Addition of a Vulnerability Component to the Flash Flood Potential Index

W. Scott Lincoln
Senior Hydrologist, NWS Lower Mississippi River Forecast Center, Slidell, LA

Jeff Zogg
Senior Hydrologist, NWS Weather Forecast Office Des Moines, IA

James Brewster
Senior Hydrologist, NWS Weather Forecast Office Binghamton, NY

June, 2016

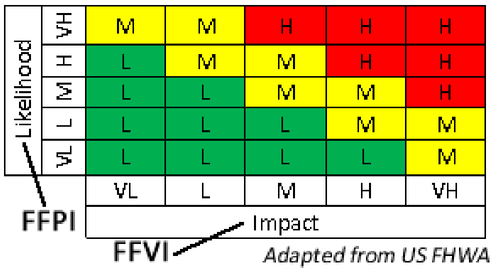
1. Introduction

The Flash Flood Potential Index (FFPI) is a method of ranking watersheds by their relative runoff potential. FFPI was developed at the National Weather Service (NWS) Colorado Basin River Forecast Center (CBRFC) in 2003 (Smith, 2003). The original methodology averaged together indeces mapped to four different physical characteristics that are related to flash flood potential: land surface slope, land use, soil type, and vegetation cover. Since the original method was presented, the FFPI has been utilized by numerous additional NWS offices and has also undergone a few alterations to methodology. Zogg and Deitsch (2013) describe utilization of the FFPI at NWS Weather Forecast Office (WFO) Binghamton, NWS WFO Mount Holly, NWS WFO State College, and NWS WFO Des Moines. In 2014, the technique was also evaluated at the NWS Lower Mississippi River Forecast Center.

It has been found that the FFPI often does not correlate strongly with the density of flash flood reports. This is likely due to a combination of deficiencies in the flash flood report database and the lack of a vulnerability component in the FFPI. Here we present a sensitivity analysis which was conducted to provide guidance on the best weighting of each physical characteristic. Then we propose the creation of a Flash Flood Vulnerability Index (FFVI) that can be used to rank watersheds by the relative impact potential from flash flooding.

1.1 Flash Flood Risk

The concept of risk is often described as having two components, the chance of an event occurring and the impact of that event, were it to occur (D'Ignazio, 2011) (US FHWA Office of Planning, Environment, & Realty Planning, 2014). For flash flood purposes, the FFPI relates to the chance of a flash flood event occurring but provides little information on what kinds of impacts would be expected. For this reason, the FFPI is not really a risk scale. An index that quantifies the relative flooding risk between watersheds would need both a flash flood potential component and a flash flood vulnerability component.



Likelihood	VH	M	M	H	H	H
	H	L	M	M	H	H
	M	L	L	M	M	H
	L	L	L	L	M	M
	VL	L	L	L	L	M
		VL	L	M	H	VH
		Impact				

Adapted from US FHWA

Figure 1. A conceptual diagram of risk as presented by the US FHWA (2014). "FFPI" and "FFVI" labels were added.

1.2 Flash Flood Vulnerability

Flash flooding differs from other short term weather impacts in that the definition of flash flooding lacks clarity; flash flooding in one area may not be considered flash flooding in a different area. Building codes, infrastructure, and location of potential impacted populations, all have a role in whether or not an event is considered a flash flood. For example, a community with more means may be better able to construct roadways to withstand more significant flooding. Such a community may also enact building codes that prevent the construction of homes in flood prone areas. The interaction between physical characteristics of a watershed and socioeconomic policy are far too complex to be discussed in this analysis. We do, however, assert that social vulnerability likely plays a role in the amount of runoff necessary to cause impactful flash flooding as well as a role in the severity of flooding once it occurs.

When looking for a way to quantify the vulnerability to flooding, one of the first factors considered was population, in particular, ambient population. Ambient population differs from the typically-reported population values in that it is not just an estimate of where people reside, but instead is an estimate of where people *are*, averaged over the entire day. This has the benefit of highlighting shopping areas, workplaces, and leisure centers that would not show up in Census estimates.

The socio-economic factors related to flash flood risk are much more complicated and outside the expertise of the authors. Emrich et al (2014) proposed utilizing the Social Vulnerability Index (SoVI) from the Hazards Vulnerability Research Institute (HVRI) in combination with the FFPI (as developed for NWS WFO Des Moines) to illustrate the risk of flooding in Florida. As described on the HVRI website, SoVI "measures the social vulnerability of different areas of the United States to environmental hazards… The index synthesizes 29 socioeconomic variables, which the research literature suggests contribute to reduction in a community's ability to prepare for, respond to, and recover from hazards. SoVI data sources [are primarily from] the United States Census Bureau" (http://webra.cas.sc.edu/hvri/products/sovi.aspx, June 2016). SoVI was thus a good choice for evaluating the vulnerability to flash flooding as it was developed to be independent of any particular disaster (Christopher Emrich, personal communication, Dec 2014).

2. Methodology

We have proposed that the flash flood risk is a combination of both the flash flood potential and the flash flood vulnerability. Flash flood potential is a combination of land surface characteristics. Flash flood vulnerability is a combination of ambient population density and HRVI's SoVI. In this section, each component of the risk calculation are described.

2.1 Flash Flood Potential Index

For the purposes of testing our proposal, the FFPI used was based upon the LMRFC method. The LMRFC method for calculating FFPI is similar to previous FFPI methods but uses slightly different datasets for physical characteristics, and also does not use a simple average of each component. The weighting of each FFPI component is based upon a sensitivity analysis.

The LMRFC method of calculating FFPI was based upon the Green & Ampt infiltration method (Green & Ampt, 1911), as implemented in the US Army Corps of Engineers HEC-HMS modeling program (US Army Corps of Engineers Hydrologic Engineering Center, 2005). This infiltration method is particularly useful for flash flood purposes because it generates runoff based upon the rate of infiltration being exceeded (saturation from above) rather than by generating runoff when a hypothetical, near-surface layer of soil becomes completely saturated (saturation from below). The latter is most applicable to river flooding applications while the former is more applicable to flash flooding because flash flooding is mostly a rainfall intensity problem.

The required parameters for running Green & Ampt in HEC-HMS are saturated hydraulic conductivity, wetting front suction head, soil moisture deficit, soil surface abstractions, imperviousness, and basin lag time. Wetting front suction head has very low impact on the magnitude of runoff and was therefore ignored. Lag time can be estimated based upon basin area and basin land surface slope. Soil surface abstractions - storage areas that must be filled before rainfall reaches the soil surface - can be estimated from land cover and canopy cover. Saturated hydraulic conductivity (HC), the approximate continuous rate of infiltration that will occur after the soil surface has become saturated, can be estimated from soil survey data. Imperviousness relates to coverage of the land surface that does not infiltrate rainfall and can be estimated via remote sensing. Soil moisture deficit can be estimated via modeling; it can also be set to an "average" value (roughly 0.2) if the FFPI analysis is being done for planning purposes. Table 1 provides an overview of how these parameters are used to create the FFPI at LMRFC.

Table 1. Components of the LMRFC FFPI methodology. The FFPI for each component is mapping to a 0 to 10 index based upon the listed method.

Dataset	Abbrev.	FFPI 0	FFPI 10	Method
Sat. hydraulic conductivity	HC	1.00	0.00	Polynomial
Moisture deficit	MD	0.50	0.00	Linear
Slope	S	0.0%	30.0%	Exponential
Land cover (reclassified to est. soil/litter abstraction)	LC	1.03	0.00	Linear
Canopy cover(reclassified to abstraction)	C	100.0% (0.15)	0.0% (0.00)	Linear
Imperviousness	I	0.0%	100.0%	Linear

Each of the individual parameters in the FFPI are set to an index from 0-10. A weighted averaged is used to create the final FFPI for any given location.

The impact of K_{sat} on runoff potential is not linear; as the value gets smaller, even the slightest changes may cause large changes to the runoff. K_{sat} was mapped to an index such that 0.01 inches/hr would correspond to an index value of 10, 0.10 inches/hr would correspond to 7, 0.25 would correspond to 5, 0.55 inches/hr would correspond to 3, and >1.00 inches/hr would correspond to 0. A polynomial was fit to these values, yielding the following equation:

$$Sat. Hydraulic\ Conductivity\ Index = \frac{-1 * \sqrt{(4 * A * HC) + B^2 - (4 * A * C)} + B}{2 * A}$$

Where HC is the saturated hydraulic conductivity value in inches/hr, set to be no less than 0.01 and no more than 1.00, and A, B, & C, are coefficients (0.0090, -0.1900, and 1.0000, respectively).

Soil moisture deficit has a linear relationship to FFPI and is described by the following equation:

$$Soil\ Moisture\ Index = 10 * MD$$

Where MD is the soil moisture deficit, expressed as a ratio. Soil moisture can be ignored (set to a rough average of 0.2) if it is unknown or if the FFPI is being developed as a planning tool rather than for realtime, dynamic purposes.

The impact of slope on runoff potential is also not linear; as the value gets larger, even the slightest changes may cause large changes to the runoff. Land surface slope was mapped to an index such that 0.01% would correspond to an index value of 0.0, 15.0% would correspond to 8.8, and >30.0% would correspond to 10. An exponential was fit to these values, yielding the following equation:

$$Slope\ Index = {LN\,(\frac{S}{A})}\Big/_{B}$$

Where S is the slope value in percent, set to be no less than 0.01 and no more than 30.00, and A & B are coefficients (0.0944 and 0.5761, respectively).

Abstractions come from two sources, the land surface and the canopy cover. The abstractions due to land cover are determined by Table 2. The abstractions due to canopy cover are determined by the ratio of cover multiplied by the maximum estimated abstraction (0.15 inches) which was approximated from rainfall studies. A combination of the initial abstractions from both sources is combined and then linearly correlated to an index. The abstractions index is computed using the following equation:

$$Abstractions\ Index = 10 * \frac{1.28 - (0.15\,C\ + LC)}{1.28}$$

Where C is the ratio of canopy cover and LC is the land cover soil surface abstraction, determined from Table 2.

Imperviousness also is mapped to an index using a linear relationship, as expressed by the following equation:

$$Imperviousness\ Index = 10 * I$$

Where I is the imperviousness, expressed as a ratio. For example, 50% imperviousness would be stored in “I” as 0.5, which would yield an Imperviousness Index value of 5.

Table 2. Estimated initial abstractions due to land cover. Combined with canopy cover abstraction to calculate an abstractions index.

Code	Description	Abstraction
11	Open water	0.00
12	Perennial snow ice	0.00
21	Low density residential	0.13
22	High density residential	0.13
23	Commercial industrial transportation	0.13
24	unknown developed	0.13
31	Bare rock sand clay	0.00
32	Quarries strip mines gravel pits	0.00
33	transitional	0.00
41	Deciduous	0.45
42	Evergreen	0.45
43	Mixed	0.45
51	Shrubland	0.40
52	unknown shrubland	0.40
61	Orchards vineyards other	0.31
71	Grasslands herbaceous	0.30
81	Pasture hay	0.58
82	Row crops	1.13
83	Small grains	1.13
84	Fallow	0.58
85	Urban recreational grasses	0.13
90	unknown wetlands	0.45
91	Woody wetlands	0.45
92	Emergent herbaceous wetlands	0.45

2.1.1 Sensitivity Analysis

A sensitivity analysis was performed to estimate the best weights of each sub-index for the FFPI. A test subbasin was created in HEC-HMS using several assumptions (Table 3). The baseline case was run with variables as close to a FFPI 5 as possible. Rainfall driving the baseline case came from the 10yr (10% annual chance equivalent) 3hr duration event. Representative values for various portions of the eastern CONUS were extracted from NOAA Atlas 14. Approximate values were 2.0"/3hr for the northeastern US, 2.5"/3hr for the northern midwest, ohio river valley, and the Appalachian Mountains, 3.5"/3hr for the mid south, and 4.5"/3hr for the immediate gulf coast. A sensivity analysis was done for the 2.5"/3hr and the 3.5"/3hr storms.

Table 3. Model parameters used for the sensitivity analysis in HEC-HMS.

Variable	Value	Comment
Area (mi2)	10.0	
Lag time (min)	90	Based upon assumed slope of 1.68% and longest flow path of 20,000ft
Canopy abstration (in)	0.075	
Soil abstraction (in)	0.30	
Moisture deficit	0.20	
Sat. hydraulic conductivity (in/hr)	0.28	
Imperviousness	10.0%	

The baseline case yielded a peak flow of 1510 cfs and 3800 cfs for the 2.5"/3hr and 3.5"/3hr storms, respectively. Changes were made to one parameter at a time to quantify the range in peak flow based upon the entire possible range of that variable (corresponding to the range of 0-10 FFPI for that variable). The magnitude of peak flow changes were compared for each dataset/variable to create the weighting for the final FFPI. Each baseline rainfall event provided a different set of weights.

Indeces for each variable were weighted based upon the results of the model sensitivity analysis. Table 4 presents the weights for two different rainfall scenarios. The 2.5in/3hr scenario is likely best for the upper midwest. The 3.5in/3hr scenario is likely best for the mid south. This change in rainfall intensity yields the biggest changes in weighting to the slope and imperviousness components. The 2.5 in/3-hr event will be referred to as LMRFC #1 and the 3.5 in/3-hr will be referred to as LMRFC #2. These weighting factors are compared to the weights for other implementations of FFPI in Table 5.

Table 4. The range in peak flows for the test basin based upon changes to each modeled variable and the resulting weights used to create the final FFPI.

Variable	PeakQ Range (2.5in)	PeakQ Range (3.5in)	Weight LMRFC#1 (2.5in)	Weight LMRFC#2 (3.5in)
Sat. hydraulic conductivity	4130 cfs	6390 cfs	25.4%	26.4%
Moisture deficit	3460	4190	20.0%	16.3%
Slope	2490	6480	16.0%	28.0%
Initial abstractions	1800	2490	10.4%	9.7%
Imperviousness	4870	5010	28.2%	19.5%

Table 5. A comparison of weighting factors for each FFPI component by version of FFPI, as reported by Zogg & Deitch (2013). Versions marked with "*" had estimated values based upon the text description.

Parameter	Related Flash Flood Modeling Process	CBRFC (2003)*	Binghamton (2009)	Mount Holly (2010)	State College (2012)*	Des Moines (2013) #1	Des Moines (2013) #2	Des Moines (2013) #3	Des Moines (2013) #4	LMRFC (2014) #1	LMRFC (2014) #2
Slope	Lag time	0.280	0.375	0.250	0.280	0.330	0.250	0.375	0.400	0.160	0.280
Land Cover	Initial Abstractions	0.240	0.250	0.250	0.280						
Soil Texture	Infiltration rate	0.240	0.250	0.250	0.220	0.330	0.250	0.250	0.200		
Vegetation/Forest Density	Initial abstractions	0.240	0.125	0.250	0.220						
Land Cover + Vegetation	Initial Abstractions					0.330	0.500	0.375	0.400	0.104	0.097
Sat. Hydraulic Conductivity	Infiltration rate									0.254	0.264
Moisture Deficit	Infiltration rate									0.200	0.163
Imperviousness	Instantaneous Runoff									0.282	0.195

2.2 Flash Flood Vulnerability Index

To test our proposed addition of a vulnerability index to FFPI, a simple average of two indeces was performed. The first part of the FFVI was ambient population density and the second part was SoVI. The indeces for these variables were created from the raw values; population logarithmically based upon manually-specified parameters and SoVI based upon quantile breaks of values (Table 6).

Table 6. Components of the proposed FFVI methodology. The FFVI for each component is mapping to a 0 to 10 index based upon the listed method.

Dataset	Abbrev.	FFPI 0	FFPI 10	Method
Ambient population density	POP	0.0	100,000	Logarithmic
Social vulnerability (SoVI)	SOVI	-21.77	+48.16	Quantiles/Polynomial

Ambient population density was mapped logarithmically such that a population value of 0 corresponding to an index value of 0 and a population of approximately 1000 corresponded to the midpoint of the index (5). Very high population values yielded smaller and smaller changes in the index values because it was assumed that changes in impact due to population would be greatest at the lower population densities. The population index is calculated based upon the following equation:

$$Population\ Index = 0.83\ LN\ (POP)\ + 0.5$$

Where “POP” is the ambient population density in persons per square kilometer.

SoVi was mapped to an index by first calculating the quantile breaks for the data values across the CONUS. A polynomial equation was then created that would create smooth index values similar to the discrete values provided by looking at the quantile breaks in the data. The SoVI Index is calculated based upon the following equation:

$$SoVI\ Index = -0.0004\ SOVI^3 + 0.0001\ SOVI^2 + 0.5177\ SOVI + 5.0$$

Where “SOVI” is the raw value from HVRI’s SoVI.

The population index and SoVI index were capped such that values below 0 and above 10 were removed. Then the indeces were then averaged together (no weighting) to create the FFVI.

2.3 Combined flash flood risk index

The FFPI and FFVI calculations were averaged together to create a new “combined flash flood risk index.” Equal weights were used for both FFPI and FFVI.

2.4 Comparison of flash flood indeces to flash flood report density

A portion of far southern Missouri in WFO Springfield’s area was chosen to test the FFPI and FFVI due to the frequency of flash flooding in the area (Figure 2). The density of flash flood reports from April 2003 to October 2014 was calculated based upon LSR data from the Iowa Environmental Mesonet (http://mesonet.agron.iastate.edu/request/gis/lsrs.phtml, retrieved November 2014). These reports were then averaged over HUC12 basins as delineated by the USGS. FFPI (LMRFC#2), FFVI, and the individual components of the proposed FFVI were also averaged over the HUC12 basins. Each index was compared against the flash flood reports density to check for correlation.

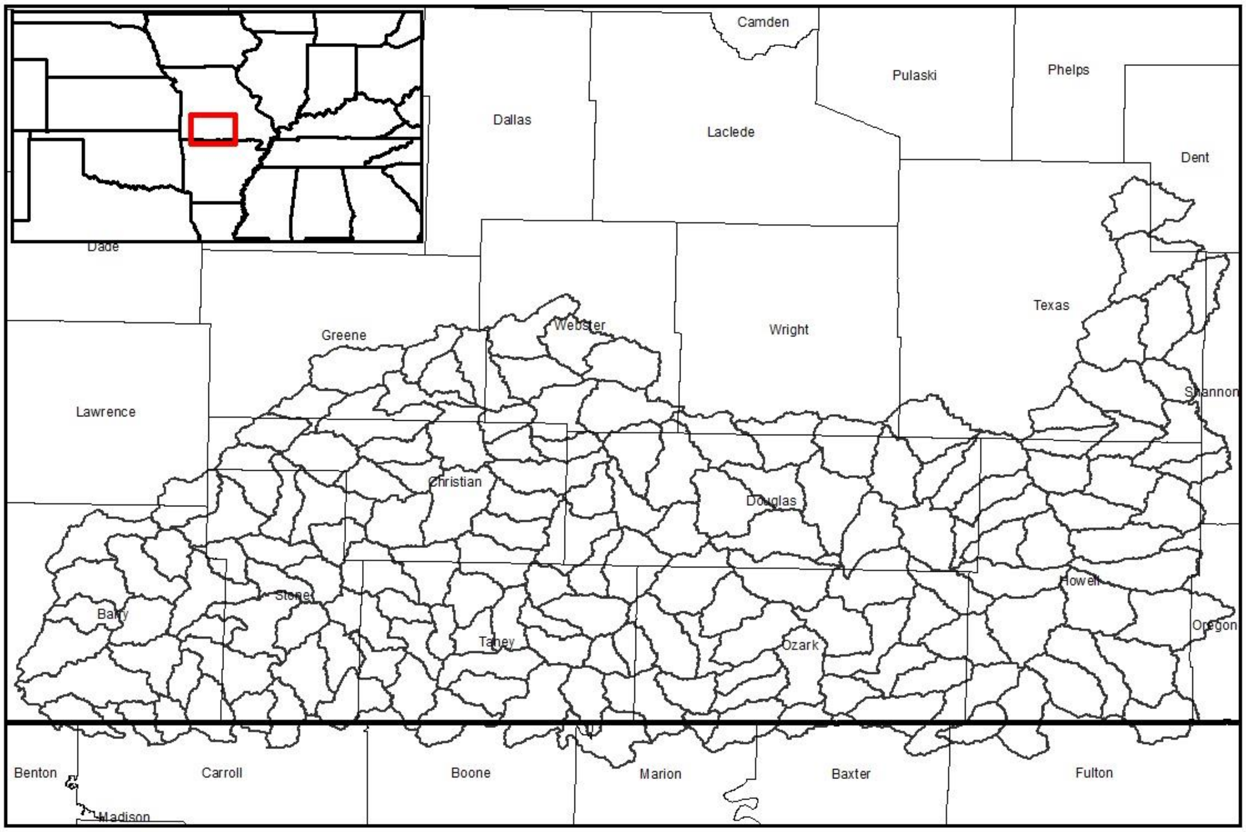


Figure 2. The area chosen to study the proposed FFVI and FFPI in southwest Missouri. Basin boundaries are the HUC12 delineations from the USGS watershed boundary dataset.

3.0 Discussion

When compared to the flash flood report density, the combined risk index showed a weak positive correlation (Figure 3). Looking at the individual components (FFPI and FFVI), only FFVI showed a positive correlation to flash flood report density (Figure 4). FFPI actually showed an apparent negative correlation (where a higher basin-averaged FFPI corresponded to lower flash flood report density), although this correlation was very weak (Figure 5).

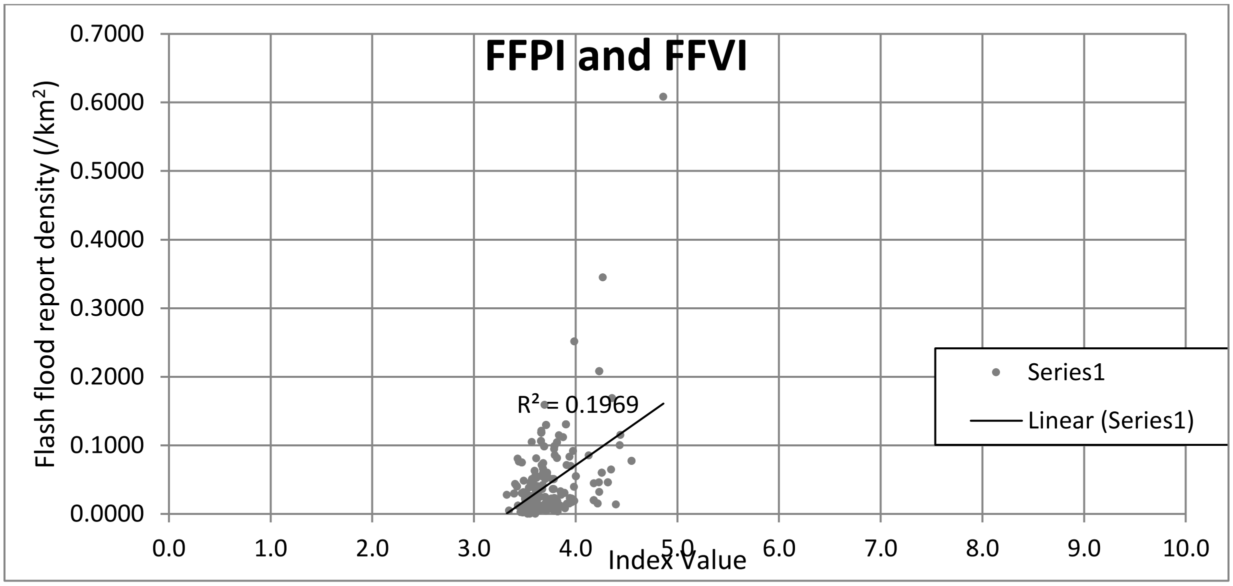


Figure 3. The combined risk index (FFPI and FFVI averaged) compared to the density of flash flood reports for the SW Missouri test area.

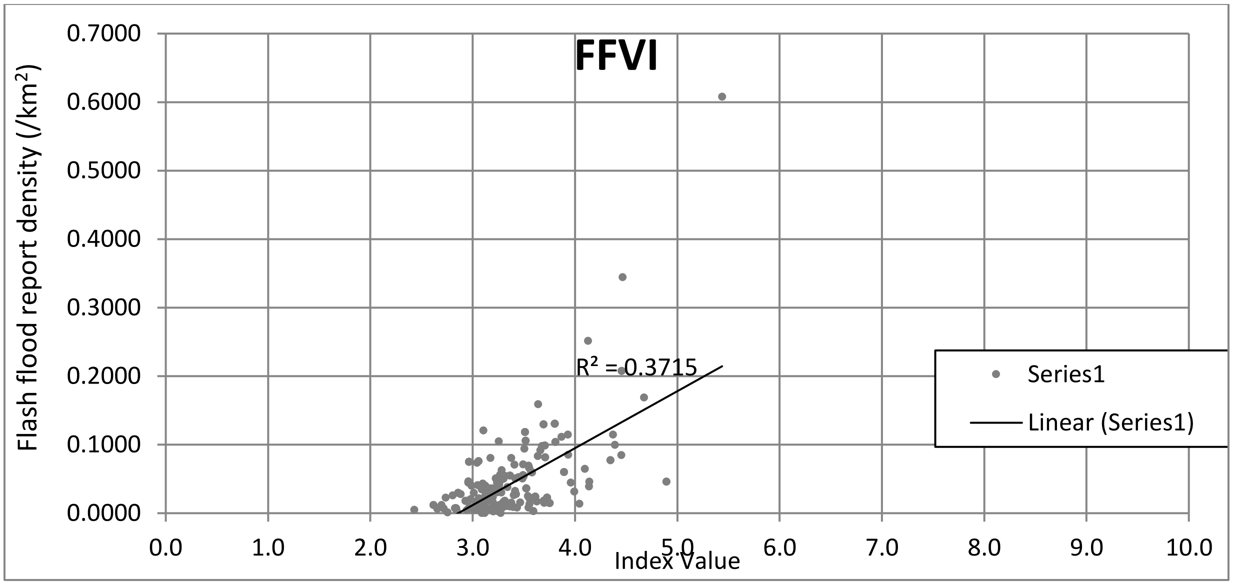


Figure 4. The proposed FFPV compared to the density of flash flood reports for the SW Missouri test area.

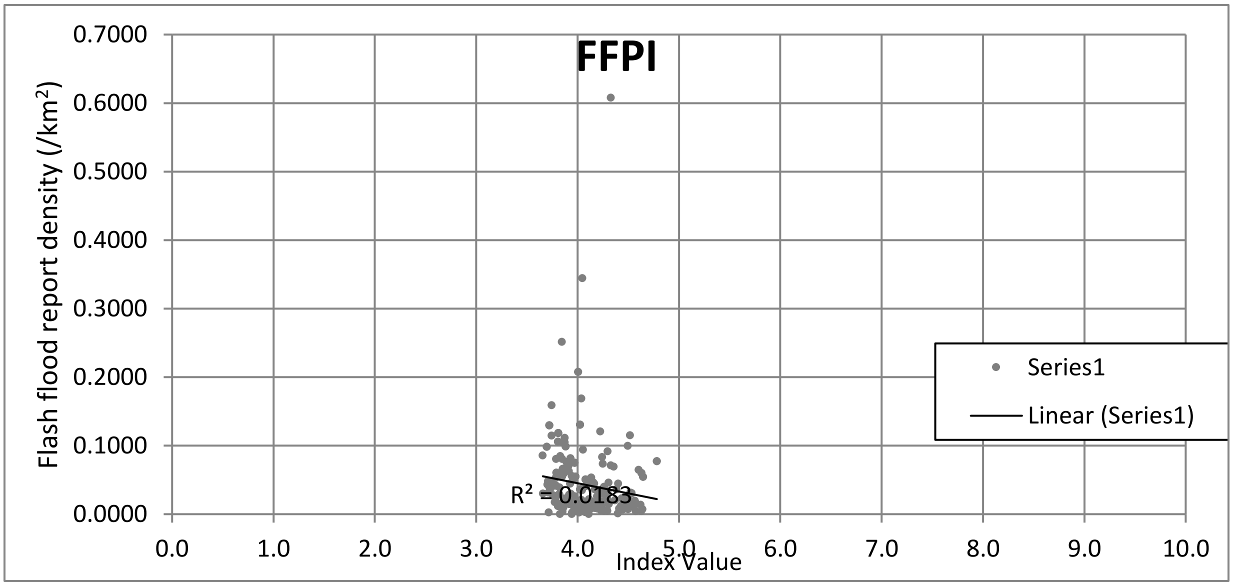


Figure 5. The FFPI (LMRFC version #2) compared to the density of flash flood reports for the SW Missouri test area.

To further discern which components of FFPI and FFVI yielded strong correlations to flash flood report density, the ambient population index, SoVI index, abstractions index, saturated hydraulic conductivity index, imperviousness index, and slope index were all analyzed.

When broken down into the separate components, only imperviousness, population, and abstractions indeces showed positive correlations (Figure 6, Figure 7, Figure 8). Of those, the strongest correlation was between imperviousness and the flash flood report density. Saturated hydraulic conductivity, which was the most sensitive runoff parameter, had no correlation to flash flood report density for the study area (Figure 9). Surprisingly, the SoVI index and slope index both showed weak, negative correlations to flash flood reports (Figure 10, Figure 11).

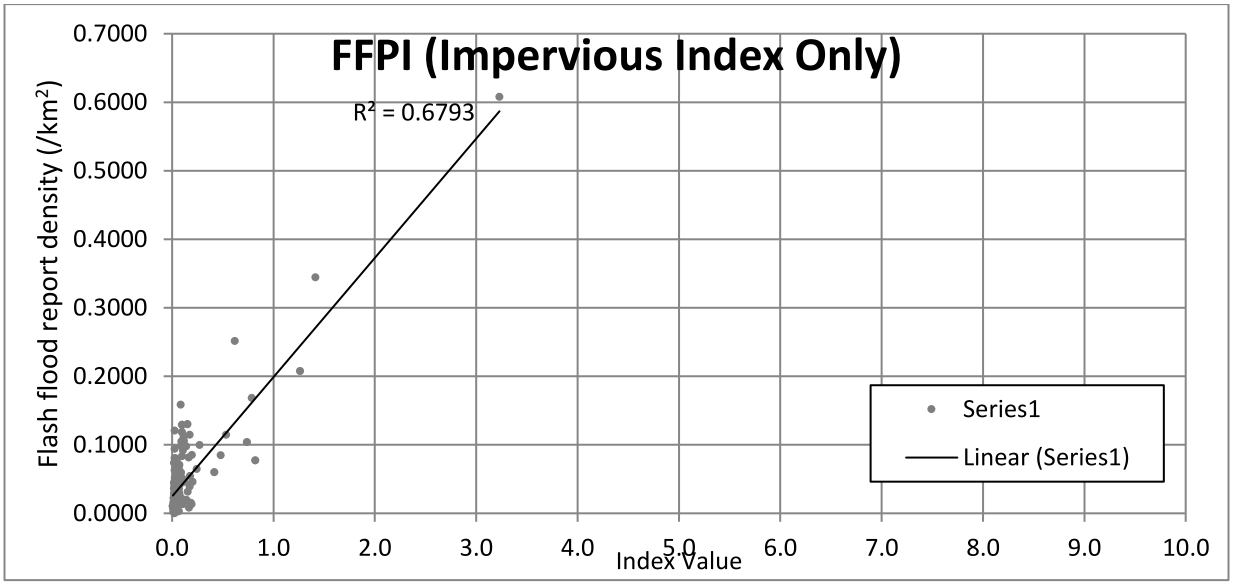


Figure 6. The imperviousness component of FFPI compared to the density of flash flood reports for the SW Missouri test area.

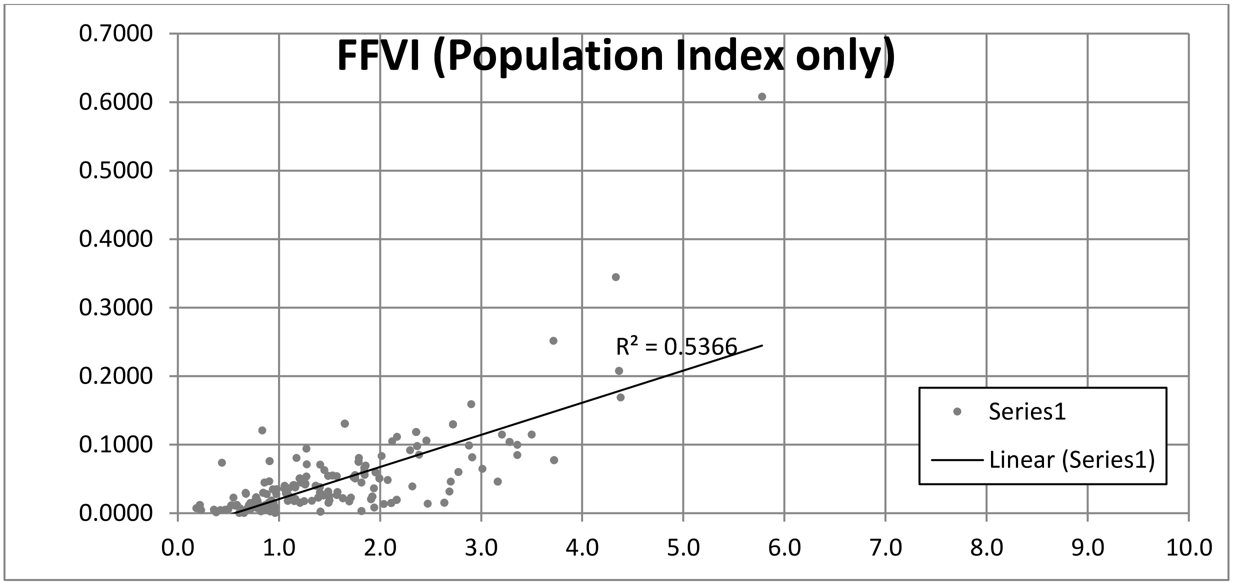


Figure 7. The population component of FFVI compared to the density of flash flood reports for the SW Missouri test area.

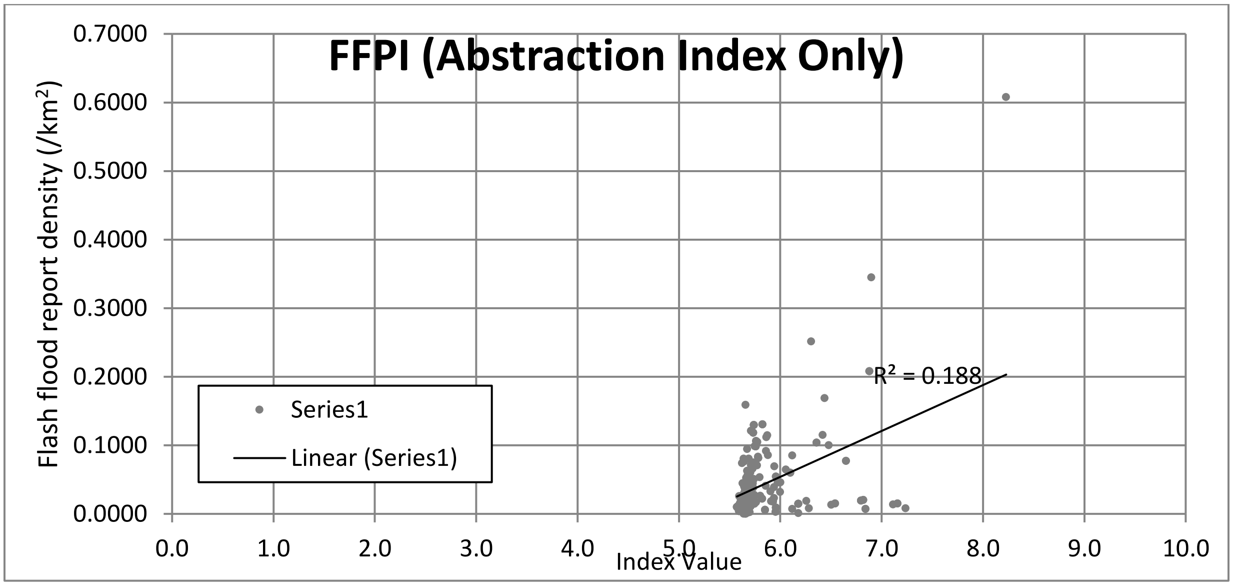


Figure 8. The abstractions component of FFPI compared to the density of flash flood reports for the SW Missouri test area.

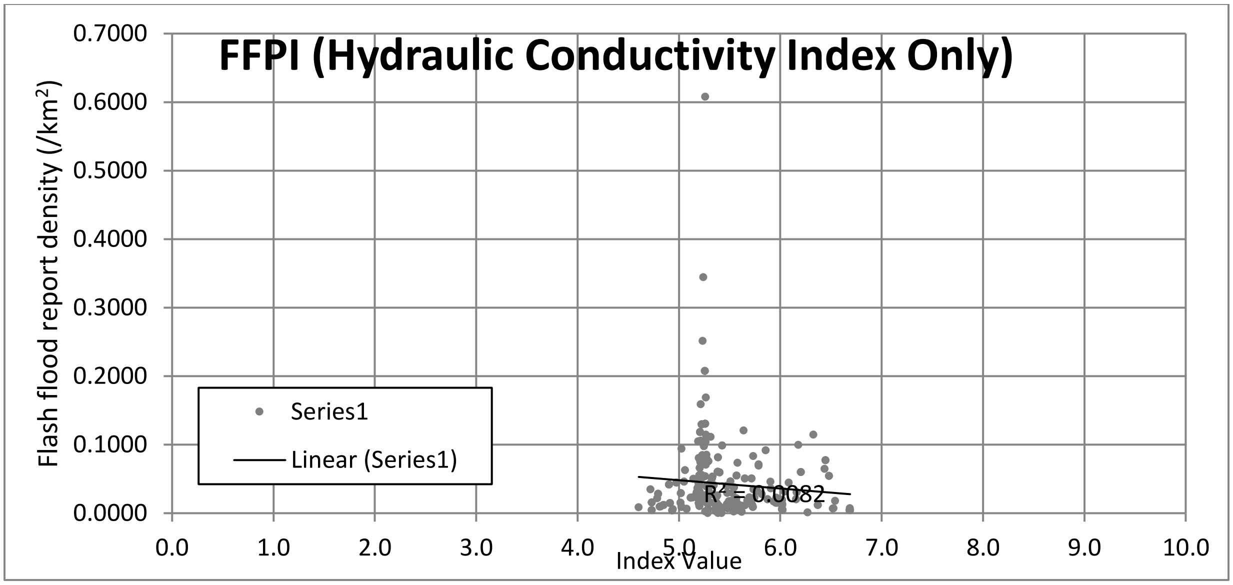


Figure 9. The saturated hydraulic conductivity component of FFPI compared to the density of flash flood reports for the SW Missouri test area.

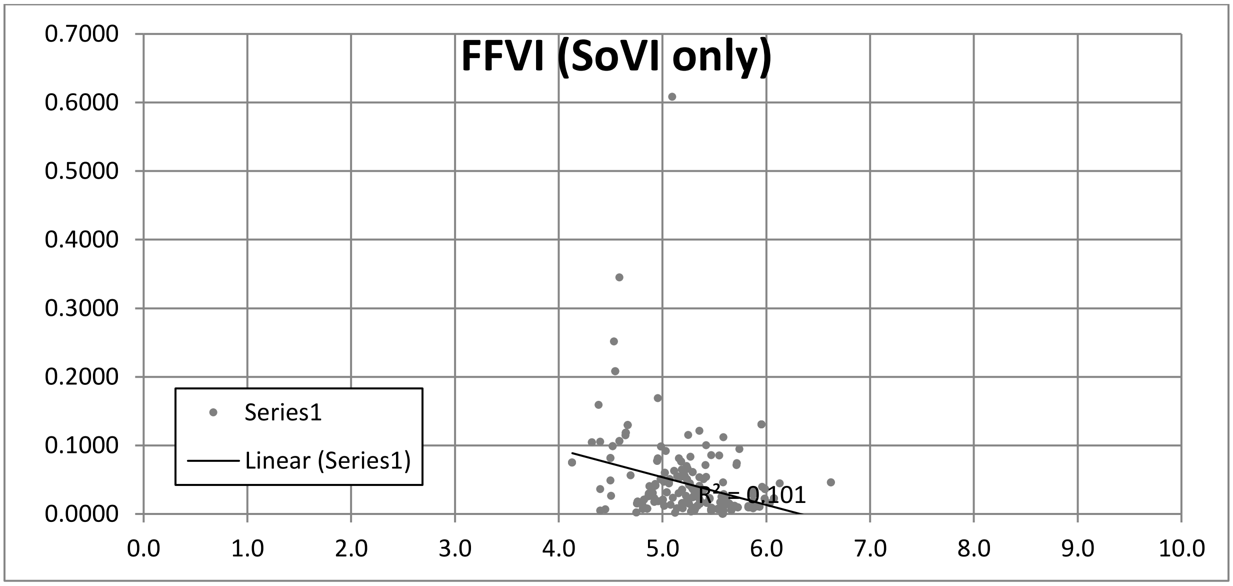


Figure 10. The SoVI component of FFVI compared to the density of flash flood reports for the SW Missouri test area.

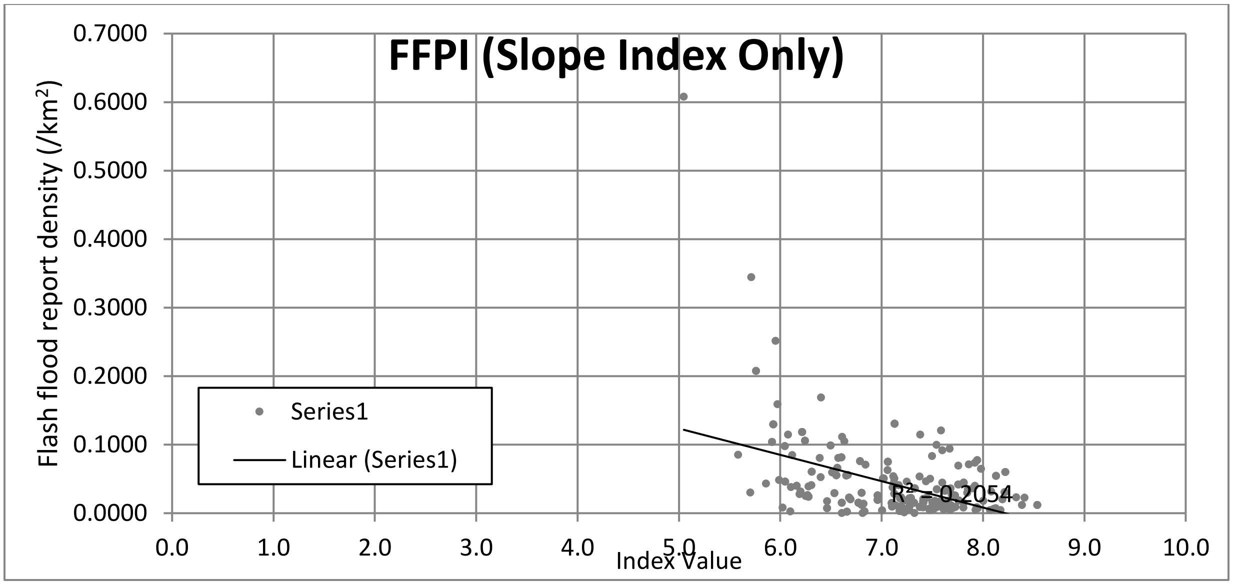


Figure 11. The slope component of FFPI compared to the density of flash flood reports for the SW Missouri test area.

One common theme between the indeces with positive correlations to flash flood report density is that they are each at least indirectly related to population, and, as mentioned, the possible bias in flash flood reports. Heavily urbanized areas are more likely where land is flatter. The process of urbanization removes agricultural lands and forests which have the highest abstractions. Urbanization also creates impervious surfaces such as buildings and roads.

Although unexpected, these preliminary results may provide more support to the idea that flash flooding is strongly related to the *impact* of the accumulated water, rather than the *location*. This simple analysis also supports concerns over the definition of flash flooding and the obvious lack of reports in areas where there are no people from which a report can originate. In some ways it makes sense that reports will be more numerous where there are more people able to witness the flash flooding. The lack of correlation between physical characteristics known to drive runoff and the eventual density of reported flash floods remains surprising, however.

4.0 Conclusions/Future Work

The FFPI has long been used as a tool for evaluating the relative flash flood potential of particular areas. One caveat to using FFPI is that it lacks information on flash flood vulnerability, an important component of the conceptual model of risk. A vulnerability index, referred to as FFVI, was proposed and tested for a portion of southwest Missouri. It was found that most components of both FFPI and FFVI had only weak correlations to flash flood report density, and sometimes this correlation was negative. The strongest correlations found were between flash flood reports and population-related components such as ambient population, imperviousness, and abstractions.

The test area utilized for this proposal is but one portion of one HSA. There are many potential explanations, in full or in part, for the behaviors we observed in the data. It may be that for this portion of Missouri, flood potential due to physical characteristics is high enough that no areas are more or less prone to flash flooding. In this case, most of the variability would be due to the population density. The population density may also be closely tied to whether or not a flash flood is reported, which may bias the flood density away from the physical characteristics. This bias in the reports may be so strong that it completely overwhelms the physical characteristics in the data and makes it difficult to reach conclusions from this type of analysis. Determining the reasons for the characteristics noted in the data is beyond the scope of this proposal, however.

More areas should be tested using these proposed techniques to further confirm the results. If a dataset of flash flood reports with less reporting bias becomes available, that dataset may provide a better comparison against the FFPI and FFVI methods proposed. Future work might also involve using different methods to convert the parameters to indeces, such as quantiles.

5.0 Acknowledgements

The authors would like to acknowledge the work of all previous FFPI developers and users including Greg Smith, Raymond Kruzdlo, Joseph Ceru, and Kevin Deitsch.

6.0 References

D'Ignazio, J. (2011). *Executive Strategies for Risk Management by State Departments of Transportation.* Retrieved June 2016, from http://onlinepubs.trb.org/onlinepubs/nchrp/docs/NCHRP20-24(74)_ResearchReport.pdf

Emrich, C. T., Morath, D. P., Bowser, G. C., & Reeves, R. (2014). *Climate-Sensitive Hazards in Florida: Identifying and Prioritizing Threats to Build Resilience against Climate Effects.* Hazards Vulnerability Research Institute. Retrieved June 2016, from http://www.floridahealth.gov/environmental-health/climate-and-health/_documents/climate-sensitive-hazards-in-florida-final-report-1.pdf

Green, W., & Ampt, G. (1911). Studies of soil physics part I - the flow of air and water through soils. *J. Ag. Sci, 4*, 1-24.

Smith, G. (2003). *Flash Flood Potential: Determining the Hydrologic Response of FFMP Basins to Heavy Rain by Analyzing Their Physiographic Characteristics.* NWS Technical Report, National Weather Service. Retrieved June 2016, from http://www.cbrfc.noaa.gov/papers/ffp_wpap.pdf

US Army Corps of Engineers Hydrologic Engineering Center. (2005). *Hydrologic Modeling System (HEC-HMS) User's Manual, Version 3.5.*

US FHWA Office of Planning, Environment, & Realty Planning. (2014). *Managing Uncertainty and Risk in Travel Forecasts.* U.S. Department of Transportation. Retrieved June 2016, from http://www.fhwa.dot.gov/planning/tmip/publications/other_reports/uncertainty_and_risk/page04.cfm

Zogg, J., & Deitsch, K. (2013). *The Flash Flood Potential Index at WFO Des Moines, IA.* NWS Technical Report, National Weather Service. Retrieved June 2016, from http://www.crh.noaa.gov/Image/dmx/hydro/FFPI/FFPI_WriteUp.pdf