variances must be matched with a probability density function (PDF), in order to generate an uncertainty distribution about the curve.[5] Version 1.4 and all previous versions of HEC-FDA pair the approximated variances with a symmetrical normal distribution. However, the uncertainty distributions produced by the ordered events approach, within the range of the historical data, tend to be asymmetrical. While the use of the symmetrical normal distribution is not new to version 1.4, it is explored by Dr. Stedinger's comments and discussed in the findings section below. The difference in the shape of uncertainty distributions produced by ordered events and approximated approaches is particularly relevant because the approximated approach is used across the entire frequency curve in version 1.4.[6] As a result uncertainty is always represented symmetrically. The reasons for this are discussed in the next paragraph.

The ordered events approach restricts estimates of flow and stage uncertainty to the observed values in the historical record. As a result, the ordered events approach underestimates uncertainty when the maximum flow or stage, associated with a given event, exceeds the highest observed flow. Previous versions of HEC-FDA attempt to correct for these underestimates by replacing *some* of the ordered events approach estimates with approximations of uncertainty – computed using the methods discussed above. In general, uncertainty about the frequency curve is expected to increase as the probability of exceedence decreases beyond the median event.[7] For this reason, previous versions of the program start at the median event flow or stage variance, computed using the ordered events approach, and compare it to the flow or stage variance of sequentially lower probability events, also computed using the ordered events approach. The first comparison point that produces a lower computed variance than the previous one marks the position at which the ordered events variance is replaced by an approximated variance paired with a normal symmetrical distribution. This computational algorithm implicitly assumes that a decrease in variance moving outward from the median is the result of underestimation due to the limited historical record. This assumption is problematic whenever the decrease in variation is an accurate

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[3] Responsiveness to changes in the slope of the frequency curve is considered to be the ordered event method's greatest strength.
[4] The "simple" and "less simple" approaches are described in qualitative and quantitative detail in the model review documentation.
[5] This is necessary anywhere on the frequency curve that the flow or stage may exceed the bounds of the historical record.
[6] It is worth noting that the approximated approach is generally required across a large portion of the frequency curve.
[7] It is also expected in increase as the probability of exceedance increases before median event.

result of the frequency curve "flattening out" above the median event – due the historical record showing less variation in flows or stages within a localized portion of the curve.[8] In this case the algorithm leads to the incorrect selection of an approximation of variance, which is likely to be too large. The algorithm also leads to improper estimates of uncertainty when the frequency curve "steepens" at the less frequent end of the curve *and* the range of the historical record leads to a truncation in the upper end of the uncertainty distribution. In this case the algorithm described above fails to recognize the truncation produced by the ordered events approach and a variance that is too low will be retained. The outcome of this fact is that version 1.2.5a of the HEC-FDA model occasionally produced the counter intuitive and inconsistent result of *increasing* uncertainty with *increased* equivalent record lengths.[9] To avoid these inconsistencies, version 1.4 instead uses the approximated variance across the entire frequency curve, rather than attempting to determine where the order statistics variance is underestimated. The "less simple" method has the advantageous property of producing approximate estimates of variance that nearly match those produced using the order statistics method.

Finally, because the "less simple" method is apt to produce larger estimates of uncertainty about infrequent portions of the graphical flood frequency curve, the variance above the one percent annual chance flood frequency event is fixed, meaning the variance at the one percent event is used for all less frequent events (the upper portion of the frequency curve). As a result, uncertainty associated with events less frequent than the one percent annual chance flood frequency event may be overestimated if the curve flattens out the beyond the one percent annual chance event, because the decrease in uncertainty will not be captured. This topic was explored by each of the reviews; their comments are summarized in the finding section below.

In summary, significant changes to computation of uncertainty about graphical frequency curves can be grouped into the following three categories: (1) the use of the so-called "less simple" method used to estimate uncertainty beyond the bounds of the historical record; (2) application of symmetrical uncertainty distributions, produced using the order statistics method and either of the considered approximation methods, throughout the graphical frequency curve; and (3) fixed variance beyond on the one percent annual chance flood frequency event.

8. FINDINGS. The following section summarizes the major comments and findings of the review. The review was conducted in Dr. Checks, and a copy of the DrChecks documentation is included as attachment c. All comment responses were backchecked and closed by the reviewers. No reviewer felt that any of their comments should delay certification HEC-FDA version 1.4.

A great deal of the comments submitted by the model reviewers pertain to the changes made to the computation of uncertainty about the graphical frequency curve. These comments are summarized below.

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[8] The frequency curve is said to "flatten out" where its slope decreases, i.e. in places where flow or stage is similar across a range of exceedance probabilities.
[9] This counter intuitive result could be produced when the frequency curve steepens above the median event , and so a larger record length is able to generate a larger computed variance.

(1) **Use of the "less simple method" used to estimate uncertainty beyond the bounds of the historical record**. *(Included under this heading are comments related to evaluation of the frequency event at which the historical record is no longer sufficiently complete to use variance estimated using the order statistics approach, to estimate uncertainty).* All three reviewers commented that the "less simple" method seems to represent an improvement over the "simple" method used by version 1.2.5a. Specifically, as expected, the implementation of the "less simple" method induced larger estimates of uncertainty than the "simple" method in steep portions of the graphical frequency curve and smaller estimates in flatter portions of the curve. While Mr. Loftin noted in several comments the "less simple" method produced extreme changes in uncertainty estimates about bends in the frequency curve, these uncertainty estimates better match one's expectation about variance around relatively steep and flat portions of the curve. In addition to producing better estimates of uncertainty it was also noted that as a result this method produces improved estimates of project performance (such as assurance).

As is noted in section 7 above, the algorithm used by HEC-FDA version 1.2.5a to identify the point at which the historical record is no longer sufficiently complete to use variance estimates produced by the order statistics approach occasionally resulted inconsistent estimates of uncertainty with regard to equivalent record lengths. One of the internal reviewers performed additional testing (beyond the data sets provided by HEC) confirming that version 1.4 does indeed address this issue, resulting in improved performance.

The external reviewer, Dr. Stedinger pointed out that while the "less simple method" represents an improvement the currently certified versions approach, the use of a beta distribution to estimate uncertainty beyond the bounds of the historical record could be preferable. The improvement would be due not only to a consistent estimate of variance, but also a more appropriate asymmetrical distribution of uncertainty compared to the currently used normal distributions. The model proponent agreed that the use of beta distribution could represent an improvement over the current approach. Testing such an approach has begun and will be considered for implementation in a future version of the model.

(2) **Application of symmetrical uncertainty distribution throughout the graphical frequency curve**. As is noted in section seven above and the model review documentation, a significant short coming of the uncertainty around a graphical frequency curve in all versions of HEC-FDA is the assumption of symmetry about the mean stage or flow associated with a given flood frequency event. This assumption is made when the variance, produced by the ordered events, or either approximation approach, is paired with a normal distribution. The external reviewer noted that the use of a beta distribution to represent the uncertainty about the entire frequency curve would eliminate the need to assume symmetry, particular where symmetry does not exist. Again, the model proponent concurred with this comment and has begun testing if such an approach could be incorporated into a future version of the model.

(3) **Fixed variance beyond the one percent annual chance flood frequency event**. It was noted that the use of a fixed value for variance for with events less frequent than the one percent annual chance event would result in an overestimate of variance in the case where the frequency curve "flattens out" beyond the one percent annual chance event. While neither reviewer thought this issue should delay the model's certification, they recommended that variance be capped (e.g. not allow to exceed) rather than fixed at one percent annual chance event's value. The model proponent agreed that should the version 1.4's methods be carried forward the use of a cap rather than a fixed value would be considered in development of the next version.

Dr. Stedinger, noted that while the "less simple" method produces the better results than any of the considered alternatives, bounding variance at the one percent annual chance flood frequency event is arbitrary and may not fully accomplish the goal of ensuring hydrologic reality, particularly if the event has a "thick tail" or as the internal reviewers noted the curve "flattens out."[10] He reiterated his stance that the use of a beta distribution to estimate uncertainty associated frequency events which produce flows or stages which are larger than those found in the historical record would eliminate the need to bind variance above the one percent event.

The reviewers commented directly upon the models general acceptability under the technical quality, system quality and usability criteria. Many of the comments related specifically to the changes in the computation of uncertainty about the graphical frequency curve and are discussed above. All three reviewers found the technical quality of the model to be sufficient. Although, several improvements viewed as consideration for future version were offered (i.e. the use of Beta distribution to represent uncertainty distributions about graphical flood frequency curves), all reviews felt there were no technical quality concerns that should delay certification of version 1.4. One comment with regard to system quality, specifically computation times was raised. However, since this time the reviewer verified that improvements to version 1.4 signicantly reduced computation times, nullifying this concern. Reviewers noted that the usability of version 1.4 represents a general improvement over version 1.2.5a. In particular, several new data import features have been added and printing capabilities are improved.

In addition to commenting on charge questions and changes to the model identified in section seven, above the reviewers also commented on a range of other issues summarized below:

(1) **Polarity of impact of changes to the computation of uncertainty about the graphical frequency curve on expected annual damage calculations**. Mr. Maestri asked if the effect of changes in graphical frequency curve computations on expected annual damage (EAD) estimates could be generalized as either positive or negative. The model proponent pointed out the changes to graphical frequency curve computations do not result

[10] A thick tail in this context describes a stage or flow probability distribution in which there is an abnormally high probability associated with the largest flows or stages.

in monotonically larger or smaller estimates of uncertainty and therefore the polarity of the changes impact on cannot be generalized (i.e. the result of the change is unbiased).

(2) **Internally generated EAD computation points along the levee fragility curve.** Mr. Maestri noted that version 1.4 uses internally generated computation points along levee fragility curves, whereas previous versions did not. The model proponent described that this improvement results in more accurate estimates of EAD, without requiring the user to "add" points to levee fragility curves to increase accuracy. While internal computation point had been a feature of previous versions of the model they were removed after version 1.2.2 due to a suspected "bug" in the computation of EAD at these internally generated points. This bug was found not to exist in the current version and internally generated computation points were re-added to the models sub-routines.

(3) **Miscellaneous improvements to the model's usability.** Mr. Maestri notes several incidental improvements to the models usability found in version 1.4. These include allowing for the direct import, rather than manual entry, of levee fragility relationships and improved printing capabilities.

(4) **Correlation of error across plans and reaches.** Dr. Stedinger pointed out that all versions of FDA could be improved by better accounting for the interdependence in uncertainties between reaches, in multi-reach project. Currently the correlation of uncertainties between reaches is not dealt with in any version of HEC-FDA, however the effect of this neglect is minimized by the fact that the errors are in fact quite highly correlated between reaches. Still, this impacts the users' ability to assess the "true" uncertainty around damage calculations. Furthermore, when comparing damages estimates produced under without project conditions to damages estimates produced under various alternative plans it is not possible to "match" the simulated value of various uncertain input variables. For instance, one cannot compare the damages that result from "high" stages being selected from with and without project condition rating curves. As a result it is difficult to accurately assess uncertainty surrounding benefit calculations. However, as is the case with uncertainty between reaches, the uncertainty between a without and with project case is generally quite highly correlated, minimizing the error introduced by this weakness in the computation. While no change related to this comment will be made to version 1.4, the model proponents and reviewer agreed to continue to explore potential improvements to the correlation of error across plans and reaches in future versions of the model and other models, such as HEC-WAT/FRA that utilize HEC-FDA's outputs.

(5) **Uncertainty in the Log-Person III (LPIII) skewness coefficient**. HEC-FDA takes the skewness coefficient as an input in the computation of LPIII analytical frequency curves. Dr. Stedinger suggested that uncertainty about this parameter be included as an input. The model proponent suggested that this parameter be included once bulletin 17-C is released, which will provide generally accepted values for uncertainty in this parameter.

9. TRANSITION PLAN. A plan for USACE user's transition between HEC-FDA versions 1.2.5a (currently certified) and version 1.4 was discussed by the model reviewers, model proponent and FRM-PCX. The lists below records some of the pertinent facts discussed during that discussion:

(1) **New models.** The process of creating a new study in version 1.4 is identical to process used to create and run a new study in version1.2.5a. Thus no training will be required to familiarize existing HEC-FDA users with the new version of the program. The cost associated adoption of version 1.4 is minimal.

(2) **Existing models.** The mechanical process of transitioning existing study files from version 1.2.5a to version 1.4 is straightforward and simple; once HEC-FDA study files created in version 1.2.5a are opened and run in version 1.4 the transition is complete. As a result, there are few costs associated with *model* transitioning.

The largest costs (in time and money) associated with transitioning from version 1.2.5a to version 1.4 are likely to be associated with the following tasks:

(3) **Updating outputs.** Existing tables, text and figures presenting model outputs in study reports, presentations and other documents will need to be edited when transitioning from version 1.2.5a to version1.4.

(4) **Explaining differences in the models results.** Economist and other project delivery team members on existing studies will need to explain changes to EAD, project performance and other HEC-FDA outputs associated with the transition from version 1.2.5a to version 1.4.

As is recorded in fact one, new studies or those without existing HEC–FDA models will bear little if any additional cost when adopting version 1.4. The costs associated updating existing *models* is also expected to be minimal, given fact two. The largest costs, in time or money, are likely to be associated with updating report documentation and explaining any changes in the plan evaluation and selection results. Put another way, the costs of transitioning are expected to be highest for studies that used version 1.2.5a to evaluate and select alternative plans, as well as generate study reports, appendices and other documentation. As a result the FRM-PCX, in consultation with the model proponents and model reviewers recommend the following:

(1) **New studies.** All new studies and those without existing HEC-FDA models adopt version 1.4 upon certification.

(2) **Existing studies prior to TSP milestone.** All existing studies with HEC-FDA version 1.2.5a or earlier models adopt version 1.4 within three months of certification, provided that they are not within three months of a scheduled tentatively selected plan (TSP) or subsequent milestone.

(3) **Existing studies at the TSP milestone.** Studies within 3 months of a tentatively selected plan adopt version 1.4 prior to their agency decision milestone.

(4) **Existing studies after the TSP milestone.** Studies that have completed their tentatively selected plan milestone not be required to adopt version 1.4.

(5) **Exceptions.** Any exceptions to these recommendations or be requested of and approved by the FRM-PCX.

10. CONCLUSIONS. As is noted above HEC-FDA has been exposed to over a decade of formal and informal review. As such it general capabilities and limitations are well understood and documented by users and developers of the model. Several versions have been certified since 2009. HEC-FDA version 1.4, the subject of this review, incorporates code-based changes that have little to no impact on model outputs and results; as well as one important computational change designed to improve the estimation of uncertainty about graphical flood flow and stage frequency curves. These changes and their impacts are summarized above, primarily in section seven. Two internal and one external model reviewer reviewed changes to the model, as well as its overall performance under the usability, technical and system quality criteria. The specifics of these reviewers charge are summarized in section five. Their findings are discussed in section eight, above. This section concludes by summarizing the reviewer's overall findings and recommendations with the following list:

(1) **Recommendation to Certify**. All three model reviewers were unanimous in their recommendation to certify HEC-FDA version 1.4. Although each reviewer recommended specific future improvements to the model none felt that any issue raised warrants a delay in the model's certification.

(2) **Improved Technical Quality**. The model's overall technical quality was found, by the reviewers, to be adequate for certification. Changes made to the estimation of uncertainty about graphical flood flow and stage frequency curves primarily affect the model's technical quality. All three reviewers felt these changes represent an improvement to the model.

(3) **Improved Usability.** The model's overall usability was found, by the reviewers, to be adequate for certification. Changes made to the model's underlying code, in order to prepare for migration to a JAVA based environment, had relatively little impact on the model outputs and results. However, the few differences that could be detected were viewed, by the model reviewers, to be positive – and most closely associated with the model's usability.

(4) **No System Quality Concerns.** The model reviewers found no significant system quality concerns.

(5) **Implementation proceeds according to recommendations listed in section nine above**.

attachment **a**:

Model Review Plan and Memorandum

DEPARTMENT OF THE ARMY
SOUTH PACIFIC DIVISION, U.S. ARMY CORPS OF ENGINEERS
1455 MARKET STREET
SAN FRANCISCO, CALIFORNIA 94103-1398

REPLY TO
ATTENTION OF

CESPD-PDP (FRM-PCX) 9 May 2013

MEMORANDUM FOR CECW-CP, ATTN: Sue Hughes and Stuart McLean

SUBJECT: Hydrologic Engineering Center Flood Damage Reduction Analysis (HEC-FDA) Version 1.4 Model Review Plan

1. The Flood Risk Management Planning Center of Expertise (FRM-PCX) requests HQUSACE approval of the enclosed subject model review plan. The plan outlines the scope and level of review for certification of the HEC-FDA 1.4 in accordance with EC 1105-2-412, Assuring Quality of Planning Models, dated 31 March 2011. The Hydrologic Engineering Center (HEC) is the model proponent. The FRM-PCX is responsible for the model review.

2. HEC-FDA is a planning model for flood risk management studies and was developed through collaborative research between Institute for Water Resources (IWR) and CEIWR-HEC. HEC-FDA has been designed to be an analytical tool used for formulation and evaluating flood risk management plans using risk analysis methods. Two versions of HEC-FDA have previously been certified by HQUSACE: Version 1.2.4 of HEC-FDA was certified in March 2009; and Version 1.2.5a was certified in June 2011.

3. HEC-FDA 1.4 is intended as the last version using the Galaxy platform, which is obsolete and difficult to support in contemporary versions of Windows. The version 2.0 of FDA currently under development uses the same computational libraries as HEC-FDA 1.4, but with a Java-based interface. HEC-FDA version 1.4 includes a significant computational refinement in the replacement of the algorithm for computing uncertainty about graphical probability curves. The methodology for computing uncertainty about graphical probability curves was changed because the version 1.2.5a order statistics methodology gave inconsistent results when comparing change in parameters as a function of the equivalent length of record. HEC-FDA 1.4 contains two different methodologies: 1) the “simple method” and 2) the “less simple method” with two variations. The new methods provide a solution to the problem while calculating reasonable confidence limits about graphical curves.

4. The FRM-PCX review of HEC-FDA 1.4 will focus on the change in methodology for computing uncertainty about graphical probability curves, as outlined in the attached model review plan. HEC is in the process of updating the model documentation prepared for earlier versions of HEC-FDA to reflect changes in version 1.4. This documentation will be completed prior to initiation of the model review and can be provided to HQUSACE upon request.

5. Please coordinate the subject model review plan with CECW-PC and the HQ Model Certification Team. Upon HQUSACE approval of the model review plan, the FRM-PCX will assemble the model review team and initiate the review in accordance with the review plan. If there are any questions regarding the review plan or the model, please contact me at (415) 503-6852.

Encl

Eric Thaut
Deputy Director, FRM-PCX

NOTE: The Model Review Plan was verbally approved by the Model Certification HQ Panel on 4 June 2013.

9 May 2013

Model Review Plan
HEC-FDA (Flood Damage Reduction Analysis)
Version 1.4

1. Purpose: The purpose of this model review plan is to outline the requirements necessary for review of the HEC-FDA 1.4 (Flood Damage Reduction Analysis) model as submitted from the Hydrologic Engineering Center (CEIWR-HEC) to the Flood Risk Management Planning Center of Expertise (FRM PCX) in support of the certification of the model for use in Civil Works planning studies. The technical quality, system quality, and usability of the model will be reviewed, as well as its conformance with current U.S. Army Corps of Engineers (USACE) policy.

2. References and Guidance: This document is in accordance with standards, procedures and guidance of USACE. The approval process will be evaluated by the guidance established in Engineering Circular (EC) 1105-2-412, dated 31 March 2011.

3. Background: HEC-FDA is a planning model for flood risk management studies and was developed through collaborative research between Institute for Water Resources (IWR) and CEIWR-HEC. HEC-FDA has been designed to be an analytical tool used for formulation and evaluating flood risk management plans using risk analysis methods.

HEC-FDA continues to be refined by HEC and its current incarnation has been on the HEC website since 2000, which means it has been exposed to numerous informal reviews and its capabilities and limitations are well understood by the users and the developers. Version 1.2.4 of HEC-FDA was certified in March 2009; and Version 1.2.5a was certified in June 2011.

FDA version 1.4 is intended as the last version using the Galaxy platform, which is obsolete and difficult to support in contemporary versions of Windows. The version 2.0 of FDA currently under development uses the same computational libraries as FDA 1.4, but with a Java-based interface. Much "housecleaning" work went into re-organizing and refining the computational and interface components in FDA 1.4, in order to prepare for a seamless replacement of the interface components. The overhaul also resulted in more robust performance than the previous version (i.e., fewer frustrating "glitches"). These internal improvements are listed in the attached Release Notes. They carry little or no effect on results.

FDA version 1.4 also brings one very significant computational refinement in the replacement of the algorithm for computing uncertainty about graphical probability curves. The methodology for computing uncertainty about graphical probability curves was changed because the version 1.2.5a order statistics methodology gave inconsistent results when comparing change in parameters as a function of the equivalent length of record. FDA version 1.4 contains two different methodologies: 1) the "simple method" and 2) the "less simple method" with two variations. The new methods provide a solution to the problem while calculating reasonable confidence limits about graphical curves. HEC recommends standardization on the Less Simple method, as explained in the Certification Report and white paper described below.

4. Certification Documentation: Significant documentation (User Manuals, Certification Report, etc.) already exists for HEC-FDA, and has been updated as needed by HEC for version 1.4. The User Manual has been updated and a draft Certification Report for Version 1.4 has been prepared, based on the reports for prior versions. The certification report addresses testing processes and quality control procedures to used to ensure that the internal improvements introduced no unintended results. It also explains the improvements to the graphical frequency analysis and the significance of the changes to Corps flood risk analyses. Finally, the certification report will address transition between versions 1.2.5a and 1.4, such as when it is appropriate to convert a study to the new version, or when to complete a study using version 1.2.5a.

The certification documentation will be reviewed by a panel of experts designated by the FRM-PCX. This panel could come to HEC or interact during their review of the certification documentation virtually. Documents to be provided include:

- Copy of software and example data model sets
- Revised manual and summary of significant revisions
- White paper explaining desirability of the Less Simple method
- Updated Certification report *(showing changes to prior cert report)*
- Description of testing plan (testing results available on request)
- Description of Standard HEC Documentation and Software QA/QC process

HEC has performed considerable testing of the alternate graphical uncertainty methods on model datasets for numerous Corps flood risk management projects. Results will be available to reviewers on request.

5. Level and Scope of Review: The level and scope of review are determined collaboratively by the PCX performing the model review, the proponent requesting model approval, and by Headquarters (CECW-P); level and scope, in turn, are mostly determined by the model category and level of review as determined by criteria outlined in EC 1105-2-412. Following the definitions in EC 1105-2-412, HEC-FDA is intended for certification as a corporate model, in that it has been developed by a USACE laboratory or FOA and has nationwide implementation.

HEC-FDA is a highly complex model compiled in a specialized programming language and contains multiple routines and computational functions. There is considered to be a high risk associated with investment decision-making based on the output of the model, since in most applications it will be used to evaluate flood risk management projects, used as an alternative analysis tool, and secondarily to be used for levee certification. The overall complexity of the model is offset by the long history of successful use on Corps studies and the limited nature of the changes from the previous certified version (1.2.5a) and the current version (1.4). Following these characterizations, a Level 4 review, as defined by EC 1105-2-412, is recommended as for HEC-FDA.

The proposed focus areas for the review are:

- Are quality control procedures adequate regarding the internal improvements, i.e., based on the provided quality control documentation, do the reviewers concur that the code changes were properly tested and likely cause no inadvertent differences in results?
- Do the reviewers agree with the replacement of the version 1.2.5 Ordered Statistics method with the version 1.4 Less Simple Ordered Statistics method? If not, would they support replacement

with the version 1.4 Simple method?
- Are the updates to documentation clear and complete?

6. FRM-PCX Review Team Composition: In collaboration with HEC, the FRM-PCX has identified two USACE subject matter experts and one external subject matter expert to serve on the review panel. The USACE hydrology and economics experts bring experience regarding the HEC-FDA use of flow- or stage-frequency information and corresponding uncertainty estimates, and thorough understanding of potential effects on project performance calculations. The external expert, Dr. Jery Stedinger, is a professor in Cornell's School of Civil and Environmental Engineering, has experience with both the USACE and U.S. Geological Survey. His research has focused on statistical issues in hydrology and optimal operation of water resource systems and he offers authority and credibility regarding statistical techniques for flood frequency analysis and associated uncertainty. The proposed review panel members are presented below.

Name	**Duty Station**	**Phone**	**Email**
Brian Maestri, Economist	MVN	(504) 862-1915	Brian.T.Maestri@usace.army.mil
Craig Loftin, Hydrology	SWF	(817) 886-1683	Craig.H.Loftin@usace.army.mil
Dr. Jery Stedinger	*Cornell University*	(607) 255-2351	Jrs5@cornell.edu

The experience and qualifications of each reviewer can be provided upon request and will be included in the final model review report.

7. Schedule of Deliverables: The following depicts the expected schedule for conducting the HEC-FDA Version 1.4 Model Review.

TASK	**Scheduled Date**	**Actual Date**
Proponent Submits Model and Draft Supporting Documentation to PCX	15Jan2013	15Jan2013
Initial Teleconference with Proponent to Discuss Scope of Model Review	15Jan2013	15Jan2013
Initiate Development of Model Review Plan	5Feb2013	5Feb2013
Teleconference to Finalize the Review Plan and Supporting Documentation with Proponent and PCX	2May2013	2 May 2013
Submit Final Model Review Plan through Planning CoP to CECW-P for Approval	9May2013	9 May2013
CECW-P Approves Model Review Plan	7 Jun2013	
Assemble Review Team and Initiate Model Review	10 Jun2013	
Initial Teleconference between PCX, Proponent, Reviewers and CECW-P to Discuss the Review	12Jun2013	
Reviewer(s) Submits Comments in Dr. Checks	10Jul2013	
Proponent Provides Initial Responses to Comments in Dr. Checks	24Jul2013	
Checkpoint Teleconference between PCX, Proponent, Reviewers, and	31Jul2013	

TASK	Scheduled Date	Actual Date
CECW-P to Discuss Comments, Responses, and Required Actions to Support PCX Recommendation of the Model for Certification		
Proponent Provides Final Responses to Comments in Dr. Checks and Completes/Submits Plan to Address Required Actions	14Aug2013	
External and Corps Reviewer Back Check Comments in Dr. Checks	21Aug2013	
Review Team Completes the Review Documentation, Including Summary of the Review and Recommendations of the Review Team	28Aug2013	
PCX Submittal of Recommendation for Approval of the Model to CECW-P for Approval	4Sep2013	
HQUSACE Approval Decision Memorandum provided to Proponent	2Oct2013	

8. Cost Estimate. The estimated PCX costs to manage and conduct the model review are summarized below:

PCX Deputy Director

Task	Proposed Hrs	Proposed Cost
Finalize the Model Review Plan (draft prepared by proponent)	8	$1,200
PCX Submittal of Model Certification Plan Model to CECW-P for Approval	4	$600
Finalize the Charge to Reviewers and Participate in Review Meetings	12	$1,800
Identify Required Actions for PCX Recommendation to Approve Model	8	$1,200
PCX Submittal of Recommendation for Approval of the Model to CECW-P for Approval	4	$600
Subtotal	**36**	**$5,400**

Review Team Coordinator

Task	Proposed Hrs	Proposed Cost
Manage Execution of Model Review	16	$2,400
Coordinate Preparation of the Review Report	16	$2,400
Subtotal	**32**	**$4.800**

Internal Team Member (2 Reviewers)

Task	Proposed Hrs	Proposed Cost
Conduct Model Review	80	$12,000
Submit Comments in Dr. Checks and Participate in Review Meetings	24	$3,600
Coordinate Comment Resolution and Complete Back Check in Dr. Checks	16	$2,400
Provide input to Review Report	16	$2,400
Subtotal	**136**	**$20,400**

External Team Member (1 Reviewer)

Task	Proposed Hrs	Proposed Cost
Conduct Model Review	50	$10000
Submit Comments and Participate in Review Meetings	12	$2,400
Coordinate Comment Resolution and Complete Back Check	8	$1,600
Provide input to Review Report	8	$1,600
Subtotal	**78**	**$15,600**

TOTAL REVIEW COST	**282**	**$46,200**

The estimated CEIWR-HEC time to prepare documentation, software, and data sets, and respond to PCX panel are approximately 3 weeks depending on CEIWR-HEC and PCX coordination requirements. The cost estimate is approximately $15,000 based on an average hourly rate of $150.

attachment **b**:

Model Documentation

including Certification Report, Summary Report and White Paper

US Army Corps
of Engineers
Hydrologic Engineering Center

Certification Report

HEC-FDA, Flood Damage Reduction Analysis Software

June 2013

Model Name:	HEC-FDA
Functional Area:	Flood Risk Management
Model Proponent:	Harry Kitch, HQ
Model Developer/Contact:	CEIWR-HEC
Year Developed:	Current version 1.4

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Appendices

Appendix C – Monte Carlo Simulation (continued)

Abbreviations

EC	Engineer Circular
EGM	Economic Guidance Memorandum
EM	Engineer Manual
ER	Engineer Regulation
ERDC	Engineer Research and Development Center (USACE)
ETL	Engineer Technical Letter
FCSDR	Flood & Coastal Storm Damage Reduction
FEMA	Federal Emergency Management Agency
FOA	Field Operating Activity
GIS	Geographic Information System
HEC	Hydrologic Engineering Center
HEC-FDA	Flood Damage Reduction Analysis
IWR	Institute for Water Resources
LP3	Log Pearson Type III
NCR	National Research Council
PCX	Planning Center of Expertise
PF	Probability of Failure
PMIP	Planning Models Improvement Program
PRA	Portfolio Risk Assessment
PROSPECT	Proponent-Sponsored Engineer Corps Training Program
USACE	United States Army Corps of Engineers

SECTION 1

Introduction

1.1 Model Purpose

HEC-FDA (subsequently referred to as "the model") is a planning model for flood risk management studies and was developed through collaborative research between Institute for Water Resources (IWR) and Hydrologic Engineering Center (HEC). HEC-FDA has been designed to be an analytical tool used for formulation and evaluating flood risk management plans using risk analysis methods.

In accordance with the Planning Models Improvement Program (PMIP): Model Certification (USACE Engineer Circular No. 1105-2-412, March 2011), certification is required for all planning models developed and/or used by the US Army Corps of Engineers (USACE). The objective of model certification is to ensure that models used by USACE are technically and theoretically sound, computationally accurate, and in compliance with USACE planning policy.

1.2 Model Certification

The model has been reviewed in accordance with requirements for the certification of planning models as identified in EC 1105-2-412 and "Protocols for Certification of Planning Models", under the Planning Models Improvement Program.

Following the definitions in EC 1105-2-412, HEC-FDA is intended for certification as a Corporate Model, in that it has been developed by a USACE laboratory or field operating activity (FOA) and has nationwide implementation. HEC-FDA was developed at HEC, an FOA, and as shown by the results of the PMIP survey, has nationwide implementation.

Levels of effort required in the certification of planning models vary according to the nature of the model to be reviewed. HEC-FDA is a highly complex model compiled in a specialized programming language and contains multiple routines and computational functions. There is considered to be a high risk associated with investment decision-making based on the output of the model, since in most applications it will be used to evaluate flood risk management projects, used as an alternative analysis tool, and secondarily to be used for levee certification. Following these characterizations, a Level 4 review, as defined by the PMIP protocols, is appropriate for HEC-FDA. In accordance with these protocols, the review team may consist of internal experts as deemed appropriate by the Flood Damage Reduction Planning Center of Expertise (PCX).

This report presents the methodology and results of the review and certification process and will make recommendations affecting the level of certification appropriate for the current version of the model (Version 1.4). HEC-FDA is intended for certification as a USACE Corporate Model.

1.3 Contribution to Planning Effort

USACE requires the use of risk analysis procedures for formulating and evaluating flood risk management measures. Such projects are generally only authorized and implemented when they are economically justified, that is, when the predicted benefits can be demonstrated to exceed the estimated costs. The required analysis involves the estimation of benefits and costs under different alternatives over a project analysis period, while taking into account the probabilistic nature of storm damage, and the uncertainty regarding the measurement of many input variables. Benefits are derived by comparing the expected damages when a flood damage protection project is in place (the "with project" condition) with the expected damages in the absence of any project (the "without project" condition). HEC-FDA is intended to provide users in the planning community with a standard analytical tool to calculate flood damages and benefits under these conditions.

1.4 Report Organization

The report is organized as follows: an overview of HEC-FDA and description of the model, its inputs, key functions, components and elements are provided in Section 2; Section 3 presents the model evaluation, including the certification criteria, model testing approach and model assessment; and Section 4 presents conclusions and recommendations.

SECTION 2

Model Description

2.1 Model Overview

2.1.1 Model Approach

HEC-FDA allows the user to perform plan formulation and project performance for flood risk management studies. Both economic flood damage and hydrologic engineering analyses are performed using a consistent study configuration (streams, damage reaches, plans, and analysis years). Three types of evaluations are available: expected annual damage (EAD), equivalent annual damage, and project performance by analysis years. Computations and display of results are consistent with technical procedures described in EM 1110-2-1619 and ER 1105-2-101.

The HEC-FDA software provides the capability to perform an integrated hydrologic engineering and economic analysis during the formulation and evaluation of flood risk management plans. The software follows functional elements of a study involving coordinated study layout and configuration, hydrologic engineering analyses, economic analyses, and plan formulation and evaluation. The model will be used continuously throughout the planning process as the study evolves from the base year without-project condition analysis through the analyses of alternative plans over their project life. Hydrologic engineering and economics (flood inundation damage analyses) are performed separately, in a coordinated manner after specifying the study configuration and layout, and merged for the formulation and evaluation of the potential flood risk management plans.

USACE requires the use of risk analysis procedures for formulating and evaluating flood risk management measures (ER 1105-2-101). They quantify uncertainty in discharge-exceedance probability, stage-discharge, stage-damage functions, geotechnical probability of failure relationship, and incorporate it into economic and engineering performance analyses of alternatives. The process applies Monte Carlo simulation, a numerical-analysis procedure that computes the expected value of damage while explicitly accounting for the uncertainty in the basic parameters used to determine flood inundation damage. HEC has developed the HEC-FDA software to assist in analyzing flood risk management plans using these procedures. Expected and/or equivalent annual damage are computed in the evaluation portion of the program.

2.1.2 Model Inputs

HEC-FDA requires a significant amount of data from external sources, and the input data requirements vary according to the size of a study. The following provides a basic outline of the individual datasets required by HEC-FDA. These inputs are described in more detail in Section 2.2.

- Study Configuration Data – the basic data defined for a study area; the physical stream locations (streams, damage reaches) and specific plans (analysis years, plans). This is data that is common for all analyses, and is required for an assignment in HEC-FDA which is an integral part of the model.
- Water Surface Profiles– a water surface profile set must consist of eight flood events and can be discharge- or stage-based for each stream in the study area. Water surface profile data may be used to develop discharge-probability functions, stage-discharge functions, and stage-damage functions.
- Exceedance Probability Functions – for economic and performance analyses an exceedance probability function is required. An exceedance probability function is the relationship between flood magnitude and the probability of exceeding that magnitude. This data maybe defined in terms of discharge (flow) or stage. This relationship can be defined through statistical or hydrologic analyses.
- Regulation Inflow-Outflow Functions – for reservoir operation and modification to unregulated exceedance probability function (if using flow). In the model this is referred to as the transform flow relationship and is entered with a defined exceedance probability function. This functions is used to define a relationship between unregulated and regulated flow, inflow and outflow, or another relationship to transform the flow defined by the exceedance probability function.
- Stage-Discharge Functions – stage-discharge functions are required when an exceedance probability function is defined in terms of discharge. The stage discharge function is used to transform the discharge into stage (and subsequently damage) for each probability. A stage-discharge function is the relationship between discharge (flow) at a river cross-section and the stage (depth) produced by that discharge. This relationship can be defined through a gage or hydraulic analysis.
- Levee Data – levee data includes the top of levee stage, failure characteristics, interior versus exterior stage relationships associated with the levee, or wave overtopping criteria.
- Damage Categories – damage category data includes a name, description, and price index (updates the monetary values of the structure that will be assigned to a damage category).
- Structure Occupancy Type Data – structure occupancy type data includes depth-percent damage functions (structure, content, and other); content-to-structure value ratio; and, the uncertainties in the first floor elevation, value ratios, and the damage in the depth-damage functions.
- Structure Modules – structure module data includes a name, a description, and an assignment to a plan and analysis year.
- Structure Inventory Data – a structure inventory is a record of the attributes of unique or groups of structures relevant to flood damage analysis. Structure inventory data is used to compute an aggregated stage-damage function by damage category at the damage reach index location station.
- Stage-Damage Functions – stage-damage functions are the relationship of direct economic costs caused by flood inundation to a range of flood stages for a given stream or damage reach. The model can compute stage-damage functions, if depth-percent damage functions, water surface profiles, exceedance probability functions, stage-discharge functions, first floor elevations, structure and content values are provided.

The basic relationships between the most signification sets of HEC-FDA input data are shown in Figure 1.

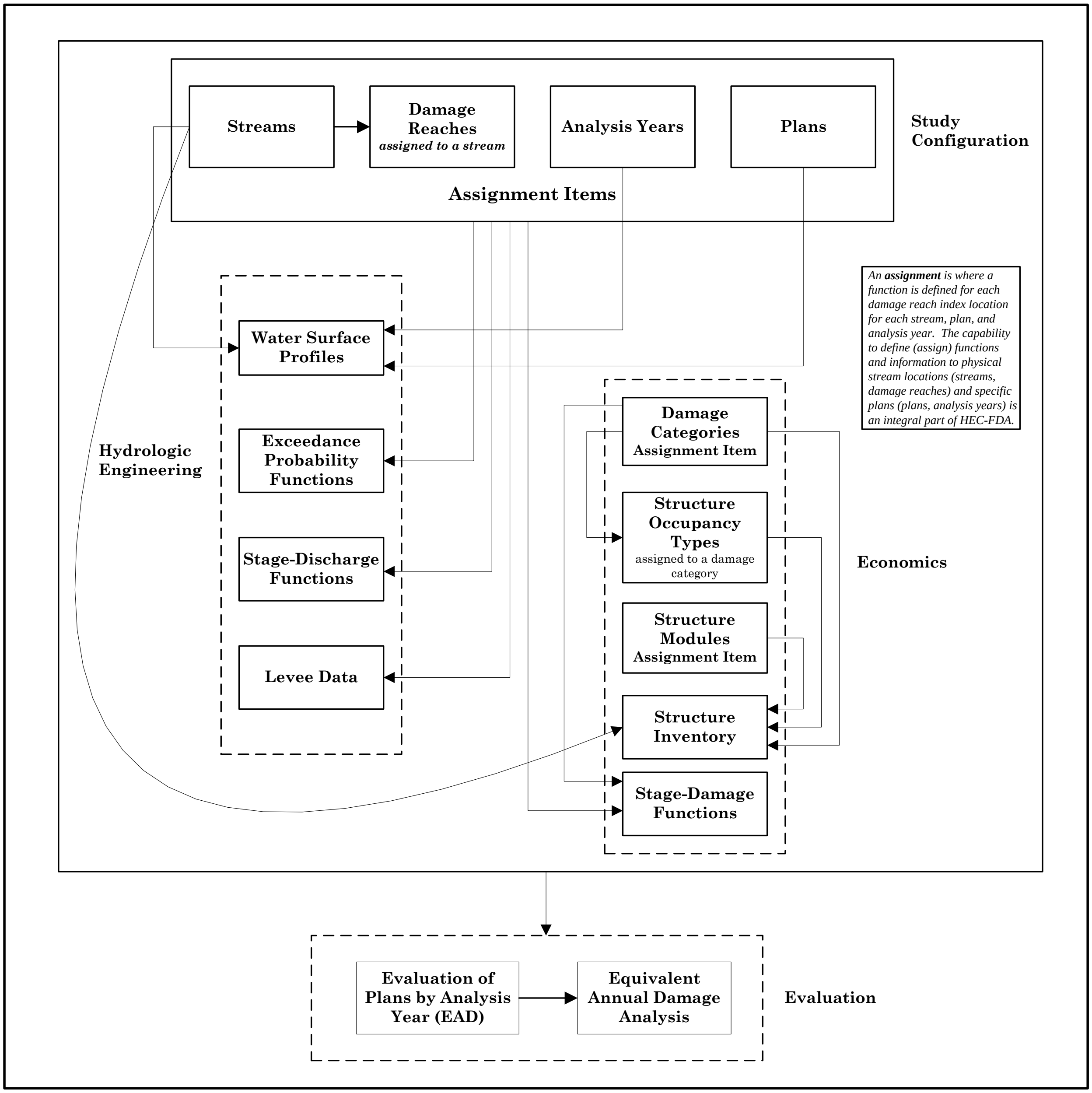

Figure 1 Relationship of Basic Data and Assignments

2.1.3 Model Outputs

HEC-FDA has several different types of output; most of this output is stored in database files, with some being saved to ASCII text files. For most of the input data, there is some form of output that is generated, since the model can generate a certain number of the functions (exceedance probability, stage-discharge, functions associated with a levee, and stage-damage functions). The output is displayed visually in the form of either plots or in a tabular format.

- Study Configuration Data – the output for this data is reports from the interface that list the entered streams, damages reaches, plans, and analysis years. For further details on output reports for streams, damage reaches, plans, and analysis years, see Chapter 3 of the HEC-FDA User's Manual (January 2013).
- Water Surface Profiles– output for this data item includes a list of entered water surface profile sets, a plot and tabular report for an individual water surface profile set, and a report that lists what water surface profile set is assigned to a plan, analysis year, and stream. For further details on output reports for water surface profiles, see Chapter 4 (Sections 4.6, 4.7, 4.8, and 4.10) of the HEC-FDA User's Manual (January 2013).
- Exceedance Probability Functions – if the user has chosen to create an exceedance probability function either from a water surface profile set, or from a statistical method, the generated probability function with uncertainty is displayed in the interface (results are saved to the database). Other available output is a list of all exceedance probability functions defined for a study, a plot and tabular report for an individual exceedance probability function, and a report that lists what exceedance probability function is assigned to a plan, analysis year, stream, and damage reach. For further details on output reports for exceedance probability functions, see Chapter 5 (Sections 5.5, 5.6, 5.7, and 5.9) of the HEC-FDA User's Manual (January 2013).
- Stage-Discharge Functions – if the user has chosen to create a stage-discharge function from a water surface profile set, the generated stage-discharge function is displayed in the interface. Also, from the interface the user can calculate the uncertainty associated with a stage-discharge function which is also displayed in the interface (results are saved to the database). Other available output is a list of all stage-discharge functions defined for a study, a plot and tabular report for an individual stage-discharge function, and a report that lists what stage-discharge function is assigned to a plan, analysis year, stream, and damage reach. For further details on output reports for exceedance probability functions, see Chapter 6 (Sections 6.4, 6.5, 6.6, and 6.8) of the HEC-FDA User's Manual (January 2013).
- Levee Data – for general levee data, the output consists of a report that lists the entered levees for a study, and a report that lists what levee is assigned to a plan, analysis year, stream, and damage reach. Other available output for a levee includes an exterior/interior relationship if defined, geotechnical probability of failure relationship if defined, and/or wave overtopping if defined. For each of these relationships the user can find output in the form of plots or tabular reports. For further details on output reports for levees, see Chapter 7 of the HEC-FDA User's Manual (January 2013).
- Damage Categories – for damage categories output consists of a report that lists the entered damage categories for a study. For further details on this report, see Chapter 8, Section 8.2.5, of the HEC-FDA User's Manual (January 2013).
- Structure Occupancy Type Data – output for structure occupancy type data includes a report that lists the entered structure occupancy types for a study, along with what damage category each structure occupancy type is assigned. Also, output available for each type of depth-percent damage function (structure, content, and other) consists of plots and tabular reports. For further details on output reports for structure occupancy types and depth-percent damage functions, see Chapter 9 of the HEC-FDA User's Manual (January 2013).
- Structure Modules – for structures modules output consists of a report that lists the structure modules for a study, and a report that lists what structure module is assigned to a plan and analysis year. For further details on output reports for structure modules, see Chapter 10 (Sections 10.5 and 10.7) of the HEC-FDA User's Manual (January 2013).

- Structure Inventory – structure inventory output consists of a report that lists the entire structure inventory for a study, plus a report that lists for each structure the assignment of a damage category, structure occupancy type, stream, and structure module. If the structure has a specific depth-damage function (structure, content, and other) output also includes plots and tabular reports. For further details on output reports for structure inventory data, see Chapter 11 of the HEC-FDA User's Manual (January 2013).
- Stage-Damage Functions – if the user has chosen to create stage-damage functions, the generated stage-damage function with uncertainty is displayed in the interface (results are saved to the database). Other available output is a list of all stage-damage functions for a study, a plot and tabular report for an individual stage-damage function, and a report that lists what stage-damage function is assigned to a plan, analysis year, damage category, stream, and damage reach. For further details on output reports for stage-damage functions, see Chapter 12 (Sections 12.4, 12.5, 12.6, and 12.8) of the HEC-FDA User's Manual (January 2013).

The model also has output that is related to the results from the computations, these results are – Damage by Analysis Years (expected annual damage), Equivalent Annual Damage Analysis, and Project Performance. These reports are consistent with requirements of USACE planning regulations for formulation and evaluation of flood risk management. Display of model results are consistent with technical procedures described in EM 110-2-1619.

1) **Damage by Analysis Year Reports** – these reports display the results of the evaluation of plans by analysis year, and are consistent with requirements of USACE planning regulations for formulation and evaluation of flood risk management plans; i.e., the results of expected annual damage (EAD) analysis. For further details on the Damage by Analysis Year Reports, see Chapter 14 of the HEC-FDA User's Manual (January 2013). There are three groups of reports available:

   <u>General Information Reports</u> – the reports from this group provide information on what plans and analysis years were used for the computation of EAD (Data Management Summary), the Monte Carlo simulation by plan, analysis year, stream, and damage reach (Monte Carlo Analysis Summary), and warning information for each model compute (Warning Message Log). For the Monte Carlo Analysis Summary, output includes results in plots and tabular reports.

   <u>Damage Reach Summaries</u> – these reports provide information about the probability functions. These functions are the "average" curves from the Monte Carlo simulation and should not be used for analytical purposes. When the user requests the model not to compute EAD, then these reports are not available. There are four different types of probability function reports: discharge-probability, stage-probability, damage-probability, and damage reduced-probability. The output is by damage reach assigned to a specific plan, analysis, and stream, with results in plots and tabular reports.

   <u>Expected Annual Damage</u> – the expected annual damage reports provide information on the calculated EAD. There are four reports available for EAD: EAD by damage categories; EAD damage reduced distribution; EAD by plans and analysis years, and EAD by analysis years.

EAD by Damage Categories – there are two reports, one report that displays the total damage by plans for a selected analysis year and the other report displays the total damage by damage reaches for a selected plan and analysis year.

EAD Damage Reduction Distribution - there are two reports, one report that displays the EAD for the without- and with-project conditions as well as the damage reduced for a selected analysis year. The report also displays the distribution of EAD reduced by plan in terms of the probability that the damage reduced exceeds a value for the probabilities of .75, .50, and .25. The other report displays the EAD for the without- and with-project conditions as well as the damage reduced for a selected analysis year. The report also displays the distribution of EAD reduced by damage reach in terms of the probability that the damage reduced exceeds a value for the probabilities of .75, .50, and .25.

EAD by Plan and Analysis Years – this report displays the EAD values for the base year and the most likely future year.

EAD by Analysis Years – this report summarizes EAD by damage reach for the based and most likely future years for a selected plan.

2) **Equivalent Annual Damage Analysis Reports** – these reports display the results of the equivalent annual damage computations, and are consistent with requirements of USACE planning regulations for formulation and evaluation of flood risk management plans. For further details on the Equivalent Annual Damage Analysis Reports, see Chapter 15, Section 15.1, of the HEC-FDA User's Manual (January 2013). There are two groups of reports available:

General Information Report – this report provides information on what plan were used for the computation of equivalent annual damage (Data Management Summary).

Summary Reports – these reports display the equivalent annual damage reduced and distributed (Reduced and Distribution), and equivalent annual damage by damage category (By Damage Categories).

Reduced and Distribution – there are two reports, one that displays the equivalent annual damage calculated for the without- and with-project conditions and the associated damage reduced by plan. Also, displays the distribution of equivalent annual damage reduced by plan in terms of the probability that the damage reduced exceeds a value for the probabilities of .75, .50, and .25. The other report displays the equivalent annual damage calculated for the without- and with-project conditions and the associated damage reduced for a plan by damage reach. Also, displays the distribution of equivalent annual damage reduced by plan in terms of the probability that the damage reduced exceeds a value for the probabilities of .75, .50, and .25.

By Damage Categories – there are two reports, one that displays the equivalent annual damage for individual damage categories by plan. The other report displays the equivalent annual damage for individual damage categories for a selected plan by damage reach.

3) **Project Performance Reports** – these reports display the information about the hydrologic/hydraulic performance of a plan. For further details on the Project Performance Reports, see Chapter 15, Section 15.2, of the HEC-FDA User's Manual (January 2013). There are three types of reports available:

Target Stages by Damage Reach – this report lists target stages by damage reach and analysis year for a selected plan. The target stage is the stage at which a percentage of the specified event's damages occur. To ensure consistency with various damage reaches, the target stage is determined as the stage associated with the percent of residual damage of a specific exceendance probability event. That is the stage where 5% damage for the 1% chance exceedance event occurs. For levees or floodwalls without geotechnical failure, the top of the project (levee) is the target stage. For levees with geotechnical failure, there is no single value for the target stage and project performance is computed based on the joint probability of annual exceedance and probability of geotechnical failure. For damage reaches that don't have levees, target stage is the stage typically associated with the start of significant damage for the with-project conditions.

Project Performance by Damage Reach – this report displays the results of project performance by damage reach for a selected plan and analysis year. This report displays:

Target Stage Annual Exceedance Probability which is the median and expected annual exceedance probabilities associated with the target stage. The median value is computed from either discharge-probability and stage-discharge functions, or from a stage-probability function. The expected value is computed from results of the Monte Carlo simulation.

Long-Term Risk which is the probability of the target stage being exceeded at least once in a 10-, 30-, and 50-year period.

Conditional Non-Exceedance Probability by Events is the assurance of containing the specific .10, .04, .02, .01, .004, and .002 exceedance probability event within the target stage, should that event occur.

Project Performance by Plan and Damage Reach – this report displays the results of project performance by plan and damage reach for a selected analysis year. This report displays:

Target Stage Annual Exceedance Probability which is the median and expected annual exceedance probabilities associated with the target stage. The median value is computed from either discharge-probability and stage-discharge functions, or from a stage-probability function. The expected value is computed from results of the Monte Carlo simulation.

Long-Term Risk which is the probability of the target stage being exceeded at least once in a 10-, 30-, and 50-year period.

Conditional Non-Exceedance Probability by Events is the assurance of containing the specific .10, .04, .02, .01, .004, and .002 exceedance probability event within the target stage, should that event occur.

Finally, the model also has results that are not available through the model interface; these results are written to ASCII text files or to a DSS file. The user must view these from outside of the HEC-FDA software.

1) Fda_EadTrace.out – this ASCII text file is created whenever a study is opened. The model will append debugging information to this file until the study is closed. This file contains debugging information that is useful only to program support people.

2) FdaResults.txt – when a report is displayed in the model an ASCII tab delimited file is also created for that report. This file enables the user to edit the file from another software program for formatting and inclusion in reports. All model reports are written to this file except for the general information reports. The model will append each report to this file until the study is closed. To view this file, since this is an ASCII text file the user can open this file with most word processing software packages, spreadsheet software packages, Notepad®, or WordPad®. To view with Notepad®, execute the Notepad® software, from the File menu, click Open, and browse to the study directory. From there open the FdaResults.txt file, see Figure 2 for the results.

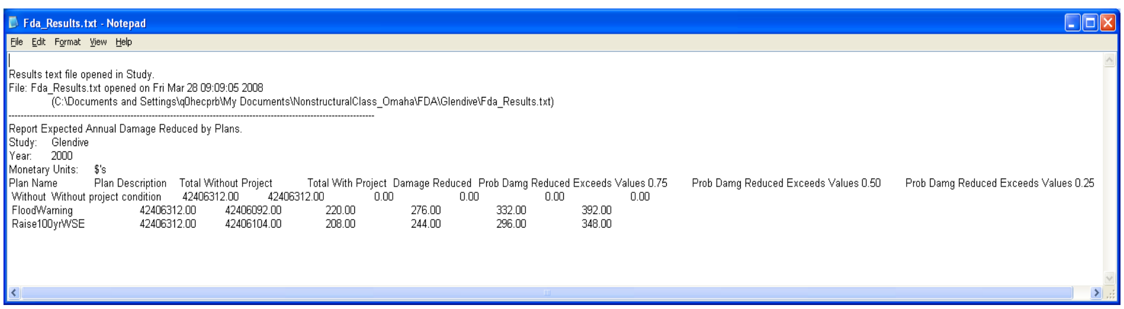

Figure 2 Example of Viewing HEC-FDA Results (text files) from Another Software Package

3) Fda_EadSimResults.dss – when the model computes expected annual damage, several types of data are written to an HEC-DSS data file – Fda_EadSimResults.dss. The data written includes user input functions such as a graphical probability function as well as output such as the relative frequency of expected annual damage. Since this result file is a DSS data file, the user will need to have the HEC-DSSVue (HEC Data Storage System Visual Utility Engine) software to view results (Figure 3).

2.2 Model Components

The supplied version of HEC-FDA has been reviewed for technical quality by the HEC-FDA development team. The model was grouped by functions and applications under four headings, which may be considered to be the four key computational components or elements of the model. Each component area was then examined separately and specific technical quality tests were developed to examine the workings and processes within each one. The quality tests included testing the ability to input data; verifying that the computational engines of the model worked,

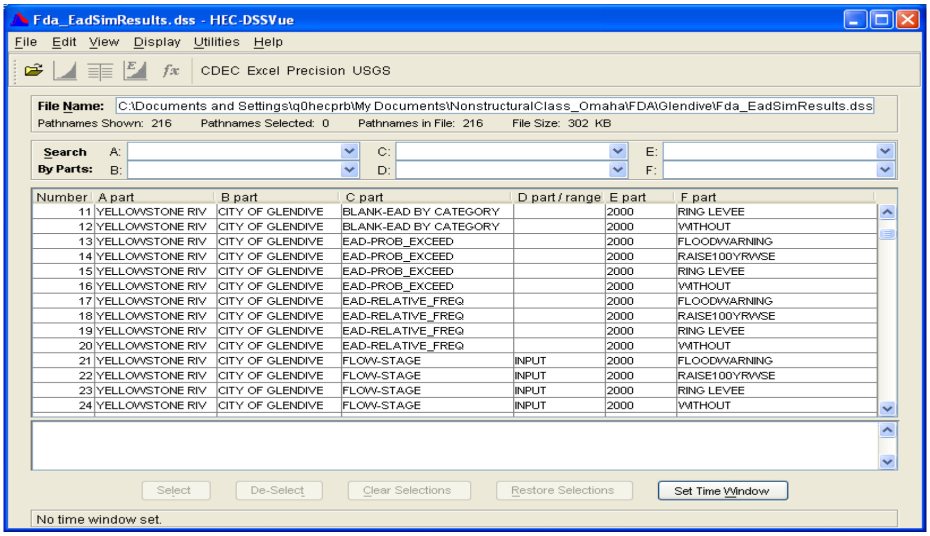

Figure 3 Viewing an HEC-FDA DSS File

and testing the output for correctness and the ability to view. These quality tests were run by the HEC-FDA development team. The four components of the model that were identified for technical examination are:

- Study Configuration
- Hydrologic Engineering
- Economics
- Evaluation

These components are described in more detail in the following sub-sections, and in further detail in the subsequent sections of this report which cover specific tests and investigations. Other aspects of the modes, such as hardware and software requirements, user interfaces, graphics displays, results, and supporting documentation have been subject to general usage rather than systematic testing for system quality and usability that has developed and evolved as the review and certification process progressed.

2.2.1 HEC-FDA Component One: Study Configuration

This component, Study Configuration, is where the physical study layout and the definition of the plans for analysis are configured for the study. This data is common for all analyses, and is built in a team environment, with the team agreeing on the study configuration. Data items under the study configuration are likely not to change during a study. Data includes streams, damage reaches, plans and analysis years.

Streams include various water bodies and are defined for the study, and therefore common for all plans and analyses. A study can have more than one stream, and a stream stationing convention must be adopted for the study. This stream stationing is used to define damage reach boundaries, damage reach index locations, water surface profiles, cross-sectional locations, and structure locations. Streams are defined by a name, with an optional description.

Damage reaches are specific geographical areas within a floodplain and are used to define consistent data for plan evaluations, and to aggregate structure and other potential flood inundation damage information by stage of flooding. Damage reaches are integral to both the hydrologic/hydraulic engineering and economic analyses. Delineation of damage reaches must be consistent with flood risk management measures; also, consideration needs to be consistent with exceedance probability function throughout the damage reach, and jurisdiction boundaries for reporting purposes. A damage reach is defined by assignment to a stream, a name, an optional description, a beginning station (downstream end), an ending station (upstream end), bank location (left, right, both), and an index location.

Plans are a set of one or more flood risk management measures or actions designed to operate over a period of time (project life). A plan is inclusive of the entire study area although it may have a flood risk management measure for a single damage reach. Plans are defined by a name, with an optional description.

An analysis year represents a static time period or year that the hydrologic/hydraulic engineering and economic data must be developed for analyses. Damage and project performance information are defined for each analysis year during the project life, such as the base year (first year of the plan operation) or most likely future year (development projection for a specific future year). The analysis year results are used to compute equivalent annual damage for a plan. Two analysis years are defined – base year and most likely future year, and then the most likely future year results are brought into current dollars with the defined interest rate.

2.2.2 HEC-FDA Component Two: Hydrologic Engineering

The Hydrologic Engineering component is where hydrology, hydraulics, and levee data are entered for the model analysis. Data includes: water surface profiles, exceedance probability functions, stage-discharge functions, and levee features. The water surface profiles are optional, but are recommended for model analysis. Profiles are required when computing aggregated stage-damage uncertainty functions at damage reach index locations. The water surface profiles must be consistent with discharge-probability and stage-discharge functions required for each plan, analysis year, stream, and damage reach.

A typical user setup for entering hydrologic engineering data would be:

1) A user would import the water surface profiles from either HEC-RAS or HEC-2. For analysis the water surface profiles must consist of eight flood events (.50-, .20-, .10-, .04-, .02-, .01-, .004-, and .002-exceendance probability flood events), and may be either discharge- or stage-based for each stream defined for the study. Stream stationing must be consistent with the damage reach and structure location stationing. A user can directly enter all of the water surface profile data directly into the model.

2) Next the user needs to define the exceedance probability functions that are required for analysis. In order to perform a flood damage analysis that considers flood events of all sizes, a relationship between flood magnitude and the probability of exceeding that magnitude is needed. This relationship is an exceedance probability function, which can

be defined in terms of discharge or stage. An exceedance probability function can be either analytical or graphical (both of these terms are defined below). For either type, the user will also need to provide the equivalent length of record. For gaged areas, equivalent record length is the number of years of a systematic record of recorded peak discharges at the stream gage. For an ungaged location, the equivalent record length is estimated based on the overall "quality" of the exceedance probability function expressed as the number of years-of-record. The equivalent record length is very important because it is directly related to the uncertainty of the exceedance probability function.

Analytical-Exceedance Probability Method – is used when a discharge-exceedance probability functions can be fitted by a Log Pearson Type III distribution. Analytical methods often apply for unregulated discharge-probability functions derived from stream gaged data or modeling. There are two methods of defining analytical discharge-probability functions; the default method is to enter the discharges for the .50, .10, and .01 exceedance probability events along with equivalent record length to compute synthetic statistics. The other method is to enter the Log Pearson Type III statistics – mean, standard deviation, skew, and equivalent record length.

Graphical Exceedance Probability Method – a graphical exceedance probability function is used when an exceedance probability function does not fit the Log Pearson Type III distribution. Typically this method is applicable for regulated flows, stage-exceedance probabilities, and partial duration functions. This method uses an approach termed order statistics. A graphical probability function is defined by specifying the discharge- or stage-probability ordinates and entering the equivalent record length. Ordered events are interpolated from the function based on the equivalent record length and error limit curves determined using order statistics. The final graphical probability function is based on mean or expected values defined by Weibull plotting positions along the curve. When entering data to define graphical probability functions, a number of data points should be used to describe the full range of the function. The ordered events method determines standard errors of points (estimates) along the curve from the relationship of each of the estimates to adjacent points and the slope of the function.

Transform Flow Relationship – for either an analytical or graphical exceedance probability function, this defines a relationship between unregulated and regulated flow, inflow and outflow, or another relationship to transform the flow defined by the exceedance probability function. This transform flow relationship could be the result of reservoir or channel routing, channel diversion, etc. It specifically allows for the isolation of the uncertainty related to the transforming mechanism, while maintaining the uncertainty of the discharge-probability function.

3) For each damage reach that has a discharge-probability function, a stage-discharge function needs to be entered, in order to transform the discharge in stage for each probability. The stage-discharge function should include enough points to define the function with the highest point representing the stage for 0.002 or 0.001 exceedance probabilities. Since the model does not extrapolate the stage-discharge function, a user should estimate a value or values for discharge (with uncertainty) that correspond to rare probabilities. The model will calculate a stage-discharge function based on water surface profiles if available.

4) For damage reaches that include a levee, you can specify levee size, failure characteristics, interior versus exterior stage relationships associated with the levee, or wave overtopping criteria. Following are the relationships that can be entered for a levee:

   Exterior-Interior Relationship – the exterior-interior relationship defines the relationship between water surface stage on the river (exterior side of the levee) versus the stage in the floodplain (interior side of the levee). This relationship is necessary if the stage in the interior will not reach the same stage that is overtopping the levee or from interior drainage issues. This relationship must be developed from hydrologic or hydraulic analyses external to the model. If the relationship is not specified, the assumption is that the floodplain fills to the stage in the river for all events that result in stages that cause levee failure or are above the top of the levee.

   Geotechnical Failure Analysis – this analysis is the relationship between water surface stage on the river (exterior side of the levee) versus the probability of levee failure. This analysis is used anytime the structural integrity of the levee is in doubt in other words, anytime the levee could fail prior to being overtopped. The geotechnical failure relationships are developed from geotechnical analysis according to existing geotechnical guidance.

   Wave Overtopping - this analysis accounts for effects of wave overtopping when analyzing levees, floodwalls, or tidal barriers. For the model this analysis is a wave height versus a still water relationship. Another relationship for wave overtopping is the effective overtopping height and resulting interior stages. These relationships are developed outside of the model using wave overtopping analyses and overtopping volume versus interior stage characteristics.

2.2.3 HEC-FDA Component Three: Economics

The Economics component is where data entry and computations to produce stage-damage functions with uncertainty for flood risk management occurs. Data includes damage categories (need to define at least one), optional structure occupancy types, optional structure modules, optional structure inventory, and stage-damage functions. A typical user setup for entering economic data would be:

1) Create damage categories (maximum of twenty), enough to facilitate detailed reporting. Damage categories are used to consolidate large number of structures into specific categories with similar characteristics for analysis and reports. The model calculates stage-damage on a structure-by-structure basis and aggregates the result for each structure to an index location. Typical damage categories are: residential, commercial, industrial, open space, and public facilities.

2) For each defined damage category, enter structure occupancy type information, however, structure occupancy types are not required. A structure occupancy type describes a class of structures (e.g., single family, no basement, raised foundation, one story) and is a

subcategory of a defined damage category. Data entered for a structure occupancy type includes:

Depth-Percent Damage Functions – a depth-percent damage function represents the damage caused to a structure, the contents of a structure, and "other" (other can be used to compute damage for any other item not accounted for in structure or content value, e.g., automobiles) for given depths of flooding at a structure. The damage is based on a percentage of the total value of the structure, content, and "other" respectively. The percent-damage is multiplied by the structure value, content value, or "other" value to get a unique depth-damage function at the structure. Depth-percent damage functions should always contains a zero damage depth, and negative depths are acceptable. The uncertainty associated with the depth-percent damage function is entered by ordinates based on the specified distribution.

USACE has provided guidance for using generic depth-percent damage functions in flood risk management studies, which is outlined in EGMs 01-03 and 04-01. These are standardized relationships for estimating flood damage and other costs of flooding, based on actual losses from flood events. These functions calculate content damage as a percent of structure value rather than content value. Using these functions within HEC-FDA requires close attention in specifying a content-to-structure value ratio. Refer to the aforementioned EGMs for further details.

Content to Structure Value Ratio – this value is used to estimate the total content value if the structure inventory does not include content value information. The content to structure value ratio is the numeric value, in percent, that represents the content value divided by the structure value for a particular structure occupancy type. The computed content value is then used to proportion the contents depth-percent damage function.

Other to Structure Value Ratio – this value is used to estimate total value of the property represented by other if the structure inventory does not include other value information. The other to structure value ratio is the numeric value, in percent, that represents the maximum other value divided by the maximum structure value for a particular structure occupancy type. The computed content value is then used to proportion the other depth-percent damage function.

Uncertainty Parameters – distributions or uncertainties that are associated with estimating the depth-damage functions, structure values, content value ratios, other value ratios and first flood stage. These are used to develop the total aggregated stage-damage-uncertainty functions by damage categories for a damage reach. These parameters include:

First Floor Stage – the standard deviation in feet (meters) of the uncertainty in the first floor stage estimate of a particular structure occupancy type. This value is based on the procedures/type of surveys used to estimate the first floor stage.

Structure Value – the error associated with structure value is entered as the standard deviation, in percent of structure value, associated with the uncertainty in the structure value estimate for a particular structure occupancy type.

Content/Structure Value – the standard deviation is a percent of the content to structure value ratio. It is associated with the error in estimating the ratio. For example, for a content to structure value ratio of fifty percent, an entered standard deviation of ten percent would mean that the plus/minus one standard deviation range is forty-five to fifty-five percent. When using the generic depth-damage relationships, do not enter a content/structure value.

Other/Structure Value – the standard deviation is a percent of the "other" to structure value ratio. It is associated with the error in estimating the ratio. For example, for a "other" to structure value ratio of fifty percent, an entered standard deviation of ten percent would mean that the plus/minus one standard deviation range is forty-five to fifty-five percent.

3) Create structure modules and assign to a plan and analysis year group. Structure modules allow the user to vary one or more structure characteristics by plan and year or to include or exclude one or more structures from a plan/year. Data entered for structure modules are a name and an optional description. There is a default structure module (Base) and any new structure is automatically assigned to the default structure module. Structure modules must be defined prior to development of a structure inventory.

4) If a study includes a structure inventory the user needs to enter or import a structure inventory. Structure inventories are a record of the attributes of unique or groups of structures relevant to flood risk management analysis. The inventory is used to compute an aggregated stage-damage function by damage category at the damage reach index location station. Required structure attributes include: the name for the structure; stream station; stream; bank designation; structure value; occupancy type; structure module; and structure stages associated with ground or first floor. Optional attributes include: content value; other value; address; coordinates (highly recommended); notes; an image; and additional structure stages for basement type flooding. Structures are assigned to a specific damage category, structure occupancy type, stream, and structure module. The structure module is used to specify which plans and analysis years the structure will be used for damage analysis. The user can enter data directly or import a structure inventory.

5) The final step for this component is the creation of stage-damage functions, which can be entered, calculated by the model, or imported. USACE defines a stage-damage function as the relationship of direct economic costs caused by flood inundation to a range of flood stages for a given river or damage reach. From the model the user can enter stage-damage functions manually or the model will calculate stage-damage functions. For the model to compute stage-damage functions the program requires the following information and the uncertainty about that information: depth-percent damage functions, first floor elevations, and structure and content values. In addition, a complete set of water surface profiles (eight profiles) must be available. Additionally, it is a good idea to have discharge exceedance probability functions and stage-discharge functions for the stage-damage function computations. For the model a complete set of stage-damage functions for all categories, damage reaches, and streams must be entered to analyze a specific plan for an analysis year. The uncertainty is defined only by the normal probability density function.

If there is no uncertainty, the user must select the normal distribution and enter zeros for the standard deviations – don't leave the uncertainty field blank.

2.2.4 HEC-FDA Component Four: Evaluation

The Evaluation component is where a user may review the study status, perform two types of analyses, and view results. The two analysis options are: 1) computation of expected annual damage and project performance (Evaluation of Plans by Analysis Year), and 2) computation of equivalent annual damage over the specified analysis period (project life) for the plan. In general, data developed and displayed under hydrologic engineering and economics represent the best estimates of the median values of the exceedance probability, stage, and damage functions for without- and with-project conditions. Uncertainty parameters of the functions are also developed for study conditions. The analyses performed and results displayed use the median valued functions and associated uncertainties as input to produce expected values as output. The computational procedure used is Monte Carlo.

1) **Evaluation of Plans by Analysis Year** – computation of expected annual damage (EAD) is the first step in the overall computation process. The model combines the exceedance probability functions, stage-discharge functions, and structure inventory data to compute EAD. Plan and damage reach project performance analyses are based on target standards defined for without-project conditions for the study. There are three different cases for determining the target:
    a. For reaches without levees, the target is based on an estimate of the stage at which significant damage begins for the without condition,
    b. For reaches with a levee that have no geotechnical failure, the target is the top of levee stage, and
    c. For reaches with a levee that have geotechnical failure, the target is based on both the annual exceedance probability and the probability of failure.

   For reaches without levees, the standards used by the model are based on the residual damage associated with a specific exceedance probability event. Performance targets are essentially the zero damage stage but normally consider minor damage to the infrastructure as acceptable and significant damage to structures as not acceptable. Consistent criteria for comparing the impacts of different measures and plans are also a goal. Experience at HEC has shown that a 5 percent residual damage associated with the .01 exceedance probability event is normally a good target stage and was adopted as the model default. The user may enter other values if they are deemed better for study conditions. The same values must be used for all calculations.

2) **Equivalent Annual Damage Analysis** – the next step in the compute process is the computation of equivalent annual damage. The expected annual damage computation for the base and most likely future conditions of a plan must be successfully computed before you can compute equivalent annual damage analysis. The flood damages associated with a plan are calculated in average annual equivalent terms. The procedures discount the expected annual damage to the beginning of the period of analysis or the base year. Future year damage values are linearly interpreted between the base and most likely future

year conditions and assumed constant from the most likely future year to the end of the analysis period. The analysis period (project life) is the period of time over which the plan has significant beneficial or adverse effects. It is normally fifty years and is not to exceed 100 years.

2.3 Externally Generated Input Datasets

A feature of HEC-FDA is that in addition to the calculations and formulae which comprise the model, it can take advantage of data from external sources. Water surface profiles sets can be imported from both HEC-2 (Water Surface Profiles, USACE, 1991) and HEC-RAS (River Analysis System, USACE, 2002). Both pieces of software export to an ASCII file, which the model can then import. Most structure inventories are built outside of the model, and are usually stored in some sort of database. Most of these databases allow the exporting of the structure data to ASCII files or in the form of a Microsoft Excel® workbook. Once again, the model can then import the data from an ASCII file.

The USACE Hydrology, Hydraulics and Coastal Community of Practice (HH&C CoP) is the group responsible for addressing the technical subjects of hydrology, hydraulics, and coastal engineering. This group has recommended HEC-RAS as a piece of software for conducting hydraulic studies, and HEC-HMS (Hydrologic Modeling System) as a piece of software for conducting hydrology studies. Both pieces of software have been accepted by the HH&C CoP to provide input to HEC-FDA.

2.4 Model Development Process

A provisional version of HEC-FDA was released in December 1996. This version of the model was released to specific USACE District and Division offices for testing and review. HEC was provided with an extensive list of updates and error fixes. Changes were made, and HEC conducted more in-depth testing. Version 1.0 of the model was released in January 1998 as the first general release of the model. Another updated version (1.1) was released in September 1999.

Version (1.2) of the model released in March 2000. Once again based on comments from users, changes were made to the model. Fixes were as follows:

- Project Performance Reports - the current version of HEC-FDA is reporting the 0.75% event conditional stage for the 1% event conditional stage. A fix has been made which corrects this problem, since the 1% event exceedance can be used for levee certification this fix could impact district results for levee certification.
- Negative Stage Values - a fix for entering negative stage values associated with a graphical stage-exceedance probability function was made.
- Flat Damage-Exceedance Probability Functions - the HEC-FDA program uses the discharge-exceedance probability, stage-discharge, and stage-damage functions to compute a damage-exceedance probability relationship during the calculation of expected annual damage (EAD). If the damage-exceedance probability function is flat, such as the

result of regulated flows or flat terrain, the program reports an error. A fix was made to correctly handle a flat damage-exceedance probability function.
- Study Water Surface Profiles - removed a warning message from this dialog.

Since the March 2000 version, several "unofficial" versions have been created. Updates to the model have included:

- increasing number of damage categories
- fix project performance table
- fix damage-frequency curves
- fix stage-damage computation errors
- created a specific version for USACE offices that extended the probability function to the 10,000 year return period
- fix for user-defined error about probability function; removed length of record
- change limit routine to simple

The current version (1.4) of the model contains the fixes listed above, plus:

- damage reaches may now contain both a geotechnical failure function and an exterior-interior stage function.
- calculations involving geotechnical failure are more accurate but still will not include uncertainty around a stage versus probability of failure (PF) function.
- calculation of "average" probability curves is more accurate
- expected annual exceedance probability has greater accuracy
- long term risk includes a period of 30 years rather than 25 years, because 30 years is the coverage length of a typical mortgage
- fixes in stage-damage calculations: price index is applied to dollars in depth-dollar damage functions; accounts for exterior-interior stages when scaling range of stages for aggregated functions
- import data: probability functions, stage-discharge functions, levee data
- output stored in an HEC-DSS file; will have a section in new User's Manual to tell the user how to access this information
- project performance output tables include levee stage and are flagged for levee/geotechnical

2.5 Model Capabilities and Limitations

HEC-FDA does sampling by function, which is required to compute net benefits and damage reduced, along with distribution of EAD. The model incorporates two USACE approaches to flood risk management analysis – consistency with scientific understanding and a reasonable risk analysis procedure.

During the review of an earlier version of ER 1105-2-101 (Risk Analysis for Flood Damage Reduction Studies), a review of HEC-FDA version 1.2 was also performed by the Water Science and Technology Board, National Research Council (NRC) in 2001. The NRC developed a list of limitations (Table 1), some of which have been addressed in version 1.4 and some that have not.

The NRC felt that the model provided explicit quantification of engineering and economic uncertainties which lead to better projects, provides new techniques which are a significant step forward, and by replacing the former levee freeboard approach, the model provides more consistent results.

Table 1
National Research Council Recommendations

Risk Measures & Modeling	
NRC Comment	**USACE Comments & Actions**
Too many types of engineering performance measures to be understood by citizens.	Concurs; annual exceedance probability (AEP) & uncertainty is calculated by the model.
Conditional non-exceedance probability (CNP) is difficult to understand.	Concurs; USACE will use internally, but will change to assurance.
Quantify each source of uncertainty and properly incorporate uncertainty in analysis.	Concurs; as methods mature, a more complete representation of all uncertainties will evolve; no change to model at this time.
Better define, estimate, and combine uncertainties.	Partially concurs; investigations to define improved approaches will be conducted and implemented; systems approach identified for R&D.
Reduce variation in estimates of water surface profiles.	Concurs; ongoing hydrology and hydraulics activity.
Identify which uncertainties are more important.	Partially concurs; determine is key variables used in risk analysis need to be expanded or modified.
Will Monte Carlo become impractical?	Non-concurrence, Monte Carlo is adequate.
Conduct ex post studies to identify failure modes.	Concurs; need to provide resources to examine projects under field conditions.
Monte Carlo should be performed on a spatial scale.	Partially concurs; compare aggregate reach approach and total system approach; need R&D funds; need to evaluate; probably not easy.
Correlation of random variables should be introduced.	Partially concurs; identify potential correlated variables and assess their importance; need R&D funds; need to evaluate; probably not easy.
Geotechnical Reliability	
NRC Comment	**USACE Comments & Actions**
Evaluate levee as a spatially distributed system.	Concurs; continues to improve this process; conceptually being addressed with PRA program; needs R&D funds.
Conduct ex post studies to identify levee failure modes.	Concurs; provide resources to examine projects under field conditions.
Use the updated geotechnical approach.	Concurs; already added to model.
Natural variability and knowledge uncertainty should be treated differently in Geotechnical modeling.	Concurs; analysis model continue to improve, no action at this time.
Consider flood duration for geotechnical reliability.	Concurs; analysis model continue to improve, no action at this time, but is an on-going effort.
Hydrologic Analysis	
NRC Comment	**USACE Comments & Actions**
Approximation used to generate mean and standard deviation for an LP3 distribution based on expected probability adjustment in 17B has no theoretical justification.	Non-concurrence; develop an estimation methodology which considers the estimation uncertainty in all the LP3 parameters. Methodology needs to be approved by interagency work group on flood frequency analysis; This issue has been debated in the professional literature for twenty years. USACE will continue to follow the established Federal interagency policy.
Can't ignore large uncertainty in skew.	Concurs; investigate method to include skewness uncertainty, and incorporate in analysis methodology as time and resources permit.
Compare synthetic rainfall to observed records to compare error.	Partially concur; will be studied as resources permit; H&H should perform with new R&D funds.
H&H should be randomized at scale of river reach rather than damage reach.	Partially concur; compare aggregate reach approach and total system approach; need R&D funds; need to evaluate; probably not easy.

Table 1 (continued)
National Research Council Recommendations

Economics	
NRC Comment	**USACE Comments & Actions**
Analysis is incorrect because it aggregates structures.	Partially concur; unclear if USACE approach is in error; should evaluate; needs R&D funds; probably not easy.
Analysis ignores the interdependence or correlation among distributions.	Partially concur; real issue is correlation of damage between reaches; should evaluate; needs R&D funds; probably not easy.
Correlation between structure and content value and correlation errors in first-floor elevations of structures at different locations.	Partially concur; identify potential of correlated variables and assess their importance; not sure USACE method is incorrect but willing to test; should evaluate; needs R&D funds; probably not easy.
Summation made over values at the damage reaches assumes that damage reaches are perfectly correlated.	Partially concur; real issue is correlation of damage between reaches; should evaluate; needs R&D funds; probably not easy.
Randomize structures jointly.	Partially concur; identify potential of correlated variables and assess their importance; not sure USACE method is incorrect but willing to test; should evaluate; needs R&D funds; probably not easy.
USACE focus is on uncertainty in damages not uncertainty in benefits.	Partially concur; should investigate computing uncertainty in damage reduced (benefits); should evaluate; needs R&D funds; probably not easy.
Consistent Terminology	
NRC Comment	**USACE Comments & Actions**
Adopt consistent terminology.	Concurs; updated guidance (ER 1105-2-101); EC 1110-2-6067 is being created.
Uncertainty should be used to describe situations without sureness.	Non-concurrence; USACE feels this is appropriately defined.
Define natural variability vs. knowledge uncertainty.	Partially concurs; academic interest only, no action at this time.
Adopt "risk analysis" terminology.	Concurs; updated guidance (ER 1105-2-101); EC 1110-2-6067 is being created.
Levee Certification	
NRC Comment	**USACE Comments & Actions**
Levee certification criterion is deficient.	Partially concurs; procedure negotiated with FEMA; EC 1110-2-6067 on levee certification is being created for further guidance.
USACE should set a single conditional non-exceedance probability for levee certification.	Initiate discussions with FEMA; EC 1110-2-6067 on levee certification is being created for further guidance.
Certification criteria shall provide a uniform level of flood protection, e.g. the median level historically provided (1/230).	Partially concurs; new policy would be the responsibility of FEMA; EC 1110-2-6067 on levee certification is being created for further guidance.
Examine a large number of FDR projects to determine median annual exceedance probability.	Partially concurs; new policy would be the responsibility of FEMA; EC 1110-2-6067 on levee certification is being created for further guidance.
Develop a table showing percentiles of variability in the annual exceedance probability of its FDR projects.	Partially concurs; new policy would be the responsibility of FEMA; EC 1110-2-6067 on levee certification is being created for further guidance.
Maintain an inventory of past projects of the amount of freeboard provided and resulting level of protection.	Partially concurs; new policy would be the responsibility of FEMA; EC 1110-2-6067 on levee certification is being created for further guidance.
Criterion for certifying a levee should be that it provides adequate protection against failure of the FDR system.	Partially concurs; new policy would be the responsibility of FEMA; EC 1110-2-6067 on levee certification is being created for further guidance.
Floodplain Management	
NRC Comment	**USACE Comments & Actions**
FDR projects should explicitly address social values.	Concurs; separate part of planning process; USACE recognizes the value if incorporating into risk analysis; major effort to bring life safety into process.
Risk analysis should consider non-structural alternatives.	Concurs; presently included in model as appropriate; could address with new research money from FCSDR.

Table 1 (continued)
National Research Council Recommendations

Floodplain Management (continued)	
NRC Comment	**USACE Comments & Actions**
Quantify ecological, health and social effects of FDR projects.	Concurs; currently USACE practice but not a risk issue; USACE is pursuing risk informed planning and decision making.
Goal of floodplain management is to use the land for greater social benefit.	Concurs; currently USACE practice but not a risk issue; USACE is pursuing risk informed planning and decision making.
Risk Communication	
NRC Comment	**USACE Comments & Actions**
Risk assessment should involve stakeholders.	Concurs; works with local sponsors; holds public meetings and workshops; USACE is pursuing risk informed planning and decision making.

A workshop on Flood Damage Reduction Analysis was held over a three-day period (6-8 February 2007) at HEC. Participants included personnel from HEC, the Institute of Water Resources (IWR), and two participants from the Dam and Levee Safety Certification Group. The purpose was to discuss the direction of flood damage reduction (FDR) analyses within USACE for the short and long term. During discussions, limitations of HEC-FDA were provided by the participants and are as follows:

- the model should compute using an event-based analysis, along with- and without-project conditions (also an NRC recommendation)
- remove price index, and use an economic update plan
- systems approach instead of the current system/component specific approach; this will better define, estimate, and combine uncertainties
- agricultural damages and uncertainties
- uncertainty about the geotechnical probability of failure curve or the fragility curve
- cost and its associated uncertainty (using MCACES methodology) needs to be added to the model

Each of these issues is being reviewed and consideration is being given to possible implementation in future versions of HEC-FDA. None of these issues should prevent the current version of HEC-FDA from being certified as they are possible enhancements not corrections to the current capability of the model.

SECTION 3

Model Evaluation

3.1 Certification Criteria

In accordance with PMIP protocols and EC-1105-2-412, HEC-FDA is subject to a Level 4 certification/review. Previous versions of the model were reviewed on the basis of technical quality, system quality and usability. These evaluations were repeated for Version 1.4 as described in this section. A description of the certification criteria, based on the PMIP model certification protocols is presented in the remainder of Section 3.1.1 through 3.1.3. Section 3.2 presents an overview of approach to model testing, including the selected approach for HEC-FDA.

The current version of HEC-FDA utilizes inputs generated in accordance with the established protocols and engineering models as the starting point for HEC-FDA and these are considered to be external model components. A detailed assessment of applicable components of HEC-FDA with respect to each of the certification criteria and discussion of significant observations during the review is presented in Sections 3.3 through 3.5. A summary of basic certification criteria outlined in the PMIP Protocols and the corresponding assessment of HEC-FDA is provided in Section 4.1.

In addition to the previously established certification criteria discussed in this section, version 1.4 underwent specialized testing as described in the HEC-FDA Version 1.4 Testing Plan. The specialized testing verified the incremental changes to the software since the previously certified version 1.2.4. It also validated general software usability and adequate quality control measures.

3.1.1 Technical Quality

Analytical tools and models used to support flood risk management analysis are expected to be based on established contemporary scientific theory. The study area and how it responds to the influences that act upon it must be realistically represented by the model's components, in the form of calculations based on the application of scientific theory. The analytical requirements of the model must be identified, and the model must address these requirements. Formulas and calculation routines that form the mechanics of the model must be accurate and correctly applied, with sound relationships between variables. The model should also be able to reflect the influences or restrictions of man-made laws, policies, and practices. The model should be logically unassailable and all assumptions, whether they pertain to natural or human-induced processes, must be valid and documented. Technically correct models with rational assumptions should produce robust, reproducible results that stand up to the rigorous scrutiny in later stages of the plan formulation process.

3.1.2 System Quality

System quality refers to the entire system used for model development, use and support, including software and hardware requirements, and data interoperability or compatibility with other systems. Efficiency and operation stability of the model have also been considered under system quality criteria. Factors such as the appropriateness of the software or programming language, correctness of programming, and availability and quality of supporting software and hardware can be considered in the assessment of system quality. The ability to import model data and/or output into other software analysis tools is another factor associated with system quality.

3.1.3 Usability

Usability refers to the overall ease and efficiency with which users are able to operate the model to obtain the relevant information required to support decisions made in the planning of flood risk management studies. The issues that can be considered during this component of the certification include:

- User friendliness of the model, including logical configuration and intuitiveness
- Availability and quality of supporting model documentation
- Availability of training and technical support for model users
- Ease of access in obtaining input data required to run the model
- Availability of the model programs or files to potential users
- Ability to extract understandable, relevant information from model outputs

3.2 Approach to Model Testing

The approach used in the review of HEC-FDA varied according to the individual assessment criteria under review. While the technical quality assessment proceeded principally according to a series of specific tests concentrating on distinct inputs, functions or calculations, the assessment of usability and to a large extent that of system quality have been based on observations drawn from the general use and operation of the model. These tests have been conducted manually by the HEC-FDA development team and include testing the usability of the model and testing the graphical user interface for various standards defined for effective and efficient usage and accessibility. Also, tests were run to verify results from computation of the model.

The version of the model subject to review and testing was made available for download as of June 2013 from http://www.hec.usace.army.mil as instructed by the developers. More details regarding the model version and installation issues are presented in Section 3.4. From the same source four data sets were obtained which the HEC-FDA development team has used as the primary test bed for the development of the model. The Bear Creek study is based on the Beargrass Creek study, in Louisville, Kentucky, and consists of two highly urbanized damage reaches on the South Fork Beargrass Creek, which drains a total of about sixty-one square miles. The flood risk management features to be analyzed are detention storage and floodwalls alone and in combination. A second data set that was provided is the Chester Creek watershed located near Philadelphia, Pennsylvania, which drains 177 km^2 area. For this data set, simulated project analysis is performed to determine feasibility of implementing several flood risk management plans. A third data set that was provided is a variation on the Bear Creek study ("BearCreek_Mix") that consists of one damage reach but includes many combinations of functions in order to test a variety of options. These included analytical probability curves, graphical probability curves, stage-probability curves, transform flow functions, interior-exterior functions, and geotechnical failure functions. A fourth data set that was provided is another variation of the Bear Creek study ("BearCrk_RAS") that includes a HEC-RAS water surface profile model in order to test the import of HEC-RAS water surface profiles.

3.3 Technical Quality Assessment

As discussed in Section 3.1.1, the technical quality assessment examined the model's ability to realistically represent conditions in the study area, and response to various flood risk management plans.

The testing approach used in the technical review of HEC-FDA was not intended to be absolutely comprehensive. Due to the complexity of the model not every constituent function, application, or calculation could be fully explored within the constraints of time and budget. The model and supporting documentation were reviewed and examined, and selected elements were identified for systematic testing, using the Bear Creek,Chester Creek, and variations of the Bear Creek data sets that are available with the current version of the model. As the review and testing process evolved, further issues and areas for closer review were identified and examined in more detail.

In general, the method used to test for technical quality was to configure the model so as to isolate individual variables, applications or processes identified for assessment, and then to modify the simulation conditions or other inputs so their response could be monitored. A number of issues were identified following examination of outputs from scenarios and simulations already specified within the reviewed version of the model. In some cases manual calculations were performed to confirm the processes involved and their accuracy of application. Some tests involved the input of technically irrational or erroneous data, in order to test the ability of the model to recognize input which may be the result of user error or faults in externally sourced data, and the ability of the model to prompt the user to revise it, as appropriate. The overall technical quality assessment also included considerations of the extent, clarity, and quality of data outputs.

3.3.1 Technical Quality Assessment of Component One – Study Configuration

As discussed in Section 2.2.1, the Study Configuration component of the model is where the physical study layout and the definition of the plans for analysis are configured for the study. This data is common for all analyses and is not likely to change during a study, and includes streams, damage reaches, plans, and analysis years. Testing for this component included testing the usability of the model and testing the graphical user interface for various standards defined for effective and efficient usage and accessibility. Currently, the model only allows two analysis years (Base Year, Most Likely Future); this does not prevent the model from being used, but is a limitation.

3.3.2 Technical Quality Assessment of Component Two – Hydrologic Engineering

As discussed in Section 2.2.2, the Hydrologic Engineering component of the model is where hydrology, hydraulics, and levee data are entered for the model analysis. This data is required for model analyses, and includes water surface profiles, exceedance probability functions, stage-discharge functions, and levee features.

- Water Surface Profiles Sets

  A water surface profile set in the model is the stream water surface stage along a stream length associated with discharge values of eight flood events. The default eight flood events are for the .50-, .20-, .10-, .04-, .02-, .01-, .004-, and .002-exceedance probability flood events. The model requires eight flood events; but the model does allow changing the probability designations. Each water surface profile set has stream stations, invert elevations, and discharge and stage values. The stage and discharge values have to increase by profile at one or more cross sections. Most water surface profiles sets are imported from HEC-RAS or HEC-2. Water surface profile sets can be used to develop discharge-probability and stage-discharge functions at an index location station within a damage reach, which ensures consistency of data. Also, a water surface profile set can be used in the creation of stage-damage functions (see Section 3.3.3).

  When developing an analytical-exceedance probability function (using Bulletin 17B procedures) for a particular plan, analysis year, stream, and damage reach, the model will use the water surface profile set for that particular plan, analysis year, and stream, and retrieve the discharge values for three exceedance probabilities - .50, .10, and, .01. The user enters an equivalent record length, saves the information, and the model will compute the analytical-exceedance probability function with uncertainty.

  The model will create a graphical exceedance probability function by retrieving the eight discharge-exceedance-probability data points from a water surface profile set for a particular plan, analysis year, stream, and damage reach. This creates a function with eight probability events, the statistics, including the uncertainty are influenced by the entire sample. Consequently the entire range of the function should be defined including an annual return 1-year event (0.999) estimated value. So the user will need to add an addition point at the 0.999 (1-year) event, along with the equivalent record length. Once the information is saved, the model will compute the graphical exceedance probability function with uncertainty.

  To create a stage-discharge function from a water surface profile set for a particular plan, analysis year, stream, and damage reach, the model will retrieve nine ordinates from the water surface profile set, this includes the invert stage (zero discharge) and the eight stage-discharge values. The model will automatically create a nine-point stage discharge function at the damage reach index location. To add uncertainty the user will need to select an uncertainty type (None, Normal, Triangular, Log Normal) or the user can have the model calculate the uncertainty by defining an uncertainty for a specific stage.

- Exceedance Probability Functions

  In order to perform a flood damage analysis that considers flood events of all sizes, a relationship between flood magnitude and the probability of exceeding that magnitude is needed. This relationship is an exceedance probability function, which can be defined in terms of discharge or stage. An exceedance probability function can be either analytical or graphical. For either type, the user will also need to provide the equivalent length of record, which is the number of years of a systematic record of recorded peak discharges at a stream gage.

In the model an analytical discharge-exceedance probability function is computed according to procedures described in Bulletin 17B. The computational procedure is either based on either entering information for Log Pearson Type III or an algorithm that the model labels "Compute Synthetic Statistics". This algorithm (default method) is used if the statistical parameters are unknown, such as at ungaged locations. The computed function should be compared with the original known discharge-exceedance probability function or with the water surface profile data by using the plot options provided in the model. If this method does not produce a function that closely matches the original known function, the graphical method should be used.

In the model a graphical exceedance probability function (discharge- or stage-exceedance probability) is defined by specifying the mean discharge- or stage-exceedance probability ordinates and the equivalent record length that describe the known function. The graphical discharge- or stage-exceedance probability function should be based on mean or ordinate expected values (such as an eye-fit curve through Weibull plotting positions). Once specified, ordered events are interpolated from the function based on the equivalent record length and error limit curves determined using order statistics. The distribution of errors is assumed to be normal about the specified function. A plot or report (tabulate) of the function and error limit curves can be created (see ETL 1110-2-537).

The primary computational change in FDA v1.4 consists of implementation of the "Less Simple" method concerning the error (uncertainty) distributions around graphical exceedance probability functions. The "Less Simple" method is an improved implementation of order statistics that addresses unsatisfactory results observed in when modeling certain projects. Details are contained in the FDA 1.4 graphical uncertainty white paper.

A flow transfer relationship may be used to define a relationship between unregulated and regulated flow, inflow and outflow, or another relationship to transform the flow defined by the discharge- exceedance probability function. The relationship is entered as x-y paired data in ascending order. Uncertainty of the dependent variable (regulated flow) is also defined. The distribution type and the distribution parameters are entered for each point on the flow transfer function.

- Stage-Discharge Functions

The stage-discharge (rating) function with uncertainty specifies the median stage-discharge functions to be used for a specific plan, analysis year, stream, and damage reach in the evaluation of flood risk management measures. The same median stage-discharge functions may be used for several plans and analysis years but not different streams or damage reaches. If water surface profiles are defined for the specified damage reach, the model will compute a nine-point stage-discharge function from the water surface profile data.

The associated uncertainty of a stage-discharge function is defined by specifying the error distribution type and entering the appropriate data for each ordinate (stage). The error distribution may also be calculated based on parameters specified for a specified stage. The uncertainty will be computed by linear interpolation between zero (at the invert stage) and the specified uncertainty and stage. The uncertainty will remain constant for ordinates greater than the specified value. The uncertainty can be defined as having a normal, log normal, triangular, or a uniform distribution.

- Levee Features

In the model, levee features include top of levee stage, failure characteristics, interior versus exterior stage relationships. The levee, floodwall, or tidal barrier characteristics are entered and other relationships are defined depending on whether the levee is subject to geotechnical failure or overtopping which may cause flooding (see EM 1110-2-1619, ETL 1110-2-547, ETL 1110-2-328, and ETL 1110-2-546).

The exterior-interior relationship defined in the model is a relationship between the water surface stage on the river or exterior side of the levee versus the stage in the floodplain or interior side of the levee. This relationship is necessary if the stage in the interior will not reach the same stage that is overtopping the levee or from interior drainage issues. This may be due to floods that result in stages near the top of the levee overtopping as designed in a safe, controlled manner, or a flood hydrograph volume not sufficient to fill the floodplain to the stage equal to the top of the levee. In either case, the relationship must be developed from hydrologic or hydraulic analyses external to the model. If the relationship is not specified, the assumption is that the floodplain fills to the stage in the river (represented by the exterior stage-discharge function for the reach) for all events that result in stages that cause levee failure or are above the top of levee.

Geotechnical failure analysis is the relationship between water surface stage on the river or exterior side of the levee versus the probability of levee failure. This feature is used anytime the structural integrity of the levee is in doubt, i.e., anytime the levee could fail prior to being overtopped. The geotechnical failure relationships are developed from geotechnical analysis according to existing geotechnical guidance. The geotechnical failure relationship is a combined probability of levee failure relationship and includes failure modes such as under seepage, slope stability, through seepage, surface erosion, etc. At this time, uncertainty about the geotechnical failure relationship is not available.

Testing consisted of re-entering the Hydrologic Engineering component data for both data sets. For the water surface profiles sets testing included importing the water surface profiles sets from HEC-RAS and HEC-2 generated files. Also, the testing included entering, modifying, and deleting the water surface profiles sets. The testing for exceedance probability functions included creating from a water surface profile, entering data for both types (analytical, graphical) of exceedance probability functions, and importing from an ASCII tab-delimited text file. Once the model has the data, when executed the model creates the exceedance probability function with uncertainty. Testing for stage-discharge functions included creating from a water surface profile, entering a stage-discharge function, and importing a stage-discharge function from an ASCII tab-delimited text file. Uncertainty for a stage-discharge function was tested by either entering the uncertainty values by hand, or have the model calculate the uncertainty based on data provided.

Since the two data sets that are provided do not cover all the available levee features, the only testing done was entering of the name, description, and top of levee stage. The testing of the relationships available for the levee was conducted using other data sets provided by USACE offices.

All of the items for the Hydrologic Engineering component have been tested and compared to results from previous test runs of previous model versions. The model passed the tests.

3.3.3 Technical Quality Assessment of Component Three – Economics

As discussed in Section 2.2.3, the Economics component of the model is where data and computations to produce stage-damage functions with uncertainty for flood risk management occurs for model analysis. This data is required for model analyses, and includes damage categories, structure occupancy types, structure modules, structure inventory, and stage-damage functions.

- Damage Categories

  Damage categories are used to consolidate large numbers of structures into specific categories of similar characteristics for analysis and reports. Typical damage categories include: residential, commercial, industrial, open space, and public facilities. At least one damage category needs to be entered with a maximum of twenty. It is recommended that the number of damage categories be kept to the minimum for computation considerations in the model.

- Structure Occupancy Types

  Structure occupancy types are defined by damage category, and the same structure occupancy type cannot be used for different damage categories. Structure occupancy types contain depth-damage functions where damage is defined in percent of value (structure, content, and other). Structures which have a direct depth-dollar damage function assigned to them have a structure occupancy type with a name that is generated by the model. Structure occupancy types are optional; however, if the model is going to compute stage-damage functions then structure occupancy types are required. Data required for structure occupancy types includes:

  Depth-Percent Damage Functions - a depth-percent damage function represents the damage caused to a structure, the contents of a structure, and "other" (other can be used to compute damage for any other item not accounted for in structure or content value, i.e., automobiles) for given depths of flooding at a structure. Depth-percent damage functions should always contains a zero damage depth, and negative depths are acceptable. The uncertainty associated with the depth-percent damage function is entered by ordinates based on the specified distribution.

Content to Structure Value Ratio - this value is used to estimate the total content value if the structure inventory does not include content value information. The ratio is entered as a whole number (i.e., enter 50 for a ratio of 50%). If the user is using generic depth-damage (EGM 04-01) relationships in the model, the user need to enter a value of 100 (100%).

Other to Structure Value Ratio – this value is used to estimate total value of the property represented by other if the structure inventory does not include other value information. The ratio is entered as a whole number (i.e., enter 50 for a ratio of 50%).

Uncertainty Parameters – distributions or uncertainties that are associated with estimating the depth-damage functions, structure values, content values ratios, other value ratios and first flood stage. These are used to develop the total aggregated stage-damage-uncertainty functions by damage categories for a damage reach. Parameters include first floor stage, structure value, content/structure value (left blank when suing generic depth-damage relationships), and other/structure value.

- Structure Modules

  Structure modules allow the model to vary one or more structure characteristics by plan and year or to include or exclude one or more structures from a plan/year. There is a default structure module (Base) and any new structure is automatically assigned to the default structure module. Structure modules must be defined prior to development of a structure inventory.

- Structure Inventory

  Structure inventories are a record of the attributes of unique or groups of structures relevant to flood risk management analysis. The inventory is used to compute an aggregated stage-damage function by damage category at the damage reach index location station. Structures are assigned to a specific damage category, structure occupancy type, stream, and structure module. The structure inventory can be entered directly or imported from an ASCII text file. For further information on developing structure inventories, refer to the following USACE reports by Institute for Water Resources:

  - "Natural Economic Development Procedure Manual - Urban Flood Damage", March 1988, 88-R-2
  - "Natural Economic Development Procedure Manual - Urban Flood Damage - Volume II: Primer on Surveying Flood Damage for Residential Structures and Contents", October 1991, 91-R-10
  - "Catalog of Residential Depth-Damage Functions", May 1992, 92-R-3
  - "Analysis of Non-Residential Content Value and Depth-Damage Data for Flood Damage Reduction Studies", April 1996, 96-R-12

Structure attributes include:

Name (required) – each structure must have a unique name – two structures cannot have the same name. If the same structure is used in more than one module, it must have a unique name for each module. The maximum length is sixteen (16) characters.

Stream Station (required) – stream station of where the structure is located on a stream and must be consistent between damage reach boundaries, damage reach index location, water surface profiles, and structure location. A valid value for a stream station is from 0 to 9,999,999.99.

Structure Value (required) – value of the structure (does not include the content value), a valid numeric value for the structure value ranges from 0 to 999,999,999.

Content Value (optional) – value of the contents (does not include the structure value) associated with a structure. A valid numeric value for the content value ranges from 0 to 999,999,999. If left blank, the model computes the content value from the content to structure value ratio that is defined in the occupancy type and the structure value. If a content value is entered, it will override the content value computed from the content to structure value ratio. If you enter zero, the content value will be zero. If the content damage is defined with a depth-direct dollar function, the content value is not used in the calculations.

Other Value (optional) – value of "other" property (does not include the structure value) such as outbuildings associated with a structure. A valid numeric value for the content value ranges from 0 to 999,999,999. If left blank, the model computes the "other" value from the other to structure value ratio that is defined in the occupancy type and the structure value. If an "other" value is entered, it will override the "other" value computed from the other to structure value ratio. If you enter zero, the content value will be zero. If the "other" damage is defined with a depth-direct dollar function, the "other" value is not used in the calculations.

Bank (required) – determines which stream bank (looking downstream) the structure is located on; the model allows the choice of either Left (default) or Right.

First Floor Stage (required) – the stages (elevations) associated with the first floor of the structure, the value must be between -300 to 30,000. Required if the ground stage and foundation height have not been entered.

Beginning Damage Depth (optional) – enter the beginning damage depth in feet (meters) relative to the first floor stage where damage begins. The beginning damage depth is normally used in the analysis of structures with basements where flood waters enter above basement floor. The beginning damage depth truncates the damage function at the specified depth. For example, if damage begins at one foot below the first floor stage, the beginning damage depth is set to -1.

Ground Stage (required) – the stage (elevation) of ground at the structure, this value must be between -300 to 30,000. Required if the first floor stage has not been entered.

Foundation Height (required) – the distance from the ground stage to the first floor stage. Required if a ground stage has been entered.

Depth-Direct Dollar Damage Functions (optional) – if the structure occupancy type for a structure is Direct, then a depth-direct dollar damage function will need to be entered. First, the model assumes the normal distribution for the first floor stage and a standard deviation for it even if it is zero (no uncertainty) must be entered. The direct-dollar functions are normally used to define unique damage potential such as some commercial, industrial, infrastructure, and public facilities. There are three types of depth-direct dollar damage functions – structure, content, and other.

Structure Coordinates (optional) – the UTM or other study adopted coordinates associated with the structure location; this is an optional item but is highly recommended.

- Stage-Damage Functions

USACE defines a stage-damage function as the relationship of direct economic costs caused by flood inundation to a range of flood stages for a given river or damage reach. From the model you can enter stage-damage functions manually or the model will calculate stage-damage functions. For the model, a complete set of stage-damage functions for all categories, damage reaches, and streams must be entered to analyze a specific plan for an analysis year. The uncertainty is defined only by the normal probability density function. If there is no uncertainty, you must select the normal distribution and enter zeros for the standard deviations – don't leave the uncertainty field blank.

Computing Stage-Damage Functions – to compute stage-damage functions (aggregated damage) the model requires that several model items be defined. These include configuration items (plans, stream, damage reaches, analysis years), water surface profiles, damage categories, structure occupancy types, and structure attributes. It is also helpful to define the discharge-exceedance probability and stage-discharge functions. The structure attributes define the parameters necessary for computing stage-damage for each structure. The discharge-exceedance probability and stage-discharge functions are used to determine the span of stages at the index location for which aggregated damage is computed.

Once all of the above parameters are defined, then computing stage-damage functions for one or more combinations of plan and analysis year can happen. The computed functions are then used in the computation of expected annual damage. If any changes occur to any of the parameters such as a structure's first floor elevation, then the model will require a re-compute of stage-aggregated damage and then expected annual damage for all plan/analysis year combinations that are dependent upon that structure.

Below is a general overview of what happens in the model when a user requests a stage-damage compute for a plan/analysis year combination, for more details on the computation procedure for stage-damage function in the model see Appendix B:

1) For each damage reach, the model calculates the range of stages at the index location. The stages represent the range from very frequent to very infrequent events based on the input functions and the uncertainty about those functions. The model then calculates the interval between stage ordinates in favorable incremental units. The model determines the minimum and maximum values (the range) and then iterates through the range to find the appropriate incremental values. It uses 1, 2, or 5 times 10^n and the number of ordinates (a maximum of sixty ordinates can be selected) to find the appropriate incremental values.

2) For the selected plan/analysis year, the model filters the structures using the structure module assignments so that it will process only those structures which are assigned to the selected module(s). It also filters the structures based on the "Year in Service" parameter.

3) The model processes each of the filtered structures. It transforms the tabulation stages that were determined in Step 1 from the index location to the structure. The transformation uses either the water surface profiles or the SID reference flood.

4) The model checks each structure to see if it has invalid data and to see if the structure is "out of the floodplain". The model will immediately proceed to the next structure if either case exists.

5) The model determines the damage category, structure occupancy type, and damage reach, and then computes stage-damage at each of the tabulation stages for a structure. Damage is computed for the structure, contents, other, and total. The damage for each tabulation stage is then aggregated to the index location. During calculations, the stage-aggregated damage functions are stored in memory. After all of the filtered structures are processed, the stage-aggregated damage functions are stored.

Testing consisted of re-entering the Economics component data for both data sets (however, the Chester Creek data set does not include a structure inventory). For the damage categories testing included entering, modifying, deleting, and importing (ASCII tab-delimited file) the damage categories. The testing for structure occupancy types included entering, modifying, deleting, and importing (ASCII tab-delimited file) structure occupancy types. Associated with structure occupancy types are the depth-percent damage functions which were tested by entering, modifying, deleting, and importing (ASCII tab-delimited file) the functions. The uncertainty associated with a depth-percent damage function is entered (also can be imported). The structure inventory testing is only done in one of the provided data sets (Bear Creek), for this data set the structure inventory is imported from an ASCII tab-delimited file. This includes the structure attributes, and the depth-direct dollar damage functions with uncertainty. Additional structure inventory testing, included entering, modifying, and deleting the structure attributes was also done.

Testing for stage-damage functions is done differently for each data set. For the Chester data set, since there is no structure inventory, the stage-damage functions are entered manually. So testing consisted of entering, modifying and deleting.. Since, the Bear Creek data set includes a structure inventory and all of the other required data pieces, the stage-damage functions are computed by the model.

All of the items for the Economics component have been tested and compared to results from previous test runs of previous model versions; the model passed all tests.

3.3.4 Technical Quality Assessment of Component Four – Evaluation

As discussed in Section 2.2.4, the Evaluation component of the model is where the computations for expected annual damage, equivalent annual damage, and project performance occur. Also, from this component the user can review the study status and view results.

- Expected Annual Damage (EAD) and Project Performance

  Monte Carlo simulation is used by the model to derive the expected annual damage corresponding to a particular plan/analysis year for a damage reach. The model needs to have several analysis variables to compute EAD and project performance. The model computes the following variables: 1) exceedance probability curves; 2) project reliability; 3) expected annual damage, 4) flood risk management benefits, and 5) probable flood stages conditional on the occurrence of a particular exceedance probability event. These variables are computed from various relationships that represent watershed runoff and economic factors important to estimating flood damage (e.g., discharge-exceedance probability, stage-discharge and stage-damage curves). The contributing relationships are characterized by both a best estimate and the uncertainty in this estimate. Details of the computational procedures are detailed in Appendix C.

- Equivalent Annual Damage

  Equivalent annual damage is computed by discounting future EAD values given the appropriate interest rate and time for discounting. EAD is calculated for the base year, however, it is common for conditions to change over time – damageable property in the floodplain may increase or decrease, urbanization upstream may cause increased runoff, or a channel may change. The necessary functions are entered for the future years, then the model interpolates stage, flow, and damage data from the base year to compute EAD for the future years. Now that EAD has been computed for each year throughout the period of analysis, the remaining step is to discount all of these values back to time zero (beginning of base year) and amortize the present value over the period of analysis. The model discounts each individual year and amortizes the sum. This computation is applied to not only the best estimate of EAD but to the distribution of possible EAD values obtained as part of the Monte Carlo simulation. This results in a distribution of equivalent annual damage.

Inundation reduction benefits are computed as the difference between with-and without-project equivalent annual damage. This differencing is performed between the distribution of equivalent annual damage values obtained for both with-and without-project condition resulting in a distribution of equivalent annual damage.

The differencing of uncertainty distributions in this manner recognizes that irrespective of the plan, the future exceedance probability of events causing floods will be the same for all plans. Consequently, differencing these distributions results in the same answer as would be obtained by obtaining the distribution of net benefits by performing Monte Carlo simulation of damage differences.

Testing consisted of re-computing the Evaluation component computations for both data sets. For the Expected Annual Damage (EAD) and Project Performance, computations were re-run for all plans and analysis years (this is eight separate runs). Results then were compared to runs from previous versions of the model.

Testing for the Equivalent Annual Damage computations were re-run for all plans (this is four separate runs), results then were compared to runs from previous versions of the model.

3.4 System Quality Assessment

The system quality of HEC-FDA has generally been assessed via the routine installation and operation of the model, rather than according to a set of discrete tests or component assessments identified in advance, although some exercises were specifically undertaken to investigate certain aspects of the model associated with system quality.

3.4.1 Installation and Operation

HEC-FDA is a Windows-based, menu driven interface application. It is a data-driven model, with the data elements stored in a relational database, while the process descriptions are embodied in the software itself (computational engine). The user interface is responsible for data editing and reporting, while the computational engines read the databases, perform the necessary simulations, writes output files and writes out information back in the appropriate databases, for additional reporting and visualization. The stage-damage function computational engine is written in C++; databases are stored using an Xbase library (Codebase) which is C++; the user interface is written in C++; the EAD and equivalent annual damage computational engines are written in FORTRAN. The output files obtained from the user interface are written to databases, while some results from the stage-damage computational engine are written to ASCII flat files. However, an assessment for suitability of the basic programming language used to compile the model and examination of the source code were not included in the scope of this particular review.

The version of the model made available for the review was downloaded with the Bear Creek, Chester Creek, and variations of the Bear Creek data sets from http://www.hec.usace.army.mil in June 2013. The data sets consisted of the input and output databases. The version number of the model was 1.4.

For the purposes of the review and certification process, the most recently available version of HEC-FDA was installed on two host computers by the HEC development team. The HEC development team found that, with the help of an IT Administrator, installation of the model was a fairly quick and straightforward process on all of the host computers. The processes of installation and the specification of target directories on the host computers for the downloading of the components were identical for each computer, and the model was fully executable and operable on both computers.

The installation and operation of HEC-FDA requires no prior installation of additional software beyond that which is commonly found in the planning community, assuming that a recent version of the Windows operation system and Microsoft Excel are industry-standard tools. The relational database embedded within the model is in Xbase format which allows the user to view the data outside of the model using additional software (i.e., Visual dBase, dBase Plus).

When successfully executed through to the generation and output of results, the HEC development team generally did not experience any problems with regard to the speed of execution when operating the model on any of the host computers.

3.4.2 Model Stability

Generally speaking the model is stable, however, there are times when the model can crash or terminate prior to completion of data entry. Usually the model is quite stable during computation of the stage-damage functions, EAD, and equivalent annual damage. For further information on reviewing several text files that the model writes, and log files and a table of known error messages, see Chapter 16 of the HEC-FDA User's Manual (January 2013).

3.4.3 Model Interoperability

The assessment of system quality also considered the ability of the model to import data to and from other software analysis tools. The HEC development team expects that most practical application of the model will make use of the model's facility to import the key project data using Excel® spreadsheets and then creating an ASCII tab-delimited text file that the model can import. The model also has the capability to export data from the database files that contain key data.

3.5 Usability Assessment

The overall assessment of model usability has been formulated through a comprehensive review of the supporting documentation and through the general use and operation of the model. The HEC-FDA development team generally divided observations and concerns regarding the usability of model into the following subject areas: Supporting Documentation, Training, Software Support/Maintenance, and User Interfaces.

3.5.1 Supporting Documentation

The usability of the model depends to a great extent on the clarity and efficiency with which the supporting documentation informs the user of the data required and the process that must be followed in order to obtain the desired outputs. The main supporting document evaluated by the HEC-FDA development team for the usability assessment was the document "HEC-FDA, Flood Damage Reduction Analysis, User's Manual, Draft, Version 1.4, January 2013". This manual is an update of the manual that was released in August 2007. The HEC-FDA development team was also provided with a package of internal documents and records pertaining to the history and development of HEC-FDA. Also, various papers and presentations have been written about using the model. Several of these have been published as Research Documents, Technical Papers, Training Documents, and Seminar Proceedings which are available at the following website www.hec.usace.army.mil.

Several USACE offices have written papers and documents on using the model in flood risk management studies. The HEC-FDA development team recommends for additional documentation that an applications guide on using the model should be written and published by HEC.

3.5.2 Training

Also, USACE provides training under the PROSPECT program on the use of the model, and the concepts of risk analysis procedures for formulating and evaluating flood risk management measures. This training increases the user's knowledge, proficiency, ability, and skill in the use of the model. Since the initial release of the model, this training has been provided on average yearly through the PROSPECT program.

3.5.3 Software Support/Maintenance

Since the model was released in 1998, the HEC has provided support to USACE and offices outside of the federal realm. Maintenance and updates have been provided ever since to USACE offices.

3.5.4 User Interfaces

The term "User Interfaces" has been taken to cover the on-screen appearance and structure of the model and the output it generates. In general the HEC-FDA development team considered this aspect of the model to be well-designed, logically structured, and visually very well presented.

- Interpretation and Post-Processing of Results

  The clarity and accessibility of generated results is a key factor in assessing the usability of the model. The current version of the model generates results in two formats: a suite of summary tables and graphs accessible through the model's user interface, and also a set of more detailed output from the stage-damage computations of the model. These sets of files are ASCII tab-delimited files, which are easily viewable in other software programs.

  The summary tables and graphs are accessible and provide the information that is required for risk analysis in USACE guidance. However, the reports and graphs could be labeled a little better, and should probably meet the formats of the report requirements stated in USACE guidance. The detailed output from the stage-damage calculations in the model supply the user with an impressive amount of results data, but the supporting documentation does not currently provide the user with comprehensive guidance as to the control of these outputs, their contents, and their interpretation. Currently in the model there is no direct way from the model's user interface to obtain key stage-damage data directly. The graphical displays generated by the model are generally well done the HEC-FDA development team thought.

- Help

  The help system provided in the model is based on the HEC-FDA User's Manual and provides general user assistance. At the dialog box level, the model also provides context-sensitive help for the user. The over all help system of the model is robust and provides excellent user assistance.

SECTION 4

Conclusions and Recommendations

4.1 General Review Summary

The following table presents a general summary of criteria used to review the model. The format mirrors the outline of technical documentation for use in model certification as suggested in the PMIP Protocols. This table is intended to provide a general overview of the more detailed discussion of the findings and observations presented in Sections 3.3 through 3.5.

General Certification Criteria	Assessment
Technical Quality	
Theory	The overall theoretical approach and methodologies on which HEC-FDA is based are valid.
Description of the system being represented by the model	The model provides an accurate and realistic representation of the physical processes affecting flood risk management and the economic consequences.
Analytical requirements and assumptions	The model fulfills technical requirements that have been based on formal documentation of analytical requirements. Not all model assumptions are explicitly documented.
Conformance with USACE policies and procedures	The model is in overall compliance with current USACE policy.
Formulas used in the model are identified and the computations are appropriate and done correctly.	Most of the formulas used in the model are generally identified in the supporting documentation.
System Quality	
Description of and rationale for selection of supporting software tool/programming language and hardware platform.	The software and hardware requirements are appropriate.
Proof that the programming was done correctly.	Examination of the source code was not included in the scope for the review of HEC-FDA. However, the model has been in practice for many years and its procedures have been reviewed by NRC and others, and have passed their tests.
Description of process used to test and validate model.	Developers used Chester Creek, PA as the principal test bed study. The review team conducted individual tests on selected parameters and applications, verified by comparison with manual calculations or output from external independently validated software where possible.

General Certification Criteria	Assessment
Ability to import data into other software analysis tools (interoperability issue).	General availability of Excel is assumed for importing and exporting of original study data.
Usability	
Availability of input data necessary to support the model.	Significant time and specialist effort is required to generate and collate most of the key input datasets, irrespective of the size of the project.
Formatting of output in an understandable manner.	In general, the format of the reports is clear and generally matches the format stated in USACE guidance. Some of the reports need to be adjusted for better user friendliness and more in-line with the USACE guidance.
Usefulness of results to support project analysis.	The content and level of detail of results is invaluable to the engineer responsible for the study.
Ability to export results into documentation.	Results can be easily exported into other documentation, subject to formatting and post-processing.
Training availability	There is adequate training within USACE for the model.
Users documentation availability and whether it is user friendly and complete	Current supporting documentation (principally the User's Manual) is considered complete, but probably could be refined so that some of the areas are more intuitive.
Technical support availability	For USACE users, the model has technical support available.
Software/hardware platform availability to all or most users.	Hardware and software requirements for installation and operation of the model are considered to be industry standard.
Accessibility of the model	Currently available for download from the HEC website.
Transparency of model and how it allows for easy verification of calculations and outputs.	The model is considered not fully transparent in some areas, and detailed guidance as to the understanding and interpretation of the output is required for verification of the results.

4.2 Certification Recommendations

HEC-FDA is a highly complex model drawing together theory and data from numerous specialist fields and disciplines into a powerful analytical tool that has widespread application in the planning community. It features an impressive degree of detail and is capable of a very high level of computational precision, providing planners with the techniques and analysis required to include appropriate flood risk management decisions.

One of the primary aims of this review and documentation was to generate recommendations regarding certification in accordance with the PMIP Protocols. This review needed to determine the extent to which the model satisfies analytical and policy requirements in USACE for risk analysis. The HEC-FDA development team recommends that the reviewed version (1.4) of HEC-FDA be certified as a USACE Corporate model for nationwide implementation.

4.3 Transition Recommendations

HEC will update its FDA web page to provide 1.4 as the certified version, and move the link to version 1.2.5a down the page to the "archived" section.

FDA version 1.4 is recommended for use by all Flood Risk Management studies at any stage. PDT's using prior versions must convert their models to version 1.4, in order to benefit from the usability improvements and standardize benefit calculations with the better graphical uncertainty method.

A PDT may appeal to the FRM-PCX to continue using FDA 1.2.5a if re-computing the results in version 1.4 will disrupt the completion of a significant milestone.

A PDT with concerns about the performance of the "Less Simple" method with regards to a specific project should consult with the FRM-PCX for technical assistance and/or to determine if another method is more appropriate. Potential alternatives include the continued use of the "Less Simple" method with alternate FDA modeling strategies, or project-specific adjustments to the 1% probability value used by the "Less Simple" method to transition between uncertainty regimes. If technical consultations with FRM-PCX determine that the "Less Simple" method is unsuitable for a certain project, then consideration will be given to running version 1.4 of FDA using either the "Simple" method or the old graphical uncertainty method implemented in v1.2.5a, and the FRM-PCX will coordinate with the PDT in order to configure its version 1.4 model files to access the chosen alternate method.

APPENDIX A

References

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These documents define policy and basic methods directly related to hydrologic engineering for flood risk management planning by USACE. All are promulgated by the Headquarters, U.S. Army Corps of Engineers (HQUSACE), Washington, DC.

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EC 1110-2-6067
Certification of Levee Systems for the National Flood Insurance Program (NFIP), Draft, April 2008. Department of the Army, USACE, Washington, DC 20314-1000.

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EP 1130-2-500
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ETL 1110-2-532
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ETL 1110-2-546

Engineering and Design – Provisions to Set Final Levee Grade for Projects Formulated Using Risk-Based Analysis, September 1995. Department of the Army, USACE, Washington, DC 20314-1000.

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APPENDIX B

Procedures for Computing Stage-Damage Functions

B.1 Introduction

This appendix describes and illustrates the calculation procedures used by HEC-FDA to compute stage-aggregated damage at the index location. The calculations require the user to already have entered supporting data. Calculations are performed by a plan/analysis year combination, if more than one plan/analysis year combination has been selected; the model processes each one independently and loops through all selected combinations.

For discussion purposes in this appendix, an imaginary study is created on Silver Creek. The study area is divided into five reaches as shown in Table B.1. There is an overlap of damage reaches SC 2L and SC 2La. That is, they represent the same stream (Silver Creek), station range (20.002 through 29.998), and bank (Left). Discussions later on will illustrate situations where this can be used to a user's advantage. For now, the discussion will center on computing stage-damage for several structures (located on the right bank) within damage reach SC 2R. The index point is located at station 25.000 (river mile 25.000). The stage-damage function for each structure is aggregated to the index location.

Table B.1
List of Damage Reaches for Silver Creek

Reach Name	Beginning Station	Ending Sation	Bank	Index Location Station	Description
SC1	20.000	20.001	Left	20.000	Bottom of study area. RM 20.000
SC 2L	20.002	29.998	Left	25.000	Reach SC 2L, Sliver Crk. Left Bank
SC 2La	20.002	29.998	Left	25.000	Reach SC 2La, Sliver Crk. Parrallels Reach SC 2L. Protected by Levee.
SC 2R	20.000	30.000	Right	25.000	Reach SC 2R, Silver Crk. Right bank.
SC 3	29.999	30.000	Left	30.000	Top of study area. RM 30.0

B.2 Setting Up the Stage-Damage Calculation

Initially, the model builds storage locations in memory for the stage-aggregated damage functions. The model determines the total number of damage reaches for all streams and the number of damage categories. For each reach, the model determines the range of stages required to cover the entire range of events from frequent to infrequent. The model attempts to determine this range first by retrieving the discharge-exceedance probability and stage-discharge functions (or stage-probability function). If these are not available, the model retrieves the water surface profile information. If this is not available, the model cannot determine the required range of stages at the index location and the calculation procedures will not proceed.

To initialize and scale the stage-aggregated damage matrix, the model must retrieve the discharge-exceedance probability and stage-discharge functions for damage reach SC 2R. Table B.2 lists Log Pearson Type III Statistics for the hypothetical damage reach SC 2R. The number of years is the

Table B.2
Log Pearson Type III Statistics for Damage Reach SC 2R

Mean	3.000
Standard Deviation	0.200
Skew	0.400
Number of Years	50

equivalent length of record and is a measure of the uncertainty in the statistics. The model computes discharge-exceedance probability curve ordinates as shown in Table B.3. Although these are generated from Log Pearson Type III Statistics, they could have been generated from either

Table B.3
Probability Ordinates, Damage Reach SC 2R

Probability	Discharge	95%	5%
0.9990	312	240	378
0.9900	393	315	464
0.9500	496	413	571
0.9000	567	483	646
0.8000	675	587	758
0.7000	770	679	859
0.5000	970	869	1,080
0.3000	1,243	1,115	1,403
0.2000	1,456	1,297	1,670
0.1000	1,834	1,606	2,168
0.0400	2,377	2,028	2,927
0.0200	2,833	2,369	3,595
0.0100	3,335	2,734	4,355
0.0040	4,081	3,263	5,530
0.0020	4,711	3,698	6,555
0.0010	5,410	4,170	7,725
0.0001	8,306	6,046	12,868

synthetic statistics or from graphical coordinates. For scaling, the model uses the extreme ordinates of flow corresponding to probabilities 0.999 and .0001 which represent return intervals of about one and 1,000 years. For risk analysis, discharges corresponding to the 95% (240 cfs) and 5% (12,868 cfs) confidence limit curves are used for computing the required scaling for stage-damage computations. Figure B.1 depicts the discharge-exceedance probability curve with confidence limits.

Once the discharge-exceedance probability curve is retrieved and the extreme discharge values are determined, the stage-discharge function is retrieved and used to determine the corresponding

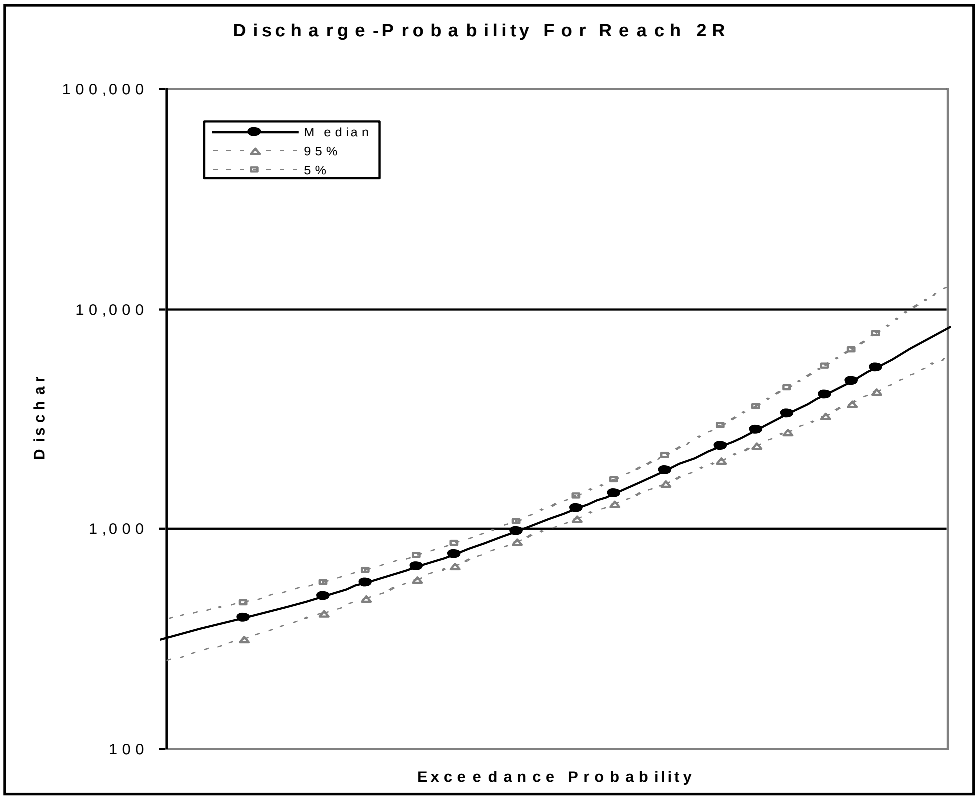


Figure B.1 Discharge-Exceedance Probability Curve for Damage Reach SC 2R

stages. Figure B.2 graphs the stage-discharge rating curve for damage reach SC 2R. Table B.4 lists the stage-discharge ordinates for damage reach SC 2R. They were computed from water

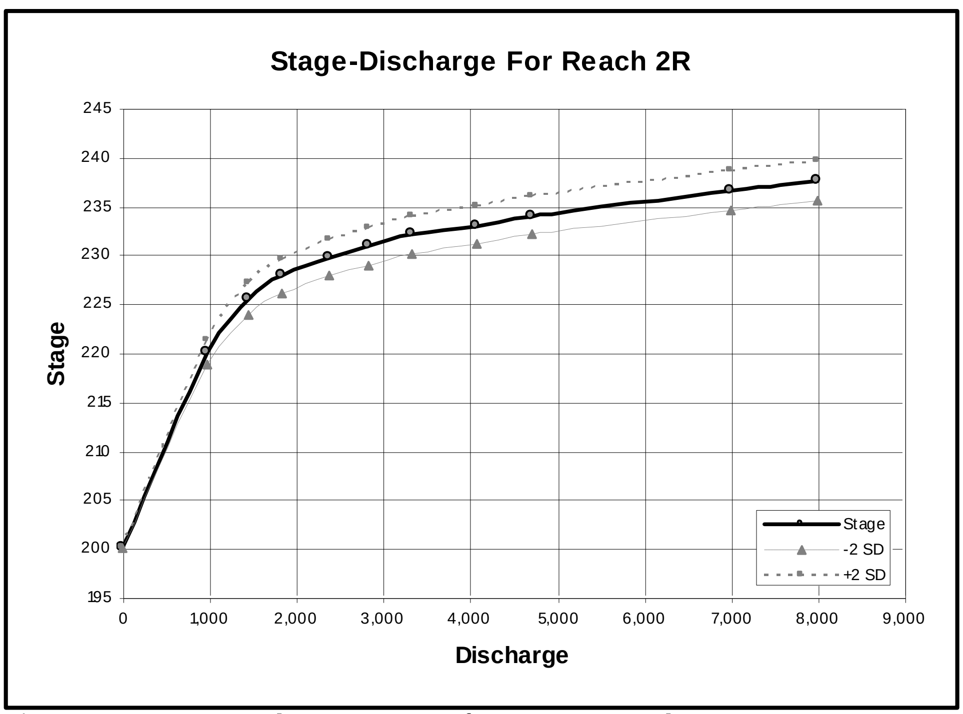


Figure B.2 Stage-Discharge Function for Damage Reach SC 2R

Table B.4
Stage-Discharge Function for Damage Reach SC 2R

Discharge	Stage	-2 SD	+2 SD
0	200.00	200.00	200.00
970	220.00	218.75	221.25
1,456	225.50	223.91	227.09
1,834	227.80	226.06	229.54
2,377	229.70	227.84	231.56
2,833	230.80	228.88	232.73
3,335	232.00	230.00	234.00
4,081	233.00	231.00	235.00
4,711	234.00	232.00	236.00
7,000	236.50	234.50	238.50
8,000	237.50	235.50	239.50

surface profiles. Since the model will not extrapolate the rating curve, additional points beyond the standard eight profiles were calculated for very high discharges of 7,000 and 8,000 cfs. Stages are interpolated from this table using the extreme discharges of the probability function with the extreme stages from the rating curve. The discharges of 240 cfs and 12,868 cfs correspond to stages of 204.64 and 239.5. Note that the maximum stage is truncated at the highest value on the rating curve for two standard deviations. The model then calculates a range of stages that meet the following criteria:

- encompass the range of stages from 204.64 through 239.5 feet.
- have an interval that is either one, two, or five times ten raised to some power. For example, 2.0×10^{-1} creates an array of stages 0.2 feet apart.
- have at least twenty but not more than thirty ordinates (this is an input option that you can change to allow a maximum of sixty ordinates). For this example, both the minimum and maximum number of ordinates was set to thirty.

For example, the stages in the stage-aggregated damage matrix for damage reach SC 2R are computed as:

- thirty ordinates
- minimum stage is 204.0 feet
- maximum stage is 262.0 feet
- interval between stages is 2.0 feet

The model now allocates memory for the array of stages and additional space for the corresponding aggregated damage and uncertainty (which will be computed) for all damage categories and stores the stages in this block of memory. All damage reaches are processed in the same manner as damage reach SC 2R.

If the discharge-exceedance probability and/or stage-discharge functions are not stored in the database, the model determines the range of stages from the water surface profile information. However, the default profiles include only a range of probability starting at 0.50. The resulting stage range could easily start too high. For example, if the functions were not available for damage reach SC 2R, the use of profile information would result in an array of thirty stages ranging from 219.0 to 248.0 feet at an interval of 1.0 feet. This may cause truncation of damage for infrequent events.

B.3 Computing Stage-Damage at Individual Structures Without Uncertainty

Once memory is allocated for the stage-aggregated damage matrices and the range of stages is determined for all reaches and all damage categories, the model begins processing all structures that meet the plan/analysis year filter. The plan year filter selects all structures which belong to the same structure modules that have been assigned. By default, the base structure module is always included although it may be an empty structure module (no structures assigned to this structure module). By default, each structure is assigned to the base structure module but it may be overridden. This section describes the processes and calculations at several structures which meet the plan/analysis year filter.

B.3.1 Calculating the Assumed Water Surface Profile Elevations at the Structures

Stage-damage at one structure is computed by calculating the water surface profile stages at the structure, determining the depth of flooding, and calculating the damage using values (structure, content, other) and depth-damage functions. The assumed stages at the structure correspond to the stages in the stage-aggregated damage function at the index location after adjusting for the slope of the water surface profile(s) between the index location and the structure. If the calculations use the water surface profiles (the eight standard profiles), the stages are adjusted using all eight profiles. If the SID reference flood water surface profile is used, then only one profile is used to adjust the stages.

Description of Sample Data – Profiles and Structures

Table B.5 lists the water surface profile stages at three cross-sections (station 20.0, 25.0, and 30.0). Stages are tabulated under their associated probability. For example, at station 25.000 (river mile 25.000), the stage for the 0.01 probability event (100 year return interval) is 232.0 feet.

Table B.5
Stage Water Surface Stage Profiles, Without Condition

Station	Invert	0.500	0.200	0.100	0.040	0.020	0.010	0.004	0.002
20.000	150.0	158.0	161.2	163.1	164.7	165.9	166.7	167.1	167.3
25.000	200.0	220.0	225.5	227.8	229.7	230.8	232.0	233.0	234.0
30.000	209.0	236.0	246.0	252.0	257.6	261.6	264.6	266.6	267.6

Figure B.3 graphically displays these same values. At the lower end of the study area (station 20.000), the profiles are relatively close compared to the upper end. The index location for reach SC 2R is at station 25.000. To illustrate the aggregation process, three identical structures are

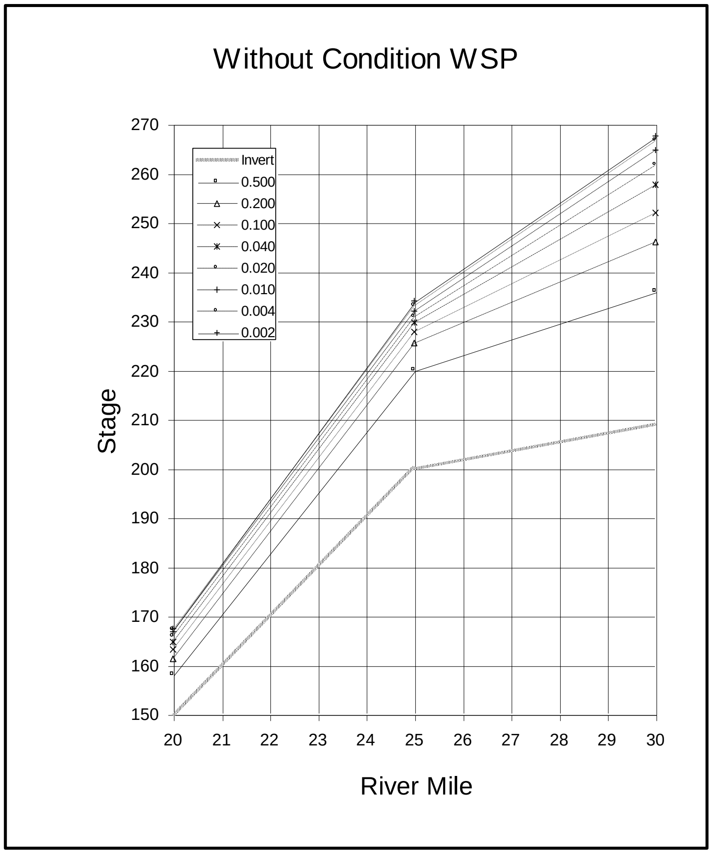


Figure B.3 Water Surface Profiles, Without Condition

used to calculate damage - one at the index location (station 25.000), and one at each of the extreme limits of the study (station 20.000 and 30.000). Table A.6 lists the appropriate characteristics for each structure. The first floor stage of each structure is located at the same stage as the 10% chance event. This will help illustrate several points about the calculations including using the eight water surface profiles as opposed to just the SID reference flood profile, having nonparallel profiles, and the location of each structure as defined by the structure station. Each structure is valued at $100,000. The contents are valued at $50,000 and it is calculated using

Table B.6
Structure Characteristics for Aggregation

Characteristic	**Structure**		
Name	**R0001**	**R002**	**R003**
Station	20.000	25.000	30.00
Structure Value	100	100	100
Content Value			
Other Value			
Bank	R	R	R
Damage Category	SF Residential	SF Residential	SF Residential
Occupancy Type	SF OS NB	SF OS NB	SF OS NB
Stream	Silver Creek	Silver Creek	Silver Creek
Module	Base	Base	Base
First Floor Stage	163.1	227.8	252.0

the global "ratio of content-to-structure value" which is defined within occupancy type SF OS NB which also contains the depth-percent damage functions. All three structures are located on the right bank.

Calculating Sample Aggregation Stages

To determine the assumed (or aggregated) water surface stages at each structure, the water surface profiles are used to generate a family of profiles which correspond to the aggregation (tabulation) stages at the index location. For structure R002 which is located at the index location, the assumed water surface stages correspond exactly to the aggregation stages. For structures R001 and R003, the assumed stages at the structure must be calculated. For aggregation stages above the rarest event (.002) or below the most frequent event (.500), aggregation profiles are parallel to the adjacent probability profile (.002 and .500 probability events respectively). Aggregation profiles between these two extremes are calculated using simple ratios of the computed water surface profiles. Table B.7 lists the aggregation profile stages at river mile 20.000, 25.000, and 30.000 which correspond to the three hypothetical structures. The lowest profile (.500 probability) is at stage 220.0 at the index location. All aggregation profiles below this minimum are parallel. For example, the .500 probability profile drops 62.0 feet from 220.0 at the index location to 158.0 feet at station 20.0. The same is true of the lowest aggregation profile which drops from 204.0 feet at the index location to 142.0 feet at station 20.00. Aggregation profiles above the maximum water surface profile are parallel to the 0.002 probability profile which reaches 234.0 feet at the index location. Aggregation profiles between 220.0 and 234.0 feet are computed using ratios. For example, the aggregation profile which has a stage of 230.0 feet at the index location has stages of 165.03 and 258.69 at river mile 20.000 and 30.000 respectively. Figures B.4 and B.5 depict selected water surface profiles and aggregation profiles for river miles 20.000 through 30.000 and 25.000 through 30.000 respectively. Note that the aggregation profile for a stage of 210.0 at the index location actually crosses below the invert at river mile 20.000 because the water surface slope is much greater than the invert.

Table B.7
Aggregation Profiles at Selected Locations

	River Mile (station)		
	20	**25**	**30**
1	142.00	204.00	220.00
2	144.00	206.00	222.00
3	146.00	208.00	224.00
4	148.00	210.00	226.00
5	150.00	212.00	228.00
6	152.00	214.00	230.00
7	154.00	216.00	232.00
8	156.00	218.00	234.00
9	158.00	220.00	236.00
10	159.16	222.00	239.64
11	160.33	224.00	243.27
12	161.61	226.00	247.30
13	163.27	228.00	252.59
14	165.03	230.00	258.69
15	166.70	232.00	264.60
16	167.30	234.00	267.60
16	169.30	236.00	269.60
18	171.30	238.00	271.60
19	173.30	240.00	273.60
20	175.30	242.00	275.60
21	177.30	244.00	277.60
22	179.30	246.00	279.60
23	181.30	248.00	281.60
24	183.30	250.00	283.60
25	185.30	252.00	285.60
26	187.30	254.00	287.60
27	189.30	256.00	289.60
28	191.30	258.00	291.60
29	193.30	260.00	293.60
30	195.30	262.00	295.60

Aggregation Methodologies

There are two methods for aggregating stage-damage to the index location. The difference between the two is the source of water surface profiles. The sources are:

- The set of eight water surface profiles.
- The SID reference flood water surface profile.

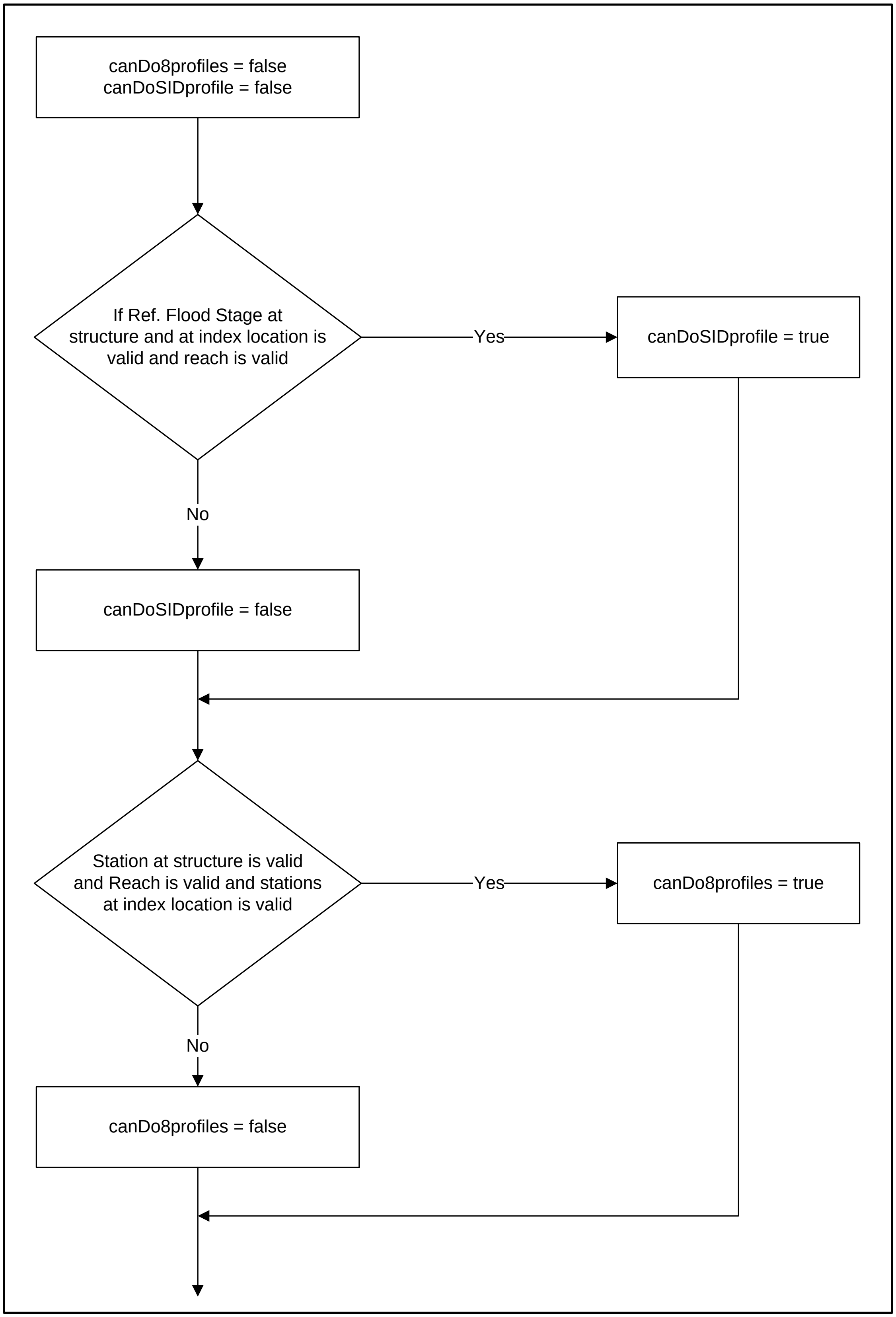


Figure B.4 Logic for Testing Data Validity of Aggregation Methodologies

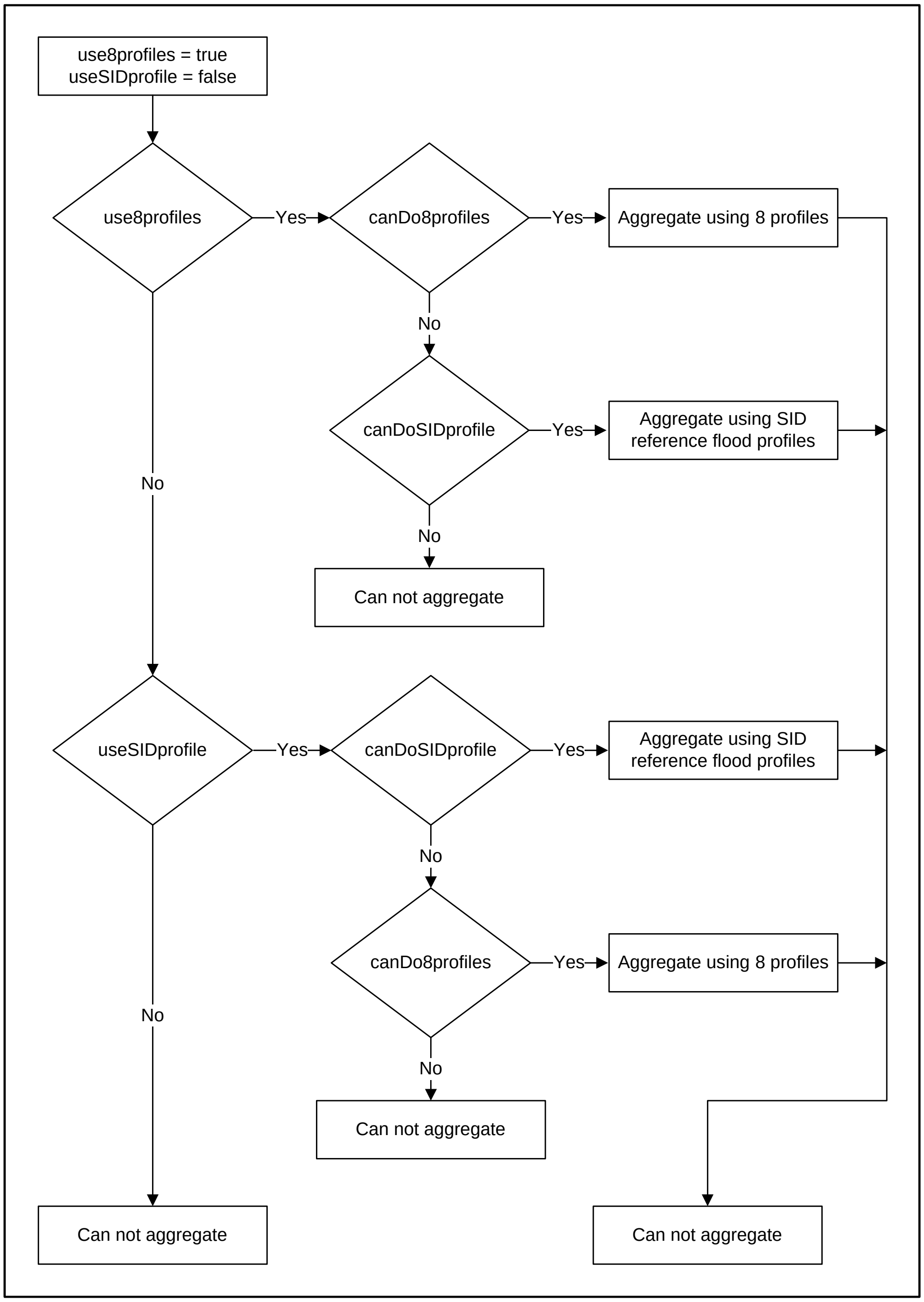


Figure B.5 Logic for Determining Aggregation Methodologies

The use of the eight water surface profiles facilitates accurate calculations when water surface profiles are not parallel. The use of the SID reference flood profile facilitates calculations using the old HEC-SID methodologies or calculations which require special circumstances. These circumstances might include:

- No profiles are available and water surface profiles are assumed to be flat.
- The profiles in the over-bank area are significantly different than those in the channel and a separate "stream" is not used.

Results using the single SID reference flood profile are identical to using eight parallel water surface profiles.

Data Requirements for Aggregation

The following data are required for aggregation using the eight water surface profiles:

- The structure must be assigned a valid stream, station, and bank.
- A set of water surface profiles must be entered for the desired plan, analysis year, and stream. The cross-section stationing must include the structure station.
- A damage reach must be defined which embodies location criteria of stream, bank, and beginning/ending stations that encapsulate those specified for the structure.

The following data are required for aggregation using the SID reference flood water surface profile:

- SID reference flood water surface stage at the structure.
- SID reference flood water surface stage at the index location.

The SID reference flood stage may be entered in the GUI for the structure but not for the index location - it must be defined either through import or using commercial database software.

Selecting the Aggregation Methodology

The user selects the desired methodology to use for aggregation. To use the SID reference flood for aggregation purposes, the analysis must have the parameter Use SID Ref Flood selected for each plan/analysis year combination. If the parameter is not selected, then the eight water surface profiles are used. However, if the structure does not satisfy the data requirements for the desired methodology, the model attempts to use the alternate methodology if data is available. This allows a mixture of methodologies within a selected plan/analysis year. Figure B.4 depicts the logic that the model uses for determining the possible aggregation methodologies for the selected structure. When aggregating damage at a structure, the model determines the possible methodologies using the logic of Figure B.4 and then uses the logic of Figure B.5 for calculation purposes.

B.3.2 Computing Damage for One Aggregation Stage Without Uncertainty

Overview

Damage is calculated at the structure for each of the stages listed in Table B.7. In this example, the three structures are located at stations 20.000, 25.000, and 30.000 and the corresponding stages are tabulated. If a structure is located between any of these stations, the model will make the appropriate interpolations. The model computation algorithm assumes the highest stage first (262.00 at the index location) and descends to the lowest (204.00 at the index location). If calculated damage is zero for three consecutive stages, the model assumes the zero-damage point has been reached and terminates calculations for the current structure. The calculation procedures accept as input the basic structure information as well as the associated data such as damage category and structure occupancy type. The following data is used as input to the calculations:

Structure Information

- Stream
- Station
- Bank
- Optional SID data (SID reach name, reference flood stage)
- First Floor Stage (or ground stage and foundation height)
- Beginning damage depth (optional)
- Damage Category Name
- Structure Occupancy Type Name
- Depth-Direct Dollar Damage Functions for this structure (optional)
- Module
- Number of Structures
- Values (structure, content, other)
- Year in Service

Related Information from the following:

- Damage Category
    - Price Index (optional)

- Structure Occupancy Type
    - Depth-Damage Functions (structure and/or content and/or other) with optional uncertainty parameters.
    - Content to Structure Value Ratio (percent)
    - Other to Structure Value Ratio (percent)
    - Uncertainty Parameters
        - First Floor Stage
        - Structure Value
        - Content to Structure Value Ratio
        - Other to Structure Value Ratio

- Streams
    - Stream Name

- Damage Reaches
    - Stream
    - Bank (left, right, or both)
    - Stations - Beginning and Ending
    - Reach Name (Used with SID reach names)

Other data/information may be entered for the structure, but it is not currently used in the computations. Some of the above data overlaps. For example, the user may define the first floor stage directly, or you may define it using the ground stage and the foundation height.

The example data set includes the occupancy type Single Family Residential, without basement. Table B.8 lists the depth-percent damage functions for the Single Family, Residential, without basement (SF OS NB) structure occupancy type. The functions are specified for structure and

Table B.8
Single Family, Residential, Without Basement
Structure Occupancy Type Damage Function

Depth (feet)	Structure (percent damage)	Contents (percent damage)
-1	0	0
0	5	2
1	7	5
2	10	15
5	25	50
10	50	80
15	70	90
20	80	95

content but there is no damage to other. Figure B.6 depicts these same functions. Figure B.7 depicts the model stage-damage calculation procedure. The aggregation profiles (shown in

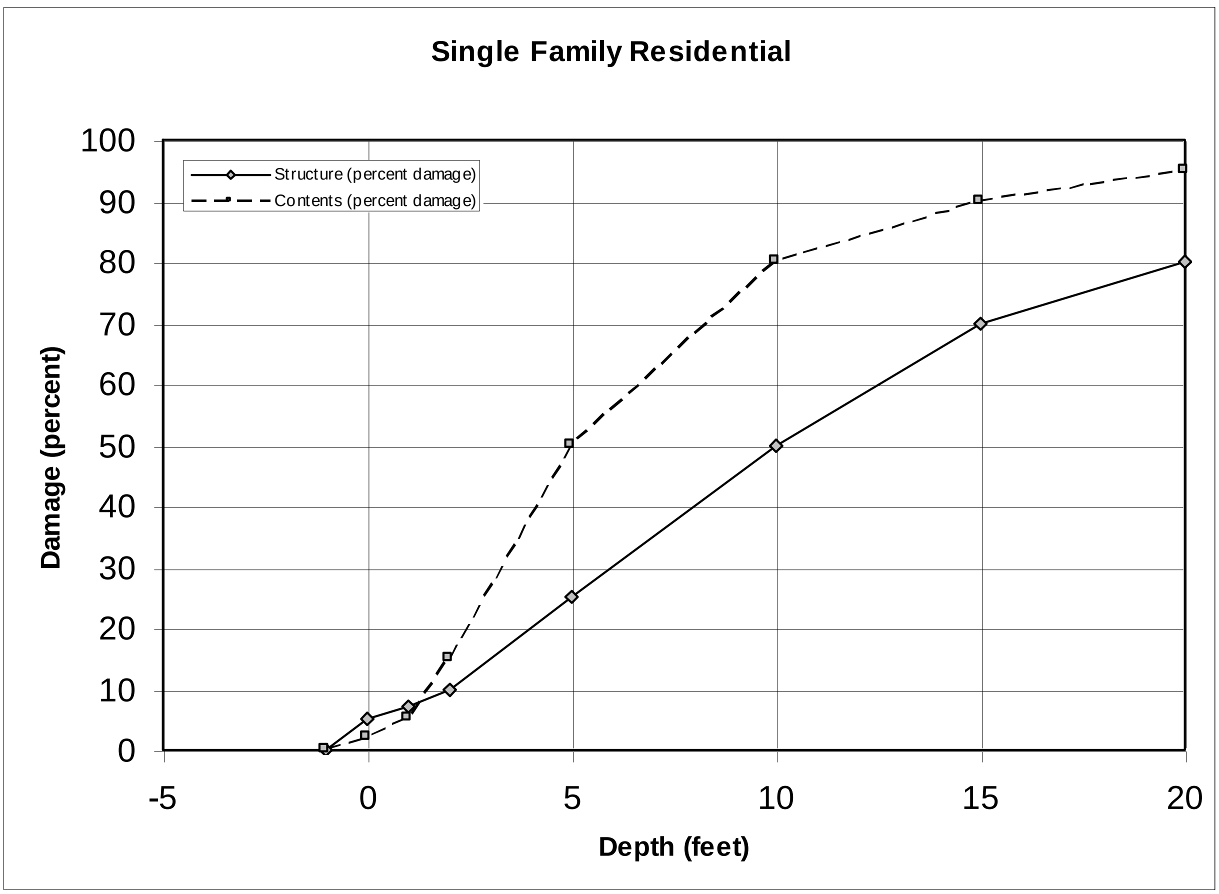


Figure B.6 Single Family, Residential, Without Basement Structure Occupancy Type Data Function

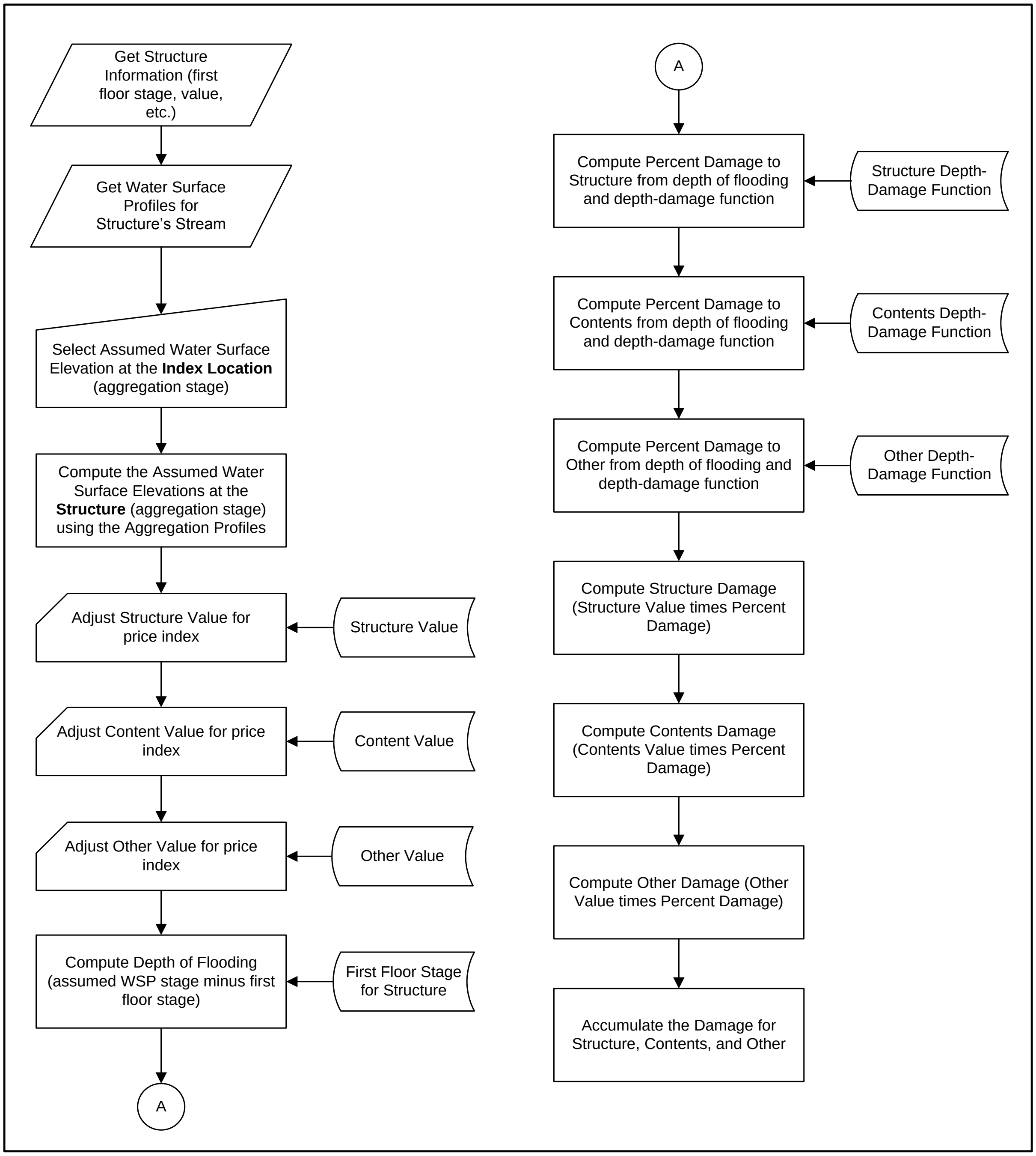


Figure B.7 Calculating Stage-Damage Without Uncertainty, One Ordinate

Figure B.8, Figure B.9 and Table B.7 are used to compute the "Assumed Water Surface Elevation at the Structure" (or Aggregation Stage) which is used to compute the depth of flooding. Figure B.7 depicts the process for one ordinate at one structure without using risk analysis procedures.

Procedure for Calculating Stage-Damage Without Uncertainty

The following section describes the stage-damage calculations depicted in Figure B.7 in more detail. Table B.9 lists and Figure B.10 graphs results for structure R003. The model writes this

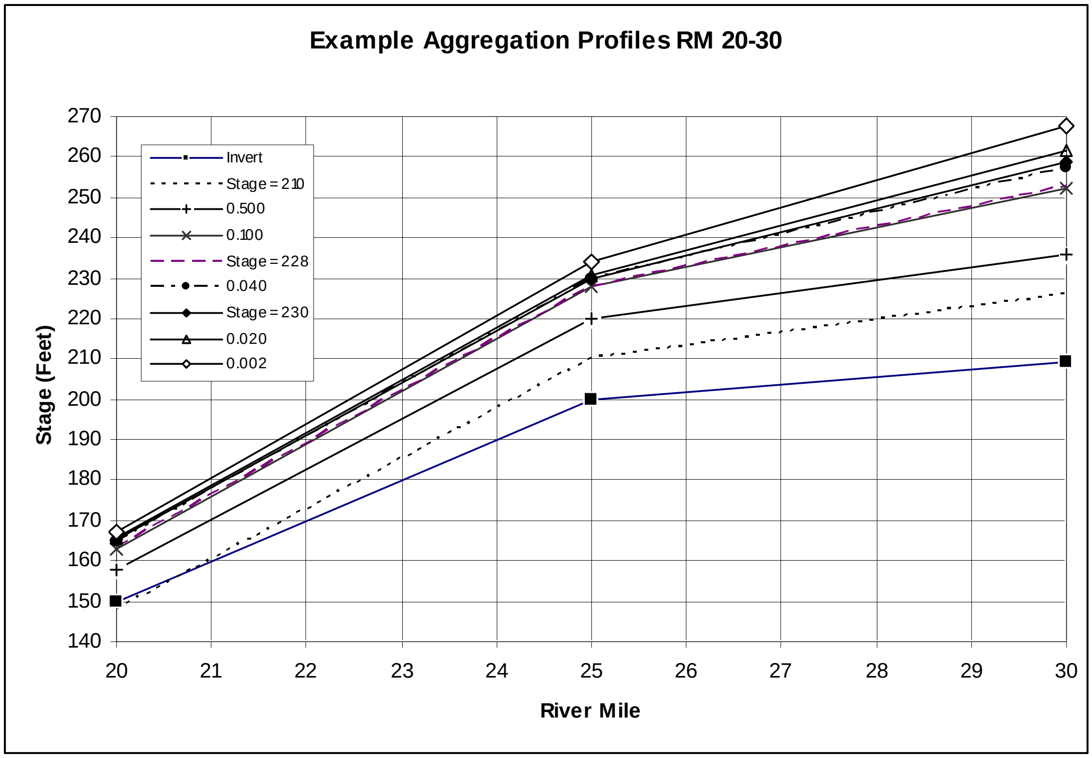


Figure B.8 Selected Aggregation and Water Surface Profiles RM 20.00 – 30.00

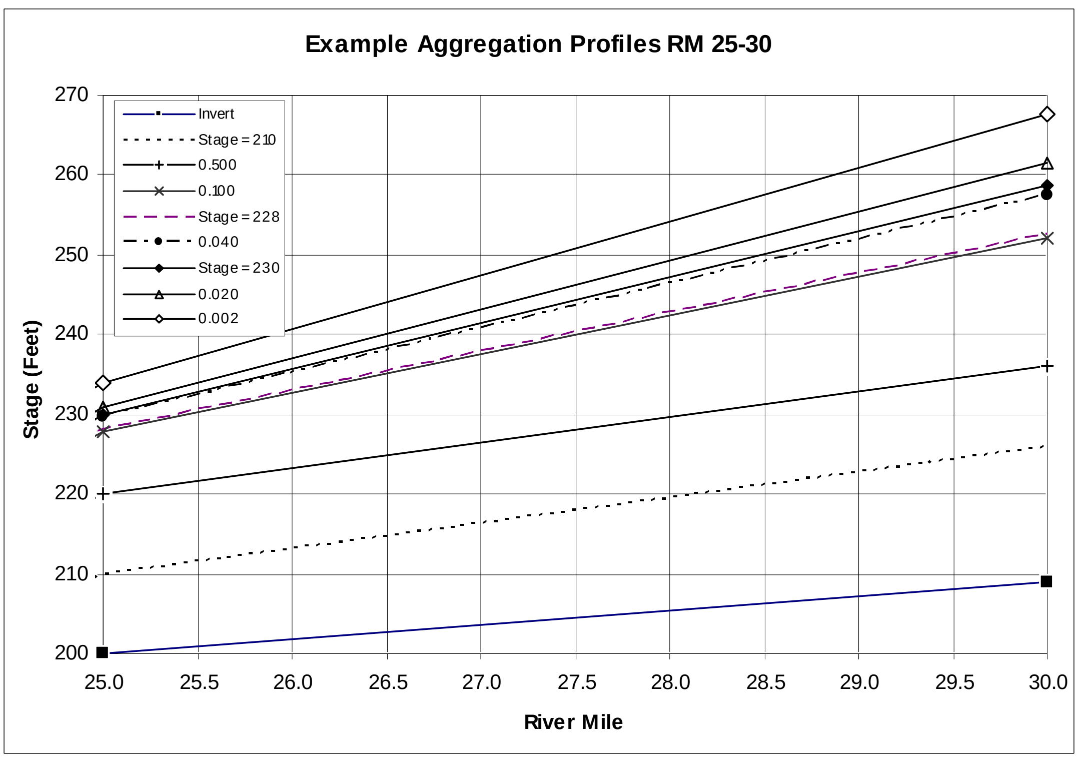


Figure B.9 Selected Aggregation and Water Surface Profiles RM 25.00 – 30.00

Table B.9
Stage-Damage Without Uncertainty for Structure R003

Structure: R0003								
Stream: Sliver Creek								
Reach: SC 2R								
Category: SF Residential								
Address:								
City:								
State:								
Index	**WS Elev @ Index**	**WS Elev @ Structure**	**Nominal Depth**	**Mean Depth**	**Structure Damage**	**Content Damage**	**Other Damage**	**Total Damage**
1	204.00	220.00	-32.00	-32.00	$0.00	$0.00	$0.00	$0.00
2	206.00	222.00	-30.00	-30.00	$0.00	$0.00	$0.00	$0.00
3	208.00	224.00	-28.00	-28.00	$0.00	$0.00	$0.00	$0.00
4	210.00	226.00	-26.00	-26.00	$0.00	$0.00	$0.00	$0.00
5	212.00	228.00	-24.00	-24.00	$0.00	$0.00	$0.00	$0.00
6	214.00	230.00	-22.00	-22.00	$0.00	$0.00	$0.00	$0.00
7	216.00	232.00	-20.00	-20.00	$0.00	$0.00	$0.00	$0.00
8	218.00	234.00	-18.00	-18.00	$0.00	$0.00	$0.00	$0.00
9	220.00	236.00	-16.00	-16.00	$0.00	$0.00	$0.00	$0.00
10	222.00	239.64	-12.36	-12.36	$0.00	$0.00	$0.00	$0.00
11	224.00	243.27	-8.73	-8.73	$0.00	$0.00	$0.00	$0.00
12	226.00	247.30	-4.70	-4.70	$0.00	$0.00	$0.00	$0.00
13	228.00	252.59	0.59	0.59	$6.18	$1.88	$0.00	$8.06
14	230.00	258.69	6.69	6.69	$33.45	$30.07	$0.00	$63.53
15	232.00	264.60	12.60	12.60	$60.40	$42.60	$0.00	$103.00
16	234.00	267.60	15.60	15.60	$71.20	$45.30	$0.00	$116.50
17	236.00	269.60	17.60	17.60	$75.20	$46.30	$0.00	$121.50
18	238.00	271.60	19.60	19.60	$79.20	$47.30	$0.00	$126.50
19	240.00	273.60	21.60	21.60	$80.00	$47.50	$0.00	$127.50
20	242.00	275.60	23.60	23.60	$80.00	$47.50	$0.00	$127.50
21	244.00	277.60	25.60	25.60	$80.00	$47.50	$0.00	$127.50
22	246.00	279.60	27.60	27.60	$80.00	$47.50	$0.00	$127.50
23	248.00	281.60	29.60	29.60	$80.00	$47.50	$0.00	$127.50
24	250.00	283.60	31.60	31.60	$80.00	$47.50	$0.00	$127.50
25	252.00	285.60	33.60	33.60	$80.00	$47.50	$0.00	$127.50
26	254.00	287.60	35.60	35.60	$80.00	$47.50	$0.00	$127.50
27	256.00	289.60	37.60	37.60	$80.00	$47.50	$0.00	$127.50
28	258.00	291.60	39.60	39.60	$80.00	$47.50	$0.00	$127.50
29	260.00	293.60	41.60	41.60	$80.00	$47.50	$0.00	$127.50
30	262.00	295.60	43.60	43.60	$80.00	$47.50	$0.00	$127.50

table to the file *FDA_SDmg.out* if the trace option is set to ten or greater. In this example, the "mean depth" and the "nominal depth" are the same because there is no uncertainty in the economic functions. Some of the following narrative describes results for the highest aggregation stage. Table B.9 lists results for all stages.

(1) Get Structure Information
Retrieve structure data from the database. Includes first floor stage, value of structure, contents, and other, etc. Table B.6 lists some of the sample structure information.

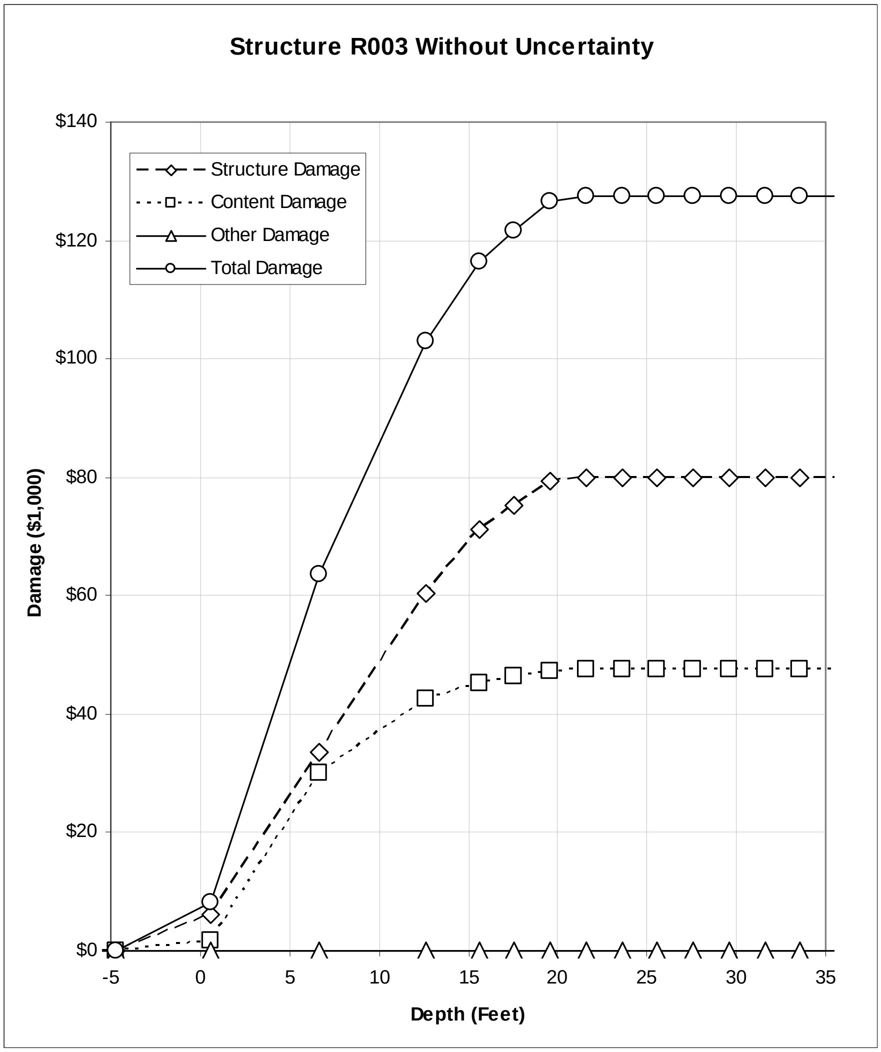


Figure B.10 Stage-Damage Without Uncertainty for Structure R003

(2) Get water surface profiles for the structure's stream
Each structure is assigned a stream. The profiles for the current structure are retrieved from the database. For the example, all structures are on "Silver Creek". If profiles do not exist for Silver Creek, the SID reference flood profile may be used. The example structures all use the water surface profiles as listed in Table B.5.

(3) Select Assumed Water Surface Elevation at the Index Location (Aggregation Stage)
The assumed (or aggregation) stages are listed in Table B.7. The index location is at river mile 25.000. The aggregation stages range from 204.0 to 262.0 feet.

(4) Compute the Assumed Water Surface Stage at the Structure using the aggregation profiles
The assumed (or aggregation stages) are calculated at the structure using the profiles listed in Table B.5. Table B.7 lists the tabulation stages at the index as well as at river mile 20.000 and 30.000 which correspond to structures R001, and R003. For example, an aggregation stage of 236.0 at the index translates into a stage of

269.6 at structure R003. Stages may be interpolated for any river mile between 20.000 and 30.000.

(5) Adjust structure value for price index
The price index is entered as a global value under "File/Study Information". The price index may also be entered by damage category and it will over-ride the global value. If left blank (undefined) the global study price index is used. The price index is simply multiplied by the structure value which is stored in the database to obtain an updated value for calculation purposes. The value in the database is not changed. For this example, the price index is 1.0 and the value for structure R003 is $100k * 1.0 or $100k.

(6) Adjust contents value for price index
Contents value is adjusted in a similar manner to the structure value. The content value must first be determined. For indirect depth-damage functions (using percent damage), it can be computed using the ratio of content-to-structure value entered with the occupancy types. This calculation can be over-ridden by entering a dollar value at individual structures. At the structure level, if the contents value is left blank (undefined), the occupancy code ratio is used. For structures having a direct depth-damage function (damage is in thousands of dollars), the content value is not used for calculations since damage is computed directly from the depth-damage function.

(7) Adjust "other" value for price index
Other value is computed in the same fashion as the contents.

(8) Compute depth of flooding (assumed WSP stage minus first floor stage)
The assumed (aggregation) stages computed above are used to determine the depth of flooding. For the example structure R003, the aggregation stage of 236.0 at the index location translates into a stage of 269.6 at the structure which translates into a depth of 17.6 feet (first floor stage is 252.0 feet).

(9) Compute percent damage to structure from depth of flooding and depth-damage function
The percent structure damage is computed using the depth of flooding (17.6 feet) from step 8 and the depth-percent damage function from occupancy type "SF OS NB". The resulting percent structure damage for a depth of 17.6 feet is 75.2%. FDA does not extrapolate depth-damage functions for depths beyond the defined depth range. For example, the maximum structural damage is 80% of the structure value.

(10) Compute percent damage to contents from depth of flooding and depth-damage function
The percent contents damage is computed in a manner similar to that for structure damage.

(11) Compute percent damage to other from depth of flooding and depth-damage function
The percent other damage is computed in a manner similar to that for structure damage.

(12) Compute structure damage (structure value times percent damage)
The structure damage is computed using the depth of flooding (17.6 feet) from step 8 and the structure value ($100k) from step 5 and the percent damage (75.2%) for the depth of flooding from occupancy type "SF OS NB" from step 9. The resulting damage is: $100k * 0.752 = $75.2k

(13) Compute contents damage (contents value times percent damage)
The contents damage is computed in a manner similar to that for structure damage.

(14) Compute other damage (other value times percent damage)
The other damage is computed in a manner similar to that for structure damage.

(15) Accumulate the damage for structure, contents and other.
The structure, contents, and other damage is accumulated for the selected stream-reach, and category. When all calculations are complete, the results are stored in the database for the calculation plan and year and are stored separately for each stream-reach, damage category, and type (structure, contents, other, and total).

B.4 Computing Stage-Damage at One Structure with Uncertainty

B.4.1 Overview

This section describes the calculation of stage-damage for structures whose economic parameters have uncertainty. The calculations are similar to those when there is no uncertainty except that one or more parameters or functions are sampled. When there is no uncertainty, calculations are done only once for each assumed (aggregation) stage. When uncertainty is included, the calculations must be performed repetitively for each assumed water surface stage (and associated depth of flooding). Figure B.11 depicts the calculation procedures for one structure with uncertainty. Although similar to Figure B.7, Figure B.11 not only reflects risk analysis computations but also depicts the calculation loop for all aggregation ordinates as well as multiple iterations when a single structure record represents multiple, identical structures.

B.4.2 Risk Analysis Calculations

The repetitive risk analysis calculations are done within the simulation loop. The model makes 100 simulations at each stage, but the user can change this using the parameter, "Compute Stage-Damage". The user may specify uncertainty parameters for the first floor stage, structure value, content value, other value, and damage in the depth-damage functions. Each of the uncertainties is defined by one or more parameters and an associated distribution. Allowable distributions include normal, log-normal, and triangular. For example, to describe the uncertainty in the first

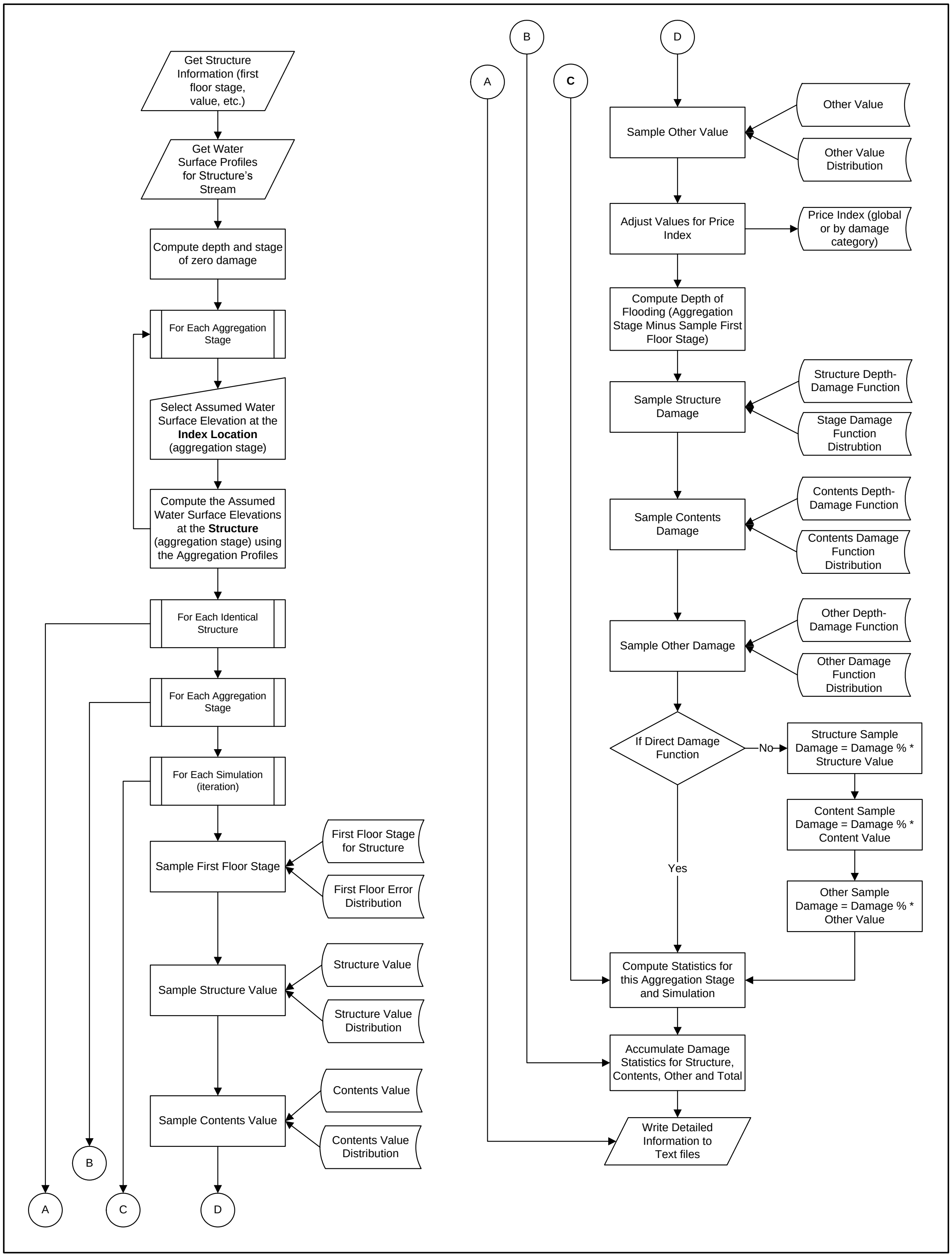


Figure B.11 Calculating Stage-Damage Without Uncertainty for One Structure

floor stage, you may define a normal distribution with a standard deviation of 0.3 feet. For each simulation, the model samples this first floor distribution to derive a simulated first floor stage with error. Similar procedures are used for values (structure, content, other) and the damage in the depth-damage functions.

B.4.3 Identical Structures

The calculation loop for identical structures allows you to enter data for one structure but specify that it represents several structures which have identical characteristics (first floor stage, value, occupancy type, etc.). A user can enter an integer which is greater than one for the parameter "Number of Structures". The model takes one structure record and iterates the calculation loop "Number of Structures" times. Each iteration is treated as a new structure with full Monte-Carlo simulation but uses the same structure information such as first floor stage, structure value, occupancy type, etc.

B.4.4 Detailed Description of Stage-Damage Calculation with Uncertainty

The following section describes in detail the stage-damage calculations depicted in Figure B.11. It is similar to the previous section on calculations without uncertainty. Table B.10 lists the uncertainty parameters for this example. Table B.11 lists results for structure R003.

Table B.10
Uncertainty Parameters for Example Problem

Parameter	Distribution	Std. Dev.
First Floor Stage	Normal	0.3 feet
Structure Value	Normal	10%
Contents Value Ratio	Normal	20%
Damage in Depth-Damage Function	Normal	5%

FDA writes this table to the file *FDA_SDmg.out* if the trace option is set to ten or greater. In this example, the "mean depth" and the nominal depth are not the same because there is uncertainty in the first floor stage. The nominal depth is the depth when no uncertainty is used whereas the mean depth is the calculated mean depth after Monte-Carlo simulations. Some of the narrative below describes results for the highest aggregation stage. Figure B.12 depicts the computed stage-damage with uncertainty function for structure R003.

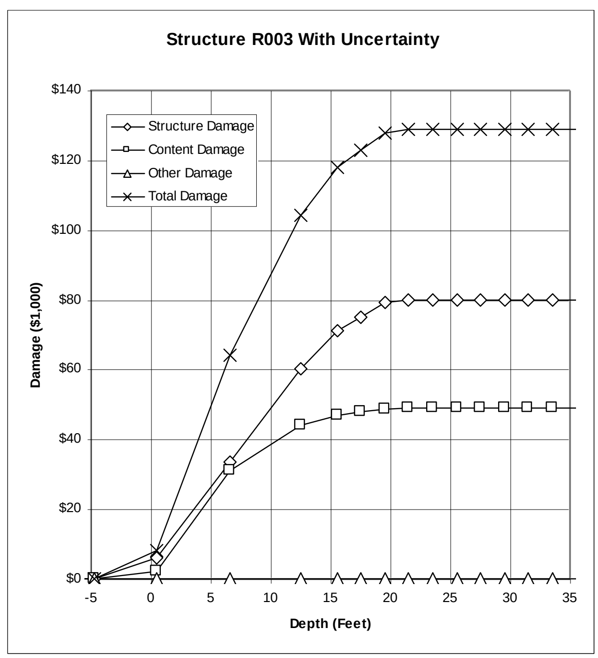


Figure B.12 Stage-Damage With Uncertainty for Structure R003

(1) Get structure information.
Retrieve structure data from the database. This includes first floor stage, value of structure, contents, and other, etc. Table B.6 lists some of the sample structure information.

Table B.11
Stage-Damage Without Uncertainty for Structure R003

Structure: R0003								
Stream: Sliver Creek								
Reach: SC 2R								
Category: SF Residential								
Address:								
City:								
State:								
Index	**WS Elev @ Index**	**WS Elev @ Structure**	**Nominal Depth**	**Mean Depth**	**Structure Damage**	**Content Damage**	**Other Damage**	**Total Damage**
1	204.00	220.00	-32.00	-32.00	$0.00	$0.00	$0.00	$0.00
2	206.00	222.00	-30.00	-30.00	$0.00	$0.00	$0.00	$0.00
3	208.00	224.00	-28.00	-28.00	$0.00	$0.00	$0.00	$0.00
4	210.00	226.00	-26.00	-26.00	$0.00	$0.00	$0.00	$0.00
5	212.00	228.00	-24.00	-24.00	$0.00	$0.00	$0.00	$0.00
6	216.00	230.00	-22.00	-22.00	$0.00	$0.00	$0.00	$0.00
7	215.00	232.00	-20.00	-20.00	$0.00	$0.00	$0.00	$0.00
8	218.00	234.00	-18.00	-18.00	$0.00	$0.00	$0.00	$0.00
9	220.00	236.00	-16.00	-16.00	$0.00	$0.00	$0.00	$0.00
10	222.00	239.64	-12.36	-12.36	$0.00	$0.00	$0.00	$0.00
11	224.00	243.27	-8.73	-8.73	$0.00	$0.00	$0.00	$0.00
12	226.00	247.30	-4.70	-4.70	$0.00	$0.00	$0.00	$0.00
13	228.00	252.59	0.59	0.59	$6.18	$1.88	$0.00	$8.06
14	230.00	258.69	6.69	6.69	$33.45	$30.07	$0.00	$63.53
15	232.00	264.60	12.60	12.60	$60.40	$42.60	$0.00	$103.00
16	234.00	267.60	15.60	15.60	$71.20	$45.30	$0.00	$116.50
17	236.00	269.60	17.60	17.60	$75.20	$46.30	$0.00	$121.50
18	238.00	271.60	19.60	19.60	$79.20	$47.30	$0.00	$126.50
19	240.00	273.60	21.60	21.60	$80.00	$47.50	$0.00	$127.50
20	242.00	275.60	23.60	23.60	$80.00	$47.50	$0.00	$127.50
21	244.00	277.60	25.60	25.60	$80.00	$47.50	$0.00	$127.50
22	246.00	279.60	27.60	27.60	$80.00	$47.50	$0.00	$127.50
23	248.00	281.60	29.60	29.60	$80.00	$47.50	$0.00	$127.50
24	250.00	283.60	31.60	31.60	$80.00	$47.50	$0.00	$127.50
25	252.00	285.60	33.60	33.60	$80.00	$47.50	$0.00	$127.50
26	254.00	287.60	35.60	35.60	$80.00	$47.50	$0.00	$127.50
27	256.00	289.60	37.60	37.60	$80.00	$47.50	$0.00	$127.50
28	258.00	291.60	39.60	39.60	$80.00	$47.50	$0.00	$127.50
29	260.00	293.60	41.60	41.60	$80.00	$47.50	$0.00	$127.50
30	262.00	295.60	43.60	43.60	$80.00	$47.50	$0.00	$127.50

(2) Get water surface profiles for the structure's stream.

Each structure is assigned a stream. The water surface profiles for the current structure are retrieved from the database. For the example, all structures are on *Silver Creek*. If water surface profiles do not exist for *Silver Cree*k, the SID reference flood profile may be used. The example structures all use the water surface profiles as listed in Table B.5.

(3) Compute depth and stage of zero damage.

The model looks at the depth-damage functions (structure, content, and other) and the optional **Beginning Damage Depth** to determine the highest depth of zero damage. For the example structure occupancy type, this is at a depth of -1 feet. Normally, the **Beginning Damage Depth** is left blank (undefined). It may be defined by individual structure if the damage functions are truncated at some depth. For example, this typically occurs for houses with basements where the damage function may start at a depth of -8 feet but water may not enter the basement until it reaches a depth of -1 foot. If some barrier prevented water from reaching structure R003 before a depth of 1 foot above the first floor, then you would define the **Beginning Damage Depth** as +1.0 foot and FDA would set the damage to zero for all aggregation depths of 1 foot or less during the Monte-Carlo simulations. The corresponding stage of zero damage is computed during the simulations as the sum of the first floor stage with error and the **Beginning Damage Depth**.

(4) Select assumed water surface elevation at the index location (aggregation stage).
The assumed (or aggregation) stages are listed in Table B.7. The index location is at river mile 25.000. The aggregation stages range from 204.0 to 262.0 feet.

(5) Compute the assumed water surface stage at the structure using the aggregation profiles.
The assumed (or aggregation stages) are calculated at the structure using the profiles listed in Table B.5. Table B.7 lists the tabulation stages at the index as well as at river mile 20.000 and 30.000 which correspond to structures R001, and R003. For example, an aggregation stage of 236.0 at the index translates into a stage of 269.6 at structure R003. Stages may be interpolated for any river mile between 20.000 and 30.000.

(6) For each identical structure, process the following steps:
Normally, the subsequent steps are processed once. If the **Number of Structures** is set to a value greater than one (1), the current structure is processed **Number of Structures** times to facilitate a crude sampling of structures. For example, if processed ten times, it is equivalent to entering ten identical structures.

(7) For each aggregation stage.
The following steps are repeated for each assumed (aggregation) stage. The stages are listed in Table B.7.

(8) For each simulation (iteration).
The following steps are repeated for each Monte-Carlo simulation. The model currently does 100 simulations, this can be adjusted.

(9) Sample first floor stage.
The first floor stage with uncertainty is computed from the first floor stage, the uncertainty distribution and the uncertainty parameters. The uncertainty data is defined with the occupancy types (indirect depth-percent damage functions) or the structure (direct depth-dollar damage functions). The uncertainty parameters are in the same units as the first floor stage. For structure R003 (first floor stage of 252.0), the uncertainty in the first floor stage is modeled using the normal distribution with a standard deviation of 0.3 feet. If a sampled error in the first floor stage was one standard deviation from the median, the sampled first floor stage would be 252.3 feet.

(10) Sample structure value.
The structure value with uncertainty is computed from the structure value, the uncertainty distribution, and the uncertainty parameters. The uncertainty data is

defined with the occupancy types. If using direct depth-dollar damage functions, the structure value is not sampled because it is built into the uncertainty of the damage function. The uncertainty parameters are entered in the percent of structure value. TableA.10 lists the uncertainty parameters for the example data. For structure R003 (value $100,000; occupancy code structure value error of 10%) a simulation error of one standard deviation would result in a sample structure value of $110,000 ($100,000 + $10,000 * 1std.dev.). The use of uncertainty in percent allows structures of different values to use the same occupancy type and still maintain reasonable errors about the median value. For example, a $200,000 house using the same example occupancy type would have a computed standard deviation of error of $20,000.

(11) Sample contents value.

Contents value is sampled in a similar manner to the structure value. The content value must first be determined. For indirect depth-damage functions (using percent damage), it can be computed using the ratio of content-to-structure value entered with the occupancy types. This calculation can be over-ridden by entering a dollar value at individual structures. At the structure level, if the contents value is left blank (undefined), the occupancy code ratio is used to compute contents value from the structure value. If using direct depth-dollar damage functions, the contents value is not sampled because it is built into the uncertainty of the damage function. The uncertainty parameters are entered in the percent of contents-to-structure value ratio. The occupancy code for this example has a ratio of 50% for contents-to-structure value ratio. For structure R003 (contents value = $100,000 times 50% = $50,000; occupancy code has a contents-to-structure value ratio error of 20%) a simulation error of one standard deviation would result in a sample contents value of $60,000 (error = $50,000 * (.5 +.5 * .2 * 1 std.dev.)). The use of uncertainty in percent allows structures of different content value to use the same occupancy type and still maintain reasonable errors about the median value. For example, a $200,000 house using the same example occupancy type would have a computed standard deviation of error of $20,000.

(12) Sample other value.

Other value is sampled in the same fashion as the contents.

(13) Adjust values for price index

The price index is entered as a global value and the price index may also be entered by damage category and it will override the global value. If left blank (undefined) the global study price index is used. The price index is simply multiplied by the structure, contents, and other values to obtain updated values for calculation purposes. The values in the database are not changed. For this example, the price index is 1.0 and the value for structure R003 is $100k * 1.0 or $100k (no error in structure value). During Monte-Carlo simulation, the price index is multiplied by the values with sampling error.

(14) Compute depth of flooding (aggregation stage minus sample first floor stage).

The assumed (aggregation) stages computed above and the sampled first floor stage are used to determine the depth of flooding. For the example structure R003, the aggregation stage of 236.0 at the index location translates into a stage of 269.6 at the structure. If the sampled first floor stage is 252.3, the depth of flooding is 17.3 feet (first floor stage without error is 252.0 feet and with a one standard deviation of error is 252.3 feet).

(15) Sample structure damage.
The sampled structure damage is computed from the sampled depth of flooding, and the sampled depth-damage function. The sampled percent structure damage is computed using the depth of flooding (17.3 feet) from Step 14 and the depth-percent damage function with uncertainty from structure occupancy type ***SF OS NB***. The resulting percent structure damage for a sampled depth of 17.3 feet is 74.6 percent (un-sampled damage function) or 78.3 percent (sampled one standard deviation away from the median damage). The model does not extrapolate depth-damage functions for depths beyond the defined depth range. For this example of structure R003 using the sampled first floor stage (252.3), the sampled structure value ($110,000), and the sampled depth-percent damage function (78.3 percent damage), the structure damage is computed as:

$$\$110,000 * 78.3\% = \$86,130.$$

This can be compared to the same calculation of structure damage without uncertainty which was $75,200. Obviously, it is very rare that the sampled parameters would always be +1 standard deviation away from the median.

The procedure for sampling structures using direct depth-dollar damage functions is the same as for with indirect depth-damage functions with the exception that damage is computed directly from sampled depth and sampled direct depth-damage functions.

(16) Sample contents damage.
The sampled contents damage is computed in a manner similar to that for structure damage.

(17) Sample other damage.
The sampled other damage is computed in a manner similar to that for structure damage.

(18) Compute statistics for this aggregation stage and simulation.
The statistics for the current aggregation stage for all simulations are computed and stored in memory before the aggregation stage is decreased for the next simulations.

(19) Accumulate the damage for structure, contents and other
The structure, contents, and other damage is accumulated in memory for the selected stream, damage reach, and damage category.

(20) Write detailed information to ASCII text files.
When all simulations are completed for the current structure, the model accumulates the current results in memory and writes various levels of calculation results to text files *FDA_SDmg.out* (stage-depth-damage by structure and by damage reach/damage category), *FDA_StrucDetail.out* (individual structure results in a tab-delimited text file

suitable for import), *FDA_SDev.out* (individual structure Monte-Carlo simulation results), and *FDA_SdErrors.out* (structure data errors). These files are described in later sections.

(21) Store results in the database.
When all calculations are complete, the results are stored in the database for the calculation plan and analysis year and are stored separately for each stream, damage reach, damage category, and structure occupancy type (structure, contents, other, and total). The EAD calculations utilize only the total damage for each damage category - not the individual structure, contents and other damage functions.

B.5 Aggregating the Stage-Damage Functions to the Index Location

The process of using either the eight water surface profiles or the SID reference flood water surface profile has been described earlier. Since the calculations are done at each structure at the aggregation stages, the results (both damage as well as statistics for uncertainty calculations) are easily accumulated to the index location. Table B.12 displays the total simulated damage for reach SC 2R. It includes aggregated damage for the three residential structures. Damage categories Commercial, Industrial, and Public do not have damage since only residential structures have been entered in this reach.

Table B.12
Total Stage-Aggregated Damage,
Damage Reach SC 2R

Total Aggregated Damage Matrix.					
Stream: Sliver Creek					
Reach: SC 2R					
	Stage	**Commercial**	**Industrial**	**Public**	**SF Residential**
1	204	0.00	0.00	0.00	0.00
2	206	0.00	0.00	0.00	0.00
3	208	0.00	0.00	0.00	0.00
4	210	0.00	0.00	0.00	0.00
5	212	0.00	0.00	0.00	0.00
6	214	0.00	0.00	0.00	0.00
7	216	0.00	0.00	0.00	0.00
8	218	0.00	0.00	0.00	0.00
9	220	0.00	0.00	0.00	0.00
10	222	0.00	0.00	0.00	0.00
11	224	0.00	0.00	0.00	0.00
12	226	0.00	0.00	0.00	0.04
13	228	0.00	0.00	0.00	20.78
14	230	0.00	0.00	0.00	100.92
15	232	0.00	0.00	0.00	180.52
16	234	0.00	0.00	0.00	219.37
17	236	0.00	0.00	0.00	259.18
18	238	0.00	0.00	0.00	295.81
19	240	0.00	0.00	0.00	322.66
20	242	0.00	0.00	0.00	342.96
21	244	0.00	0.00	0.00	360.14
22	246	0.00	0.00	0.00	372.30
23	248	0.00	0.00	0.00	381.77
24	250	0.00	0.00	0.00	386.38
25	252	0.00	0.00	0.00	386.55
26	254	0.00	0.00	0.00	386.55
27	256	0.00	0.00	0.00	386.55
28	258	0.00	0.00	0.00	386.55
29	260	0.00	0.00	0.00	386.55
30	262	0.00	0.00	0.00	386.55

APPENDIX C

Monte Carlo Simulation

C.1 Overview

Monte Carlo simulation (Davis and Rabinowitz 1967) is used in HEC-FDA to derive the expected annual damage corresponding to a particular plan/analysis year for a damage reach. The expected annual damage (EAD) is the mean damage obtained by integrating the damage exceedance probability curve for the damage reach. The damage-exceedance probability function is obtained from the discharge-exceedance probability, stage-discharge, and damage-stage functions derived at a damage reach index location. The inclusion of uncertainty for these variables requires a numerical integration approach be applied. Without uncertainty, the damage-exceedance probability curve can be obtained directly without resorting to numerical simulation approaches.

Monte Carlo simulation is the numerical integration approach. It relies on an exceedance probability analysis of samples of the contributing random variables obtained from the generation of random numbers. Although inelegant, the technique is computationally efficient in comparison with other techniques as the number of contributing variables exceeds about five.

C.2 Numerical Integration with Monte Carlo Simulation

Expected annual damage is the probability weighted average of all possible peak annual damages. It is also termed the mean or expected annual damage. As a simple example of computing a probability weighted average, consider the rolling of a die. The probability of obtaining any outcome of any roll of a die is 1/6, since the probability of obtaining any face of the die is considered equally likely (at least if the die is fair). The probability weighted average is then computed as:

$$\sum_{i=1}^{i=6} d_i p_i = \frac{1}{6}(1+2+3+4+5+6) = 3.5 \qquad (1)$$

where d_i is the possible outcome of rolling a die, and pi is the probability of the outcome. The probability weighted average or expected outcome of 3.5 obtained in equation (1) could be obtained by performing a die rolling experiment. The experiment would just involve many trials of rolling the die and averaging the outcome. As the number of trials becomes large the average obtained will equal 3.5.

Performing trials with the die is an application of a Monte Carlo simulation to obtain an average. In rolling the die, random integers are obtained in the inclusive interval 1 to 6, and a statistical analysis of the outcome is performed to obtain an average. Consequently, Monte Carlo simulation or application of Equation 1, are equivalent procedures for obtaining the mean or expected value.

Other statistical characteristics of rolling a die could be obtained, such as by performing a class category analysis on the outcomes to determined the probability of obtaining any outcome. If this were done, the probability of obtaining any die face in a single trial would be found to be 1/6.

This same type of sampling experiment can be performed to obtain EAD. Computation of EAD is somewhat more difficult in that damage is a continuous random variable, unlike the outcome of rolling a die, which has discrete outcomes. Consequently, damage probability is either stated for an interval, or more typically as, the probability of exceeding a particular value. These probabilities are defined by the damage exceedance probability function or equivalently, the cumulative distribution function as defined by:

$$P[D > d] = F(D) = \int_d^\infty f(D)dD \tag{2}$$

where D is the annual damage, F(D) is a function defining the damage exceedance probability curve, f(D) is the probability density function (units of probability per increment of damage), and P[D>d] is read as "the probability that D exceeds d."

The probability density function can be used to calculate the EAD or equivalently the probability weighted average damage by performing the following numerical integration:

$$EAD = \int_0^\infty Df(D)dD \sim \sum_{i=1}^{i=N} D_i \Delta_p \tag{3}$$

where the integral in equation (3) is approximated by a sum as in equation (1), Δp is the probability of damage being in an interval, D_i is the midpoint damage of this interval, and N is the number of intervals (Figure C.1). The approximation turns the integration of a continuous random variable into that of a discrete variable much as in the computation of the average outcome for rolling a die shown in Equation 1. The difference between the equations is that Equation 1 is exact and the probability is for a discrete outcome; whereas, Equation 3 is approximate and Δp is an interval probability.

The numerical integration is necessary because the damage-exceedance probability function is not defined by a continuous analytic function making an analytic integration impossible. Given that an exact analytic value cannot be obtained, how good is the approximation provided in Equation 3? The approximation can be made as accurate as possible by decreasing the interval Δp, or equivalently, increasing the number of intervals shown in Figure C.1.

Recognizing that equal probability increments implies that Δp=1/N, where N is the number of increments in Figure B.1, Equation 3 can be rewritten as:

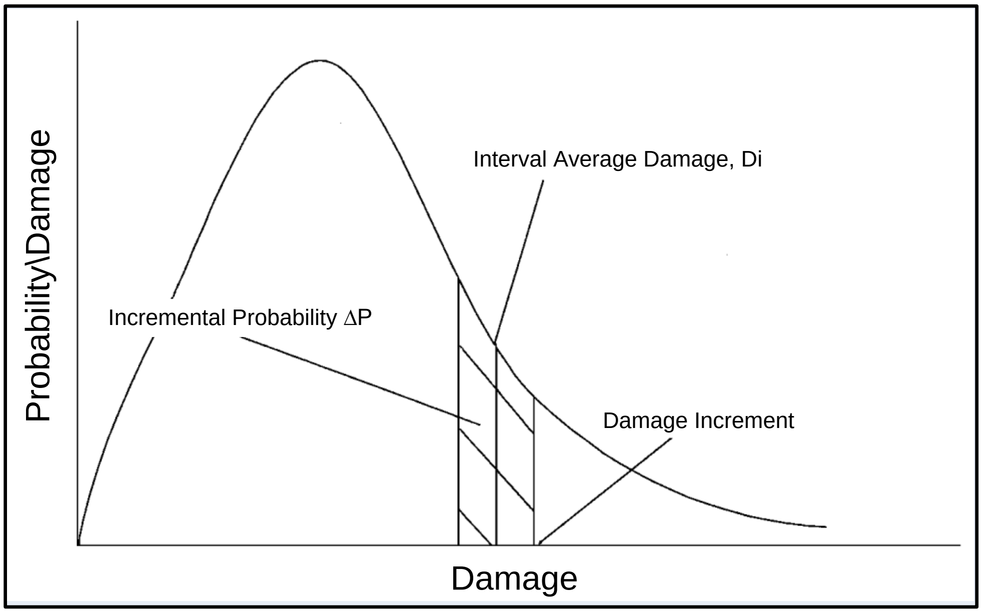


Figure C.1 Numerical Integration of Probability Density Function to Obtain EAD

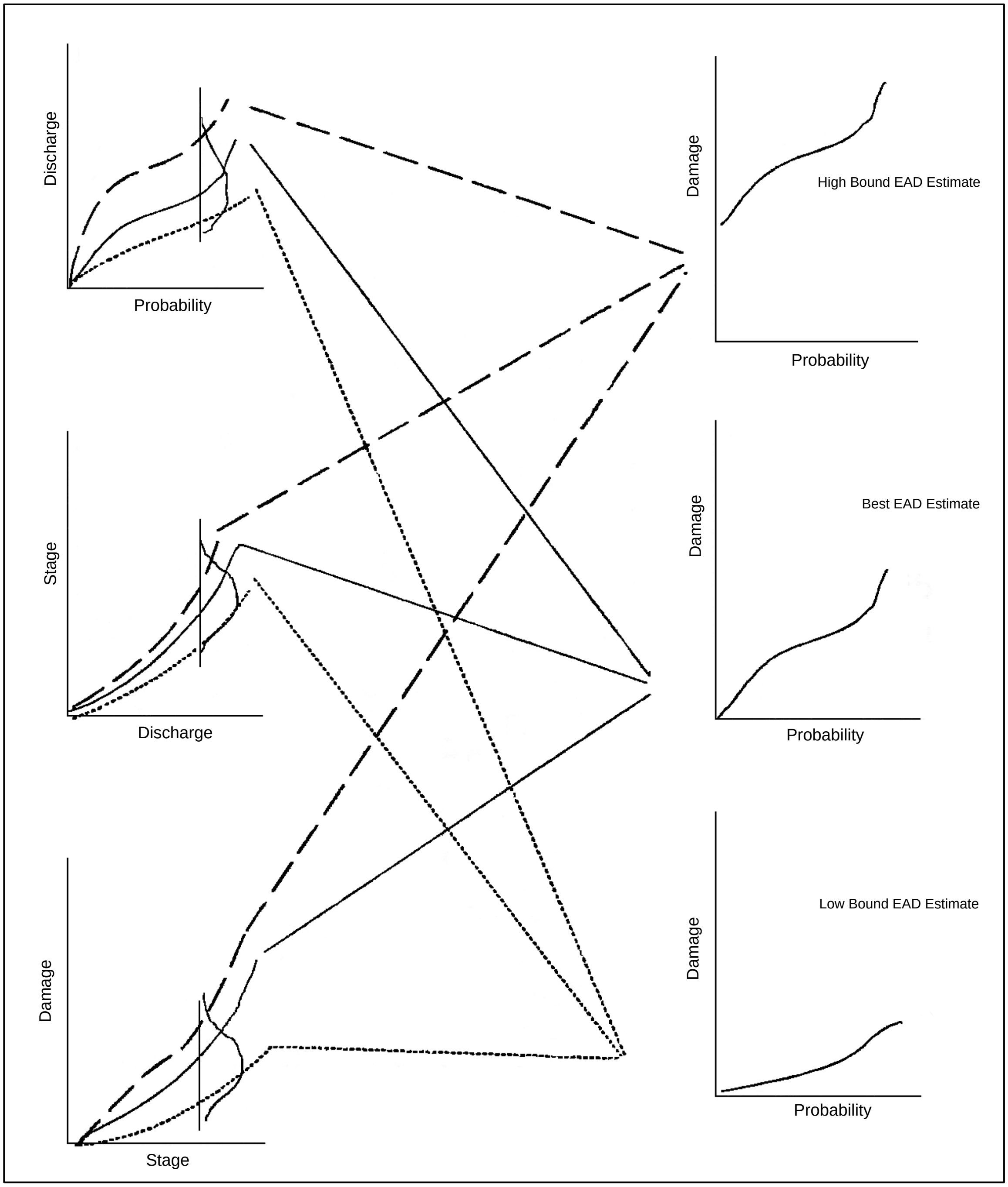
$$EAD = \sum_{i=1}^{i=N} D_i \Delta p = \sum_{i=1}^{i=N} \frac{D_i}{N} \qquad (4)$$

C.3 Computing Expected Annual Damage, Exceedance Probability, and Event Probabilities

The inclusion of uncertainty in estimates of the variable contributing to damage makes it possible to obtain both a best estimate of expected annual damage and a distribution of possible values about this best estimate. Additionally, an expected set of exceedance probability functions and event conditional stages can be computed as a consequence of providing these estimates of uncertainty.

The relationship between estimation uncertainty and the distribution of EAD can be understood by considering a sensitivity analysis application to computing EAD with a flow-exceedance probability curve, rating curve and stage-damage relationship as shown in Figure C.2. The figure shows that high-bound, low-bound and best estimates of each relationship are combined to obtain a corresponding range in estimates of EAD. This range in estimates could be thought of as defining a rough distribution of possible EAD estimates. The difficulty with this sensitivity analysis approach is that the relative likelihood of the range in estimates is not known.

Monte Carlo simulation is used to improve on the sensitivity analysis by integrating all possible random occurrences of the contributing relationships as shown in Figure C.3. This differs from the basic Monte Carlo application described in the previous section by obtaining a random sample of relationships or random functions instead of obtaining a random sample of individual values. The algorithm used to obtain random samples of each relationship is described later.



FigureC.2 EAD Computation Sensitivity Analysis

The Monte Carlo algorithm used to obtain the distribution and best estimate of EAD, expected exceedance probability curves and event related conditional stage exceedance probability proceeds as follows:

1. **Obtain a random sample of the contributing relationships**
   Each relationship is sampled to obtain a single realization of the discharge-exceedance probability, the stage-discharge (rating) and the stage-damage functions.

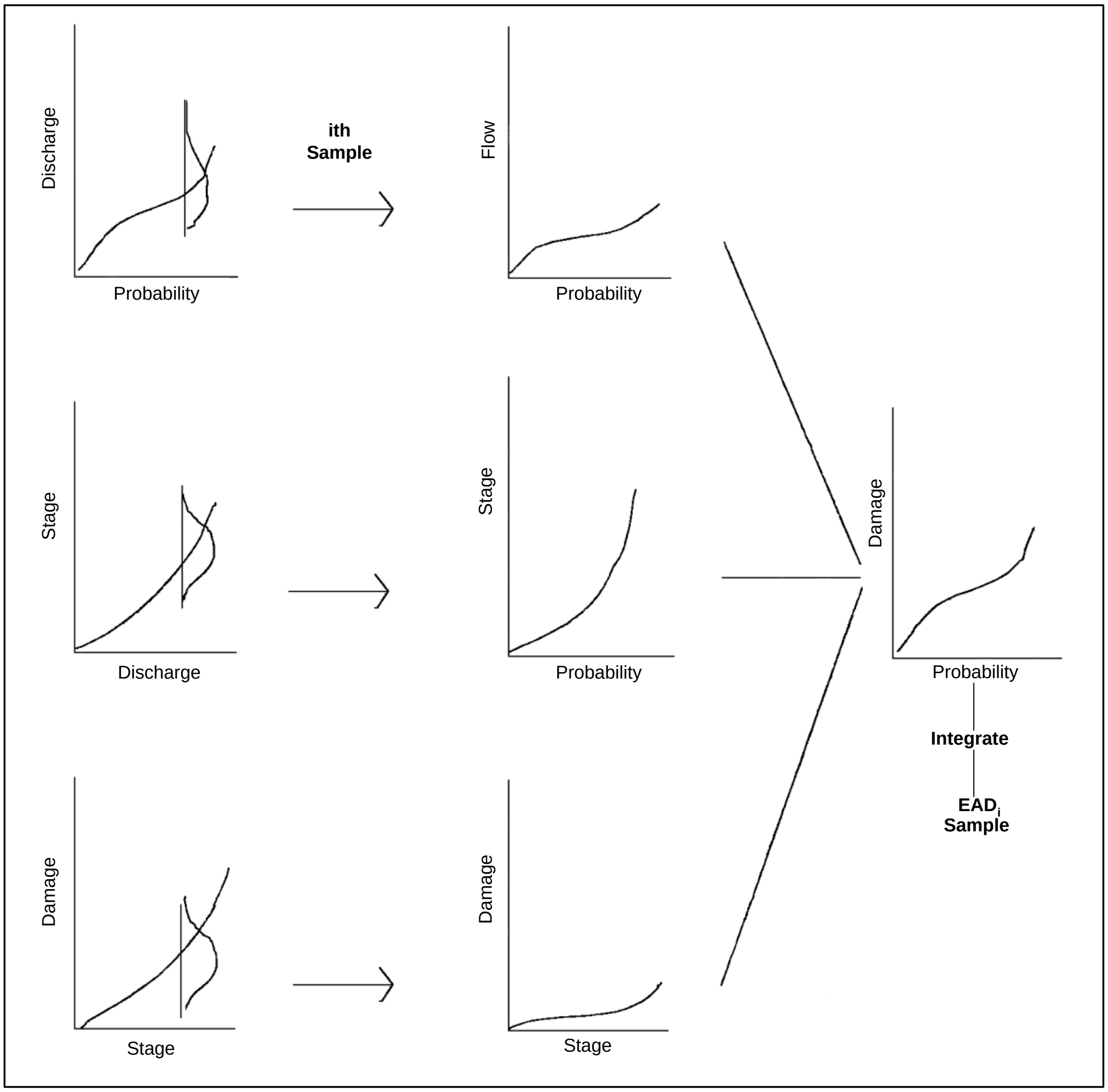


Figure C.3 Monte Carlo Simulation Algorithm for Estimating EAD

2. **Compute exceedance probability curves**
   Compute the stage-exceedance probability function by using the rating curve to transform the sample discharge-exceedance probability function into a stage-exceedance probability curve; and, compute the damage exceedance probability function by using the sample stage-damage function to transform the stage-exceedance probability curve into a damage-exceedance probability function.

3. **Save intermediary results for computing expected exceedance probability curves**
   Intermediary results are saved for the computation of expected exceedance probability functions by adding discharges, stages and damages for specified probabilities to values summed for previous simulation.

4. **Save intermediary results for computing event conditional stage probabilities**
   Event conditional stages are saved for later estimation of conditional stage exceedance probabilities. The stages are conditional on specified exceedance probabilities (e.g., conditional on the 0.1, 0.02, 0.01 stage being exceeded). The stage for each of the events

of interest is saved in a stage class interval. For example, consider that a stage of 21.56 corresponds to the 0.01 exceedance probability for the sample stage exceedance probability curve obtained in Step 2. This value is saved in a predetermined class interval that may have minimum and maximum limits of respectively, 21.0 and 22.0.

5. **Save intermediary results for computation of EAD**
The EAD for the sample contributing relationships is computed by integrating the damage exceedance probability curve. This value is both added to a sum of EAD values from previous iterations and saved in a damage class interval.

6. **Repeat sampling Steps 1 through 5**
Additional samples of exceedance probability curves and EAD are obtained by repeating Steps 1 through 5. Sampling ceases when an accuracy criterion is met.

7. **Compute expected exceedance probability curves**
Divide the summed values obtained in Step 3 for discharge, stage and damage for each exceedance probability by the number of samples.

8. **Compute conditional event stage distributions**
The process in Step 4 of placing stages in class intervals results in an exceedance probability histogram of stages for each exceedance probability event of interest. Table C.1 provides an example of some possible results for the 0.01 exceedance probability event. As shown in the table, the exceedance probability histogram is converted into an event conditional exceedance probability function.

Table C.1
Calculating Event Conditional Stage Exceedance Probability from Monte Carlo Simulation Frequencies

Lower Limit Stage	Upper Limit Stage	Frequency	Cumulative Frequency	Cumulative Probability	Exceedance Probability
<21.0	21.0	200	200	0.01	0.99
21.0	22.0	5000	5200	0.26	0.74
22.0	23.0	10000	15200	0.75	0.25
23.0	24.0	5000	20200	0.99	0.01
24.0	25.0	100	20300	1.0	0.0
25.0	25.0>	0	20300	1.0	0.0

9. **Compute best estimate of EAD and Distribution of EAD**
The best estimate of EAD is computed as the average of the samples summed in Step 5. The class interval exceedance probabilities for EAD are converted to an exceedance probability distribution using the same procedure for event conditional stages (Table C.1).

In performing this simulation, only the stage versus total damage relationship is used to obtain the damage exceedance probabilities function and corresponding EAD. Damage-exceedance probability functions and EAD for damage categories are proportioned in the same ratio as the traditional (no uncertainty) category damage is to the tradition total damage values.

C.4 Monte Carlo Simulation Options for Calculating EAD

The Monte Carlo simulation can be expanded to include other contributing relationships in the calculation of EAD. Table C.2 describes the options for including other relationships. Notice that some relationships involve uncertainty calculations and others (levee effects and interior stage versus exterior stage relationships) are specified without uncertainty. The

Table C.2
Contributing Relationships Used in EAD Calculation

Contributing Relationship	Uncertainty Distribution
Flow/stage frequency curve	yes
Flow transform	yes
Rating curve	yes
Wave overtopping of flood wall or levee	yes
Levee impact on damage	no
[1]Exterior versus interior stage	no
Stage versus damage	yes

[1] Used to directly convert exterior river stage, interior levee failure stage, or with wave overtopping

inclusion of additional relationships does not require any new aspect of performing the simulation except to require the creation of additional random samples of another relationship. For example, Figure C.4 displays the additional step of using the flow transform to convert a reservoir inflow-exceedance probability curve to a regulated exceedance probability curve.

C.5 Sampling Algorithm for Numeric Integration

C.5.1 Overview

Application of Monte Carlo simulation requires a method for producing random samples and criteria for determining the number of samples needed to obtain a numerical integration with pre-specified accuracy. The algorithms (previously described) produce random samples of the contributing relationships that are combined to obtain samples of EAD, exceedance probability functions and event conditional stage probabilities. This sampling depends on the algorithm for generating random numbers. The generation of random numbers and the random sampling of contributing relationships is the means by which Monte Carlo simulation performs a numerical integration. As previously discussed, the numerical integration accuracy increases with the number of simulations. The criteria used to determine the number of simulations for a desired level of accuracy is described in the next section. The related problem of obtaining a numerically accurate integration of the damage-exceedance probability function is also discussed later.

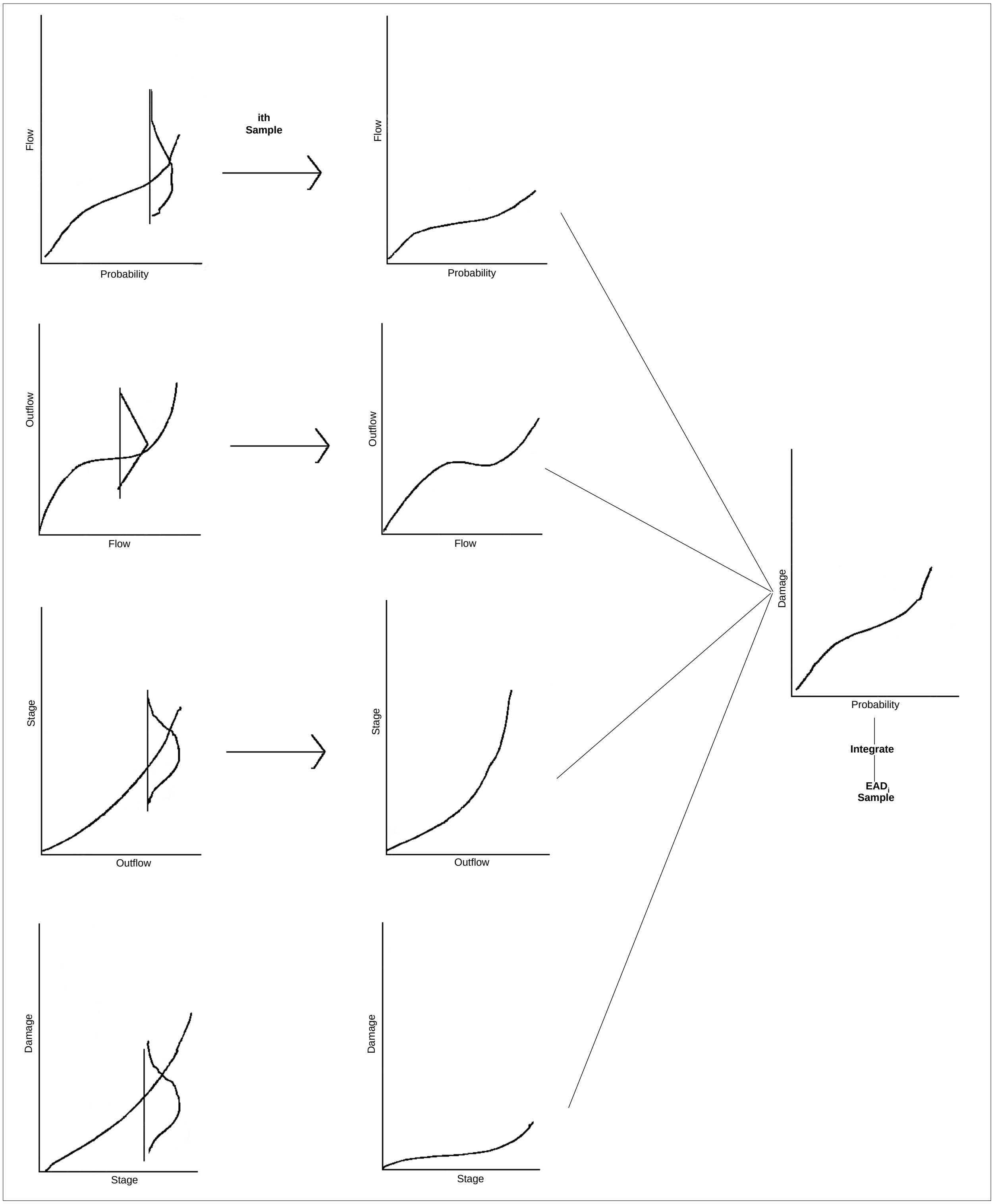


Figure C.4 Adding Computation of Regulated Outflow to Monte Carlo Algorithm for Computing EAD

C.5.2 Sampling from the Log-Pearson III Distribution

Random samples of a log-Pearson III (LPIII) exceedance probability curve are obtained from random samples of the mean and standard deviation of the logarithm of the flow, computing a log-normal relationship and adjusting for the skew of the distribution. This scheme produces the same sampling variability inherent in the calculation of confidence limits and expected probability as described in Bulletin 17B (IACWD, 1982), the federal guidelines for performing flood-flow exceedance probability analysis.

The random sampling is based on a Bayesian statistical approach for assessing uncertainty (Stedinger, 1983). A goal of Bayesian estimation is to develop the distribution of possible population parameters (the posterior distribution) by combining statistics of the observed sample (e.g., observed stream flows), and other information on the probable range of population parameters (the prior distribution). In this instance, the prior distribution is based on the assumption that an equally likely set of parent populations could have produced the estimated sample mean, standard deviation and resulting log-normal distribution. The resulting posterior distribution of the population mean and standard deviation is given by:

$$P[\mu > m] = F(\mu) = \Phi\left(\overline{X}, \frac{S}{\sqrt{N}}\right) \qquad (5)$$

$$P[\sigma^2 > s] = F(\sigma^2) = \frac{(N-1)S^2}{\chi^2_{(N-1)}} \qquad (6)$$

where $\overline{X}$ and S are respectively the sample mean and standard deviation of the logarithm of flow values obtained from a record length of N years, μ is the population mean, Φ( ) is the normal distribution defined by the parameters shown, σ is the population standard deviation, and $\chi^2_{(N-1)}$ is the chi-square distribution with N-1 degrees of freedom. Random estimates of the log-normal distribution are obtained by generating random estimates of normal and chi-square numbers, applying Equations 5 and 6 to obtain μ and σ and computing the distribution (Figure C.5).

This scheme for computing uncertainty does not account for the effect of shape or skew that is a characteristic of the LPIII distribution. This omission of the sampling uncertainty in skew is in keeping with the approach taken in the Bulletin 17B guidelines where sampling error is only estimated for a log-normally distributed variate. Consequently, the sampling scheme used for the LPIII distribution follows the Bulletin 17B method of computing uncertainty for a log-normally distributed variate and applying this uncertainty to an LPIII distribution with the same mean and standard deviation as the log-normal distribution. Given this estimation of uncertainty, the samplings of the LPIII distribution (Figure C.6) proceeds as follows:

1. **Compute log-normal and LPIII distributions from sample statistics**
   The log-normal and LPIII distributions are calculated using the following frequency factor equations:

$$\log_{10} Q^s = \overline{X} + Z_p S \qquad (7)$$

$$\log_{10} Q_G^S = \overline{X} + K_{G,P} S \qquad (8)$$

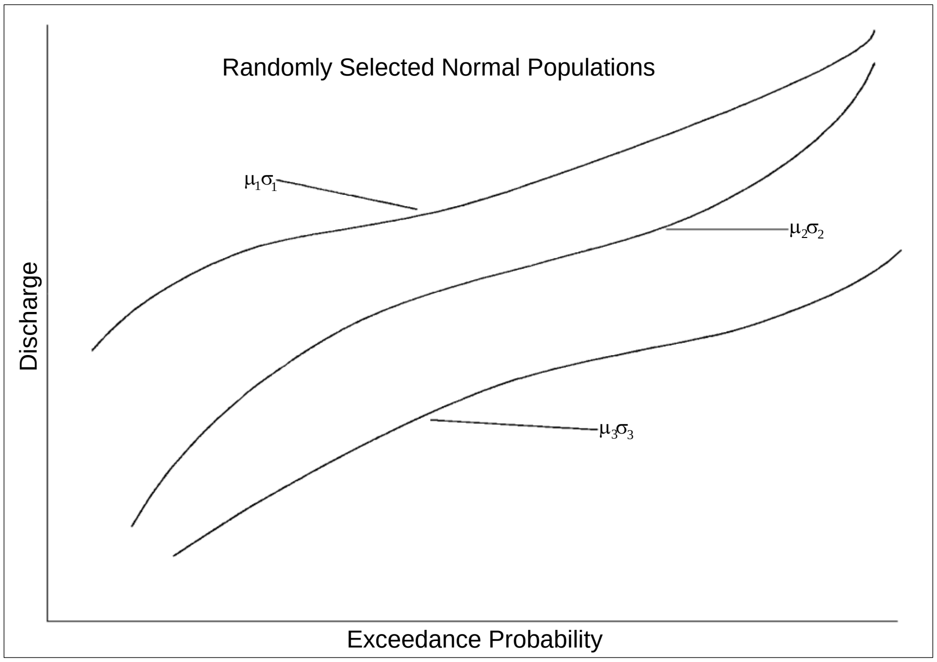


Figure C.5 Random Samples of Normal Populations from Population Parameters μ, σ

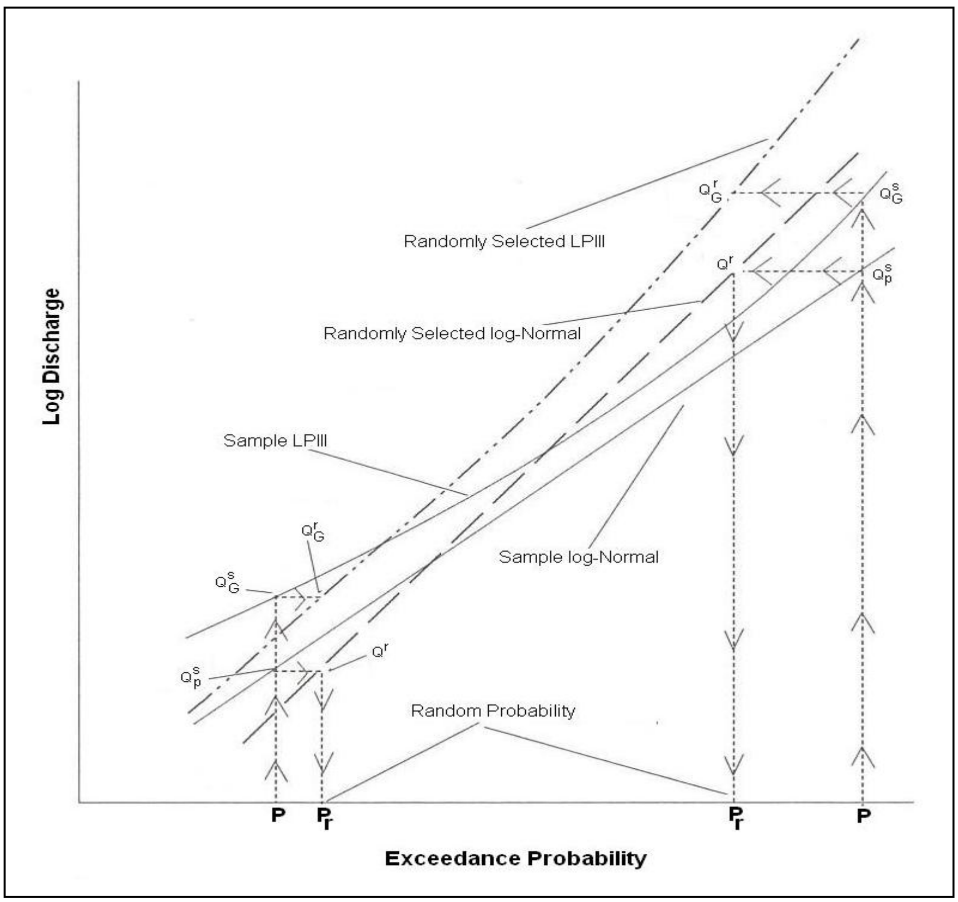


Figure C.6 Random Selection of LPIII Distribution from Random Log-Normal Distribution where Q^s and Q_G^s are respectively the flows for the log-normal and LPIII distribution, Z_p is the standard normal deviate and $K_{G,P}$ is the LPIII deviate for a sample skew G, and exceedance probability P.

2. **Randomly select a sample normal distribution**
Utilize Equations 5 and 6 to obtain a sample of the population mean and standard deviation. Compute the log-normal distribution from the population values as:

$$\log_{10} Q^r = \mu + Z_p \sigma \tag{9}$$

3. **Calculate the random probabilities resulting from the randomly selected normal distribution**
Compute the random probability associated with the randomly selected normal distribution for a discharge with exceedance probability computed from Equation 7 as:

$$P_r = \Phi^{-1}\left(\frac{\log_{10} Q_P^s - \mu}{\sigma}\right) \tag{10}$$

where $Q_P^s = Q^r$ is the flow value computed by Equation7 for exceedance probability P and Φ^{-1} is the inverse normal distribution (i.e., given a flow value, the inverse provides the exceedance probability).

4. **Utilize the random probabilities to obtain a random sample of the LPIII frequency curve**
Assign the random probability P_r to a flow value $Q_G^r = Q_G^s$, where Q_G^s was obtained from Equation 8. Compute as many pairs of P_r, Q_G^r values as needed to adequately define the sample LPIII exceedance probability curve.

C.5.3 Random Sampling of Graphical or Non-Analytic Relationships

The sampling of non-analytic or graphical relationships is necessarily ad hoc because a statistical sampling theory is not available. The algorithm used in this instance applies to any of the other contributing relationships used in the computation of EAD: 1) non-analytic stage or graphical exceedance probability curves; 2) discharge transforms; 3) rating curves; 4) wind waves and 5) stage damage relationships.

Random sampling of any of the graphical relationships is done by calculating the values for a particular confidence limit (Figure C.7). The algorithm is simply employed by: 1) generating a uniform random number between 0 and 1; and 2) calculating the confidence limit values for the particular relationship of interest. For example, if 0.95 is the value resulting from the randomly selected value, then the 95% chance confidence level confidence limit is calculated as the randomly selected relationship for the algorithm described previously. Note, that the confidence limit for a contributing relationship is randomly selected independently of other confidence limits randomly selected for other contributing relationship used in the Monte Carlo simulation.

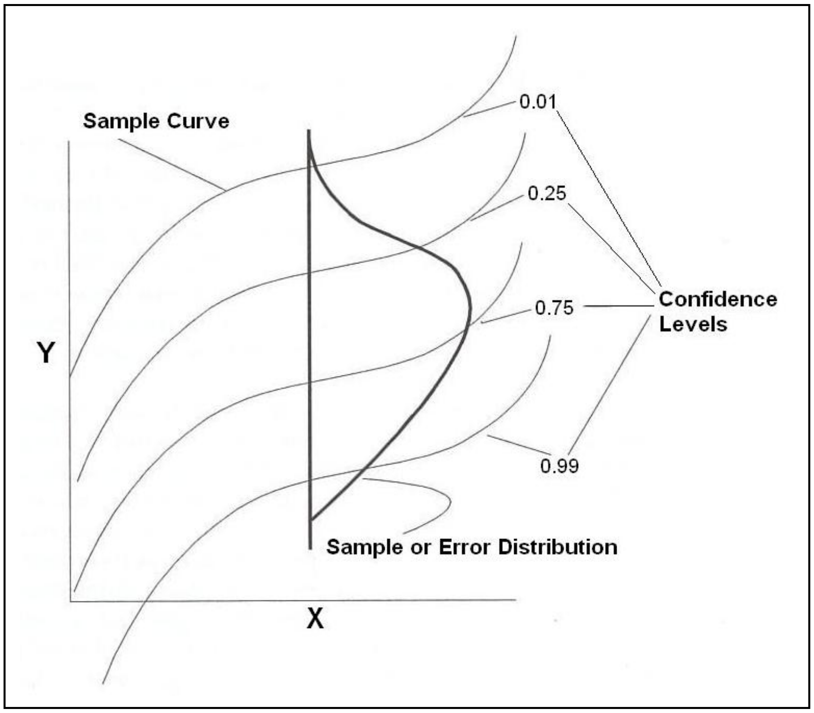


Figure C.7 Sampling of Non-Analytic or Graphical Relationships

Classical statistical theory cannot be used to justify sampling possible population values from confidence limits as is done with this algorithm. Instead, justification for this algorithm must be sought from the sampling of the log-Normal distribution described in the previous section, which relies on a Bayesian approach. As was pointed out, the Bayesian approach results in the same uncertainty distribution for population values as is obtained with a classical statistical approach to obtain the uncertainty distribution used in the 17B guidelines. In the case of the approach for graphical exceedance probability curves, the sampling from confidence limits obtained from an uncertainty distribution might be justified in analogy with this Bayesian approach.

The difficulty with this algorithm is that the sampling based on confidence limit values is very restrictive on the possible shapes of the graphical relationship. This restriction on shape results in some overestimation in the variance of the derived distribution of EAD. However, generalizing the shapes used in the sampling algorithm depends on some parametric representation of the graphical relationships. The representation is not available, leaving the current algorithm as the best available at this time.

C.5.4 Random Sampling of Uncertainty Relationships Using a Random Number Generator

The sampling of uncertainty distributions depends on the generation of uniform random numbers in the range 0.0 to 1.0 by the linear congruential method (Davis and Rabinowitz, 1967) and the transformation of the uniform numbers to the distribution desired. The linear congruential method takes the form:

$$X_{n+1} = \frac{(aX_n + b) \bmod m}{m} \tag{11}$$

where X_n is the previous number selected, X_{n+1} is the current number to be generated, a and b are constants, *m* is a constant known as the modulus, and "mod" is the modulus or remainder function. The sequence is started for n=1 by a seed value that is set to a default value within the software. The selection of the constants and seed value is critical for an effective generation's scheme. This generation scheme, as well as any other using a computer algorithm, is considered to produce pseudo-random numbers because the sequence repeats with period depending on the selection of the constants in equation (11). The constants are selected as shown in Table C.3 to obtain a long period of random numbers that is approximately equal to the size of the modulus, m. The resulting sequence of numbers has characteristics that are effective for performing numerical integration with Monte Carlo simulation.

Table C.3
Constants for Linear Congruential Method[1]

seed	1331124727
a	65539
b	0
m	2147483647

[1] Constants appropriate for 32-bit machine. Used in Equation 11.

The uniform random numbers can be used to randomly sample the graphical relationship directly. As described in the previous section, a number selected at random between 0.0 and 1.0 can be used to select the confidence level for selecting a graphical curve.

The application to the LPIII distribution requires that deviates from both a normal distribution and a chi-square distribution be obtained from a transformation of the numbers randomly sampled from a uniform distribution. The normal deviates can be obtained from the following transform due to Box and Muller (1958) (also see, Press et al., 1989):

$$n_i = u_i \left[-\frac{2\ln(s)}{s} \right] \tag{12}$$

$$n_{i+1} = u_{i+1} \left[-\frac{2\ln(s)}{s} \right] \tag{13}$$

where u_i and u_{i+1} are numbers randomly selected from a uniform distribution defined between -1.0 and 1.0, n_i and n_{i+1} are numbers that will be normally distributed, and s is computed as:

$$s = \left(u_i^2 + u_{i+1}^2\right)^{\frac{1}{2}} \qquad s \geq 1.0 \tag{14}$$

The application of this transform is accomplished by converting the uniform numbers generated over the range 0.0 to 1.0 in Equation 11 by letting $u_i = 2(X_i) - 1.0$. When the resulting uniformly distributed numbers result in s < 1.0, the current pairing is discarded and a new pair is generated. On the average, about 1.27 uniform random variates are needed to generate a single normally distributed variate.

Chi-square deviates are obtained by applying the inverse theorem (see Mood et al., 1969, theorem 12, Chapter 5). This theorem is applied by interpolating a chi-square variate from a table of the chi-square cumulative distribution function given a random probability equal to a number generated from the uniform distribution using Equation 11. The algorithm used to compute the chi-square distribution was obtained from Press et al. 1989, pg 160. The algorithm utilizes the following relationship between the chi-square and incomplete gamma function:

$$P\left[\chi^2_{N-1} < y\right] = G(a,x) = \int_0^x e^{-t} t^{a-1} dt \qquad 0 \le x \le \infty \tag{15}$$

where N is the period of record used to compute the sample standard deviation of the LPIII distribution, a = (N-1)/2, x = (y/2), and G( ) is the incomplete gamma function.

C.5.5 Numerical Error Tolerance for Simulations

The numerical integration accuracy of the Monte Carlo simulation improves with the number of simulations. The accuracy criteria developed for the simulation relies on the central limit theorem for the mean and the asymptotic normality of uncertainty distributions about exceedance probability curves. The central limit theorem (see Mood et al., 1969) states that the sample mean of any random variable is asymptotically normally distributed about the population value. In the case of this application of Monte Carlo simulation, the sample EAD results from a finite number of simulations, and the population value is the value that would be obtained from an infinite number of simulations (i.e., the no numerical error solution).

The following confidence limit results from asymptotic normality of the sample EAD:

$$P\left[-z_{1-\alpha} \le \frac{M_{EAD} - \mu_{EAD}}{\frac{S}{\sqrt{n}}} \le z_{1-\alpha}\right] = 1.0 - \alpha \tag{16}$$

where M_{EAD} is the average EAD obtained from n simulations, μ_{EAD} is the numerical error EAD, S is the standard deviation of the damage exceedance probability curve estimated after n simulations, and $z_{1-\alpha}$ is the standard normal deviate for confidence level α. This confidence limit can be rearranged to produce an error bound of the numerical integration error:

$$\frac{z_{1-\alpha} S}{M_{EAD}\sqrt{n}} = \frac{M_{EAD} - \mu_{EAD}}{M_{EAD}} \le \varepsilon \tag{17}$$

where ε is a tolerance for the confidence level α. The error bound is set in the software such that α=0.95, ε=0.01 and n≤**500,000**. If the limiting number of simulations is reached the computation of EAD terminates with a warning.

A similar error bound is computed for exceedance probability function. In this case, the computed quantile (e.g., flow, stage or damage) is the mean value derived for the exceedance probability of interest. The error bound focuses on the exceedance probability where the corresponding quantile has the largest estimation standard error. This estimation standard error is set to S in Equation 17 and computed as part of the simulation. The confidence limit and tolerance are set equal to that used for the error bound of EAD. The simulations will terminate only when the error tolerance for both estimating exceedance probability function and EAD is met or when the maximum number of simulations is reached.

The error bounds constrain the numerical integration error of the simulation but does not reduce the uncertainty in estimates of EAD or exceedance probability curves. The uncertainty in estimate is a function of the error in models and estimates of parameters as indicated by the uncertainty distributions provided. The uncertainty shown by the sensitivity analysis depicted in Figure C.2 is not altered by the number of simulations performed. Rather, the number of simulations reduces the numerical error involved in combining the relationships via the algorithm depicted in Figure C.3.

C.5.6 Integrating the Damage-Exceedance Probability Function to Obtain EAD

The final computation in an individual Monte Carlo simulation is to integrate the damage-exceedance probability function to obtain a sample value of EADi as shown in Figure C.3. The damage-exceedance probability function is not analytic being derived from rating curves, stage-damage relationships, etc., that are not analytic. Consequently the following trapezoidal integration scheme is used to obtain an estimate of EAD_i:

$$EAD_i = \int_0^{\infty} D f_i(D) dD \sim \sum_{j=1}^{j=h} \overline{D_j}\,\overline{f_{i.j}} \Delta D_j \sim \sum_{j=2}^{j=h-1} \overline{D_j}\left(p_j - p_{j+1}\right) + D_1 p_1 + D_h p_h \qquad (18)$$

where $f_i(D)$ is the probability density function (PDF) obtained from the ith simulation, for annual damage, D; h is the number of incremental intervals of size ΔD used to approximate the differential dD; $\overline{D_j}$ and $\overline{f_{i,j}}$ are the average values of D and $f_i(D)$ over this interval, and the difference of exceedance probabilities over this interval $\left(p_j - p_{j+1}\right) = \overline{f_{ij}} \Delta D$; and, D_1p_1 and D_hp_h are end point approximations to the end intervals of integration, zero and infinity. The assumption is made in the software that $D_1 = 0$, resulting in $D_1p_1 = 0$.

The trapezoidal rule approximation accuracy improves with increasing number of intervals, h. The number of intervals is determined by computing EAD for damage exceedance probability curves determined by a sensitivity analysis such as shown in Figure B.2 prior to performing the Monte Carlo simulation. The sensitivity analysis is performed by obtaining damage exceedance probability curves by combining confidence limit estimates of the contributing relationships at the same confidence level. The confidence limits investigated are obtained for confidence levels, 0.5, 0.75, 0.25, 0.9, 0.1, 0.99, 0.01, 0.999, 0.001.

The number of intervals, h, is obtained by performing recursive integration for each confidence limit investigated in the sensitivity analysis. The recursive procedure involves: 1) selecting an interval size; 2) computing EAD; 3) dividing the interval size in half, where appropriate, and re-computing EAD; 4) computing the relative difference between EAD values obtained in steps (2) and (3); and 5) determining if the relative difference in step (4) is less than 1%; if this tolerance is met; then the interval used in step (2) is selected; otherwise steps, 2-4 are repeated with the interval size used in step (3) used in step (2). The division of interval sizes in step (3) is only performed when the interval size reduction will make a significant difference to the computation of EAD. This limits the number of intervals used which is important to the computational efficiency of Monte Carlo simulation. The more intervals used, the more computational time required to perform a simulation. Intervals are divided until the error tolerance is met or the maximum number of 200 is obtained. Experience has shown that 200 intervals provide sufficient accuracy given the data typically available.

C.6 Uncertainty Distributions

C.6.1 General

The estimation of uncertainty distributions for the contributing relationships will involve a certain amount of judgment, except for the case of a flow or stage exceedance probability curve where the uncertainty is determined from the length of record. The judgment used in estimating uncertainty for other contributing variables should correspond to the same factors contributing to uncertainty in the exceedance probability curves. The uncertainty in the exceedance probability functions is due to the estimation uncertainty in the parameters, which are the mean and standard deviation for the LPIII (the skew being ignored).

This focus on parameter uncertainty effectively examines the uncertainty in the mean relationship given a set of scattered observations. In other words, the focus is on the uncertainty in fitting an exceedance probability function to an observed set of plotting positions and does not reflect the scatter of the plotting positions about the best estimates.

To understand the difference between uncertainty in fitted relationships and the uncertainty due to scatter, consider a split sample exceedance probability analysis of a gage having 100 years of record. Estimate both pairs of frequency curves and determine the top ranked event from separate 50-year records. In general, the difference between the 1% chance flow estimated by the frequency curves will be considerably less than the difference between the top ranked events. The smaller variation in the fitted relationships, as compared to the plotting positions, represents the difference between uncertainty for best fit relationships and that for scatter about these relationships. If uncertainty in the contributing relationships such as rating and stage-damage curves is based on scatter, then the specified uncertainty will be too great. This in turn will probably increase the magnitude of the EAD best estimate and certainly increase the variance of the EAD distribution.

Therefore, the principle focus of estimating uncertainty should be on the potential variation in the best estimate of the contributing relationship. Consequently, if a sensitivity analysis is performed to determine the uncertainty in a contributing relationship, such as in varying Manning n to determine errors in rating curves, then the parameters varied should be reasonably likely to occur together. Combining extreme parameter values probably reflects scatter rather than the reasonable variation in a fitted relationship.

The error distribution about exceedance probability curves is determined by the effective record length and the type of exceedance probability curve specified. In the case of the LPIII distribution, the uncertainty is computed as described previously. Also, refer to ETL 1110-2-537 for the method used to calculate the uncertainty distribution for non-analytic (graphical exceedance probability curves). Normal, log-normal and triangular error distributions are available for specifying uncertainty about other contributing relationships, as is described in the next two sections.

C.6.2 Triangular Error Distribution

The triangular distribution is the simplest available for use with contributing relationships that are not exceedance probability functions (Figure C.8). This triangular distribution is specified for either: 1) each paired value describing the contributing relationship (e.g., discharge- stage function); or, 2) for a specified value in the paired relationship (e.g., for 1,000 cfs corresponding to a stage of 10.0 feet). In the case of the specified value, the bounds on the error distribution are linearly interpolated to zero for values less than this specified value and remains unchanged for values greater than this value.

The parameters of the distribution are the mode and the range. The mode is the most frequently occurring value, or the peak of the probability density function for the triangular distribution. The range is simply defined by the minimum and maximum possible values for the dependent variable in the paired relationship.

Inspection of Figure C.8 shows that the triangular distribution need not be symmetric. The effect of the asymmetry is to cause the mean or expected value associated with the triangular distribution to be different than that for the mode. Consequently, Monte Carlo simulation will produce on the average a contribution relationship that is different than might be assumed to occur when specifying the mode as a no uncertainty estimate of the relationship.

C.6.3 Normal and Log-Normal Distributions

The normal distribution is specified by a mean and standard deviation of the errors (Figure C.9). The log-normal distribution also is specified by a mean and standard deviation of the logarithms (base 10) of interest. Consequently, estimation of the errors needs to be performed in log space

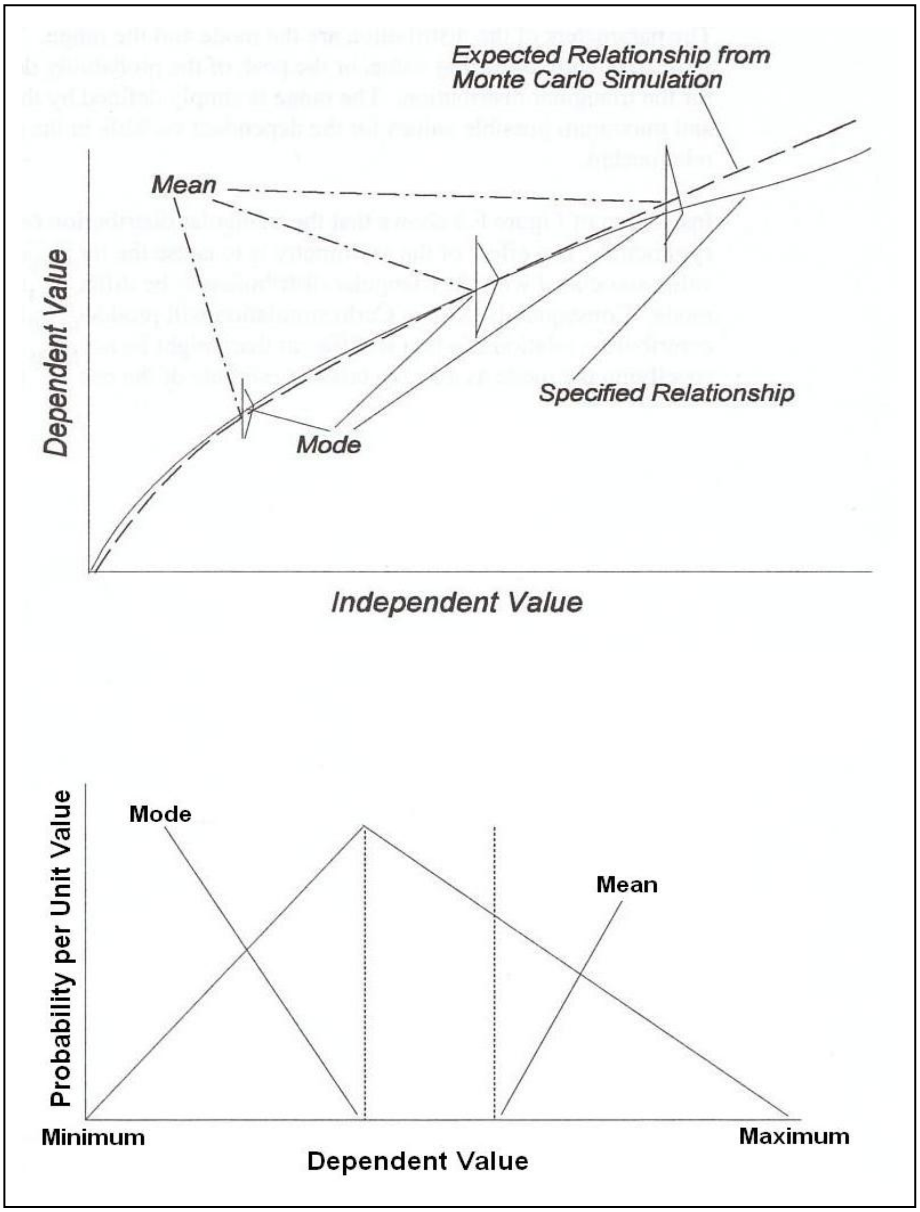


Figure C.8 Triangular Distribution Application

for this distribution. For example, the paired values of discharge and stage should be plotted on $\log_{10}$-$\log_{10}$ scale; and the best fit relationship and the errors should be determined from this scale. The relationship is then specified by the untransformed best fit values (i.e. by taking anti-logs of the best fit) together with the standard errors of the logarithms.

The normal distribution is symmetric with respect to the mean. Consequently, the mean or expected relationship obtained from the Monte Carlo simulation will be the same as the specified relationship. This differs from the average result obtained with an asymmetric triangular uncertainty distribution as explained in the previous section and shown in Figure C.9. The estimation of the log-normal distribution is most conveniently performed in log-space, thus reducing the problem in estimating a normally distributed log variate. However, the log-normal uncertainty distribution is asymmetric when plotted on a linear scale, and, like an asymmetric

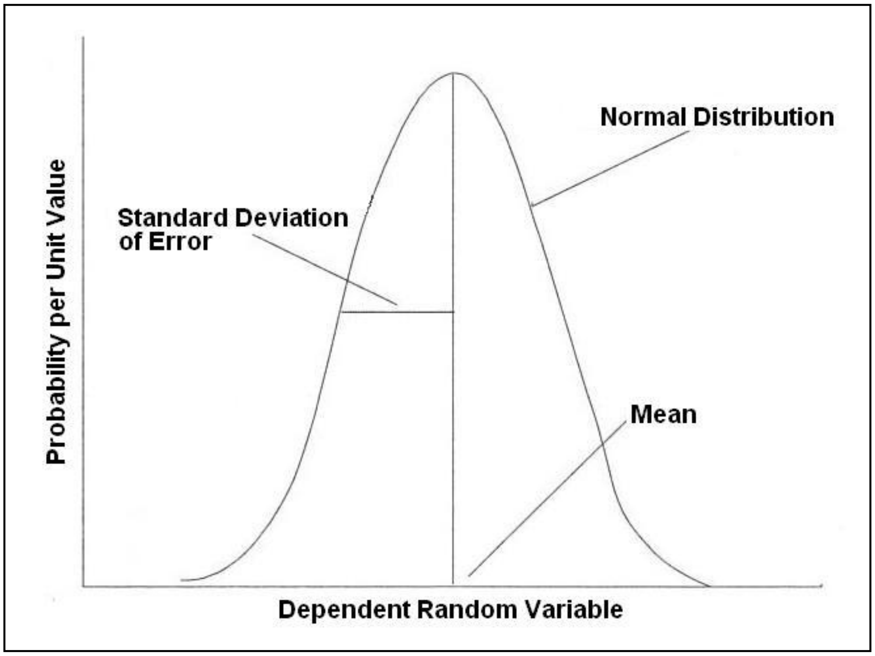


Figure C.9 Normal Distribution of Errors

triangular distribution, will result in an average relationship that differs from the specified relationship when performing a Monte Carlo simulation.

C.6.4 Application to Stage versus Damage Relationships

The Monte Carlo simulation algorithm reduces the computational effort required by only computing total damage. However, stage versus damage is specified for each damage category with a corresponding uncertainty in the estimates. The total damage is easily obtained by aggregating the specified (no uncertainty) estimates in the case of triangular and normally distributed uncertainty distributions. Logarithms of the specified estimates are added in the case of log-normally distributed uncertainty distributions.

The uncertainty distributions are not so easily aggregated. The assumption is made that the uncertainty estimates are uncorrelated. Consequently, the standard errors of the normal distribution and the log standard errors for the log-normal distribution can be added by summing these standard errors squared and taking the square root (variances added). The triangular distribution is handled in the same manner in that the maximum and minimum ranges are added to obtain the range of an equivalent triangular distribution.

C.7 Levee Analysis

Computation of damage exceedance probability functions with levees is straight forward when the levee only fails due to overtopping, but requires some additional computations when geotechnical failure can occur. The computation of the damage exceedance probability curve for levee failure due to overtopping only is easily done by setting the zero damage point to a stage corresponding to the top of levee. The integration of the damage exceedance probability curved using equation (18) to obtain EAD is then applied as without a levee.

The computation of the damage exceedance probability curve when geotechnical failure is possible needs to consider the probability of failure below the top of levee. The damage exceedance probability curve is calculated in this situation as follows (Figure C.10):

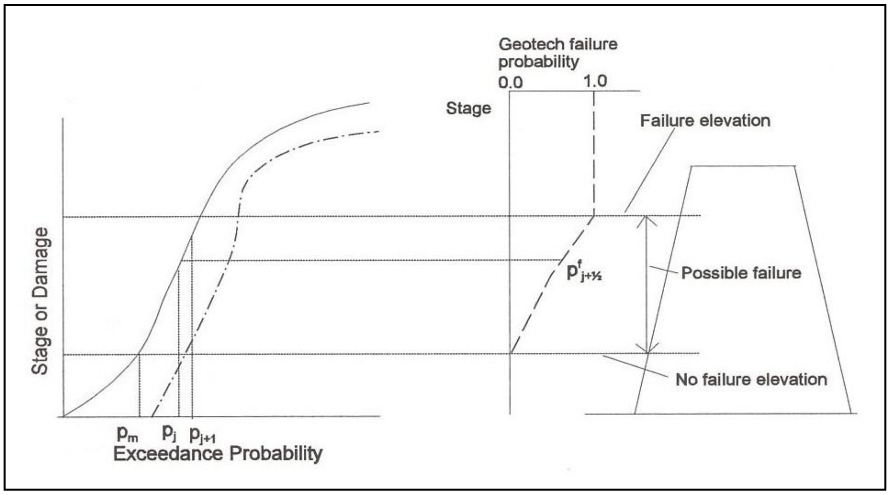


Figure C.10 Damage Considering Levee Geotechnical Failure

$$P\left[d_j \le D < d_{j+1}\right] = \left(p_j - p_{j+1}\right)p^f_{j+\frac{1}{2}} \qquad p_j \le p_m \tag{19}$$

where P[d_j-≤ D < d_{j+1}] is read as "the probability that the annual damage, D, will be in the interval $d_{j-1\le}$ to d_j"; p_m is the exceedance probability corresponding to the stage that cannot cause damage due to geotechnical or overtopping failure; p_j and p_{j+1} are the exceedance probabilities for stages that cause damage corresponding to $d_{j\le}$ and d_{j+1} in the absence of the levee; and $p^f_{j+1/2}$ is the failure probability of the levee for the stage with exceedance probability midway between p_j and p_{j+1}. Equation 18 then can be applied to this damage exceedance probability curve to obtain EAD by letting:

$$\overline{D_j} = \frac{d_j + d_{j+1}}{2} \tag{20}$$

and substituting:

$$\left(p_j - p_{j+1}\right)p^f_{j+1/2} \rightarrow \left(p_j - p_{j+1}\right) \tag{21}$$

C.8 Project Reliability and Flood Risk Computations

Reliability is computed as the exceedance probability for a target stage or the likelihood of levee failure. Flood risk is defined as the probability of one or more exceedances of the target stage or levee failures in a specified number of years.

The target stage is determined by interpolation from the stage versus damage relationship using a specified fraction of a damage for a specified exceedance probability. This damage is determined from a damage-exceedance probability function obtained by combining traditional estimates of the contributing relationships (i.e., contributing relationships without uncertainty) for the without-project condition.

The exceedance probability for this stage or the levee failure probability is specified as both a "median" and “expected” value. The median value is obtained from the stage-exceedance probability curve obtained by the traditional (no uncertainty) method. The expected value is obtained by averaging the target stage or levee failure probability over all the Monte Carlo simulations.

The risk of flooding one or more times in NR years is computed as:

$$R = 1 - (1 - p)^{N_R} \tag{22}$$

where p is either the probability of exceeding the target stage or levee failure. An expected value of R is reported as the average over all Monte Carlo simulations.

C.9 References

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HEC-FDA Version 1.4 Summary Report

There have been many changes to HEC-FDA since version 1.2.5a. The two major areas of change are:

- Wide-ranging internal code improvements that facilitate the future migration to a Java-based interface.
- Implemented the "Less Simple" method for computing uncertainty about graphical probability curves.

The internal code changes have an insignificant effect on results, but rectify some previously limiting design decisions, expand and simplify user access to more model results and data, and fix some bugs encountered along the way. In particular, the database software was totally rewritten and all memo fields (with the exception of the water surface profiles) are written in tab-delimited text format rather than binary format so that the user can visualize and edit the data. The change in the database allows users to edit data outside of FDA by cutting and pasting between a spreadsheet and the memo field using dBASE or MS Access. The internal overhaul also improved the modeler experience regarding some long-standing usability issues with the program.

The methodology for computing uncertainty about graphical probability curves was changed because the order statistics methodology implemented in FDA 1.2.5a gave inconsistent results when comparing change in parameters as a function of the equivalent length of record. There were two finalists among several candidates for the new algorithm: the "simple method" and the "less simple method". The new methods provide a solution to the problem while calculating reasonable confidence limits about graphical curves. HEC chose Less Simple as the superior method and coded it as the default, although both methodologies remain implemented in FDA 1.4. This improved implementation of order statistics carries a significant impact on the performance calculations for some projects.

This report is presented in four sections:

1) Summary of changes to version 1.4 since version 1.2.5a
2) Description of the algorithms to compute uncertainty about graphical probability curves
3) Overall observations about the methods
4) Comparison of results from version 1.4 (two uncertainty methods) versus 1.25a.

Two appendices give specific examples from different data sets:

- Appendix A, HEC-FDA Version 1.4 Graphical Probability Curve Uncertainty versus Equivalent Length of Record
- Appendix B, HEC-FDA Version 1.4, Comparison of results with previous versions

Section 1: Summary of Changes to HEC-FDA Version 1.4 since Version 1.2.5a

The following summarizes the program changes and is organized by functional area:

- Expected annual damage calculations including calculation of uncertainty about graphical probability curves (EADLIB library).
- Stage-aggregated damage calculations (SD library).
- Database code (DB library)
- Graphical user interface (GUI) code

EADLIB Library

The changes to the EADLIB library include:

1. Changed diagnostic output that is written to text files for greater clarity.
2. Fixed various minor bugs
3. Replaced the order statistics method with the "less simple" method of calculating uncertainty about graphical probability curves.
4. Added checks to prevent divide by zero calculation in interpolation routines. This prevents some computational aborts.
5. Made several modifications in output including initializing the DFSIM array to zero so that if there is no damage, zeroes are printed in results tables (it was giving bogus numbers).

SD Library

The changes to the SD library included some related to the changed database code and others related to enhancements or bugs. They include:

1. Changed a lot of the formatting for clarity.
2. Modified the code that stores computed stage-aggregated damage functions. FDA now attempts to replace stage-damage results if already existing rather than continually deleting results and appending new results with new ID's. This maintains clarity internally to the database and economizes on the need for new internal identifiers.
3. Enhanced the computed stage-aggregated damage naming scheme. If a record is new, FDA generates the function name from the plan / year / reach / category so that it is recognizable when editing the file with dBASE.
4. Increased the function names from 16 to 32 characters which allows the user greater flexibility in naming functions, structures, etc..
5. Modified the calculation for the range in stages needed for calculating stage-aggregated damage including cases when negative stages are used. Previously, the stage range did not always go low enough to capture all the damage.
6. Changed the import/export routines to handle longer function names.
7. Changed the import/export routines to additionally import/export frequency curves, rating curves, and levee data.
8. Made numerous changes to be compatible with new database code.
9. Modified import/export to manage two lists of exceedance probabilities: 1) default, and 2) current.
10. Changed the way structures are filtered for computing stage-aggregated damage to take advantage of the database library query capability for more robust filtering.

DB Library

The DB library was completely rewritten to facilitate converting from the older database of version 1.2.5a and storing data in tab delimited text format in memo fields. The changes include:

1. Added miscellaneous utility methods to enhance internal database management.
2. Added a class to update the database from version 1.2.5 to 1.40.
3. Made major changes to database code for new database format where data written to memo fields is written in tab-delimited format (rather than binary format). This excludes the water surface profiles for efficiency reasons. Also made changes for additional fields such as date, sort key, etc. For example, there is a date stamp in every record that records the last date/time that a record was stored in the database.
4. Modified the error distribution class to correct some problems with triangular distributions.
5. Modified the code to store exceedance probabilities with the water surface profile object making it possible to have different probabilities for different WSP sets.
6. Internally, removed the event type from the water surface profile class. Instead, the profile is accessed by integer index or exceedance probability. This was done for internal programming reasons.
7. Modified the analysis years to be treated like plans, reaches, etc. using internal ID's rather than integer year number. Allows the user to change years while maintaining integrity of database.
8. Renamed several of the database files so that they are consistent and recognizable by the user.
9. Increased the function names from 16 to 32 characters to add flexibility in user naming schemes.

GUI Code

1. Results reports are written to the tab delimited file Fda_Results.txt for import into spreadsheets and inclusion in reports.
2. Made many modifications so that GUI could access new database code.
3. Modified the "add record" mode to append a blank record and update the record navigator so that it would properly display the current record location.
4. Corrected problem with triangular distribution in depth-damage functions.
5. User can now edit the "Without" plan. The user can internally change the pointer from the without plan to some other plan. It requires the use of dBASE or MS Access.

Section 2: Description of Algorithms for Computing Uncertainty about Graphical Probability Functions

ETL 1110-2-537 gives a detailed description of the order statistics algorithm for determining the uncertainty about graphical probability functions, and provides examples of that algorithm and two simplified algorithms associated with it. A short summary of each method is presented below.

Order Statistics Method Description

The order statistics method is based on both order statistics and the binomial distribution. No assumption need be made concerning the analytic form of the frequency curve. Under these circumstances the statistic derived to estimate uncertainty is termed "non-parametric" or, more to the point, "distribution free." ETL 1110-2-537 contains more detail on this method, but simply described, the uncertainty around a particular quantile of the graphical frequency curve is based on the likelihood of a certain number of ordered observations in a random sample being less than that quantile, which is described with the binomial distribution. The order statistic approach is therefore limited to calculating uncertainty in the estimated frequency curve for the range of observed data or, alternatively, the likely observations in the equivalent length of record. For example, when 20-years of data are available, the largest event likely to have occurred is near the 5% exceedance probability event, and the order statistics approach will only be able to define the distribution of uncertainty (and so accurately estimate the confidence interval) for quantiles ranging approximately from 0.25 to 0.75. Extrapolating the uncertainty estimates beyond the range of data is performed by using *asymptotic approximations* of uncertainty distributions. *(These asymptotic approximations are also used below as simpler methods of defining the uncertainty distributions.)* Both the order statistic estimates and asymptotic estimates of uncertainty are based on the equivalent record length, n. The transition between the order statistic method and the approximations is made by redefining the record length, n, at the limits of the observed data that produces the same standard error. In order to make use of this combined uncertainty description, the standard deviations computed from the order statistics estimates and the asymptotic approximations are paired with a Normal distribution as the final description of uncertainty around a graphical frequency curve. FDA version 1.2.5 (and all previous versions) use the order statistic methodology.

"Simple Method" Description

The "simple method" is based on one of the asymptotic approximations used to extrapolate the order statistics method, but is used for the entire probability curve rather than just the extremes. Therefore, it does not use order statistics. The simple method is based on the uncertainty in a Normal distribution. Using the quantile definition $Y_p = M + Z_p S$ and the standard error of the mean, M and the variance S^2, the variance of the quantile S_Y^2 is described by:

$$S_Y^2 = \frac{S^2}{n} + Z_p^2 \frac{S^2}{2n}$$

where M is the mean of the frequency curve, S is the standard deviation of frequency curve, n is the record length, S_Y^2 is the variance of the quantile Y_p estimate, and Z_p is a normalized deviate computed as:

$$Z_p = \frac{Y_p - M}{S}$$

"Less Simple Method" Description

The "less simple method" is based on the other asymptotic approximation used to extrapolate the order statistics method. This approximation is based more closely on the features of the order statistics method, and provides a result with the same characteristics, such as smaller uncertainty when the frequency curve is flatter, and larger uncertainty when it is steeper. Here, the variance of the quantile S_Y^2 is described by the variance of a sample count for the Binomial distribution, where $S_X^2 = p(1-p)n$. Conversion to a proportion, and use of a first order Taylor expansion, provide:

$$S_Y^2 = \frac{p(1-p)}{n\, f(y)^2}$$

where S_Y is the standard deviation of the uncertainty distribution, p is the non-exceedance probability, n is the record length, and f(y) is the probability density function (PDF) for variable Y, derived from the frequency curve of interest. Note that the PDF is the inverse of the slope of the frequency curve, which is a CDF with probability on the horizontal axis.

Because the "less simple method" is based on the inverse slope of the CDF or frequency curve, it can get very large for the extreme ends of curve (where a CDF slope approaches zero). In order to avoid unreasonable results, the standard deviation computed for the 0.01 quantile is used all quantiles larger ($p < 0.01$), and the value for the 0.99 quantile is used for all quantiles smaller ($p > 0.99$).

Version 1.4 adopted use of the "less simple" method for determining uncertainty.

Section 3: Overall Observations about the methods

When using the 1.2.5a implementation of order statistics and the “simple” method, uncertainty is computed based on the overall slope of the function. This has the undesirable affect that the lower end of the curve affects the uncertainty about the upper end of the curve. With the “less simple” method, the uncertainty in not a function of the overall slope of the function – it is a function of the localized slope. In the figures below, two estimates for the 0.999 exceedance probability were made (1 cfs and 100 cfs). The first figure below contains version 1.25a results which show a difference in uncertainty about the upper end of the curve compared to the second figure which contains version 1.4 results using the less simple method which show no difference in uncertainty in the upper end of the curve.

With the less simple method, there is less uncertainty when slope is flat and more uncertainty when the slope is steep. The figures below show results from version 1.25a and 1.4. The version 1.25a uncertainty at the 0.01 exceedance probability ranges from 28,800 to 232,000 cfs whereas the version 1.4 uncertainty at the 0.01 exceedance probability ranges from 57,500 to 115,800 (at plus and minus two standard deviations).

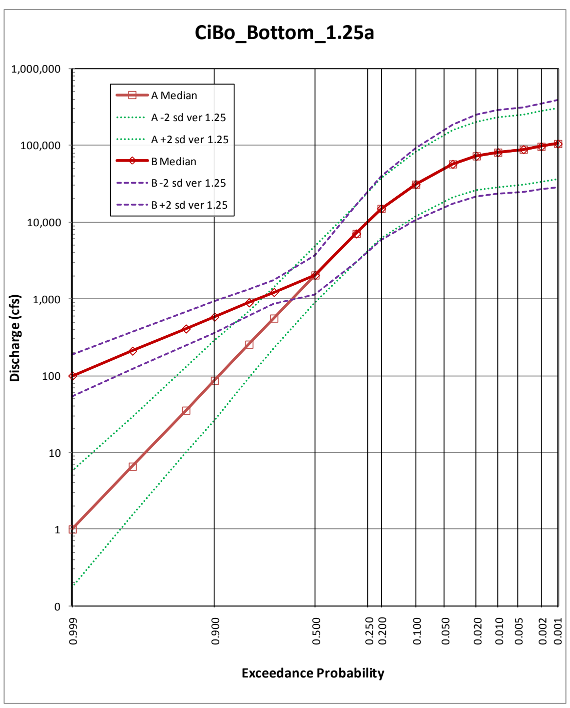

Figure 1 Cibolo Creek, version 1.25a

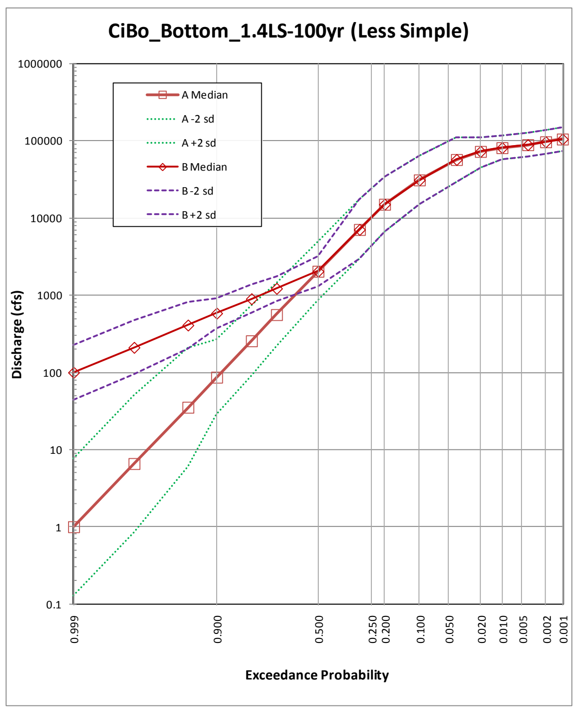

Figure 2 Cibolo Creek, version 1.4 Less Simple

Figure 3 shows a stage-probability curve that has a very flat portion around the 0.10 exceedance probability and a very steep portion around the 0.01 exceedance probability. It is an excellent example of how the slope of the curve affects the uncertainty about the curve. The version 1.4 less simple method (LS) is sensitive to this slope. At 0.10 exceedance probability, the difference between plus and minus 2 standard deviations is 0.98 (version 1.2.5) and 0.17 (version 1.4 LS). At 0.01 exceedance probability, the difference between plus and minus 2 standard deviations is 1.39 (version 1.2.5) and 9.38 (version 1.4 LS).

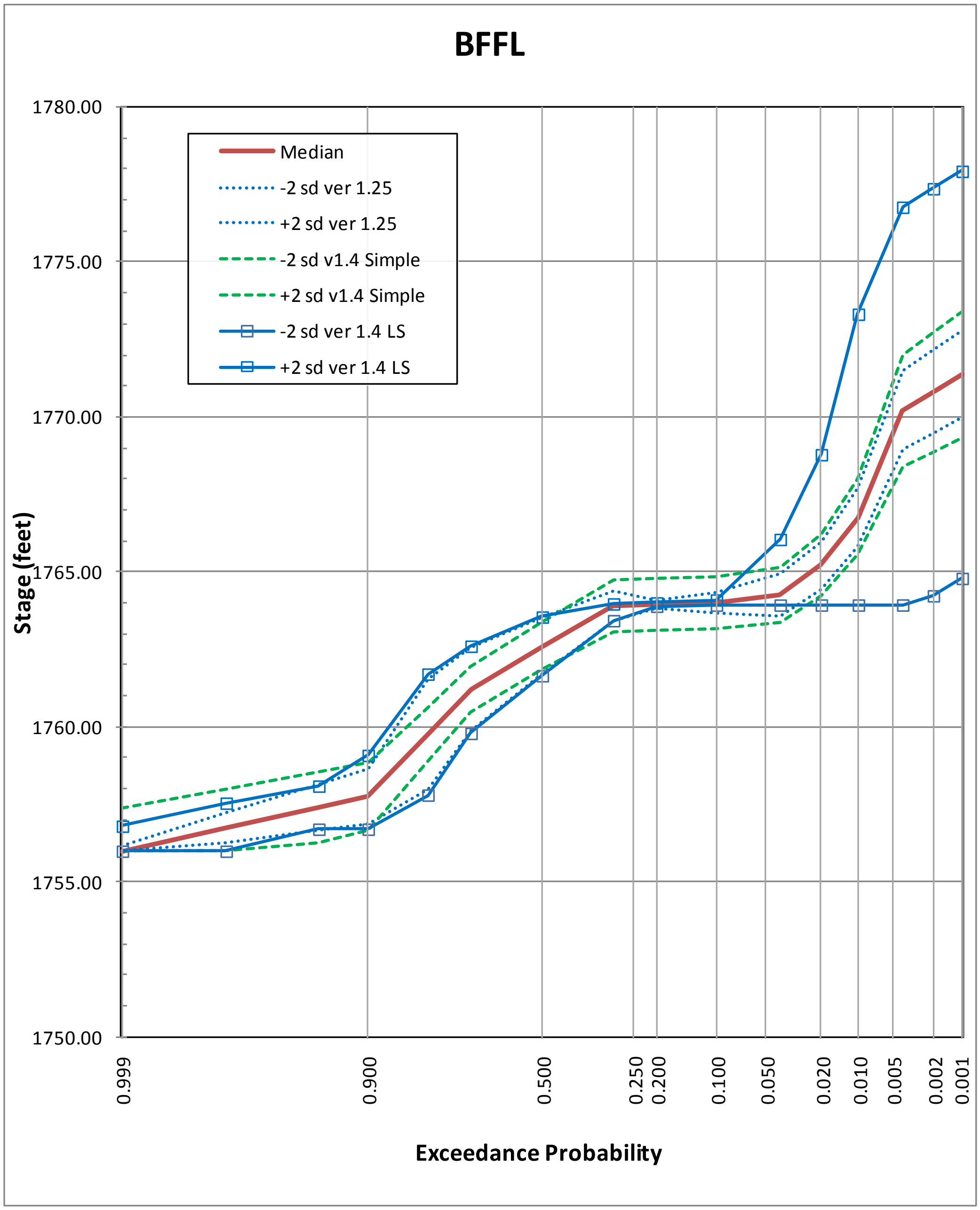

Figure 3 BFFL standard deviation related to slope

While the order statistics methodology used in 1.2.5a accounts for the local slope in the probability function as well as the overall slope of the curve, many times it gave inconsistent results when comparing expected annual damage (EAD), annual exceedance probability (AEP), and conditional nonexceedance probability (CNP) versus the equivalent length of record. One would assume that for longer equivalent lengths of record, there should be less uncertainty about the probability function because it is based on more data. However, this was not always the case with the method in 1.2.5a, so alternative methods were developed and installed into version 1.4 to solve this problem. Of those, the final two candidates were the "simple" method and the "less simple" method.

Figures 4 and 5 depict examples for one location where, for varying equivalent length of records, the levee height was adjusted to get a 90% conditional non-exceedance probability. Version 1.25a produced better results exhibits a glitch at an equivalent length of record of 35 years. In this particular case, version 1.4 using the less simple method resulted in "certified" stages higher than those with previous version of the program, but that trend cannot be generalized for other data sets. Like other example data sets, version 1.4 produced a smooth curve when certified stages were plotted against the equivalent length of record. Equivalent comments could be made concerning the results of EAD when plotted against the equivalent length of record as shown in figure 5.

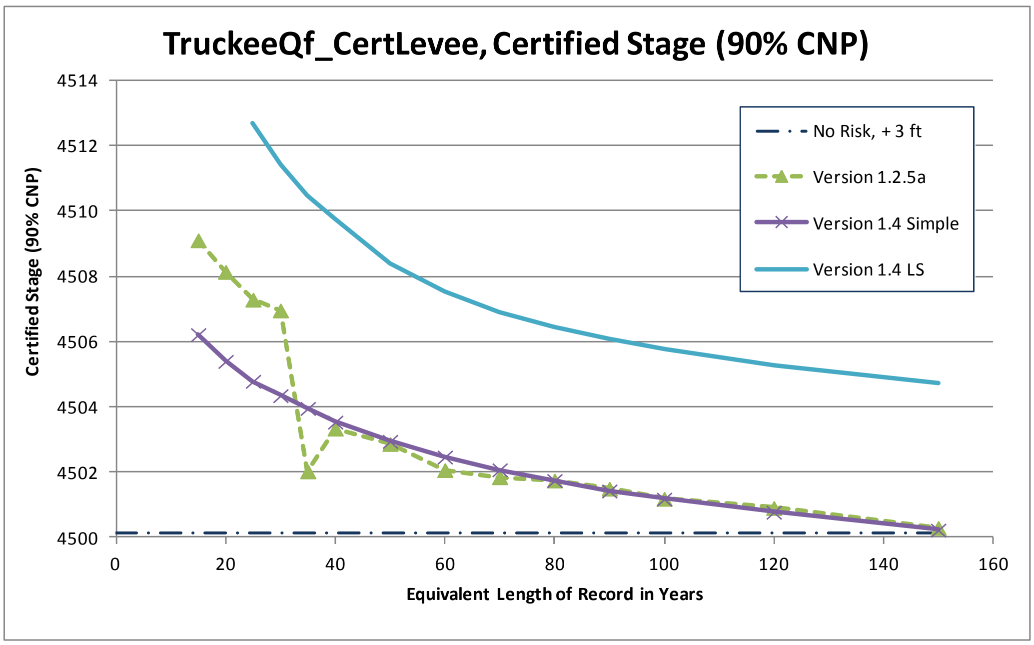

Figure 4 Truckee Discharge-Probability Certified Stage

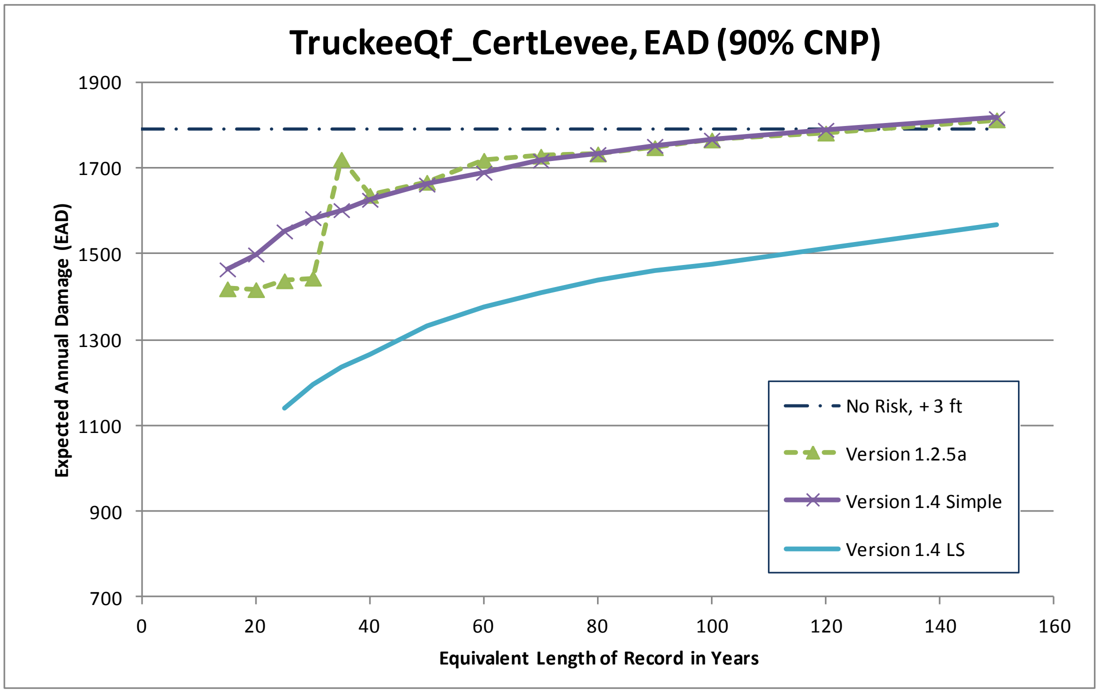

Figure 5 Truckee Discharge-Probability, EAD for Certified Stage

In the above example, the levee height was changed for each equivalent length of record to maintain a constant conditional nonexceedance probability of 90%. In the following example, the levee height was held constant while the equivalent length of record was varied, and the resulting EAD, CNP, and AEP values were plotted versus the equivalent length of record. Similar to when the CNP was held constant at 90%, version 1.4 produced the smoothest results with no inconsistencies as shown in Figure 6.

While the above demonstrates results for just one example location, it produces results that are indicative of other example locations as shown in Appendix A. Using version 1.4 with the "less simple" method produces consistent results compared to those of versions 1.2 and 1.25a.

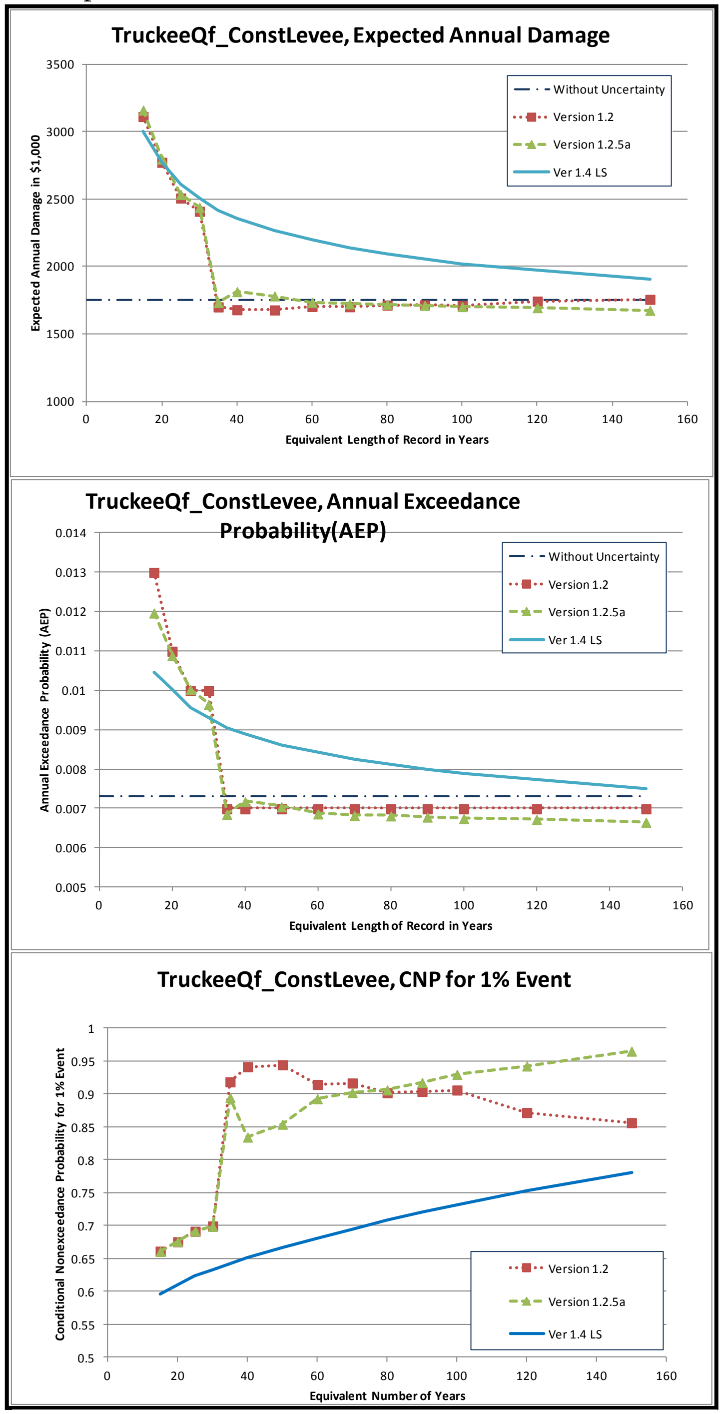

Figure 6 Levee Constant, Parameter versus Equivalent Length of Record

Figure 7 depicts the discharge-probability curve for reach 9 of the BearWs5s data set. It includes confidence limits of plus and minus two standard deviations for three versions of the program: version 1.2.5a, 1.4 simple method, and 1.4 less simple method. In this case, the uncertainty about the curve for versions 1.2.5a and 1.4 less simple method are similar whereas the results for version 1.4 simple method shows less uncertainty. This cannot be generalized for all data sets.

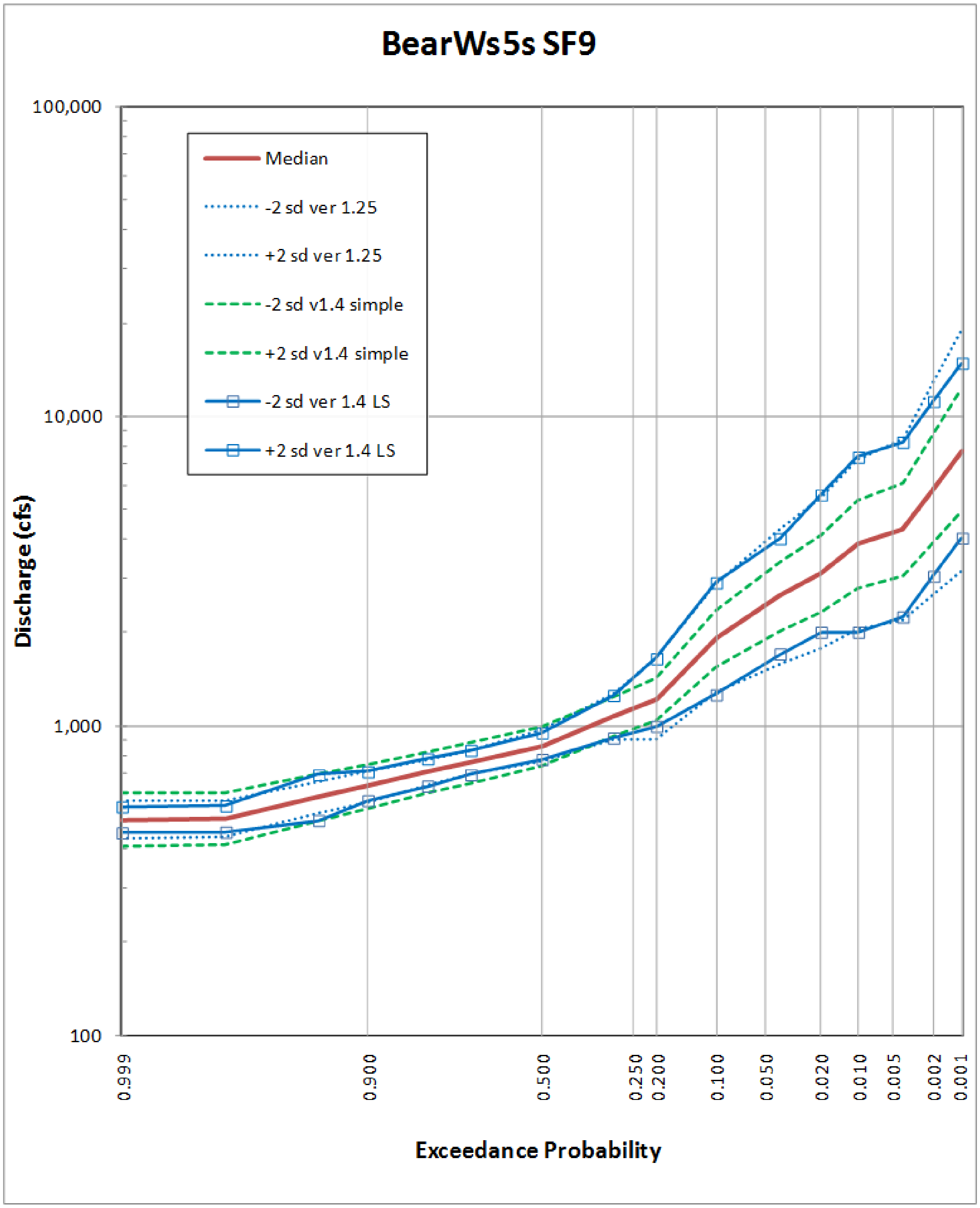

Figure 7 BearWs5s, Reach SF 9, Discharge-Probability

Section 4: Comparison of Results from Version 1.4 versus 1.25a

This subsection compares results between versions 1.25a and 1.4 with the less simple method for a number of different studies which include mostly graphical probability curves. Comparisons include expected annual damage (EAD), mean annual exceedance probability (AEP), and 1% CNP (conditional non-exceedance probability for the 1% chance event). It also compares quantiles in the probability function at exceedance probabilities of .50, .01, and .002. Rather than comparing results by varying the equivalent length of record, these examples fix the equivalent length of record and compare results between versions and plans. All examples are for graphical probability functions except the Chester Creek example and one plan of the "ArTest" example which have analytical probability curves.

Table 1 Studies included in this analysis:

Study	Probability Type	Q @ 0.01	Median AEP Without	CNP Without	EAD Without	Notes
Anacostia	Flow	38,790	.0036	.7200	933	Colmar Manor
ArTest	Flow	353,200	.0091	.3414	250,030	
BearWs5s	Flow	6,198	.8678	.0000	958	
BearWs5s_SF09_GIT	Flow	3,850	.8688	.0000	597	
ClearCrkMain	Flow	38,269	.7444	.0045	21,695	Reach 19
Colorado	Flow	410,402	.0535	.0345	3,241	Lake LBJ
Dallas Floodway	Flow	119,800	.0013	.9863	10,286	East
Des Plaines	Flow	6,193	.0535	.0474	19,843	C123_R2
Kansas City	Flow	241,000	.0031	.8277	30,763	KSCID
Yuba	Stage	-	.0342	.8893	14,238	FDR1
Chester	Flow	18,991	.0594	.0003	79	Analytical

Table 1 Data Sets Used for Plan Comparison

FDA Version 1.4 Comparison											
			Flow at +1 Standard Deviation for selected Probabilities								
			0.5			0.01			0.002		
Study	Plan	Yea	V1.2.5a	V1.4	Difference	V1.2.5a	V1.4	Difference	V1.2.5a	V1.4	Difference
Anacostia	Without		9,137.0	9,179.0	42.0	51,776.0	65,026.0	13,250.0	98,183.0	116,021.0	17,838.0
ArTest	Without		44,711.0	44,831.0	120.0	454,480.0	483,104.0	28,624.0	786,150.0	801,065.0	14,915.0
BearWs5s	Without		912.0	903.0	(9.0)	5,285.0	5,331.0	46.0	8,634.0	8,072.0	(562.0)
BearWs5s_SF09_GIT	Without		912.0	903.0	(9.0)	5,285.0	5,331.0	46.0	8,634.0	8,072.0	(562.0)
ClearCrkMain	Without		598.0	582.0	(16.0)	3,441.0	3,875.0	434.0	5,386.0	5,690.0	304.0
Colorado	Without		15,338.0	13,361.0	(1,977.0)	621,126.0	574,381.0	(46,745.0)	1,033,367.0	909,875.0	(123,492.0)
Dallas Floodway	Without		31,146.0	31,209.0	63.0	146,706.0	169,356.0	22,650.0	263,968.0	293,051.0	29,083.0
Des Plaines	Without		2,920.0	2,884.0	(36.0)	6,959.0	6,996.0	37.0	8,318.0	8,197.0	(121.0)
Kansas City	Without		56,421.0	56,432.0	11.0	289,433.0	310,804.0	21,371.0	421,305.0	439,769.0	18,464.0
Yuba	Without		56.0	56.1	0.0	78.8	76.9	(1.9)	91.6	88.3	(3.4)
Chester	Without		3,251.0	3,251.0	0.0	21,560.0	21,560.0	0.0	36,962.0	36,962.0	0.0

Table 2 Comparison of Flows for Plan Comparison Data Sets

FDA Version 1.4 Comparison										
		Expected Annual Damage			Annual Exceedance Probability			Conditional Non-Exceedance Probability for 1% Event		
Study	Plan	V1.2.5a	V1.4	Difference	V1.2.5a	V1.4	Difference	V1.2.5a	V1.4	Difference
Anacostia	Without	645	933	288	0.00540	0.00840	0.00300	0.8506	0.7200	(0.1306)
ArTest	Without	245,576	250,030	4,454	0.02077	0.02050	(0.00027)	0.3261	0.3414	0.0153
BearWs5s	Without	971	958	(13)	0.86070	0.86014	(0.00056)	0.0000	0.0000	0.0000
BearWs5s_SF09_GIT	Without	608	597	(11)	0.86069	0.86120	0.00051	0.0000	0.0000	0.0000
ClearCrkMain	Without	21,759	21,695	(64)	0.57199	0.70850	0.13651	0.0039	0.0045	0.0006
Colorado	Without	6,637	3,241	(3,396)	0.07532	0.05800	(0.01732)	0.2246	0.0345	(0.1901)
Dallas Floodway	Without	8,426	10,286	1,860	0.00137	0.00140	0.00003	0.9999	0.9913	(0.0086)
Des Plaines	Without	19,470	19,843	373	0.00511	0.00550	0.00039	0.8219	0.8138	(0.0081)
Kansas City	Without	26,567	30,763	4,197	0.00448	0.00520	0.00072	0.8849	0.8277	(0.0572)
Yuba	Without	15,762	14,238	(1,524)	0.03777	0.03430	(0.00347)	0.7844	0.8362	0.0518
Chester	Without	79	79	0	0.06390	0.06390	0.00000	0.0003	0.0003	0.0000

Table 3 Comparison of EAD, AEP, and CNP for Plan Comparison Data Sets

FDA Version 1.4 Comparison											
			Flow at +1 Standard Deviation for selected Probabilities								
			0.5			0.01			0.002		
Study	Plan	Years	V1.2.5a	V1.4	Difference %	V1.2.5a	V1.4	Difference %	V1.2.5a	V1.4	Difference %
Anacostia	Without		9,137.0	9,179.0	0.5	51,776.0	65,026.0	25.6	98,183.0	116,021.0	18.2
ArTest	Without		44,711.0	44,831.0	0.3	454,480.0	483,104.0	6.3	786,150.0	801,065.0	1.9
BearWs5s	Without		912.0	903.0	(1.0)	5,285.0	5,331.0	0.9	8,634.0	8,072.0	(6.5)
BearWs5s_SF09_GIT	Without		912.0	903.0	(1.0)	5,285.0	5,331.0	0.9	8,634.0	8,072.0	(6.5)
ClearCrkMain	Without		598.0	582.0	(2.7)	3,441.0	3,875.0	12.6	5,386.0	5,690.0	5.6
Colorado	Without		15,338.0	13,361.0	(12.9)	621,126.0	574,381.0	(7.5)	1,033,367.0	909,875.0	(12.0)
Dallas Floodway	Without		31,146.0	31,209.0	0.2	146,706.0	169,356.0	15.4	263,968.0	293,051.0	11.0
Des Plaines	Without		2,920.0	2,884.0	(1.2)	6,959.0	6,996.0	0.5	8,318.0	8,197.0	(1.5)
Kansas City	Without		56,421.0	56,432.0	0.0	289,433.0	310,804.0	7.4	421,305.0	439,769.0	4.4
Yuba	Without		56.0	56.1	0.1	78.8	76.9	(2.4)	91.6	88.3	(3.7)
Chester	Without		3,251.0	3,251.0	0.0	21,560.0	21,560.0	0.0	36,962.0	36,962.0	0.0

Table 4 Comparison of Flows for Plan Comparison Data Sets, Change in percent

FDA Version 1.4 Comparison										
		Expected Annual Damage			Annual Exceedance Probability			Conditional Non-Exceedance Probability for 1% Event		
Study	Plan	V1.2.5a	V1.4	Difference %	V1.2.5a	V1.4	Difference %	V1.2.5a	V1.4	Difference %
Anacostia	Without	645	933	44.6	0.00540	0.00840	55.6	0.8506	0.7200	(15.4)
ArTest	Without	245,576	250,030	1.8	0.02077	0.02050	(1.3)	0.3261	0.3414	4.7
BearWs5s	Without	971	958	(1.3)	0.86070	0.86014	(0.1)	0.0000	0.0000	-
BearWs5s_SF09_GIT	Without	608	597	(1.9)	0.86069	0.86120	0.1	0.0000	0.0000	-
ClearCrkMain	Without	21,759	21,695	(0.3)	0.57199	0.70850	23.9	0.0039	0.0045	14.3
Colorado	Without	6,637	3,241	(51.2)	0.07532	0.05800	(23.0)	0.2246	0.0345	(84.6)
Dallas Floodway	Without	8,426	10,286	22.1	0.00137	0.00140	2.2	0.9999	0.9913	(0.9)
Des Plaines	Without	19,470	19,843	1.9	0.00511	0.00550	7.6	0.8219	0.8138	(1.0)
Kansas City	Without	26,567	30,763	15.8	0.00448	0.00520	16.1	0.8849	0.8277	(6.5)
Yuba	Without	15,762	14,238	(9.7)	0.03777	0.03430	(9.2)	0.7844	0.8362	6.6
Chester	Without	79	79	0.0	0.06390	0.06390	0.0	0.0003	0.0003	0.0

Table 5 Comparison of EAD, AEP, and CNP for Plan Comparison Data Sets, Change in percent.

Comparison of Results for Graphical Probability Curves by Varying the Equivalent Length of Record

This subsection summarizes results for a number of studies which have graphical probability curves. The equivalent length of record was varied from 15 to 150 years and the results were plotted versus the equivalent length of record. The results were: 1) expected annual damage, 2) the mean annual exceedance probability, and 3) the conditional nonexceedance probability for the 1% event (assurance). The intent was to verify that the results would logically vary with changes in the length of record.

The studies included for this analysis are shown in Table 6.

Table 6 Summary of HEC-FDA Graphical Uncertainty Test Studies

Study	Probability Type	Q @ 0.01	Median AEP	CNP Range	EAD Range	Description
Ala Wai Canal R2	Flow	14,500	0.0065	58-78	157-409	Steep upper end beyond .004. Function is convex. Triangular distribution on rating curve. All versions, EAD, AEP & CNP progress as expected.
Ala Wai Canal R3	Flow	1,650	0.0079	53-62	505-1455	Steep upper end especially beyond 0.004. Function is convex. Triangular distribution on rating curve. All versions, EAD, AEP & CNP progress as expected.
BearWs4	Flow	3,850	0.0029	67-99	59-200	Levee sizing workshop. Function is convex. Rating curve was extended to 1,000 year flow because 3rd levee size was above maximum stage in rating curve. This test uses a lower levee to compare results from varying equivalent length of record. All versions, EAD, AEP & CNP progress as expected except ver. 1.2.5a at 15 years.
BFFL	Stage	-	0.0078	58-99	93-153	SA-1 has significant regulated zone with flat curve followed by a steep curve. Function has multiple inflection points. Removed geotechnical, it started above 0.001 stage. Ver 1.4LS has much more uncertainty at upper, steep portion of curve. Ver. 1.2.5a EAD fairly constant but increases at 120 & 150 years, EAD & CNP is reverse of what is expected but constant from 15-50 years. Ver. 1.4LS has much greater EAD & AEP and muc lower CNP for lower equivalent record length.
CIBOLOCRK	Flow	81,600	0.0529	0-35	784-8074	Upper end is flat. Function is concave. Ver. 1.4LS uncertainty at upper end is small. Trend of EAD, AEP & CNP is expected except for Ver 1.2.5a at 15 yrs.
ETL 537_Example 1	Stage	-	0.0020	65-95	2.6-16.6	First example (stage-probabilityt) from ETL 1110-2-537. Function is mostly convex. Uncertainties are fairly close. Damage curve is hypothetical. Levee inserted. EAD, AEP, & CNP trend is expected.
ETL 537_Example 2	Flow	17,600	0.0020	60-99	2.61-9.57	Second example (discharge-probability) from ETL 1110-2-537. Function is convex. Ver 1.4 simple has less uncertainty than ver. 1.2.5a & 1.4LS. Damage curve is hypothetical. Levee inserted. Ver 1.2.5a has big jump in EAD, AEP & CNP around 35 years but follows ver 1.4 closely for years 15-35.

Feather_R2	Stage	-	0.0050	78-99	45-122	FDR2, somewhat flat before 0.01 and then steep. Function is convex. Ver 1.2.5a has greater uncertainty at upper end. Ver. 1.4 simple & 1.4LS EAD, AEP & CNP basically correct trend. Ver 1.2.5a inconsistent.
NBLE	Stage	-	0.0430	0-36	.46-16.6	Without, very steep from 0.10 to 0.04, flat at upper end. Function is S shaped. Ver 1.4LS uncertainty less than v 1.2.5a & 1.4 simple at upper end. Large difference in EAD between without risk and with risk for ver. 1.4 simple. No levee, AEP is .046. Ver 1.2.5a has a spike at 25 years but otherwise has less EAD than ver. 1.4 simple.
RioGrande_FlowEven	Flow	1,259	0.0081	58-90	911-3172	Flow values entered as integers. Function is convex. Verson 1.2 & 1.2.5a EAD & CNP overall trend correct but very inconsistent and some counter trends. Very similar to FlowOrig except at 30 years which is very different.
RioGrande_FlowOrig	Flow	1,259	0.0081	58-90	911-3172	VERSION 1.2.5A. Flow values entered to 0.01 cfs in version 1.2.5a. Function is convex. Some EAD don't converge (15 yrs, ...). Some inconsistencies in EAD, AEP & CNP with version 1.2.5a. For years > 90, ver. 1.2.5a and 1.4 are extremely close.
TruckeeQf_CertLevee	Flow	20,700				Vary levee top to get 90% CNP. Levee range 4500.98-4508.13. For years > 35, vers. 1.2.5a and 1.4 simple are fairly close. Ver 1.4LS EAD is higher than 1.2.5a & 1.4 simple.
TruckeeQf_ConstLevee	Flow	20,700	0.0073	60-97	1673-3159	Levee top constant. Function is slightly convex. Ver. 1.2.5a and 1.4 simple uncertainty nearly the same. EAD & CNP mostly consistent. EAD w/o risk is not the lowest.
TruckeeSf_CertLevee	Stage	-				Vary levee top to get 90% CNP. Levee range 4499.6-4504.8. Ver 1.2.5a trends the wrong way. At 150 years, ver 1.4 simiple requires a levee 7 feet lower than ver. 1.2.5a & 1.4LS.
TruckeeSf_ConstLevee	Stage	-	0.0074	57-99	1889-2897	Levee top constant. Function is convex, flat at lower end. Prob curve steep above 0.02. Ver 1.4LS has greatest uncertainty at upper end. Version 1.2.5a has EAD & CNP inconsistent and trending the wrong way for greater years. EAD w/o risk is not the lowest.
ValleyCity	Flow	6,100	0.0068	64-99	4.20-6.40	Reach 8, Regulated to about 10 year. Good to use to compare against BFFL. Function is S shaped. Ver 1.2.5a and 1.4 simple uncertainty very similar. Original levee was 100 year + 3 feet. Reduced it by 0.5 feet. Ver 1.25a & 1.4 simple EAD & AEP are inconsistent. Ver 1.2.5a and 1.4 EAD varies very little and may cause the unexpected trend in results. Ver 1.2.5a and 1.4 simple CNP trend correctly and are similar except at the ver. 1.2.5a spike at 100 years. Ver 1.4LS has much higher EAD.
Wharton Colo	Flow	94,574	0.0079	48-58	47-243	Q-prob with convex shape - flatter at top. Ver 1.2.5a & 1.4LS very similar. CNP is virtually constant but very low (median AEP is .008, CNP is about .61). Rating curve is very flat at top. All versions EAD & AEP trend as expected.
Wharton Crestmont	Stage	-	0.0300	0-7	98-116	Upper end flat. Steep part between 0.04 to 0.02. Ver 1.2.5a has least uncertainty at upper end. Median AEP is .03 but ver 1.4 has smooth, consisent trend of EAD, AEP & CNP while 1.2.5a are very inconsistent. Ver 1.4LS has higher EAD than 1.2.5a & 1.4 simple.

Yuba	Stage	-	0.0038	76-99	13-33	Prob. curve steeper from .10 to 0.04, otherwise fairly straight, slightly convex. Ver 1.4 simple and 1.4LS EAD & AEP are somewhat close. Ver 1.2.5a EAD, AEP, & CNP are inconsistent.

The figure below shows all of the discharge-probability curves normalized such that the discharge for the 0.50 exceedance probability is 1,000 cfs for all curves. This provides a visual comparison of the slopes of the curves. The order statistics and the less simple methods utilize the localized curve slope to determine the uncertainty whereas the “simple method” does not.

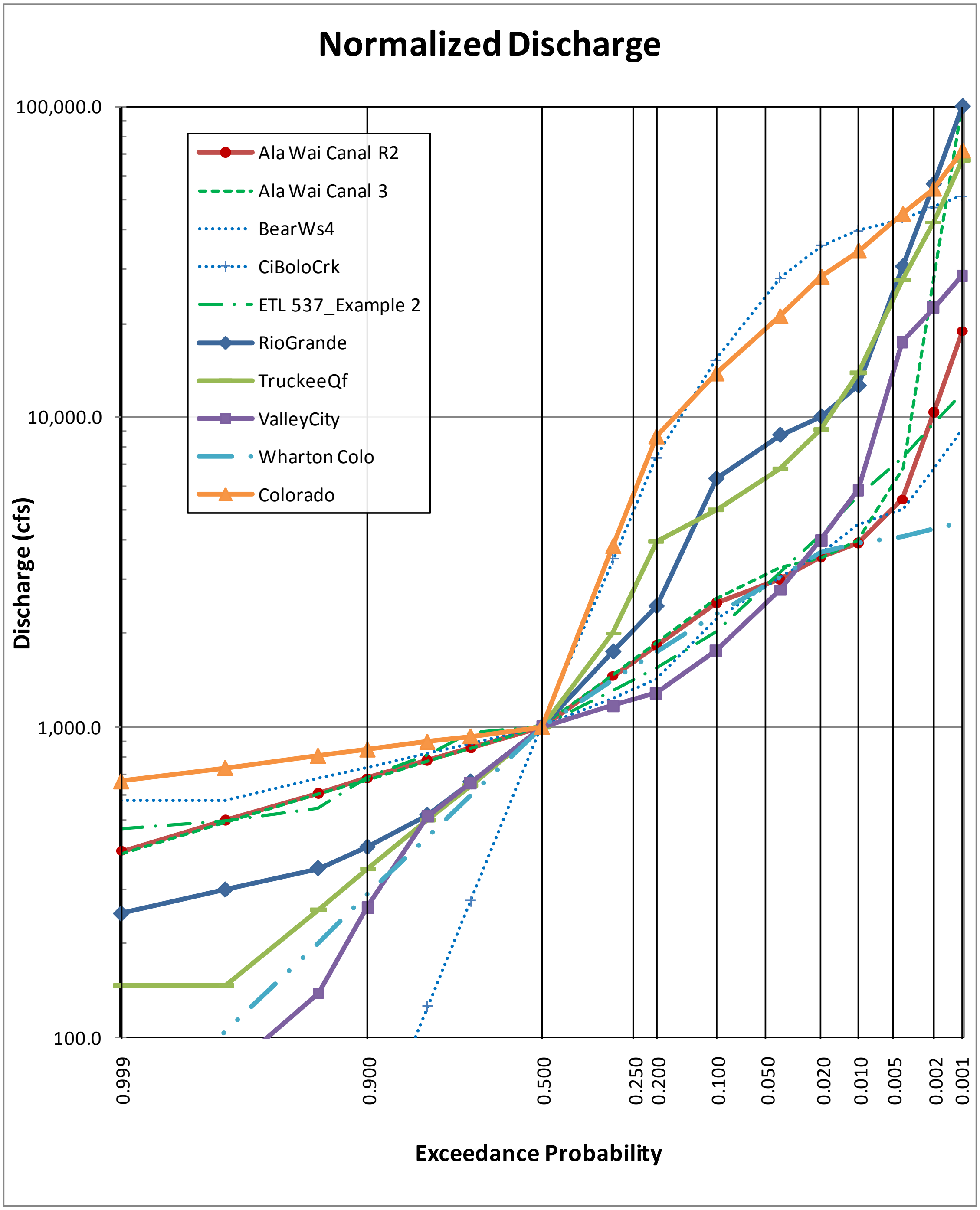

Figure 8 Normalized Discharge-Probability Curves for Graphical Data Set

Appendix B depicts results for individual damage reaches. Tables 7 and 8 show a comparison of results between versions 1.25a and 1.4. As can be seen, for this sample, results from version 1.4 are not consistently higher or lower than those from version 1.25a.

FDA Version 1.4 Comparison											
			Expected Annual Damage			Annual Exceedance Probability			Conditional Exceedance Probability for 1% Event		
Study	Plan	Years	V1.2.5a	V1.4	Difference	V1.2.5a	V1.4	Difference	V1.2.5a	V1.4	Difference
Ala Wai Canal R2	Without	50	272.0	262.7	(9.4)	0.01190	0.01035	(0.0016)	0.629	0.689	0.0608
Ala Wai Canal R3	Without	50	945.1	696.9	(248.2)	0.01576	0.01126	(0.0045)	0.550	0.566	0.0160
BearWs4s	Without	50	125.3	116.7	(8.6)	0.00633	0.00596	(0.0004)	0.764	0.783	0.0191
BFFL	Without	50	93.9	119.6	25.7	0.00770	0.00892	0.0012	0.997	0.640	(0.3567)
Cibolo Crk	Without	50	3,185.9	1,299.9	(1,886.0)	0.06322	0.05915	(0.0041)	0.217	0.001	(0.2152)
ETL Example 2	Without	50	4.4	5.2	0.8	0.00318	0.00374	0.0006	0.931	0.875	(0.0554)
ETL Example3	Without	50	6.2	8.8	2.6	0.00458	0.00642	0.0018	0.844	0.753	(0.0907)
Feather R2	Without	50	89.5	48.8	(40.7)	0.00942	0.00499	(0.0044)	0.848	0.985	0.1373
NBLE_A	Without	50	0.9	0.6	(0.3)	0.04398	0.04680	0.0028	0.032	0.000	(0.0316)
RioGrande	Without	50	2,274.8	1,087.4	(1,187.4)	0.01995	0.00971	(0.0102)	0.628	0.637	0.0084
TruckeeQf	Without	50	1,677.6	2,263.1	585.5	0.00705	0.00861	0.0016	0.854	0.666	(0.1880)
TruckeeSf	Without	50	1,889.1	2,484.5	595.5	0.00723	0.00905	0.0018	0.923	0.624	(0.2996)
Valley City	Without	50	4.1	4.7	0.7	0.00670	0.00765	0.0009	0.992	0.742	(0.2507)
Wharton Colo	Without	50	83.5	91.1	7.6	0.01284	0.01420	0.0014	0.535	0.552	0.0170
Wharton Crestmont	Without	50	98.2	108.2	10.0	0.03128	0.03329	0.0020	0.000	0.000	0.0000
Yuba	Without	50	23.2	17.8	(5.4)	0.00663	0.00500	(0.0016)	0.854	0.896	0.0423

Table 7 Comparison of EAD, AEP, and CNP for Graphical Data Sets

FDA Version 1.4 Comparison											
			Expected Annual Damage			Annual Exceedance Probability			Conditional Exceedance Probability for 1% Event		
Study	Plan	Years	V1.2.5a	V1.4	Difference %	V1.2.5a	V1.4	Difference %	V1.2.5a	V1.4	Difference %
Ala Wai Canal R2	Without	50	272.0	262.7	(3.4)	0.01190	0.01035	(13.0)	0.629	0.689	9.7
Ala Wai Canal R3	Without	50	945.1	696.9	(26.3)	0.01576	0.01126	(28.6)	0.550	0.566	2.9
BearWs4s	Without	50	125.3	116.7	(6.9)	0.00633	0.00596	(5.8)	0.764	0.783	2.5
BFFL	Without	50	93.9	119.6	27.4	0.00770	0.00892	15.8	0.997	0.640	(35.8)
Cibolo Crk	Without	50	3,185.9	1,299.9	(59.2)	0.06322	0.05915	(6.4)	0.217	0.001	(99.3)
ETL Example 2	Without	50	4.4	5.2	18.9	0.00318	0.00374	17.6	0.931	0.875	(5.9)
ETL Example3	Without	50	6.2	8.8	41.4	0.00458	0.00642	40.2	0.844	0.753	(10.7)
Feather R2	Without	50	89.5	48.8	(45.5)	0.00942	0.00499	(47.0)	0.848	0.985	16.2
NBLE_A	Without	50	0.9	0.6	(35.2)	0.04398	0.04680	6.4	0.032	0.000	(100.0)
RioGrande	Without	50	2,274.8	1,087.4	(52.2)	0.01995	0.00971	(51.3)	0.628	0.637	1.3
TruckeeQf	Without	50	1,677.6	2,263.1	34.9	0.00705	0.00861	22.1	0.854	0.666	(22.0)
TruckeeSf	Without	50	1,889.1	2,484.5	31.5	0.00723	0.00905	25.2	0.923	0.624	(32.5)
Valley City	Without	50	4.1	4.7	16.6	0.00670	0.00765	14.2	0.992	0.742	(25.3)
Wharton Colo	Without	50	83.5	91.1	9.1	0.01284	0.01420	10.6	0.535	0.552	3.2
Wharton Crestmont	Without	50	98.2	108.2	10.2	0.03128	0.03329	6.4	0.000	0.000	-
Yuba	Without	50	23.2	17.8	(23.3)	0.00663	0.00500	(24.6)	0.854	0.896	5.0

Table 8 Comparison of EAD, AEP, and CNP for Graphical Data Sets, Difference in percent

Estimating Uncertainty due to Sampling Error for a Graphical Frequency Curve: Advantages and Disadvantages of the Order Statistics Method

HEC, July 2013

One of the updates in FDA version 1.4 is improvements to the method of specifying the uncertainty around a graphical (empirical, non-analytic) frequency curve. A method that makes use of Order Statistics has been used in FDA since the earliest versions of the software, and is described in USACE ETL 1100-2-537. The method has strengths but also limitations. One of the limitations became apparent several years ago, and an effort was made to either improve the application of the Order Statistics method, or find a simple replacement for the method. ***The primary difficulty exists for frequency curves that have a steep slope or a change in slope above the 1% quantile.***

This document discusses the strengths and limitations of the Order Statistics method, and some options considered for use in FDA. The chosen option is noted, and areas for future improvement are discussed.

Background

For an empirical or graphical frequency curve that defines the probability distribution of annual peak stages or flows in a regulated stream channel, the lack of an analytical distribution means there is no analytically-based description of the uncertainty in an estimated distribution due to sampling error. Therefore another method for estimating that uncertainty is needed, to define both a 90% confidence interval and an entire PDF of uncertainty for random sampling in Monte Carlo studies.

The order statistics approach is described in USACE ETL 1100-2-537. In this approach, the CDF of uncertainty around a particular quantile Y_p of a graphical frequency curve is computed based on the sample of values used to estimate the frequency curve. The method applies the Binomial distribution to define the likelihood that each ordered sample member Y_i is less than quantile value Y_p, given the assumption that each sample member is an independent trial with likelihood p of exceeding Y_p. Equations 1 and 2 define the value of the CDF around Y_p at each Y_i. The CDF is constructed one ordered sample member Y_i at a time, and compiled into a single distribution around quantile Y_p. Figure 1 shows the construction of a CDF of uncertainty around a quantile Y_p, for a sample of size N=20, and the associated PDF.

$$P[Y_i \leq Y_p] = P[i^{th} \text{ ordered observation} \leq Y_p] \qquad (1)$$

$$P\left[Y_i \leq Y_p\right] = \sum_{j=i}^{j=n} \binom{n}{j} p^{n-j}(1-p)^j \qquad (2)$$

Note that the computation described above does not explicitly include the numeric value of each sample member used to estimate the frequency curve. Rather it defines the probability associated with each value based on its position in the sample. Therefore, where many values are close together, the resulting uncertainty distribution is narrow, and where values are widely spaced (implying more difficulty in estimating the exceedance probability for each), the distribution is also wide.

When the graphical frequency curve is estimated by some transformation of an unregulated flow frequency curve, or computation of individual flow or stage quantiles from balanced, frequency-based precipitation events, a sample of values does not exist. In this case, a **synthetic sample** is used in the place of an observed sample of values. The synthetic sample is created simply by interpolating values from the graphical curve corresponding to plotting positions with an assumed record length, N.

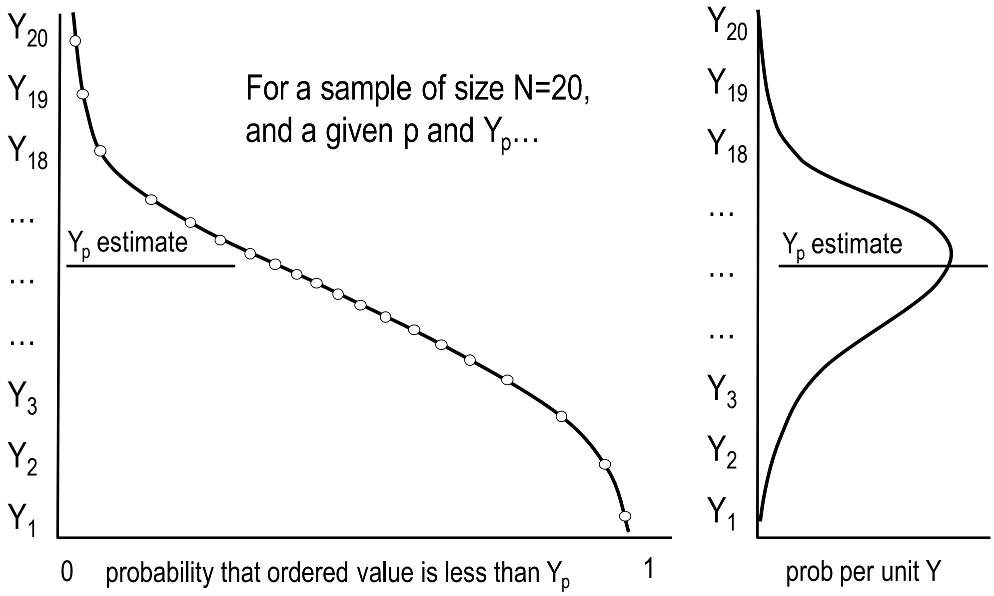

Figure 1. Construction of CDF of likelihood each ordered sample member is greater than quantile Y_p

Strengths and Limitations

Use of the actual or synthetic sample values in constructing the CDF of uncertainty around each quantile Y_p leads to both the method's greatest strength and greatest limitation. Figure 2 depicts a stage frequency curve in a regulated stream. A sample size of N = 60 and the Weibull plotting position was used to generate a synthetic sample from the curve, which is displayed on the left. The PDFs constructed at several of the quantiles are displayed, which should be imagined on a Z-axis coming out of the page. Two properties are of the uncertainty PDFs are immediately visible; (1) the sensitivity of the PDFs to local slope of the frequency curve (a strength of the method), and (2) the PDFs being defined only within the range of the sample (a limitation of the method).

First, (1) the PDFs show a sensible shape to the uncertainty distribution that is dependent on the local slope of the frequency curve, being less when the frequency curve is flat, and greater where the curve is steeper. Although in this method the uncertainty distribution is defined "vertically" around stage at each quantile, sampling error in fact leads to uncertainty in the exceedance probability associated with each sample member, which is the horizontal location of that value. Figure 3 shows the same frequency curve with an incremental adjustment in exceedance probability in each direction, to give an idea what uncertainty might look like in both horizontal and vertical directions. As expected, where the curve is flatter, horizontal movement causes little change in the curve, and so the uncertainty PDF is narrow. Where the curve is steep, horizontal movement causes a great deal of change in the curve, and so the uncertainty PDF is wide.

Further, the uncertainty PDFs are appropriately asymmetrical at the edge of a local change in slope, such as at either edge of the steep portion of the curve (exceedance probabilities 25% and 10%). The tails of the uncertainty PDF extend further in the direction of the rest of the frequency curve (i.e., toward a steeper slope), and less in the direction away from the rest of the curve (i.e., toward a shallower slope.) In other words, the uncertainty at a given quantile does not extend further than the neighboring section of the frequency curve.

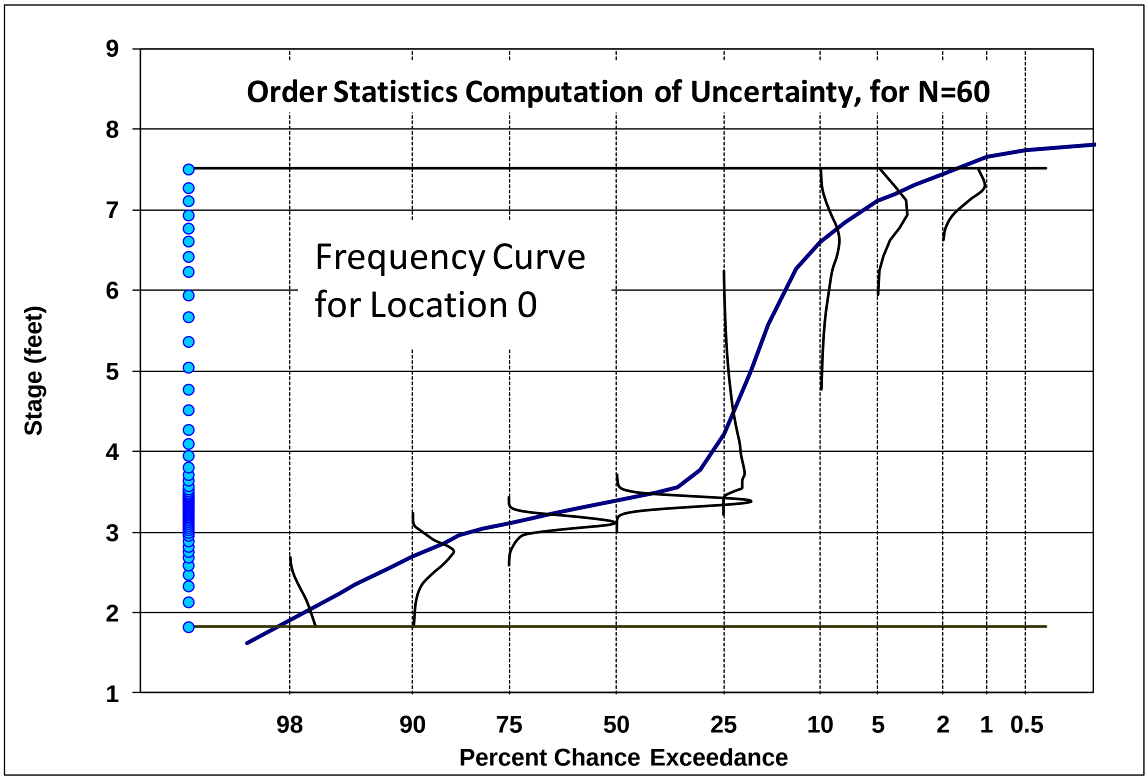

Figure 2. Order Statistic Method uncertainty PDFs around frequency curve with local changes in slope

Second, (2) the uncertainty PDFs constructed from use of the Binomial distribution are defined for each sample member, and therefore are only defined within the range of the sample, representing a significant limitation to defining the required uncertainty distribution at the extreme ends of the frequency curve. Note in Figure 2 that for N=60 the PDFs are incomplete at the 2% and 98% exceedance probabilities, and would be even less complete further out either tail. The larger the sample, the wider this range of definition, however even for a relatively large sample size of N=100, the PDF is not complete at 2% or 1% exceedance probability, which is the portion of the frequency curve for which it is most important to define uncertainty. ***This inability to define uncertainty around the upper end of the frequency curve leads to the primary challenge in the use of the Order Statistics method.***

To help display the result of the incomplete PDFs, Figure 4 includes the mean and standard deviation of each Order Statistics PDF (computed with a trapezoidal rule numerical integration), with pink squares to show the mean and error bars to show the standard deviation. Note that when the PDFS are not complete at the tails of the frequency curves, the computed mean and the standard deviation show error, with the means diverging toward the frequency curve median and the standard deviations being underestimated. Note, displaying the standard deviation does not capture the asymmetry in the PDFs.

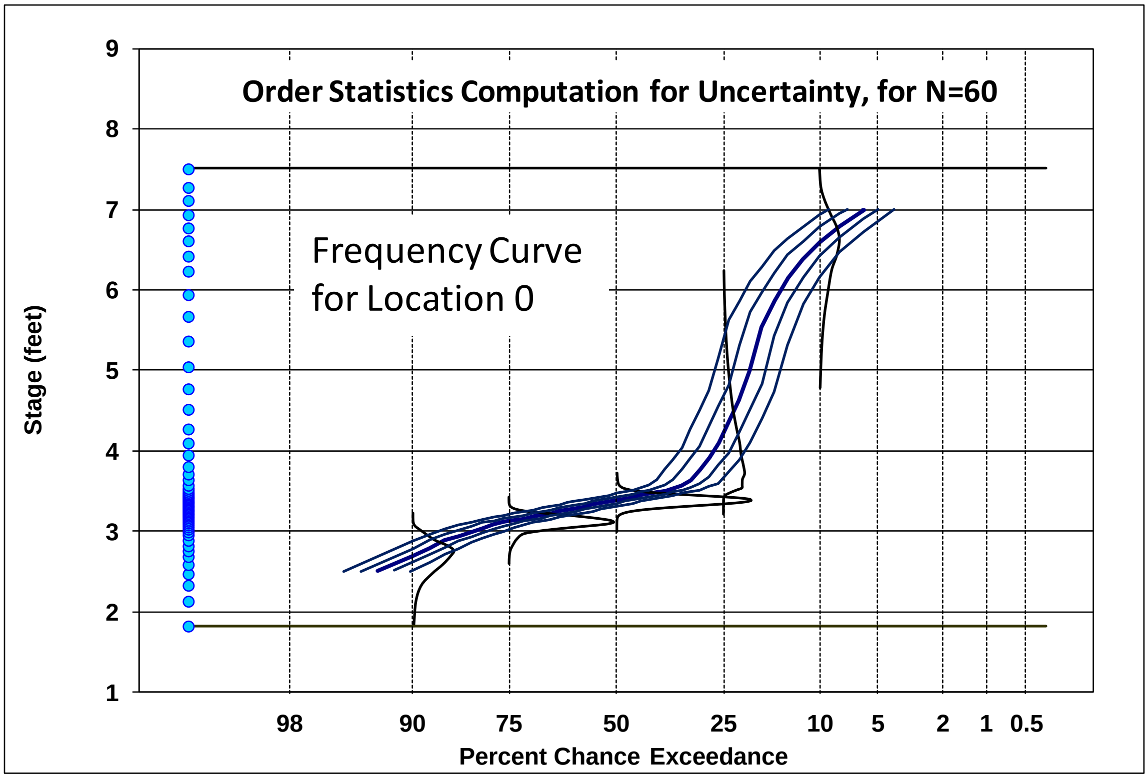

Figure 3. Incremental horizontal movement of frequency curve to depict range of uncertainty

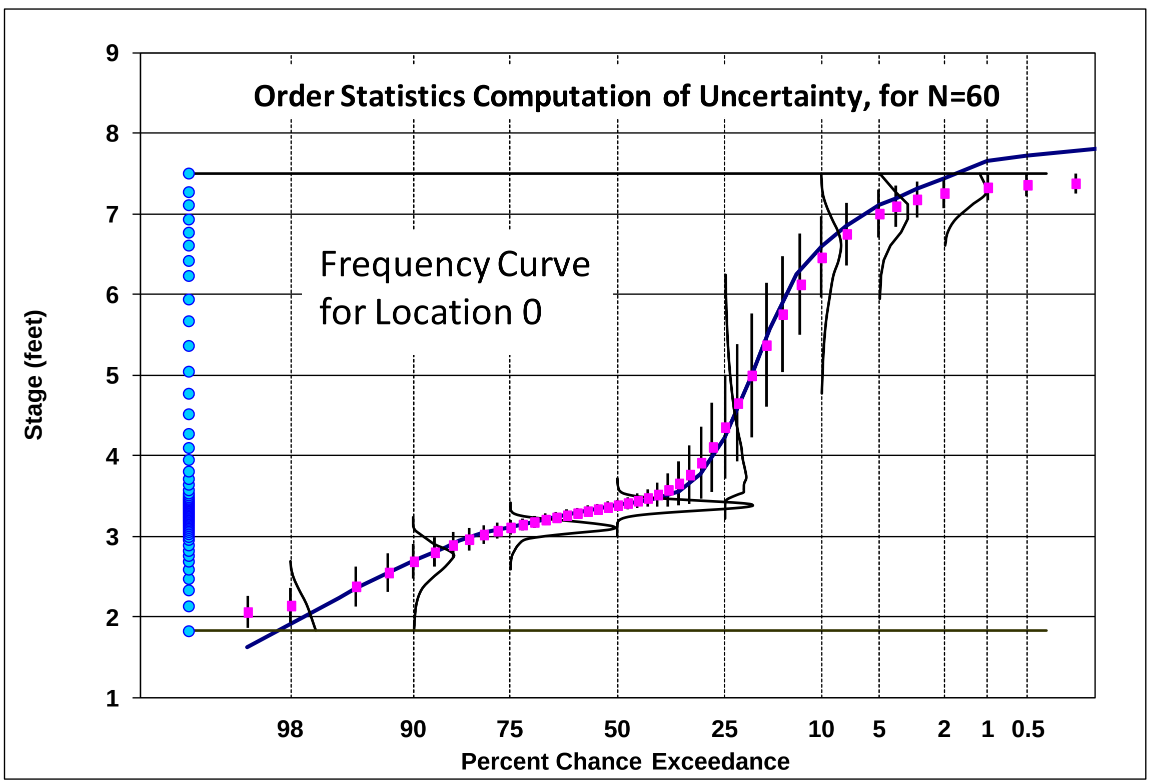

Figure 4. Mean and standard deviation of the Order Statistics Uncertainty PDFs

Approximation of Uncertainty Beyond the Range of the Sample

Because the Order Statistic method can generate uncertainty PDFs only within the range of the sample, either actual or synthetic, an approximation beyond that range is needed. Considering the use of the Binomial distribution in the Order Statistics method, one useful approximation is based on the variance of a sample proportion of Binomial trials as an estimate of exceedance probability, and the fact the Binomial distribution can be approximated by the Normal distribution for large N. The derivation of the formula is described in ETL 1110-2-537, but in short, the approximation uses a 1st order Taylor expansion around the mean of the quantile estimate, to transform the uncertainty in exceedance probability p to the uncertainty in variable Y. The resulting approximation of the variance of uncertainty is given as:

$$S_Y^2 = \frac{p(1-p)}{N\,f(y)^2} \qquad (3)$$

where S_Y is the standard deviation of the uncertainty distribution, p is the exceedance probability, N is the record length, and f(y) is the probability density function (PDF) for variable Y, derived from the frequency curve of interest. Note that the PDF is the inverse of the slope (or, first derivative) of the frequency curve, which is a CDF with probability on the horizontal axis. ***This approximate variance produces nearly the same result as the actual variance of a complete Order Statistics PDF for a given quantile.*** *(This fact is verified in a later section, comparing to Order Statistics PDFs with N=1000.)*

Because only the variance may be estimated in this way, rather than the entire PDF, this variance is then **paired with a Normal distribution** to define the uncertainty PDF around quantile Y_p. Further, for continuity and for convenience in Monte Carlo sampling, the variance of the Order Statistics PDF is also computed and paired with a Normal distribution across the entire frequency curve, including the middle range for which the Order Statistics PDF is complete. (Figure 4 displays the standard deviations of the Order Statistics PDFs as error bars around the means.) Because the actual Order Statistics PDF is not used, this practice has the disadvantage of losing the asymmetry of the PDF around local changes in slope, as the Normal distribution is symmetrical.

Another useful approximation for the variance can be used when the graphical frequency curve is nearly analytic at the extremes, and is based on the uncertainty in a Normal distribution.

$$S_Y^2 = \frac{S^2}{N} + Z_p^2\frac{S^2}{2N} \qquad (4)$$

where Z_p, a normalized deviate, is computed as $Z_p = (Y_p - M)/S$, and M is the mean of the frequency curve, S is the standard deviation of frequency curve, and S_Y^2 is the variance of the quantile Y_p estimate.

With either approximation (Equation 3 or Equation 4), in order to create a smooth transition from the Order Statistics variance to the approximated variance, the values of S_Y are "matched" at the transition quantile by computing the value of N for which the approximated variance equals the Order Statistics variance, and using that value of N_a in the approximation equation for the remaining outwardly moving quantiles.

Challenges to Using the Approximation

Whichever approximation is used (Equation 3 or Equation 4), the two main challenges to the approximation of the uncertainty variance are (1) at what quantile to begin using the approximated variance in place of the variance of Order Statistics PDF, and (2) the fact that the variance will be paired with a symmetrical Normal distribution.

For (1), a simple rule for when to switch from the variance computed from the Order Statistics PDF to the approximated variance is when the percentage of the PDF defined by the range of the sample falls below a certain threshold, such as 98% complete. For all quantiles for which this threshold is not met, the approximated variance is used.

However, earlier versions of FDA (including version 1.2.5) used a different method to define at which quantile to switch to use of the approximation. When moving outward from the median of the frequency curve, in general the uncertainty of the quantile estimate (the variance) should increase. A decreasing variance can be a sign that the PDF is incomplete. Therefore, the rule used was to find first the quantile (moving outward from the median) at which the variance computed from the Order Statistics PDF began to decrease, and switch to the chosen approximation at that quantile, computing the value of N that would "match" the Order Statistics variance.

An expected outcome for any method for defining uncertainty is that as the assumed sample size N increases, the uncertainty and so the computed should variance decrease. Figure 5 shows the computed standard deviations (square root of variance) of the Order Statistics PDFs across a frequency curve of channel stage, for increasing assumed sample size N. The frequency curve itself (**Frequency Curve for Location 1**) is plotted on the right vertical axis, and standard deviations on the left. Moving right from the median, note the rise in the uncertainty where the frequency curve becomes steep, and the fall as it becomes flatter. However, is not obvious here whether the decrease in standard deviation is solely due to the flatter slope, or also due to the Order Statistics PDFs being incomplete, causing their computed variance to be underestimated. The black diamonds are added to show the last quantile for which the PDF is at least 98% complete, identifying the last standard deviation which could be accurate. (Note that only for N=140 or greater can we expect the decrease in computed standard deviation to actually result from the decreased slope of the frequency curve at the upper end, and that the peak variance is perhaps accurate.)

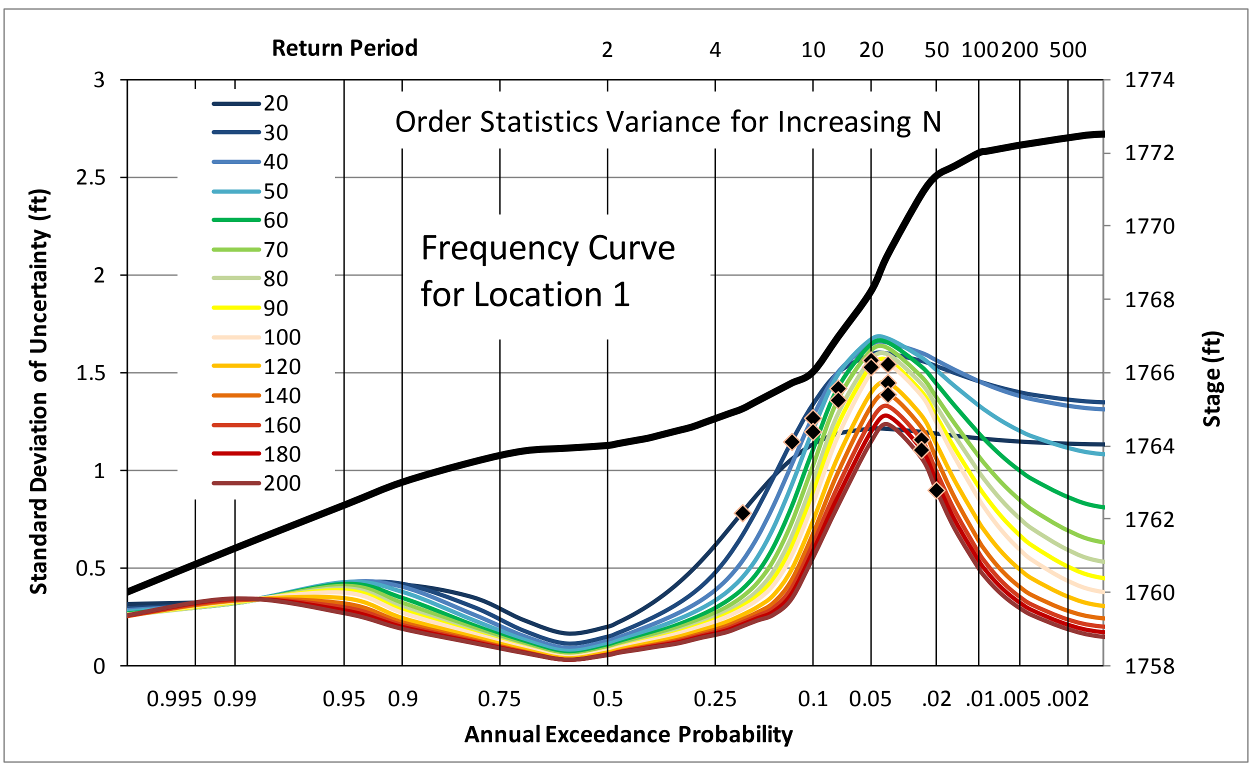

Figure 5. Variance of Order Statistics PDFs for range of sample sizes, N

While this figure shows the expected outcome of standard deviation decreasing as N increases, we see a hint of difficulty with sample sizes as small as N=20 and N=30, for which the Order Statistics PDF is incomplete low enough (close enough to the median) that the steeper slope at higher quantiles is not recognized, and variances are therefore lower than for larger N for the steep portion of the curve.

Given this challenge to the Order Statistics method when a frequency curve has a steep slope or a change in slope in the higher quantiles (above 2% or 1% chance exceedance, depending on N), the older method of choosing the "match point" (i.e, the quantile at which the Order Statistics variance begins to decrease) lead to some difficulties that were not discovered at the time. Primarily, for small sample sizes, the PDFs are incomplete at lower quantiles having uncertainty variance much smaller than at the higher quantiles (if estimation could be made), *leading to an underestimate of the uncertainty without recognition that the PDFs were incomplete*. Further, with a larger assumed sample size N, the same Order Statistics computation would generate complete PDFs for higher quantiles having larger variance, and so less underestimation of the uncertainty. This difficulty leads to uncertainty at the upper end of the frequency curve increasing with assumed sample size N, rather than decreasing.

Figure 6 shows an example of this difficulty for a frequency curve in which there is a steep portion at a high quantile, beyond the range of complete PDFs for small sample sizes (**Frequency Curve for Location 2**). We expect the variance of uncertainty to increase for the steep portion between p=0.05 and 0.005, as it does between p=0.9 and 0.75, and for larger sample sizes this is true. But the variances of the Order Statistics PDFs increase with increasing sample size N at the upper end of the frequency curve, because larger sample sizes provide enough sample range for the PDFs to recognize and widen in the area of the steep slope. For smaller N, the Order Statistics computation "ends" at a quantile for which the frequency curve is quite flat, with associated small variance. Recall the black diamonds show the last quantile for which the Order Statistics PDF is complete, and even for N=200 it has not yet reached the maximum variance. (Note, this figure shows only the computed Order Statistics variances, and not the results of the extrapolation.)

The older method of defining the "match point" quantile to switch to the approximated variance (mentioned above) is unaware of complete or incomplete PDFs, and rather chooses the quantile at which the variance starts to decrease, moving outward from the median, to switch to the approximated variance. Further, because the N_a used in the approximation formula is chosen to match the variance at the match point, it could be quite high for the lower variances from small assumed sample sizes, N. This example is one in which the method in FDA 1.2.5 would provide a poor result. Figure 7 adds these "match points" to the previous figure, showing that they are to the right of the markers showing the final complete Order Statistics PDFs.

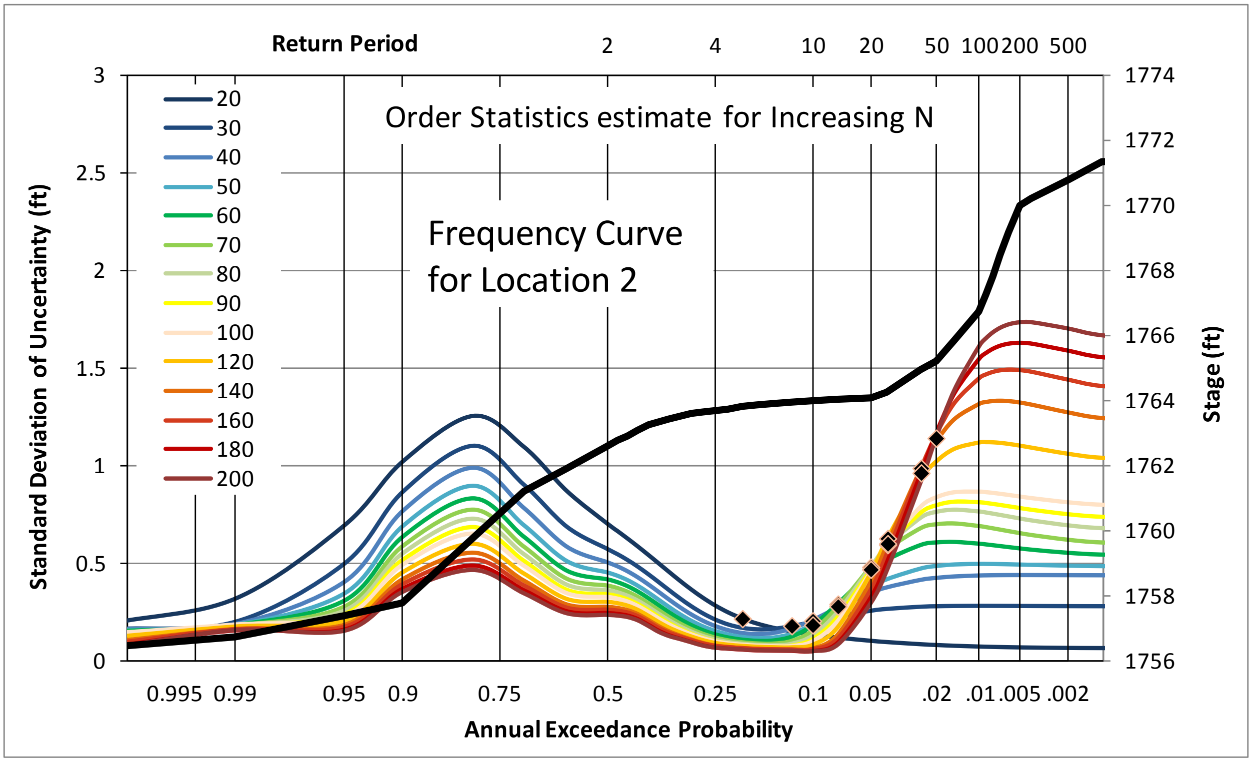

Figure 6. Variance of Order Statistics PDFs for range of sample sizes, N, for frequency curve that is steep in the upper quantiles

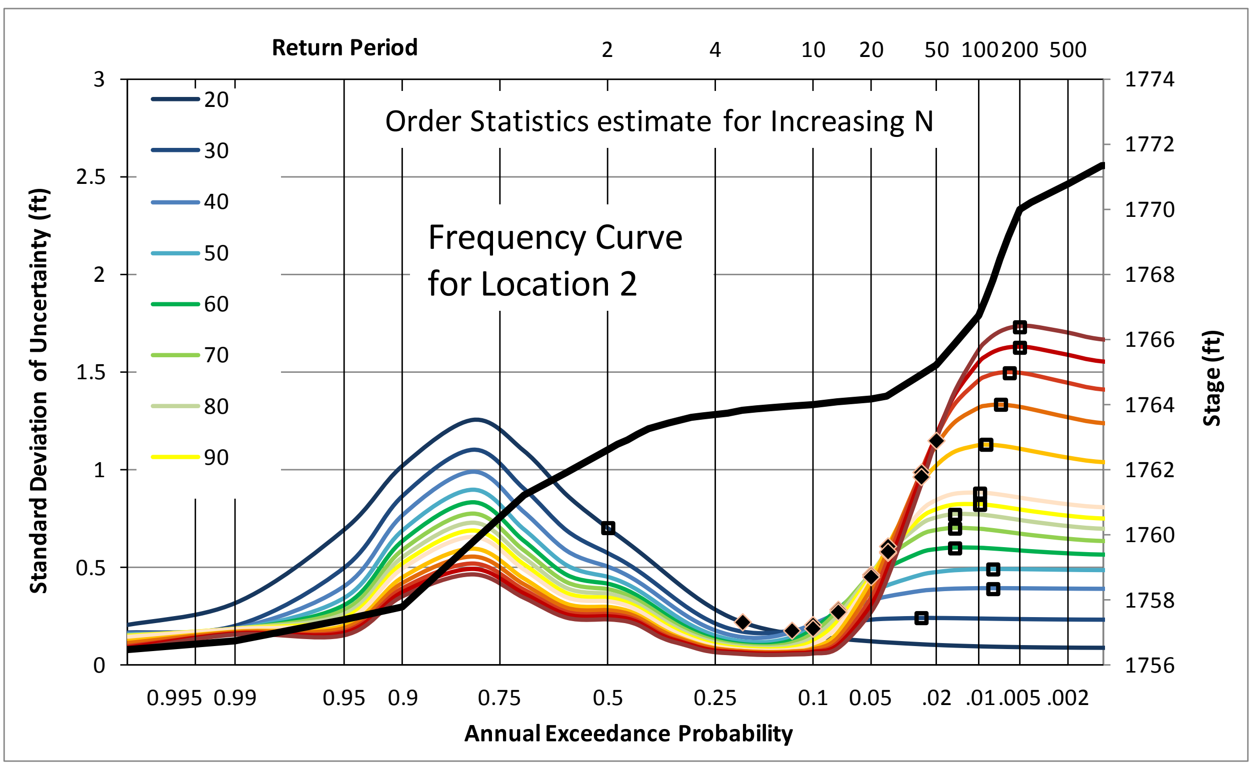

Figure 7. Added location of approximation "match points" from older version of FDA

Alternatives to the Original Order Statistics Method

Once the difficulty presented in Figure 6 was discovered, some incremental improvements to the Order Statistics method were considered.

A. One solution is to compute the Order Statistics PDFs and their variances for **sample size <u>N=1000</u>**, to benefit from the wider range of sample members from the 0.999 to the 0.001 quantiles, producing complete PDFs for more of the frequency curve. The variances of those PDFs are then scaled back to the desired N by multiplying by N/1000. With N=1000, the Order Statistics PDFs are complete between the p=0.005 and p=0.995 exceedance probabilities. (While this solution produces the entire Order Statistics PDFs, including their asymmetry, those PDFs unfortunately cannot be scaled back to the correct sample size N as the variance can.) Figure 8 shows the Order Statistics PDFs generated from sample size N=1000, as well as the synthetic sample on the left. Figure 9 shows the scaled variances for each sample size. (Note, the fact the empirical frequency curve is interpolated between defined points is visible in the blockiness of the computed variances.) It is clear that the uncertainty in the upper end of the frequency curve is actually significantly higher than was estimated with the previous method. The black diamonds showing the quantile with last complete Order Statistics PDF from each sample size N, and the resulting standard deviation, remains on the plot. Even with N=1000, an approximation formula would be needed beyond the p=0.005 and p=0.995 quantiles.

B. As alternative solutions, either of the approximation formulas (Equations 3 and 4) can be used to compute the variance of uncertainty for the entire frequency curve, rather than only for the extreme quantiles for which the Order Statistics PDF is not defined.

- Use of Equation 4 to compute variance has been referred to as the **<u>"Simple Method"</u>** and was an early solution. However, Equation 4 is not as responsive to changes in the slope of the frequency curve, and so uncertainty is not low enough in the flat parts of the curve, or high enough in the steep parts of the curve. Figure 10 shows the variances computed from the "Simple Method" for 'Frequency Curve for Location 2.' Note that although they increase for the extreme quantiles, they are not low where the curve is flat nor high where it is steep.
- Use of Equation 3 has been referred to as the **<u>"Less Simple Method"</u>** and was considered more recently. Equation 3 produces nearly the same variance as the Order Statistics PDF in the range that the PDF is complete, making it a good replacement for the Order Statistics method. Figure 11 shows the variances computed from the "Less Simple Method" for 'Frequency Curve for Location 2.' Comparison with Figure 6 shows the similarity to the original Order Statistics computation where PDFs are complete, and comparison with Figure 9 shows the similarity to the variances computed with N=1000 and scaled back to the desired N.

The "Less Simple Method" is used in FDA version 1.4, with the caveat that the variance <u>does not increase</u> beyond the 1% quantile, but instead remains constant for higher quantiles. This constraint is included because the "Less Simple Method" produces uncertainty that can be much larger than FDA version 1.2.5. Some of this increase is due to the previous underestimation of uncertainty, and some is due to the lack of hydrologic reality in the computation of uncertainty. (Figure 11a shows the "Less Simple method" exactly as implemented in FDA version 1.4. Note the wider Y-axis range.)

While this added constraint improves the result for most frequency curves, a drawback is seen with a frequency curve that flattens beyond the 1% quantile. In such a case, the expected decrease in the uncertainty that should occur in the flat region does not occur, as the larger 1% quantile variance is maintained, keeping the uncertainty too large. A further refinement in future versions might restrict the increase in the variance beyond the 1% quantile, but allow decrease out to the 0.2% quantile.

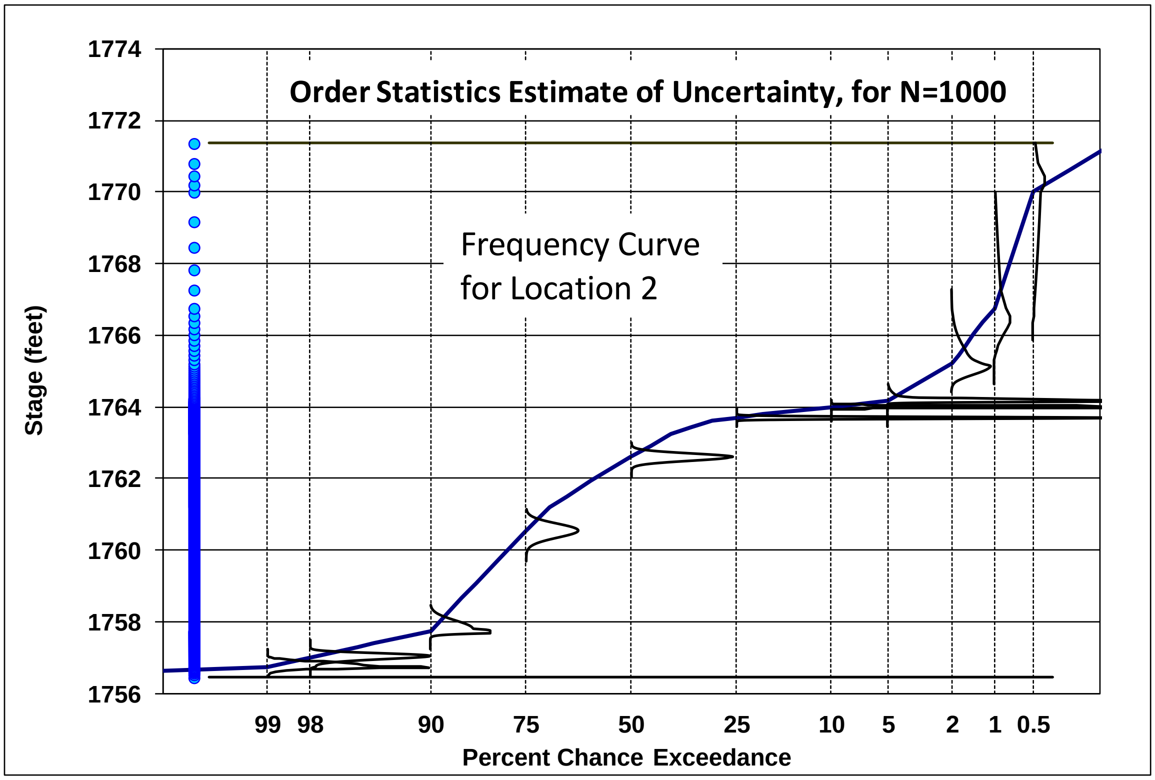

Figure 8. Order Statistics PDFs for FREQUENCY CURVE 2 from N=1000

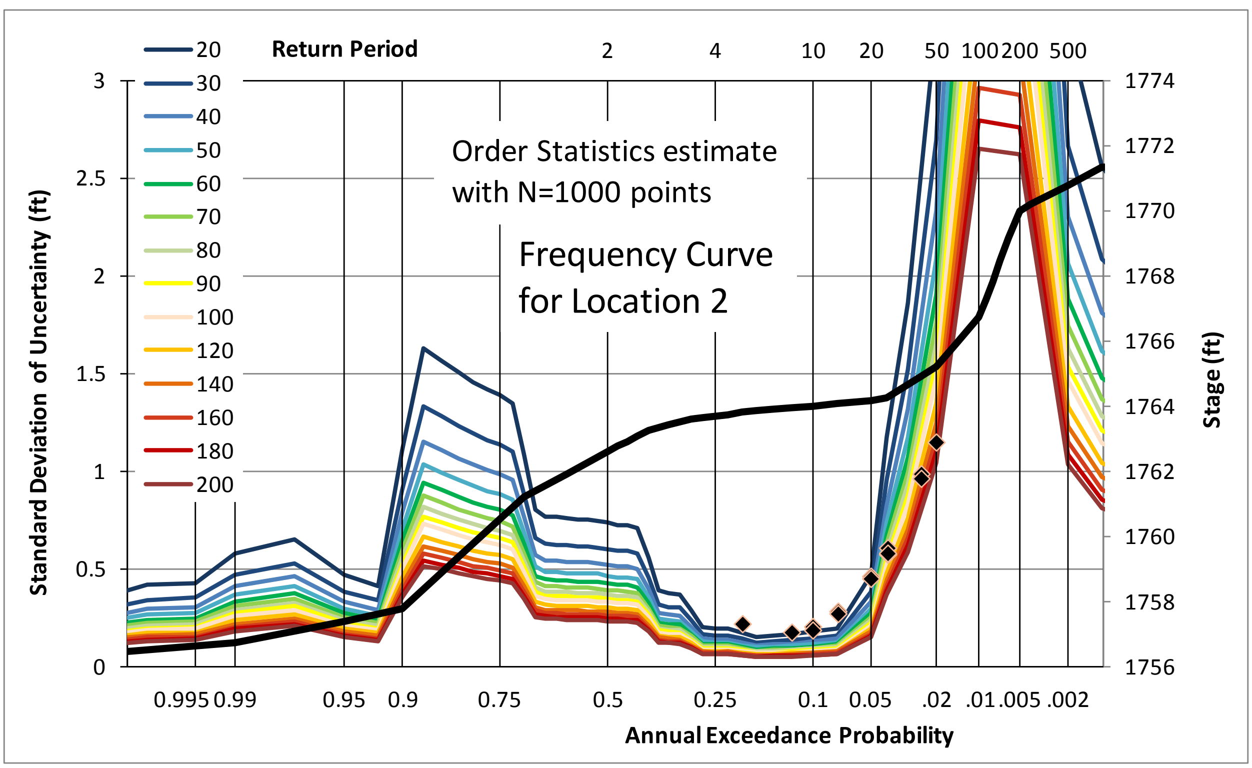

Figure 9. Variance for range of sample sizes, N, scaled from Order Statistics PDFs from N=1000 for frequency curve that is steep in the upper quantiles

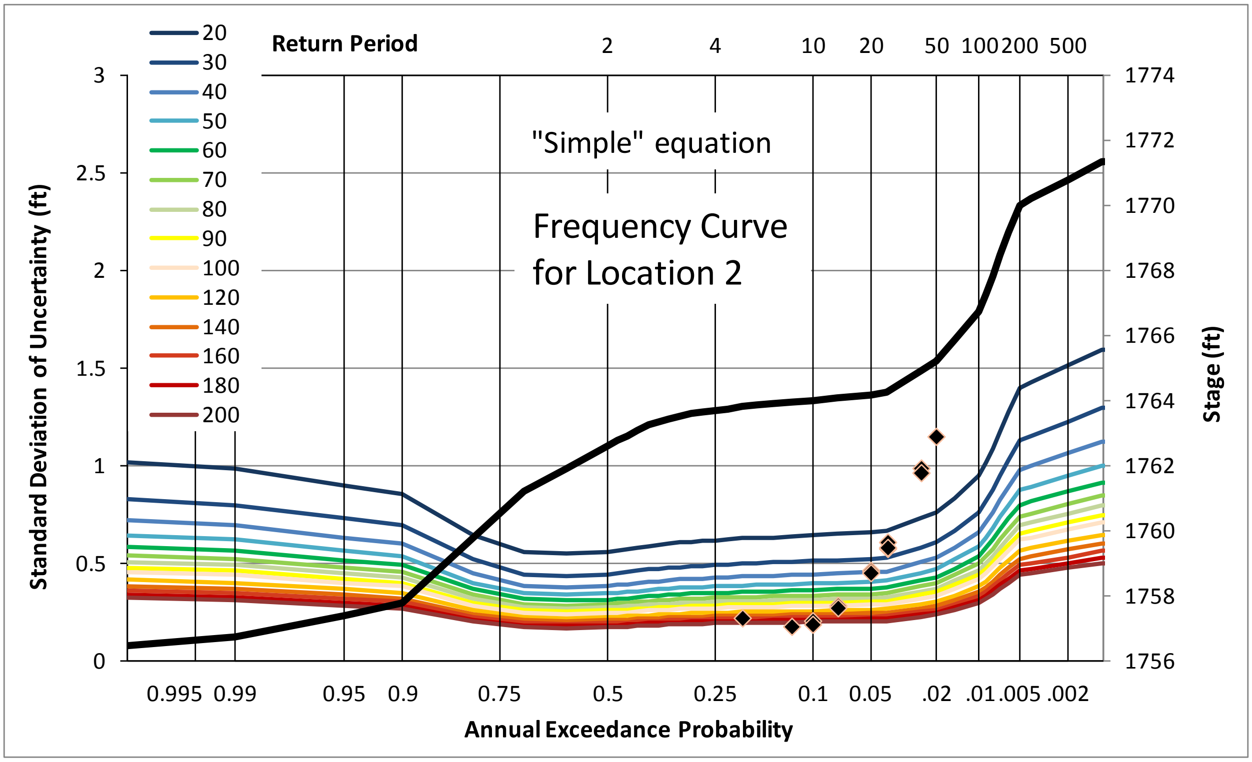

Figure 10. Variance for range of sample sizes, N, using Simple Method (Equation 4) for frequency curve that is steep in the upper quantiles

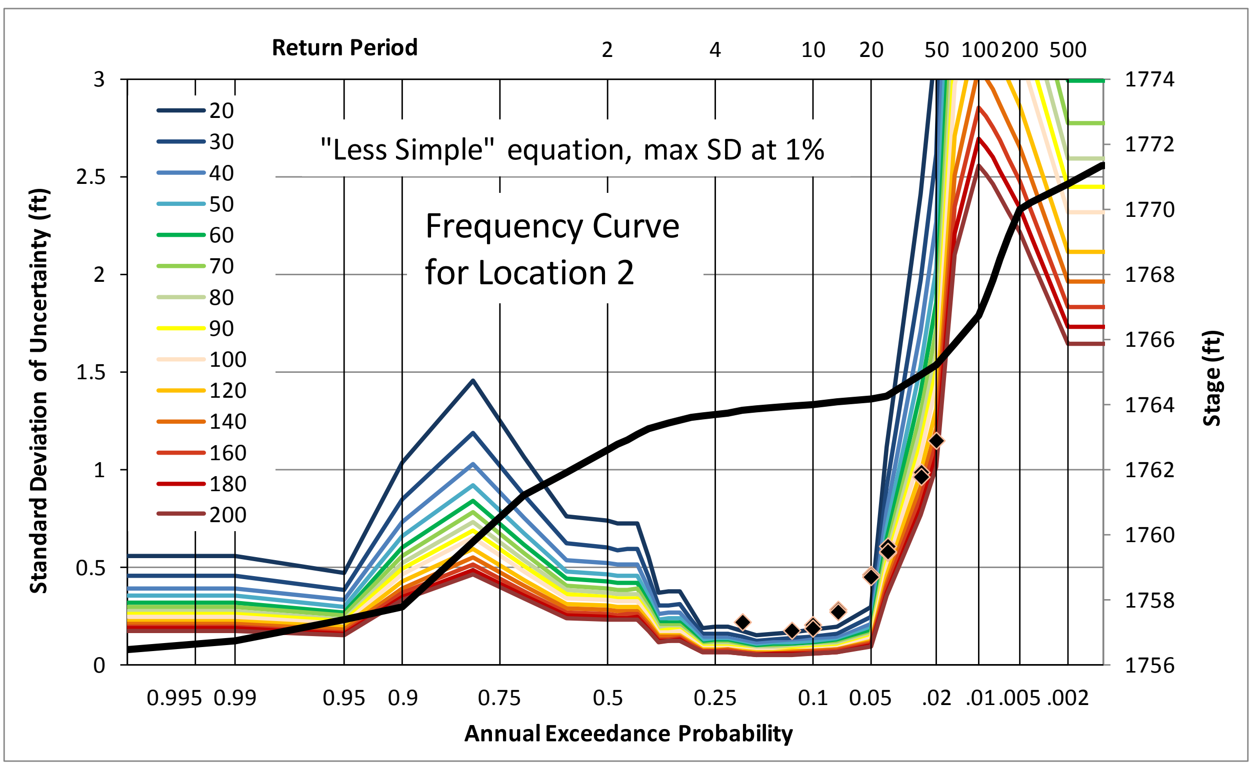

Figure 11. Variance for range of sample sizes, N, using Less Simple Method (Equation 3) for frequency curve that is steep in the upper quantiles

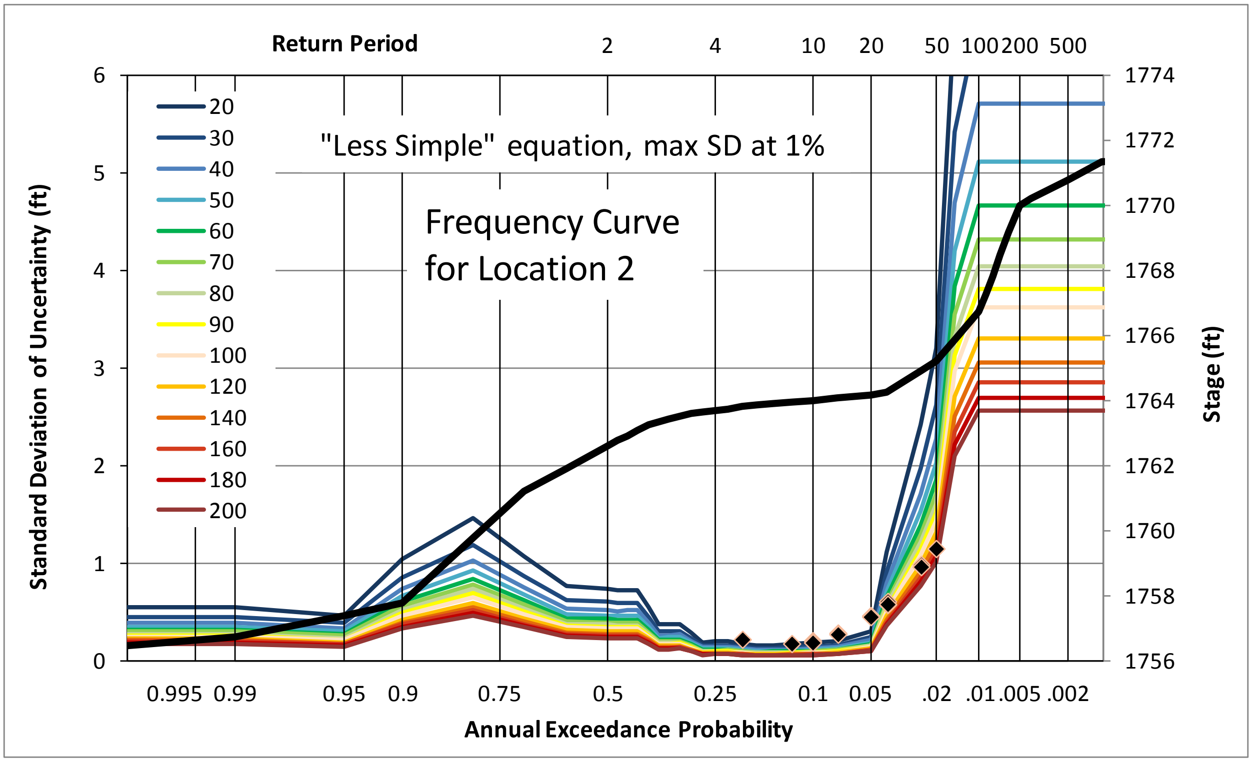

Figure 11a. Variance for range of sample sizes, N, using Less Simple Method (Equation 3) for frequency curve that is steep in the upper quantiles. As in FDA version 1.4, variance fixed at 1% quantile.

Remaining Challenges to Current Methods

A remaining difficulty with all of the methods discussed in this document is the fact that the actual distributions of uncertainty are asymmetrical, yet the computed variances are combined with Normal distribution which is symmetrical. Figure 2 demonstrated the asymmetrical PDFs near a local change in slope of the frequency curve. Locations with frequency curves like this are those that produce poor results with uncertainty defined with a Normal distribution. Figure 12 shows the 90% confidence interval around the 'Frequency Curve for Location 2' based on the Less Simple Method and a sample size of N=100.

Note that in the steep part of the frequency curve, using a symmetrical Normal distribution leads to uncertainty in the low direction that does not make sense based on the shape of the curve. The same effect often creates a similar "bulge" in the upward direction as a frequency curve flattens. While the edges of the confidence interval are not generally considered frequency curves in themselves, when FDA randomly samples a new frequency curve for each Monte Carlo realization, the curve is generated in the same way as these confidence intervals, and so sampled frequency curves could show these effects and so make little sense.

In the display of the confidence interval, as well as in the generation of the randomly sampled frequency curves, a correction is performed on the curve. Starting from the bottom of the curve (high exceedance probability) and moving upward, the curve is forced to be non-decreasing. And starting from the top of the curve (low exceedance probability) and moving downward, the curve is forced be non-increasing. This correction ensures reasonable confidence interval and sampled frequency curves. The solid confidence interval in Figure 12 includes the correction.

Although the correction just described makes the frequency curves usable, an asymmetrical distribution of uncertainty would produce a better result. Therefore, future versions of FDA would benefit from a method for deriving uncertainty that produced entire PDFs out to the far ends of the frequency curve that are realistically asymmetrical.

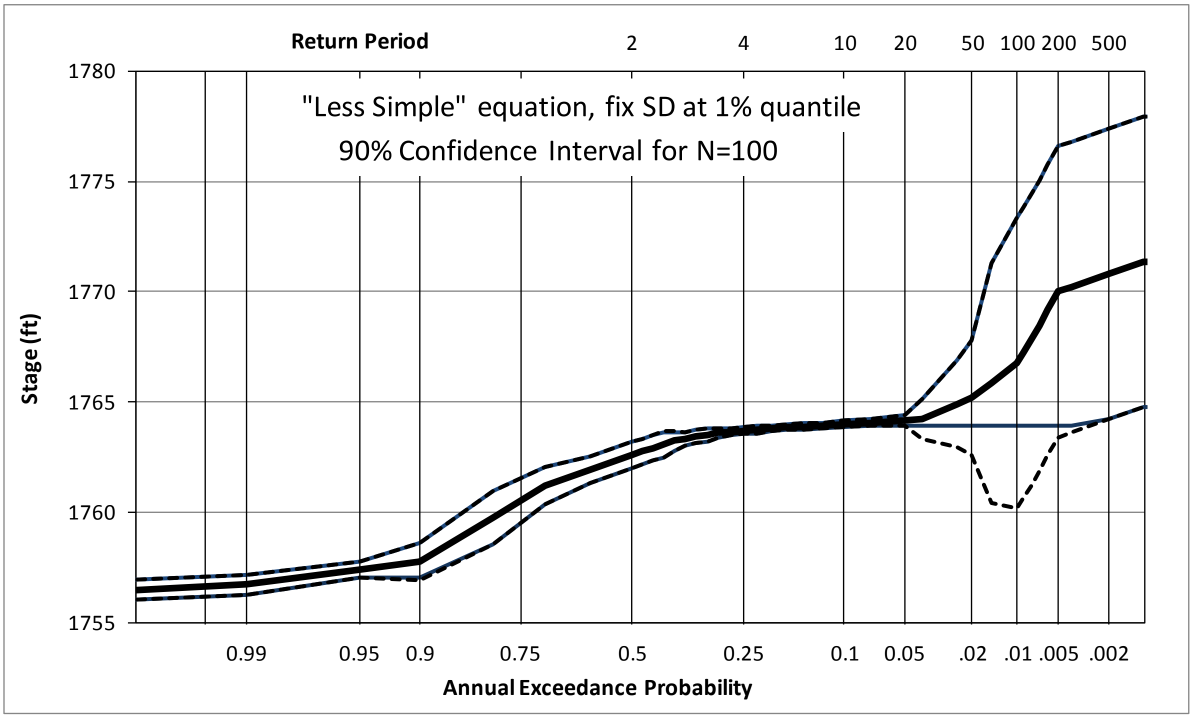

Figure 12. 90% confidence interval from "Less Simple Method" based on computed variance of uncertainty paired with a Normal distribution, for N=100

A simpler potential adjustment to the method in future versions of FDA would be to not recompute a sample size N_a at the "match point" for use with the approximated variances, which can lead to error if the local slope of the frequency curve at the match point is quite different to the slope of the frequency curve at higher quantiles. This adjustment would only apply with continued use of the Order Statistics method, and would not be relevant were another method chosen.

Conclusion

FDA version 1.4 includes the "Less Simple Method" of computing uncertainty around a graphical (empirical) frequency curve. This method includes a constraint fixing the uncertainty variance at the 1% quantile for use at higher quantiles of the frequency curve, and pairs the computed variances with a Normal distribution at each quantile.

This method was chosen among the methods discussed herein because it maintains the benefits of the Order Statistics computation, being responsive to local changes in slope.

attachment **C**:

Dr. Checks Report

Comment Report: All Comments
Project: hec-fda 1.2.4 model review
Review: hec-fda 1.2.4 model review
Displaying 45 comments for the criteria specified in this report.

Id	Discipline	Section/Figure	Page Number	Line Number
5324928	Economics	n/a	n/a	n/a

Comment Classification: **For Official Use Only (FOUO)**

The review issue is the adjustments made to uncertainty bands in Version 1.4 beyond the 1 percent quantile. In the HEC White Paper dated July 2013, the document indicates that the "Less Simple Method" used in Version 1.4 includes a caveat that variance is not allowed to increase beyond the 1% quantile, instead remaining constant for all higher quantiles. As Figure 11 illustrates, this creates an issue with curves that flatten after the 1% quantile, since the decrease in uncertainty that should result from the flatter part of the curve is lost, meaning the uncertainty for the higher quantiles is overestimated. Why does Version 1.4 not allow the uncertainty to decrease for quantiles beyond 1%? In other words, why is the variance above the 1% AEP held constant, rather than capped (with ceiling not a floor)? Recommend considering if adjustment can be refined in Version 1.4.

Submitted By: Brian Maestri (504-862-1915). Submitted On: Aug 22 2013

Revised Sep 20 2013.

1-0 Evaluation **Concurred**

As noted in the white paper, allowing the uncertainty to decrease beyond the 1% exceedance probability (at least as far as the 0.2% exc prob) would be a good idea. However I did not think of the idea until writing the white paper and so it was not considered for version 1.4. Changes in the uncertainty require a lot of testing, too much to do now. But the idea might be used in the next update (version 2.1).

Submitted By: Beth Faber (530 756 1104) Submitted On: Oct 11 2013

1-1 Backcheck Recommendation **Close Comment**

Recommend a cap on uncertainty bands especially for probability curves that flatten after the 1% quantile rather than a constant uncertainty band be considered for next update in version 2.1.

Submitted By: Brian Maestri (504-862-1915) Submitted On: Nov 26 2013

Current Comment Status: **Comment Closed**

Id	Discipline	Section/Figure	Page Number	Line Number
5324969	Economics	n/a	n/a	n/a

Comment Classification: **For Official Use Only (FOUO)**

A comparison of Version 1.2.5a model results to Version 1.4 results for the Morganza to the Gulf evaluation (using 1,000 iterations for each version): without project damages were 2.5 percent higher using Version 1.4 relative to Version 1.2.5a, Levee Alternative (ALT35) damages were 5.2% higher, and Levee Alternative (ALT100)) damages were 9.1% higher. In general, under what circumstances should we expect damages to be higher using Version 1.4 Less Simple Method relative to Version 1.2.5a? Attached is a screenshot of the results and the models can be provided upon request.

(Attachment: HEC_Comparison_of_Models.xlsx)

Submitted By: Brian Maestri (504-862-1915). Submitted On: Aug 22 2013

1-0 Evaluation **For Information Only**

It cannot be generalized that version 1.4 will produce higher EAD. In the small, unscientific sample of FDA studies, version 1.4 produced more EAD in the majority of the cases. I couldn't verify that in the case of Morganza, the differences were such a high percentage. From the spreadsheet, the version 1.2.5a without plan EAD was 6045 and the version 1.4 without plan EAD was 6065 (for all reaches). That's not to say there couldn't be differences of 10% or more in other studies. Usually, EAD will be higher when the uncertainty about the graphical curve is higher. Version 1.4 doesn't always calculate higher uncertainty so it cannot be generalized what circumstances will produce higher 1.4 uncertainty and both 1.2.5a and 1.4 calculate higher uncertainty for steeper portions of the curve.

Submitted By: Robert Carl (530.756.1104) Submitted On: Aug 29 2013

1-1 Backcheck Recommendation **Close Comment**

Recommend documentation state that it cannot be generalized that version 1.4 will produce higher or lower expected annual damages relative to version 1.2.5a.

Submitted By: Brian Maestri (504-862-1915) Submitted On: Nov 26 2013

Current Comment Status: **Comment Closed**

5325082	Economics	n/a	n/a	n/a

Comment Classification: **For Official Use Only (FOUO)**

The review issue is that the results from using data from an evaluation in New Orleans confirms that uncertainty can increase despite a longer period of record using the current version of the model, and that using the proposed Version 1.4 model can correct for this result. The significance of this issue is that the application of the proposed model to the current version of the model for this example confirms the issues highlighted by the model developers. Recommend HEC review test data and incorporate as confirmation of their recommendation that the proposed model is produces more logically consistent results relative to the current version. Attached are results from a test run that show an increase in the equivalent record length using Graphical Analysis actually leading to more uncertainty rather than less uncertainty using Version 1.2.5a. However, when Version 1.4 was used, then this inconsistency was corrected. A comparison of results from changes in equivalent record lengths for 20 years, 50 years, and 80 years, using graphical analysis shows the uncertainty ranges surrounding the stage-probability curves and the corresponding damage results using Version 1.2.5a and Version 1.4 for the Larose to Golden Meadow (LGM) evaluation. The LGM evaluation is a flood risk management evaluation containing approximately 10,000 structure records and only two reaches. The results show that when the equivalent record length was increased from 20 years to 50 years and then to 80 years using Version 1.2.5a, the uncertainty actually increased relative to 20 years and the corresponding damage results also increased relative to 20 years. The graphs of the uncertainty are also included in the attachment highlighting the increase in confidence bands for 50 years and 80 years of equivalent record length relative to 20 years. When the equivalent record length was increased from 50 years to 80 years, then uncertainty declined for 80 years relative to 50 years (but not to 20 years) as expected along with a decline in the damage results, using Version 1.2.5a. However, when Version 1.4 Less Simple Method was used with a 20 year, 50 year, and 80 year equivalent record length, then uncertainty surrounding the stage-probability decreased and corresponding damages decreased as longer equivalent record lengths were entered into the model. The models used in this comparison can be provided upon request.

(Attachment: Period_of_Record_Test.xlsx)

Submitted By: Brian Maestri (504-862-1915). Submitted On: Aug 22 2013

Revised Sep 20 2013.

1-0 Evaluation **Concurred**

This was a helpful test, and we appreciate your effort.

Submitted By: Beth Faber (530 756 1104) Submitted On: Oct 11 2013

1-1 Backcheck Recommendation **Close Comment**

Closed without comment.

Submitted By: Brian Maestri (504-862-1915) Submitted On: Nov 26 2013

Current Comment Status: **Comment Closed**

5325089 Economics n/a n/a n/a

Comment Classification: **For Official Use Only (FOUO)**

The review issue is the added time it takes to execute Version 1.4 relative to current version of the model. A comparison of the execution time for using Version 1.4 and Version 1.2.5a to develop aggregated stage-damage relationships, expected annual damages, and project performance statistics for two flood risk management evaluations (one with a large number of structure records and reaches and the other with a smaller number of structure records and reaches) was performed at New Orleans District and Version 1.4 took approximately twice as long to produce results as Version 1.2.5a. Should we expect the execution time for Version 1.4 to be longer than the execution time for Version 1.2.5a? Can improvements be made to the proposed model to reduce the execution time? Recommend the longer execution time of Version 1.4 relative to current version be noted in the documentation for the new version of the model.

Submitted By: Brian Maestri (504-862-1915). Submitted On: Aug 22 2013

Revised Sep 20 2013.

1-0 Evaluation **Concurred**

At the time of review, a "debug" version of the program was distributed to the reviewers. Subsequently, HEC created a stable "release" version of FDA 1.4 that does the computations about twice as fast as the "debug" version. The "release" version of the program will be the certified version of the program. Computation times will be about the same as with version 1.2.5a and will not require additional documentation in the user's manual.

Submitted By: Robert Carl (530.756.1104) Submitted On: Oct 10 2013

1-1 Backcheck Recommendation **Close Comment**

The "release" version of FDA 1.4 was tested at District and it can be confirmed that computation time was reduced relative to the original version distributed to reviewers.

Submitted By: Brian Maestri (504-862-1915) Submitted On: Nov 26 2013

Current Comment Status: **Comment Closed**

5325112	Economics	n/a	n/a	n/a

Comment Classification: **For Official Use Only (FOUO)**

The review concern is that an earlier version of the HEC-FDA model incorporated a technique that is currently being proposed for Version 1.4, but was not incorporated into the current model. In the HEC-FDA, Computations with Fragility Curves memo, dated 7 August 2013, the memo indicates that Model 1.4 will internally generate computation points (184 points) when using fragility curves to compute damage. This improvement will provide more accurate results when levee fragility curves are incorporated into the evaluation without the user being required to enter additional points to improve accuracy. The memo indicates that Version 1.2.2 and the latest Version 1.4 internally generated calculation points. Recommend addressing why were the internally generated calculation points for fragility curves were not incorporated into Version 1.2.5a, but should be used in Version 1.4.

Submitted By: Brian Maestri (504-862-1915). Submitted On: Aug 22 2013

Revised Sep 20 2013.

1-0 Evaluation **Concurred**

For version 1.2.4 and 1.2.5, the fragility curve points were used because during a study review using version 1.2.2, it was found that there were inaccurate results when using the internal computation points. It was felt that by using the fragility points to define the computation points, it allowed the user to control the computation points for all cases. However, we haven't been able to duplicate this problem and, for all the most recently observed cases, the fragility curves spanned a significant range of stages and better results would be obtained by using the internal computation points. Part of the problem was that users didn't add additional fragility curve points to get good computational points. Part of the reason for this was that it was very tedious and time consuming do to so, the user's didn't realize the importance of doing this, and the documentation didn't explain this. Version 1.4 user's manual will have additional text added describing the difference in calculations between versions 1.2.5a and 1.4.

Submitted By: Robert Carl (530.756.1104) Submitted On: Oct 10 2013

1-1 Backcheck Recommendation **Close Comment**
Recommend text be added to documenation describing the difference in calculation between the versions 1.2.5a and 1.4 when fragility curves are used in the evaluation.

Submitted By: Brian Maestri (504-862-1915) Submitted On: Nov 26 2013

Current Comment Status: **Comment Closed**

5325126 Economics n/a n/a n/a

Comment Classification: **For Official Use Only (FOUO)**

Review concern is the floodplain detail for an alternative provided by the model is overwritten when more than one alternative is executed in the HEC-FDA model. In the HEC-FDA Version 1.4 Summary Report, the changes to the model between Version 1.2.5a and Version 1.4 are listed. The FDAStructDetail.Out report file contains detail on the number of structures flooded for various probability events and other flood damage detail used by many Corps economists. This report is only available for the last project alternative executed by the HEC-FDA model. Recommend consideration be given to storing or saving the results for each of the previous alternatives, including the without-project condition, and for making these reports available to the user of future versions of the model. The floodplain detail is usually requested by USACE reviewers for each alternative and this feature would help users of the model to efficiency provide the information.

Submitted By: Brian Maestri (504-862-1915). Submitted On: Aug 22 2013

Revised Sep 20 2013.

1-0 Evaluation **Concurred**
There is an option to append results to the Fda_StructDetail.out file (and the Fda_SDmg.out and the Fda_SDev.out files). Under Economics->Compute Reach Stage-damage Functions with uncertainty, select the menu items Options->Compute Options and check the desired boxes. By checking the append boxes, results will be appended to whatever are already written to the file(s) so the user may want to delete the file first before executing a series of calculations.

Submitted By: Robert Carl (530.756.1104) Submitted On: Oct 10 2013

1-1 Backcheck Recommendation **Close Comment**
Helpful information on options provided by current model to save or store outputs of the model.

Submitted By: Brian Maestri (504-862-1915) Submitted On: Nov 26 2013

Current Comment Status: **Comment Closed**

5325137 Economics n/a n/a n/a

Comment Classification: **For Official Use Only (FOUO)**

The review issue is that the Version 1.4 allows fragility curves to be directly imported into the model while the current version does not. This will save time for the users of the newer version to enter these inputs relative to the current version especially for a large number of reaches. In the HEC-FDA Version 1.4 Summary Report, the changes to the model between Version 1.2.5a and Version 1.4 are listed. In the SD Library, summary point 7 indicates that import/export routines were changed in Version 1.4 to allow import/export of levee fragility data. This feature greatly reduces the time required to enter fragility curves relative to other versions of the model especially when there are a large number of reaches behind the Federal or local levees.

Submitted By: Brian Maestri (504-862-1915). Submitted On: Aug 22 2013

Revised Sep 20 2013.

1-0 Evaluation **Concurred**
Concur that this greatly reduces the time required.

Submitted By: Robert Carl (530.756.1104) Submitted On: Oct 10 2013

1-1 Backcheck Recommendation **Close Comment**
Closed without comment.

Submitted By: Brian Maestri (504-862-1915) Submitted On: Nov 26 2013

Current Comment Status: **Comment Closed**

5325149	Economics	n/a	n/a	n/a

Comment Classification: **For Official Use Only (FOUO)**

The review issue is the direct import of uncertainty regarding stage-probability relationships from other H&H models such as ADCIRC. In the HEC-FDA Version 1.4 Summary Report, the changes to the model between Version 1.2.5a and Version 1.4 are listed. In the SD Library, summary point 7 indicates that import/export routines were changed in Version 1.4 to allow import/export of various engineering inputs, has consideration been given to allowing users of future versions of the HEC-FDA model to import the uncertainty or confidence bands from other H&H models directly into the HEC-FDA model? As an example, the ADCIRC model, which is designed for coastal evaluations, uses a joint probability method to assign confidence bands. These confidence bands could be imported directly into the HEC-FDA model. Recommend briefly addressing if uncertainty can be imported from other H&H models including ADCIRC.

Submitted By: Brian Maestri (504-862-1915). Submitted On: Aug 22 2013

Revised Sep 20 2013.

1-0 Evaluation **Concurred**

Currently, there is a "back door" way override the use of the equivalent length of record and specify the standard deviation of error at every input point on the probability curves. It still assumes a normal distribution of error about the curve. It is not included in the GUI so it requires the user to open the database files with Microsoft Access or dBASE and edit the database files. Adding this capability to the GUI for versions 1.4 or 2.0 is not being considered at this time. This could be an addition for version 2.1. It would require a bigger effort if the distribution was not normal about the curve.

Submitted By: Robert Carl (530.756.1104) Submitted On: Oct 10 2013

Backcheck not conducted

2-0 Evaluation **Concurred**

With regard to importing uncertainty in relationships developed by other H&H models... Many of HEC's software products are incorporating Monte Carlo simulation of their inputs and parameters, which will allow analysis of these uncertainties. Currently, such Monte Carlo runs are for a single flow or hydrograph, not the full range needed for the curves brought into FDA. But given this helpful suggestion, the ability to define uncertainty around the full range of flows could be an added ability, to facilitate import to FDA. So an import might be possible in the future.

Submitted By: Beth Faber (530 756 1104) Submitted On: Oct 11 2013

2-1 Backcheck Recommendation **Close Comment**

Recommend considering direct import of uncertainty from other H&H models for future versions after version 1.4.

Submitted By: Brian Maestri (504-862-1915) Submitted On: Nov 26 2013

Current Comment Status: **Comment Closed**

5325151	Economics	n/a	n/a	n/a

Comment Classification: **For Official Use Only (FOUO)**

[**Critical/Flagged.**]

Review issue is allowing for importing of the equivalent record length (in years) by reach for each alternative rather than having to manually enter into the program. In the HEC-FDA Version 1.4 Summary Report, the changes to the model between Version 1.2.5a and Version 1.4 are listed. In the SD Library, summary point 7 indicates that import/export routines were changed in Version 1.4 to allow import/export of various engineering inputs, has consideration been given to allowing users of future versions of the HEC-FDA model to enter or import the equivalent record length (number of years) for each study area reach along with the flow or stage-probability relationships for each alternative when graphical analysis is used? In some Districts, such as New Orleans, all of the reaches have the same equivalent record length. When there are a significant number of reaches, the entry of equivalent record lengths using graphical analysis can be a time consuming task. A utility DOS program developed by HEC is currently being used to help save time on the entry of this value for all reaches. The need for this DOS program would be eliminated if the equivalent record lengths could be imported directly into the model for each reach. Recommend incorporating the capability into the proposed version to allow for more efficient entry of data.

Submitted By: Brian Maestri (504-862-1915). Submitted On: Aug 22 2013

Revised Sep 20 2013.

1-0 Evaluation **Non-concurred**

It's not planned to import just the equivalent length of record. In version 1.4, the graphical probability functions can be imported with the equivalent length of record. The ability to globally set the equivalent length of record could be considered for version 2.1.

Submitted By: Robert Carl (530.756.1104) Submitted On: Oct 10 2013

1-1 Backcheck Recommendation **Close Comment**

Will version 1.4 allow for the direct import of equivalent record length with the stage-probability relationships for each reach without having to manually enter the equivalent record length for each reach in the model or having to use a utility DOS program for import?

Submitted By: Brian Maestri (504-862-1915) Submitted On: Nov 26 2013

Current Comment Status: **Comment Closed**

5325156	Economics	n/a	n/a	n/a

Comment Classification: **For Official Use Only (FOUO)**

Review issue is use of triangular probability distributions was corrected for proposed version of the model. What problems were corrected in the proposed version relative to the current version? In the HEC-FDA Version 1.4 Summary Report, the changes to the model between Version 1.2.5a and Version 1.4 are listed. In the DB Library and GUI code, summary point 4 indicates that problems with triangular distributions were corrected. Many Districts currently use triangular probability relationships to represent the uncertainty surrounding the depth-damage relationships. Are the results using the current model close enough to being consistent for investment decisions? Is the log-normal probability distribution feature for expressing uncertainty in depth-damage relationships in Version 1.4 functional? Recommend briefly addressing corrections made to proposed version when using triangular probability distributions to represent uncertainty surrounding an engineering or economic input.

Submitted By: Brian Maestri (504-862-1915). Submitted On: Aug 22 2013

Revised Sep 20 2013.

1-0 Evaluation **Concurred**

The known error was for stage-discharge rating curves that had a calculated triangular distribution – the user entered the stage and corresponding max./min. for that point and the program computed the max./min. for the other ordinates. After entry and computation, the box for computation parameters was blank. Also, the user had to enter relative max./min. rather than total max./min. As far as is known, the log-normal feature works for depth-damage functions. The version 1.4 user's manual or release notes will be expanded to include a description of the correction.

Submitted By: Robert Carl (530.756.1104) Submitted On: Oct 10 2013

1-1 Backcheck Recommendation **Close Comment**
Closed without comment.

Submitted By: Brian Maestri (504-862-1915) Submitted On: Nov 26 2013
Current Comment Status: **Comment Closed**

5325158	Economics	n/a	n/a	n/a

Comment Classification: **For Official Use Only (FOUO)**

Review issue improvements to the printing of results using Version 1.4 of the HEC-FDA model. The proposed version of the model allows the user to print results, which previous versions did not always allow. This is positive feature for presenting results in meetings and in reports. Can further improvements be made to have results formatted to fit on one page for direct import in reports? Many users must create tables and re-typed the results into reports? Recommend attention be given to printing of results issues for uses of the proposed model.

Submitted By: Brian Maestri (504-862-1915). Submitted On: Aug 22 2013

Revised Sep 20 2013.

1-0 Evaluation **Non-concurred**
Any improvement to printing in version 1.4 was purely coincidental as there was no effort put into this. The print feature uses very old commercial libraries that haven't been supported for nearly 20 years and have been prone to instabilities. At this point it is impractical to make changes to the reports and any future development in this area will have to be done in version 2.0.

Submitted By: Robert Carl (530.756.1104) Submitted On: Oct 10 2013

1-1 Backcheck Recommendation **Close Comment**
Recommend revising printing features of the model for versions after version 1.4.

Submitted By: Brian Maestri (504-862-1915) Submitted On: Nov 26 2013
Current Comment Status: **Comment Closed**

5325167	Economics	n/a	n/a	n/a

Comment Classification: **For Official Use Only (FOUO)**

Review issue is documenting the added capability to store results using the Version 1.4 relative to the current version of the model. In the HEC-FDA Version 1.4 Summary Report, the changes to the model between Version 1.2.5a and Version 1.4 are listed. In the GUI code section, summary point 1 indicates that results reports are written to the tab delimited file Fda_Results.txt for import into spreadsheets and for inclusion in reports. This improvement will save time for analysts displaying the results in Corps reports. In a test run, we found that many of the result displays in the previous versions of the model, such as the exceedance-probability damage relationship by study area reach for each alternative, which incorporates the risk surrounding the engineering and economic inputs, were not available as text files in earlier versions, but are now available for Version 1.4.

Recommend that the User's Manual or release notes detail that the user must first open the desired results in the model and then close the display within the model before results will available as a read-only text file with the desired results.

Submitted By: Brian Maestri (504-862-1915). Submitted On: Aug 22 2013

Revised Sep 20 2013.

1-0 Evaluation **Concurred**

We haven't found it necessary to close the display of the results report before opening Fda_Results.txt as a read-only text file. However, we will add to the description to indicate the user may have to close the display within the model before results will be available.

Submitted By: Robert Carl (530.756.1104) Submitted On: Oct 10 2013

1-1 Backcheck Recommendation **Close Comment**

Thanks for clarification, my comment was not correctly stated. If results of the model are viewed and the Fda_Results.txt file is opened, then these results are automatically stored in the Fda_Results.txt file. However, if additional model outputs or results are viewed, then these results will not be stored until the Fda_Results.txt file is closed and then re-opened.

Submitted By: Brian Maestri (504-862-1915) Submitted On: Nov 26 2013

Current Comment Status: **Comment Closed**

5325193	Economics	n/a	n/a	n/a

Comment Classification: **For Official Use Only (FOUO)**

Review issue is can additional output data, such as the exceedance-probability damage relationships, be stored and made available for each structure record for Version 1.4. This information would be helpful in assessing non-structural measures on a structure-by-structure basis with risk and uncertainty incorporated into the results. Recommend consideration be given to having exceedance-probability damage relationships be made available in a text file for each structure record for the proposed version of the model rather than only by reach as in the current version of the model.

Submitted By: Brian Maestri (504-862-1915). Submitted On: Aug 22 2013

Revised Sep 20 2013.

1-0 Evaluation **Concurred**

At the present time, there are no plans to compute and write to a text file, damage-probability for each structure. You can currently get stage- damage functions for each structure in a text file if the trace level is turned up high enough. It would be possible to add probability to this table but at a computational cost and it would not include risk calculations for the probability curve. It could be implemented in version 2.1.

Submitted By: Robert Carl (530.756.1104) Submitted On: Oct 10 2013

1-1 Backcheck Recommendation **Close Comment**

Recommend for consideration for versions after version 1.4.

Submitted By: Brian Maestri (504-862-1915) Submitted On: Nov 26 2013

Current Comment Status: **Comment Closed**

5325202	Economics	n/a	n/a	n/a

Comment Classification: **For Official Use Only (FOUO)**

Review issue is how to transition to the proposed version of the model from the current version. After reviewing the Transition Recommendations in Section 4.3 of the Certification Report, would the approach be to not require the implementation of results using the Version 1.4 for previously authorized projects or certified levees, use results from Version 1.4 as a sensitivity analysis for on-going near completion evaluations, and require use of Version 1.4 for on-going not near completion evaluations. Does this approach parallel the path in which HEC plans to implement Version 1.4 if becomes the certified version of the model? Recommend determining a milestone in the planning process by which the transition to using results from the newer version of the model.

Submitted By: Brian Maestri (504-862-1915). Submitted On: Aug 22 2013

Revised Sep 20 2013.

1-0 Evaluation **Concurred**

This comment relates to the HEC version transition recommendations in Section 4.3 of the Certification Report (version of 22May13). HEC essentially proposes conversion to FDA 1.4 as soon as possible for any study, but with FRM-PCX able to allow exceptions where justified.

Per Eric Thaut's email of 30July2013, the FRM-PCX will recommend an approach for transitioning to version 1.4 in its report to HQ for certification. HEC defers to FRM-PCX regarding transition policies, and refers the comment to FRM-PCX.

Submitted By: Beth Faber (530 756 1104) Submitted On: Oct 23 2013

1-1 Backcheck Recommendation **Close Comment**

Submitted By: Brian Maestri (504-862-1915) Submitted On: Nov 26 2013

Current Comment Status: **Comment Closed**

5347426	Hydrology	n/a	Figure 3 graphic on page 7/18	n/a

Comment Classification: **Public (Public)**
(Document Reference: FDA 1.4 Summary Report 20130328.docx)

1. In this example, a seemingly unreasonable degree of stage uncertainty prevails, ironically for even the recommended "Less Simple" approach. Is this simply an anomaly of how (actual "where") the approach transitions into the parallel set of bands in the region beyond a given probability?
2. Reasonableness of projected uncertainties with Stage vs. Frequency functions.
3. Moderate to High
4. Discussion and justification of this uncertainty bandwidth

Submitted By: Craig Loftin (817-886-1683). Submitted On: Sep 09 2013

Revised Sep 27 2013.

1-0 Evaluation **Concurred**

Yes, that is the reason. This is kind of a "worst case" for this method. The computed uncertainty incorrectly falls off at the extremes (> 500-year), and can be extremely large at somewhat less than those extremes (200-year to 500-year), and so a point was chosen at which fix the uncertainty, not letting it get larger or smaller. The chosen point is the 1% exceedance probability. This curve that flattens at the top is a challenge, because the uncertainty should decrease in the flat area, before then increasing some amount as it moves to the right (toward higher return periods.) As noted in comment (and response) 5324928, a considered improvement is to prevent uncertainty from getting larger after 1%, but allow it to get smaller, at least as far as the 0.2% (500-year) before remaining constant from that point to the right.

Submitted By: Beth Faber (530 756 1104) Submitted On: Oct 11 2013

1-1 Backcheck Recommendation **Close Comment**

Closed without comment.

Submitted By: Craig Loftin (817-886-1683) Submitted On: Dec 02 2013

Current Comment Status: **Comment Closed**

5347427	Hydrology	n/a	Overall	n/a

Comment Classification: **Public (Public)**
(Document Reference: FDA 1.4 Summary Report 20130328.docx)

1. Abrupt bends in frequency curves generally reflect non-continuity in the function. In such cases, would there be justification for considering segmented confidence bands, configured in such a manner as to generally reflect parallelity to the frequency curve over each particular segment?
2. Discontinuities in applied function(s).
3. Moderate to Low
4. Contemplation for consideration in future versions of HEC-FDA.

Submitted By: Craig Loftin (817-886-1683). Submitted On: Sep 09 2013

Revised Sep 27 2013.

1-0 Evaluation **Concurred**

Agree that the abrupt bends in the frequency curve present the greatest challenge to defining the uncertainty, and are the reason simpler solutions are less successful.

Segmenting the curve to define uncertainty the more regular sections seems appealing. But the the abrubt bend causes greater resulting uncertainty (in one direction) in the neighboring segments, which might not be captured if we separated them. In other words, defining uncertainty in each segment, as if the entire curve were similar to that segment, would underestimate the uncertainty on either side of the bends.

Note, the "simple method" does something very similar to this suggestion, but without needing segmentation. It was not the ultimate choice because the method is insensitive to the slope changes in the curve.

Submitted By: Beth Faber (530 756 1104) Submitted On: Oct 23 2013

1-1 Backcheck Recommendation **Close Comment**

Closed without comment.

Submitted By: Craig Loftin (817-886-1683) Submitted On: Dec 02 2013

Current Comment Status: **Comment Closed**

5347428	Hydrology	n/a	Figure 4 graphic on page 12/18	n/a

Comment Classification: **Public (Public)**

(Document Reference: FDA 1.4 Summary Report 20130328.docx)

1. In this example, why don't all three of the displayed 90% CNP curves at least begin to converge for larger equivalent record lengths?
2. Confusion on the part of reviewer.
3. Moderate to Low.
4. Simple explanation.

Submitted By: Craig Loftin (817-886-1683). Submitted On: Sep 09 2013

Revised Sep 27 2013.

1-0 Evaluation **Concurred**

Assuming TruckeeQf figure 4, pg 8. Good observation. With a large enough record length (and therefore small enough uncertainty) the 90% CNP stage should approach the best estimate 1% stage. 1.2.5a and "simple" get there by 150 years. The "less simple" curve doesn't reach it by 150 years, and might not reach that point until extremely high record length. This is consistent with the larger uncertainty at the 1% event shown in page A-38 of appendix A.

Submitted By: Beth Faber (530 756 1104) Submitted On: Oct 23 2013

1-1 Backcheck Recommendation **Close Comment**
Closed without comment.

Submitted By: Craig Loftin (817-886-1683) Submitted On: Dec 02 2013
Current Comment Status: **Comment Closed**

5347429	Hydrology	n/a	Table 7 on page 18/18	n/a

Comment Classification: **Public (Public)**
(Document Reference: FDA 1.4 Summary Report 20130328.docx)

1. Initially, this reviewer was surprised (and concerned) with how the CEP at the 1% Event fell so drastically on the "Cibolo Crk" example (etal), when going from V1.25a to V1.40. Subsequently, following our own series of test runs on other independent examples, some similar trends were noted.
2. Potentially drastic shif in levee reliability statistic between old and new versions.
3. High to Moderate.
4. Please comment as to whether users should anticipate that the levee "non-reliability" statistic will indeed rapidly approach zero around the same range of target stage for which the previous version of the program would indicate a substantial "non-reliability".

Submitted By: Craig Loftin (817-886-1683). Submitted On: Sep 09 2013

Revised Sep 27 2013.

1-0 Evaluation **Concurred**
I think there's some confusion resulting from a typo in the document, as the tables say "conditional exceedance probability" rather than "conditional non-exceedance probability," which is being referenced in the comment as CEP, and "non-reliability." I think the values in the table are non-exceedance, and so the CNP. With CNP, we usually call it "assurance" or "reliability," rather than "non-reliability". Apologies for the typo, and resultant confusion.

To address the comment, for CNP, in the limit (no uncertainty) this value will go to either 0% or 100%, depending on whether the top-of-levee is above or below the best estimate of the 1% stage. And 1.4 will either be greater than or less than 1.2.5a depending on both whether the uncertainty is larger or smaller, and whether the levee is above or below the best estimate 1% stage.

Submitted By: Beth Faber (530 756 1104) Submitted On: Oct 11 2013

1-1 Backcheck Recommendation **Close Comment**
Closed without comment.

Submitted By: Craig Loftin (817-886-1683) Submitted On: Dec 02 2013
Current Comment Status: **Comment Closed**

5347430	Hydrology	n/a	Introduction, page A-1 (etal)	n/a

Comment Classification: **Public (Public)**
(Document Reference: HEC-FDA Ver 1.4 Appendix A GraphicalProbFuncUncertainty.docx)

1. How is "local slope" defined? In the prior versions of the program, are the confidence bands developed from "point-to-point" along the graphical function or does a trend in slope (i.e. over a range of probability) control the projected degree of uncertainty? Could it be that the user should have been manually smoothing the array, in order to avoid exaggerated error patterns? While I am on that topic, should the user have been and currently be encouraged to consider applying a reasonably-fit analytical curve, to ensure a more stable treatment of uncertainties?
2. Desire for optimally stable function(s).
3. Moderate to Low.
4. Discussion related to "best" guidance for users.

Submitted By: Craig Loftin (817-886-1683). Submitted On: Sep 09 2013

Revised Sep 27 2013.

1-0 Evaluation **Concurred**

Local slope is the slope of the frequency curve (inverse slope of the CDF of flow or stage) at any given exceedance probability. The order statistics method used in prior versions of FDA incorporated the local slope implicitly – the "synthetic sample" of points has the points far apart where slope is steep, and close together where slope is flat, resulting in wider or narrower uncertainty distributions, respectively. In the "less simple" method, the local slope is used explicitly. We've tried to avoid having the computation of uncertainty something the user would have to manually edit, however some of the challenges to the method could be overcome if we allowed some edits by informed users.

(Note, Currently, there is a "back door" way override FDA's uncertainty computation, and specify the standard deviation of error at every input point on the probability curves. It is not included in the GUI so it requires the user to open the database files with Microsoft Access or dBASE and edit the database files. Adding this capability to the GUI for versions 1.4 or 2.0 is not being considered at this time.)

Yes, we generally suggest use of an LP3 curve if possible, modified by a transform of unregulated to regulated flow and from flow to stage. In some cases that isn't possible, but the LP3 uncertainty is more stable, so when it is possible, it's recommended.

Submitted By: Beth Faber (530 756 1104) Submitted On: Oct 23 2013

1-1 Backcheck Recommendation **Close Comment**

Closed without comment.

Submitted By: Craig Loftin (817-886-1683) Submitted On: Dec 02 2013

Current Comment Status: **Comment Closed**

5347431	Hydrology	n/a	Graphic on page A-32	n/a

Comment Classification: **Public (Public)**
(Document Reference: HEC-FDA Ver 1.4 Appendix A GraphicalProbFuncUncertainty.docx)

1. What is "NBLE_A"? The function is essentially non-continuous and likely represents a stage frequency curve upstream from an embankment and/or control structure, but it is certainly not surprising that it wreaked havoc with the estimation of confidence bands. Quite clearly, the proposed methodology handles this situation far better than does the prior versions.
2. Desire to understand the source and/or nature of this frequency curve.
3. Low
4. Simple explanation.

Submitted By: Craig Loftin (817-886-1683). Submitted On: Sep 09 2013

Revised Sep 27 2013.

1-0 Evaluation **Concurred**
The damage area is border by a railroad embankment that, once overtopped, results in an overflow situation where for decreasing exceedance probability, there is very little change in stage.

Submitted By: Robert Carl (530.756.1104) Submitted On: Oct 10 2013

1-1 Backcheck Recommendation **Close Comment**
Closed without comment.

Submitted By: Craig Loftin (817-886-1683) Submitted On: Dec 02 2013

2-0 Evaluation **Concurred**
Agree that "less simple" does better in this case. It's because the dramatic changes in slope happen to the left of the 1% event, and so are computed successfully and used.

Submitted By: Beth Faber (530 756 1104) Submitted On: Oct 11 2013

Backcheck not conducted

Current Comment Status: **Comment Closed**

5347433	Hydrology	n/a	Graphic on page A-35	n/a

Comment Classification: **Public (Public)**
(Document Reference: HEC-FDA Ver 1.4 Appendix A GraphicalProbFuncUncertainty.docx)

1. Not meaning to question the testing source data, this reviewer would simply be curious to know where this particular frequency curve was applied. If it is the Rio Grande familiar to us Texians, it would seem to reflect unreasonably low discharges for given annual exceedance probabilities.
2. Reasonableness of discharge frequency curve (i.e. magnitude thereof)
3. Low
4. Simple explanation.

Submitted By: Craig Loftin (817-886-1683). Submitted On: Sep 09 2013

Revised Sep 27 2013.

1-0 Evaluation **For Information Only**

Unfortunately, I have forgotten the source of the data and do not know where this study was located.

Submitted By: Robert Carl (530.756.1104) Submitted On: Oct 10 2013

1-1 Backcheck Recommendation **Close Comment**

Closed without comment.

Submitted By: Craig Loftin (817-886-1683) Submitted On: Dec 02 2013

Current Comment Status: **Comment Closed**

5347434	Hydrology	n/a	Graphic on page A-41	n/a

Comment Classification: **Public (Public)**

(Document Reference: HEC-FDA Ver 1.4 Appendix A GraphicalProbFuncUncertainty.docx)

1. As noted in review comment 1 above, a seemingly unreasonable degree of stage uncertainty prevails, ironically for even the recommended "Less Simple" approach. Is this simply an anomaly of how (actual "where") the approach transitions into the parallel set of bands in the region beyond a given probability?
2. Reasonableness of projected uncertainties with Stage vs. Frequency functions.
3. Moderate to High
4. Discussion and justification of this uncertainty bandwidth.

Submitted By: Craig Loftin (817-886-1683). Submitted On: Sep 09 2013

Revised Sep 27 2013.

1-0 Evaluation **Concurred**

Yes, exactly, this is again a case where the slope is very steep at the 1% event, and the resultant large uncertainty carries to the right as constant (parallel bands). A more appropriate solution would be smaller uncertainty around the flatter upper end of the curve, but the method cannot compute it at the small exceedance probabities. As noted in another comment, there is potential, in a future version, to allow decrease of uncertainty (but not increase) between the 1% and 0.2% events.

Submitted By: Beth Faber (530 756 1104) Submitted On: Oct 11 2013

1-1 Backcheck Recommendation **Close Comment**

Closed without comment.

Submitted By: Craig Loftin (817-886-1683) Submitted On: Dec 02 2013

Current Comment Status: **Comment Closed**

5347435	Hydrology	n/a	Graphics on page A-50 and A-52	n/a

Comment Classification: **Public (Public)**
(Document Reference: HEC-FDA Ver 1.4 Appendix A GraphicalProbFuncUncertainty.docx)

1. Although it is understandable that the uncertainties in stage would theoretically be minimized at the rare end of this frequency curve, it is difficult to envision how the CNEP would so quickly approach zero, for even a nominal number of equivalent record years.
2. Reasonableness of CNEP statistic relative to equivalent record length.
3. Moderate to Low.
4. Simple explanation.

Submitted By: Craig Loftin (817-886-1683). Submitted On: Sep 09 2013

Revised Sep 27 2013.

1-0 Evaluation **For Information Only**
This must be a case where the top-of-levee is below the 1% stage. As uncertainty decreases and so the distribution around the 1% stage tightens, CNP decreases because there is less and less of the distribution that remains below the top-of-levee. It is about a 33 year levee or about a 0.03 AEP. This could also be described as there is more of the distribution above the top-of-levee so fewer non-exceedances.

Submitted By: Robert Carl (530.756.1104) Submitted On: Oct 10 2013

1-1 Backcheck Recommendation **Close Comment**
Closed without comment.

Submitted By: Craig Loftin (817-886-1683) Submitted On: Dec 02 2013

Current Comment Status: **Comment Closed**

5347436	Hydrology	n/a	Overall	n/a

Comment Classification: **Public (Public)**
(Document Reference: HEC-FDA Ver 1.4 Appendix A GraphicalProbFuncUncertainty.docx)

1. What is your view(s) regarding the idea of having USACE Districts manually test their HEC-FDA 1.25a setups with a range of equivalent record lengths, to simply ensure that their adopted results (EAD's, etc.) fall in the stable portion of the hypothetical curve relative to equivalent record length?
2. Concerns with the prior version(s) might be proven inconsequential on many studied projects to date.
3. Moderate to High
4. Have USACE Districts test for the sensitivity on any/all potentially affected projects.

Submitted By: Craig Loftin (817-886-1683). Submitted On: Sep 09 2013

Revised Sep 27 2013.

1-0 Evaluation **Concurred**
HEC views it as good practice for PDT's to make the suggested tests to consider whether their existing FDA 1.2.5a results are significantly affected by shortcomings in the graphical uncertainty method used in that version.

If the comment proposes to formalize such checks as part of the version transition policies, then HEC defers to FRM-PCX, per Eric Thaut's email of 30July2013.

Submitted By: Beth Faber (530 756 1104) Submitted On: Oct 23 2013

1-1 Backcheck Recommendation **Close Comment**
Closed without comment.

Submitted By: Craig Loftin (817-886-1683) Submitted On: Dec 02 2013

Current Comment Status: **Comment Closed**

5347437	Hydrology	n/a	Graphics on pages B-7 and B-16	n/a

Comment Classification: **Public (Public)**
(Document Reference: HEC-FDA Ver 1.4 Appendix B Comparison of Version Results.docx)

1. Ideally, the graphical approach should almost exactly replicate the analytical approach, whenever the graphical points tend to follow a Log Pearson Type III trend. Although the projections are typically much less critical in the frequent end of the curve, there "may" be some room for improvement in how the "Less Simple" method deals with that range, at least in this particular example. It does appear to have handled "Chester" (Graphic on page B-16) much more consistently.
2. Consistency in results when frequency curve is essentially Log Pearson Type III, but run with graphical method.
3. Moderate to High.
4. Consider recommending that users apply analytical method, whenever the frequency curve is essentially that.

Submitted By: Craig Loftin (817-886-1683). Submitted On: Sep 09 2013

Revised Sep 27 2013.

1-0 Evaluation **Concurred**
Typically, uncertainty in an empirical frequency curve is greater than that of an analytical curve, because we've removed a piece of information – the assumed probability distribution. So results would not replicate the analytical approach, but rather be more uncertain. All of the considered methods for empirical (graphical) curves tend to work a bit better when the curve is very close to analytical. But the example on page B-7 shows that the lower end, far below the median, can be as challenging as the upper end. In this case, the uncertainty widens even more at the low end than the upper because of the slightly negative skew. The same solution of fixing the uncertainty 1% in from the end is used.

The Chester example on B-16 is Log Pearson 3, not graphical, so the graphical methods were not used in this case. And as noted in another comment, agree that LP3 is more stable and we do recommend it's use when feasible.

Submitted By: Beth Faber (530 756 1104) Submitted On: Oct 11 2013

1-1 Backcheck Recommendation **Close Comment**
Closed without comment.

Submitted By: Craig Loftin (817-886-1683) Submitted On: Dec 02 2013
Current Comment Status: **Comment Closed**

5347438	Hydrology	n/a	NA	n/a

Comment Classification: **Public (Public)**
(Document Reference: Changes since Version 1.2.4.docx)

no comments

Submitted By: Craig Loftin (817-886-1683). Submitted On: Sep 09 2013

1-0 Evaluation **Concurred**
No comments.

Submitted By: Robert Carl (530.756.1104) Submitted On: Oct 10 2013

1-1 Backcheck Recommendation **Close Comment**
Closed without comment.

Submitted By: Craig Loftin (817-886-1683) Submitted On: Dec 02 2013
Current Comment Status: **Comment Closed**

5347439	Hydrology	n/a	NA	n/a

Comment Classification: **Public (Public)**
(Document Reference: CPD-72.pdf)

no comments, based on subject matter discussion with Robert Carl, HEC on 09 September 2013

Submitted By: Craig Loftin (817-886-1683). Submitted On: Sep 09 2013

1-0 Evaluation **Concurred**
No additional comments.

Submitted By: Robert Carl (530.756.1104) Submitted On: Oct 10 2013

1-1 Backcheck Recommendation **Close Comment**
Closed without comment.

Submitted By: Craig Loftin (817-886-1683) Submitted On: Dec 02 2013
Current Comment Status: **Comment Closed**

5347440 Hydrology n/a Page 9/13, last 2 paragraphs n/a

Comment Classification: **Public (Public)**

(Document Reference: Estimating Uncertainty White Paper v2.docx)

1. This reviewer appreciates your inclusion of the phrase "lack of hydrologic reality in the computation of uncertainty". As we have often noted during this Risk-and-Uncertainty Analysis Era, we are far more uncertain about how to define the uncertainties than we are uncertain about the magnitudes of the variables under consideration themselves. Proceeding into the last paragraph on page 9/13, your reminder that the "Less Simple Method" can result in unreasonably exaggerated spread in the confidence bands beyond the 1% quantile, essentially answers my first review comment on the Summary Report and my fourth review comment on Appendix A.
2. Practicality of computed results.
3. Moderate to Low
4. Maintain honesty and openness with users, regarding any known weaknesses in HEC-FDA solutions.

Submitted By: Craig Loftin (817-886-1683). Submitted On: Sep 09 2013

Revised Sep 27 2013.

1-0 Evaluation **Concurred**

Thanks for looping back to the earlier comments.

Submitted By: Beth Faber (530 756 1104) Submitted On: Oct 11 2013

1-1 Backcheck Recommendation **Close Comment**

Closed without comment.

Submitted By: Craig Loftin (817-886-1683) Submitted On: Dec 02 2013

Current Comment Status: **Comment Closed**

5347442 Hydrology n/a Pages 12/13 - 13/13 and Figure 12 n/a

Comment Classification: **Public (Public)**

(Document Reference: Estimating Uncertainty White Paper v2.docx)

1. Truncating the confidence bands to ensure that each always has a positive (actually zero or greater) slope across the frequency scale would appear to inadvertently bias uncertainties in the upper direction, over the range within which our flood risk management project study reaches contribute to expected annual damages and levee reliability statistics. As such, this correction may ensure "reasonably sloped" sampling frequency curves, but not necessarily ensure "reasonable confidence interval and sample frequency curves" per se. Would it not significantly skew the effective (mass-averaged) frequency curve near the 0.01 AEP, in examples such as that shown in Figure 12?
2. Reasonableness of computed results.
3. Moderate to High.
4. Avoid solution schemes which achieve a minor goal, but introduce unnecessarily biased results.

Submitted By: Craig Loftin (817-886-1683). Submitted On: Sep 09 2013

Revised Sep 27 2013.

1-0 Evaluation **For Information Only**
The single example shown was perhaps not a good representation of the results of the correction. It just as often makes the high end of the frequency curve lower, with no systematic bias. In fact, if the sampled curve is above the original (like the upper 90% confidence line), we start at the top and move left, making sure the curve is non-increasing. It is only for a lower sampled curve that we start at the bottom and move right, making sure the curve in non-decreasing.

Submitted By: Beth Faber (530 756 1104) Submitted On: Oct 11 2013

1-1 Backcheck Recommendation **Close Comment**
Closed without comment.

Submitted By: Craig Loftin (817-886-1683) Submitted On: Dec 02 2013

Current Comment Status: **Comment Closed**

5347443	Hydrology	n/a	Overall	n/a

Comment Classification: **Public (Public)**
(Document Reference: Estimating Uncertainty White Paper v2.docx)

1. This paper is a bit heavy on statistical jargon and concepts than this H&H reviewer can fully comprehend, but it clearly conveys the story of just how complicated is the definition of uncertainties-about-the-frequency-curve.
2. (No concern whatsoever)
3. None
4. Keep up this kind of good work!

Submitted By: Craig Loftin (817-886-1683). Submitted On: Sep 09 2013

Revised Sep 27 2013.

1-0 Evaluation **Concurred**
Thank you.

Submitted By: Beth Faber (530 756 1104) Submitted On: Oct 11 2013

1-1 Backcheck Recommendation **Close Comment**
Closed without comment.

Submitted By: Craig Loftin (817-886-1683) Submitted On: Dec 02 2013

Current Comment Status: **Comment Closed**

5347444	Hydrology	n/a	Section 3, page 3 (etal)	n/a

Comment Classification: **Public (Public)**
(Document Reference: Testing Plan FDA 1_4_20130501.docx)

1. In future reporting, you might consider adding the word "upward" or "downward" after either of these terms.
2. Clarity for readers.
3. Low
4. Take advantage of such "low hanging fruits" in future reporting/documentation.

Submitted By: Craig Loftin (817-886-1683). Submitted On: Sep 09 2013

Revised Sep 27 2013.

1-0 Evaluation **For Information Only**
I'm not sure which terms should come before the words "upward" or "downward".

Submitted By: Robert Carl (530.756.1104) Submitted On: Oct 10 2013

1-1 Backcheck Recommendation **Close Comment**
Closed without comment.

Submitted By: Craig Loftin (817-886-1683) Submitted On: Dec 02 2013
Current Comment Status: **Comment Closed**

5347445 Hydrology n/a Overall n/a

Comment Classification: **Public (Public)**
(Document Reference: Testing Plan FDA 1_4_20130501.docx)

1. This document presents a well organized and thorough approach for testing the software. Expected Outcomes, Summary, and Conclusion are all logical and well presented.
2. (No concern whatsoever)
3. None
4. Keep up this kind of good work!

Submitted By: Craig Loftin (817-886-1683). Submitted On: Sep 09 2013

Revised Sep 27 2013.

1-0 Evaluation **Concurred**
Thank you, from the certification team.

Submitted By: Beth Faber (530 756 1104) Submitted On: Oct 11 2013

1-1 Backcheck Recommendation **Close Comment**
Closed without comment.

Submitted By: Craig Loftin (817-886-1683) Submitted On: Dec 02 2013
Current Comment Status: **Comment Closed**

5347446 Hydrology n/a NA n/a

Comment Classification: **Public (Public)**
(Document Reference: HEC-FDA Calculations with Fragility Curves.pdf)

This review is still pending as of 09 (and 27) Sept 2013; however, this reviewer has discussed the underlying fragility curve "stage resolution" issue with program proponent Robert Carl, HEC, and does not anticipate finding any significant issues with the described/proposed approaches embedded within V1.40 "Less Simple".

Submitted By: Craig Loftin (817-886-1683). Submitted On: Sep 09 2013

Revised Sep 27 2013.

1-0 Evaluation **Concurred**
Comment noted. Thanks for including.

Submitted By: Beth Faber (530 756 1104) Submitted On: Oct 11 2013

1-1 Backcheck Recommendation **Close Comment**
Closed without comment.

Submitted By: Craig Loftin (817-886-1683) Submitted On: Dec 02 2013

Current Comment Status: **Comment Closed**

5356787 Hydrology n/a n/a n/a

Comment Classification: **Public (Public)**

Stedinger Review. White Paper with comments will be a second comment.

(Attachment: Jery_Stedinger_Comments_HEC-FDA.docx)

Submitted By: Jery Stedinger (607-255-2351). Submitted On: Sep 17 2013

1-0 Evaluation **Concurred**
Attached document has been dispersed into subsequent comments.

Submitted By: Beth Faber (530 756 1104) Submitted On: Oct 11 2013

1-1 Backcheck Recommendation **Close Comment**
Close comment. Resolutions discussed below.

Submitted By: Jery Stedinger (607-255-2351) Submitted On: Nov 08 2013

Current Comment Status: **Comment Closed**

5356788 Hydrology n/a n/a n/a

Comment Classification: **Public (Public)**

White Paper with Stedinger Comments.

(Attachment: Estimating_Uncertainty_White_Paper_v2-JRS.docx)

Submitted By: Jery Stedinger (607-255-2351). Submitted On: Sep 17 2013

1-0 Evaluation **Concurred**
Attached document has been dispersed into subsequent comments.

Submitted By: Beth Faber (530 756 1104) Submitted On: Oct 11 2013

1-1 Backcheck Recommendation **Close Comment**
Close comment. Resolutions discussed below.

Submitted By: Jery Stedinger (607-255-2351) Submitted On: Nov 08 2013

Current Comment Status: **Comment Closed**

5387241 Hydrology n/a n/a n/a

Comment Classification: **Public (Public)**

(Document Reference: ER 1105-2-101, sec. 7.b.)

Comment (1) of 10 posted today.

Description of concern: Text on pg. 2-15 of the certification report shows that "data...represents the best estimates of the median values of the exceedence probability, stage, and damage function." Use of medians would be problematic and unusual in this context.

Statement of significance: While this should not prevent HEC from going forward with the new HEC-FDA version 1.4, but this should addressed.

Recommended action: See attachment submitted on 17-Sep-2013 for suggestions. Text should be clarified and appropriateness of use of median values confirmed.

Basis for comment: Comment based on technical expertise and experience of reviewer; ER 1105-2-101 sec 7.b.–- expect engineering calculations to "progress to the ultimate goal."

Submitted By: Jery Stedinger (607-255-2351). Submitted On: Oct 11 2013

Revised Oct 11 2013.

1-0 Evaluation **For Information Only**
There's a chance the sentence is not clearly stated, leading to misunderstanding. I've reworded the sentence as follows:

"In general, data developed and displayed under hydrologic engineering and economics represent the user-entered best estimates (median values) of the exceedance probability, stage, and damage functions for without- and with-project conditions. Uncertainty parameters of those functions are also developed and entered by the user. The Monte Carlo analyses performed (and results displayed) use the above-mentioned median functions and their associated uncertainties as input, and produce expected values of performance metrics as output."

So, the user inputs are both the medians values and the uncertainties for summary relationships, and the outputs are expected values (and distributions) of metrics. Does this clarification answer the comment?

Submitted By: Beth Faber (530 756 1104) Submitted On: Oct 23 2013

1-1 Backcheck Recommendation **Close Comment**
Close comment. I misunderstood what was being done and new sentence clarifies the issue. Resolved.

Submitted By: Jery Stedinger (607-255-2351) Submitted On: Nov 08 2013

Current Comment Status: **Comment Closed**

5387257	Hydrology	n/a	n/a	n/a

Comment Classification: **Public (Public)**
(Document Reference: ER 1105-2-101, sec. 7.b.)

Comment (2) of 10 posted today.

Description of concern: While the "less simple method" is superior to the other uncertainty descriptions considered in the white paper, it does have certain problems with describing the distribution of quantile uncertainty, as described in the attachment.

Statement of significance: This is the overarching concern raised in the review. While this should not prevent HEC from going forward with the new HEC-FDA version 1.4, results should be improved with a modest extension of the method, as described in the attachment.

Recommended action: See attachment submitted 17-Sep-2013 for description of recommended use of continuous Beta distribution coupled with the derived graphical frequency curves to describe the distribution of quantile uncertainty, and technical remarks embedded throughout the white paper. USACE should not settle permanently on the "less simple" method, but continue to pursue more appropriate mathematical techniques for describing and combining distributions from different sources of uncertainty.

Basis for comment: See attachment for references. Comment also based on technical expertise and experience of reviewer; ER 1105-2-101 sec 7.b.–- expect engineering calculations to "progress to the ultimate goal."

Submitted By: Jery Stedinger (607-255-2351). Submitted On: Oct 11 2013

Revised Oct 11 2013.

1-0 Evaluation **For Information Only**
HEC has made a preliminary demonstration of the use of the Beta distribution for quantile uncertainty. It is not yet successful, but we're planning further coordination with commenter.

Submitted By: Beth Faber (530 756 1104) Submitted On: Oct 23 2013

1-1 Backcheck Recommendation **Close Comment**
Close comment. Good, we agree.

Submitted By: Jery Stedinger (607-255-2351) Submitted On: Nov 08 2013
Current Comment Status: **Comment Closed**

5387270 Hydrology n/a n/a n/a
Comment Classification: **Public (Public)**
(Document Reference: ER 1105-2-101, sec. 7.b.)

Comment (3) of 10 posted today.

Description of concern: Uncertainty distribution for multi-reach projects may be computed incorrectly if errors are correlated from reach to reach. Interdependence should be considered.

Statement of significance: Should not prevent HEC from going forward with new version, but should be addressed eventually (as previously communicated to HEC.)

Recommended action: See attachment submitted 17-Sep-2013 for recommendations and references.

Basis for comment: See attachment for references. Comment also based on technical expertise and experience of reviewer; ER 1105-2-101 sec 7.b.–- expect engineering calculations to "progress to the ultimate goal."

Submitted By: Jery Stedinger (607-255-2351). Submitted On: Oct 11 2013

Revised Oct 11 2013.

1-0 Evaluation **Concurred**
Have asked reviewer for some clarification of the wording, as it seems the computation (adding quantiles of the EAD distribution) is more in question if errors are independent, rather than correlated, while correlation would make the computation more correct.

However, the concern is still clear. HEC has discussed "re-looping" FDA to consider all locations and all alternatives within each realization, to allow analysis of a sample of EAD-reduced, and also a sample of total EAD across locations. However, this a bigger job than 1.4 update allowed.

A discussion with the commenter produced the suggestion of simply storing or writing the EAD computed from each realization for all locations and alternatives, and adding or subtracting these values for each realization afterward. This shortcut could be very effective, provided we ensure that the same random values are used and the same number of realizations are computed for each location and alternative. (Might require performing the compute twice.)

This shortcut, and perhaps the entire re-looping idea, will be considered in future versions of FDA (2.1 at the earliest).

Submitted By: Beth Faber (530 756 1104) Submitted On: Oct 23 2013

1-1 Backcheck Recommendation **Close Comment**

Close comment. The comment was garbled somewhere, and I corrected the comment below. The reply correctly interpreted the comment and correctly reflects the issue. We agree.

Corrected comment: "Uncertainty distribution for multi-reach projects may be computed incorrectly. Note that errors are correlated from reach-to-reach. Interdependence should be considered."

Submitted By: Jery Stedinger (607-255-2351) Submitted On: Nov 08 2013

Current Comment Status: **Comment Closed**

5387276	Hydrology	n/a	n/a	n/a

Comment Classification: **Public (Public)**

(Document Reference: ER 1105-2-101, sec. 7.b.)

Comment (4) of 10 posted today.

Description of concern: Distribution of differences between without- and with-project damages should be computed correctly to describe uncertainty in benefits. This requires consideration of interdependence between errors across projects.

Statement of significance: Should not prevent HEC from going forward with new version, but should be addressed eventually (as previously communicated to HEC.) Enhancement to method as recommended likely to show that actual uncertainty in estimated project benefits less than indicated if errors are independent (as now treated.)

Recommended action: See attachment submitted 17-Sep-2013 for recommendations and references. Likely need to adopt something such as paired-data confidence interval.

Basis for comment: See attachment for references. Comment also based on technical expertise and experience of reviewer; ER 1105-2-101 sec 7.b.–- expect engineering calculations to "progress to the ultimate goal."

Submitted By: Jery Stedinger (607-255-2351). Submitted On: Oct 11 2013

Revised Oct 11 2013.

1-0 Evaluation **Concurred**

Same as response to comment 3 of 10. Have asked reviewer for some clarification of the wording, as it seems the computation (subtracting quantiles of the EAD distribution) is more in question if there is no interdependence, while more interdependence would make the computation more correct.

However, the concern is still clear. HEC has discussed "re-looping" FDA to consider all locations and all alternatives within each realization, to allow analysis of a sample of EAD-reduced, and also a sample of total EAD across locations. However, this a bigger job than 1.4 update allowed.

A subsequent discussion with the commenter produced the suggestion of simply storing or writing the EAD computed from each realization for all locations and alternatives, and adding or subtracting these values for each realization afterward. This shortcut could be very effective, provided we ensure that the same random values are used and the same number of realizations are computed for each location and alternative. (Might require performing the compute twice.)

This shortcut, and perhaps the entire re-looping idea, will be considered in future versions of FDA (2.1 at the earliest).

Submitted By: Beth Faber (530 756 1104) Submitted On: Oct 23 2013

1-1 Backcheck Recommendation **Close Comment**

Close comment. This comment does not seem garbled, and the response correctly reflects the concern. We agree.

Submitted By: Jery Stedinger (607-255-2351) Submitted On: Nov 08 2013

Current Comment Status: **Comment Closed**

5387282 Hydrology n/a n/a n/a

Comment Classification: **Public (Public)**

(Document Reference: ER 1105-2-101, sec. 7.b.)

Comment (5) of 10 posted today.

Description of concern: Assessment of uncertainty in LP III flood frequency distribution should be revised to include description of uncertainty in skewness coefficient and the interaction of that error with the other parameters.

Statement of significance: Should not prevent HEC from going forward with new version, but should be addressed eventually (as previously communicated to HEC.)

Recommended action: See attachment submitted 17-Sep-2013 for recommendation. The proposed revision of Bulletin 17B, denoted Bulletin 17C, includes correction, which could be incorporated in HEC-FDA.

Basis for comment: See attachment for references. Comment also based on technical expertise and experience of reviewer; ER 1105-2-101 sec 7.b.–- expect engineering calculations to "progress to the ultimate goal."

Submitted By: Jery Stedinger (607-255-2351). Submitted On: Oct 11 2013

Revised Oct 11 2013.

1-0 Evaluation **Concurred**

The uncertainty distribution of the skew statistic is being investigated as part of the B17C update. The addition of uncertainty in skew to FDA is not planned before that update is completed and made official. However, when the update is official, the sampling of skew will be included, and will follow the distribution recommended in 17C or associated materials, in future versions of FDA.

Submitted By: Beth Faber (530 756 1104) Submitted On: Oct 23 2013

1-1 Backcheck Recommendation **Close Comment**

Close comment. Good. Progress will be made. We agree.

Submitted By: Jery Stedinger (607-255-2351) Submitted On: Nov 08 2013

Current Comment Status: **Comment Closed**

5387288	Hydrology	n/a	n/a	n/a

Comment Classification: **Public (Public)**

(Document Reference: ER 1105-2-101, sec. 7.b.)

Comment (6) of 10 posted today.

Description of concern: Documentation and application are not clear regarding what processes are being described as "variability" in the expected annual damage computation and what processes are included in the uncertainty distributions that result in the uncertainty distribution attributed to EAD and other performance metrics.

Statement of significance: Should not prevent HEC from going forward with new version, but should be addressed eventually (as previously communicated to HEC).

Recommended action: See attachment submitted 17-Sep-2013 for recommendations and references.

Basis for comment: See attachment for references. Comment also based on technical expertise and experience of reviewer and recommendations in NRC (2000); ER 1105-2-101 sec 7.b.–- expect engineering calculations to "progress to the ultimate goal."

Submitted By: Jery Stedinger (607-255-2351). Submitted On: Oct 11 2013

Revised Oct 11 2013.

1-0 Evaluation **Concurred**

Agree that currently, the annual peak flow (represented by the flow-frequency curve) is the only variable treated as natural variability, as it is transformed into the damage-frequency curve and integrated to compute EAD. All other uncertainties are treated as knowledge uncertainties, as they affect (and add to) the distribution of uncertainty around EAD.

The differences between natural variability and knowledge uncertainty are being handled very carefully in the newer HEC-WAT/FRA software, but improvements are not planned for FDA.

Submitted By: Beth Faber (530 756 1104) Submitted On: Oct 23 2013

1-1 Backcheck Recommendation **Close Comment**
Close comment. Okay. This is a documentation issue, not a computational issue. My recommendation was understood.

Submitted By: Jery Stedinger (607-255-2351) Submitted On: Nov 08 2013

Current Comment Status: **Comment Closed**

5387298	Hydrology	n/a	n/a	n/a

Comment Classification: **Public (Public)**
(Document Reference: ER 1105-2-101, sec. 7.b.)

Comment (7) of 10 posted today.

Description of concern: Documentation on page 3-14 regarding "differencing" of distributions is not clear. In computing the benefits for a project, it makes sense to compute for each possible realization of uncertain parameters, the with-project and without-project damages. Then by sampling over uncertain parameters, one gets a distribution of possible damages reflecting uncertainty. And the distribution of the paired difference between the with-project and without-project damages for the same sets of parameters describes the uncertainty distribution of project benefits. How does differencing the distributions result in the same answer as would be "...obtained by obtaining the distribution of net benefits by performing Monte Carlo simulation of damage difference"?

Statement of significance: Should not prevent HEC from going forward with new version, but should be researched and addressed in subsequent versions.

Recommended action: See attachment submitted 17-Sep-2013 for recommendations and references. Why not store the expected annual damages for sets of unique combinations of generated uncertain parameters, and then actually compute the differences between with- and without-project damages to quantify the uncertainty distribution of benefits? This could also be done to capture the distribution of what is called the equivalent annual damages.

Basis for comment: See attachment submitted 09-Sep-2013 for references. Comment also based on technical expertise and experience of reviewer; ER 1105-2-101 sec 7.b.–- expect engineering calculations to "progress to the ultimate goal."

Submitted By: Jery Stedinger (607-255-2351). Submitted On: Oct 11 2013

Revised Oct 11 2013.

1-0 Evaluation **Concurred**
Current HEC staff isn't sure where the statement about "differencing distributions" derives from, and are investigating the source of the text to determine the meaning.

Response is the same as that to comments 2 and 3 of 10. HEC has discussed "re-looping" FDA to consider all locations and all alternatives within each realization, to allow analysis of a sample of EAD-reduced, and also a sample of total EAD across locations. However, this a bigger job than 1.4 update allowed.

This comment contains the suggestion referenced in responses to 2 and 3 of 10 -- simply storing or writing the EAD computed from each realization for all locations and alternatives, and adding or subtracting these values for each realization later. This could be very effective, as long as the same random values are used and the same number of realizations are computed for each location and alternative. (Might require performing the compute twice.)

This shortcut, and perhaps the entire re-looping idea, will be considered in future versions of FDA (2.1 at the earliest).

Submitted By: Beth Faber (530 756 1104) Submitted On: Oct 23 2013

1-1 Backcheck Recommendation **Close Comment**
Close comment. If neither of us can understand what was meant by differencing the distributions, then perhaps the text should be removed. I anticipate that in a future version of these computations, costs for different projects and different reaches with different uncertainty replicates will be handled differently. We agree about the benefits of "re-looping." Resolved!

Submitted By: Jery Stedinger (607-255-2351) Submitted On: Nov 08 2013

Current Comment Status: **Comment Closed**

5387306	Hydrology	n/a	n/a	n/a

Comment Classification: **Public (Public)**
(Document Reference: ER 1105-2-101, sec. 7.b.)

Comment (8) of 10 posted today.

Description of concern: Use of "equivalent annual damages" to describe the discounted value of EAD in each year of the planning period is a poor choice of terms. It seems you want to say discounted expected annual damages (DEAD). The term "equivalent annual damages" loses the word "expected," which is very important because the expectation has been computed over the flood frequency curve. It fails to include "discounted" clarifying how time has been accounted for and that such discounting is the issue.

Statement of significance: Should not prevent HEC from going forward with new version, but should be addressed as this is likely to confuse analysts and readers of Corps reports if term is adopted.

Recommended action: Use alternative term that describes better the idea that the value is both "expected" and "discounted."

Basis for comment: See attachment for references. Comment also based on technical expertise and experience of reviewer. ER 1105-2-100: documentation should be clear.

Submitted By: Jery Stedinger (607-255-2351). Submitted On: Oct 11 2013

Revised Oct 11 2013.

1-0 Evaluation **For Information Only**

Note, these are terms used by the Corps, and not really under the purview of HEC, or the FDA software, to change.

The acronym EAD is used only to refer to Expected Annual Damages, and Equivalent Annual Damages is always written out fully, which can hopefully reduce confusion slightly. It is true that the word "Expected" has been dropped, but we don't necessarily see that the meaning is lost.

Just for information, to ensure our common understanding of the term, the computation of Equivalent Annual Damages involves computing the present value of EAD from each future year of project life, summing them, and then annuitizing the total present value to get an annual equivalent.

More importantly, the acronym DEAD (for Discounted EAD) is not a great improvement...

Submitted By: Beth Faber (530 756 1104) Submitted On: Oct 23 2013

1-1 Backcheck Recommendation **Close Comment**

Close comment. Agreed that DEAD is not attractive. My comment was understood. Appreciate suggestion that care can avoid misunderstandings. Resolved.

Submitted By: Jery Stedinger (607-255-2351) Submitted On: Nov 08 2013

Current Comment Status: **Comment Closed**

5387313	Hydrology	n/a	n/a	n/a

Comment Classification: **Public (Public)**

(Document Reference: ER 1105-2-101, sec. 7.b.)

Comment (9) of 10 posted today.

Description of concern: The certification study gives for the NRC publication a date of 2001, and no title. Page 2-17 does not give a complete citation for NRC study.

Statement of significance: Shortcomings in documentation interfere with proper understanding of technical issues.

Recommended action: Use complete citation:
National Research Council, Risk Analysis and Uncertainty in Flood Damage Reduction Studies, National Academy Press, Washington, D.C., 2000

See http://www.nap.edu/catalog.php?record_id=9971

Basis for comment: ER 1105-2-100: Documentation should be complete and reliable.

Submitted By: Jery Stedinger (607-255-2351). Submitted On: Oct 11 2013

Revised Oct 11 2013.

1-0 Evaluation **Concurred**
The citation will be fixed. Thank you for pointing out the error.

Submitted By: Beth Faber (530 756 1104) Submitted On: Oct 23 2013

1-1 Backcheck Recommendation **Close Comment**
Close comment. Resolved.

Submitted By: Jery Stedinger (607-255-2351) Submitted On: Nov 08 2013
Current Comment Status: **Comment Closed**

5387319	Hydrology	n/a	n/a	n/a

Comment Classification: **Public (Public)**
(Document Reference: ER 1105-2-101, sec. 7.b.)

Comment (10) of 10 posted today.

Description of concern: Bounding the variance of quantiles to the variance of the 99 percentile seems arbitrary. The source of the problem seems to be the use of a normal distribution model to define quantile uncertainty. It does not incorporate how the slope of the frequency curve may change. There seems to be a nice patch proposed on page 12 of the white paper. However, I would suggest a solution is better than a patch. If one uses the Beta distribution coupled with the graphical frequency curve G(y), there should be no such inconsistencies. The Beta quantiles will be a monotonic function of increasing q = j/N+1, and the graphical frequency curve is monotonic, so monotonic increasing frequency curves should result for every uncertainty level. G(Y) reflects characteristics of a reach, such as bounds on flows.

Statement of significance: Should not prevent HEC from going forward with new version, but should be researched and addressed in subsequent versions.

Recommended action: See earlier comment re: use of Beta distribution as an alternative to current method.

Basis for comment: ER 1105-2-101 sec 7.b.-- expect engineering calculations to "progress to the ultimate goal."

Submitted By: Jery Stedinger (607-255-2351). Submitted On: Oct 11 2013

Revised Oct 11 2013.

1-0 Evaluation **Concurred**

We agree that the choice of the 1% exceedance probability for fixing the variance is arbitrary, although other points were tested with less acceptable results. As noted in the response to comment 2 of 10, we have made a preliminary demonstration of the use of the Beta distribution for quantile uncertainty. It is not yet successful, but we're planning further coordination with commenter.

Submitted By: Beth Faber (530 756 1104) Submitted On: Oct 23 2013

1-1 Backcheck Recommendation **Close Comment**

Close comment; need to work on Beta distribution approximation. I am sorry that initial efforts to implement the Beta idea were not successful, and I have not had time to pursue it further. I hope we can work on that for a future implementation of these computations. Clearly, an improvement needs to be demonstrated and tested, and that has not happened. So proceeding with the "less-simple" algorithm is the reasonable decision at this time. We agree.

Submitted By: Jery Stedinger (607-255-2351) Submitted On: Nov 08 2013

Current Comment Status: **Comment Closed**

Supplemental Response to Review Comments 5387270, 5387276 and 5387298

Background: The review comments noted above concerned the fact that possible independence of errors in multi-reach projects is ignored in the computation of uncertainty in EAD and EAD-reduced. HEC acknowledged these concerns as valid and noted that they could be addressed through future enhancements to FDA, although the required changes are beyond what is planned. Instead, future focus in on the newer software HEC-WAT/FRA, which is handling this issue more carefully. HEC also agreed to provide a supplemental document describing this issue, which is the purpose of this document.

Discussion: FDA's Monte Carlo simulation performs an entire EAD with uncertainty computation for every index point and every alterative (without-project, and various with-project) separately. The result is a probability distribution of EAD (or, EAD distribution), representing the uncertainty in that value, for every index point and alternative.

However, we are most often interested in combinations of these separate values, such as EAD reduced (between an alternative and the without-project condition), or a sum of EAD at multiple index points. Hence we want an EAD distribution for EAD-reduced, and an EAD distribution that sums locations.

The most correct way to develop the EAD distributions for EAD reduced or for the sum of EAD at multiple index points would be to compute every index point and every alternative for every Monte Carlo realization. Then, for each realization, the EAD reduced or the EAD sum would be computed, and the ultimate EAD uncertainty distributions would be developed directly from those values. To perform the computation in this way, the EAD computation in FDA would have to be "re-looped" to perform a single Monte Carlo simulation at multiple points and conditions, rather than separate Monte Carlo simulations for each. This change would not be trivial, although the effort required has not been investigated.

Currently, FDA computes values for EAD-reduced and EAD sums as follows. The method is to subtract each quantile of a with-project EAD distribution from the same quantile of the without-project EAD distribution. Similarly, for the sum of EAD at various index points, each quantile of the distribution at each index point is added to the same quantile of the distribution at the other points. ***This computation in effect assumes that the causes of the uncertainty in EAD are perfectly correlated between locations and between alternatives***. Those causes include the uncertainty in: frequency, flow/stage relationship, regulation, and stage/damage relationship. While these uncertainties are not perfectly correlated between index points, the correlation is quite high. Similarly, while they are also not perfectly correlated between the without and with-project conditions, they are often very highly correlated if the relationships are either the same or computed in a similar manner. For example, often the same flow-frequency curve, with its associated uncertainty, is used for without and with-project conditions, and for several index points (after minor adjustment). Thus the error in that frequency is the same for each and thus perfectly correlated.

Therefore, while FDA's computation of EAD-reduced and EAD sums is less than optimal from a theoretical standpoint, the error introduced in the result is fairly small.