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Annual Exceedance Probability Analysis

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ANNUAL EXCEEDANCE PROBABILITY ANALYSIS

by

Masako Amai Gardner

A thesis submitted to the faculty of

Brigham Young University

in partial fulfillment of the requirements for the degree of

Master of Science

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BRIGHAM YOUNG UNIVERSITY

GRADUATE COMMITTEE APPROVAL

of a thesis submitted by

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This thesis has been read by each member of the following graduate committee and by majority vote has been found to be satisfactory.

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BRIGHAM YOUNG UNIVERSITY

As chair of the candidate's graduate committee, I have read the thesis of Masako Amai Gardner in its final form and have found that (1) its format, citations, and bibliographical style are consistent and acceptable and fulfill university and department style requirements; (2) its illustrative materials including figures, tables, and charts are in place; and (3) the final manuscript is satisfactory to the graduate committee and is ready for submission to the university library.

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ABSTRACT

ANNUAL EXCEEDANCE PROBABILITY ANALYSIS

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Master of Science

Annual Exceedance Probability (AEP) is the method used by U.S. Army Corps of Engineers (USACE) to determine the probability of flooding caused by the failure of a levee or other flood control structure. This method shows the probability of flooding only at one particular location at a time. In order to overcome the limitation of AEP, a new method of studying flood probability, called an AEP map, was presented. By using hydrologic and hydraulic modeling software, an AEP map can be created to determine and visualize the spatial distribution of the probability of flooding. An AEP map represents a continuous solution of the probability of flooding and can be used to derive not only the limits of the typical 100-year inundation, but any other return period including the 20-year, 50-year, 500-year storm flood. The AEP map can be more useful than traditional flood hazard maps, since it makes it possible to evaluate the probability of flooding at any location within the floodplain. In the process of

creating the AEP map, it is necessary to run number of simulations in order to accurately represent the probability distribution of flooding. The objective of this research, given a desktop computer of today's capacity, is to demonstrate the convergence of AEP maps after a reasonable number of simulations, so that users can have some guidelines to decide how many simulations are necessary. The Virgin River, UT is the primary study area for this research, with Gila River, AZ also used to support the results. The result of this research demonstrates the convergence of AEP maps by illustrating the convergence of water surface elevations computed as part of the hydraulic simulation leading up to the floodplain delineation model. If the average water surface elevations converge, then the resulting floodplain delineation (AEP maps) should also converge. The result proves that AEP maps do converge with a reasonable number of simulations. This research also shows the convergence of floodplain areas to demonstrate the convergence of AEP maps.

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Most importantly, I am forever grateful for my loving, kind, patient, and understanding husband, Dallen, and for his support and help. I could not have accomplished this work without my dearest husband.

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Flooding is one of the major disasters that frequently occur in the US. According to the Federal Emergency Management Agency (FEMA), 53 water related incidents including tornadoes, storms, typhoons, hurricanes and flooding, occurred in the U.S during 2003, and 27 of them included flooding (FEMA Frequently, 2004). A Flood is defined as “a general and temporary condition of partial or complete inundation of normally dry land areas from:

1. Overflow of inland or tidal waters,
2. The unusual and rapid accumulation or runoff of surface waters from any source, or
3. Mudslides caused by flooding” (Allen, 2004)

Flooding causes extensive damage to buildings and other structures and affects thousands of human lives. In order to minimize damage from these disasters, levees, dams, and detention basins, are constructed near rivers and streams. However, large storms occur in populated areas that can result in catastrophic damages to cities. To protect and help these citizens financially, Flood Insurance Study (FIS) by FEMA offers flood insurance to the properties near a water body. FIS utilize a Flood Insurance Rating Map (FIRM), which shows the flood boundaries on a 2D map, to decide which properties should be insured. However, FIRMs only demonstrates which area will be inundated or not inundated for a certain size of flood, and they do not consider the severity (depth) or uncertainty of flooding. Because the flood analysis includes many uncertainties in the parameters such as precipitation data, topographic data, and geographic data used for modeling, the floodplain boundary on a FIRM cannot be 100 percent accurate. Therefore, the U.S. Army of Corp Engineers (USACE) currently studies flood risk analysis called Annual Exceedance Probability (AEP) Analysis that considers the uncertainty in these parameters. When flooding occurs, excess water will spread outside a river and flood over a levee. An AEP analysis determines the probability of overtopping a levee caused by flooding along a given reach of a river system (USACE, 1996). However, this analysis determines the probability of overtopping a levee for only one reach at a time. Instead of finding the probability of overtopping a levee, finding the probability of flooding will be more useful for FIS. It is also more helpful to find the probability of any location instead of the probability of one location at a time. The National Research Council (NRC) stated that the AEP method by USACE needs some improvement to present the probability of flooding spatially (NRC,1995).

Smemoe (2004) presented a way to overcome the limitations of the USACE AEP method by suggesting the development of an AEP map. An AEP map is similar to a FIRM, but it considers the uncertainties of parameters. An AEP map presents the probability of flooding everywhere within the inundation limits and can be used to derive floodplain boundaries for several return periods instead of a single inundation limit for the 100-year boundary. The fundamental process in making AEP maps is to run a sequence of both hydrologic and hydraulic models to define a floodplain boundary. Figure 1-1 illustrates the process of a simulation.

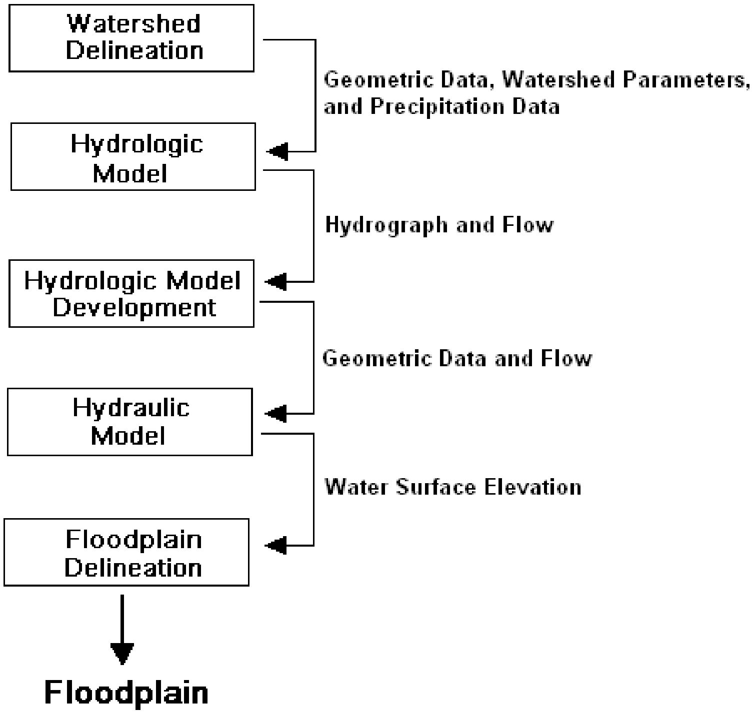


Figure 1-1: One Simulation

In order to create AEP maps, several instances of the simulations are run with different input values to create multiple flood boundaries. By combining these flood boundaries, the probability of flooding can be determined for AEP maps. Currently, there is no guideline showing how many simulations are necessary to create reasonably accurate AEP maps. Therefore, the objective of this research is to illustrate the convergence of AEP maps after a reasonable number of simulations utilizing typical desktop computers so that it can be shown that spatial AEP can be practical for flood study analyses. If AEP maps were developed correctly, they could replace the current method of defining flood boundaries used in FIRM (Smemoe, 2004). Smemoe (2004) suggested to run at least 100 simulations, because 100 simulations would sample well ranged input values (peak flow values) by using the random sample method called Latin Hypercube Method. However he did not give the guideline of how many simulations are necessary to obtain well-ranged outputs. 100 simulations with well-ranged flow values might not be enough to create well-represented AEP map. Therefore, it is valuable to provide guidelines for the number of simulations necessary for confidence in using AEP maps. For example, if 1,000,000 simulations were run, it would likely be adequate to create a credible AEP map, but it would take an excessive amount of time and data management to come up with an AEP map. If ten simulations were run, it would be very fast, but the AEP map would not present an accurate probability of flooding. For this reason, this research demonstrates the convergence of AEP maps so that AEP maps can become more practical.

Chapter 2 describes the relevant background to this flood research Flood Insurance Study (FIS). FEMA organizes FIS, and it uses the Flood Insurance Rating Map (FIRM) to determine insured areas near water. The chapter explains what a FIRM is and how it is created. It also explains the details of the FIS program.

Chapter 3 outlines the flood research done by USACE. USACE uses Annual Exceedance Probability (AEP) method for the design of levees. The chapter explains what AEP is, and it also lists some limitations of this AEP method.

Chapter 4 introduces the concept of a spatially derived AEP maps using the WMS in conjunction with HEC-1 and HEC-RAS. The process of creating AEP maps is discussed in this chapter.

Chapter 5 provides an outline of how to decide the convergence of AEP maps. The chapter also provides guidelines for required simulation time. The results of two study cases, Virgin River UT and Gila River, AZ will be included.

Chapter 6 includes the conclusion from this research and case studies. This chapter also talks about the possible future study.

2 Flood Insurance Study (FIS)

The Flood Insurance Study (FIS) by FEMA is a part of the National Flood Insurance Program (NFIP) and provides guidelines for how flood study should be conducted. It offers technical information of floodplain management measures and develops the flood risk information used to provide accurate actuarial flood insurance premiums (FEMA Guidelines, 2004). It also includes guidelines for the creation of Flood Insurance Rate Maps (FIRMs) used for establishing flood insurance. This chapter explains what a FIRM is, how a FIRM is created, and how properties are insured against flooding.

2.1 What is a FIRM?

A FIRM is a map that designates those areas subject to an insurance premium because of their potential for natural flooding due to nearby bodies of water. All land within the map's indicated inundation limit or floodplain line is subject to a flat insurance rate that protects owners against the disasters of flooding. In determining which areas must be insured against this natural disaster, the FIRM uses a 100-year recurrence interval, also known as the 100-year flood or storm. The 100-year recurrence interval is the risk established by FEMA that indicates whether a given area should be protected with flood insurance (FEMA, 1999). The 100-year flood is the flood with at least a one-percent-chance of occurrence, and properties inside the map's indicated floodplain lines have a 26 percent chance of flooding over the life of a 30-year mortgage (Allen, 2004).

The guidelines for the creation of a FIRM are established and maintained by FEMA. Any private insurance industry, community, and federal or state agency, among others, can request a FIRM. A sample of FIRM is illustrated in Figure 2-1.

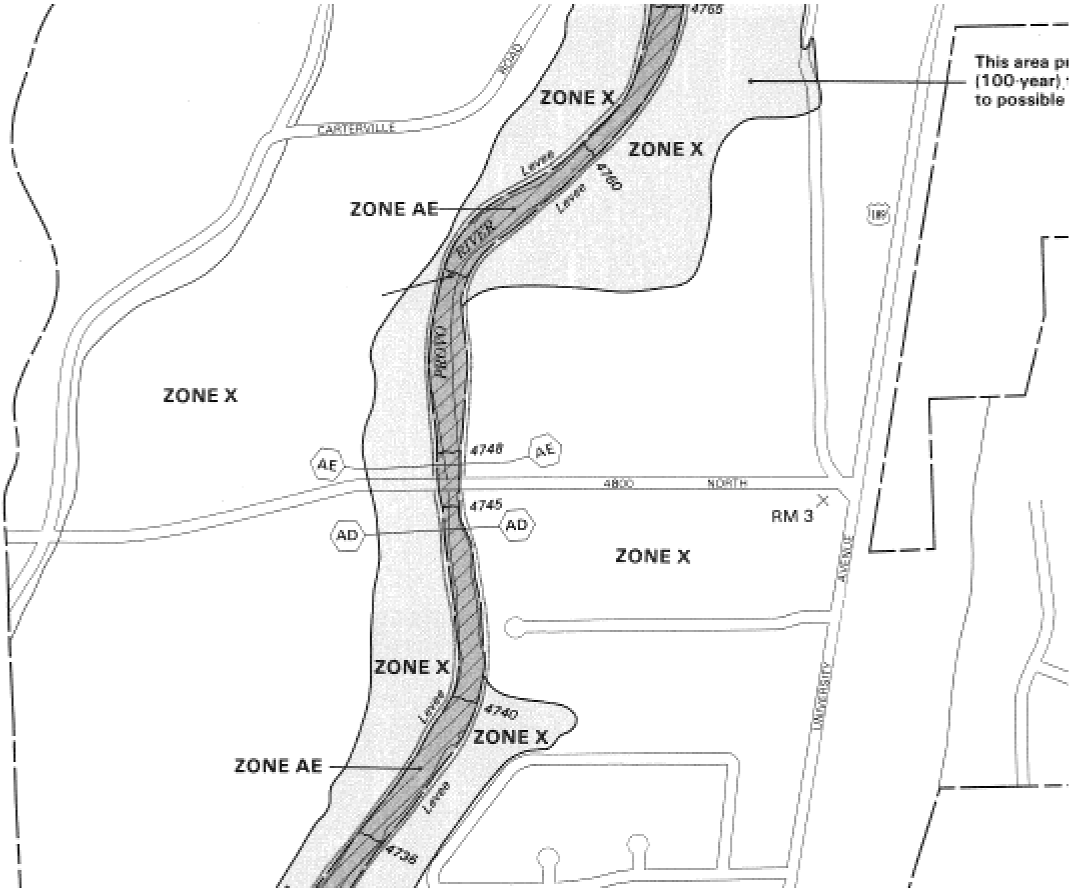


Figure 2-1: Sample FIRM

The figure illustrates the river shown in the gray color, 100-year-floodplain which is also called as the Special Flood Hazard Area (SFHA) shown in a lighter shaded color, and major streets. There are some zones indicated within the floodplain, and each zone indicates a class of flooding as summarized in Table 2-1 (FEMA Zone Designation, 2004).

Figure 2-1 includes the cross section locations, and each community has detailed information of the cross section in FIS. The FIS for any community can be viewed or purchased through FEMA (FEMA Store, 2003). A FIRM also contains a 500-year floodplain, local landmarks to better identify the region, and a FEMA designated floodway (FEMA Frequently, 2004). A floodway is the land within a given region that is so prone to flooding that construction of building is un-insurable. Figure 2-2 illustrates the floodway.

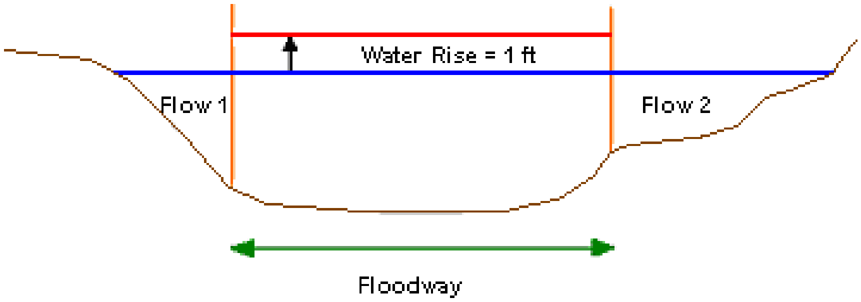


Figure 2-2: Floodway

Table 2-1: Different Zones in SFHA

Zones	***Explanation***
Zone A	1 percent annual chance floodplain determined by FIS with approximate methods of analysis. The flood depth in this zone is unknown.
Zone AE & A1-A30	1 percent annual chance floodplain determined by FIS with detailed methods of analysis. The base flood elevation in this zone is usually shown on the map.
Zone AH	1 percent annual chance shallow flooding with a constant water surface elevation. The average depth for this zone is between 1 and 3 feet. The base flood elevation in this zone is usually shown on the map.
Zone AO	1 percent annual chance shallow flooding with sheet flow on sloping terrain. The average depth for this zone is between 1 and 3 feet. The average flood depth in this zone is usually shown on the map. This zone includes alluvial fan flood hazards.
Zone AR	Area protected by flood control structures. New structures in this have to raise lowest floor at least 3 feet.
Zone A99	1 percent annual chance floodplain protected by a Federal flood protection system where construction has reached specified statutory milestones.
Zone D	Possible flood hazard area, but undetermined. No analysis is done in this zone. Insurance is not required, but available.
Zone V	1 percent annual chance coastal floodplains with storm wave's hazard. No base flood elevation is known.
Zone VE	1 percent annual chance coastal floodplains with storm wave's hazard. The base flood elevation is shown.
Zone B, C, & X	Outside the 100-year floodplains. Areas of 1 percent annual chance sheet flow flooding with less than one foot depth. Area of 1 percent annual chance stream flooding with less than 1 square mile drainage area.

FEMA also has been working on a new product called the Digital Flood Insurance Rate Map (DFIRM). A DFIRM is a digital version of a FIRM, and it can be used for cartographic mapping and analysis software. It is especially designed to be used with Geographic Information Systems (GIS) (FEMA Digital, 2003). Because the DFIRM is more useful and adaptable to computer software, it is replacing the traditional FIRM.

As explained, FIRM only has the flood boundaries, and there is no evidence of uncertainties of parameters involved in the flood study. As National Research Council (NRC) stated, it is necessary to determine the probability of flooding due to the uncertain parameters (NRC, 1995). Therefore the new way of the flood study method will be discussed in the later chapters.

2.2 Obtaining a FIRM

The easiest way to obtain a FIRM is through the FEMA Flood Map Online Store at http://store.msc.fema.gov/. For just a couple of dollars, anyone can purchase a FIRM. You can request a hard copy or download an image onto a CD. Any established FIRM within the United States is available and can be found by using the state, county, and community names, an address, a map, or even a FIRM panel ID (FEMA Store, 2003). If one does not have access to the Internet, one can call the Map Service Center at 1-800-358-9616 and request the desired FIRM. Any FIRM within over 19,000 communities participating in the NFIP is available (FEMA Frequently Used Term, 2004).

2.3 Purchasing Flood Insurance

Until 1968, there was no type of insurance available that protected owners against natural flooding. This type of insurance was so risky and expensive that private insurance companies did not offer it (Allen, 2004). However houses were still built near rivers and creeks. When floods caused severe damages to these properties, these were no way but the government had to help them financially. As the result, taxpayers had to pay for these residents who still decide to build houses near rivers knowing the high risk of flooding. But in 1968, the government established a program to protect owners from the natural disasters of flooding. This program is called the Nation Flood Insurance Program or NFIP. NFIP had two objectives: the first was to offer the opportunity to purchase flood insurance while the second was to encourage communities to implement and enforce measures that reduced the risk of floods in Special Flood Hazard Areas (SFHA). Through the NFIP, the government takes responsibility for insuring against flood damages (FEMA, 1995).

If one wants to insure their property against natural flooding, then before building or adding onto a house, the first thing that should be done is to check whether the property of interest lies within a community that participates in the NFIP. There are communities that have not yet agreed to adopt the required floodplain management ordinances of the NFIP, or have been suspended or withdrawn from the program (FEMA Guidelines, 2004). In order to find out whether a community participates in the NFIP, one can contact an insurance agent or the community's building permit office, or read the NFIP Community Status Book. The NFIP Community Status Book also contains the most recent FIRM for the area. If the property of interest meets the following three conditions, then one is required to have flood insurance (Bankers, 2001):

1. The property's corresponding community participates in the NFIP
2. The property is in a flood hazard zone
3. Financing or refinancing a loan that insures improved property or an affixed mobile home

If a community does not participate in the NFIP, then flood insurance is not available. Consequently, no federal financial assistance is provided to damages caused by floods in these communities (Allen, 2004).

If a community is participating in the NFIP but a property does not meet the other two conditions mentioned above, then one has the choice to purchase or not purchase flood insurance. Typically, people who own property that is situated far from any kind of beach believe flood insurance is unnecessary. However, it may come as a surprise to these owners that only three percent of all damage caused by floods involves property located near a beach. The loan period for a typical mortgage is 30 years. Within this relatively short period of time, houses located within a Flood Hazard Flood Area have a 26% chance of experiencing damage caused by floods (Allen, 2004). Making the need for flood insurance even more desirable is the fact that homeowners' insurance generally does not cover damages caused by floods (FEMA Guidelines, 2004).

If one decides to purchase flood insurance, there are about 85 private companies that offer the federal government's NFIP. It takes about 30 days from the time that you purchase your home to process and insure the property against natural flooding. This insurance has coverage of up to $250,000 for residential buildings and $500,000 for non-residential buildings. These funds cover not only damages to the buildings but also any damages to the contents of the buildings. However, there is a limited coverage of $250 for damage to the contents of the buildings; therefore expensive contents such as jewelries and artwork need separate coverage. Moreover, flood insurance does not cover the following structures (Allen, 2004).

- Building located entirely above open water (ex. boat houses)
- Structures other than buildings (ex. fences, retaining walls, swimming pools, and underground structures)
- Structures outside buildings (ex. walkways, decks, driveways and patios)

There are additional limits to the insurance coverage of basements and enclosed areas beneath the lowest floor. What's more is that the insurance covers only the equipment that would be necessary in rebuilding a building, such as utility connections, sump pumps, well water tanks, additional pumps, furnaces, and so forth. However, clean-up costs are included.

3 Flood Studies by the U.S. Army Corps of Engineers

The U.S. Army Corps of Engineers (USACE) has a number of responsibilities including oversight of all navigation on sea, flood control, environmental protection, disaster response, and military construction. The USACE has eight divisions throughout the U.S., 41 district offices located in the U.S., Asia and Europe, and headquarters in Washington DC. The flood control division of the USACE builds and manages dams, helps prevent flood damage, and restores the environment. When the flood control division conducts research into flood damage prevention, a study of risk and uncertainty analysis is crucial in order to best determine how to use financial resources to prioritize construction of flood protection structures. Flood analysis always involves a certain element of uncertainty in its results due to the choice of hydrologic and hydraulic functions and parameters. In order to determine a region's probability of flooding, while also taking into account the inevitable element of uncertainty, the USACE developed a method called the Annual Exceedance Probability (AEP) (USACE, 1996).

3.1 AEP

AEP developed by the USACE is the method to consider the uncertainty involved in flood study, and it is able to determine, though one at a time, the probability of over topping a levee at one location. For example, if an annual exceedance probability of a 15-foot-tall-levee at location A is 0.01; it means that there is a one percent chance of overtopping the 15-foot-levee at this location in any given year. To calculate a flood probability such as this, the USACE utilizes two mathematical functions. These two functions are the rating function of discharge and the discharge-frequency function. Figure 3-1 illustrates the relationship between these two functions (Smemoe, 2004).

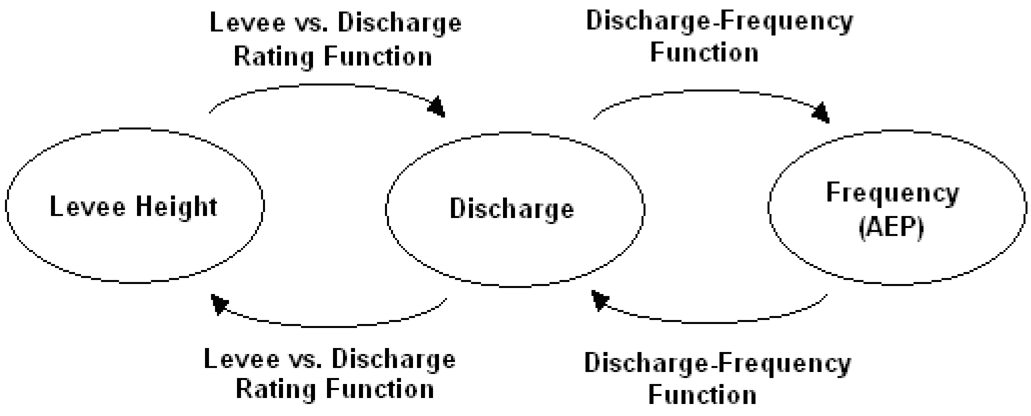


Figure 3-1: Relationship between Levee Height and AEP

Given the height of the levee, the first function, the rating function of discharge, will reveal the flood discharge necessary to overtop the levee. If one already knows the flood's discharge, then the same function will work vice-versa to give the levee height which the known discharge can overtop. With the flood discharge in hand, one can plug this number into the discharge-frequency function to determine the frequency of the flooding. This frequency is the AEP, or flood probability, for the given location. If the AEP is already known, the discharge can be found with the discharge-frequency function. These two functions interact in such a way that as long as one of the three variables is known, then all three can be determined. The USACE uses this relationship iteratively to determine how many times the interest size of flood defined by the discharge or the flood frequency will overtop the levee (USACE, 1996).

3.2 Limitations of the AEP

The current AEP method used by the USACE accounts for uncertainly, but it has some disadvantages when it comes to flood analysis. One of the biggest drawbacks is that the AEP method is not spatial. It is applicable only for a single point or levee failure, and it does not account for subsequent inundation areas. Figure 3-2 illustrates these disadvantages.

As shown in Figure 3-2, current AEP method has flood probabilities at only certain locations. However, these probabilities at red stars mean nothing for the rest of the area in the figure. Each red star indicates knowledge about whether the levee at that location (or reach) will fail or not for a given magnitude of flood, but says nothing about the extent of flooding or relationship to the entire river system. Knowing the probability of failure at locations indicated by red stars will not define the probability of flooding at the houses or at the green star location. It could be close to the probabilities of red stars, but it could be different.

Furthermore, the National Research Council (NRC) reported in 1995, “A framework is needed to understand the structure of risk and uncertainty analysis

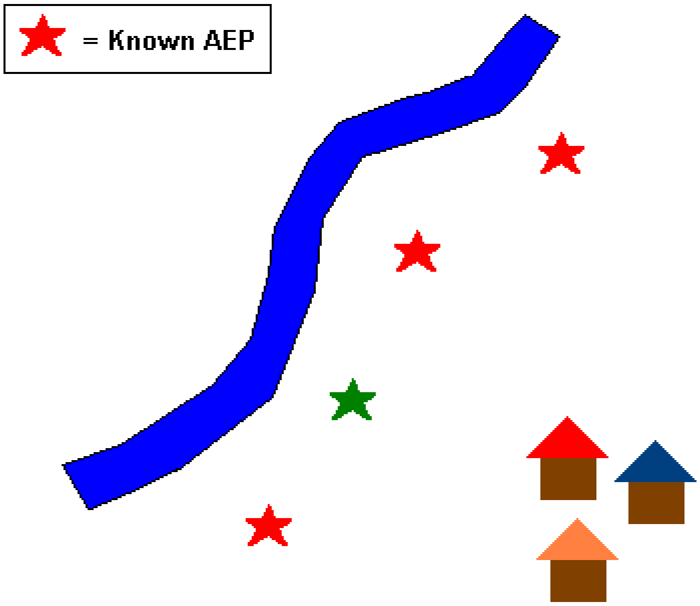


Figure 3-2: Discrete AEP

efforts for flood protection project evaluation, and to understand the relative roles of the natural variability of flood volume, reservoir operations, hydraulic system performance, stage-discharge errors, and uncertainty in hydrologic, hydraulic, and economic parameters (NRC, 1995)." The NRC suggested that there is a need for a better technique to understand the range of uncertainty spatially.

The other disadvantage of the current AEP method is that it is time consuming. In order to determine the flood probability using the current AEP method, an accurate discharge rating function and discharge-frequency function for the interested area are necessary. When these two functions are not available, a number of samples are needed to calculate the flood probability for the AEP method. In order to have a representative number of samples, monitoring must take place for a number of years.

It is important that these samples come directly form the area of interest. If the area of interest is a short distance away from an area that has already been studied and for which many accurate samples are available, it may still be necessary to start over the data gathering again for the appropriate number of samples. For these reasons, the current AEP method requires a lot of effort.

As discussed, the AEP method by USACE counts uncertainly, but it has limitations: discrete probability and time consuming. In order to determine the flood probability without these disadvantages, Smemoe (2004) developed a new method called AEP map that is spatial with less effort to analyze flood probability.

4 The Spatial AEP Map

Smemoe (2004) developed a method for creating a map with the AEP for every location using computer software. Hydrologic or hydraulic models, or Geographic Information System (GIS) can create this AEP map, but this research uses the Watershed Modeling System (WMS), which is the same software Smemoe used in his study. While this new AEP map does not give the probability of overtopping a levee, it does reveal the flood probabilities for every area on the map. Contours of probability are shown on the example AEP map illustrated in Figure 4-1.

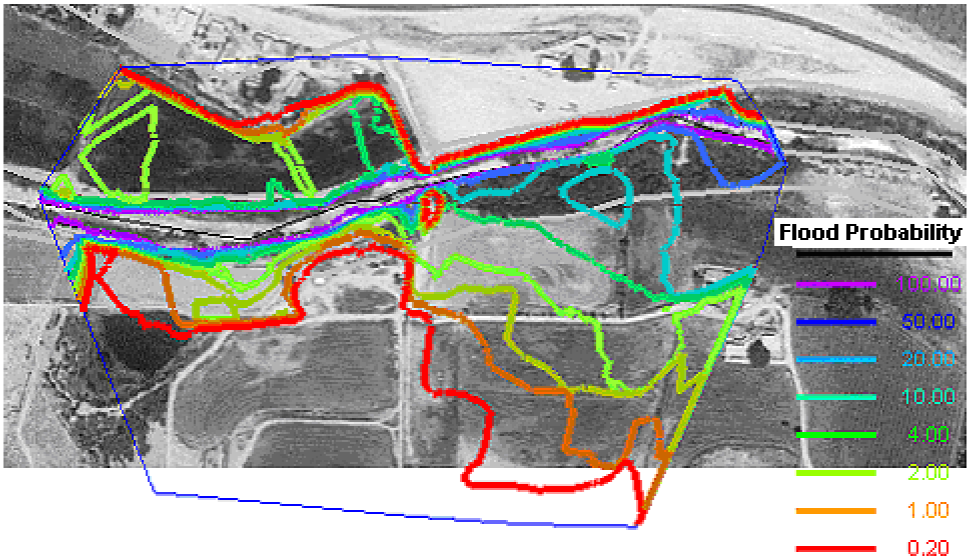


Figure 4-1: AEP Map (Virgin River, UT)

This new method not only made the process of calculating the AEP a lot faster, but it also made the AEP more practical for a flood study. Instead of having to calculate the AEP for every location of interest, one can quickly look at the new AEP map and comparatively see the AEP for many different regions. Smemoe's work explained the several stages in the process of creating an AEP map as summarized in Figure 4-2 (Smemoe, 2004).

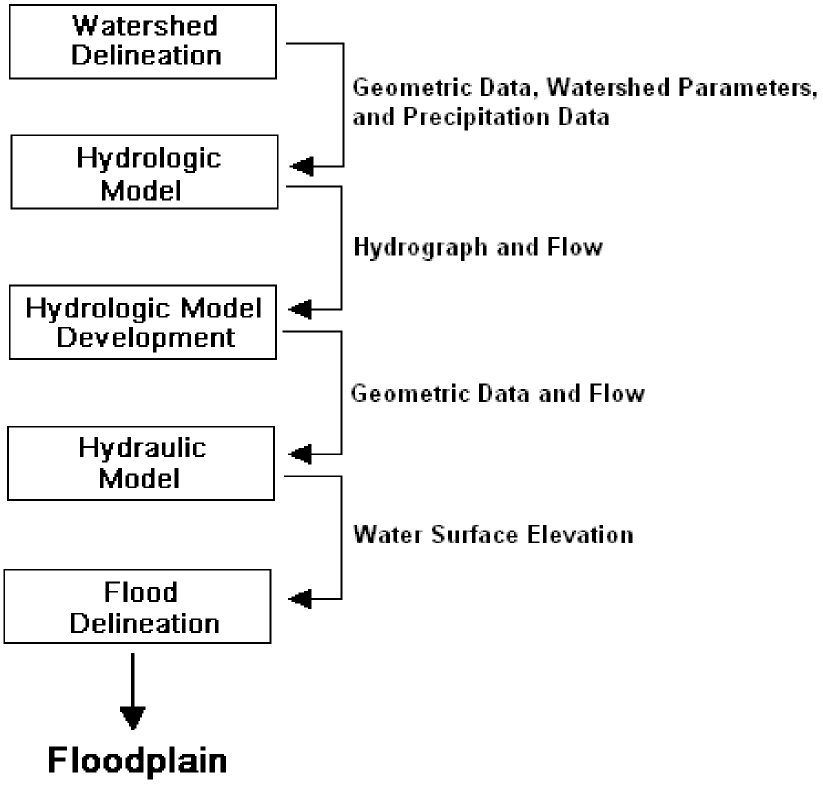


Figure 4-2: Process of Creating AEP Maps

First, using the geometric data, a watershed is delineated for the area of interest. With the delineated watershed and precipitation data, a hydrologic model is run to calculate the peak flow at the outlet of the watershed, and this is assigned as the inlet flow of a river. Then, a hydraulic model is run with the flow value and the geometric data of a river and nearby floodplain area, and the model determines water surface elevations along a river. Finally, these water surface elevations are used in conjunction with a digital terrain model to delineate a floodplain. This diagram and explanation represents a single run for creating one floodplain. With the current programming of WMS, this process of creating floodplains can be repeated many times to analyze the probability of flooding for particular study area. The detailed process of each stage is summarized in the following sections.

4.1 Watershed Delineation

The first process of creating a floodplain is to delineate watershed, and the elevation data including DEM and TIN (Triangular Irregular Network) can determine the boundary lines of a watershed. Typical watershed is show in Figure 4-3.

This process of delineating watershed can be done with WMS, and the delineated watershed can be exported out to run a hydrologic model.

4.2 Hydrologic Model

This research uses HEC-1 to run a hydrologic model with the delineated watershed. The computer software, HEC-1 was developed by the U.S. Army Corps of Engineers to compute flood hydrographs. It computes these flood hydrographs by plugging in the variables of an actual or hypothetical storm. HEC-1 is unit hydrograph based and it has four primary components: basins, reaches, reservoirs, and diversions.

Figure 4-3: Watershed

This software has a number of capabilities, of which are listed below:

- Rainfall-snowfall-snowmelt determinations
- Unit hydrographs via direct ordinates or Clark, Snyder or SCS methods, or by kinematic wave transforms
- Hydrograph routing by level-pool reservoir, average-lag, modified Puls, Muskingum, Muskingum-Cunge, and kinematic wave methods
- Complete stream system hydrograph combining and routing (USACE HEC-1, 2005)

In the process of creating AEP maps for hydrologic analysis, HEC-1 uses precipitation data and watershed parameters such as watershed area, slope, elevation, soil type, and land use as inputs. It then generates a hydrograph from which the peak flow rate can be exported for use in the hydraulic analysis to determine water surface elevations.

4.3 Hydraulic Model Development

The hydrologic model explained in the last section calculates the peak flow value that is necessary for the hydraulic model. While peak flow values can be generated with a hydrologic model, they can also be derived from historical data at a gaged stream location, or using statistical analysis at an ungaged station. The USGS has compiled a series of regression equations in a national database that can be used to estimate peak flows of ungaged watersheds from gaged watersheds. This database is called the National Flood Frequency (NFF) program (USGS, 2004). For this research the NFF program was used to generate a probability distribution function of peak flows for a watershed, and the Stochastic Model discussed in later sections uses this calculated probability distribution function.

4.4 Hydraulic Model

After running a hydrologic analysis, a hydraulic analysis is performed to generate water surface elevations by using HEC-RAS. HEC-RAS also produced by the U.S. Army Corps of Engineers, does hydraulic analysis for one-dimensional and unsteady or steady flow (USAEC HEC-RAS, 2005). This software is available to the public as well and WMS uses HEC-RAS to generate water surface elevations. HEC-RAS uses geometric data such as the cross section, channel slope, hydraulic structures (bridges, culverts, or weirs), manning roughness, and peak flow data as inputs. With these parameters, HEC-RAS outputs flow rates, water depth, rating curves, and water surface elevation used for delineating floodplain. (Smemoe, 2004) WMS was programmed so that it can execute HEC-RAS, and the special feature of WMS explained in later sections can allow parameters in HEC-RAS to be changed to run numbers of simulations without a user intervention.

4.5 Flood Delineation

Finally the water surface elevations computed by the hydraulic model are used to delineate a floodplain. When a river is flooded, water will rise to where the water surface elevation equals the existing ground elevation. The lines connecting these points become the boundary of the floodplain for the particular return period of the flood being analyzed. This is how a single floodplain is delineated, and the current practice for most flood studies. However, to create AEP maps, a number of floodplains must be delineated with different "probable" flood sizes for a given recurrence interval. Instead of running the process of creating one floodplain numbers of times manually, WMS uses a Stochastic Model process so that the analyses can be run in batch mode in order to delineate a number of floodplain boundaries.

4.6 Stochastic Model

The word Stochastic is Greek and means, "involving or containing a random variable or variables" and "Involving chance or probability (American, 2000)." This research requires running a lot of hydrologic and hydraulic analyses to create accurate AEP maps. The Stochastic Model sequence is illustrated in Figure 4-4.

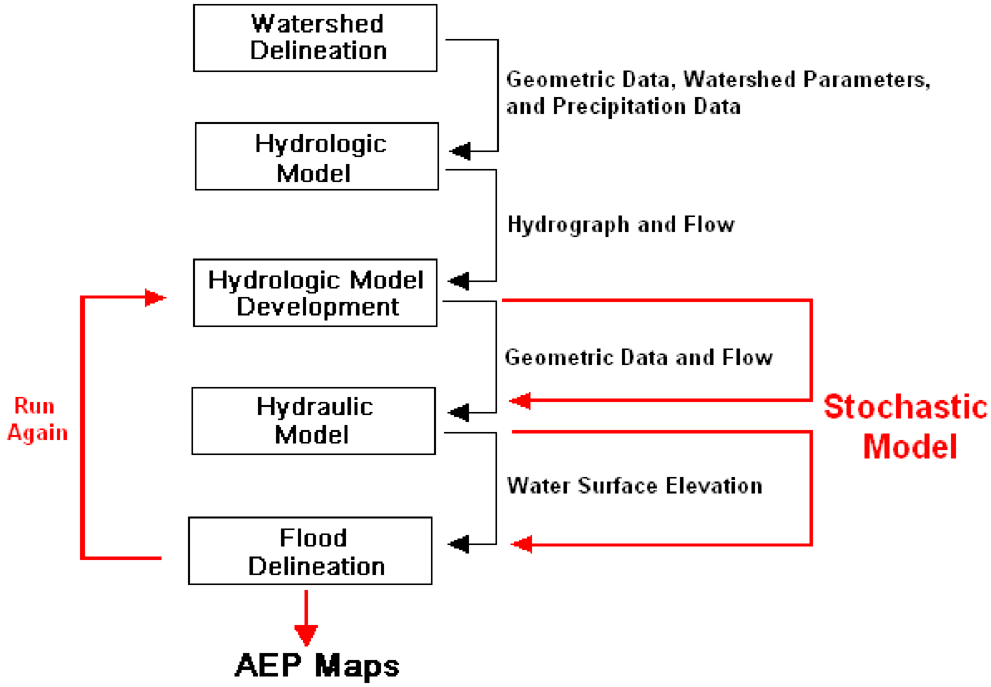


Figure 4-4: Process of Creating AEP Maps

The first step of the Stochastic Model is to delineate watershed, and then a hydrologic model is run to calculate peak flow values. For this research instead of running a hydrologic model, the NFF method was used to define the peak flow distribution. After choosing a peak flow from the peak flow distribution, the Stochastic Model takes over to run a number of simulations, given that the user provides all the necessary parameters. Then the Stochastic Model within WMS runs HEC-RAS and it does the hydraulic analysis. After the hydraulic analysis is completed, HEC-RAS exports the water surface elevation to WMS. WMS keeps this data and runs HEC-RAS again with a different flow value in order to get a different water surface elevation.

As stated, each time the Stochastic Model runs the hydraulic model, a different random input value is chosen within the range of values specified by the user (in this case computed by NFF). For the input value, such as flow rate for this study, the user can specify the distribution of possible values using a max, min, mean, and standard deviation. This study used the peak flow distribution defined by NFF instead of defining the distribution manually. After defining the distribution, either a Monte Carlo method or a Latin Hypercube method (as programmed in WMS) can be used to choose values randomly (Smemoe, 2004)

In this research, one variable, which is peak flow value, is chosen by using Latin Hypercube method, because this method enables to sample the entire range of possible values with a fewer number of runs than the Monte Carlo method can. When a user specifies the distribution of a variable, WMS generates a Probability Density Function (PDF) according to the max, min, mean, and standard deviation. The Latin Hypercube method divides this PDF into as many segments as the number of simulations a user specifies. A PDF divided into nine equal area segments is shown in Figure 4-5.

A flow value for a given simulation is randomly chosen from each of the divided segments in the PDF. For example, if a user specified 100 for the number of simulation to create one AEP map, the Latin Hypercube method would divide the PDF into 100 segments and then choose a value in random order from each of the 100 segments. If a user changed the number of simulations to be 200 for the second AEP map, the Latin Hypercube method would divide PDF into 200 segments and randomly

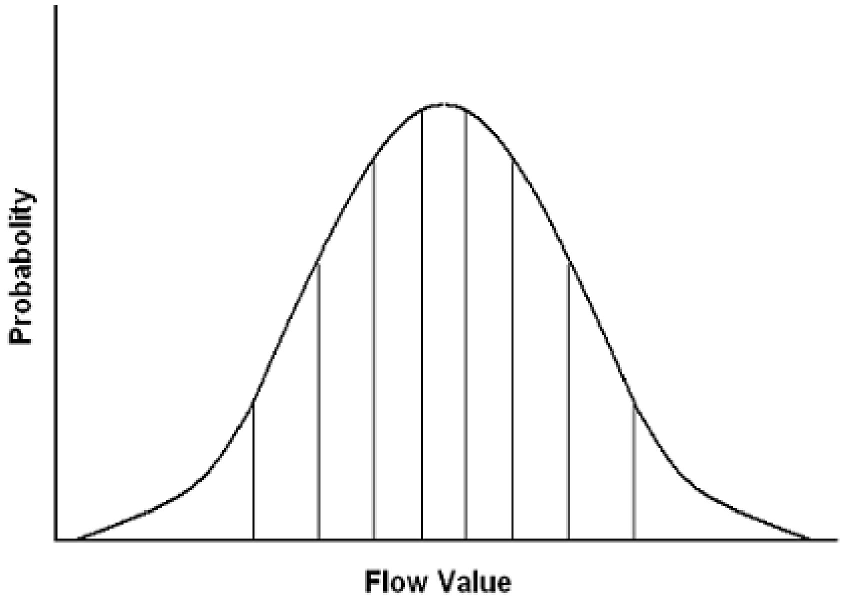
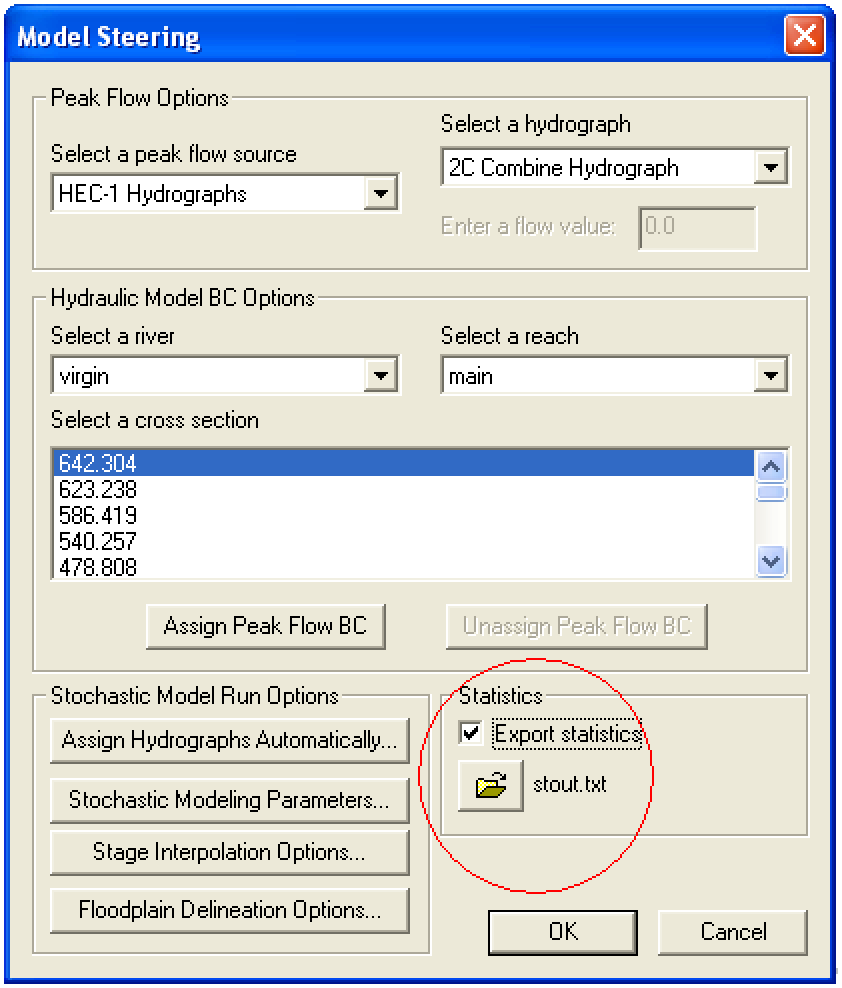


Figure 4-5: Divided PDF for Latin Hypercube Method

pick a value from each segment (Olsson, 2002). For each Stochastic Model simulation, the water surface elevations from HEC-RAS are computed and stored in WMS before the next simulation is run. These water surface elevations can be exported as a text file as shown in the Figure 4-6.

These water surface elevations are used in WMS to generate an instance of a floodplain limit used to create the new AEP maps. The water surface elevations generated in the stochastic simulation were valuable in determining one criteria of convergence for the AEP as discussed in the next section.



Select a peak flow source: HEC-1 Hydrographs

Select a hydrograph: 2C Combine Hydrograph

Enter a flow value: 0.0

Select a river: virgin

Select a reach: main

Select a cross section:
642.304
623.238
586.419
540.257
478.808

☑ Export statistics

stout.txt

Figure 4-6: Exporting Water Surface Elevation

4.7 AEP Map

After a specified number of simulations are run by the Stochastic Model, WMS summarizes the appropriate boundary of the floodplain using the exported water surface elevation and the topographic information. Inundation limits are determined for each set of water surface elevations (corresponding to each simulation) by locating where the water surface and the existing ground elevations coincide. The result is a spatially distributed map of flood probabilities. For example, a given location in the floodplain is flooded in exactly half of the simulations then we could say that it has a 50 percent probability of flooding, or 2-year recurrence interval. These probabilities can be used directly for a cost analysis, or individual recurrence intervals contoured as illustrated in the AEP maps shown in Figure 4-7.

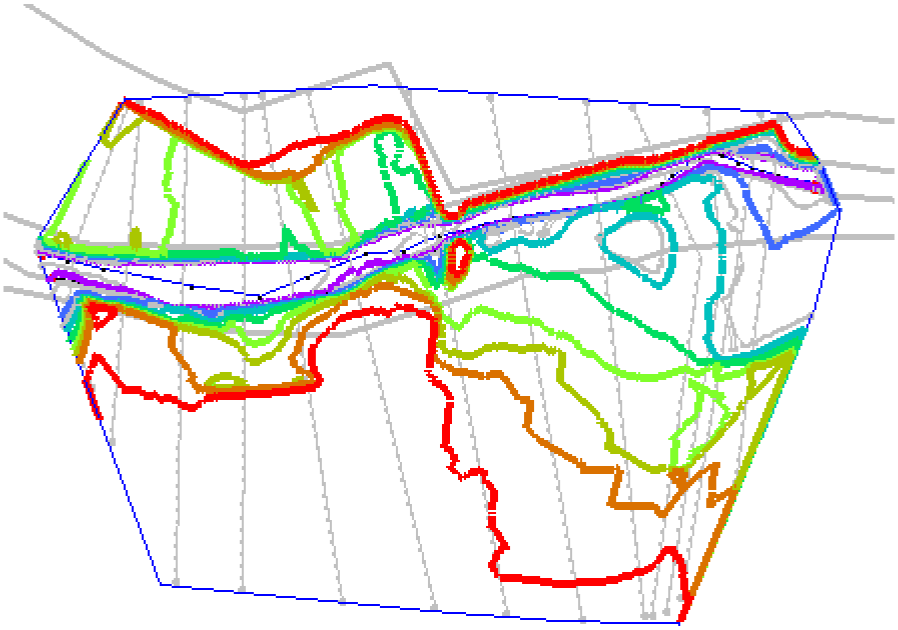


Figure 4-7: Flood Boundaries as Generated by WMS (Virgin River, UT)

In this figure, the red line illustrates the 500-year-flood (0.2 percent probability) boundary, and the brown line illustrates the 100-year-flood (one percent probability boundary.

4.8 AEP Map vs. FIRM

The AEP map shown in the last section is a part of the Virgin River, Utah. The Virgin River is located close to the border of Utah, Nevada, and Arizona, and it is located between St. George and Zion National Park. Figure 4-8 shows the approximate location of this study.

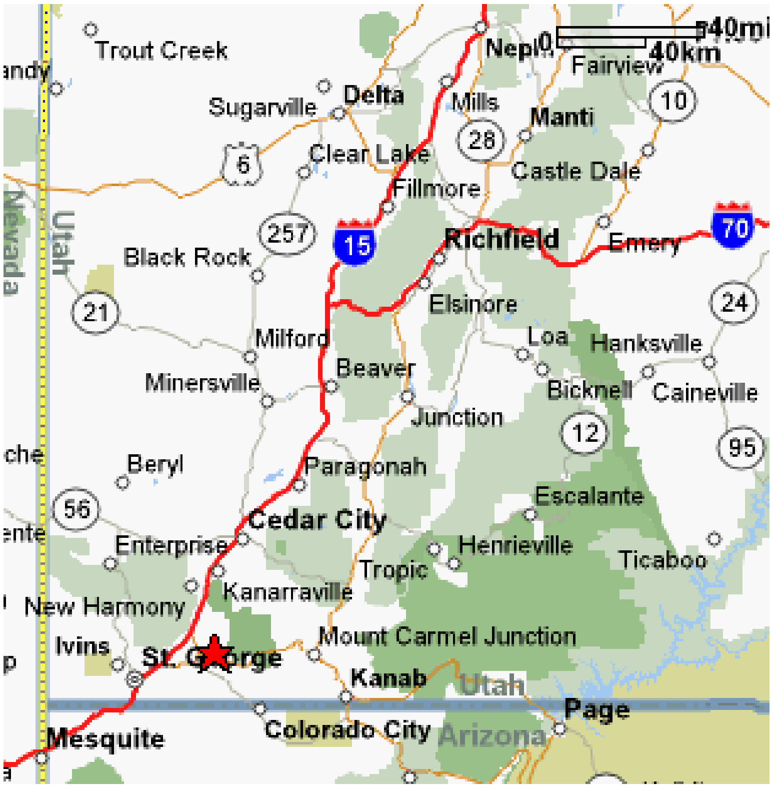


Figure 4-8: Location of Virgin River

An AEP map created with this new method defines continuous flood probability. From this contours on AEP maps, flood probability are easily found at any location within a map. Figure 4-9 illustrates the FIRM for this region (FEMA Store, 2003), and the area circled in red is the part of the river where this study was conducted.

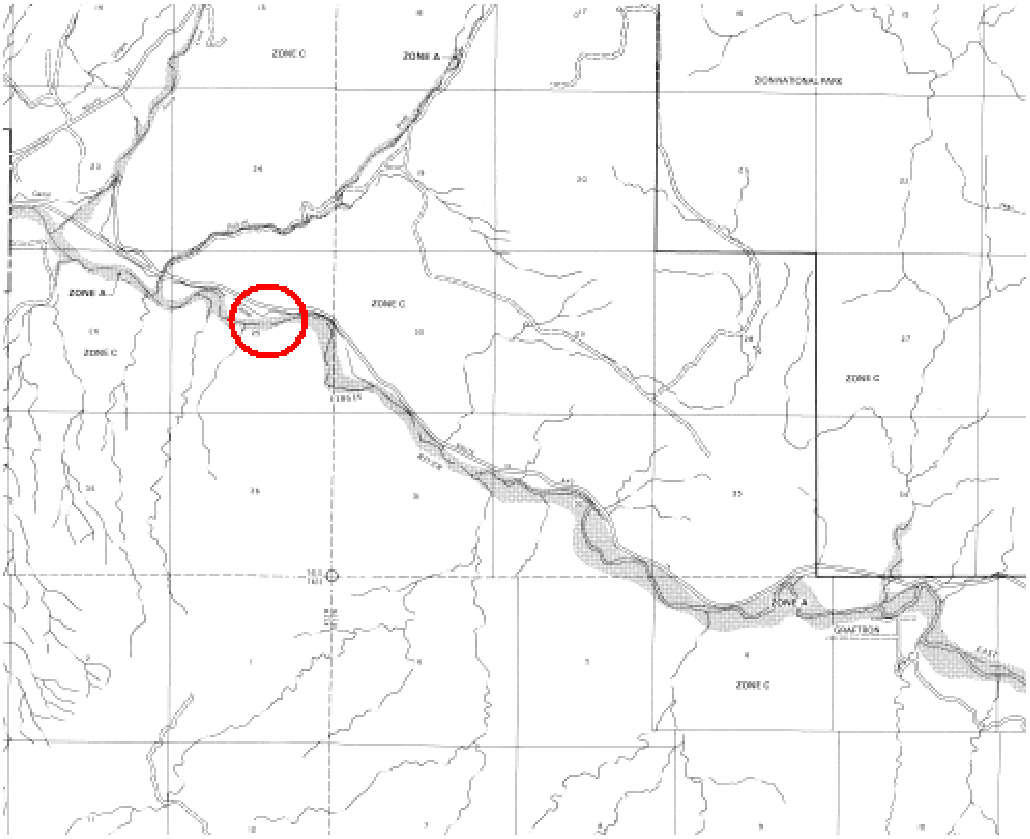


Figure 4-9: FIRM for Virgin River

The figure shows the Virgin River and 100-year-floodplain (shaded area). In order to compare FIRM and AEP map, the FIRM above was imported into WMS. The closed up image of FIRM and AEP map with 100-year-flood boundaries is shown in Figure 4-10.

The red lines are the 100-year-flood boundaries generated in AEP map, and the dotted area shown in the Figure 4-10 is the 100-year-floodplain in FIRM. The floodplain boundaries of AEP map and FIRM are similar except the region circled in green. There is a small difference in elevation in the green circle, and a small change in water surface elevation can change the floodplain boundary significantly. However, besides the area with small elevation difference, the boundary from the FIRM and the boundary from AEP map are generally similar.

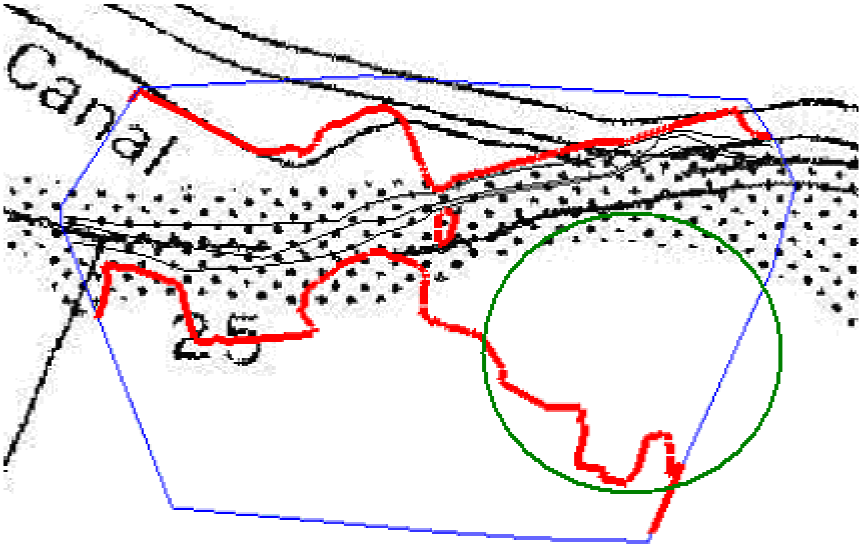


Figure 4-10: RIFM and AEP Map for Virgin River

5 Required Number of Simulations

AEP maps are generated with several uncertain parameters including roughness coefficients, precipitation, flow rate, and manning coefficients. In order to account for the uncertainty of these modeling parameters, some number of simulations must be run in WMS using the stochastic modeling approach. However, there is no guideline explaining how many simulations are needed for accurate AEP maps. If only a small number of simulations are used, and the values of the variables utilized for the model are not accurate, the created map will be inaccurate, or at least not fully represent the inherent uncertainty. However, a perfectionist may feel the need to run a million or more simulations, and while the final result may be more accurate; this effort would be overly time-consuming and costly in terms of data storage. Therefore, showing the convergence of AEP maps (AEP maps become reasonably accurate) after an appropriate number of simulations would be valuable for users so that they can decide how many simulations are needed for their desirable accuracy.

5.1 Criteria Considered for Convergence

In order to show that AEP maps converges, meaning that the extents stop changing, after a reasonable number of simulations, two criteria were monitored to see if some kind of trend could be observed:

1. Water surface elevations generated by HEC-RAS
2. The flooded area generated by WMS

5.1.1 Average Water Surface Elevation

In the process of creating the new AEP maps, the hydraulic analysis is performed by HEC-RAS, and the result is the computations of the water surface elevations for each cross section in the model. WMS uses these water surface elevations and the existing ground elevations to generate the floodplain boundaries. One of the criteria to determine when AEP maps are reasonably accurate is to see when the average water surface elevations outputted by HEC-RAS converge to within a given tolerance. The reason why average water surface elevations are monitored is because when the average water surface elevation obtained from HEC-RAS converges, then further runs would not be likely to significantly alter a computed AEP map. The red line Figure 5-1 in illustrates the average water surface elevation at one of the cross sections computed by HEC-RAS.

Figure 5-1 demonstrates that the average water surface elevation at particular cross section is increasing. This is a problem because it means that wat6er surface elevation never converges. However, because numbers of simulations are run, the average water surface elevation should converge. Therefore, every simulation was watched very closely. After checking all the parameters in WMS, the problem causing the divergence of average water surface elevation was discovered. When the Latin Hypercube Method was used to choose random flow values with the Stochastic Model

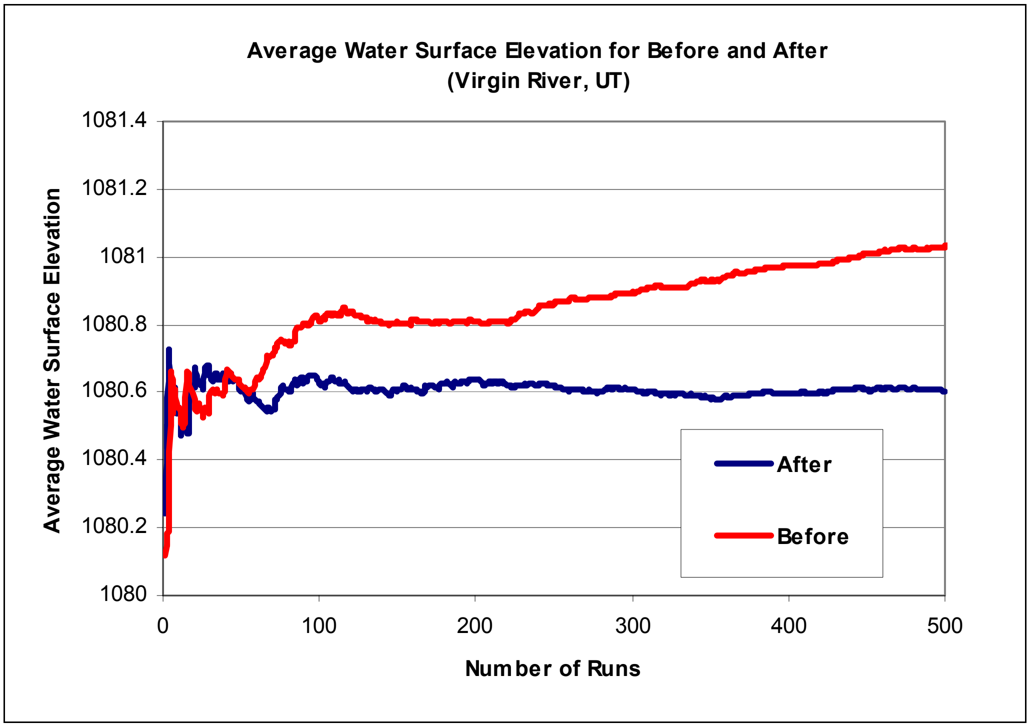


Figure 5-1: Average Water Surface Elevation Before and After

method in WMS, the flow values were chosen according to the PDF. The PDF a user specified is divided into segments with equal areas. Then one flow value from each segment in the PDF curve was chosen, and they were used as input for hydraulic analysis as shown in Figure 5-2.

This method chooses flow values from each segment beginning at the left and moving to the right along the PDF shown in Figure 5-2. This means that the values chosen from the PDF curve are increasing, with the highest value always being used last showing why the average water surface elevations are not converging. The input flow values of the hydraulic model are getting bigger and bigger, so the outputs (water

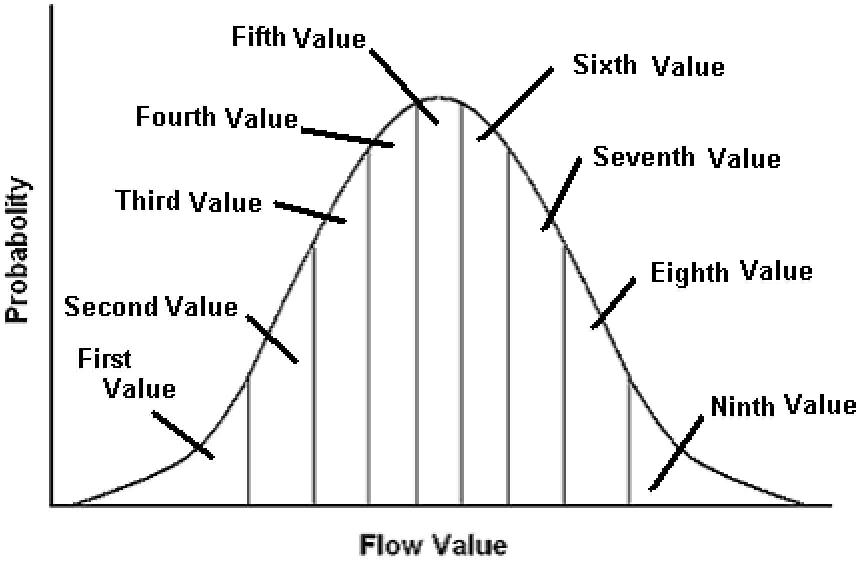


Figure 5-2: Choosing Values from PDF Curve

surface elevations) are of course increasing. This Latin Hypercube method still follows the distribution of flow value as a user specified and chooses flow values randomly from each segment, but they are not chosen in a random order. This method of choosing flow values does not represent the unpredictable occurrence of peak flow values occurring in nature. Therefore, WMS was modified so that flow values are still chosen from each divided PDF segment, but not from smaller segment to larger segment. The Latin Hypercube method is utilized in the reprogrammed version of WMS again to choose flow values that still meet the range a user specifies, but this time the average flow values converge as would be expected. Figure 5-1 shows the difference of average water surface elevations between the two versions; one is before the reprogramming of WMS that become appears to diverge and the other is after reprogramming (where flow values from each segment are chosen randomly), converges as the number of random values increase.

After reprogramming WMS, a new set of flow values was used in HEC-RAS for hydraulic analysis of this research. HEC-RAS will take these flow values and calculate the water surface elevations at each cross section. If enough simulations are run, the average water surface elevation calculated by HEC-RAS should approach to a constant value. In other words, the average water surface elevation should converge and stabilize. For this study, many simulations for the Virgin River model were run in WMS between 200 and 1000 runs. The average water surface elevations from these runs are shown in Figure 5-3.

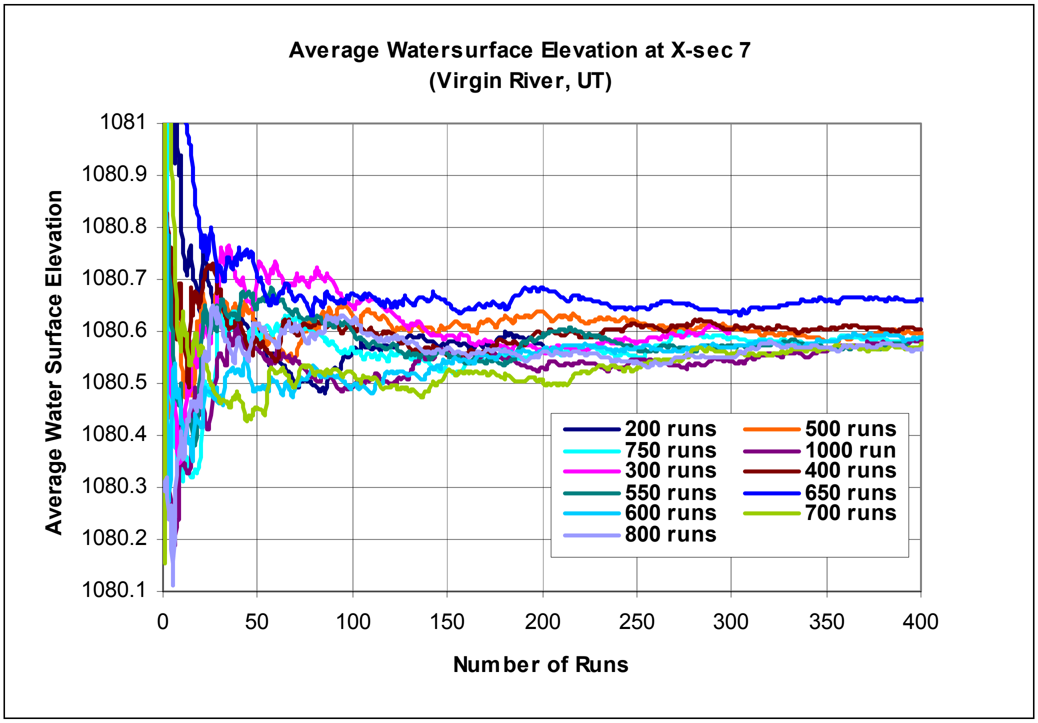


Figure 5-3: Average Water Surface Elevation (Virgin River, UT)

This figure illustrates that the average water surface elevation converges. When about 150 simulations were run, the average water surface elevations stabilized.

However, it is difficult to decide when the water surface elevation actually converges from this figure. For this purpose, the difference of average water surface elevations between each run and the previous run are calculated. The differences in average water surface elevations are plotted in Figure 5-4.

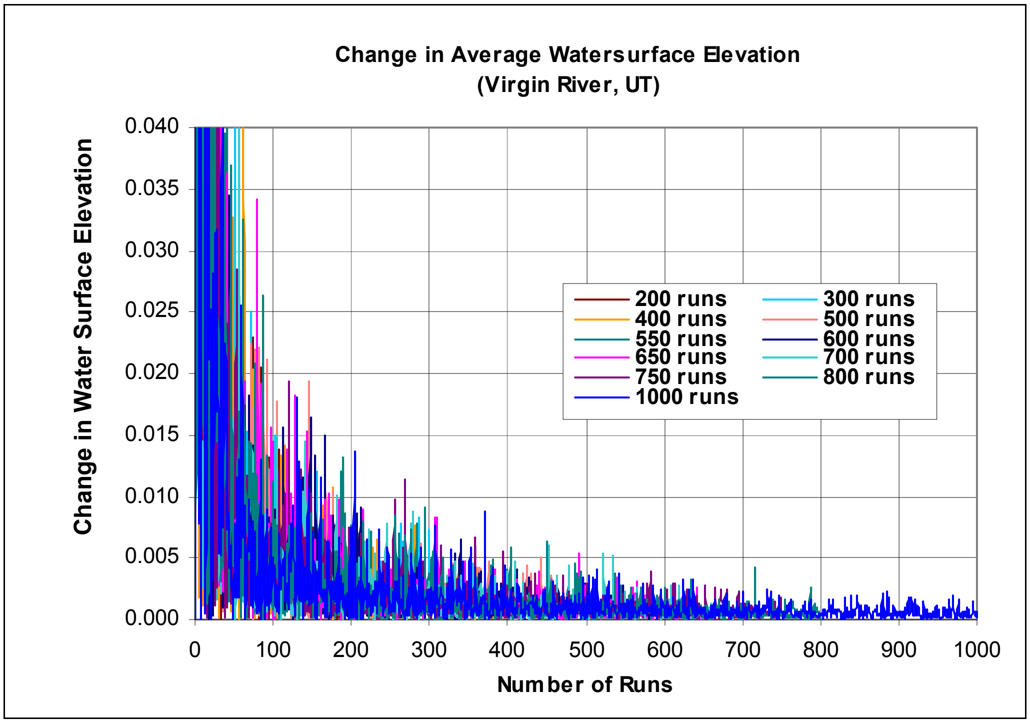


Figure 5-4: Change in Average Water Surface Elevation

This figure demonstrates that overall the average water surface elevation converges as the number of simulations increases because the changes in average water surface elevation are decreasing. From this figure, it is possible to say the water surface elevation is converged when the change between each run becomes smaller than certain desired tolerance. However, this method of finding convergence does not work every time. For example if very similar flow values are selected (randomly) for the first few simulations then the difference in average water surface elevation computed from these runs might well be less than some defined tolerance. If so, the simulation would thought to be converged even thought only a few simulations were run. In order to eliminate this problem, the averages of changes in average water surface elevation were calculated for this research.

Figure 5-5 shows the average of last ten changes in average water surface elevation between 200 runs and 700 runs.

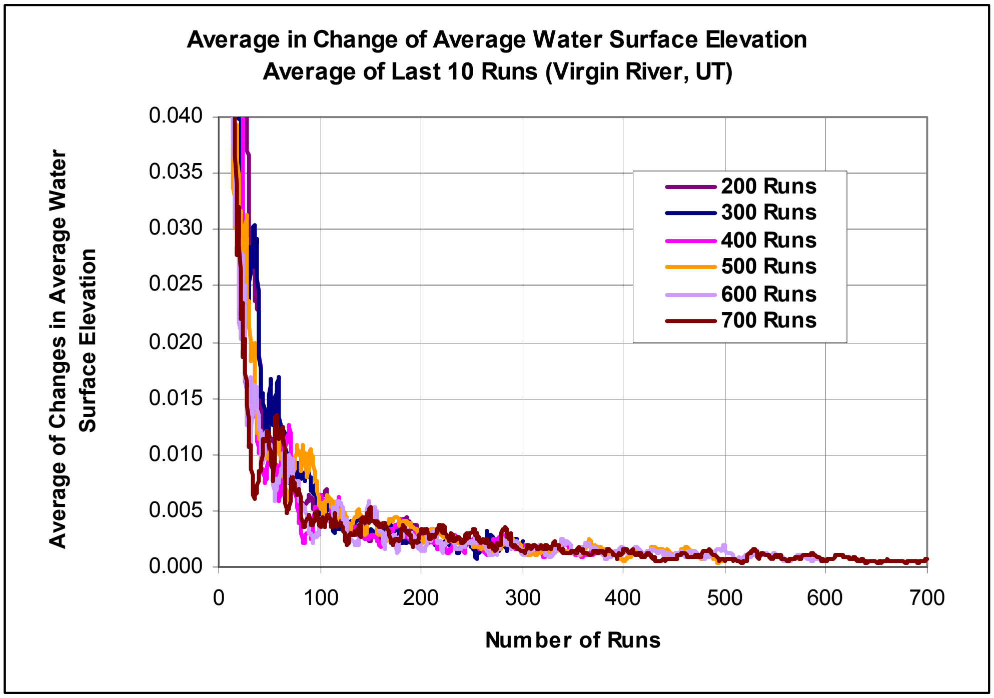


Figure 5-5: Average in Change of Average Water Surface Elevation-Last 10 Changes

Figure 5-5 shows smoother graphs than Figure 5-4 does, because it takes the average of previous ten changes instead of finding the difference from just one previous value. Because this figure still has some small discontinuities, the average of the previous 20 and 50 changes in average water surface elevation were also calculated.

Figure 5-6 demonstrates the average of the last 20 changes, and Figure 5-7 demonstrates the average of the last 50 changes.

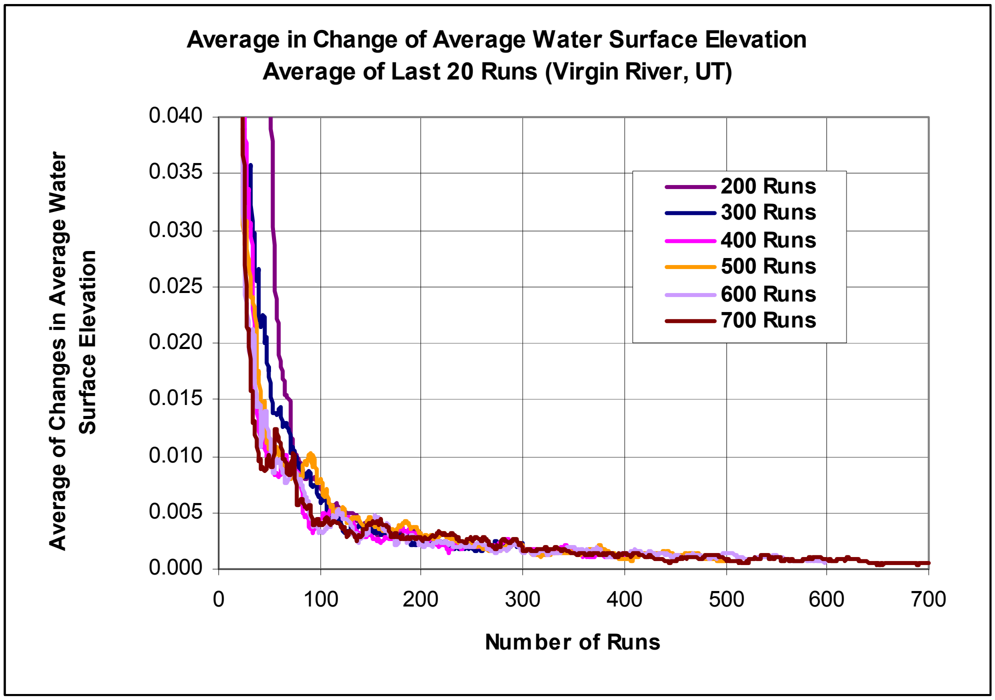


Figure 5-6: Average in Change of Average Water Surface Elevation-Last 20 Changes

Figure 5-6 and Figure 5-7 demonstrate that the graphs become smoother without the discontinuities. These figures indicate convergence, and that further runs are not necessary. Such a graph could help a user decide when to stop running. While this approach is effective in determining convergence, it has a drawback. This method gives higher average values of changes in average water surface elevation than the

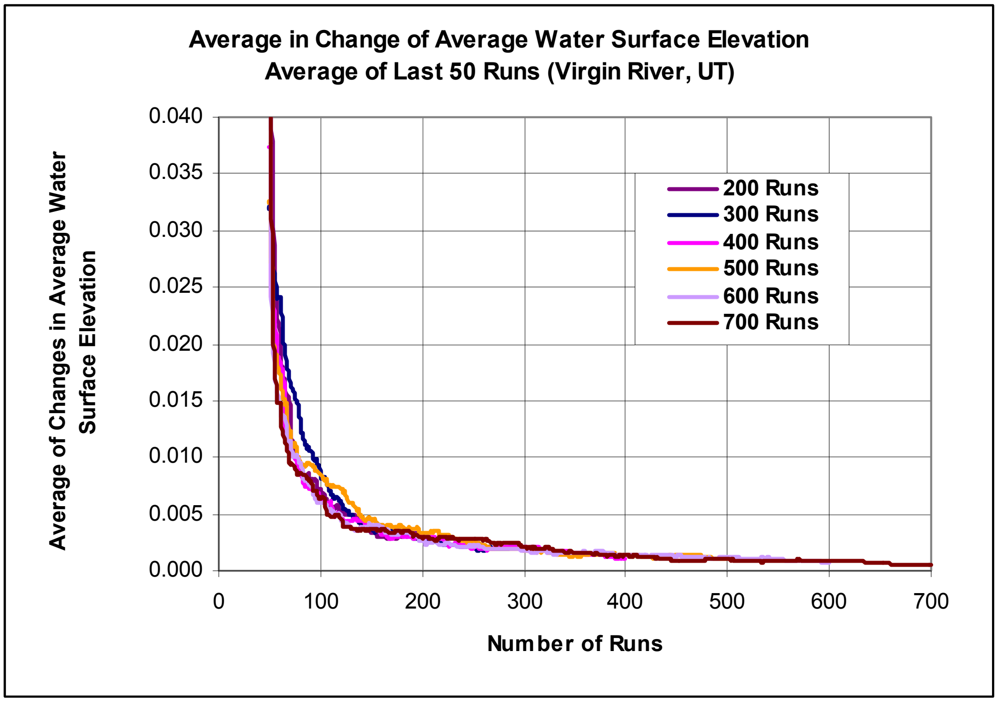


Figure 5-7: Average in Change of Average Water Surface Elevation-Last 50 Changes

actual values. For example, if average of the last 50 values is taken at the 60th simulation, these 50 values are most likely to be higher than the value at the 60th simulation as demonstrated in Figure 5-8.

Because last 50 values are higher than the actual value at the 60th simulation, this method does not give a correct average value. For this reason, averages of the last ten changes and the next ten changes of average water surface elevations were calculated. In this case, the previous ten values (likely to have higher changes in average water surface elevations) will be balanced out with next ten values (likely to be lower). It will not be perfectly balanced because the values are not linearly

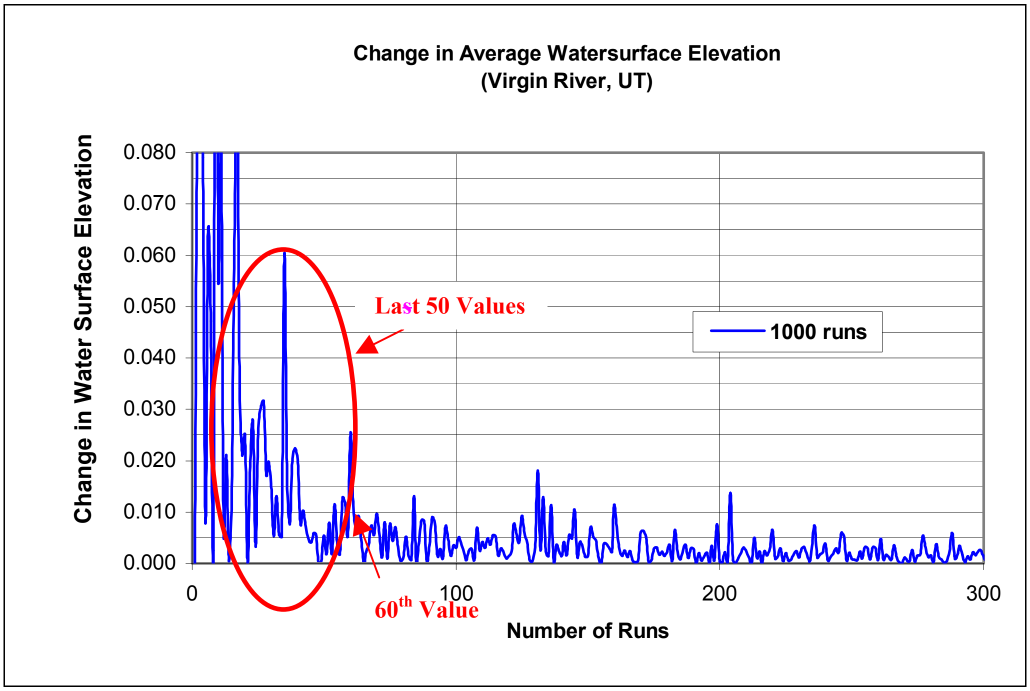


Figure 5-8: Change in Average Water Surface Elevation –1000 Runs

decreasing. For example the last ten values at the 20th simulation are decreasing more rapidly than the next ten values. Therefore, when these twenty values are averaged, it will still be little higher than the real average value at the 20th simulation. However, because the difference is relatively small, this method was kept for this research.

Figure 5-9 shows the averages of the last five values and the next five values between 200 and 700 runs. In order to smooth out the graphs, the averages of the previous 10 and the next 10, and the previous 25 and the next 25 changes were calculated as shown in Figure 5-10 and Figure 5-11 respectively.

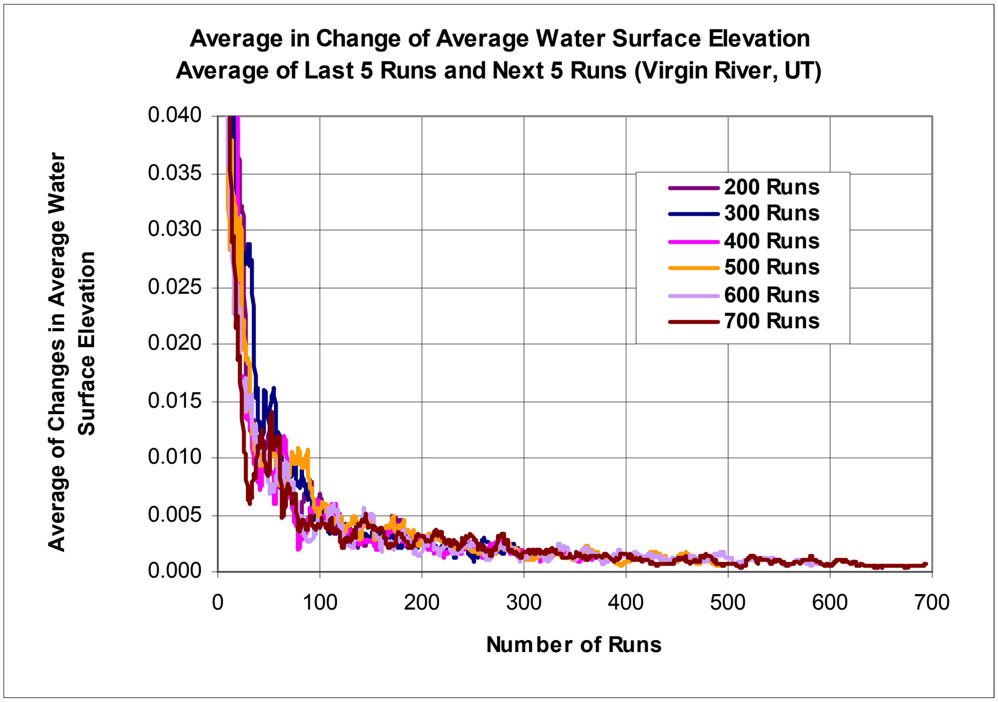


Figure 5-9: Average in Change of Average Water Surface Elevation (Last 5 and Next 5)

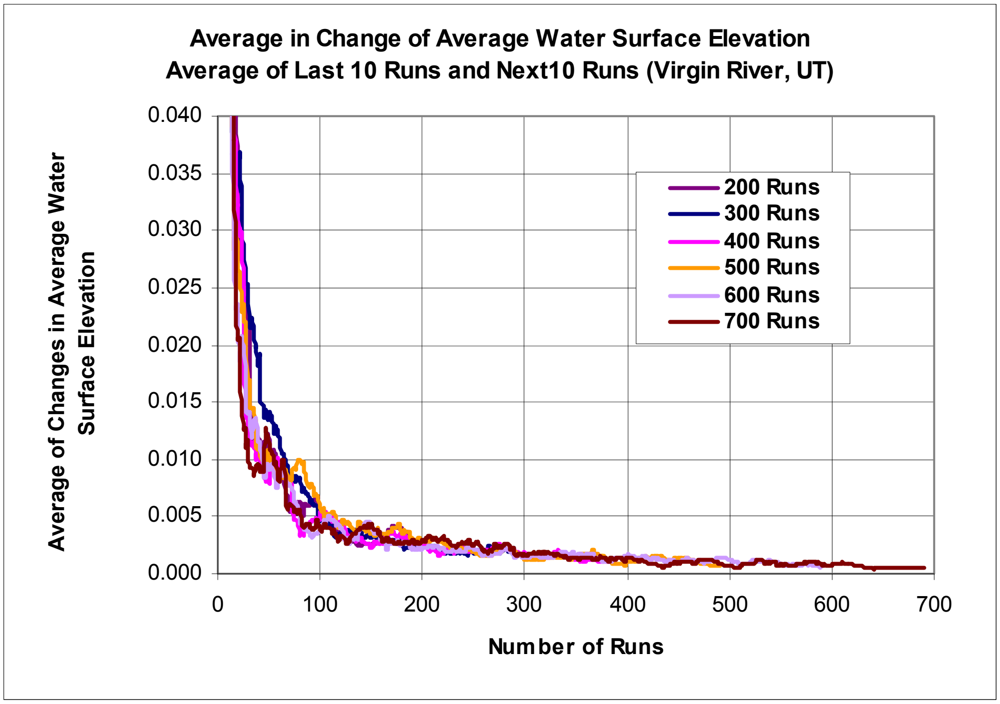


Figure 5-10: Average in Change of Average Water Surface Elevation (Previous 10 and Next 10)

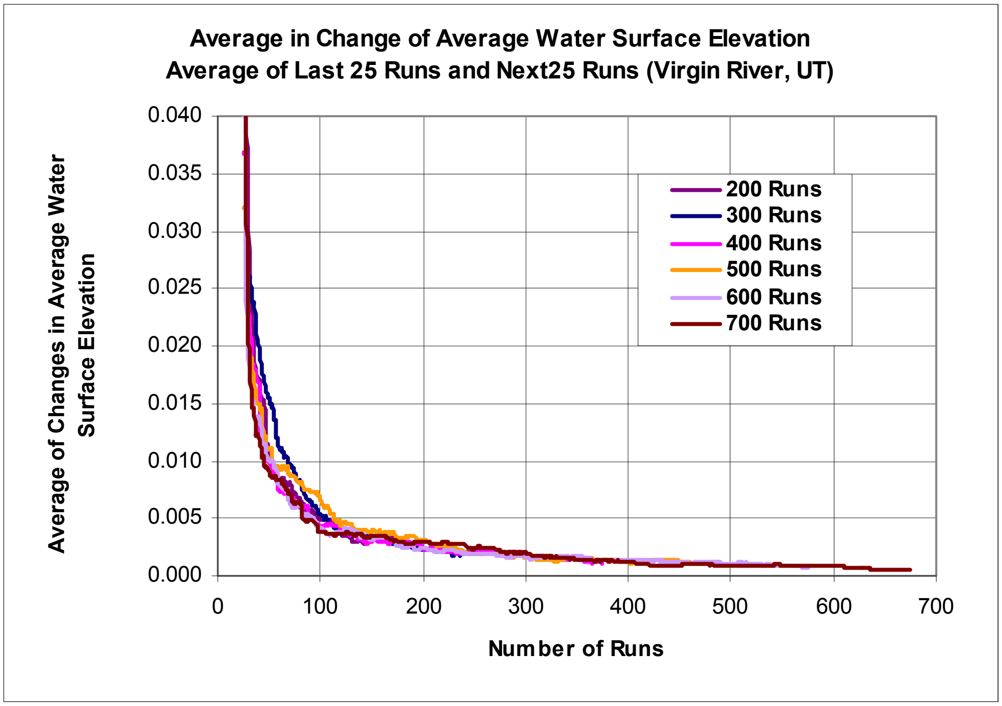


Figure 5-11: Average in Change of Average Water Surface Elevation (Previous 25 and Next 25)

WMS chooses a different set of flow values every time when a user runs the next model with the same number of simulations or chooses different number of simulations for the next model. Because different sets of numbers are inputted into the model, it is normal to obtain different results each time. For example, the first model with 500 runs uses different flow values in a different order than the second model of 500 runs, and consequently the output of the first model will be slightly different from the second model. If the difference is not significant then the results will be considered acceptable. However, if the difference ends up extremely large then it would not be acceptable. Therefore, in order to check for this possible problem, four 500 runs simulations were also run. The average water surface elevations for these simulations are shown in Figure 5-12.

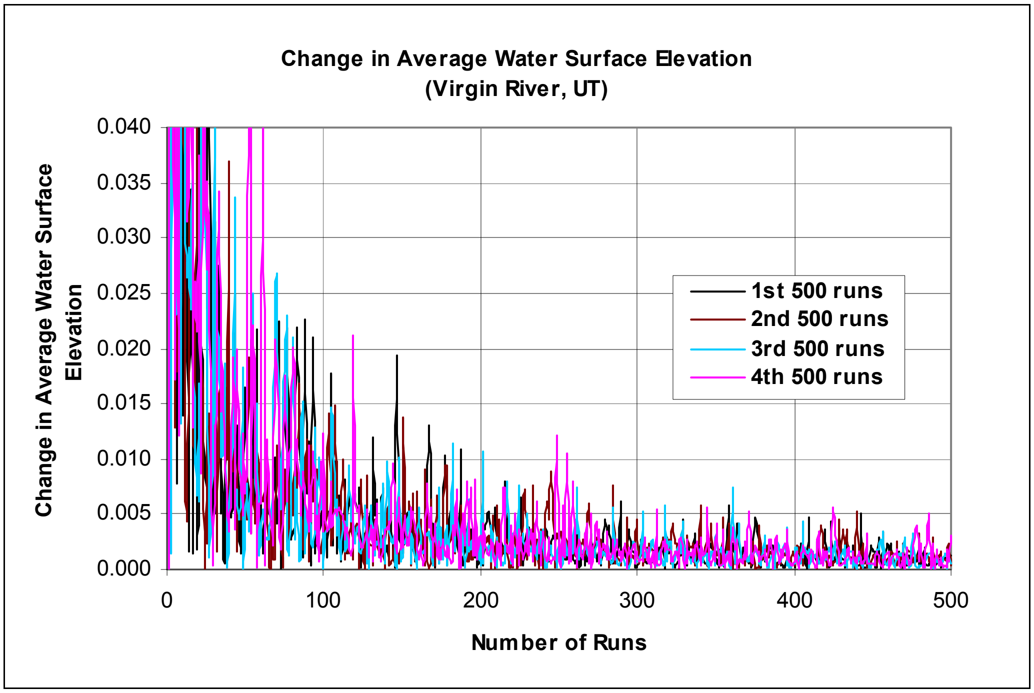


Figure 5-12: Water Surface Elevations for Four 500 Runs

Again, the changes in average water surface elevation were calculated and are shown in Figure 5-13. According to this result, there is hardly any difference in these four models. This shows that the difference from different sets of runs does not matter, since the result is very similar.

The averages of the previous 10, 20 and 50 changes in average water surface elevation of first 500 runs are shown in Figure 5-14. Also the average of previous five with next five, last ten with next ten, and last 25 and next 25 changes are also shown in Figure 5-15.

Figure 5-14 shows some difference at the beginning of the graph, but not in Figure 5-15. This is because Figure 5-14 considers only previous values; it tends to have higher values.

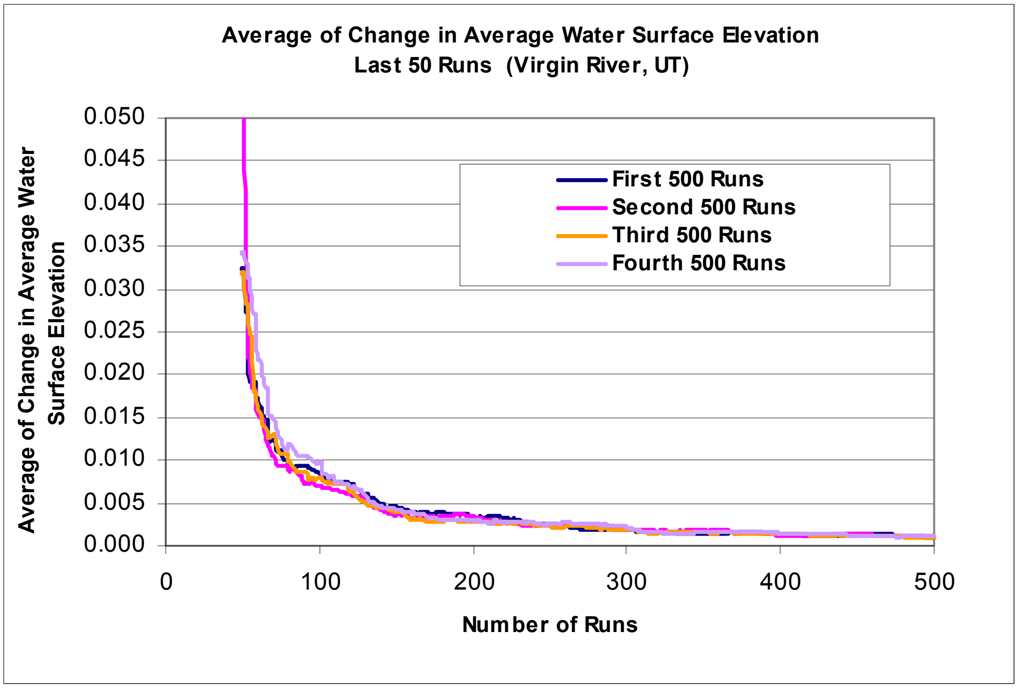


Figure 5-13: Changes in Average Water Surface Elevation –Four 500 runs (Last 50)

This same study was also done for the Gila River in Arizona, and several simulations with between 200 and 750 runs were run. The average water surface elevations for each simulation are shown in Figure 5-16.

Figure 5-16 reveals that the simulation with around 200 runs gives a relatively stable water surface elevation. But again, it is hard to decide when the water surface elevation actually converges. Therefore, the averages of the water surface elevations are also calculated. The change in average water surface elevation for the Gila River for several different number of simulations and four 500 runs are shown in Figure 5-17 and Figure 5-18 respectively.

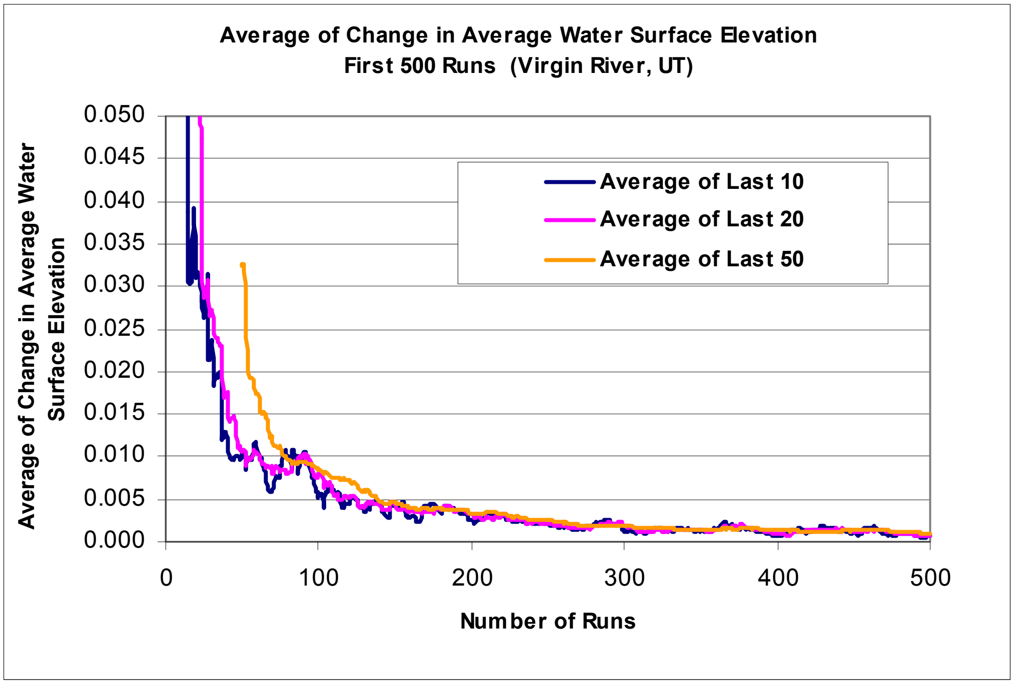


Figure 5-14: Average of Changes in Average Water Surface Elevation for First 500 Runs (Last 10, 20, and 50)

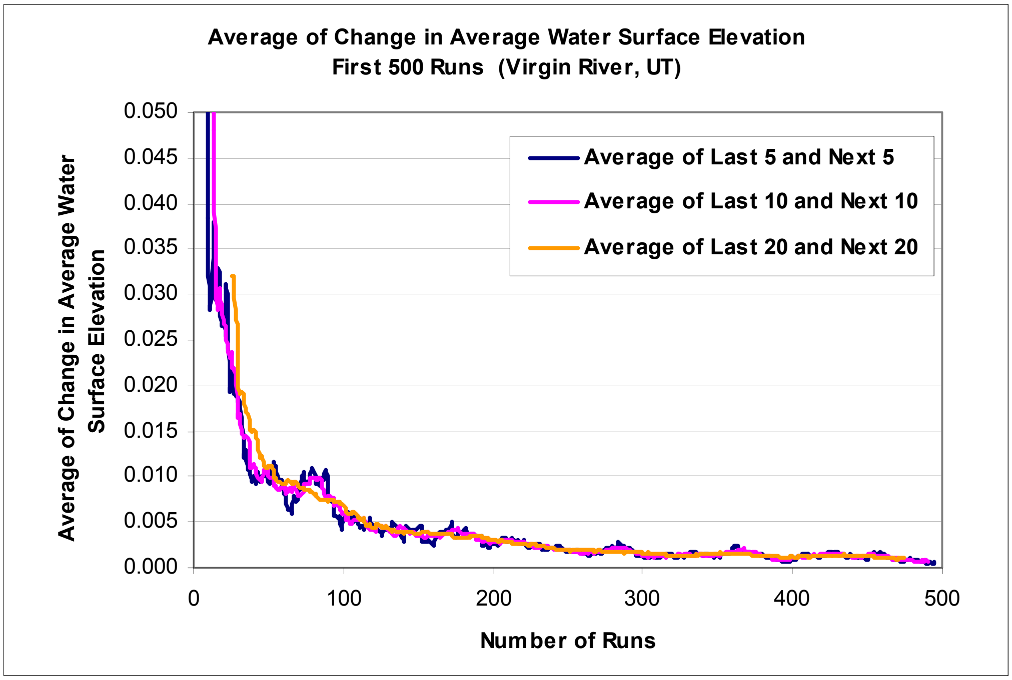


Figure 5-15: Average of Changes in Average Water Surface Elevation for First 500 Runs (Last 5 Next 5, Last 10 Next 10, and Last 25 and Next 25)

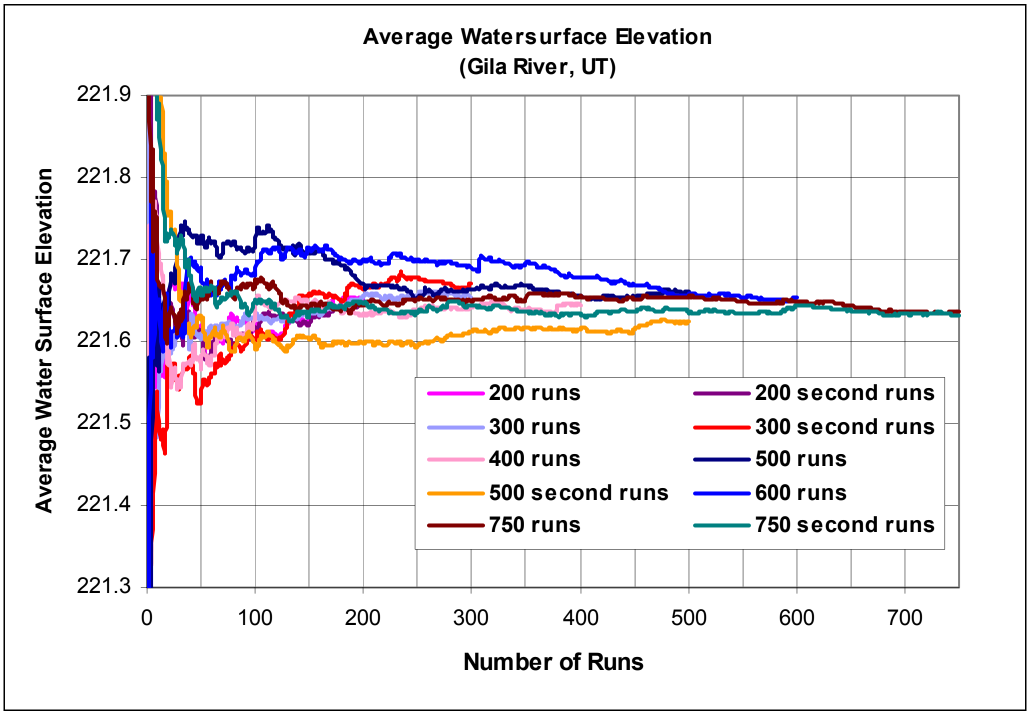


Figure 5-16: Average Water Surface Elevation (Gila River, UT)

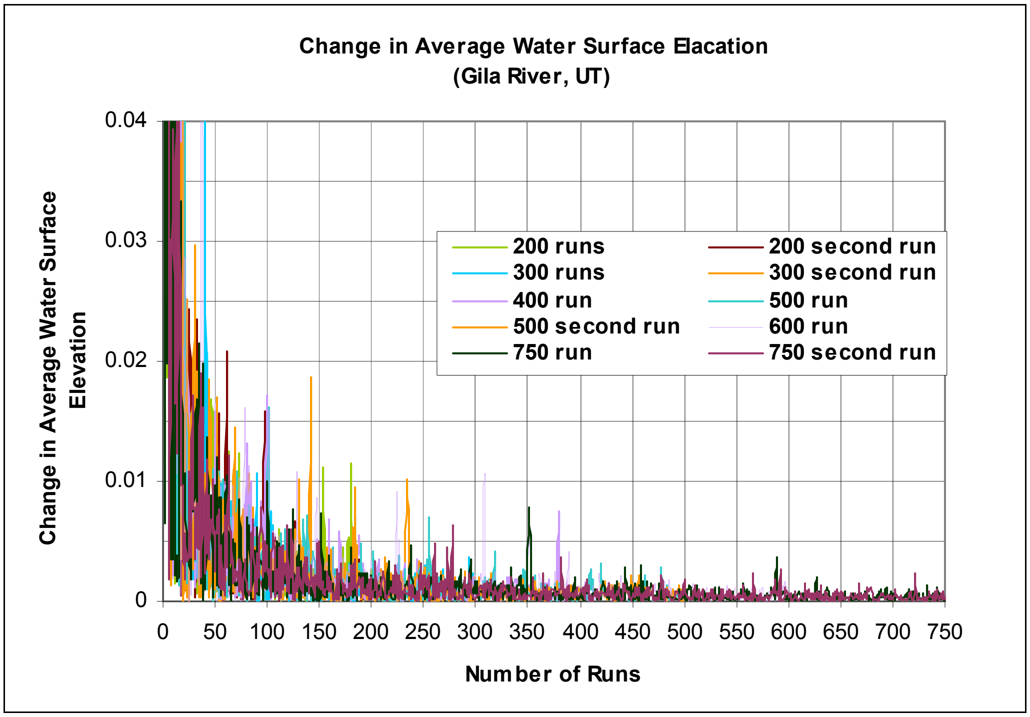


Figure 5-17: Change in Average Water Surface Elevation

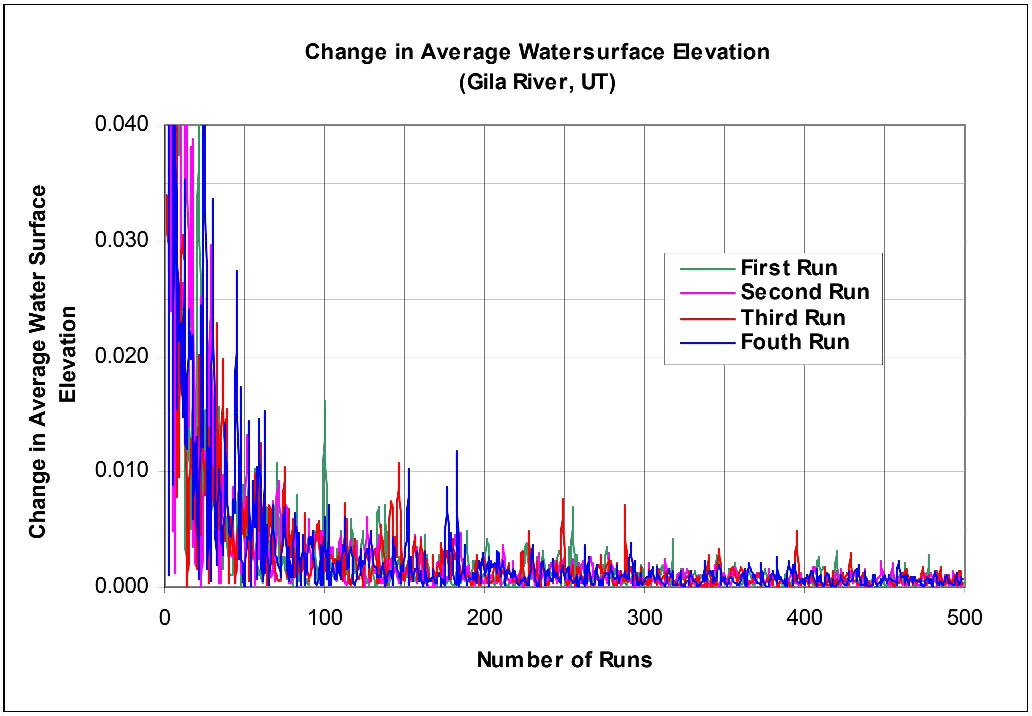


Figure 5-18: Change in Average Water Surface Elevation (Four 500 runs)

Again, in order to make the graph smoother the averages of the previous 25 and next 25 changes in average water surface elevations were calculated for the Gila River model as shown below.

This case study of Gila River, AZ also shows the same result; when the number of simulations increases, average water surface elevation converges. The number necessary for AEP maps is depending on the tolerance a user desires.

5.1.2 Floodplain Area

The second criterion to see the convergences of AEP maps after some number of simulations is to check the floodplain area generated by WMS. AEP maps created

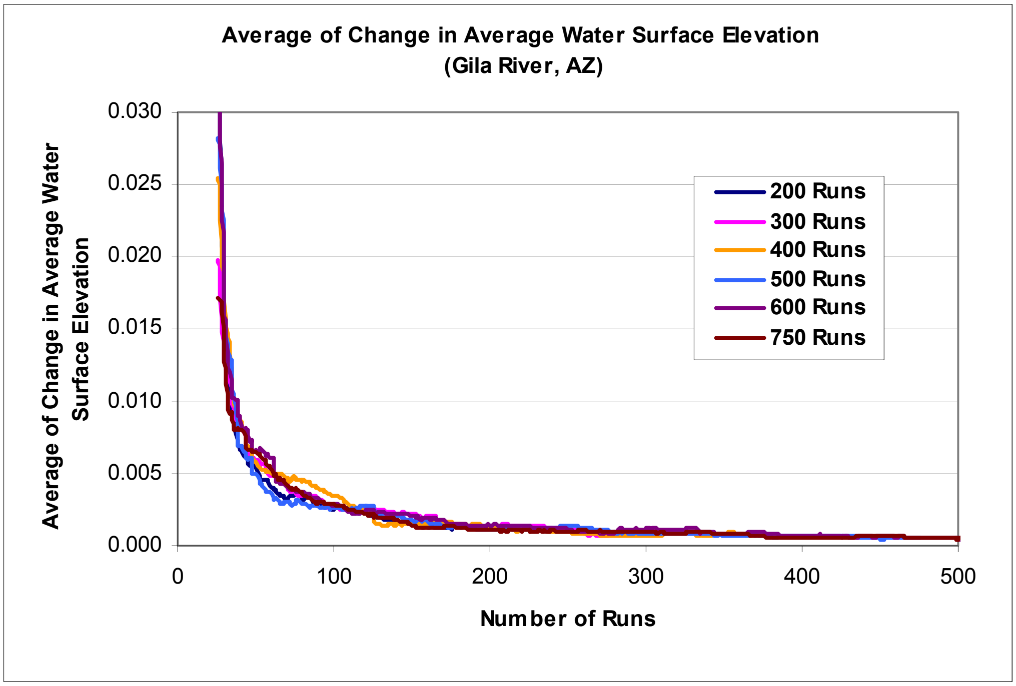


Figure 5-19: Average of Change in Average Water Surface Elevation (Gila River)

by WMS contain the floodplains of the different flood recurrence intervals. The flood sizes of the 50-year, 100-year, and 500-year-floodplain boundaries in the Virgin River with different number of runs were used for comparison in this study. These flood boundaries created by WMS are illustrated in Figure 5-20.

The orange lines represent the boundaries of the probability of a 0.2 percent, or 500-year flood. The pink lines represent a 100-year flood (one percent) and the blue lines are for a 50-year-flood (two percent). These three boundaries, generated by WMS, are exported to a Geographic Information System (GIS) and the areas of each floodplain are then calculated. The results of the different floodplain areas are summarized in Table 5-1.

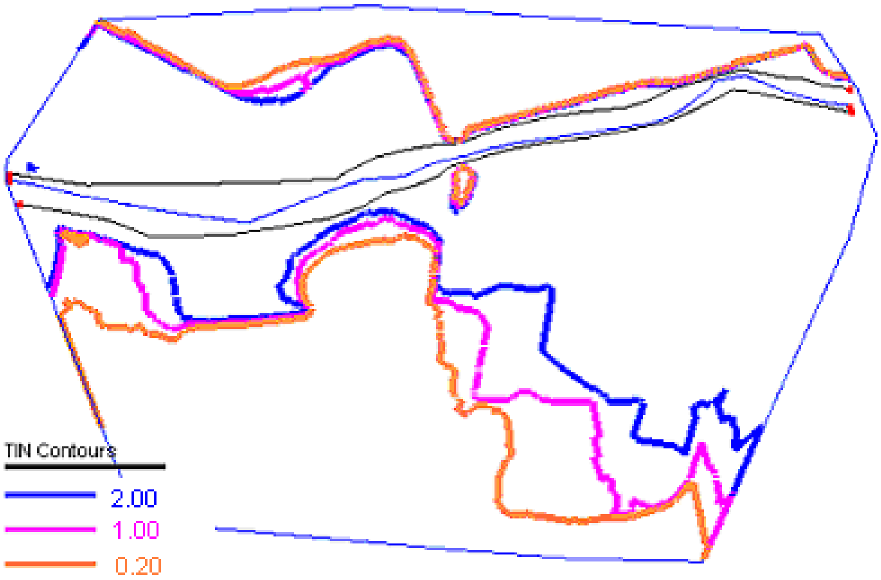


Figure 5-20: Floodplain Boundaries for 50, 100, and 500 Year Storms (Virgin River, UT)

The table shows that, generally, the percent change in floodplain areas starts around 20 percent and as the number of runs increase, the percent change decreases closer and closer to one percent. To see the change in area better, the floodplain areas of the 500, 100 and 50-year floods are plotted in the following Figure 5-21.

Table 5-1: Floodplain Area in Virgin River

	500 year flood			100 year flood			50 year flood		
# of runs	Area (ft^2)	Diffe-rence	%	Area (ft^2)	Diffe-rence	%	Area (ft^2)	Diffe-rence	%
200	160444.5			147932.6			145997.1		
300	158068.2	2376.4	1.5%	122982.8	24949.7	20.3%	109309.4	36687.7	33.6%
400	130182.6	27885.5	21.4%	117218.6	5764.2	4.9%	106117.5	3191.9	3.0%
500	150482.0	20299.4	13.5%	131495.3	14276.7	10.9%	123712.2	17594.7	14.2%
550	150086.4	395.7	0.3%	128041.2	3454.1	2.7%	113183.2	10529.0	9.3%
600	148041.5	2044.8	1.4%	126408.1	1633.1	1.3%	109926.7	3256.5	3.0%
650	154801.2	6759.6	4.4%	136365.8	9957.7	7.3%	119759.9	9833.2	8.2%
700	156949.0	2147.9	1.4%	135658.3	707.4	0.5%	115400.7	4359.2	3.8%
750	150254.4	6694.7	4.5%	128395.3	7263.0	5.7%	111773.7	3627.0	3.2%
1000	150798.2	543.8	0.4%	126989.5	1405.8	1.1%	113438.8	1665.1	1.5%

Figure 5-21 demonstrates that the areas of the floodplains are converging as a higher number of simulations are run for all three different flood sizes. In order to determine when it is converged, the change in area for each flood size is calculated and shown in Figure 5-22.

This figure shows that as the number of simulations run increases, the change in area for all flood sizes generally become smaller. In order to determine the convergence, some level of tolerance must be established. However, a tolerance with an area such as 10,000 square meters does not have the same meaning for the all three flood sizes, because areas of three flood sizes are different. The average floodplain for each flood size is summarized in Table 5-2.

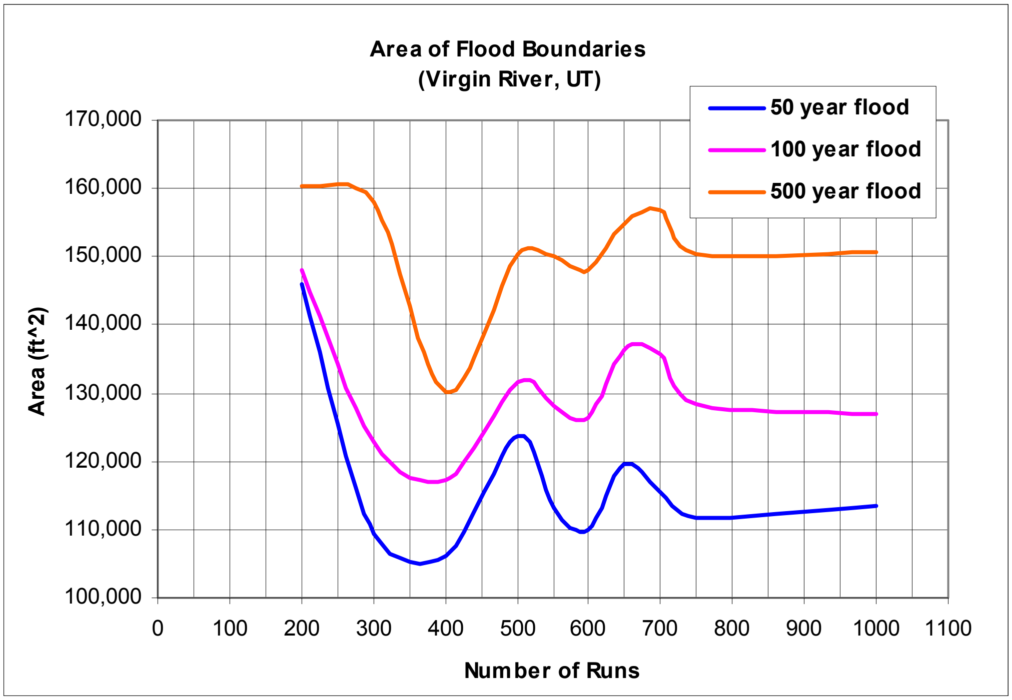


Figure 5-21: Area of Flood Boundaries

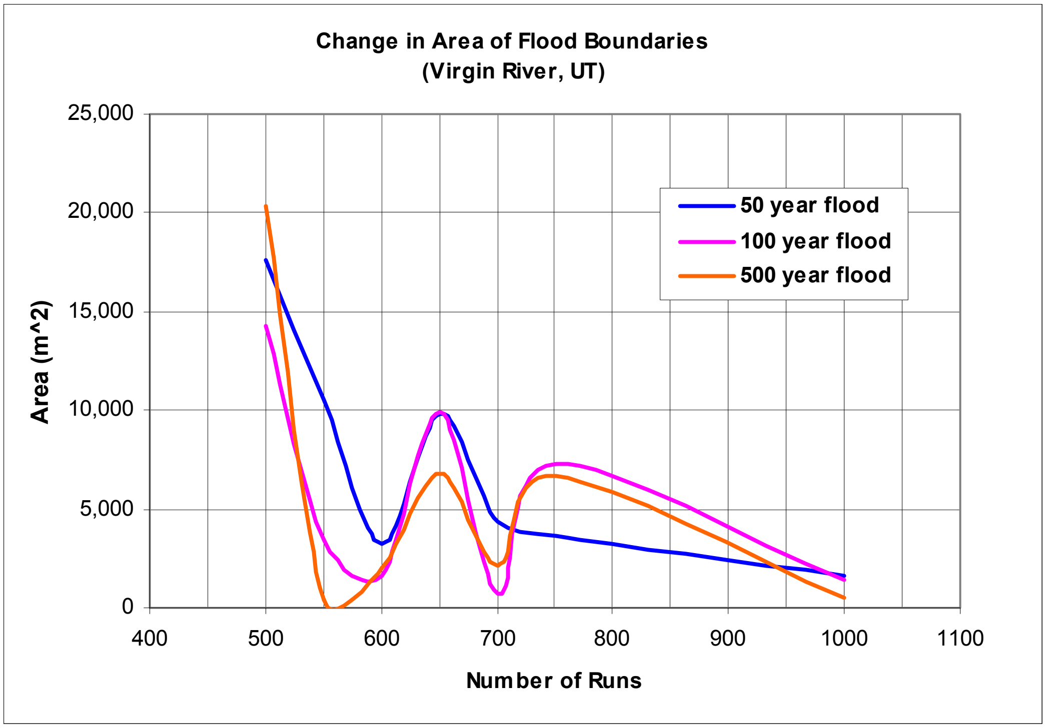


Figure 5-22: Change in Floodplain Area

As the table shows, the floodplain area of a 500-year-flood is almost 30 percent bigger than the floodplain area of a 50-year-flood. This means 10,000 square feet for a 50-year floodplain has an entirely different meaning from 10,000 square feet for a 500-year-floodplain. Therefore, the percent change in floodplain area is determined to show the convergence. Figure 5-23 illustrates the change in floodplain area for each of the flood sizes.

Table 5-2: Average Floodplain Area

	50-year-flood	100-year-flood	500-year-flood
Average Area (m²)	116861.9	130148.8	151010.8
Comparison with 50-year-flood	100%	111%	129%

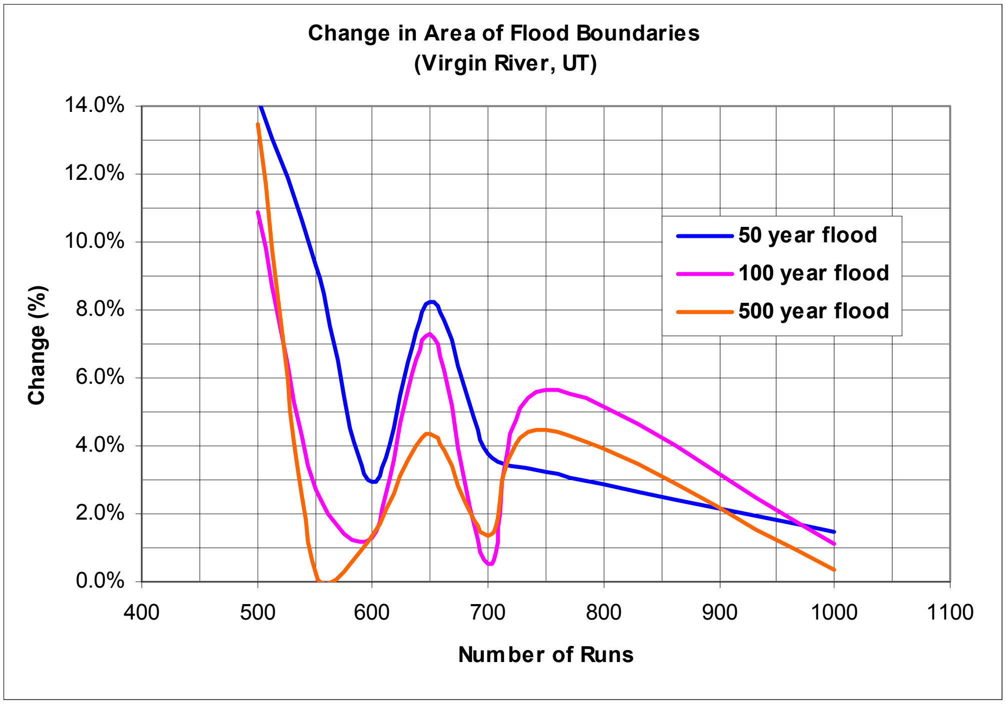


Figure 5-23: Change in Area of Floodplain

From this figure, a user can decide how many simulations are necessary according to the desired tolerance.

The one thing needed to be considered for this second criterion, monitoring the floodplain area, is that this criterion deals with elevation data to delineate floodplains. However the elevation data is not always accurate, therefore there are inherently more uncertainties involved in this criterion than in the first criterion that is average water surface elevation.

5.2 Simulation Time

After deciding how many simulations are essential to create an AEP map with the desired tolerance, it is useful to know the estimated simulation time needed to run the Stochastic model. This simulation depends upon several factors: the number of simulations, the size of the model, the spacing of points on the centerline and cross section in hydraulic models, resolution of underlying digital terrain model, and computer processor speed and memory capacity. In order to determine a general guideline for the required time of simulation, a number of models were run for two different locations. The computer used for this analysis has 3.0 GHz Pentium 4 processor with the 1.0GB of memory. Table 5-3 depicts the information of the two different models. Before running stochastic models, all the displays, including scatter points, river points, and TIN, in WMS are turned off to reduce the time of simulation. Also, no other programs besides WMS are running at the same time in order to use all of the memory of the computer.

Table 5-3: Comparison of the Gila River and the Virgin River

River Name	Gila River	Virgin River
Length of river segment	9717 m	667 m
Possible Maximum reach of flood	2500 m	500 m
Spacing of Points on centerline and cross sections	300 m	10 m
Number of Cross Sections	10	13

Figure 5-24 illustrates the simulation time for these two locations. This result shows that it will take approximately 15 to 25 minutes to run 300 simulations, 30 to 50

Figure 5-24 Simulation Time

minutes to run 500 simulations, and 45 to 60 minutes to run 700 simulations. But again, the simulation time may vary depending on many different aspects. A user can run as many simulations as one desires until one feels that the convergence is achieved, and this result of simulations time can be used to estimate the general running time according to the number of simulations.

6 Conclusion

This research introduces the guidelines of creating AEP maps developed by Smemoe (2004). AEP maps are a new method of representing the continuous probability of flooding with the consideration of uncertainties. The current flood study called Annual Exceedance Probability (AEP) used by the U.S. Army Corps of Engineers can only define the probability of overtopping a levee at one particular location at a time, but the new AEP map can illustrate flood probabilities spatially. If these AEP maps are created correctly, they can improve the flood study analysis and introduce new method of creating the Flood Insurance Rating Map (FIRM).

Because AEP maps are generated with several uncertain parameters including roughness coefficients, precipitation, flow rate, and manning coefficients, some number of simulations must be run in order to account for these uncertainties. However, there is no guideline as to how many simulations are necessary to create a reasonably accurate AEP map. Therefore, this research demonstrated the convergence of AEP maps after running a reasonable number so simulations by monitoring when AEP maps stop changing. In order to show when AEP maps stop changing, meaning convergence of AEP maps, two criteria were monitored in two case studies. The first criteria was water surface elevations as calculated by the hydraulic model and the second criteria was floodplain area generated by WMS.

In the process of running many simulations, one fact was discovered. The current method (Latin Hypercube method) in WMS chooses input values randomly, but it did not input these values into simulations in a random order. It was choosing in the order of the smallest to the largest. In Latin Hypercube method, a user assigns a PDF for input values. Then the PDF curve is divided into as many segments as a user desires. This method chooses one value from each segment starting from the most left segment containing smaller values towards to the most right segment containing larger values. Therefore, the current method inputs values into the simulation in the order of the smallest to the largest. As the input flow values increases, the outputs of water surface elevations are increasing as well. Therefore, it was impossible to create reasonably accurate AEP maps, because outputs never stop changing. In order to eliminate this problem, WMS was reprogrammed so that it would produce random values in random order.

In this research, water surface elevations and the floodplain areas were studied for two case studies. One of the ways to decide when the AEP maps are converged is to monitor the average of changes in average water surface elevation. When the average of the previous 25 changes and the next 25 changes in average water surface elevation are plotted, it gives smooth graph that makes it easier to determine convergence. Figure 6-1 shows the average of changes in average water surface elevation for the Virgin River, UT.

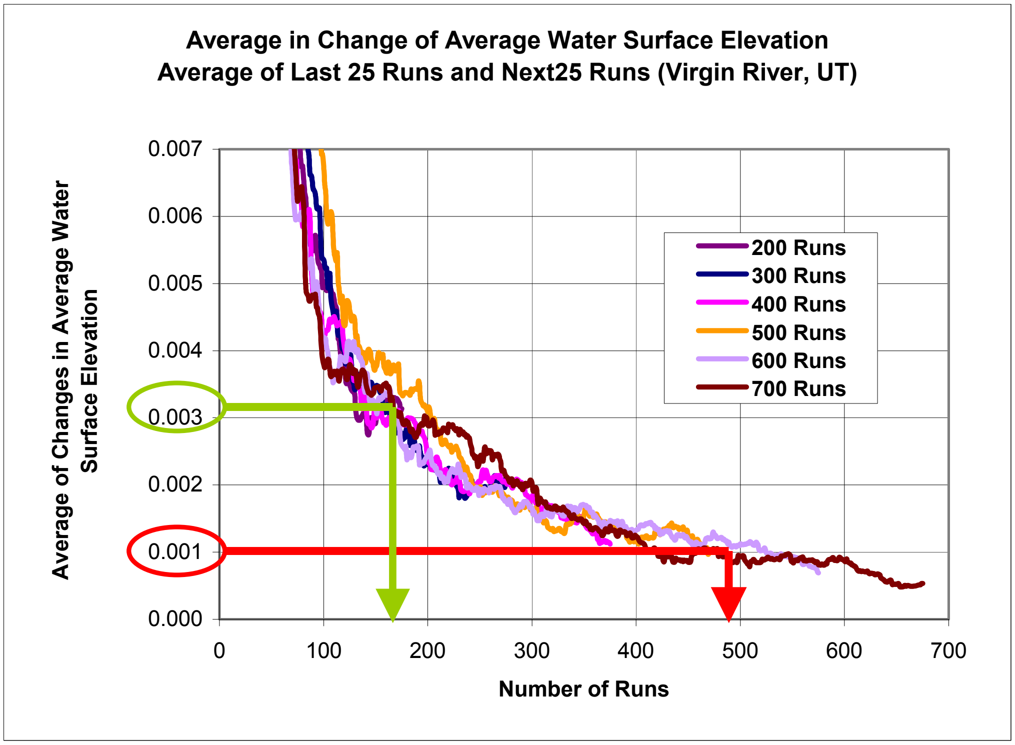


Figure 6-1: Result of Water Surface Elevation

If a user needs the tolerance of 0.003 meter for the convergence, one can stop the model after running approximate 160 simulations. If a user desires the tolerance of 0.001 meter for a better convergence, one can run approximate 490 simulations. These estimated numbers of simulations necessary for convergence are depending on the size of the model and other factors including cross section spacing and detail of elevation data. Therefore if a user can monitor graph such as Figure 6-1 while running the model, one can decide when to stop the model depending on the desired tolerance.

This research also studies the areas of floodplains to see the convergence. Many numbers of simulations were run to calculate the areas for 50, 100, and 500-year-floods. Figure 6-2 illustrates the floodplain area with different numbers of simulations.

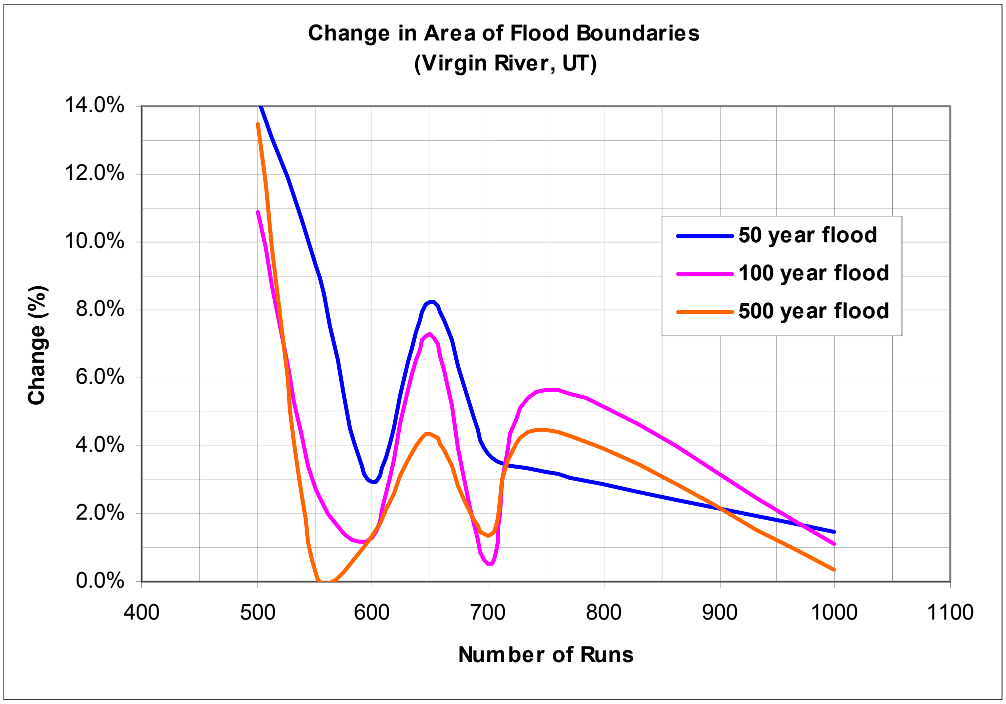


Figure 6-2: Result of Floodplain Area

This result also shows that the floodplain areas are converging as the number of simulations increases. The number of simulations needed to create AEP maps is depending on a user's desired accuracy. Again, if a user wants to decide on the convergence with the floodplain area instead of water surface elevation, graph like Figure 6-2 should be displayed when the model is running so that one can know when it is enough to obtain a user's desired accuracy in AEP maps.

This research also illustrates the estimated simulations time for different number of simulations. Figure 6-3 shows the expected time takes to run different number of simulations.

Figure 6-3: Result of Simulation Time

Typically it will take around 30 to 50 minutes to run 500 simulations, and 45 to 60 minutes to run 700 simulations with today's typical computer capacity. These expected simulation time could be used to estimate the simulation time when a user already knows how many simulations are necessary. However, the length of simulations can vary depending on the capacity of computers and model sizes.

Finally, the research of this thesis can be extended in different ways. As mentioned, if WMS can be reprogrammed so that a user can monitor the graph of water surface elevation or floodplain area from each simulation, it will be useful because a user can stop the model when one feels AEP maps converged before the specified number of simulations are finished. This can save users' time and computer memory.

The other thing can be done in the future is to run more models for different places. This research used two locations: Virgin River in Utah and Gila River in Arizona. The reason of using only two locations is because it is difficult to obtain detailed elevation data necessary for hydraulic models. The elevation data, Digital Elevation Model (DEM) is easy to obtain for just about anywhere in the U.S., but the current highest resolution of DEM is ten meters. It means that a precise point of elevation is known for every ten meters of area. Having elevation data every ten meters along a river will not be able to represent cross sections of a river well enough for this study. Therefore, more detailed elevation data is needed. Surveying along a river and the area next to a river will give detailed elevation, but it might be difficult to go visit the site and will probably be time-consuming. For this research, a different type of elevation data set, Triangular Irregular Network (TIN), was used to get the geometric data of the Virgin River and the Gila River. However, TINs are not available everywhere in the U.S. In fact, it is difficult to obtain a TIN for a desirable area. For future research, if detailed elevation data is available, more models can be run for different locations so that it will give more dependable results.

The other thing can be done from this study is to utilize the result of simulations. When a user already know the desired tolerance before running a model, WMS can be reprogrammed so that it will automatically stop the model when the specified tolerance is met. This will save time because a user will not be wasting time running unnecessary simulations. When the model meets the tolerance specified by a user, WMS will stop the model and provide an AEP map for the area of interest.

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