Creating an Ensemble of Flash Flood Guidance Models to Assess Physical Flash Flood Processes and Model Skill in the Ohio River Basin

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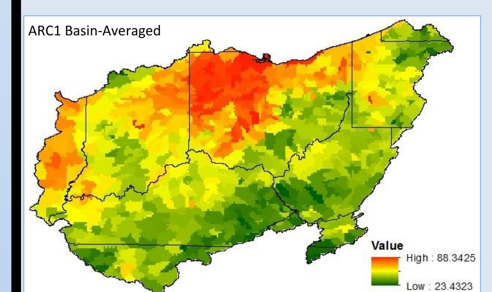
Purpose

Weather Forecast Offices (WFO) issue flash flood warnings, watches, and advisories based primarily on Flash Flood Guidance (FFG) issued by River Forecast Centers (RFC). Unfortunately, a lack of understanding (by both hydrologists and meteorologists), little to no post-event analysis to verify FFG values, and in many cases settling with a single-value FFG technique can create distrust and confusion, for forecasters, in a potentially life-saving product. Because each RFC is physiographically, geologically, and hydrologically different from each other, we propose an ensemble approach to analyze which method is best. Given known strengths and weaknesses of each model component as well as a general understanding of flash flood scale hydrology, we also hypothesize that underlying physical flash flood processes can be inferred. A multi-model approach to flash flood guidance can not only provide insight to actual flash flood processes, but it can also help in scientifically identifying a "best" model for the Ohio River Basin.

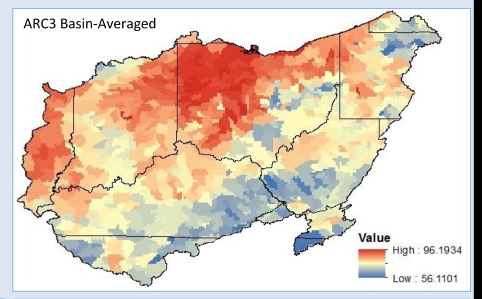
Natural Resources Conservation Service (NRCS) Curve Number Method

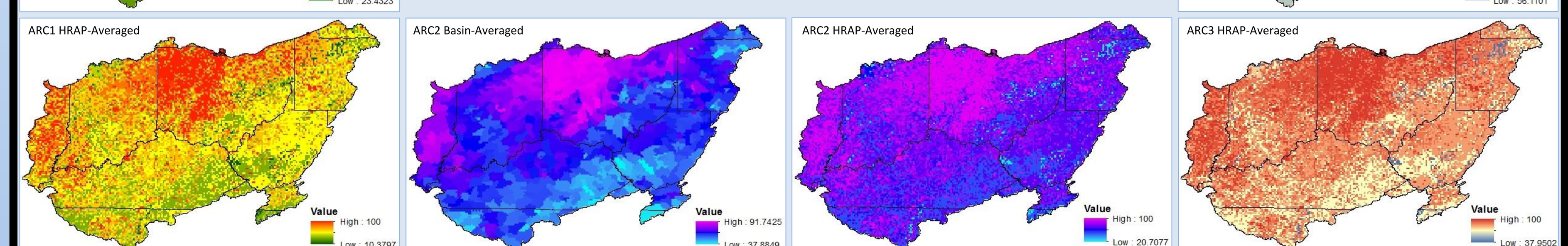
Developed primarily for agricultural runoff modeling in the 1950's, the NRCS curve number method has morphed into many different versions for varying hydrologic applications (*Hawkins et al., 2009*) In 2005, *Schmidt et al.* rearranged the curve number method to produce FFG for National Weather Service RFC's.

S_{sm} = Initial abstraction for interpolated soil moisture Q_x = Threshold runoff *x* hours
FFG_x = rainfall in *x* hours required for flash flooding to begin



$$P = \frac{0.05S_{sm} + Q_x \pm \sqrt{2Q_xS_{sm} + {Q_x}^2}}{2}$$
$$P = FFG_x$$





The images above are antecedent runoff curve number grids representing a wet, (ARC1), average (ARC2), and dry (ARC3) condition. They were first developed using high resolution soil and land use data, and then upscaled to HRAP (4x4KM resolution) *(Welch, 2006).* Basin averages, based on the OHRFC subdivisions of basins, were then calculated to create the basin-lumped version of the ARC's

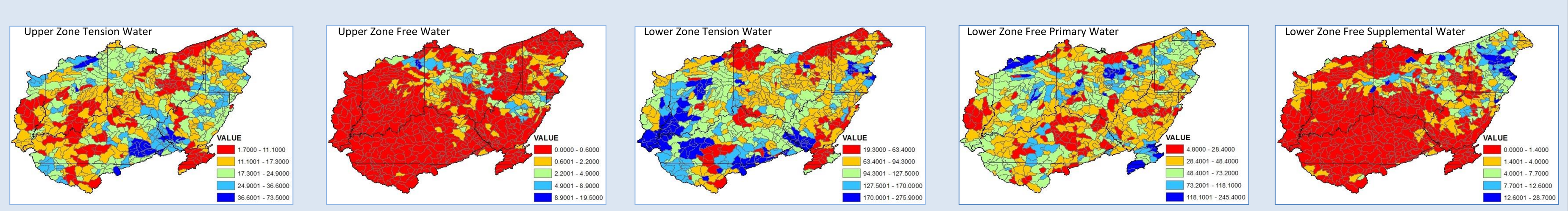
The Upper Zone states of the SAC-SMA (see below) are used in conjunction with the above grids to create current curve number states. This is then combined with a threshold runoff component to calculate FFG. Gridded and lumped calculations are used in the FFG ensemble.

Sacramento Soil Moisture Accounting (SAC-SMA) model Method

Used extensively within the National Weather Service River Forecast Center's, the SAC-SMA is a rainfall-runoff model that generates soil moisture states every 6 hours *(NWS, 2002).* While originally used exclusively for hydrologic river forecasting, the NWS developed a "reverse" equation that determines the amount of rainfall to generate runoff.

This method can be run in a basin-lumped fashion (how most RFC's generated FFG until the mid 2000's) or in a gridded-HRAP fashion (Office of Hydrologic Development's Research Distributed Hydrologic Model)

$$R_{Ef_{t_r}} = \left\{a\left[-\frac{t_r}{F} + \frac{1}{F} + \frac{1}{F\Omega}ln\left(\frac{F - Ge^{\Omega t_r}}{F - G}\right)\right] + ax_F^0 t_r\right\} + \frac{r_f - ax_F^0 - P_0}{(x_F^0)^2}\left[-\frac{1}{F\Omega(-F + G_e^{\Omega t_r})} + \frac{t_r}{F^2} + \frac{1}{(GF\Omega - F^2\Omega)}\right]$$
$$+ \frac{r_f - ax_F^0 - P_0}{(x_F^0)^2}\left[\frac{1}{F^2\Omega}ln\frac{F - G}{F - Ge^{\Omega t_R}}\right] + \frac{r_f - ax_F^0 - P_0}{(x_F^0)^2}\left\{+2x_F^0\left[-\frac{t_r}{F} + \frac{1}{F\Omega}ln\left(\frac{F - Ge^{\Omega t_r}}{F - G}\right)\right] + (x_F^0)^2 t_r\right\}$$ *(Ntelekos, 2005)*



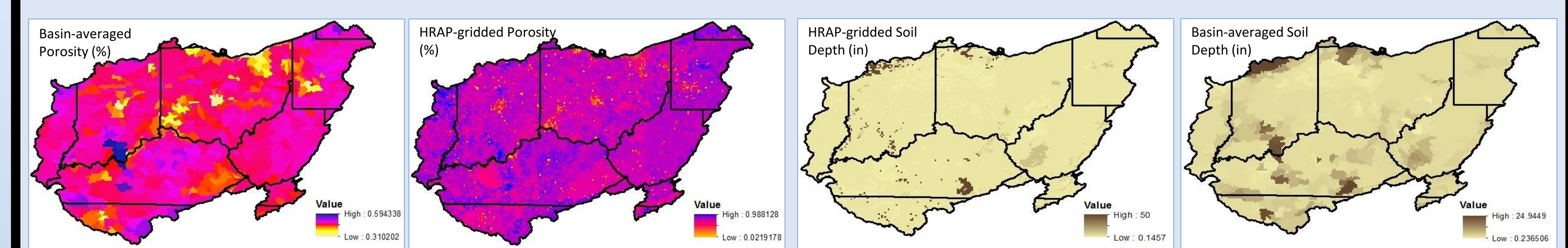
Like the NRCs method, both gridded and lumped inputs to the model are used in the FFG ensemble. The SAC-SMA (gridded and lumped versions), however, create their own soil moisture states.

Saturation/Infiltration Excess Overland Flow Method

Essentially a post-processing technique, this method is used to evaluate soil-water storage as it relates to runoff-available storage. Using zonal states from the SAC-SMA (gridded and lumped), SIEOFG will output a surface water deficit which will be added to threshold runoff to create an FFG value.

n = porosity FFG_x = rainfall in x hours required for flash flooding to begin SD_x = Soil Depth for x hours SM_x = Soil Moisture for x hours TR_x = Threshold runoff in x hours $Swint_{(1-3)}$ = Soil Moisture at SAC-SMA pre-defined depths

$$FFG_x = [(n * SD_x) - (n * SD_x * SM_x)] + TR_x$$
$$SM_{1HR_t} = \left[\left(Swint_{1_t} * 6.7\right) + \left(Swint_{2_t} * 13.3\right) + \left(Swint_{3_t} * 20\right)\right]/40$$



This method is unique in the sense that it deals only with the Vadose zone under saturated conditions. This method will hypothetically outperform other models in relatively shallow soil, low-slope parts of the basin.

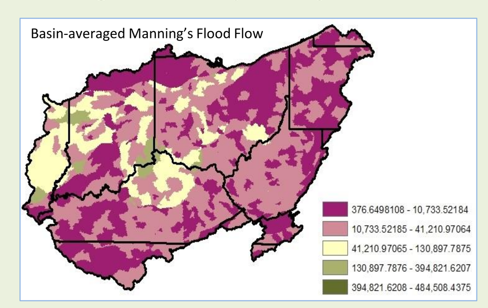
Threshold Runoff Models

To compliment the three FFG models (gridded and lumped), the ensembles will also include four different threshold runoff techniques (gridded and lumped). The equation governing threshold runoff is as follows

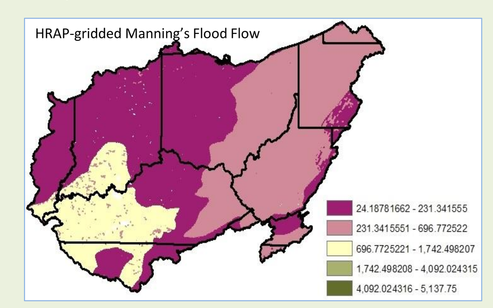
R = Threshold Runoff (in) Q_p = Flooding Flow (cfs) q_{pR} = Unit hydrograph peak for a specific duration t_r

$$R = {Q_p}/{q_{pR}A}$$

Manning's Steady, Uniform Flow Resistance Formula (Chow et al., 1988)

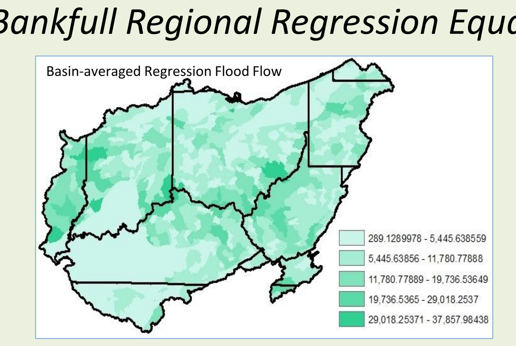


$$Q_p = Q_{bf} = \frac{B_b D_b^{5/3} S_c^{0.5}}{n}$$
$$n = 0.43 S_c^{0.37}/D_b^{0.15}$$

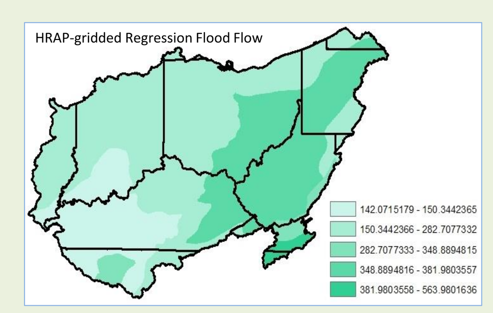


Data is obtained from USGS regional regression equations.

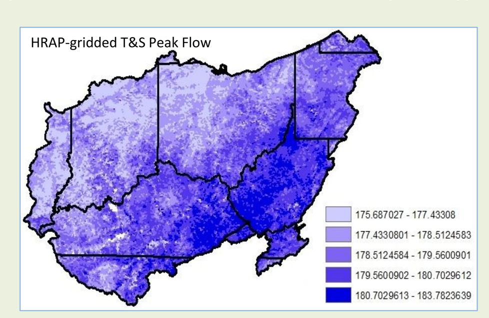
Bankfull Regional Regression Equations



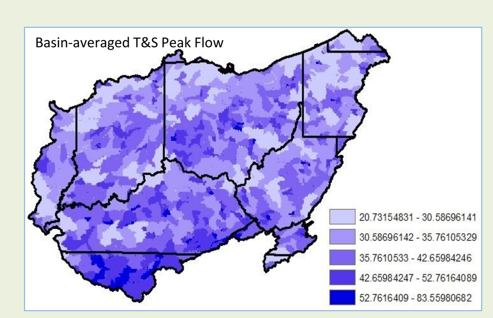
$Q_p = xA^y$ with A = Area



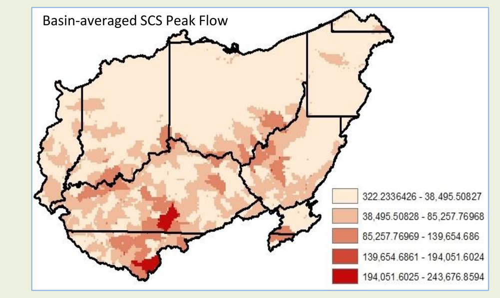
Taylor and Schwarz Model for qpR (Bhunya et al., 2011)



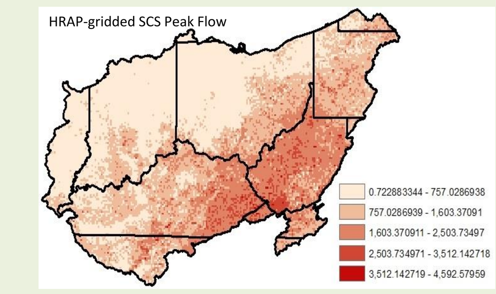
$$q_{pR} = \left(\frac{382}{LL_c^{0.36}}\right)e^{m_2 D}$$



Soil Conservation Service (SCS) Method for Peak Unit Hydrograph Flow



$$q_{pR} = \frac{484}{T_R}$$

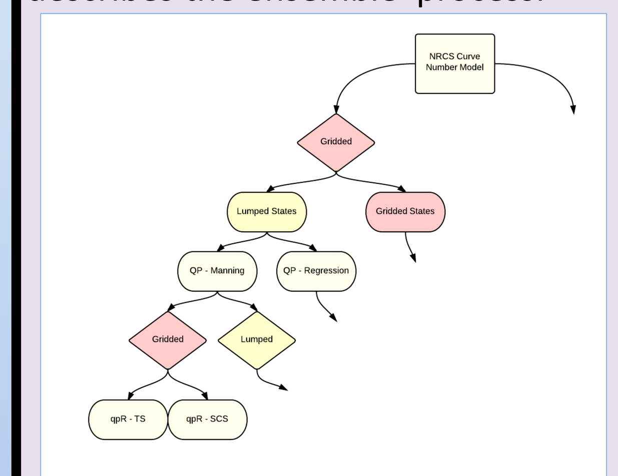


Uses NRCS Triangular Unit Hydrograph method (*Schmidt et al., 2005*)

Generating the Ensembles in CHPS – FEWS

(Community Hydrologic Prediction System – Flood Early Warning System)

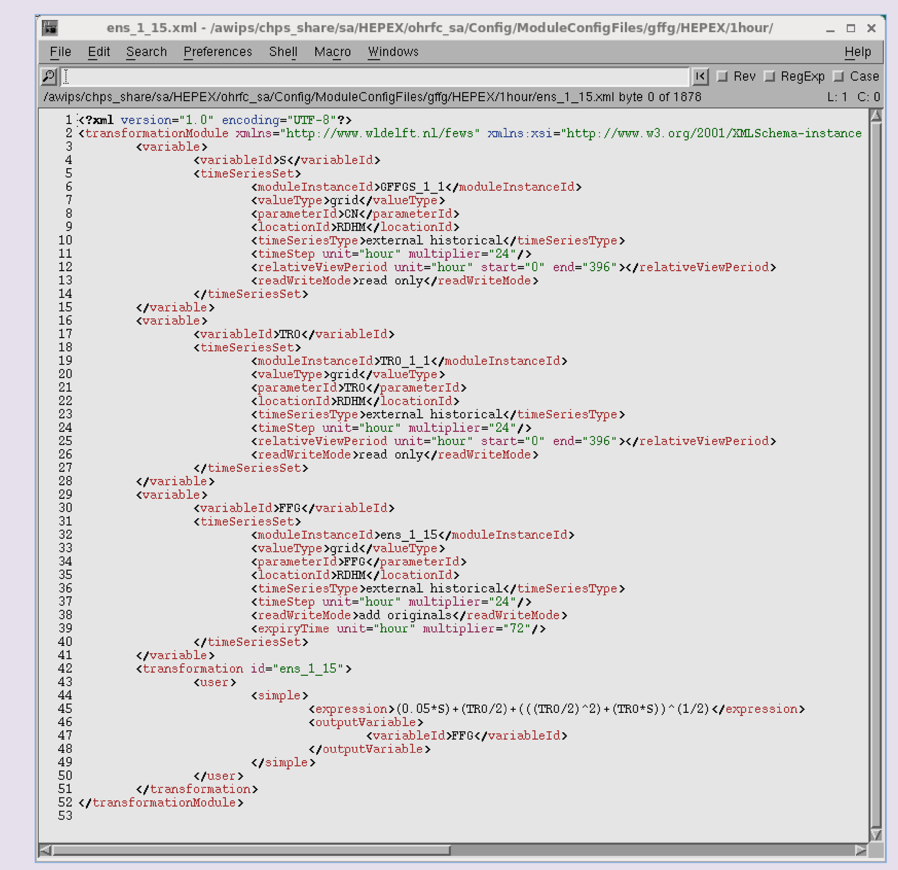
To handle the large quantity of data and calculations, CHPS-FEWS was chosen to run the ensembles. The ensembles will be run from 12-01-2012 to 11-30-2013 at 24 hour time steps. These dates were chosen because of the archived hourly QPE and QTE that will be used to generate the SAC-SMA states. Each rainfall/runoff model will run with lumped inputs and with gridded inputs (giving six) Those six models will then be combined with the four combinations of Threshold Runoff (gridded and lumped) giving eight threshold runoff models. A sample flow chart, below, describes the ensemble process.



After preliminary model runs are completed, the final grids will be converted to scalar. This will allow us to geographically isolate HRAP-sized locations in the OHRFC's variable physiographic, hydrologic, and geologic regions. Regions to be isolated are as follows…

1. Kentucky – Green Basin
   Karst geology
2. Indiana – Wabash Basin
   Low-slope, deep soils
3. West Virginia – Monongahela Basin
   Mountainous, deep valleys
4. Ohio – Great Lakes Basin
   Low-slope, Lacustrine soils

A sample XML-based configuration file showing how the ensembles will be organized can be viewed on the right.



This project is currently in the development and testing phase. Once reliable time series data can be generated, statistics such as standard deviation and variance will be calculated. We also expect to analyze convergence/divergence measures as they could apply in an operational Setting using FFG ensembles.

References

1. Hawkins, R. H., Ward, T.J., Woodward, D.E., Mullem, J.A., (2009). *Curve Number Hydrology: State of the Practice*. Reston, VA: America Society of Civil Engineers
2. Schmidt, J.A., Anderson, A.J., Paul, J.H. (2005). Spatially-Variable Physically-Derived Flash Flood Guidance. *American Meteorological Society,* (6B.2), 1-12.
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6. Bhunya, P.K., Panda, S.N., Goel, M.K. (2011). Synthetic Unit Hydrograph Methods: A Critical Review. *The Open Hydrology Journal*, 5, 1-8.