HYDRAULIC MODEL DEVELOPMENT AND HYDROLOGIC ANALYSIS OF EAST NISHNABOTNA RIVER AND RED OAK CREEK NEAR RED OAK, IOWA

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January 2018

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INTRODUCTION

In July 2014, Red Oak signed a Provisionally Accredited Levees (PAL) agreement with the Federal Emergency Management Agency (FEMA). The PAL agreement requires that the levee owners provide data and documentation to show the levee system complies with Federal standards. The owners are required to provide the necessary data and documentation within 24 months to support accreditation. During the PAL agreement period, FEMA flood insurance rate maps (FIRMs) continue to show the levee providing protection from the 1-percent-annual-chance flood.

The levee structure is decertified if the data and documentation does not satisfy the NFIP minimum standards for reducing major flood risk. The area behind the levee is then designated as a high-risk area, requiring flood insurance for mortgages from federally regulated or insured lenders. This change in the FIRM could drastically affect those who continue to live in mapped high risk areas, and would likely negatively affect the community's historic downtown area.

The Iowa Flood Center (IFC) has agreed to provide assistance in the form of engineering data to the City of Red Oak and its consultant engineer, JEO Consulting Group, Inc. (JEO) for the FEMA PAL requirements and a potential future FIRM Letter of Map Revision (LOMR). The engineering analyses include hydrologic and hydraulic modeling of the East Nishnabotna River and Red Oak Creek.

PART I: GENERAL HYDRAULIC MODEL DEVELOPMENT

The hydraulic model was developed using the U.S. Army Corps of Engineers (USACE) Hydrologic Engineering Center's River Analysis System (HEC-RAS) version 5.0.3. The newest software version is capable of both one- and two-dimensional simulation of flood flow, and has quickly become widely used in the engineering community. HEC-RAS is a powerful computational and visualization tool, with the ability to rapidly analyze multiple flow and geometry scenarios.

The East Nishnabotna River and associated floodplain on the riverward side of Red Oak's levee system was modeled using a one-dimensional hydraulic model. The main channel of Red Oak Creek was modeled using a one-dimensional hydraulic model, coupled to two-dimensional hydraulic models of overbank areas on the interior side of the levee system. The exchange of flow between the one- and two-dimensional model domains is modeled using a weir structure. Culverts passing through the levee structure were also modeled and coupled to the East Nishnabotna River one-dimensional model to allow for consideration of high tail water conditions.

UNITS AND COORDINATE SYSTEM

All units are in feet. Elevations included in the model geometry reference the North American Vertical Datum of 1988 (NAVD88). The horizontal coordinate system is Iowa State Plane South (1402).

Data leveraged from previous studies referencing the National Geodetic Vertical Datum of 1929 (NGVD29), were converted to NAVD88 using corrections from the National Oceanic and Atmospheric Administration's (NOAA) VERTCON tool.

TOPOGRAPHIC AND BATHYMETRIC DATA SOURCES

Topographic information was provided by IDNR in the form of one-meter resolution bare-earth LiDAR datasets collected in April 2007 and May 2010. These data were used for all overbank cross-sections areas or two-dimensional flow areas.

East Nishnabotna River bathymetry was collected by IFC in September 2015. Bathymetric measurements were collected using a SonTek RiverSureyor M9 acoustic Doppler profiler (ADP) deployed from an inflatable kayak. The face of the transducer was submerged 0.4 feet (0.12 meters) below the water surface, a depth sufficient to prevent entrained air interfering with measurements. The reported accuracy of the depth measured by the vertical echo-sounder is 1% of the measured depth with a resolution of 0.003 feet (0.001 meters).

Horizontal and vertical positions were measured using a Trimble R8 RTK global navigation satellite system (GNSS). The Trimble R8 is rated with horizontal and vertical accuracy of ± 0.03 feet and ± 0.07 feet, respectively, with real-time corrections from a ground-based reference station. Real-time corrections were provided via cellular modem by the Iowa Real Time Network (IaRTN), a statewide system of reference stations operated by the Iowa Department of Transportation (IDOT).

SonTek RiverSurveyor Live software was used to integrate system components, and store measured data. Depth was recorded at each position along the kayak's path at a rate of 1 Hz. Transects were spaced one channel width apart, approximately 150 to 200 feet. East Nishnabotna River bathymetry was interpolated from transect to transect in GIS, creating a continuous surface of channel bathymetry that was mosaicked with the overland LIDAR topography to create a digital elevation model (DEM).

Top of levee elevations and typical levee cross-sections were also collected using the Trimble R8 GNSS. Locations of levee and bathymetry measurements are shown in Figure 1.

Red Oak Creek channel bathymetry was leveraged from the currently effective FEMA hydraulic model developed using HEC-2 software. Paper copies of HEC-2 input cards were manually digitized and organized in HEC-2 text format for import into HEC-RAS. The model was developed by Stanley Consultants, Inc. for the original FEMA flood insurance study (FIS) in 1978. In 1990, a revision of the hydrologic and hydraulic analyses was completed by USACE Omaha District. Elevations originally referenced NGVD29, but were converted to NAVD88.

CROSS-SECTIONS

East Nishnabotna cross-sections were extracted from a DEM developed using the one-meter resolution LiDAR and an interpolated bathymetry surface. Cross-section locations are shown in Figure 2. All cross-section station elevation points were reduced to 500 points using the "Minimize Area Change" filter available within HEC-RAS.

The final East Nishnabotna River model was extended approximately 4,000 feet downstream of the bathymetry measurements collected by IFC at the request of JEO. Trapezoidal channel inverts at cross-section stations 1969 and 0 were estimated by extrapolating the measured channel invert elevation at station 4054, using the bed invert slope from stations 7546 to 4054. Channel bank slopes at stations 1969 and 0 were extended downwards until intersection with the extrapolated bed invert elevation at each cross-section. All other cross-section station elevation data was extracted from LiDAR data at stations 1969 and 0.

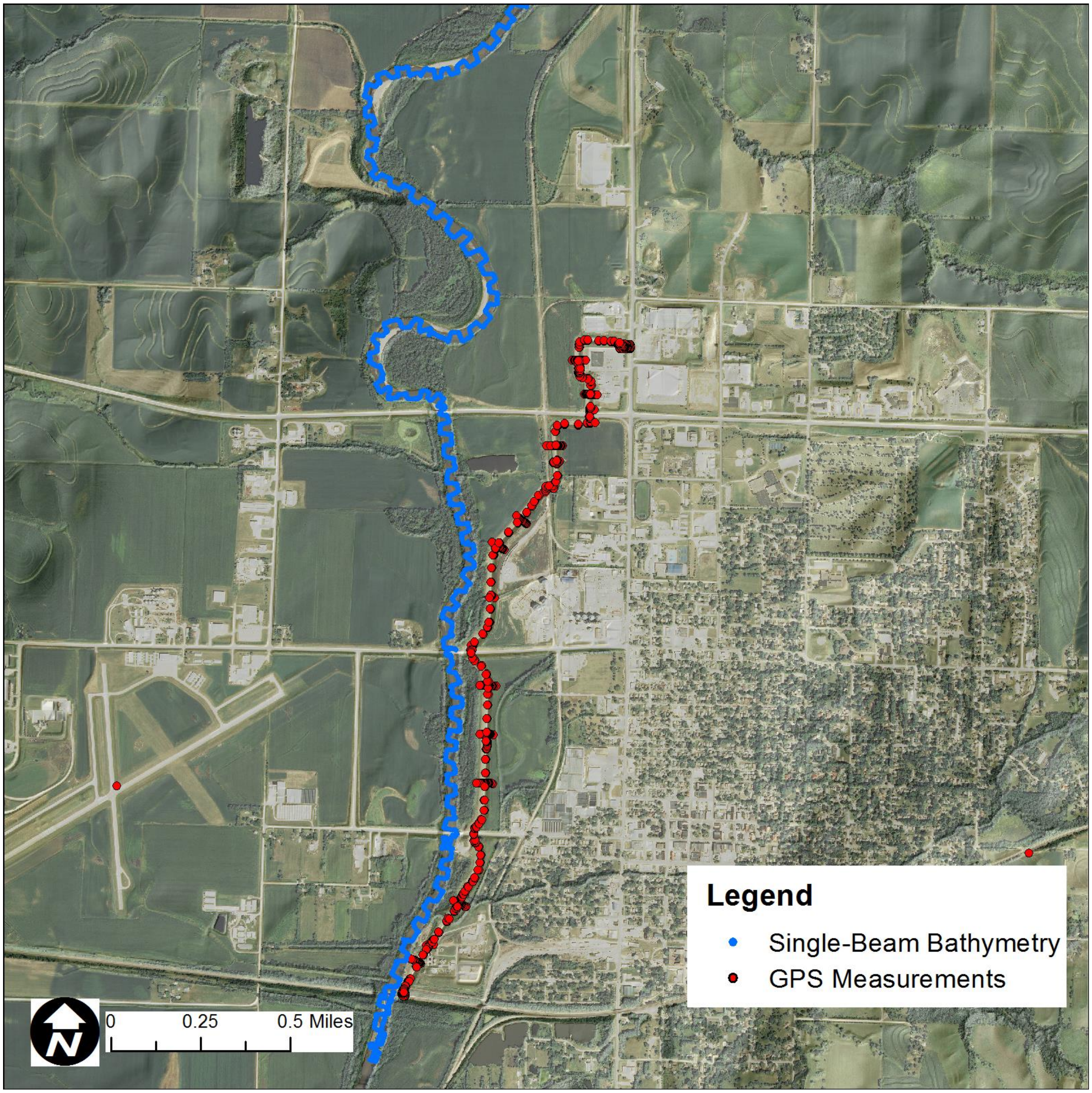

Figure 1. IFC measurements of East Nishnabotna River bathymetry and top of levee elevations

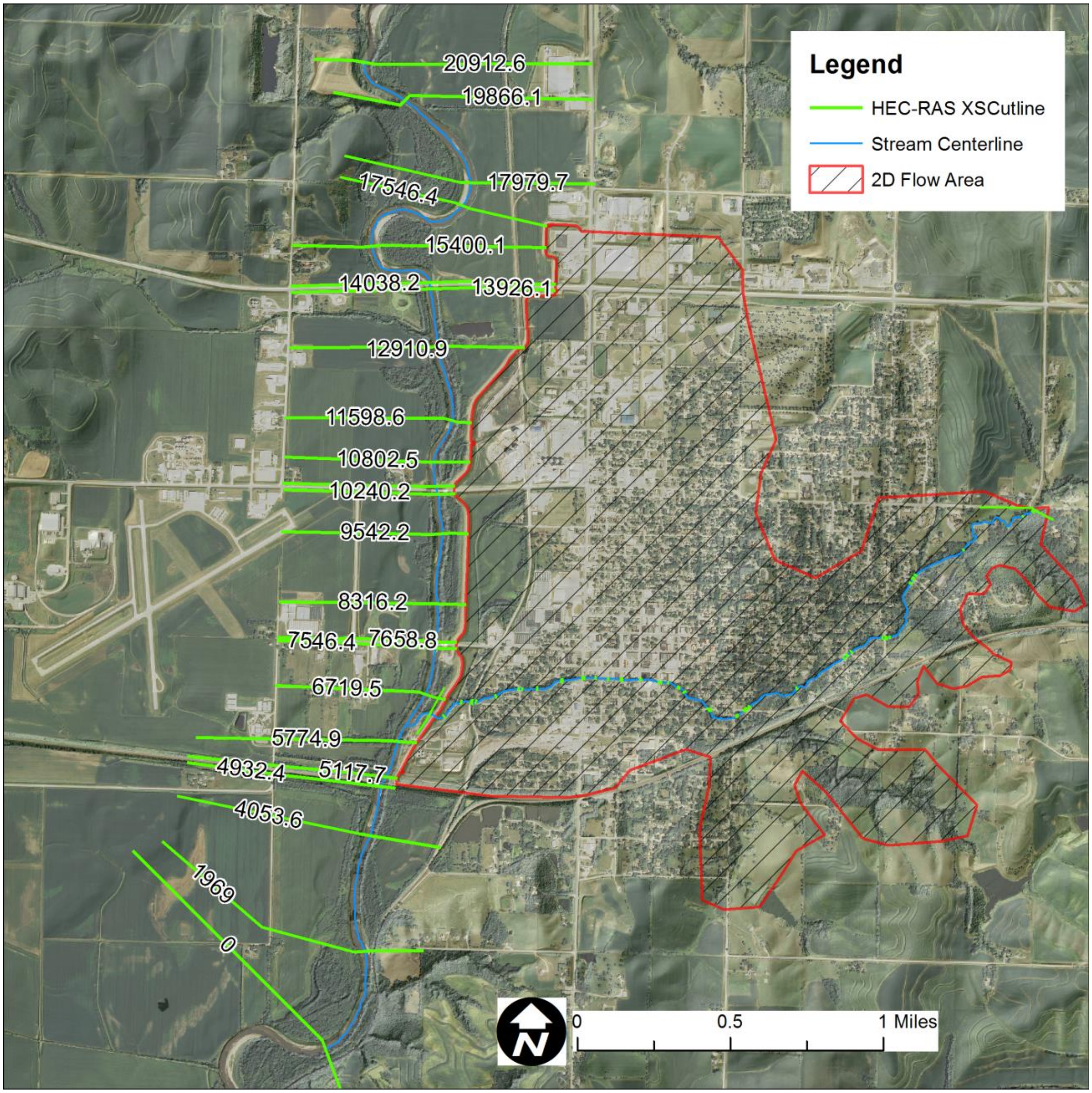

Figure 2. Cross-section and 2D flow area locations for each stream modeled using HEC-RAS

Energy losses due to contraction or expansion of flow were captured using contraction and expansion coefficients. The absolute difference in velocity head between two cross-sections are multiplied by coefficients to estimate the energy loss due to change in flow area. Typical transitions in this model and the corresponding coefficients used are shown in Table 1. These coefficients are recommended by the HEC-RAS Hydraulic Reference Manual. These coefficients are not used in unsteady flow simulations, the intended use of this model.

Table 1. Contraction and Expansion coefficients

Transition	Contraction	Expansion
No transition loss computed	0	0
Gradual transitions	0.1	0.3
Typical bridge sections	0.3	0.5

Ineffective flow areas were used to represent contractions and expansions of flow by removing conveyance areas near road and railroad embankments. The majority of ineffective flow areas are non-permanent, such that the conveyance area becomes active when the ineffective flow area is overtopped. Some ineffective flow areas are permanent to prevent over-estimation of conveyance.

Red Oak Creek cross-sections include all the original HEC-2 station-elevation data. It was necessary to manipulate the model in order to utilize the two-dimensional overbank model derived from LiDAR, rather than the overbank HEC-2 cross-sectional areas. This is accomplished by designating how water is exchanged across the lateral structure, between the one-dimensional model of Red Oak Creek's channel and the overbank two-dimensional model. The headwater position within the one-dimensional model's lateral structure was designated next to the left or right bank station. This allowed the overbank topography within the cross-section to be ignored, utilizing only channel geometry to determine water surface profiles along the channel. Water is then allowed to enter or leave the two-dimensional overbank model derived from LiDAR data.

Spatial locations of Red Oak Creek cross-sections were determined using geo-referenced GIS shapefiles developed by Strategic Alliance for Risk Reduction (STARR) for FEMA as part of Montgomery County's redelineation mapping process, under contract No.HSFEHQ-09-D-0370, Task Order No.HSFE07-10-J-0003, in 2014.

OVERBANK AREAS

The levee system's interior area was modeled using a two-dimensional model derived from LiDAR data. HEC-RAS flow area meshes can use structured or unstructured cells, varying in number of sides from 3-8 sides. Typical computational cells were square and had dimensions of

30-feet. Breaklines were used along the centerline of roadways and embankments to ensure crown elevations were captured.

The default Diffusion Wave equations were utilized for simulations due to subcritical flow conditions, relatively low velocities and gradual flow fluctuations present in the two-dimensional hydraulic model domains.

ROUGHNESS COEFFICIENTS

Spatially-varied Manning's n roughness values were developed based on typical values recommended by Chow (1959), and parameterized by a 2009 High-Resolution Land Cover (HRLC) dataset developed by IDNR. A table summarizing Manning's n parameterization is shown in Table 2.

Channel roughness values for the East Nishnabotna River were set to 0.032, based on the calibration and validation process discussed this document. Channel roughness values for Red Oak Creek were taken directly from the currently effective FEMA HEC-2 hydraulic model. These roughness values, ranging from 0.02 to 0.045, were selected by USACE based on visual inspection, aerial and field photos, and engineering judgement.

Table 2. Manning's n roughness values parameterized using high-resolution land cover data.

HRLC Classification	Manning's n
barren / fallow	0.020
coniferous forest	0.150
corn	0.035
cut hay	0.040
deciduous medium	0.050
deciduous short	0.120
deciduous tall	0.100
grass 1	0.040
grass 2	0.040
roads / impervious	0.015
shadow / no data	0.020
soybeans	0.035
structures	0.500
water	0.032

wetland	0.032

BRIDGE STRUCTURES

Bridge structures crossing the East Nishnabotna River were incorporated into the HEC-RAS model using as-built plans provided by IowaDOT and Montgomery County. Bridge deck high- and low-chord elevations reported in the as-built plan sets were adjusted based on field measurements collected by IFC in September 2015. Pier and abutment geometry information were also incorporated into the HEC-RAS model. Top of roadway embankment elevations were extracted from LiDAR data. Geometry of the BNSF railroad bridge crossing East Nishnabotna River at station 5007 was incorporated using the effective FEMA model for East Nishnabotna River developed by Stanley Consultants using its proprietary CH20A software. Elevations were adjusted using a field measurement of the approximate high chord elevation collected by IFC.

Bridge structures crossing Red Oak Creek were incorporated into the HEC-RAS model using geometry contained in the HEC-2 model, adjusted to NAVD88. It is possible that some of these structures have been modified or replaced since the development of the effective FEMA model.

Energy methods were selected to model low and high flow conditions at each bridge structure on the East Nishnabotna River and Red Oak Creek.

LEVEE CONSIDERATIONS

Outlet structures along the levee system were incorporated into the model using geometry data included in the levee's Operation and Maintenance Manual provided by USACE Omaha District. Invert elevations were provided by JEO, collected as part of the PAL agreement. The main outlet for Red Oak Creek was incorporated as an inline structure in the one-dimensional model, other structures were incorporated as connections to the 2D flow areas. The five structures modeled as connections to the 2D flow areas were modeled as culverts with flap gates. Intermediate storage areas were created at each structure to enable connection to the East Nishnabotna River model for consideration of high tail-water conditions. Small lateral weir structures were also created at relevant points along the East Nishnabotna River model to allow flow exchange with the intermediate storage areas.

CALIBRATION AND VALIDATION

The East Nishnabotna River model was calibrated for low-flow conditions, less than 10,000 cubic feet per second, by altering channel roughness values to reproduce the United States Geological Survey (USGS) rating curve at river gaging station (06809500). The model was validated at higher flows using the same established rating curve. A plot showing the simulated rating curve using the HEC-RAS model, along with the USGS Rating Curve is shown in Figure 3. Simulation results from a previous MIKE FLOOD hydraulic model of the East Nishnabotna River developed by IFC are also shown for comparison. The simulation results closely follow the established rating curve for the full range of flows at this location.

A plot showing water surface profiles using the FEMA effective East Nishnabotna River 100-year discharge (42,300 cfs) simulated using the HEC-RAS and MIKE FLOOD models is shown in Figure 4. Both models depict the water surface being approximately 2-4 feet lower than the effective FIS water surface profile for this reach.

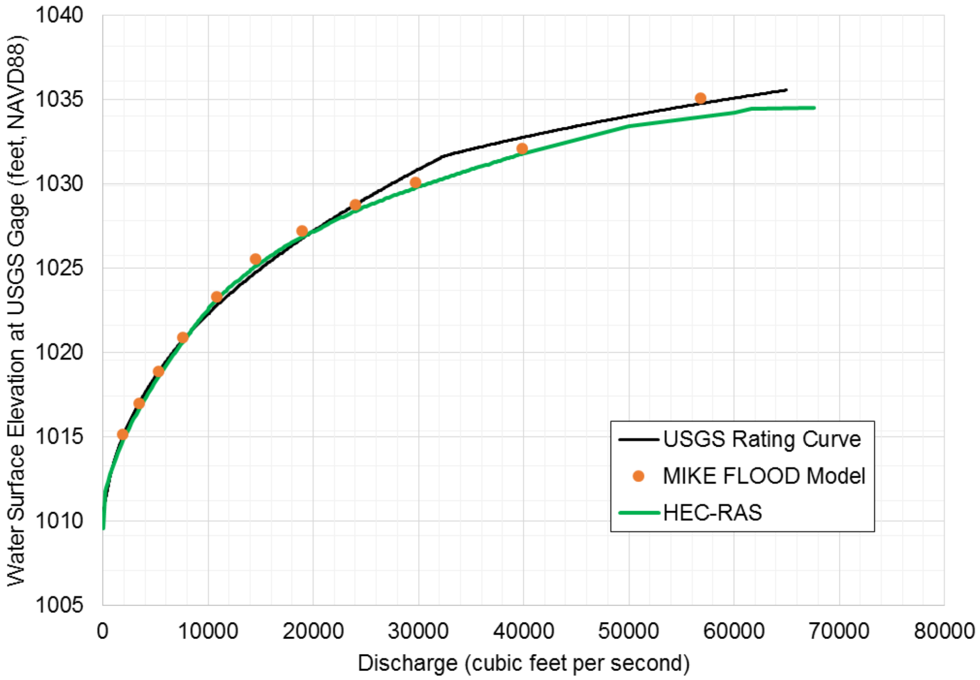

Figure 3. Comparison of simulated rating curves using the HEC-RAS model, a previous MIKE FLOOD model, and the established USGS Rating Curve at the East Nishnabotna River gaging station (06809500)

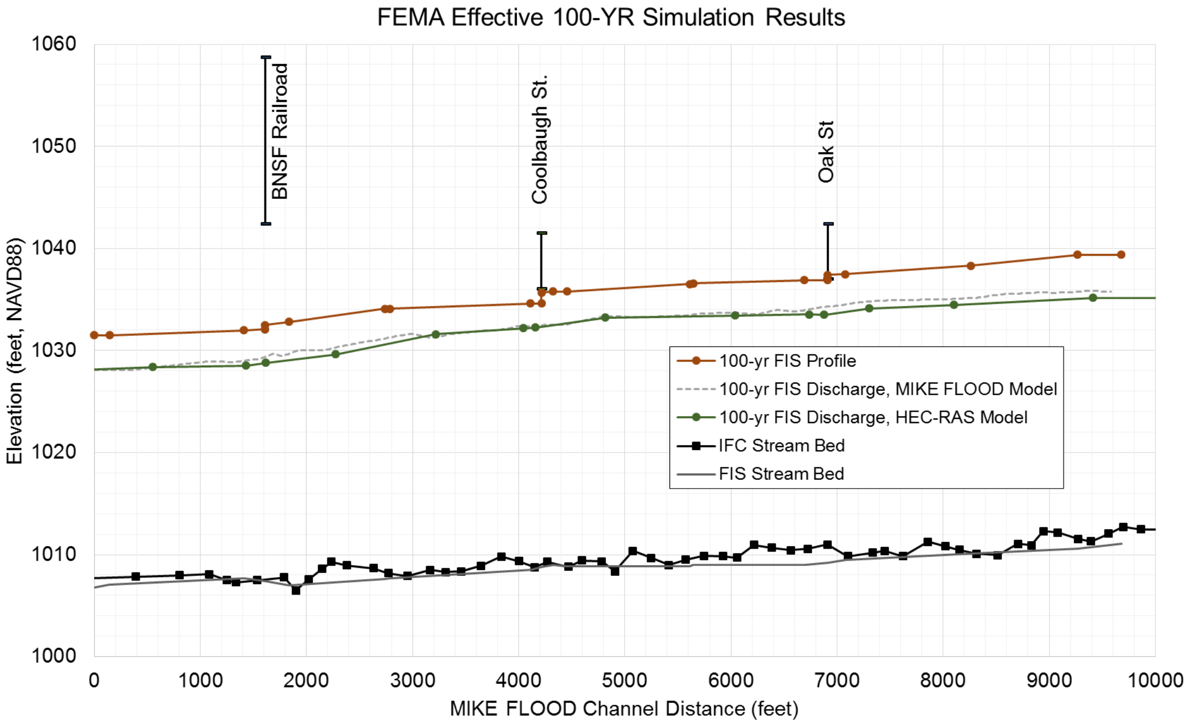

Figure 4. Simulation results using the effective 100-year discharge. The simulated HEC-RAS water surface profile is plotted with results from a MIKE FLOOD model, and the effective FEMA FIS 100-year water surface profile.

PART II: GENERAL HYDROLOGIC ANALYSIS APPROACH

East Nishnabotna River flow frequency estimates were calculated using a Bulletin 17B analysis of annual peak discharge estimates. These estimates were then weighted using regional skew estimates, as suggested by the Interagency Advisory Committee on Water Data (1982).

Red Oak Creek flow frequency estimates were estimated using a lump-parameter hydrologic model developed using USACE Hydrologic Engineering Center's Hydrologic Modeling System (HEC-HMS).

BULLETIN 17B ANALYSIS

Peak discharge estimates for the East Nishnabotna River were provided by the USGS at river gaging station 06809500. The systematic record length was 89 years, encompassing years 1917-1925 and 1936-2015, as shown in Figure 5. Regional regression equation parameters were provided by Eash (2001).

Flow frequencies were estimated using procedures described in Bulletin 17B guidelines created by the Hydrology Subcommittee of the Interagency Advisory Committee on Water Data (Interagency Advisory Committee on Water Data, 1982). A Bulletin 17B analysis was completed using USACE Hydrologic Engineering Center's Statistical Software Package (HEC-SSP) Software to estimate the discharges at selected exceedance probabilities. A regional skew value of -0.465 and a regional skew mean-square error (MSE) of 0.156 were used as regional skew parameters based on Eash (2013). The station and regional skew coefficients can be combined to form a better estimate of skew (Interagency Advisory Committee on Water Data, 1982). A weighted skew was determined by weighting the station skew and the regional skew as shown in the following equation (Interagency Advisory Committee on Water Data, 1982):

$$G_W = \frac{MSE_{\bar{G}}(G) + MSE_G(\bar{G})}{(MSE_{\bar{G}} + MSE_G)}$$

Where: G_W = weighted skew coefficient

G = station skew

$\bar{G}$ = generalized skew

$MSE_{\bar{G}}$ = mean-square error of generalized skew

MSE_G = mean-square error of station skew

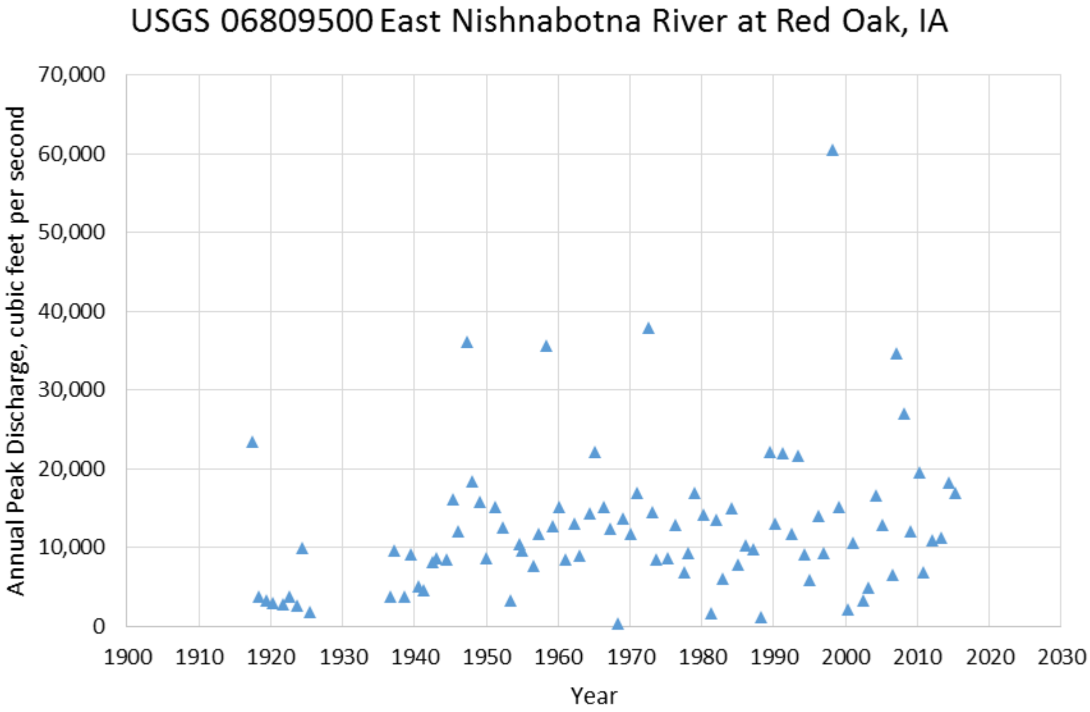

Figure 5. Annual peak discharge estimates at USGS river gaging station 06809500 at Red Oak, Iowa

A plot showing the results of the Bulletin 17B analysis is shown in Figure 6. Annual-Chance Probability estimates for the 0.2, 0.5, 1, 2, 4, and 10-percent discharges are shown in Table 3.

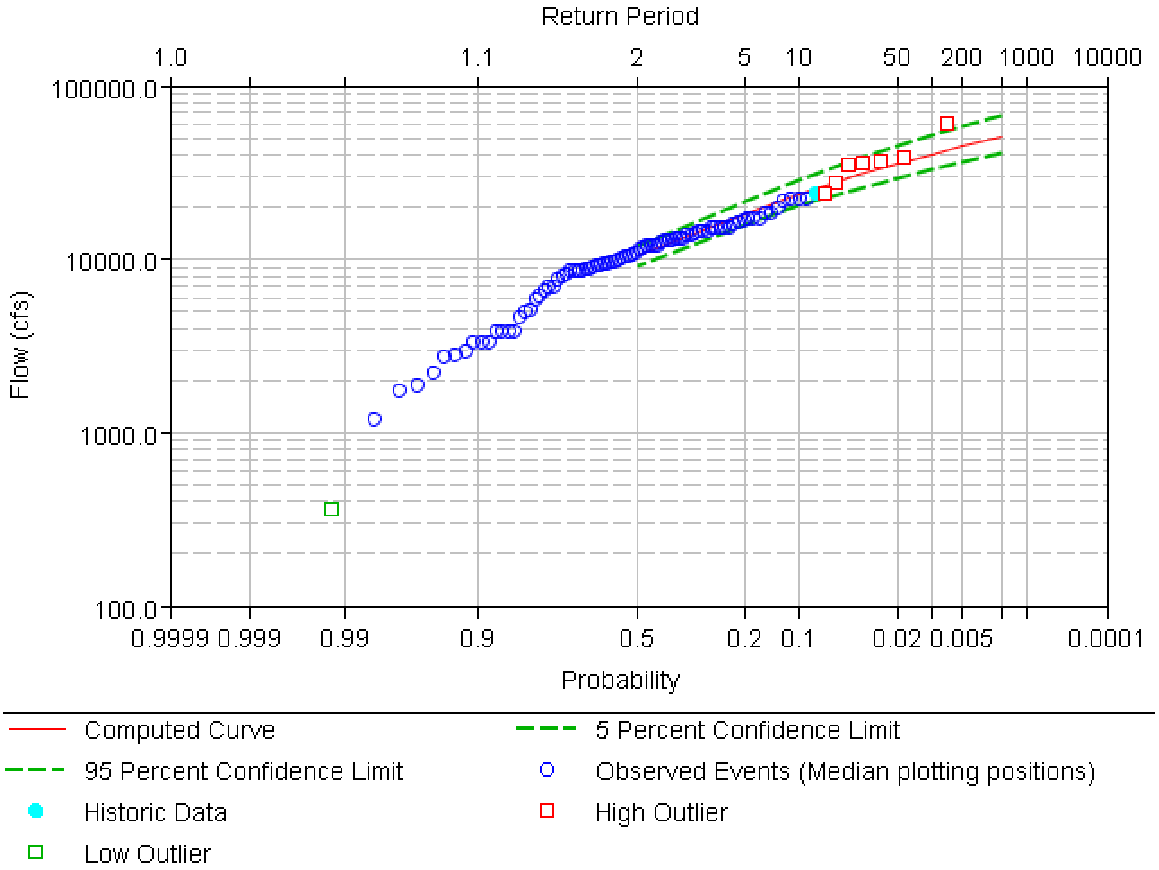

Figure 6. Results from HEC-SSP Bulletin 17B analysis

Table 3. Percent-Annual-Chance Probability estimates developed using a Bulletin 17B analysis

Return Year	Percent-Annual-Chance Probability	Bulletin 17B Estimate, cfs
10	10	23720
25	4	30560
50	2	35540
100	1	40380
200	0.5	45080
500	0.2	51090

Weighted Results

Flood flow frequencies estimated using the Bulletin 17B analysis can be improved by weighting the estimates with estimates calculated using regional regression equations shown in Table 4 (Eash, 2001). Weighted discharge estimates were calculated using the following equation (Eash, 2001):

$$Q_{t(wg)} = \frac{(Q_{t(pg)})(ERL) + \left(Q_{t(rg)}\right)(EYR)}{(ERL + EYR)}$$

Where: $Q_{t(wg)}$ = weighted discharge estimate for recurrence interval t

$Q_{t(pg)}$ = discharge estimate using log-Pearson Type III (Bulletin 17B)

ERL = effective record length

$Q_{t(rg)}$ = regional regression discharge estimate using Eash (2001)

EYR = equivalent years of record for the regional regression equations

The effective record length (ERL) of a gaging station is defined in Eash (1993), using the following equation:

$$ERL = LS + (HST - LS)\left[0.55 - 0.1\left[log_e\left(\frac{ph}{1 - ph}\right)\right]\right]$$

Where: LS = systematic record length, in years

HST = historic record length, in years

ph = 1.0 – (np/HST), where np is the number of historic and extremely large discharge (high outlier) peaks

Table 4. Eash (2001) Single-Parameter USGS Regional Regression Equations for the State of Iowa. (Equivalent years of record associated with the equations are shown in parentheses)

Single Parameter Regression Equations
$Q_{10} = 728 \times A^{0.465}$ (13.5 years)
$Q_{25} = 1120 \times A^{0.441}$ (20.5 years)
$Q_{50} = 1440 \times A^{0.427}$ (24.0 years)
$Q_{100} = 1800 \times A^{0.415}$ (25.9 years)
$Q_{200} = 2200 \times A^{0.403}$ (26.5 years)
$Q_{500} = 2790 \times A^{0.389}$ (26.0 years)

Final weighted discharge estimates along with weighting parameters are shown in Table 5.

Table 5. Parameters used to calculate final weighted discharge estimates using Eash (2001).

Return Year	Percent-Annual-Chance Probability	Bulletin 17B Estimate, $Q_{t(pg)}$, cfs	Equivalent Record Length, *ERL*, years	Regional-Regression, $Q_{t(rg)}$, cfs	Equivalent Years of Record, *EYR*, years	Final Weighted Discharge, $Q_{t(wg)}$, cfs
10	10	23,720	92.1	17,161	13.5	22,880
25	4	30,560	92.1	22,429	20.5	29,080
50	2	35,540	92.1	26,220	24	33,610
100	1	40,380	92.1	30,208	25.9	38,150
200	0.5	45,080	92.1	34,029	26.5	42,610
500	0.2	51,090	92.1	39,239	26	48,480

HYDROLOGIC MODEL DEVELOPMENT

The lumped parameter HEC-HMS model of Red Oak Creek was developed using HEC-GeoHMS, an ArcGIS extension. Basin characteristics were derived from LiDAR elevation data, the 2011 United States Department of Agriculture (USDA) National Land Cover Dataset (NLCD), and USDA Natural Resources Conservation Service's (NRCS) SSURGO soil data.

Subbasins delineated using the HEC-GeoHMS tool are shown in Figure 7. The average HEC-HMS subbasin area was 0.25 square miles. A grid of Soil Conservation Service (SCS) curve numbers, shown in Figure 8, was generating using land cover and SSURGO soil data. Curve number designations for each land cover and soil combination are shown in Table 6. The curve number grid was used to aggregate curve numbers for each subbasin. The SCS Unit Hydrograph method was used as the rainfall runoff transform method. Muskingum Routing was used for routing channel hydrographs through the drainage system upstream of the City of Red Oak.

Table 6. SCS curve numbers based on land cover and SSURGO Hydrologic Soil Group.

	SSURGO Hydrologic Soil Group			
2011 NLCD Description	A	B	C	D
Open Water	10	10	10	10
Developed, Open Space	49	69	79	84
Developed, Low Intensity	57	72	81	86
Developed, Medium Intensity	81	88	91	93
Developed, High Intensity	89	92	94	95
Bare Rock/Sand/Clay	98	98	98	98
Deciduous Forest	32	58	72	79
Evergreen Forest	32	58	72	79
Mixed Forest	32	58	72	79
Shrub/scrub	32	58	72	79
Grassland/Herbaceous	49	69	79	84
Pasture/Hay	49	69	79	84
Row Crops	67	78	85	89
Woody Wetlands	10	10	10	10
Emergent Herbaceous Wetlands	10	10	10	10

Rainfall hyetographs were developed based on hypothetical storm distributions with durations of 3-, 6-, 12-, and 24-hours as defined by Huff and Angel (1992). The 3- and 6-hour storm hyetographs had a first-quartile storm distribution, the 12-hour storm had a second-quartile storm distribution, and the 24-hour storm had a third-quartile storm distribution. NOAA Atlas 14 Point Precipitation Frequency Estimates, shown in Table 7, were used to determine total rainfall depths for a given storm duration (Perica et al., 2013). It was assumed the NOAA Atlas 14 precipitation depth estimate for a given probability would produce the corresponding annual exceedance probability discharge. For example, the 1-percent annual chance precipitation depth would produce the 1-percent annual chance discharge. An areal reduction factor developed by Hershfield (1961) was used to convert the NOAA Atlas precipitation depths at a point to a precipitation depth distributed across the entire Red Oak Creek watershed. Hyetographs for each storm duration and corresponding rainfall depths for the 100-year precipitation event are shown in Figure 9.

Table 7. NOAA Atlas 14 Point Precipitation Frequency Estimates (inches), prior to an areal reduction factor being applied.

	Average recurrence interval (years)									
Storm Duration	1	2	5	10	25	50	100	200	500	1000
3-hr	1.81	2.15	2.79	3.39	4.33	5.14	6.03	7	8.41	9.57
6-hr	2.16	2.53	3.26	3.96	5.1	6.09	7.2	8.43	10.2	11.7
12-hr	2.51	2.91	3.67	4.42	5.63	6.69	7.88	9.19	11.1	12.7
24-hr	2.86	3.29	4.12	4.91	6.17	7.27	8.48	9.83	11.8	13.4

Based on simulations of each storm duration, it was determined that the 6-hour duration storm produced the largest 100-year peak discharges on Red Oak Creek. Peak Discharges for each storm duration using the 100-year precipitation depth are shown for select locations in Table 8.

Table 8. HEC-HMS simulated peak discharges for given storm durations and 100-year return period precipitation depths.

	HEC-HMS Peak Discharge (cubic feet per second)			
Location	3-Hr Storm (6.0 in)	6-hr Storm (7.1 in)	12-hr Storm (7.7 in)	24-hr Storm (8.3 in)
at Summit Street	4,331	4,459	3,650	2,681
at Forest Avenue	4,455	4,589	3,819	2,821
at 8th Street	5,364	5,543	4,968	3,742
at Northern Railroad	5,349	5,533	4,953	3,738
at mouth	5,770	6,016	5,448	4,128

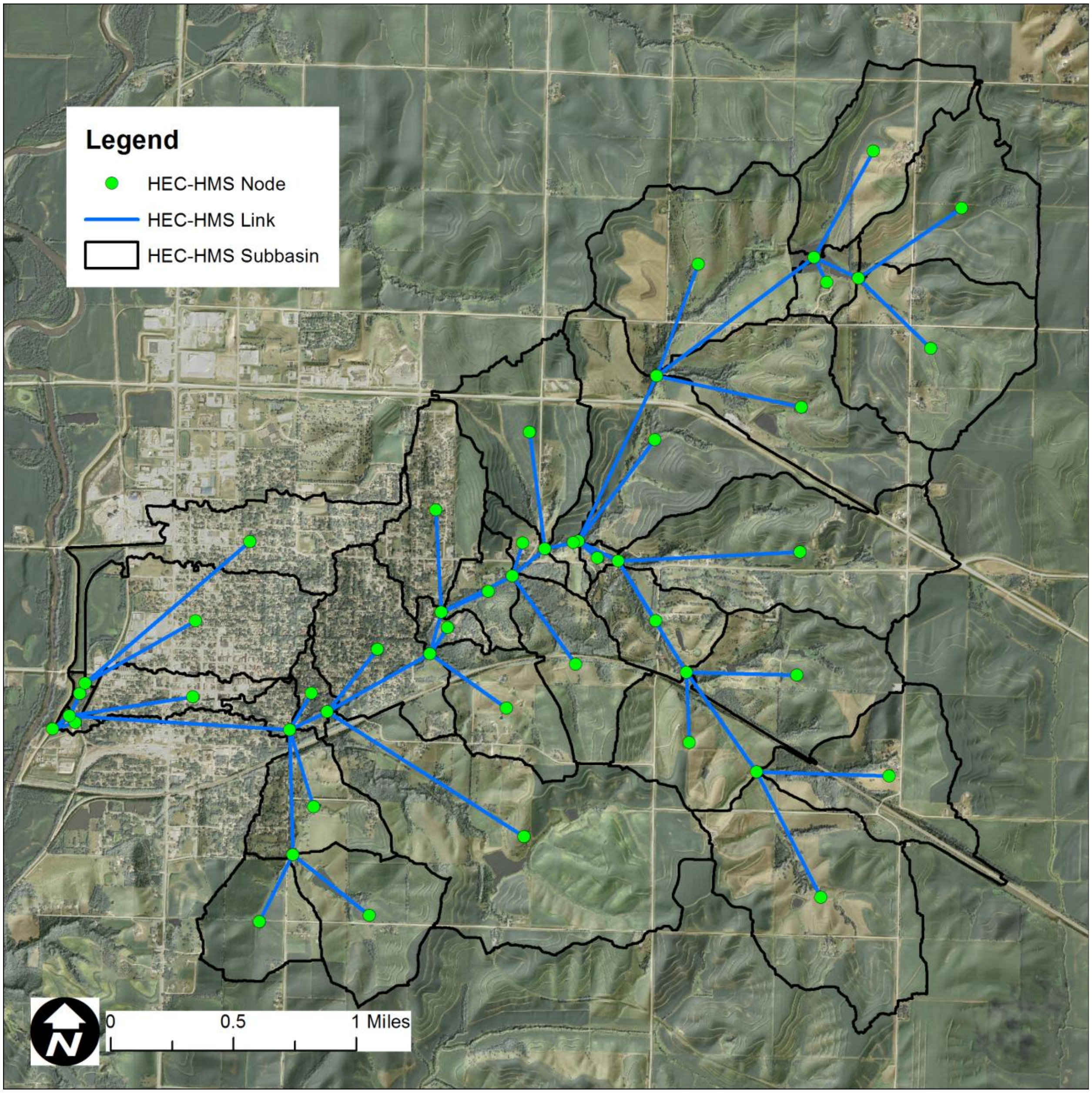

Figure 7. HEC-HMS Subbasin delineation

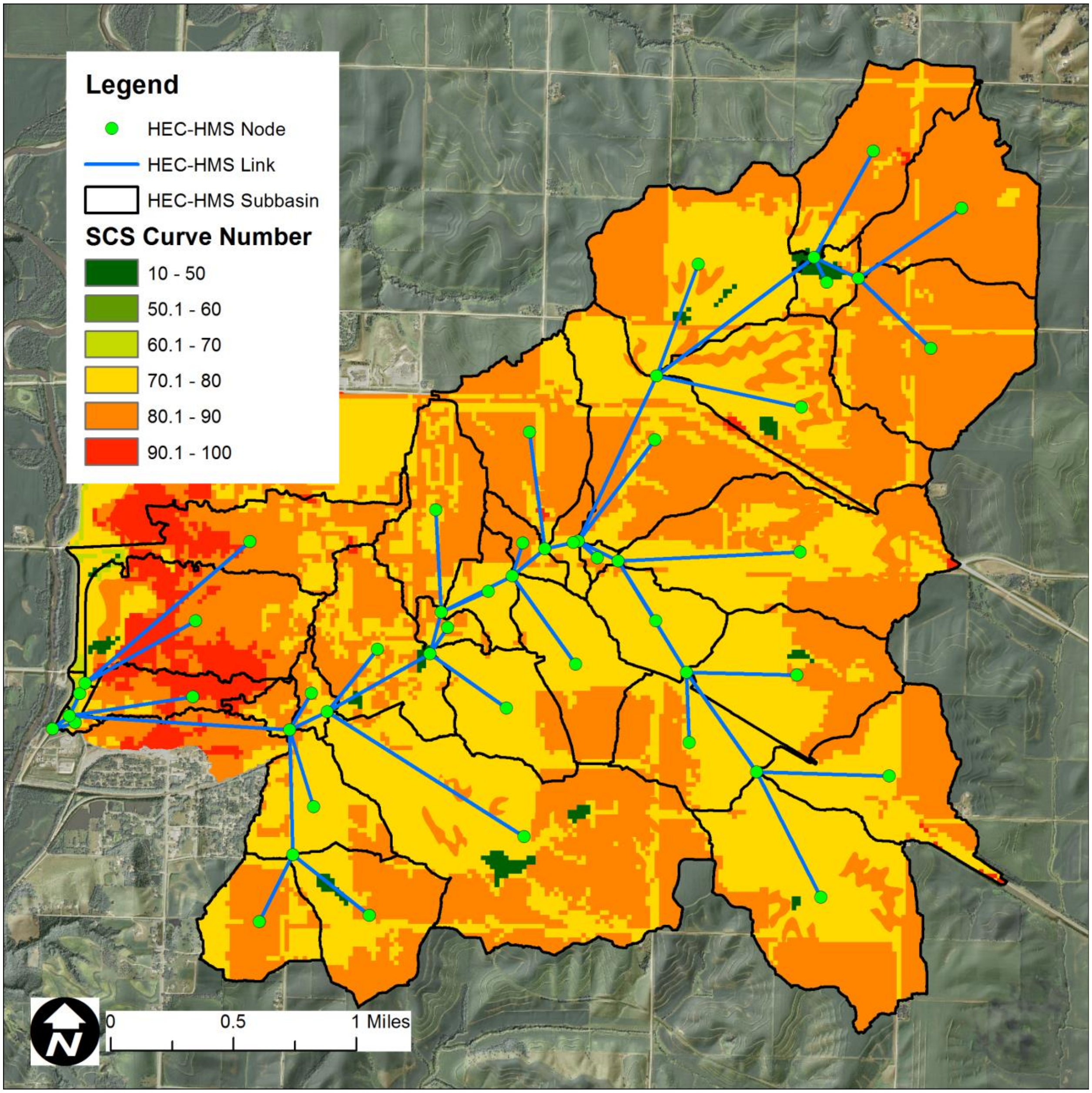

Figure 8. SCS Curve Number grid used to generate aggregated subbasin values

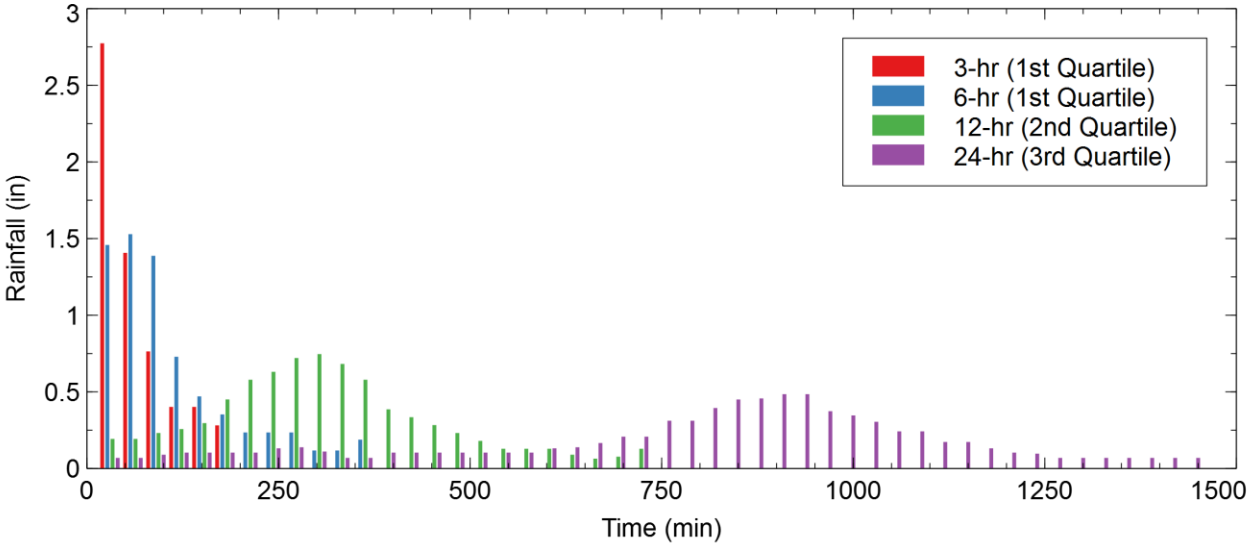

Figure 9. Hyetographs from Huff and Angel (1992), for each storm duration and corresponding 100-year precipitation depth. Rainfall is aggregated in 30 minute bins.

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