MODELING EXTREME FLOOD HYDROLOGY FOR GRAND COULEE DAM

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Abstract: The Bureau of Reclamation is conducting a Hydrologic Hazard Analysis (HHA) for Grand Coulee Dam to develop probabilistic flood frequency estimates for use in a dam safety risk analysis. The major challenges of this study include: 1) developing methodology capable of modeling hydrology for a 74,100 square mile international drainage basin, of which approximately 39,500 square miles are situated in the province of British Columbia, Canada, and 2) modeling a basin that is regulated by 76 major dams located within the Columbia River Basin (CRB) that are owned and operated by a mix of the U.S. federal, state, provincial, or local government, public utilities, and private entities. Following an extensive literature review and investigation into previous and current studies in the CRB, Reclamation is using a multiple methods approach, leveraging the modeling and data analysis completed by other agencies and universities for operations planning, climate change impacts assessments, and the Columbia River Treaty review. Two methods will be used to characterize hydrologic hazards at Grand Coulee Dam: the Expected Moments Algorithm (EMA) with streamflow and paleoflood data to estimate peak-flow statistics; and applying the Variable Infiltration Capacity (VIC) rainfall-runoff model and one-dimensional hydraulic models to develop flood peak and volume hazard curves. The two methods are used in order to: (1) ensure consistency between the rainfall-runoff model and streamflow data (including historical data and paleofloods); (2) provide data and models to estimate and extrapolate hydrologic hazard curves to annual exceedance probabilities (AEPs) of interest; and (3) include uncertainty estimates for the hydrologic hazard curves. The VIC hydrologic output will be used as input to the U.S. Army Corps of Engineers' (USACE) Hydrologic Engineering Center's Watershed Assessment Tool (HEC-WAT).

INTRODUCTION

The Bureau of Reclamation is conducting a Hydrologic Hazard Analysis (HHA) for Grand Coulee Dam to develop probabilistic flood frequency estimates for use in a dam safety risk analysis. Reclamation uses the most updated data and technology, as available and appropriate, to estimate hydrologic risk at dams. When dam loading estimates do not reflect the current information and technology available at one of its facilities, whether it is hydrologic, seismic, or static loading, it is common practice to perform an Issue Evaluation (IE) study to update the loading parameters. The hydrologic loadings for Grand Coulee Dam are being updated to Reclamation's current standard of practice.

The major challenges of this study include: 1) developing methodology capable of modeling hydrology for a 74,100 mi^2 international drainage basin, of which approximately 39,500 mi^2 are situated in the province of British Columbia, Canada, and 2) modeling a basin that is regulated by 76 major dams located within the Columbia River Basin (CRB) that are owned and operated by a mix of the U.S. federal, state, provincial, or local government, public utilities, and private entities. Most of the dams located within the CRB will not play a direct role in estimating hydrology for Grand Coulee Dam; however they will play an important role in estimating how the CRB will be operated as a system. Figure 1 shows the dams that were modeled in the USACE's Columbia River Treaty (CRT) review including Grand Coulee Dam. The project will rely on maximizing the use of previous and current flood studies for Grand Coulee Dam and the CRB.

Grand Coulee Dam is a concrete gravity structure located on the Columbia River in north-central Washington State, located approximately 75 miles west-northwest from Spokane, Washington. The towns of Grand Coulee and Coulee Dam are located immediately upstream and downstream, respectively, of the dam. The drainage basin is composed of mountainous terrain as well as large expanses of high desert plains in eastern Washington, eastern Oregon, and western Idaho. Elevations range from approximately 1,300 feet at the dam crest to over 13,000 feet in the mountains throughout the drainage basin. The CRB has large variations in mean annual precipitation. West of the Cascade Mountains, many regions receive over 30 inches of precipitation annually, while east of the Cascades precipitation is less than 20 inches, with some areas receiving as little as 7 inches (Climate Impacts Group, 2014). Annual precipitation in the Cascade Mountains can be as much as 100 inches. By several accounts, more than 70% of streamflow in the region originates as mountain snowpack (Hamlet et al. 2005; Elsner et al. 2010). Most of the drainage basin accumulates a snowpack throughout the winter followed by rainy periods in the spring and early summer. The high flow period for the Columbia River is driven by snowmelt during the spring and early summer from warming temperatures and rain.

There are two important large scale studies conducted in the CRB that will provide much of the data, modeling and methodology to conduct this study. The USACE has made a large effort to review the river operations, hydraulics, and hydrology involved in updating the 2014/2024 revision to the Columbia River Treaty between the U.S. and Canada (USACE, 2012). This effort has involved developing a detailed model of the Columbia River System, called the Watershed Assessment Tool (WAT), which includes updated terrain and bathymetry, river operations, routing scenarios, climate change, and potential updates to the Columbia River Treaty. The model is capable of estimating daily and flood control operations for the Columbia River system. The model is also capable of computing Monte Carlos simulations of river routings incorporating multiple forecast, operations and hydrology scenarios.

The northwest report of the Third U.S. National Climate Assessment (Snover et al., 2014) assesses the state of climate change in the northwest United States, including the CRB. This report primarily draws from recent studies, including the Washington State Climate Change Impacts Assessment (2009) and the Oregon Climate Assessment Report (2010). The report represents the key climate change issues in the growing body of regional research. The Washington State Climate Change Impacts Assessment (Miles et al. 2010) used climate projections from the Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment

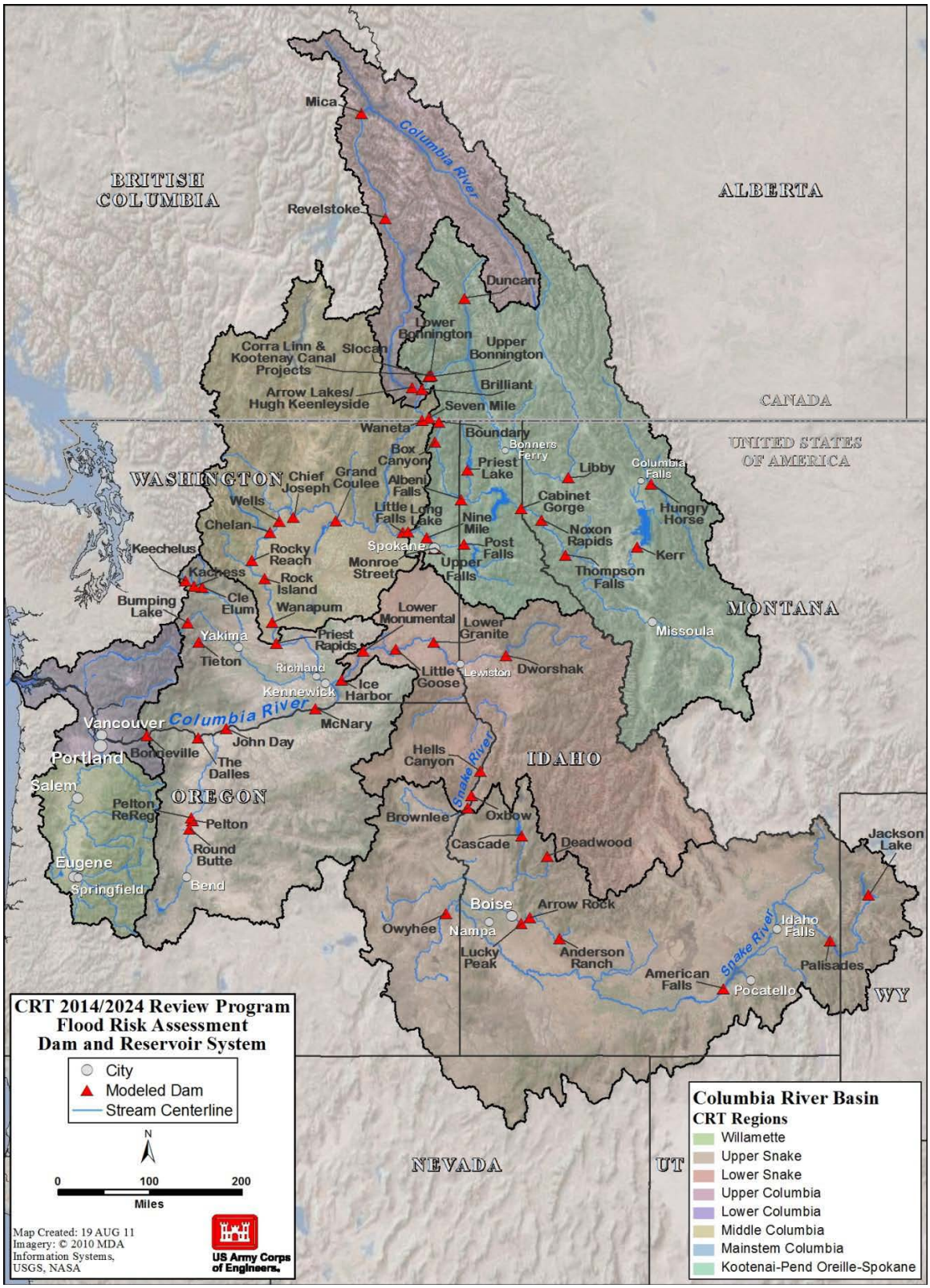

Figure 1 Image illustrating the dams that were modeled as part of the USACE CRT 2014/2024 Review Program, including Grand Coulee Dam (USACE, 2012).

Report (IPCC, 2007). Building on the modeling developed as part of the Washington State Climate Change Impacts Assessment, the Columbia Basin Climate Change Scenarios Project culminated in a comprehensive database of climate and hydrologic scenarios to support climate change analysis and adaptation planning. The intent of work is to provide a range of data for a variety of end users, including planning officials and research scientists. Some advances from this effort include hydrologic model calibration and development of additional climate change scenarios.

HYDROLOGIC HAZARD ANALYSIS

Reclamation uses a multiple methods approach to estimate hydrologic hazard for higher-level dam safety studies, including Issue Evaluations (IE) and Corrective Action Studies (CAS) at specific facilities (Reclamation, 2013). Multiple methods will be used to estimate the hydrologic hazard at Grand Coulee Dam. The approach uses two methods: 1) Expected Moments Algorithm (EMA) streamflow statistics and paleoflood data, and 2) rainfall statistics along with rainfall runoff and hydraulic modeling. The two methods are used in order to: (1) ensure consistency between the rainfall-runoff model and streamflow data (including historical data and paleofloods); (2) provide the data and models to estimate and extrapolate hydrologic hazard curves to AEPs of interest (Swain et al., 2006); and (3) include uncertainty estimates for the hydrologic hazard curves. Both methods will leverage and attempt to incorporate much of the past and ongoing work completed by Reclamation, University of Washington (UW), USACE, and Bonneville Power Administration (BPA).

Streamflow Statistics: EMA (Cohn et al., 1997) is a moments-based parameter estimation procedure that was designed to incorporate many different types of systematic, historical, and paleoflood data into flood frequency analysis. EMA assumes the LP-III distribution best represents the distribution for annual floods. EMA develops approximate confidence intervals using normal theory with and without an adjustment to correct for the correlation between the quantile estimate and its estimated standard deviation (Cohn et al., 2001). EMA has been documented in several journal articles (Cohn et al., 1997; England et al., 2003a; England et al., 2003b; Cohn et al., 2001) and provides a suitable flood frequency model. EMA has been applied by Reclamation at many sites for peak-flow frequency (England et al., 2003b; Swain et al., 2006; England, 2012).

Streamflow statistics will be calculated using EMA and will leverage the hydrology work completed by the USACE for the Columbia River Treaty Review (USACE, 2012). The EMA analysis will use the 2010 no regulation no irrigation (NRNI) dataset (BPA, 2014), synthetic floods developed by the USACE, and paleoflood data. The 2010 NRNI dataset (BPA, USACE, Reclamation) has a period of record (POR) daily from 1929-2008.

The EMA analysis will directly incorporate paleoflood and historic flood estimates into the LPIII analysis. The 1894 flood is the flood of record at most locations along the Columbia River and will be an important parameter in the study. Synthetic floods developed by the USACE may also be used in the EMA analysis or may be used to develop additional synthetic floods specific to flooding at Grand Coulee Dam.

The results of the EMA analysis are flood peak discharges, however the shape and volume of the hydrograph are needed. Flood hydrographs will be developed using several different methods and will then be scaled according to flood peak discharge to represent similar flood patterns. The USACE has developed balanced hydrographs from past large floods. Hydrographs have been developed in the past for historic large floods, such as the 1894 and 1948 floods. These hydrographs may be scaled according to flood peak discharge to represent similar flood patterns. Calibrated rainfall runoff and hydraulic models are part of this hydrologic hazard project and may be used to develop flood hydrographs representative of the runoff patterns for the drainage basin. For a hydrograph scaling approach it may be most appropriate to use a suite of hydrographs that represent historic floods and scale the hydrographs according to peak discharge. Representative hydrographs have been developed for historic large floods on the Columbia River.

Paleoflood Data: Paleoflood information will be used in this study to help extrapolate estimates of the flood frequency beyond the historical record. Paleofloods are past or ancient floods that were not observed by traditional means, but are often preserved in the sedimentary record (Figure 2). Most conventional estimates for the frequency of large floods are based on extrapolations from stream gaging records, and commonly utilize record lengths shorter than 100 years. Paleoflood hydrology ties together estimates associated to peak discharge and age developed from geomorphic and geologic evidence.

The Columbia River, as one of the largest river systems in the U.S. and one famously known as the avenue for the glacial Lake Missoula outburst floods, will require a substantial field effort to develop paleoflood data for this study. Four general locations have currently been proposed as sites to collect paleoflood information: two from the major tributaries that flow into Lake Roosevelt (the mainstem Columbia River and the Spokane River), one at a location downstream of Grand Coulee Dam on the mainstem Columbia River, and the last at a location near The Dalles, OR. The site at The Dalles, OR is intended to serve as a location where paleoflood data

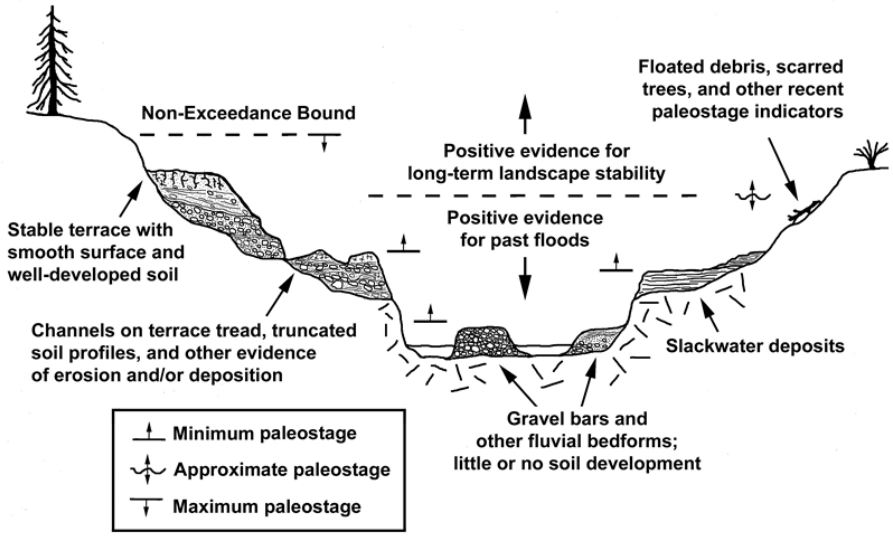

Figure 2 Idealized channel cross-section illustrating the concept of a non-exceedence bound and the fluvial landforms and related deposits associated with paleofloods.

can be developed downstream of the confluence with other major tributaries to the Columbia (i.e., the Yakima and Snake Rivers). The four sites outlined for the study are intended to collect data at key points within the basin that were considered vital and to keep overall study costs downs. A broader range of locations along the mainstem Columbia River upstream of Lake Roosevelt and an additional site on the Clarks Fork may be needed to reconcile the contributions to the reservoir.

Rainfall Statistics and Rainfall Runoff Modeling: The rainfall statistics and runoff modeling approach will use a combination of custom meteorological inputs, stochastic rainfall runoff modeling, hydraulic modeling, and paleoflood data to estimate a range of floods (peaks and volumes) with annual exceedance probabilities (AEPs) from 10^{-3} to 10^{-6}, or as needed for Reclamation dam safety risk-based decision-making. The general concepts that are proposed focus on leveraging the existing Variable Infiltration Capacity (VIC) rainfall-runoff model and the USACE Hydrologic Engineering Center's Watershed Assessment Tool (HEC-WAT) hydraulic model, and their ongoing applications within the Columbia River basin.

Extreme storm rainfall and snowpack data sets will be developed by Reclamation while leveraging the existing work. The custom meteorological inputs will be used as forcings in the VIC Model developed for the Columbia Basin Climate Change Scenarios Project. The VIC model and associated input datasets were developed at 1/16th degree latitude/longitude spatial resolution over the CRB as part of climate change studies. The VIC hydrologic output will be used as input to the HEC-WAT model. The Columbia River HEC-WAT model was developed by the USACE for the CRT Review and is capable of routing flows through the extensively regulated CRB to develop frequency flow estimates for Grand Coulee Dam. This approach will allow for the development of hydrologic hazard estimates at Grand Coulee Dam, and quantify associated uncertainties.

Meteorology: A major effort of this work is to develop custom extreme storm rainfall and snowpack data sets for use as meteorological forcings in the VIC rainfall-runoff model. Some key meteorological assumptions for this study are as follows.

1) Grand Coulee Dam is a major flood control dam with approximately 5.185 million acre-feet (MAF) of dedicated flood storage on the Columbia River system (USACE, 1991), that is operated on a very strong seasonal cycle (USACE, 1997; USACE, 1999; USACE, 2003; USACE, 2012). Meteorological inputs will primarily focus on the late spring and early summer April-May-June (AMJ) season in order to maximize potential CRB inflow volumes.
2) Combined flood control storage within the CRB upstream of Grand Coulee Dam is approximately 33.8 MAF (USACE, 1991; USACE, 2003), including storage at Mica, Arrow, Duncan, Libby, Hungry Horse, and Grand Coulee. In order to examine the potential effects of extreme floods on dam safety at Grand Coulee Dam, estimated extreme storm rainfalls in combination with snowmelt runoff are needed.
3) Snowpack depths and snowmelt runoff potential, in combination with extreme rainfall, are also key meteorological considerations, given the CRB flood storage. The application of season-specific or synoptic mechanism-specific frequency and extreme storm analyses may be investigated to confirm these assumptions are valid.

Meteorology will be developed by leveraging existing data and analyses that use historical and reanalysis data sets, as well as gathering and analyzing new data. It is anticipated that the analysis of 20 individual storm events, including spatial and temporal precipitation distributions, moisture fluxes, storm centering and orientation, will be performed. The main data sets initially include the following:

- the 1/16th degree precipitation and temperature gridded data (1915-2006) from Deems and Hamlet (2010) with consideration of recent updates (Livneh et al., 2013);
- observed point precipitation and temperature from the Global Daily Climatology Network (GDCN) and Global Historical Climatology Network (GHCN)
- daily precipitation, temperature, and related variables from the NRCS SNOTEL network;
- Climate Forecast System Reanalysis (CFSR) data (Saha et al., 2010);
- trajectory analyses and relevant meteorological fields from recent work by Alexander et al. (2013); and
- model runs of individual storms, historical events and ensembles over the CRB using the Weather Research and Forecasting (WRF) regional climate model by University of Washington and U.S. Army Corps of Engineers.

Specific precipitation and temperature perturbations and storm sequencing scenarios will be developed from these data sets. Climate change inputs and hybrid delta scenarios used in the CRB climate change studies commissioned by the State of Washington under House Bill 2860 (Hamlet et al., 2010) will also be considered. Meteorological scenarios may be added to investigate the potential influence of climate change.

Seasonality of extreme storm events will initially focus on analysis of April, May, June (AMJ) rainfall and snowmelt runoff sequences for specific flood years (Table 1). To date, detailed hydrometeorological analyses of the events listed in Table 1, including spatial and temporal patterns, depth-area-duration data, inflow moisture and associated analyses have not been completed. The initial data analysis of the extreme storm season may also be expanded to include warm-season events in summer (July-August) and fall (September-October) after investigation of storm hydrometeorology and snowmelt volume within this large region.

Table 1 Major spring storms in the CRB used for flood risk assessment (USACE, 2012)

Water Year	**Flood Dates**	**Comments**	**Key References**
1894	May 20 - June 15	May rain-on-snow; used as design event for the CRB system-wide flood control (USACE, 1991)	USGS (1949); USACE (1991); USACE (2009)
1948	May 19-23; May 26-29	May rain-on-snow; rainfall	USGS (1949); USACE (1991); USACE (2009)
1956	May 20 – June 6	predominately snowmelt	USACE (2012)
1971	May 31 (peak)	rain may have been predominant	USACE (2012)
1972	May 31 – June 14	snowmelt with some rain	USACE (2012)
1974	May and June	snowmelt	USACE (2012)
1997	May and June	snowmelt with some rain	USACE (2012)

The areal coverage of large precipitation events will be a main driver of extreme flooding. One objective is to develop storm centerings that are capable of producing extreme floods for the project area. The location of the storm centering will drive the possible areal extent of the storm as orographic effects from the Coastal and Cascade Mountains, as well as the aridity of eastern Washington and western Idaho will help to define the possible sizes and locations of storms.

Regional precipitation frequency analysis using L-Moments (Hosking and Wallis, 1997) will be used to estimate extreme storm rainfall point (10 mi^2) probabilities. The storm rainfall inputs will be developed for annual exceedance probabilities (AEPs) ranging from about 10^{-2} to 10^{-6}. Analyses will be done for several (two to three) regions to represent extreme storm rainfall sequences over various combinations of the CRB. The approach that will be developed for this study focuses on partial-area storm rainfall, and existing techniques that are adequate for smaller basins that will need to be modified because of the large CRB watershed.

One critical factor of this study is to couple the storm rainfall sequences in combination with snowmelt runoff. The largest runoff events (to date) have occurred in May and June (Table 1) and are extreme rainfalls in combination with a large snowpack. Spatial coverage of snowpack and snowpack depths are critical components. Scenarios using seasonal snowpack, temperatures, and melt sequences of individual events, such as the record May-June 1948 sequence, will be developed.

Many of the dams within the CRB, including Grand Coulee Dam, are operated for flood control. Seasonal snowmelt forecasting is an important component of flood control and will be examined for potential inclusion in this study. USACE (2012) indicates that forecast error (as well as operations) is a critical aspect to the CRB. The potential to include forecasts and associated forecast errors will be explored.

Rainfall-Runoff Modeling: The Variable Infiltration Capacity (VIC) model (Figure 3) developed for the Columbia Basin Climate Change Scenarios Project (CBCCSP) (Hamlet et al. 2013) will be used to estimate flows from extreme storms, in combination with other meteorological forcings. The CBCCSP came about through a collaboration of the Washington Department of Ecology, the Bonneville Power Administration, the Northwest Power and Conservation Council, the Oregon Water Resources Department and the British Columbia Ministry of the Environment. The project built upon hydrologic model development from the Washington State Climate Change Impacts Assessment (Miles et al. 2010). Specifically, the Variable Infiltration Capacity (VIC) model and associated input datasets were developed at $1/16^{th}$ degree latitude/longitude spatial resolution (approximately 30km^2 or 7400 acres per cell) over the Columbia Basin and coastal drainages within Washington and Oregon. The model was calibrated on a monthly timestep over 12 subbasins of the Columbia Basin. Hydrologic variables such as snowpack, runoff, soil moisture, and evapotranspiration were produced at the grid resolution of the VIC model, and simulated natural streamflow (absent any management effects) was generated at approximately 300 locations throughout the basin.

The VIC model will be used to evaluate the implications of extreme hydrometeorological conditions on the Columbia Basin with respect to flood risk and water management. Frequency precipitation estimates will be used in the historic rainfall database to model extreme floods that

take into account the large drainage basin and multiple sub-basins in the VIC model. A separate interface may be developed to run the perturbed meteorology in a stochastic format with a Monte Carlos method to randomly select the stochastic inputs to the VIC model, run the model, and post processes the results while keeping track of the model parameters for each run. Climate change, and its potential impacts on extreme floods, will also be included in this study. The meteorological forcings to VIC will include appropriate future climate scenarios.

Hydraulics and River Operations Modeling: The USACE developed the HEC-WAT model to integrate the multiple functions of a river system that contribute to flood risk management. The HEC-WAT modeling framework will be used to route flood flows downstream using realistic dam operations. Items such as river regulation, hydropower generation, and structural inventory are modeled and integrated into HEC-WAT to provide an automated approach to develop the metrics necessary to define flood consequences and risk.

High resolution terrain data were collected for both terrestrial and bathymetric conditions. Terrestrial data were collected using LiDAR, which was processed into digital elevation models. Bathymetric data were collected by hydrologic surveys, which resulted in a set of three-dimensional cross-sections. These data were integrated into a seamless terrain model representing elevations on the land and underwater, which was subsequently incorporated into the hydrologic and hydraulic models developed for this study.

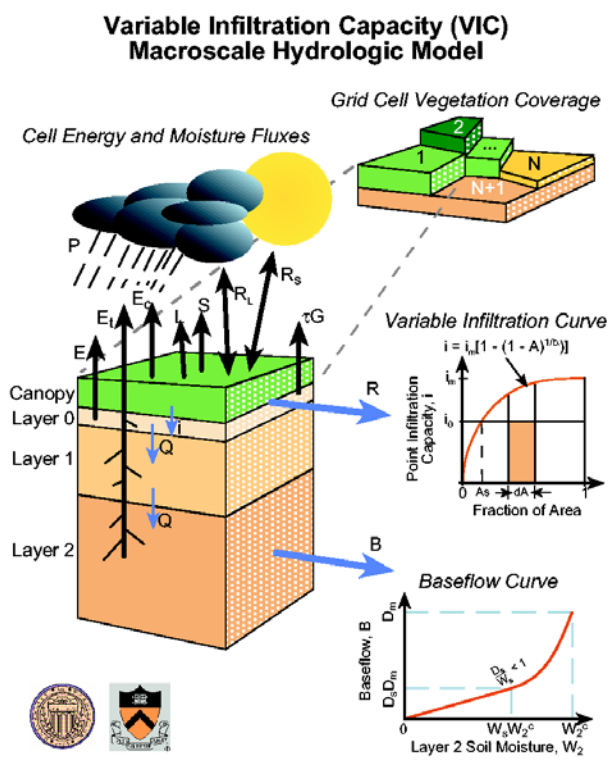

Figure 3 Overview schematic of Variable Infiltration Capacity (VIC) Model.

SUMMARY

Reclamation is performing a HHA for Grand Coulee Dam for use in a Dam Safety risk analysis. Due to the extraordinary large size of the Grand Coulee Dam drainage basin, Reclamation is taking a collaborative approach to the study that leverages the data collection, analyses, and modeling completed by other agencies and universities in both the United States and Canada. A multiple methods approach is being used, that is standard Reclamation practice for high level hydrologic studies, which combines streamflow and rainfall statistics with paleoflood data, hydrograph scaling, rainfall runoff and hydraulic modeling. A detailed HHA of this level has not been completed for Grand Coulee Dam in the past due to the expense and complicated nature of modeling. Leveraging the past and current work being completed in the CRB will allow Reclamation to complete an IE level HHA study for Grand Coulee Dam and help guide dam safety decisions for extreme floods.

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