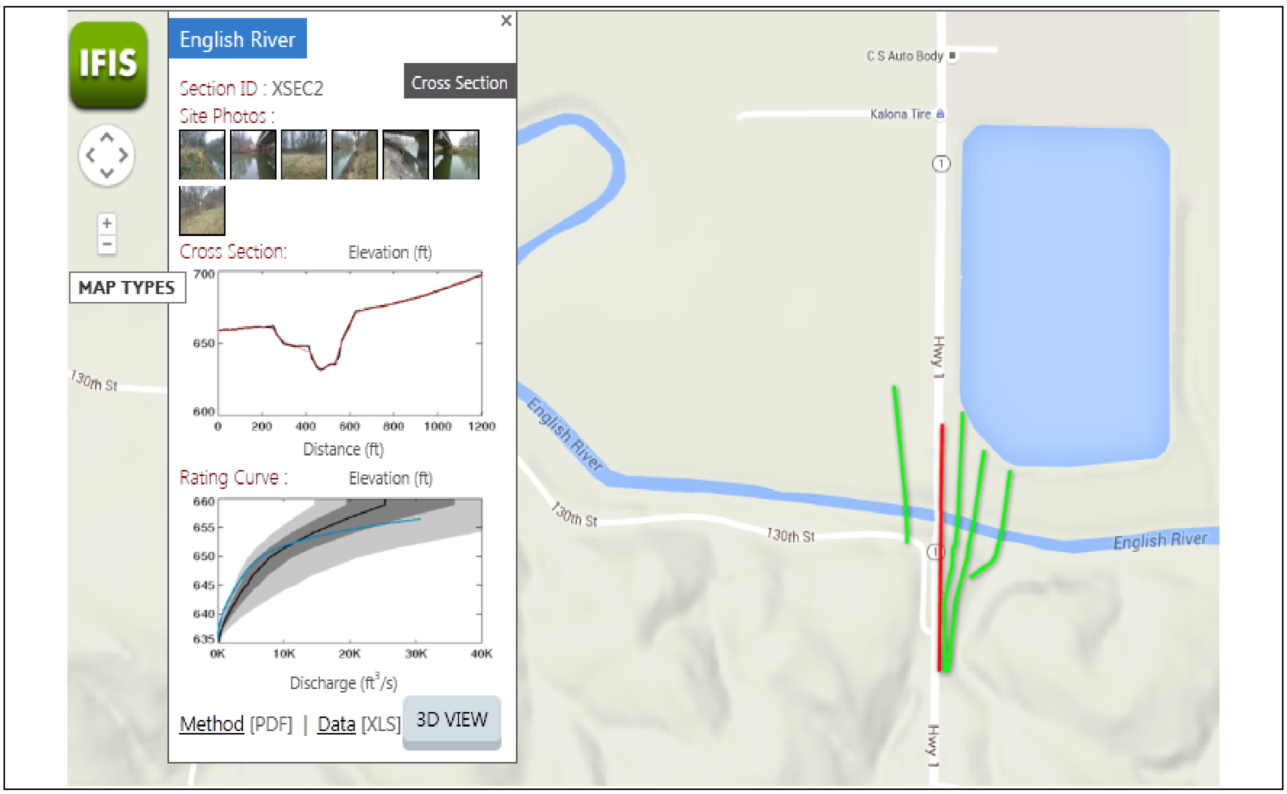
Iowa Bridge Sensor Demonstration Project
Phase I and Phase II Executive Summary Report

Floodplain Management Services
Silver Jackets Pilot Study



Final Report

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SILVER JACKETS PROGRAM

The Silver Jackets Program provides a formal and consistent strategy for an interagency approach to planning and implementing measures to reduce the risks associated with flooding and other natural hazards. State-led Silver Jackets teams bring together multiple state, federal, and local agencies to learn from one another, facilitate collaborative solutions, leverage resources, and reduce flood risk and other natural disasters. Within the U.S. Army Corps of Engineers (USACE), the Silver Jackets Program facilitates implementation of its Flood Risk Management Program at the state level. USACE established the Flood Risk Management Program to work across the agency to focus its policies, programs, and expertise and to align USACE activities with counterpart activities of other federal, state, regional and local agencies in order to manage and reduce flood risk.

PURPOSE OF REPORT

This study documents the survey methods, procedures, hydrology and hydraulic analyses, development of the bridge sensor rating curve methodologies, product strengths and limitations, peer review, evaluation of the rating curve products, and implementation costs. The bridge sensor data serves to supplement U.S. Geological Survey (USGS) gage sites and **not** replace the high quality of the USGS gage site data. Bridge sensor rating curves are intended for locations where no other means of hydraulic measurement are available as a means to provide some level of flood awareness for communities.

IOWA BRIDGE SENSOR DEMONSTRATION PROJECT PROPOSAL

Iowa's severe flooding in 2008 demonstrated the need for more extensive monitoring of the state's rivers and streams in real time. To address this, the Iowa Flood Center (IFC) developed and maintains a statewide network of stream stage sensors designed to measure stream height and transmit data automatically and frequently to the Iowa Flood Information System (IFIS), where a user can view the sensor locations and data in real-time. The IFC maintains a network of over 250 stream stage sensors across the state. Support for sensor deployment has come from the State of Iowa, Iowa Department of Natural Resources and the Iowa Department of Transportation.

The Iowa Bridge Sensor Demonstration Project leverages the existing IFC bridge sensor network data for stage-discharge rating curve development at IFC bridge sensor locations. Study partners (USACE, IFC, National Weather Service (NWS), USGS, Iowa Department of Natural Resources (IDNR), Homeland Security Emergency Management Department (HSEMD)) prioritized state-wide rating curve needs and developed a standard procedure for rating curve data collection by leveraging available data from Iowa state-wide LiDAR data, existing site specific HEC-RAS (HEC, 2010) models, and bridge plans.

The study was divided into two phases to evaluate different methodologies. Phase I and Phase II funding [$45,000 / Phase] provided to USACE was applied to bi-monthly team coordination web-meetings, project documentation and reporting, and selected site channel cross-section data collection and processing. Soundings were collected in the channels by USACE survey crews. Elevation data was collected for the water surface for each bank station at each cross-section, as well as overbank data points which were used to tie the survey data in with LiDAR data. State-wide available LiDAR elevation data was used for the overbank area to complete the cross-sections. The IFC provided project in-kind IFIS web support and rating curve development methodology and analysis. The USGS provided in-kind technical oversite. The IDNR, NWS, and HSEMD provided in-kind workgroup oversight and all project partners provided in-kind independent peer review members for project products.

During Phase I of the project, five bridge sensor locations were selected to evaluate a slope-conveyance method to produce rating curves. During Phase II, five additional bridge sensor rating curve sites were selected to expand the database for the slope-conveyance methodology assessment. Phase II provided an opportunity to refine the Phase I application and update the rating curve development for all ten sites using the step-backwater method to better quantify and minimize methodology uncertainties at stream locations where USGS gage stream flow data is not readily available. The pilot project sites are all near to a USGS gage for evaluation of the rating curves produced; however, the implementation is intended for locations without a USGS gage nearby.

When available, USACE utilized previously developed and calibrated HEC-RAS hydraulic models for cross-section geometry. Three of the five Phase I site rating curve plots and one of the five Phase II site rating curve plots show HEC-RAS model step-backwater method results computed for recent flood plain management studies independent of this pilot study. Locations having a recent HEC-RAS model calibrated to the local USGS gage rating curve are noted in Table 1. Due to the presence of the calibrated model, full cross-section data were not collected at these locations for the demonstration project.

IFC rating curves and USGS gage rating curves were compared at the ten selected locations to assess the accuracy of the bridge sensor rating curves. The locations selected for both Phase I and Phase II can be seen in the map included as Figure 1.

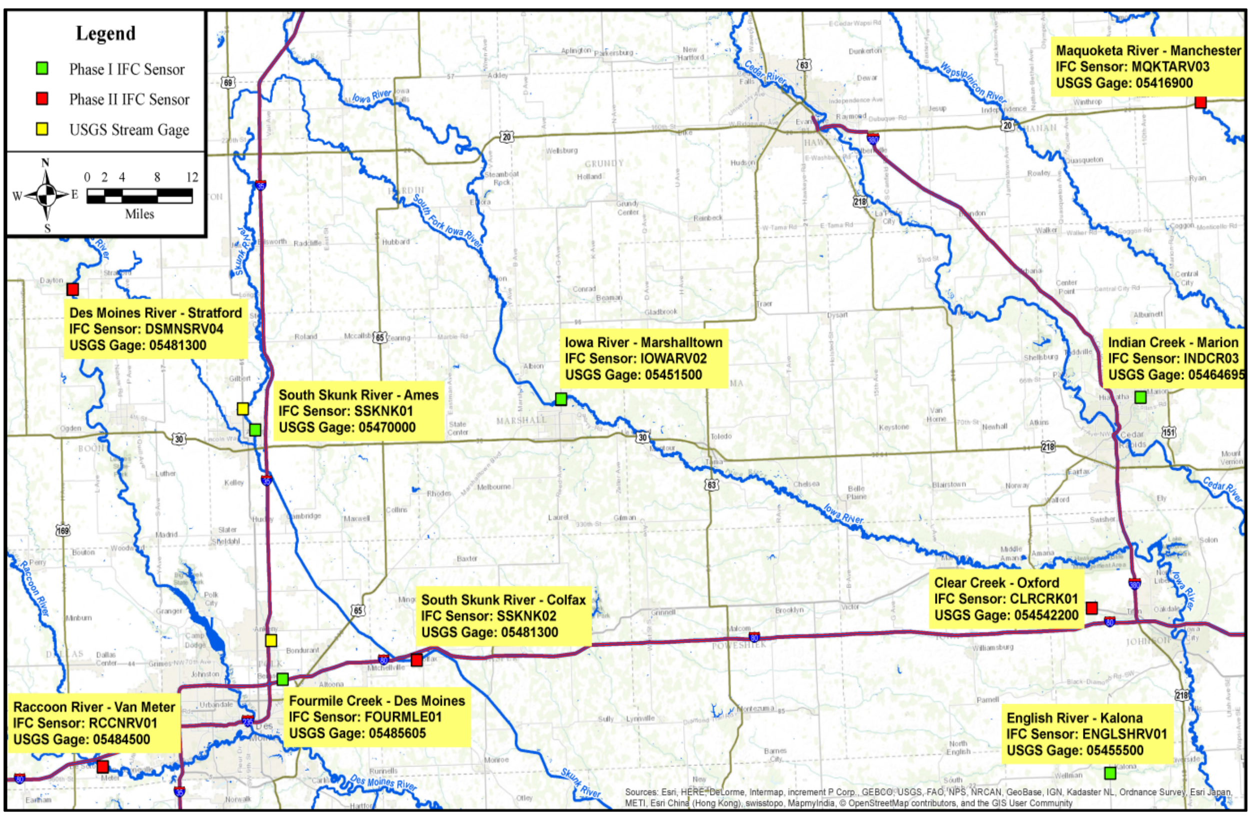

Figure 1: Iowa Bridge Sensor Rating Curve Phase I and Phase II Locations

Sites used in this assessment were selected by the interagency team members. Site selection was consistent with the requirements of the proposed methodologies to develop rating curves, and was based upon 1) the identification of collocated bridge sensor / USGS stream gage sites for rating curve comparison; 2) providing a range of drainage area, stream slope, and period of record; 3) proximity to Interstate 80 or USACE Rock Island District headquarters to minimize survey crew travel time; 4) recent existing HEC-RAS model availability to minimize the number of cross-sections collected; and 5) relatively straight reach of stream without a significant change in water slope in the study reach. If a specific site was found to be especially desirable, the IFC installed a bridge sensor at the site. The interagency team members specified and identified the number and location of cross-sections needed at each gage site for rating curve development based on the site specific channel geometry and standard hydraulic engineering practice.

Table 1: Bridge Sensor Rating Curve Sites Selected

PHASE I SELECTED SITES	**USGS Station Number**	**Drainage Area (sq. mi.)**	**Length of USGS Record (years)**	**Recent HEC-RAS Model**
ENGLISH RIVER AT KALONA	05455500	574	76	
INDIAN CREEK AT MARION	05464695	68	3	HEC-RAS
FOURMILE CREEK AT DES MOINES *	05485640	93	44	HEC-RAS
SOUTH SKUNK RIVER AT AMES *	05470000	315	96	
IOWA RIVER AT MARSHALLTOWN	05451500	1,532	84	HEC-RAS
PHASE II SITES SELECTED SITES				
CLEAR CREEK NEAR OXFORD	05454220	58	83	
DES MOINES RIVER NEAR STRATFORD	05481300	5,452	48	
RACCOON RIVER AT VAN METER	05484500	3,441	100	
SOUTH SKUNK RIVER AT COLFAX	05471050	803	30	
MAQUOKETA RIVER AT MANCHESTER	05416900	275	50	HEC-RAS

(*) Indicates sites where IFC and USGS sensors are not collocated.

RATING CURVE METHODOLOGY AND ASSUMPTIONS

The detailed description of the Iowa Flood Center Real-time Stage Sensors rating curve methodologies is provided in Appendix A ~ *Development of the Rating Curves for the Iowa Flood Center Real-time Stage Sensors, Iowa Flood Center, June 2016* ~ of this report. Briefly stated, two different methodologies were applied: 1) a slope-conveyance method, here called slope-conveyance method based on Rantz (1982), and 2) the step-backwater method computed using a one-dimensional hydraulic HEC-RAS model (HEC, 2010). It is worth noting that the first method is a very simplistic method, where a rating curve is obtained using the Manning's equation at a single cross-section without averaging conveyance across sections, and thus has limitations. The step-backwater method computed using HEC-RAS is well established in hydraulic engineering, and takes into account the changes in the geometry of the cross-section in the channel, among many other considerations.

In both cases, a general approach that handles the uncertainty of estimating the Manning's roughness was included. The approaches use Monte Carlo simulation to consider a range of feasible values of roughness in the channel derived from expert knowledge, and a range of slopes provided by surveyed data. The slope-conveyance approach is computationally inexpensive and does not require calibration. The derived rating curves consider implicitly the uncertainty of parameter estimation by providing an envelope of feasible realizations. A representative rating curve can be obtained as the median of the realizations.

Discharge ratings at USGS streamgages are generally empirically derived from periodic measurements of discharge and stage (Kennedy, 1984). The measurements of discharge are often made by direct means, such as mid-section measurement methods (Turnipseed and Sauer, 2010). At times, various types of indirect measurements are computed to define areas of the discharge rating where direct discharge measurements may not be available (Rantz and others, 1984). The rating curves obtained as part of the pilot project were compared with USGS rating curves active at the time of the survey. To quantify the difference between the USGS rating curves and the computed IFC rating curves, the root mean square error (RMSE) was calculated.

RATING CURVE RESULTS

The summary of the Phase I and Phase II site rating curve results are shown in Figures 2 through 11 of the full report. Three of the five Phase I site rating curve plots and one of the five Phase II site rating curve plots show HEC-RAS model step-backwater method results computed for recent flood plain management studies independent of this pilot study. Due to the natural shifting present in the rating curves, the USGS rating curve shown for each site is the curve that was current at the time the cross-section bathymetry data was collected. Table 1 lists the sites as well as the USGS gage number and length of record. Dates of the field survey and the USGS rating curve number and date can be found in Table 10 of the full report.

PHASE I METHOD RESULTS

The rating curves obtained using the slope-conveyance method for the full cross-section produced RMSE values, as shown in Table 2 and Table 3. Despite its simplicity and readiness for implementation without extensive maintenance, the results presented in this study show that the slope-conveyance method, as proposed here, has limitations. The main weakness of the slope-conveyance method is associated with the reliance on the geometrical characteristics of only one cross-section at a time, hence not being able to consider the effect of the transition between the cross-sections along the reach.

PHASE II METHOD RESULTS

The rating curves obtained using the HEC-RAS step-backwater modeling approach produced RMSE values, as shown in Table 2 and Table 3. The rating curves obtained using the HEC-RAS step-backwater method compare better to the curves developed by the USGS than the slope-conveyance method.

Table 2: RMSE (in feet) and Average % Error Using Slope-Conveyance and Step-Backwater Methods

Bridge Sensor Location Name	Drainage Area (sq. mi.)	Slope-Conveyance			Step-Backwater		
		Over Bank	Within Channel	Full Section	Over Bank	Within Channel	Full Section
English River at Kalona	574	5.8 (-0.6)	1.2 (-0.08)	3.4 (0.07)	5.2 (0.58)	1.3 (-0.06)	3.1 (-0.05)
Indian Creek at Marion	68	1.2 (0.31)	1.3 (0.27)	1.3 (0.31)	1.4 (0.14)	1.7 (0.21)	1.6 (0.16)
Iowa River at Marshalltown	1,532	3.2 (-0.31)	0.8 (0.07)	2.4 (-0.10)	0.9 (-0.1)	1.0 (-0.1)	0.9 (-0.08)
Clear Creek at Oxford	58	1.2 (-0.07)	0.9 (-0.02)	1.0 (-0.03)	1.1 (-0.13)	0.7 (-0.01)	0.8 (-0.06)
South Skunk River at Colfax	803	3.7 (-0.06)	2.4 (-0.33)	3.5 (0.13)	1.1 (0.01)	0.9 (0.11)	1.1 (0.01)
Raccoon River at Van Meter	3,441	2.4 (0.10)	3.8 (0.45)	3.2 (0.34)	1.6 (-0.19)	0.7 (-0.01)	1.2 (-0.07)
Des Moines River at Stratford	5,452	3.4 (-0.11)	1.0 (0.16)	2.6 (0.10)	1.4 (0.11)	1.7 (0.18)	1.6 (0.14)
Maquoketa River at Manchester	275	8.6 (-0.84)	2.4 (-0.09)	6.2 (-0.46)	2.0 (-0.21)	0.6 (-0.05)	1.4 (-0.10)

Table 3: RMSE (in cfs) and Average % Error Using Slope-Conveyance and Step-Backwater Methods

Bridge Sensor Location Name	Drainage Area (sq. mi.)	Slope-Conveyance			Step-Backwater		
		Over Bank	Within Channel	Full Section	Over Bank	Within Channel	Full Section
English River at Kalona	574	8,266 (-38)	366 (11)	4,646 (-6)	7,912 (-33)	188 (8)	4,439 (5)
Indian Creek at Marion	68	1,332 (-46)	395 (-56)	1,017 (-52)	844 (-32)	351 (-48)	665 (-43)
Iowa River at Marshalltown	1,532	56,356 (306)	644 (-48)	41,780 (92)	2,335 (15)	1,046 (61)	1,867 (41)
Clear Creek at Oxford	58	2,345 (41)	143 (3)	1,353 (5)	2,084 (55)	86 (6)	1,187 (15)
South Skunk River at Colfax	803	65,045 (47)	790 (-117)	58,735 (-38)	2,052 (0)	417 (-46)	1,861 (-1)
Raccoon River at Van Meter	3,441	11,813 (-27)	4,814 (-63)	8,860 (-51)	12,216 (28)	747 (-3)	8,442 (11)
Des Moines River at Stratford	5,452	22,201 (19)	2,838 (-32)	16,655 (-27)	4,270 (-11)	2,676 (-29)	3,648 (-20)
Maquoketa River at Manchester	275	73,631 (431)	8,886 (93)	51,227 (365)	5,957 (35)	618 (17)	4,136 (27)

CONCLUSIONS AND RECOMMENDATIONS

The step-backwater method computed using HEC-RAS requires more cross-section geometry information from the channel than the slope-conveyance method. The HEC-RAS–step-backwater method also necessitates surveying enough cross-sections downstream from the sensor of interest that the HEC-RAS model will produce accurate results at the location of the sensor. The distance between the most upstream and downstream section ranges between 3,000 and 6,000 feet. This condition is necessary to guarantee the stability of the flow along the channel reach within the hydraulic model and for the model to achieve a normal depth solution downstream of the sensor (Davidian, 1984). In a strict sense, the slope-conveyance approach requires only one cross-section that is representative of the channel's hydraulic conditions at the stream-stage sensor. The implementation of the slope-conveyance model used to calculate the rating curves only takes into account the geometry of one cross-section at a time, and does not consider the interpolation between the sections.

The most important limitation that applies to both methods is that the produced rating curves do not take into account changes over time to the stage-discharge relationship, in contrast with this capability in the USGS gaging approach. Both methods also require a good estimation of the water-surface slope, but the value that is used as input is based on the observed slope at the time of the survey. For the slope-conveyance method, the calculation of the rating curve uses the input range of values directly in Manning's equation. The HEC-RAS step-backwater method uses an initial slope value in the model set-up. However, the model performs several iterations to solve the one-dimensional equation of flow along the channel, producing a profile of the energy line that can change from section to section. The effort required to produce a rating curve using the step-backwater method is greater than what is needed for the slope-conveyance method. The most time- and money-consuming tasks are the cross-section surveys (including the post-processing with LiDAR information on the overbanks) and the set-up of multiple models in HEC-RAS to produce inputs for the Monte Carlo simulations.

Given the limitations of the slope-conveyance method, the applicability of the rating curves should be narrowed to the cross-section area below the bankfull level. Their multiple limitations lead to inaccurate results in the floodplain. For the purpose of the Iowa Flood Center, it is important to provide reliable information of stage and discharge on flooding events. Therefore, the rating curves obtained using the step-backwater method result in a more useful product.

ANTICIPATED USE OF BRIDGE SENSOR RATING CURVE METHODOLOGY

The implementation of the bridge sensor rating curve methodology utilizing the step-backwater method is a suitable resource of flow data to supplement established USGS stream gage data at locations that do not currently have a USGS stream gage. The methodology and products are not intended to replace established stream gage data. However, the products do provide water level and flow information at locations that are currently not served by the USGS gaging systems. Counties and communities using the IFIS web site and products accept the limitations to the accuracy of the information provided by IFIS. Counties and communities using the bridge sensor rating curve methodology would need to be aware that the channel cross-section geometry will need to be periodically verified. The on-line availability of this data, where no other data is available, allows flood response teams to use their limited time and resources in a more efficient and effective manner rather than engaging in repetitive, time-consuming field reconnaissance in anticipation of an impending high water flood event.

Upon completion of peer review of the demonstration project, the rating curves will be user-ready on-line, accessed by a password protected page on the Iowa Flood Center website for the ten gages studied. In addition to showcasing this technology through Silver Jacket State and National presentations, the Bridge Sensor Silver Jackets Team members will be sharing the information state-wide. Small community resiliency will be enhanced by the installation of the affordable bridge sensor technology flood response tool.

PROJECT COST PER BRIDGE SENSOR/RATING CURVE

Estimated costs for each bridge sensor are provided in Table 4.

Table 4: Estimated Cost Per Bridge Sensor

TASK	RESPONSIBLE AGENCY	COST
IFC Bridge Sensor Deployment	IFC	$3,500
Field Survey [4 channel cross-sections]	USACE	$2,500
HEC-RAS Model Development	USACE	$1,000
Application of Rating Curve Method / IFIS Posting	IFC	$1,500
COST PER BRIDGE SENSOR/RATING CURVE		$8,500

REFERENCES

Benson, M.A. and T. Dalrymple, 1967*; General field and office procedures for indirect discharge measurements.*

Davidian, J. (1984). Computation of water-surface profiles in open channels: US Geological Survey Techniques of Water-Resources Investigations, book 3, chap. *A15*, *48*.

HEC-RAS River Analysis System, Version 4.1.0, U.S. Army Corps of Engineers, Hydrologic Engineering Center, Davis, California, January 2010.

Kennedy, E.J., 1984, *Discharge ratings at gaging stations: U.S. Geological Survey Techniques of Water-Resources Investigations*, Book 3, Chap. A10, 59 p.
(Also available at https://pubs.usgs.gov/twri/twri3-a10/.)

Rantz, S.E., and others, 1982, *Measurement and computation of streamflow: U.S. Geological Survey Water-Supply Paper 2175*, v. 2, 631 p.
(Also available at http://pubs.usgs.gov/wsp/wsp2175/html/wsp2175_vol2.html.)

Turnipseed, D.P., and Sauer, V.B., 2010, Discharge measurements at gaging stations: U.S. Geological Survey Techniques and Methods Book 3, Chap. A8, 87 p.
(Also available at https://pubs.usgs.gov/tm/tm3-a8/.)