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FLOOD RISK MANAGEMENT WITH HEC-WAT AND THE FRA COMPUTE OPTION

Christopher N. Dunn P.E., D. WRE[1] Penni R. Baker[2] and Matt Fleming[3]

1. *Director, U.S. Army Corps of Engineers, Institute for Water Resources, Hydrologic Engineering Center, 609 Second Street, Davis, CA 95616; ph: 530 756-1104; fax: 530 756-8250; christopher.n.dunn@usace.army.mil*
2. *Software Programmer, U.S. Army Corps of Engineers, Institute for Water Resources, Hydrologic Engineering Center, 609 Second Street, Davis, CA 95616; ph: 530 302-3726; fax: 530 756-8250; penni.r.baker@usace.army.mil*
3. *Senior Hydraulic Engineer, U.S. Army Corps of Engineers, Institute for Water Resources, Hydrologic Engineering Center, 609 Second Street, Davis, CA 95616; ph: 530 756-1104; fax: 530 756-8250; matthew.fleming@usace.army.mil*

Abstract: The United States Army Corps of Engineers (USACE) policy states USACE will analyze its water resources projects, including flood risk management projects, using risk analysis and watershed, systems and life-cycle approaches. However, software to directly support these requirements has not been available. The current software used within USACE to perform these analyses, HEC-FDA (Flood Damage Reduction Analysis), has a number of limitations that preclude it from readily or intuitively performing these types of analyses. For this reason and others, USACE's Hydrologic Engineering Center (CEIWR-HEC) developed the Watershed Analysis Tool (HEC-WAT). HEC-WAT was initially developed to assist Project Delivery Teams (PDT's) conduct water resources studies of complex riverine systems with an integrated, comprehensive and systems based approach. However, since USACE also requires a life-cycle analysis, HEC added capability through the Flood Risk Analysis (FRA) compute option that allowed risk analysis computations while incorporating a life-cycle approach. HEC-WAT/FRA includes systems and life-cycle approaches, event-based sampling, parameter sampling, and the ability to do scenario and alternative analyses. Applications of the FRA compute include levee certification studies, dam and levee safety studies, and planning and design studies. An initial implementation of HEC-WAT/FRA was constructed for the Columbia River Treaty (CRT) 2014/2024 Review project. The goal of the CRT Review is to provide United States decision makers with the necessary information to support a decision regarding the future of the CRT with Canada. A series of studies was performed to collect information to assess renegotiation alternatives. This paper will describe the HEC-WAT/FRA and how it was used to assess current treaty operations and possible future treaty alternatives. This presentation will also describe the scientific advancements included within HEC-WAT/FRA and how it will advance USACE modeling approaches for flood risk analysis.

Key Words: Flood Risk, USACE, HEC, HEC-WAT, water resources

1. INTRODUCTION

One of the primary missions of USACE is to manage the nation's water resources. For a variety of reasons, including budgetary, it is critical that the nation's water resources be studied and managed using a collaborative and comprehensive approach implementing system and watershed concepts while incorporating risk and life-cycle analyses.

To support these requirements, USACE has written several pieces of guidance and policy that state that water resource studies shall be performed with risk analysis techniques using an integrated, comprehensive, and systems based approach. However, implementing true watershed and systems approaches with risk and life-cycle analysis can be difficult. The Corps current certified flood risk management tool, HEC-FDA (Flood Damage Reduction Analysis), represents the system as a number of independent projects rather than integrated system. Therefore, a new water resources planning tool needed to be developed that would include explicit systems, watershed and life-cycle capabilities along with the risk analysis computations currently found in HEC-FDA.

To address these issues USACE has developed HEC-WAT to study and manage the nation's water resources in a systems and watershed approach while incorporating risk and life-cycle capabilities. The HEC-WAT framework integrates the software commonly used by multi-disciplinary teams to perform comprehensive system type studies. HEC-WAT also allows a Project Delivery Team (PDT) to perform alternative analyses in an intuitive and collaborative manner.

For these reasons, the Columbia River Treaty PDT became interested in implementing HEC-WAT and elected to use it for the CRT 2014/2024 study. The Columbia River watershed and its accompanying infrastructure to manage the water resources is one of the most sophisticated examples of an integrated, comprehensive system that could be found in the United States.

2. CURRENT APPROACH

Since 1996, USACE has used the HEC-FDA, Flood Damage Reduction Analysis, software to perform risk analyses for system studies. HEC-FDA is a plan evaluation and plan formulation tool that helps to answer the question "Which proposed flood damage reduction plan is the best from an economic standpoint?" HEC-FDA provides the capabilities to evaluate the with and without project alternatives and compares the alternatives using expected damage and damage reduction benefits. HEC-FDA also develops project performance metrics for comparison of alternatives and levee certification incorporating risk analysis capabilities.

CEIWR-HEC documented these capabilities by conducting a study using HEC-FDA to apply risk analysis methodologies to levees of the Sacramento River Flood Control Project (SRFCP). The study (CEIWR-HEC, 2009) identified potential system-wide hydraulic impacts from alteration and modification to the levees. The SRFCP is a large system that includes regulated and unregulated inflows, watercourses, bypasses, hydraulic structures, and tidal influences. The evaluation of the hydraulic impacts resulting from modifications to the SRFCP system required a comprehensive approach that considered all relevant interactions of system elements. This study provided the steps necessary to conduct a comprehensive, system-wide study using the HEC-FDA tool. The project report documented the tools, data, and the risk analysis process used for conducting a system-wide risk analysis study. However, the report also discussed the limitations of the method.

The main limitation for HEC-FDA is that it still looks at a system of projects as a number of independent projects. This issue and others raised by the National Research Council, current users of HEC-FDA and CEIWR-HEC clearly showed that USACE needed a tool that included explicit systems analysis capabilities. In addition, to take advantage of life cycle capabilities, a significant overhaul of the flood risk analysis strategy had to occur.

3. HEC-WAT

To address these needs, CEIWR-HEC developed the Watershed Analysis Tool (HEC-WAT). HEC-WAT is an interface that streamlines and integrates a water resources study using software commonly applied by multi-disciplinary teams that comprise a typical PDT. Many pieces within the CEIWR-HEC suite of software are implemented within HEC-WAT thus allowing a study team to perform many of the necessary hydrologic, hydraulic, and planning analyses from a single interface.

HEC-WAT also allows the PDT to perform an alternative analysis in an intuitive and collaborative manner. This ease of use provided by the HEC-WAT framework improves a study team's ability to facilitate, convene, advise, and work collaboratively. HEC-WAT strives to involve modelers early in the study process, which encourages a collaborative team approach.

HEC-WAT is not replacing existing software but rather the framework allows unique pieces of software to work together. The integration of the individual pieces of software within the HEC-WAT framework is achieved through the concept of a "plug-in". The plug-in is what allows the individual pieces of software to integrate without requiring special code in HEC-WAT to support the individual pieces of software (Figure 1). There are numerous ways to implement plug-ins; therefore, the plug-in concept should allow a plug-in to be developed for any software that might be included in the HEC-WAT framework. With the plug-ins, HEC-WAT provides the analysis framework, but does not know anything about the individual pieces of software. The individual pieces of software provide the editors, reports, computational analyses, etc. and are not intended to contain HEC-WAT specific code. HEC-WAT provides a framework to coordinate the study, while the individual pieces of software provide the analytical computations. As the HEC-WAT matures, additional pieces of software outside of the HEC family can be incorporated.

The major pieces of software currently implemented are shown in Figure 1.

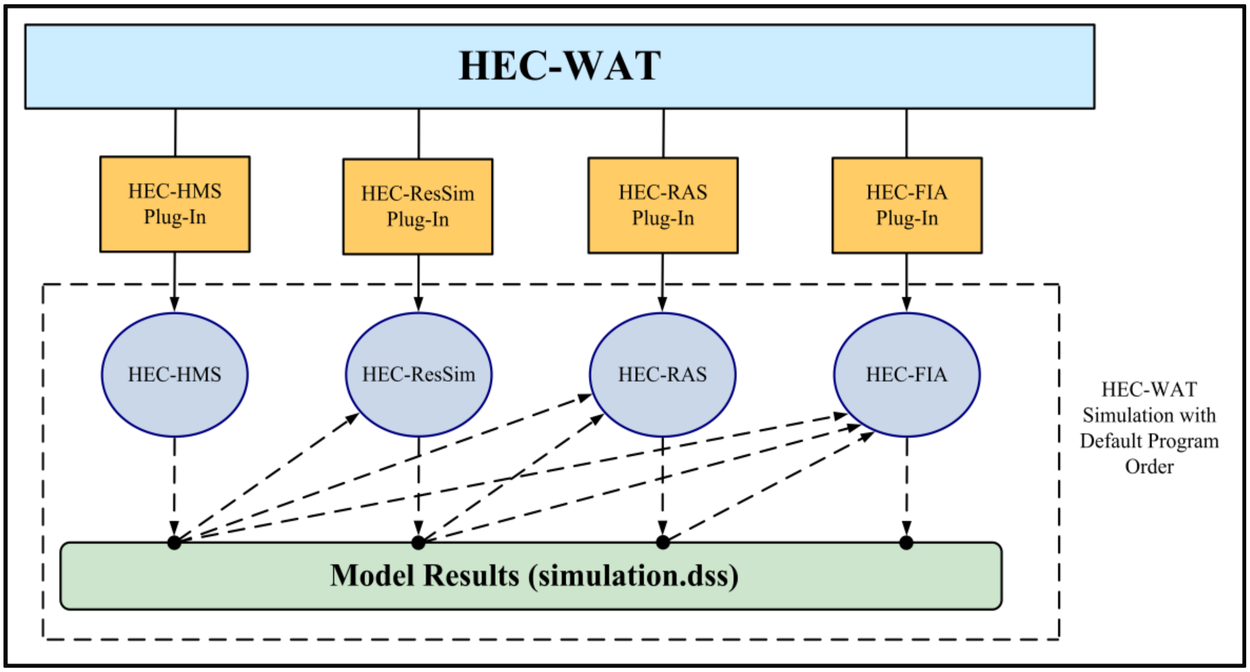

Figure 1: HEC-WAT Framework

- HEC-HMS is a standalone application designed to simulate the precipitation-runoff process of a watershed system. In the HEC-WAT sequence, HEC-HMS is a hydrologic rainfall-runoff model that provides flow data into and downstream of reservoirs.
- HEC-ResSim is a standalone application that is used to model reservoir operations at one or more reservoirs whose rule-based operations are defined by a variety of operational goals and constraints. The software simulates reservoir operations for flood management, low flow augmentation and water supply for planning studies, detailed reservoir regulation plan investigations, and real-time decision support. In the HEC-WAT sequence, HEC-ResSim provides peak flow/stages, flow hydrographs, or stage hydrographs to the hydraulics model.
- HEC-RAS is a standalone application that allows the user to perform one-dimensional steady flow, unsteady flow, sediment transport/mobile bed computations, and water temperature modeling. HEC-RAS and thus HEC-WAT will soon include two-dimensional capabilities as well. The HEC-RAS Mapper tool available from the HEC-RAS interface calculates inundation boundary and water depth maps. HEC-RAS computes the river stages, water surface profiles, and levee breach information that is used to compute consequences in the HEC-WAT sequence.
- HEC-FIA is a standalone application that evaluates consequences using either observed or forecasted hydrographs (hydrograph-based) or depth grids (GIS-based). For a specified analysis, the software evaluates urban and agricultural flood damage, area inundated, number of structures inundated, and consequences. The consequences shall include economic and loss-of-life. HEC-FIA also provides information on actions for flood managers to take.

The HEC-WAT tool allows USACE and its partners and stakeholders to conduct their studies in a coordinated fashion. Coordination begins as each model uses the common schematic that is built within the HEC-WAT interface. The common schematic demands that each team use the same nomenclature for each of their models and alternatives. A schematic (Figure 2), is usually built from background layers such as shapefiles and DEM's to visually represent the watershed and to provide a spatially correct representation of the watershed. The individual models can be built and edited in or outside the HEC-WAT and model results are viewed by selecting the elements found on the schematic. Once the models are in HEC-WAT, the models can be run in sequence. The storage of data is organized by DSS (CEIWR-

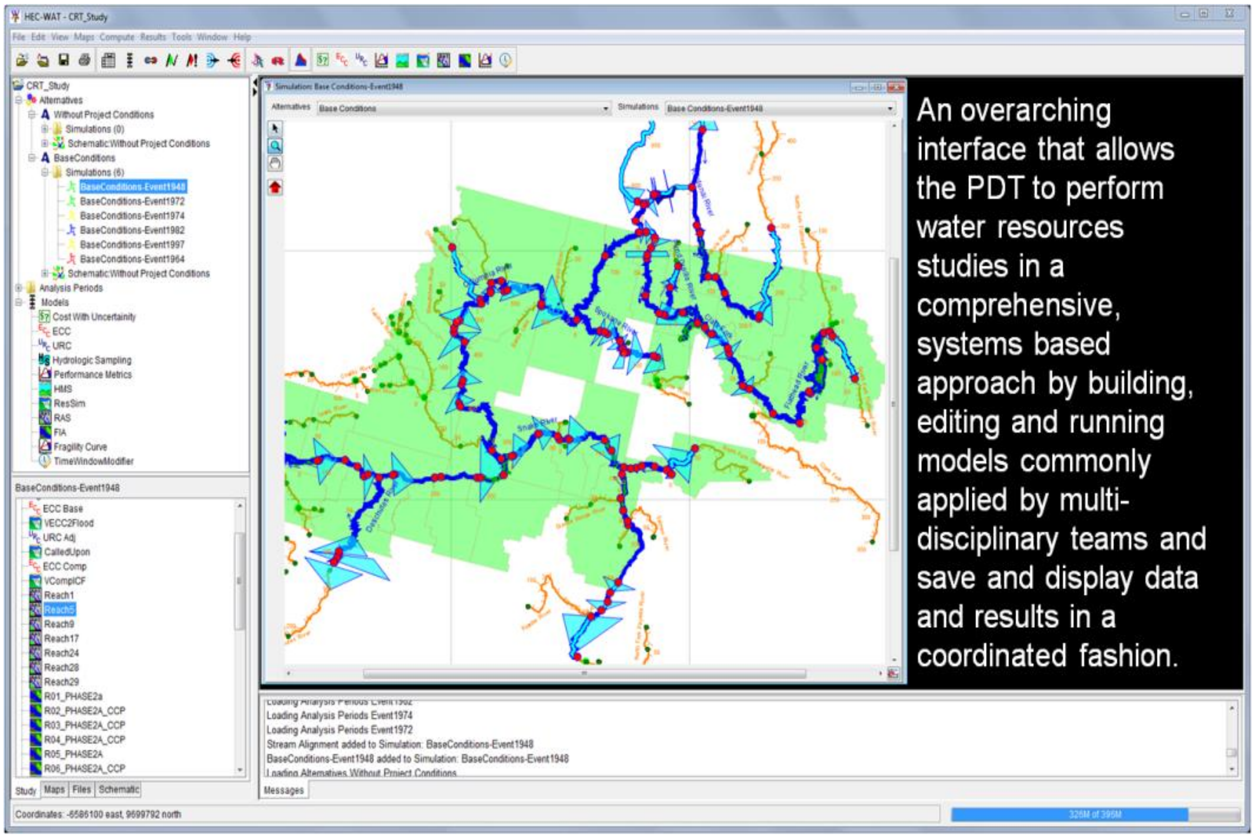

Figure 2: HEC-WAT Schematic - Columbia River System

HEC's Data Storage System) and a simple DSS linking device is used to connect the models. The models themselves, the input data, and the results are all stored in the HEC-WAT's directory structure. Therefore, all data and files used to make decisions are easily retrieved. Alternative analyses can be performed, and output from multiple alternatives can be viewed at the same time making alternative analyses and selection easier.

The basic building block of a schematic is the stream alignment. The stream alignment is a representation of the streams as they travel through the watershed. Because all models will share the naming convention and geo-referencing data, the stream alignment will generate a consistency between models and study alternatives.

The next important schematic element is the common computation point (CCP), which is a location where a model transfers data to other model. CCP's could also be locations where results are needed for model development or alternative analysis. The CCP's will be consistent for all models and should be placed on the schematic based on knowledge of possible study alternatives. Other elements that need to be defined in the shared schematic are flood damage reduction and/or ecosystem restoration measures. All objects within the schematic, the watershed area, stream alignment, CCP's and flood damage reduction or ecosystem restoration measures can be used across multiple alternatives.

The shared schematic and models that use the schematic are defined as an alternative. With the addition of events and time periods to be used by all the models, simulations are created which facilitate system analysis. From the HEC-WAT interface the user can edit a model and then run one model at a time or re-run the entire simulation. For example, once the models are built, the modeling team may want to see if a different infiltration rate would lead to higher flows and thus increased damage.

Using consistent schematics, data, and tools, alternative results will be easier to compare making the trade-off analysis and selection easier as well. Both ecosystem restoration and flood risk management alternatives will eventually be created directly within HEC-WAT. To view any hydrologic element (computation points, reservoirs, river reaches, impact areas, storage areas etc.), the element can be selected on the schematic and a list of tabular or graphical output will be available. The user could be oblivious to which model actually produced the results.

4. HEC-WAT, FLOOD RISK ANALYSIS OPTION

For over two decades, USACE has required all Corps planning processes use risk analysis and life-cycle approaches. However, as previously discussed, there are few tools to support these requirements. Therefore, CEIWR-HEC created a compute option within HEC-WAT called Flood Risk Analysis (FRA) that helps to analyze complex riverine systems while addressing the flood risk management, system and life-cycle requirements (Figure 3).

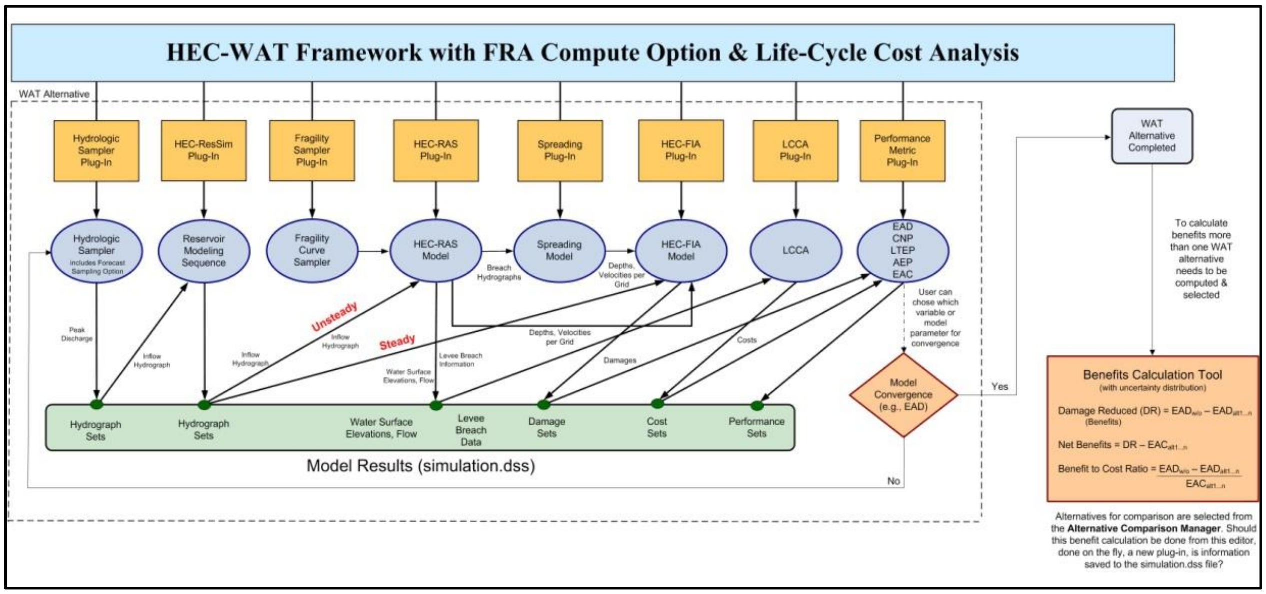

Figure 3: HEC-WAT Framework with FRA Compute Option

The FRA option includes sampling and solution techniques, uncertainty definitions, and system-wide component fragility and performance interactions/relationships for these complex riverine systems. The capabilities evolved from previous efforts and are detailed in the software design document (USACE, 2008). HEC-WAT can be used nationwide for levee certification, levee assessment, planning and design studies and advance the Corps modeling approach for risk and life-cycle analysis.

The FRA computational methodology starts with the definition of a project alternative and a single scenario of the project life cycle (e.g., fifty years) being simulated by sampling the flood events over the duration of the life cycle. The system performance, that is, how the levees perform during an event, and flood characteristics will determine when and if breaches occur. If breaches do occur, the impacts will be calculated based on flood inundation and related consequences. The consequences shall include economic, environmental and loss-of-life. Life cycle modeling will include the deterioration of projects over time, rehabilitation, repair and flood recovery when necessary. Using the life cycle approach accounts for situations when damage is substantial and the characteristics of the consequence area are altered prior to the next flood event, thus not double accounting for flood losses.

The FRA option performs a Monte Carlo analysis, during which sampling of not only flood events but uncertainties about hydrologic, hydraulic, reservoir operations, geo-technical and economic parameters occur. When an FRA compute is initiated, the model alternatives for that particular run are executed repeatedly for sampled flood events and model parameter estimates until convergence about the parameters and/or the EAD (Expected Annual Damage) is achieved. Computational methodologies had to be created, since the FRA compute will be quite intensive. For large studies, distributed computing and use of multiple processors may be required. The following paragraphs describe a few of the new methodologies that have been implemented within the FRA compute option.

Hydrologic Sampling is the first step in the FRA compute. It samples the hydrology to create thousands of years of annual flood flows. The realizations of the hydrologic record will be divided into fifty-year life-cycles. With FRA performing an event-based analysis, the hydrology information is needed as a time series of flow to be used by other models in HEC-WAT to then be routed through the system under study.

To capture the likelihood of levee failure, fragility curves will be sampled at each project location for each event. In a systems context with multiple failure modes/locations, sampling of those fragility curves, including uncertainty, is required for each realization of an FRA simulation. If the computed water surface elevation meets or exceeds the stage sampled from the fragility curve, the levee is assumed to fail and water spills into the interior area. After a large number of simulations, this would result in the evaluation of the full range of failure possibilities over the entire system. This sampling and failure routine would define the system load distributions as well as inundation delineations in the consequence areas of interest.

In order to evaluate and compare alternative flood risk measures, including levees, USACE utilizes several economic and performance metrics. These metrics are used to assist in communicating risk as required in Corps guidance (USACE, 2006). These include EAD, Annual Exceedance Probability (AEP), Conditional Non-exceedance Probability (CNP) and Long Term Risk. HEC-WAT with the FRA compute option computes each of these metrics.

EAD is the mean or average of all possible values of damage. In FRA, computing EAD and the distribution of the EAD starts by sampling the flow frequency curve and then ultimately compiling damage for 500-year realizations. As EAD is computed for each 500 year period, these 500-year estimates of EAD will be stored as a population of EAD estimates. Once the final mean EAD is computed, then the population of EAD estimates can be used to define a distribution of EAD.

AEP is the probability of getting wet at a given location (i.e., consequence area location, grid cell, threshold stage location, or a fragility curve location) in any given year considering the full range of possible floods and project performance. During a Monte Carlo simulation, the AEP is estimated based on how many times an area was recorded as being wet or a stage exceeded versus the total number of events. Like the EAD estimates, an estimate of AEP will be generated for each realization, and a resulting sample of AEP estimates will provide the AEP distribution.

CNP or "assurance" is the probability that a project will be able to contain a flood of specified frequency. For example, USACE requires that, for a levee system to be found in accordance with National Flood Insurance Program (NFIP) levee system evaluation requirements, it must have at least a ninety percent chance of containing the 1% annual chance exceedance flood. In an FRA compute, assurance will be computed at predefined locations within the system, generally defined by the location of system components and their associated fragility functions.

Long-Term Risk is the probability that a target stage or system component will be exceeded at least once during the course of a specified term (e.g., thirty years, the typical life of a home mortgage).

5. DISTRIBUTED COMPUTING

The use of distributed computing greatly decreases the compute time of an FRA compute; especially for the evaluation of large, sophisticated projects like the CRT. The long compute times are a logical outcome of satisfying the USACE requirements of using watershed and systems approaches for planning projects while also employing risk assessment and life-cycle concepts. To explicitly address a systems approach within a large watershed, all components of the watershed must be somewhat interrelated so upstream actions are reflected in downstream impacts as well. For example, if a levee breached upstream, the volume of water lost due to the upstream breach must be represented as the flood travels downstream. Therefore, one model must inform the next. In large watersheds with numerous models approximating numerous physical processes, the overall simulation for only one event can take hours on a single computer. Now, due to USACE analysis requirements, there is a need to run tens of thousands of events. To run this simulation on one machine, the entire simulation would take tens of thousands of hours. It is impractical to wait that long for a single compute. Therefore, distributed computing was implemented. Distributed computing greatly reduced the time it took to perform a single simulation for one CRT alternative from months to a few hours. The distributed computing option is flexible; it can be performed from a single computer with multiple virtual machines, a Local Area Network of several computers, or on a cloud service.

6. APPLICATION FOR THE COLUMBIA RIVER TREATY 2014/2024

The Northwestern Division (CENWD) of USACE, along with several stakeholders needed to perform a series of hydraulic and hydrologic technical studies to collect critical information to support a pending decision by the United States pertaining to the future of the Columbia River Treaty with Canada. A requirement of the review was to develop a comprehensive, systems evaluation approach for the Columbia River Basin and to evaluate the current and future flood risk within the Basin (Figure 4) which included hydropower operations. Because of these requirements the CENWD PDT determined that the HEC-WAT/FRA was the tool needed to evaluate treaty alternatives using EAD and other criteria.

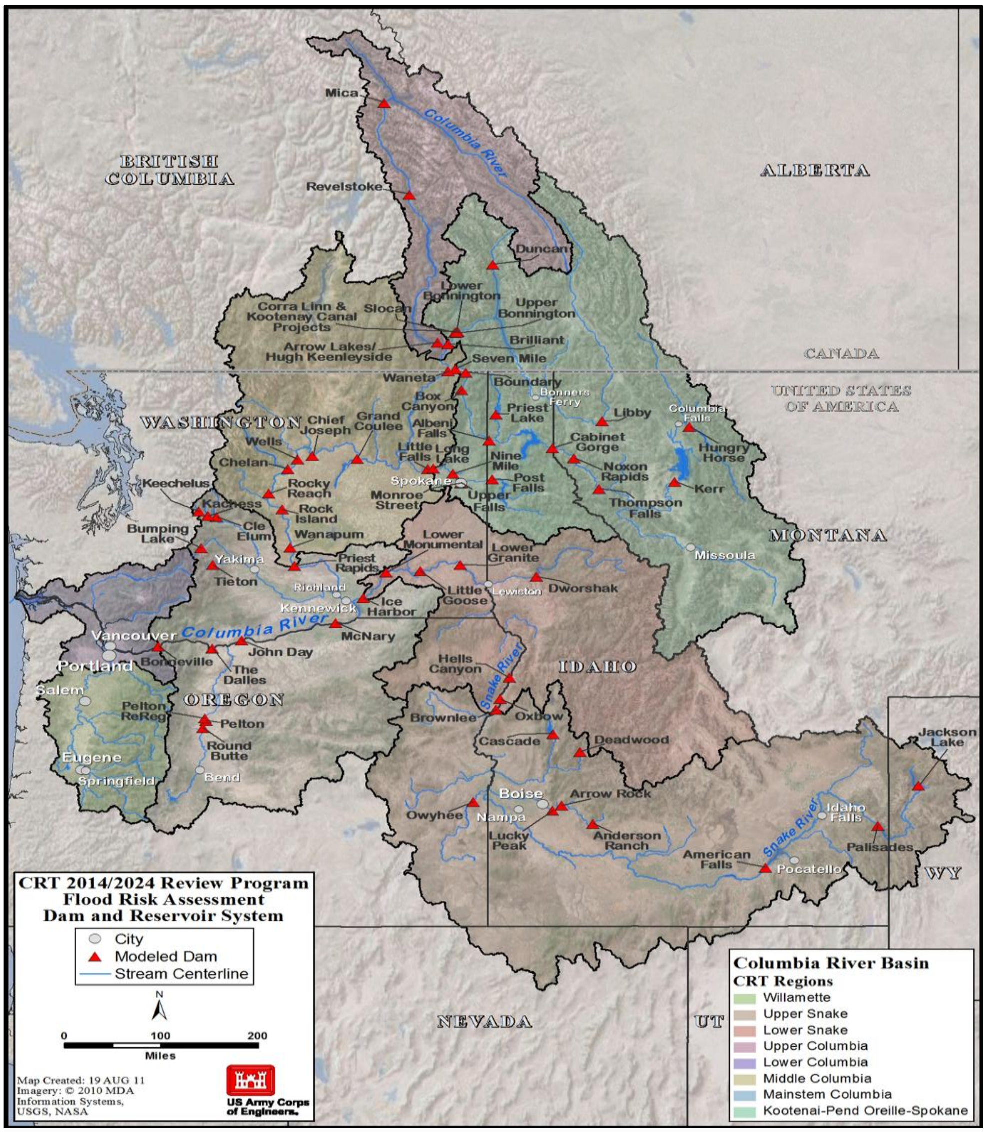

Figure 4: Columbia River Basin

Models implemented within HEC-WAT were developed by the CRT PDT to help understand the level of flood risk from the current operation of the system and to evaluate the flood risk from alternative reservoir operation scenarios (both in Canada and the United States). Sixty-five reservoirs were modeled using multiple pieces of software. These models also included CENWD local software (URC (Upper Rule Curves) and ECC (Variable Energy Content Curves)). The HEC-ResSim software was used to create a model for hydropower operations and constraints and a model for flood control.

Twenty-six hydraulic models were developed using the HEC-RAS software. The eight unsteady models were included directly in the FRA compute sequence. The other eighteen steady flow models were used to develop flow-stage relationships that were provided to the reservoir software. For consequence modeling, the HEC-FIA software was used for the twenty-six identified areas. This included a structure inventory of over 185,000 structures.

Seventy years of hydrologic data (flows and forecasts) were collected and assembled including sixteen synthetic floods that were also generated. Fragility curve information for the levee systems within the basin were also collected and entered into the hydraulic models.

Deterministic runs of the HEC-WAT CRT watershed were performed to create a baseline for verification of the FRA compute results. The deterministic runs included the reservoir modeling only and then runs that included all the models. The FRA computes started with 5,000 event simulations of the reservoir modeling only (average 1.75 days for one simulation using eleven computers); there was about seventy of these simulations run. The next FRA compute for the reservoir modeling was a 50,000 event run for an alternative (simulation took about fourteen days using thirty computers).

Once the reservoir modeling results were verified by the CRT PDT, the FRA computes were conducted on the full sequence of models. FRA computes of 5,000 events were performed for several alternatives, each averaging about 14 days using ten computers. For the 50,000 event FRA computes, the average execution took 14 days but using 100 computers through cloud computing. For these, the execution time was an average of about twenty-five minutes per event with distributed computing and other time reducing capabilities (e.g., narrowing of time windows for specific models, skipping of models based on certain thresholds, improvements to various applications being used in the computing sequence) being employed. At the beginning of the process, computes were averaging about ninety minutes per event.

By the end of the CRT Study, the U.S. Entity had sufficient information from the HEC-WAT/FRA study results and from other sources to write a position paper on the future of the CRT after 2024. They recommended the Treaty be modernized to reflect the current and future needs of the Columbia Basin. This decision may not have been as defensible without the development and implementation of HEC-WAT/FRA.

7. CONCLUSION

To help study and manage the nation's water resources in a holistic and comprehensive approach while implementing system and risk concepts, USACE developed and has now implemented HEC-WAT. The application of the Columbia River Treaty 2014/2024 shows the HEC-WAT with the FRA compute option is a tool that meets the USACE requirements. Developing software collaboratively with the CRT PDT accelerated the development of HEC-WAT with the FRA compute option; built significant relationships within the PDT; and brought a high visibility to the development effort and the HEC-WAT software itself. The building of innovate features such as the plug-in capability and the distributed computing will be used by other projects with our software as well.

Performing a study concurrent to software development has its pros and cons. Because CRT was a highly visible project with tight deadlines there was a lot of pressure to provide results with software that was still being built. However, being involved with the CRT study allowed for thorough testing of the HEC-WAT interface which proved beneficial and made the software more stable. Also, having a study allowed us to verify that the algorithms within HEC-WAT/FRA were working correctly. These steps are valuable in that they will contribute to the certification process and customer acceptance of the software.

Technical challenges that still need to be overcome include how to incorporate life cycle modeling that addresses rehabilitation, repair and flood recovery; consequence evaluation; uncertainty analysis trade-offs between detailed modeling and important sources of uncertainty; risk communication; modeling multiple failure modes; planning transformation; and the future of planning analysis in USACE.

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