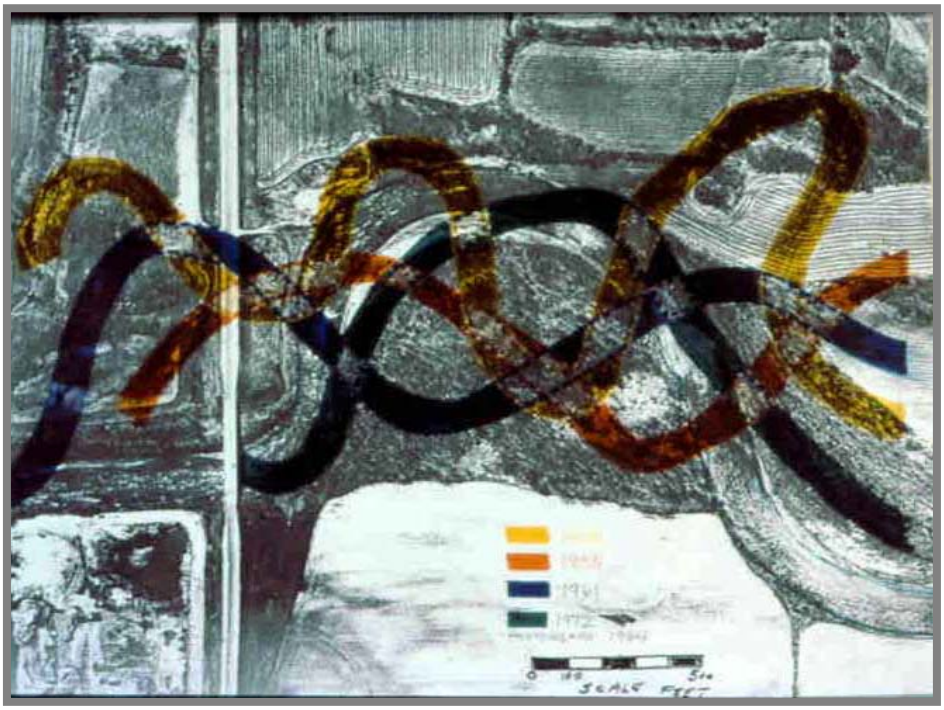
TR-567
Development of Stage-Discharge Relations for Ungaged Bridge Waterways in Western Iowa

FINAL REPORT



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15. ABSTRACT

Stage-discharge relations constitute a viable, alternative technique for estimating accurately flow for ungaged sites. In this research, we have utilized pressure transducers and Large Scale Particle Image Velocimetry techniques to develop stage-discharge relations at eleven sites in the Hungry Canyon Area (HCA) of southwestern Iowa under different hydrologic conditions. We have employed these data to calibrate and verify an established hydrologic model and then we have used this model to provide a stage-discharge relation for different hydrologic conditions (i.e. rating curves). The benefits of the project are numerous including that the discharge data will be used for a number of purposes, including operational decision making in the HCA about the design of water-control and conveyance structures, input for hydraulic and hydrologic models, and calculation of sediment and other water-quality constituents transport and "loads", and for decision making. This project has also pointed out the difficulties in measuring flows in ungaged streams with ice jams, steep banks, erodible beds, and floating debris.

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1. PROJECT SYNOPSIS

1.1 Introduction and chronology of project activities

Accurate and continuous information about stream discharge data are a prerequisite for analyzing many hydrologic, geomorphologic, and ecological processes in streams. However, direct measurements of stream discharge are laborious, costly, and sometimes impractical especially during high flows or floods.

Therefore, discharge records are usually obtained from surrogate variables such as stage, or water depth, which can be measured easily and more accurately. Stage and discharge are often related through regression techniques, i.e., fitting a power law curve through the data. This stage – discharge relationship is known as a *flow rating curve* and their use for stream discharge predictions is a standard practice for agencies like the U.S. Geological Survey (USGS).

This report summarizes the work conducted by IIHR-Hydroscience & Engineering at the University of Iowa, to establish in the Hungry Canyons Alliance (HCA) region of southwestern (SW) Iowa, a stage-discharge relationship for 11 ungaged streams most of which are in the drainage networks of the East and West Nishnabotna Rivers, as well as the Boyer and Nodaway Rivers.

This project from its inception entailed three major activities, namely, **(1)** performance of in-situ flow discharge measurements using Large Scale Particle Image Velocimetry (LSPIV) technology; **(2)** performance of stage monitoring (i.e. flow depth in terms of a reference point) using semi-automated in-stream pressure transducer sensors; and **(3)** processing and compilation of flow discharge measurements with corresponding stage data at the 11 sites in the Hungry Canyon Alliance (HCA) region.

The project included the following three major activities: (1) performance of in-situ flow discharge measurements using Large Scale Particle Image Velocimetry (LSPIV) technology; **(2)** performance of stage monitoring (i.e., flow depth in terms of a reference point) using semi-automated, in-stream pressure transducer sensors from Global Water, Inc.; and **(3)** processing and compilation of flow discharge measurements with corresponding stage data at the 11 sites. The activities were to be completed within a 3-year period (08/01/2006 to 07/31/2009).

These three major activities were supported with extensive surveying of the cross sections at the gaging locations, calibrating the Global Water pressure transducer sensors used to measure stage, and designing/ testing the pressure transducer set-up (e.g., logger and cable connectivity) in the laboratory. Figure 1 provides a side view of the original IIHR set-up, although modifications to this set-up were performed later to improve the sensor endurance in adverse weather conditions.

Figure 1. Installation of Water Level Loggers.

These adverse weather conditions were ascribed to the flashy nature of the flow in the monitored streams, the presence of ice or debris, and extensive freeze-thaw. All these conditions resulted in damages similar to the one shown in figure 2.

Figure 2. Damage to the cable of the pressure transducer caused by the extensive freeze-thaw.

Due to the complexity of the project resulting from the adverse weather conditions (described above) and excessive bank failure, 7 of the 11 pressure transducers were damaged within a year of their installation (year 1). These damages limited the amount of continuous stage data collected semi-automatically at the sites. On the contrary, the LSPIV measurements

were successful. However, the measurements were inherently not continuous with time and limited to the preplanned field excursions.

In year 2, concerted efforts were taken with the HCA board to repair and reinstall the pressure transducers in order to facilitate continuous recordings of stage. Laboratory testing was also conducted to refine the design of the sensor installation to provide a more robust set-up, which could withstand the severe weather conditions. Immediately following these studies, the findings were presented to the HCA and Iowa Highway Research Board (IHRB). Recommendations were provided for a more rigorous design of the existing pressure transducer set-up (see figure 12in *Section 4. Methodology*). The HCA board requested that the PIs provide additional recommendations for automated stage recording sensors that did not require submersion into water (some of these recommendations are included in *Section 6. Conclusions and Recommendations*) (years 2&3). Further, due to the weather-triggered delays more time was deemed necessary in order to complete compilation and processing of the flow discharge measurements with corresponding stage data at the 11 sites in the HCA region. **This led to the extension of the project for 1 additional year.**

In response to the request for considering a non-intrusive sensor, the PIs provided a different type of sensor, namely, a laser system level, which is more robust and can be installed remotely (figure 24 in *Section 6. Conclusions and Recommendations*). The laser system was proposed to be mounted from the bridge at each site thus minimizing the effects of ice and floating debris, and improving their operation and survivability in the long run (year 3). Further, the laser system would include a datalogger for direct transfer of the data to the HCA office. The HCA board was planned to pay for the cost of the sensors (about $35K) while the IHRB approved additional funding for continuation and compilation of all flow discharge measurements with the corresponding stage data at the 11 sites in the HCA region.

During the extension period of the project the UI team focused on the performance of more LSPIV measurements representing a wide range of flow conditions. These measurements along with the measurements collected during the first year of the project and also since 2004 were compiled in order to educate an established flow-discharge predictor model, which incorporates watershed hydrology into the discharge prediction using GIS tools.

Uncertainties regarding future logistics and maintenance of the proposed laser sensor network at the 11 sites of HCA led to the decision by the HCA board not to proceed with the investment in the laser system despite that the features of the proposed laser sensor were generally attractive.

Despite this deviation from the original plan (specifically the continuation of the stage measurements to be conducted during the extension period of the project) the IIHR team focused

on the performance of more LSPIV measurements covering a wide range of flow conditions (year 4). These measurements, along with the measurements collected during years 1 and 2 of the project, were collectively employed in order to calibrate an established flow-discharge predictor model (Coulthard, 1999; Coulthard et al., 2007), which incorporates watershed hydrology to develop the stage- discharge prediction using GIS tools (year 4). Independent data sets collected by the PI and his collaborators at different sites within the HCA from another IHRB project TR-521 (Field investigation of hydraulic structures facilitating fish abundance & passage through bridges in western Iowa streams; Papanicolaou and Dermisis, 2006) were also employed to verify model performance. In addition, the methods and approach developed by Eash (1993) and the USGS in Iowa City were considered for estimating the discharge using the channel width and drainage area.

The model will be described in *Section 4. Methodology* of the proposal. Further, the field and model results with the rating curves will be presented in *Section 5. Results*. Comparisons of the study findings regarding discharge-stage predictions with other studies in the HCA region are also provided.

To summarize, the original 3-year project (08/01/2006 to 07/31/2009), which was funded jointly by the Iowa Highway Research Board (IHRB; $112,000) and the Hungry Canyons Alliance (HCA; $70,000), was extended by the IHRB for 1 more year (until 07/31/2010) (IHRB; $45,030) in order to collect additional flow and stage data and thus meet the overarching goal of this research i.e., development of the stage-discharge relationship for the 11 ungaged-streams in the HCA region of western Iowa. **This goal was reasonably met herein by providing data and methods, which can be transferable to sites with similar hydro-geomorphology.**

1.2 Critical review of stage-discharge relations (rating curves)

Stage (H_g) – discharge (Q) ratings are generally treated as following a power curve, similar to the form given by the following equation (International Organization for Standardization, 1983; Kennedy, 1984; Herschy, 1995, 1999):

$$Q = c\left(a + H_g\right)^b \tag{1}$$

in which b is an index exponent, and a, c are constants. The discharge measurements must cover the range of flows observed at the site and must continue over time to account for temporal changes in the rating. For most stations the rating will be a compound curve consisting of different segments (see, as an example, Figure 23 in *Section 5. Results*), each of which may follow the form of equation 1, but have unique values of c, a, and b.

Historically, two schools of thought have been followed to develop a unique relation between the stage and discharge for an open channel. The first approach describes the flow in the channel using an open-channel flow formula such as the Chezy or Manning equations. These equations were developed for steady, uniform flow, but errors from using these equations for gradually varied flows are expected to be small (Chow, 1959). Early development of ratings was done by treating the slope and resistance coefficient as constant in these equations (Stevens, 1907). **Later investigations attempted various approaches to account for the effect of changes in resistance and slope.** These all have resulted in empirical methods to fit ratings and auxiliary correction curves to measured data.

The second approach is based on treating the stream flow as flow over a weir. This concept is commonly referred to as the "control" for the rating. If the flow can be treated as flow over a weir, then the discharge (Q) can be described by an equation in the following format:

$$Q = C_w L_w \left(H_g - a\right)^b \tag{2}$$

in which C_w, is a weir constant, L_w is the length of the weir, and b is an exponent, which is theoretically equal to *1.5*. This concept gives rise to referring to the offset, a in equation 1 as the "gage-height of zero flow" and to the concept of "shifting controls" or "shifts" (Rantz et al., 1982). Because most gauging stations do not measure the critical depth over a well-defined weir, the "gage-height of zero flow" is a mathematical constant determined by successive approximations to obtain the best fit between measured discharges and stages. Similarly, "shifts" are adjustments to the rating that are attributed to changes in the "control". The shifts are determined by empirical adjustment of the rating curve to fit measurements made since the rating was developed (Rantz et al., 1982). The need to routinely measure discharge at the site (typically ten or more measurements annually) to define these shifts arises because the theoretical basis for stage-discharge relations had been inadequately defined. If ratings were developed by considering the relevant terms of the open-channel flow equations, the effects of changes to the channel or control will be reflected in the rating without the need for empirical shifts.

In reality, the discharge in a channel is a function of not only the stage, but also the water-surface slope, change of area A along the channel, change of flow with time (unsteadiness), and possibly other factors. In other words, the stage-discharge relation is not unique but multi-valued, which is often seen by discontinuities or loops in rating curves. Loops and discontinuities in ratings may result from a number of physical factors, such as unsteady flow from a flood wave, change in channel or overbank storage, changes in slope from downstream effects, changes in channel geometry or bedform, or possibly other factors such as secondary currents.

The time scales of many of these changes (days, weeks, or longer) are much greater than the time scales for changes in discharge (minutes, hours). For example, in many streams, the geometry will change during major floods followed by armoring, which will tend to maintain the geometry until the next major flood. Thus, a theoretically developed rating based on understanding of the fluid mechanics of the flow can readily and easily be updated or re-established, without flow measurements, provided the channel geometry information is available. In contrast, whenever the channel cross section changes the old data and empirical rating curve no longer describe the relation between stage and discharge (Schmidt 2002).

1.3 Importance of project, project data transferability, and lessons learned

Discharge is one of the most important variables that control fluvial, geomorphologic, and ecological processes in streams. Aggradation/ degradation, channel scour during floods, local scour around structures, fish habitat degradation, and formation of river bends, as well as fining, coarsening and armoring of stream-beds are just a few examples depicting a stream's response to changes in flow discharges. Figure 3 (which also appears in the report cover) illustrates the response of the East Nishnabotna River alignment under different flow discharges during approximately the last fifty years. It is a challenge for engineers to predict the channel response to natural events without knowledge of the flow discharge.

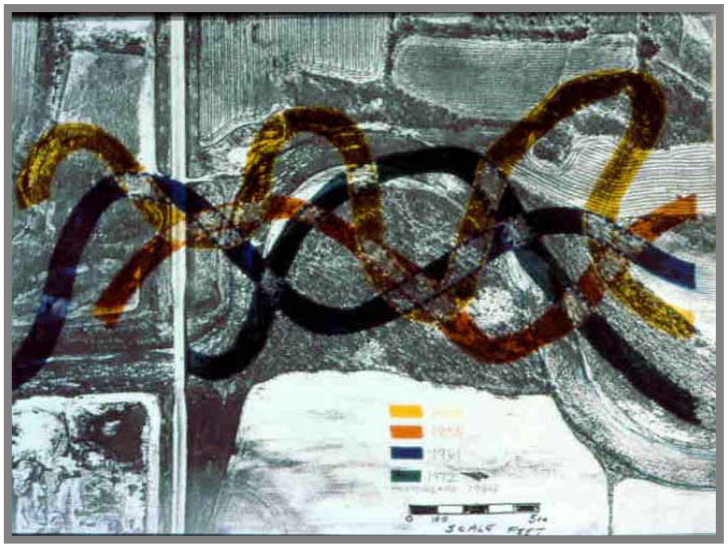

Figure 3. The meander shifts of the East Nishnabotna River, Iowa, pose an on-going concern for scour at the bridge crossing of Highway 174.

Measurements of stream discharges can also provide information about floods, as well as wet and dry seasons of a certain stream. It can also help in evaluating the performance of existing structures and their effects on the fluvial, geomorphologic, and ecological characteristics of the stream. Statistical analysis of flow discharge records statewide can enhance decision-

making, the effective design of hydraulic structures, and our ability to model and predict changes in river morphology as they affect bridge waterways crossings.

Duration curves for discharge, as an example, are essential tools in evaluating structure outflow capacity, maximum erosion and deposition rates, as well as backwater effects created by the presence of structures, minimum depth in streams for fish migration, and the optimum geometry and rock size for rock-weir hydraulic structures. In addition, information on discharge can help us predict the lateral shift of channels in space and time and thus ensure that the channel goes under the bridge and not through its abutment as it is shown, for example, in figure 4.

Finally, because the stage-discharge relations have been developed based on the drainage area and channel cross sectional width, the utility of the stage-discharge relations is that can be used for making discharge predictions in ungaged channels in this region as long as the width *B*, the average flow depth, *H*, and the drainage area, *DA* are known (Leopold et al. 1964; Papanicolaou and Dermisis 2006).

Figure 4. Embankment failure, Brushy Creek, IA (by Rob Ettema personal communication).

2. OBJECTIVES & TASKS

The primary goal of the project was to establish a stage-discharge relationship for 11 ungaged-streams in the HCA region. Throughout the course of the project and during its extension period added tasks were performed in order to meet this goal. The following **tasks** summarize all the activities performed from the inception of the project all the way to its completion:

Task 1. Specify the locations for conducting flow measurements based on the IDNR and HCA recommendations. The HCA compiled the list of sites presented in table 1 of *Section 3. Study Sites*.

Task 2. Obtain basin characteristic for all corresponding sites. This includes drainage area, stream-bed gradient and land factor, which is an index of soil cover.

Task 3. Define hydraulic measurement procedures and perform flow-depth measurements under different hydrologic conditions. A set of established sensors, non-intrusive measurements (e.g., LSPIV), and visual inspections were employed to perform the measurements. The monitoring effort entailed the following activities:

Sub-Task 3a: Calibration of the Global Water transducers in the laboratory for stage monitoring .
Sub-Task 3b: Installation of the Global Water transducers at the 11 sites and monitoring of the stage.
Sub-Task 3c: Modification of the installation design for the Global Water transducers to withstand better ice and debris impact.
Sub-Task 3d: Completion of discharge measurements using Large Scale Particle Image Velocimetry (LSPIV) complemented with surveys.
Sub-Task 3e: Processing of the LSPIV data.

Task 4. Educate the hydrologic model (introduced in section 1.1) by calibrating it using the data collected in Task 3 and perform modeling of flow – stage for all 11 sites.

Task 5. Compare the model predictions with the collected data and USGS data. Perform error statistical analysis.

Task 6. Compilation of a final report containing the stage-discharge rating curves and provide recommendations for the most suited sensors ("lessons learned") for watersheds exhibiting similar characteristics.

3. STUDY SITES

As part of Task 1, 11 ungaged streams located in the HCA region were identified. Figure 5 provides a detailed map of SW Iowa and includes information concerning (1) the location of the 11 sites (yellow circles); (2) USGS gage stations (green triangles); (3) local MESONET climatic stations used to acquire precipitation data for the modelling simulations (red squares); (4) elevation of the watersheds corresponding to the 11 study sites ranging between 298 m and 475 m a.s.l.; and (5) stream networks (blue lines). Figures 6-11 are images off the 11 sites. As seen from the pictures, the sites were located in close proximity to grade control structures (i.e., riprap and grouted weirs, fish ladders), which were built in various locations in the HCA region to prevent streambed degradation and the formation/ propagation of knickpoints (Thomas et al. 2009).

During Task 2 we obtained basin characteristic for all corresponding sites. Table 1 provides information concerning the location of each site, site ID, stream network, drainage area (*DA*), channel width (*B*), and the MESONET climatic station corresponding to each site. It should be noted that *DA* was determined using the ArcGIS 9.3 software to obtain the watershed area that is drained through each site and average *B* for the whole channel length (headwaters to mouth) was determined using Google Earth™. Lastly, table 2 includes information for the 5 USGS stream gages considered in this study, including the *DA* and *B* obtained from the USGS on-line database (http://waterwatch.usgs.gov/) and Google Earth™. Please note that for the HCA gaging locations the width, *B*, was determined with direct surveys.

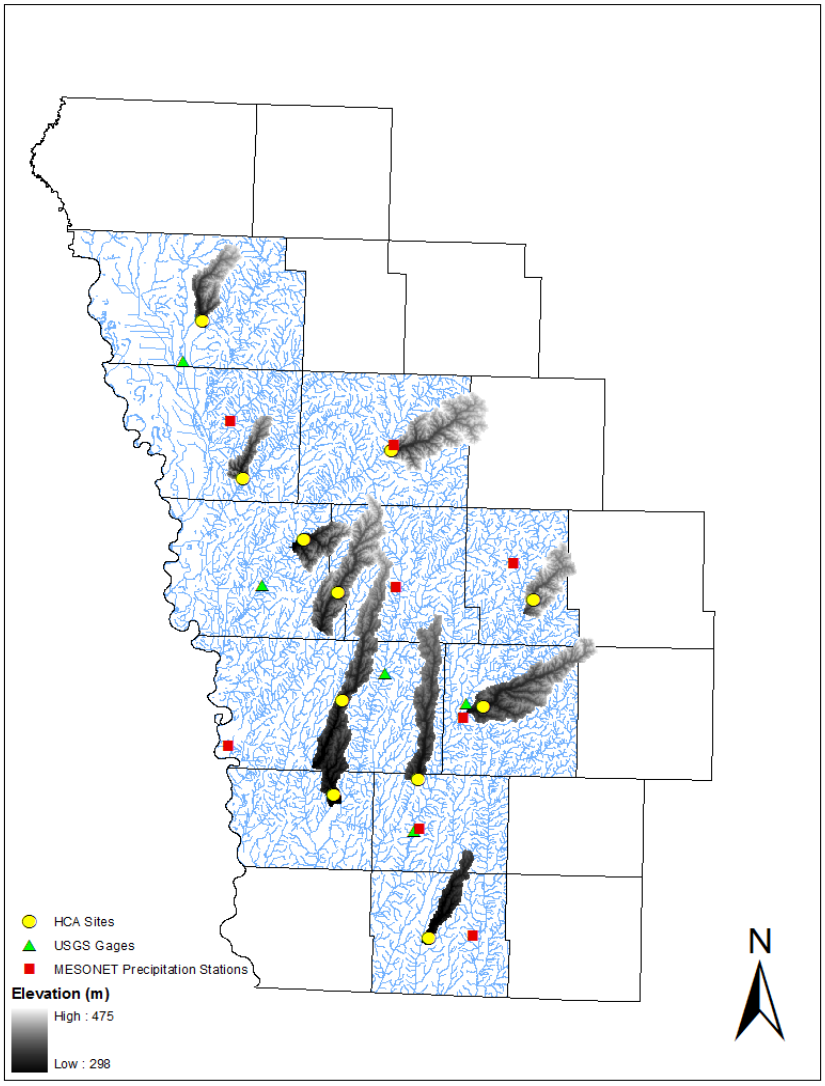

Figure 5. Map of the 11 sites in HCA area (yellow dots) with Digital Elevation Maps of the corresponding watershed. The locations of the USGS gages (green triangles) and the Iowa Environmental MESONET precipitation stations (red squares) considered in this study are present, as well.

Figure 6. Picture from sites 06_9_F located in Harrison County (left) and 01_2 located in Monona County (right).

Figure 7. Picture from sites EWP_309_104 located in Mills County (left) and 69_6114_1_23 located in Page County (right).

Figure 8. Picture from sites 99_8 located in Audubon County (left) and L_EWP_22,23,24 located in Woodbury County (right).

Figure 9. Picture from site 02_2_F located in Shelby County (left) and L_EWP_8339_26 located in Pottawattamie County (right).

Figure 10. Picture from sites 69_6114_9_6 & 05_9_F located in Montgomery County (left) and 00_11 & 04_26 located in Cass County (right).

Figure 11. Picture from site 99_14 located in Crawford County.

Table 1. Location and characteristics of the 11 sites including the nearest climatic stations used to obtain precipitation data for each site.

Location (county)	**Site ID**	**Stream**	**Drainage area, *DA* ($x10^9$) (ft^2)**	**Width, *B* (ft)**	**Climatic Station (MESONET)**
Harrison	06_9_F	Picayune Creek	0.84	16	Harlan
Monona	01_2	Jordan Creek	0.86	18	Harlan
Mills	EWP_309_104	Mud Creek	0.92	18	Council Bluffs
Page	69_6114_1_23	Tarkio River	1.12	20	Clarinda
Audubon	99_8	David's Creek	1.28	32	Audubon
Woodbury	L_EWP_22,23,24	Wolf Creek	1.59	30	Castana
Shelby	02_2_F	Mosquito Creek	2.04	15	Harlan
Pottawattamie	L_EWP_8339_26	Silver Creek	2.29	30	Lewis
Montgomery	69_6114_9_6 & 05_9_F	Walnut Creek	2.43	29	Red Oak
Cass	00_11 & 04_26	Turkey Creek	3.07	50	Lewis
Crawford	99_14	E. Boyer River	3.54	100	Denison

Table 2. The USGS stream gages considered in this study.

Location (county)	**USGS stream gage (ID)**	**Drainage area ($x10^9$) (ft^2)**	**Width (ft)**
Woodbury	W. Fork Ditch at Hornick (06602020)	11.24	35
Cass	E. Nishnabotna River near Atlantic (06809210)	12.15	125
Pottawattamie	W. Nishnabotna River at Hancock (06807410)	16.98	125
Harrison	Boyer River at Logan (06609500)	24.28	140
Montgomery	E. Nishnabotna River at Red Oak (06809500)	24.92	140

4. METHODOLOGY

4.1 Overview on sensors, models, and statistical analysis

As part of Task 3, the IIHR team proposed a detailed methodology to semi-automate the stage monitoring process of the 11 ungaged streams via sensor technology, viz. use of sophisticated transducers equipped with data loggers by Global Water Instrumentation, Inc. Concomitantly, several LSPIV measurements were performed under a wide range of hydrologic conditions during the project duration to determine the discharge in the selected streams and relate it to the corresponding stage obtained by the Global Water transducers.

The stage data from the *Global Water transducers* were recorded to attached data loggers (found at the HCA sites) at selected intervals specified by the user (e.g., every 1 min, every 1 hr). Typically, data were downloaded every 3 to 5 months by visiting the sites. Data storage capacity of the sensors was dependent of the frequency of the data recording. The time series depth (stage) data recordings from the data logger were obtained in raw format and converted to ascii format through a batch process program provided by the manufacturer. Once the depth data were converted into a user readable format, they were correlated to the LSPIV measurements.

The *LSPIV measurements* were not only necessary for calibrating the sensors readings for the existing flow conditions but also for enhancing the record of data that was collected during the Papanicolaou and Dermisis (2006) TR-521 study. Although TR-521 provided unique information about the stability of riprap structures and hydraulic performance of the structures in HCA with respect to fish passage, it did not provide stage –discharge relations for a wide range of flow conditions due to the dry conditions that existed during the course of the study. More importantly the Papanicolaou and Dermisis (2006) study required the manual use of equipment for measuring stage and flow at all times. Our methodology proposed herein with the existing dataloggers has in parts addressed this problem by minimizing the number of visits required for collecting the data in years 1 and 2. More importantly, the sensors (when operational in years 1 and 2) allowed continuous monitoring of flow, something that is not feasible with traditional monitoring. The data collected in years 1 and 2, in addition to the data collected by Papanicolaou and Dermisis (2006), were used to educate and calibrate the model to

In a nutshell the proposed *sensor and models* infrastructure provided the first orchestrated monitoring/computational effort in SW Iowa and provided stage-discharge ratings of statistical importance.

What makes this study very attractive is the wide range of *DA* sizes which we dealt with during the course of the project. The *DAs* considered varied between 30 sq. miles to 130 sq. miles. As a result we were able to test the performance of the rating curve not only for a wide range of flow conditions but also for different scale resolutions.

model flow and stage in all 11 sites for a much wide range of flow conditions. The model predictions and USGS data were considered in the error statistical analysis.

In a nutshell this infrastructure provided the first orchestrated monitoring effort in SW Iowa and provided stage-discharge ratings of statistical importance. What makes this study very attractive is the wide range of *DA* sizes, with which we dealt during the course of the project. The considered *DAs* varied between 30 and 130 sq. miles. As a result we were able to test the performance of the rating curve not only for a wide range of flow conditions but also for different scale resolutions.

4.2. Tasks 1 & 2

The selection and characteristics of the 11 sites have been summarized in tables 1 and 2 of *Section 3. Study Sites* of this report.

4.3. Task 3

In order to complete Task 3 (provide measurement procedures and perform flow-depth measurements), the following sub-tasks were performed:

4.3.1 Sub-Tasks 3a, 3b, 3c

The aim here was to perform (a) Calibration, (b) Installation of 11 stage sensors and related software (interface program) for data acquisition (Excel, Database, etc...) and (c) Modification of the sensor installation design.

A fundamental measurement for any hydrologic system is the depth of water at a particular point, which is also known as stage. Stage is either measured in situ (sensor is located in the water) or remotely (sensor is located out of the water), with each type having certain advantages. The Global Water sensors used in this study are standard pressure transducers, which are relatively inexpensive and easy to install. A single unit consists of a pressure transducer, which is connected to self-contained datalogger through a cable. The datalogger is powered by two 9-V batteries and can store data for extended periods (typically 3 to 5 months). The sensor measures the pressure of the overlying water, which is related to the depth of the water. A laptop or PDA can easily download the stored data.

The Global Water pressure transducers were placed in stilling wells (figure 12). The stilling well pipe had several large diameter holes (1/2") near the sensor location in order to eliminate velocity effects on the sensor and smaller diameter holes (1/4") near the top of the pipe to allow air movement when the water goes up and down. The sensor cable and transducer were attached to the pipe and the bends were placed parallel to the bed (figure 12). The cable was vented at the top to compensate for changes in barometric pressure. The pipe had UV protectors and was flexible thus

allowing it to conform to the contours of the river bank. The pipe was either buried in the river bank and/or fastened to the bank with steel bars of U-shape (U-stakes) driven into the bank. A standard slip cap was used to protect the top of the datalogger (figure 12).

Figure 13 summarizes the key components of the improved system design, which showed endurance in adverse weather compared to the system shown in figure 1. This modified design incorporated rebar hooks, a chained-garden hose to protect the cable and prevent the cable damages similar to those shown in figure 1, and T-posts to protect the sensor. The T-posts were spaced 2 ft. apart to minimize blockage effects of flow due to debris laying atop of the structures (figure 13).

As figure 14 shows the PI and co-authors of this report have tested the location of the probe in relation to the bed in order to determine the location of the probe that triggers less resistance to the flow. It was shown (figure 14d) that the vertical location provided the highest resistance instead the probe placed in parallel and in line to the flow direction had the most desirable results. This design was considered in all future probe installations.

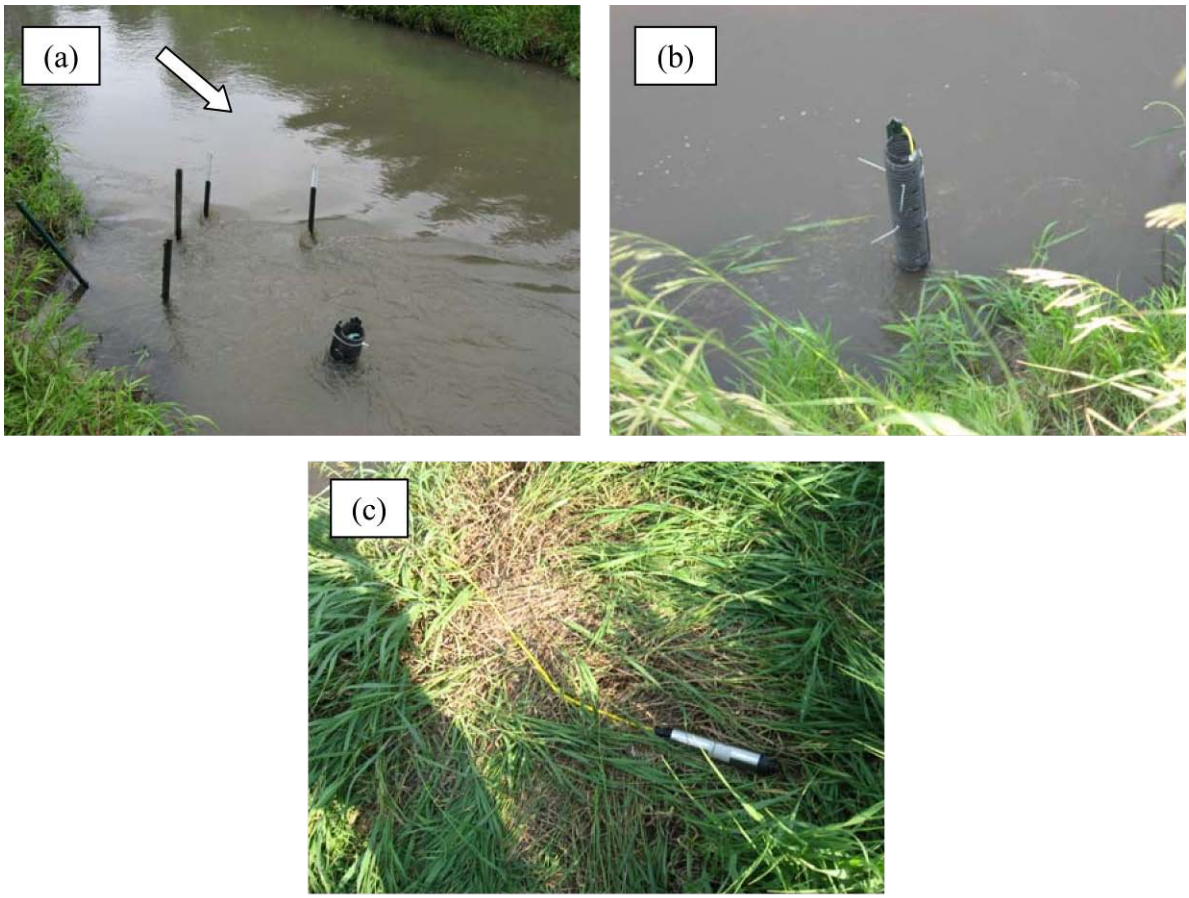

Figure 12. Pressure transducer. (a) Pressure transducer installed in a stilling well among T-posts (white arrow shows the flow direction). (b) Close up of the stilling well. (c) Enclosed datalogger that is attached to the pressure transducer.

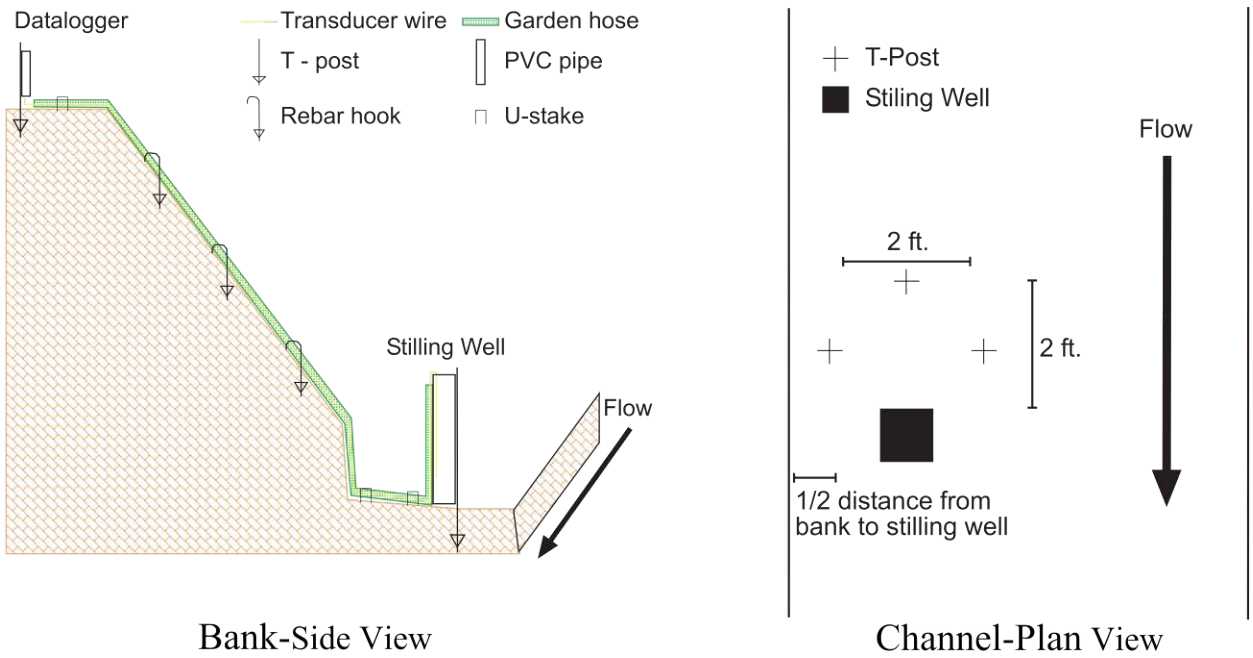

Figure 13. Schematics from the installation of Water Level Loggers.

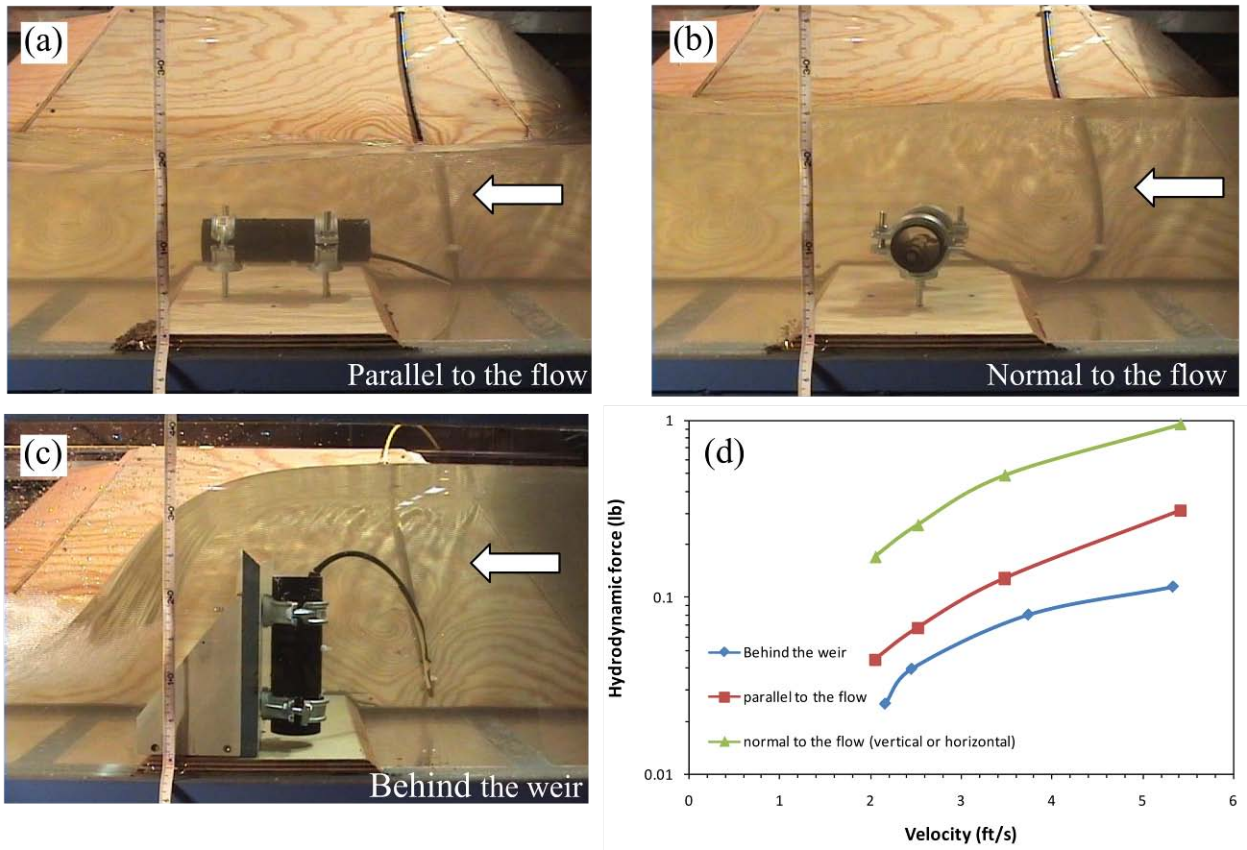

Figure 14. Testing the position of the pressure transducer in the laboratory (white arrow shows the flow direction).

4.3.2 Sub-Task 3d,3e

These sub-tasks included the completion of discharge measurements using the Large Scale Particle Image Velocimetry (LSPIV) technique complemented with surveys. LSPIV measurements were conducted by an experienced three-man team from IIHR with assistance from HCA personnel (J. Thomas). This technique has been successfully used for other IHRB-funded projects conducted by this team, namely TR-521 (Papanicolaou and Dermisis, 2006).

LSPIV measurements were performed during the following periods, representing a variety of flow conditions:

Period 1: fall 2004 and spring/summer 2005 (i.e., October-November 2004, May-June 2005)
Period 2*: summer/fall 2007 (i.e., June and September 2007)
Period 3: summer 2008 (i.e., June 2008)
Period 4: spring/summer 2010 (i.e., March to July 2010)
_* for the period 2 flow tracker measurements were performed.

In a nutshell, LSPIV is a newly developed, but robust technique that provides remote measurements of the free surface velocity. Although limited to the free surface velocity measurements, the LSPIV measurements could provide the mean and turbulent flow conditions under high flow events within a reach quickly and accurately. LSPIV is non-intrusive and inexpensive as it requires only a standard camcorder and a geodetic survey (figures 15a, b, and A1) to describe the Region of Interest (ROI). During the LSPIV measurements, the camera was attached to a mast that raised high enough to capture the ROI (figures 15a, b).

The LSPIV technique involved four major components: illumination, seeding, image recording, and image processing. Instantaneous velocity measurements were obtained by measuring the displacement of particles (seeded material) between successive images. By seeding the flow with material lighter than the density of water (e.g., use of mulch in figure 15c), the motion of flow was traced, provided that sufficient contrast between the seeded material and background existed (illumination). A video camera captured the flow (image recording) within the ROI in the form of images. The images were digitized on a frame-by-frame basis by a frame grabber (image processing) and processed using a commercial Particle Image Velocimetry program (LSPIV 2.0). By utilizing the LSPIV 2.0 software, the 2-dimensional (2-D) flow field depicted with the vectors on the water surface was obtained (figure 15d). Velocity information was extracted using the cross-correlation method, which was computed between interrogation areas in the first and second image within a specified search region (Kim, 2006). The pairs of particles showing the maximum cross-correlation coefficient were considered to define the velocity vector field. With appropriate selection of the parameters for the imaging technique, the errors in the measurement of the mean velocity were less than 1.5 % (Muste et al., 2004).

In conjunction with bathymetry data the program estimated the flow discharge Q by assuming that the mean velocity is 85% the free surface velocity (Kim, 2006). Bathymetry data were obtained by performing detailed survey of in the 11 sites. A Leica TC-605 total station was used and detailed topographic plots were produced in the vicinity of the sensors. The survey of the sensors (figure A2) led to the determination of the cross sections, the ROI for the LSPIV measurements and the water surface profile (figure 15e).

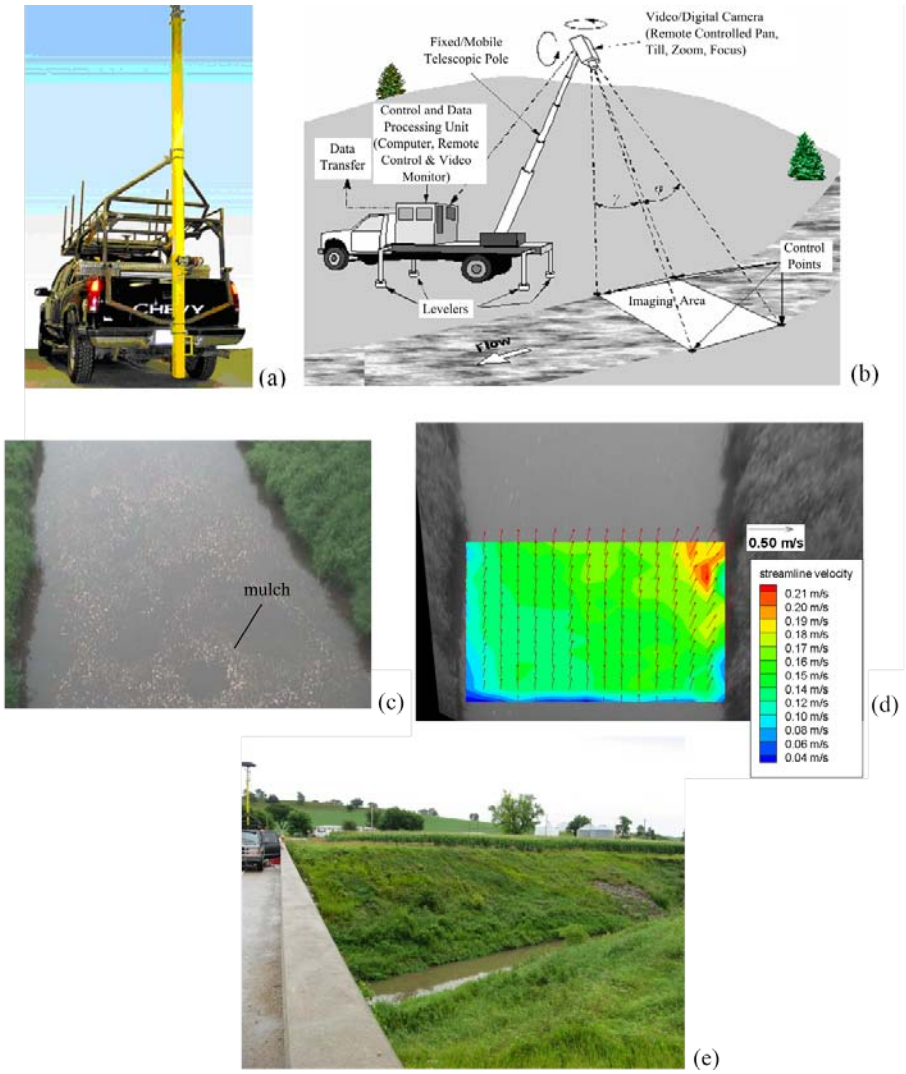

Figure 15. (a) The LSPIV truck used in this study; (b) Sketch showing the principles of operation for the LSPIV truck; (c) Seeding of the flow with mulch in Silver Creek (Pottawattamie County); (d) LSPIV result of the streawise velocity contour plot in the Silver Creek; (e) LSPIV set-up in Jordan Creek (Monona County).

These discharge data were correlated with concurrent stage measurements to develop a stage-discharge rating curve. Use of this curve will allow future stage measurements recorded using the laser system to quickly be converted to discharge.

4.4. Task 4

This task included the education of a cellular automata model (identified in section 1.1) by calibrating it using the data collected in Task 3. This model is a two dimensional flow and sediment transport "cellular" model (e.g., Coulthard et al. 1996). Cellular models in hydro-geomorphology are defined by representing the modeled landscape with a grid of cells (figure 16) and the development of this landscape is determined by the interactions between cells (for example fluxes of water and sediment) using rules based on simplifications of the governing physics (Nicholas, 2005).

The model allows the user to input a Digital Elevation Model (DEM) of a river catchment and rainfall data, then let the model evolve. It features hydrological processes, multidirectional routing of river flow, slope processes (soil creep, mass movement), fluvial erosion, and deposition over a range of different grain sizes. The nature of the cellular model allows interactions between the cells of a DEM to generate feedbacks and complex responses. Below, brief information is given concerning the hydrologic and hydraulic routing, which are the two key processes of interest in this study for the development of the stage-discharge equations.

Hydrologic routing: The hydrologic routing of the model is based on TOPMODEL (Beven and Kirkby, 1979). For each grid cell, a runoff threshold is calculated which is based upon the amount of water that will infiltrate through the soil. A key variable that controls infiltration in the soil is the "*m*" value. The *m* defines the rise and fall of the soil moisture deficit (Beven and Kirkby, 1979). Essentially, *m* is used to simulate the effects of changing vegetation cover on catchment hydrology, which is derived from the effect that *m* has on the recession limb of the flood hydrograph. A high *m* value slows the rate of decline of the recession limb for the hydrograph and reduces the transmissivity within the soil, therefore imitating the effect that vegetation cover would have on the catchment. A lower *m* value (sparser vegetation) allows more transmissivity through soil as there is a quicker decline in soil moisture deficit; it imitates all the factors associated with water movement and water storage with regard to vegetation. In this study, the *m* value varied between 0.01-0.03 (Welsh et al., 2009) to account for the heterogeneity in vegetation in the different catchments. After infiltration is calculated, the runoff is multiplied by the grid cell size to obtain discharges which is added to every cell. For more information on the hydrologic routing is provided in Coulthard (1999).

Hydraulic routing: The discharge calculated from the hydrological model in each individual cell is then routed to neighboring cells. This is carried out through a 'scanning' procedure that works across the catchment in four directions (from north to south, east to west, west to east and south to north) pushing flow to the adjacent cells.

The inputs needed to run the model are simple and require little parameterization or empirical data when compared with other hydrological models (e.g., Mike-SHE: Abbot et al., 1986). Table 3 provides a summary of the main input data required to run the cellular model for the 11 sites. The model requires an hourly rainfall record as the input for a hydrological model. In this study, the Iowa MESONET database (http://mesonet.agron.iastate.edu/) was used and data included hourly precipitation measurements for an 8-yr period (2002-2010). The climatic stations that were used for the 11 sites are shown in figure 5 (red squares) and in table 1.

The cellular model also requires a raster DEM for the catchment. Editing and correcting the 11 DEM was an important part of a model simulation(see figures A3-A13). This was carried out simply using the Arc-Hydro extensions toolkit for ArcGIS 9.3.

The duration of an 8-yr simulation for an individual site varied between a couple of days to a week, depending on the size of the catchment and the number of events occurring throughout the simulation period. The outputs of the model included the water depth in the uplands and in the main channels (see example in figure 17) and the flow discharge at the catchment outlet.

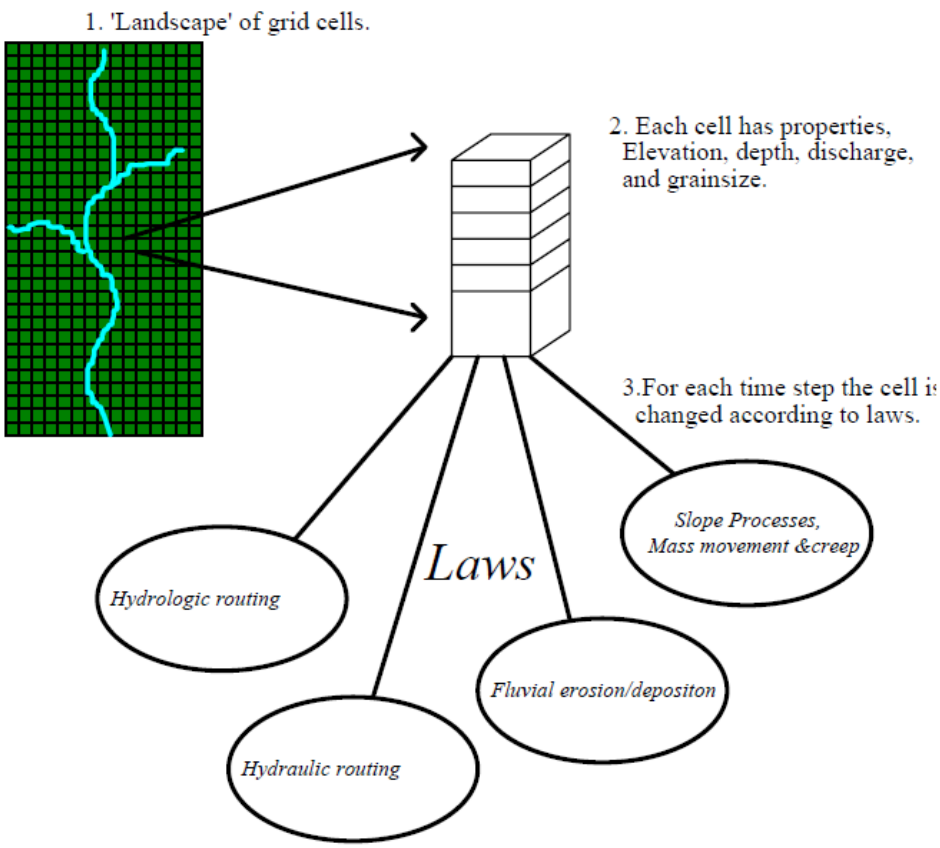

Figure 16. Schematic diagrams of the key processes operating in the cellular model (adopted from Coulthard, 1999).

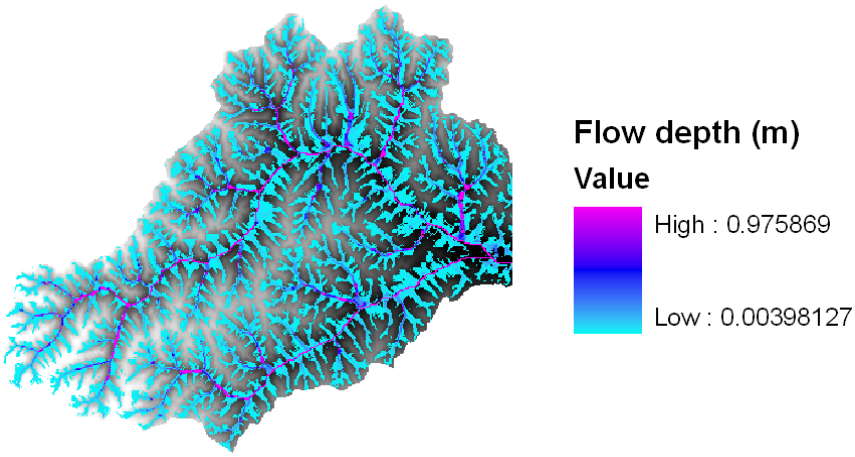

Figure 17. Example of the simulated flow depth in Picayune Creek (Harrison County) using the hydrologic model.

Table 3. Basic input parameters for the CELLULAR MODEL model.

Input Data	Description	Source
Precipitation data	8-yr hourly data (period 2002-2010)	Iowa Environmental Mesonet database
DEM	30 m resolution	USGS & NRGIS Library

4.5. Task 5

Task 5 included the comparison of the model predictions with the LSPIV/pressure transducer and USGS datasets, as well as the performance of a regression analysis to develop the stage-discharge relationship. The predicted model's (i.e., stage-discharge regression equation) accuracy was evaluated after calibration through statistical error analysis (Shahin et al., 1993) namely, the coefficient of determination (R^2), root mean square error (*RMSE*) and mean absolute error (*MAE*), defined as:

$$R^2 = 1 - \frac{\sum_j^N \left(M_j - P_j\right)^2}{\sum_j^N \left(M_j - \overline{M}\right)^2} \tag{3}$$

$$RMSE = \sqrt{\frac{1}{N}\sum_j^N \left(M_j - P_j\right)^2} \tag{4}$$

$$MAE = \frac{1}{N}\sum_j^N abs\left(M_j - P_j\right) \tag{5}$$

where, N is the sample size, and M_j and P_j are the simulated (or measured) and predicted values, respectively, and $\overline{M}$ is the average simulated (or measured) value. R^2 is a statistical measure of how well the regression equation approximates the data points; an R^2 of 1.0 indicates that the regression equation perfectly fits the data, whereas a 0.0 value indicated poor performance of the equation. The statistical metrics *RMSE* and *MAE* are negatively oriented scores where lower values are better with a perfect agreement between the measured and predicted values when the calculated values approach zero.

5. RESULTS

Figure 18 presents the stage-discharge results from the model simulations (8-yr period 2002-2010) as well as the field data from the LSPIV measurements (period 2004-2010 as discussed in section 4.3.2) for the 11 sites. Specifically, the plot in figure 18 provides the dimensionless flow depth (i.e., $x = H/B$) vs. the flow discharge, Q, written in a dimensionless form as:

$$y = \frac{Q}{\sqrt{gDA^{0.5}B^{4.0}}} \tag{7}$$

where, Q is the flow discharge (in cfs), g is the acceleration due to gravity (in ft/s^2), DA is the drainage area of the site (in ft^2), B is the width of the channel (in ft), and H is the flow depth (in ft). Table 1 provides the DA and the B of the channel for the different sites in units of ft^2 and ft, respectively.

Using the statistical software SAS 9.2, a regression analysis was performed to obtain an empirical equation between the dimensionless flow discharge and depth based on the model simulations, similar to equation (1). This analysis yielded the following equation:

$$\boxed{\frac{Q}{\sqrt{gDA^{0.5}B^{4.0}}} = 0.0127 * \left(\frac{H}{B}\right)^{1.87}} \; (R^2 = 0.70, RMSE = 142.8\,\text{cfs}, MAE = 9.89\,\text{cfs}) \tag{8}$$

The exponent for the flow depth, H, (i.e., equivalent to the exponent b in equation 1) was found to be 1.87, close to the reported value of 1.5 in previous studies (Schmidt, 2002).

Figure 19 presents the predicted (based on equation 8) vs. the model simulated data. The bold line indicates perfect agreement between the two datasets. In addition, figure 20 shows the ratio of the discharge determined from the numerical simulation and the one determined by equation (8) plotted as a function of the simulated discharge. The median line is shown together with those for the 1, 10, 90 and 99 percentiles.

Measured data from the LSPIV measurements were compared against the predicted data. Along the same lines, figures 21 and 22provide similar information with figures 19 and 20 with the difference that the predicted data from the stage-discharge equation are compared against the LSPIV measurements.

Figures 18 - 22 reveal a consistent trend in stage-discharge relation, which has been reported in the literature viz., for the low flow magnitude events there is larger scatter in the (x=$\frac{H}{B}$ $y = \frac{Q}{\sqrt{gDA^{0.5}B^{4.0}}}$) points comparatively to higher flows. This variability is attributed herein to different reasons such as pronounced secondary currents during low flow conditions and higher potential for an experimental error during the low flows. The latter is due to the dispersed movement of the seeding material at low flows (these flows are dictated by low Pecklet numbers <10). On the contrary at high flows the seed particles mostly move in the downstream direction (advection). With respect to the modeling predictions, a similar behavior is observed in the predicted values during low flow events. Again this variability is attributed to the departure of flow from the uniform flow depth conditions and the highly unsteady nature of the flow during low flow conditions. Most of the equations in all models assume uniform flow and steady conditions. The departure from the uniform flow conditions results to errors in the estimation of Manning's n.

Lastly, figure 23 compiles the simulated and measured data with USGS stage-discharge data found in the vicinity of the 11 sites. The compilation of the data shows a very good agreement of the USGS data with the measured and predicted data of this research. This agreement is present for different DA sites and for the high flow event segments of the USGS rating curves (sections where $\frac{H}{B}$ is nearly raised to the power of 3).

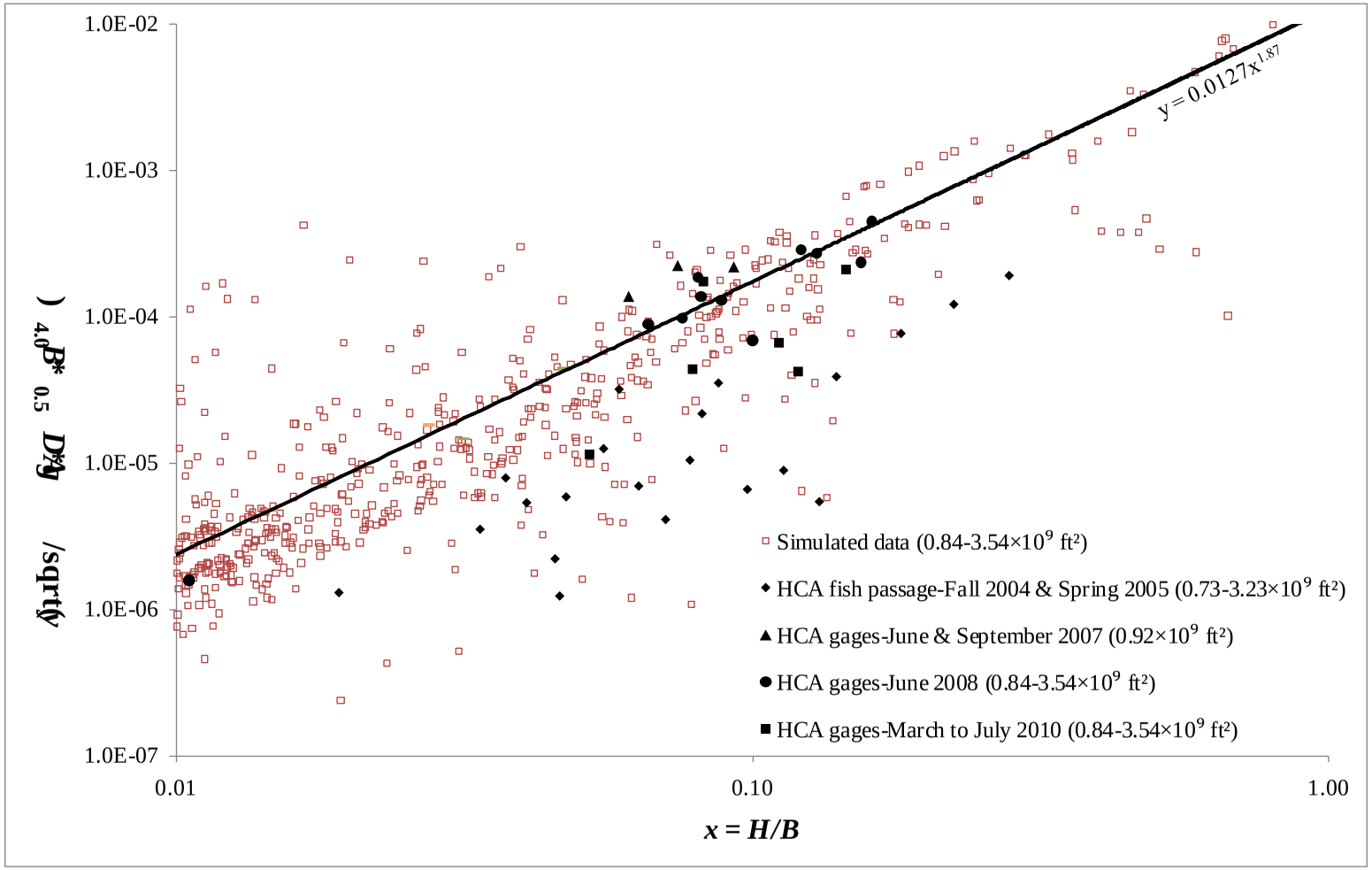

Figure 18. Comparison between the simulated stage-discharge data with measured data from the current study and previous field measurements in the HCA area (Papanicolaou and Dermisis 2006).

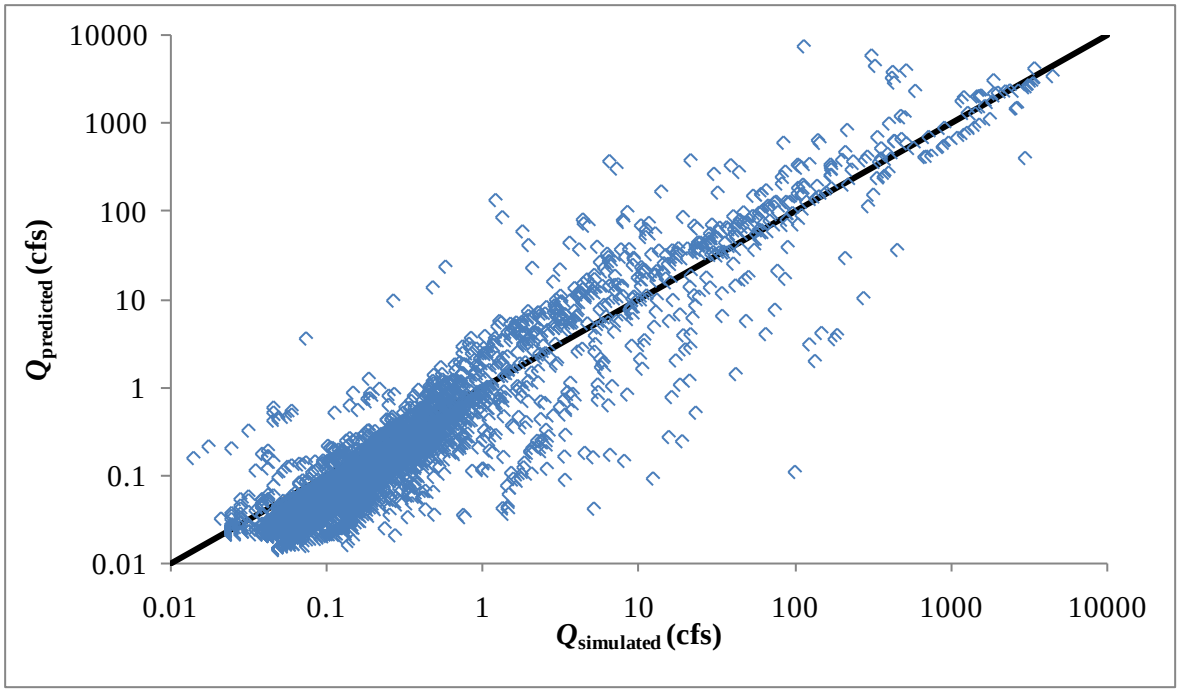

Figure 19. Predicted (regression equation) vs. simulated data. The bold line indicates perfect agreement between the two datasets.

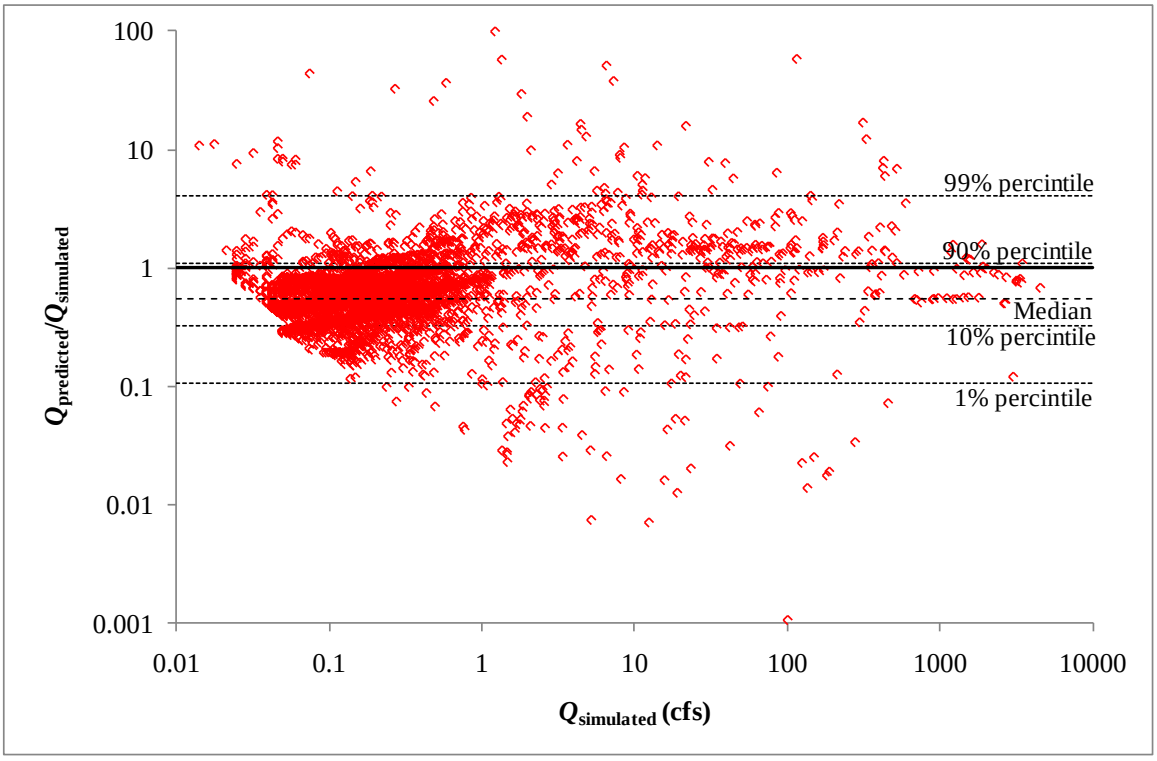

Figure 20. Ratio of the predicted discharge ($Q_{predicted}$) using the developed regression formula to the simulated discharge ($Q_{simulated}$) as a function of the simulated discharge. The bold line indicated perfect agreement.

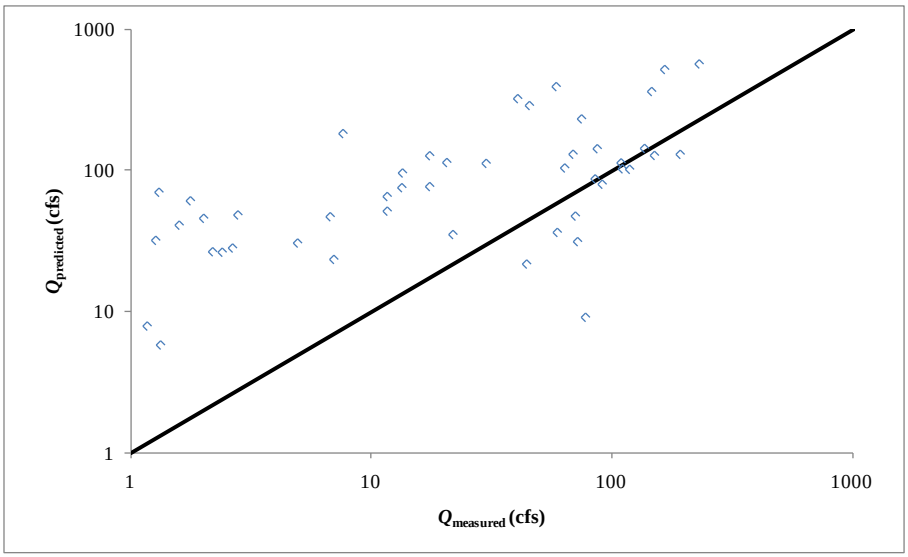

Figure 21. Predicted (regression equation) vs. measured data. The bold line indicates perfect agreement between the two datasets.

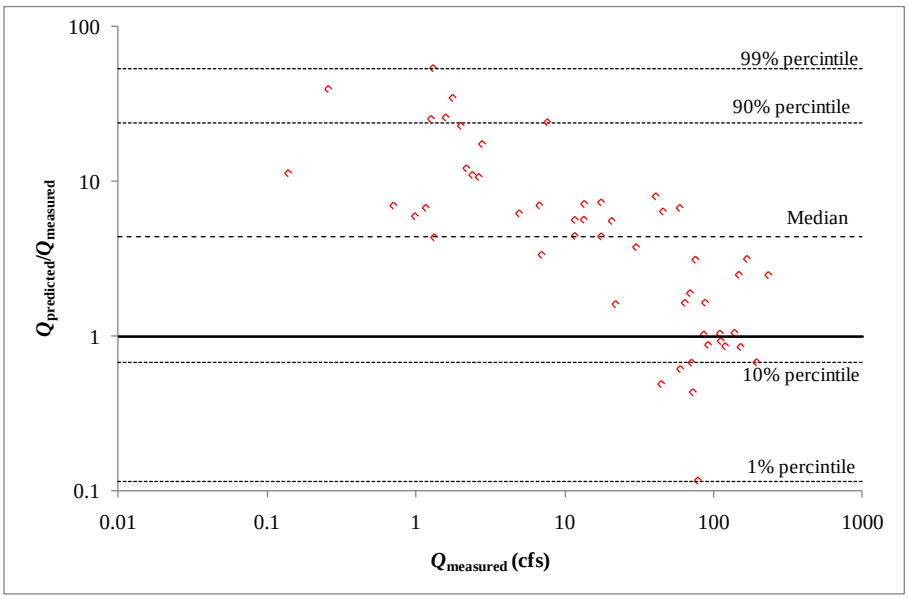

Figure 22. Ratio of the predicted discharge ($Q_{predicted}$) using the developed regression formula to the measured discharge ($Q_{measured}$) as a function of the measured discharge. The bold line indicated perfect agreement.

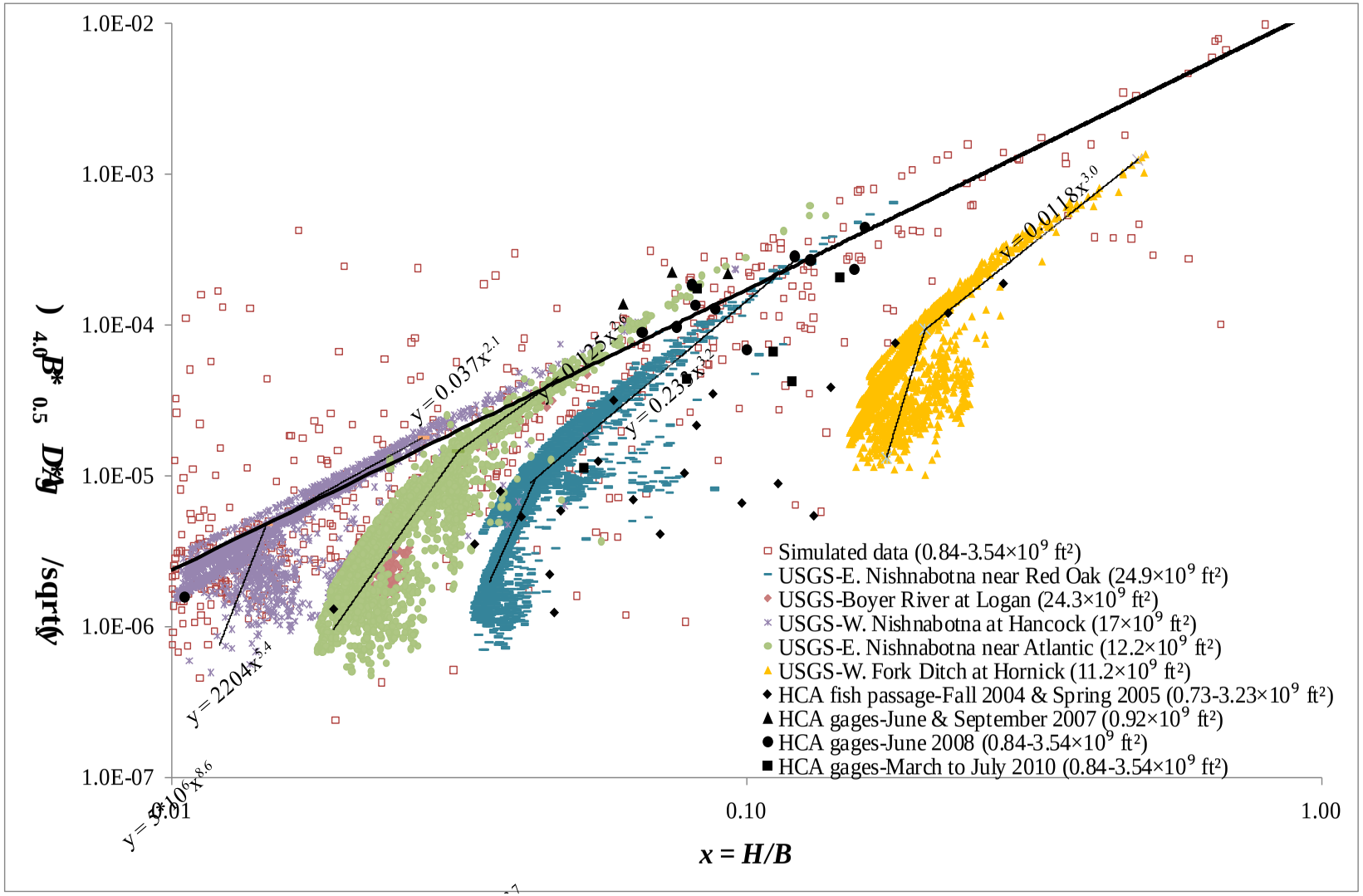

Figure 23. Comparison between the simulated stage-discharge data with measured data from the current study and previous field measurements in the HCA area (Papanicolaou and Dermisis 2006). Measured data for the period 2002-2010 from the USGS gage stations located in close proximity to the 11 sites are also plotted.

6. CONCLUSIONS AND RECOMMENDATIONS

This study has offered a new rating curve for the HCA (Equation 8) and an improved insight on several issues pertinent to stream gaging. Our conclusions are organized as follows:

(1) Importance of study

In a nutshell this infrastructure provided the first orchestrated monitoring effort in SW Iowa and provided stage-discharge ratings of statistical importance. What makes this study very attractive is the wide range of *DA* sizes, with which we dealt during the course of the project. The *DAs* considered varied between 30 and 130 sq. miles. As a result we were able to test the performance of the rating curve not only for a *wide range of flow conditions* but also for *different scale resolutions*.

Comparisons of the study findings regarding discharge-stage predictions with other studies in the HCA region show a striking agreement; the dimensionless representation of the data makes the proposed flow rating curve attractive to use at sites with similar hydro-geomorphology.

(2) Instrumentation recommendations

Standard pressure transducers such as the ones manufactured by Global Water are relatively inexpensive and easy to install, which makes them extremely mobile and useful for short-term projects. However, the Global Water set-up –as it is provided by the distributor- does not provide high endurance during the extensive presence of ice, debris, and freeze-thaw triggered bank failures. The authors provided an improved design which has made the pressure transducers more robust and suited for conditions found in Iowa (also recommendations were made for the probe orientation, see figure 14). In addition the authors suggested an non-intrusive system, a Laser Level Sensor system, made by LaserTech. The laser sensors do work better in turbulent environments and because they are not immersed in water (see figure 24) are not susceptible to damages similar to the ones found for the pressure transducers.

Figure 24. Remote water level sensors. Laser level measuring stage in a highly turbulent site in Iowa. (b.) An example of a laser level system. (c.) An example of a radar system installed remotely.

(3) Model

The use of a cellular automata model to perform hydrologic and hydraulic routing, under different flow conditions especially for high flows when measurements are not easy to obtain can be complementary to different monitoring programs. The model predictions show a very good agreement with the measured data of this research.

(4) Network design and maintenance

A gaging network should be designed for future modifiability and flexibility. Therefore they must be built simply, but with future expandability in mind. Cost of equipment, licensing fees, steepness of learning curve, and maintenance load are all points of failure. Developing network-wide standards and interoperability solutions, such as interfacing new sensor and instrument types with existing USGS interfaces is “a must”. Providing training to network engineers and field technicians on sensor selection and the operation and maintenance of sensor network components (e.g., sensor calibration protocols) is another important component that should not be underestimated.

7. REFERENCES

Abbot, M.B., Bathurst, J.C., Cunge, J.A., O'Connell, P.E., and Ramussen, J. 1986. An introduction to the European Hydrological System – Systéme Hydrologique Européen, 'SHE', 1: history and philosophy of a physically-based, distributed modelling system. *Journal of Hydrology*. 87:45–59.

Beven, K. J., and Kirkby, M. J. 1979. A physically based variable contributing area model of catchment hydrology. *Hydrological Science Bulletin*. 24(1):43-69.

Chow, V. T. 1959. Open-Channel Hydraulics, McGraw-Hill, New York.

Coulthard, T. J. 1999. Modelling Upland Catchment Response to Holocene Environmental Change. Phd Thesis, School of Geography, University of Leeds, U.K. 181pp.

Coulthard, T.J., Hicks, D.M., and Van De Wiel, M.J. 2007. Cellular modelling of river catchments and reaches: Advantages, limitations and prospects. *Geomorphology*. 90:192–207.

Coulthard, T.J., Macklin, M.G., Kirkby, M.J., 1996. A cellular automaton fluvial and slope model of landscape evolution. In: Abrahart, R.J. (Ed.), Proceedings of the 1st International Conference on Geocomputation, University of Leeds, 17–19 September 1996, Leeds, UK, pp. 168–185.

Eash, D.A. 1993. Estimating Design-flood Discharges for Streams in Iowa Using Drainage-basin and Channel-geometry Characteristics. Water-Resources Investigations Report 93-4062. U.S. Geological Survey, Iowa City, IA.

Herschy, R.W. 1995. Streamflow measurement. 2nd Edition, E & FN Spon, London, UK, 524 p.

Herschy, R.W. 1999. Hydrometry: Principles and Practice. Second Edition, John Wiley and Sons, New York, NY, 376 p.

International Organization for Standardization. 1983. Liquid flow measurement in open channels- Part 2: Determination of the stage-discharge relationship. ISO Standards 1100/2-1982, from Measurement of liquid flow in open channels –ISO Standards Handbook 16, International Organization for Standardization, Geneva, Switzerland, pp. 154-186.

Kennedy, E.J. 1984. Discharge ratings at gaging stations. Techniques of Water-Resources Investigations Book 3, Chapter A 10, U.S. Geological Survey, 58 p.

Kim, Y. 2006. Uncertainty analysis of non-intrusive measurement of river discharge using image velocimetry. Ph.D. Dissertation, The University of Iowa, Iowa City, Iowa.

Leopold, L.B., Wolman, M.G., and Miller, J.P. 1964. Fluvial Processes in Geomorphology. W.H. Freeman, San Francisco, California.

Muste, M., Xiong, Z., Schöme, J., Li, Z. 2004. Validation and Extension of Image Velocimetry Capabilities for Flow Diagnostics in Hydraulic Modeling. *J. Hydraul. Eng.* 130(3):175-185.

Nicholas, A.P. 2005. Cellular modelling in fluvial geomorphology. *Earth Surface Processes and Landforms*. 30:645-649.

Papanicolaou, A., and Dermisis, D. 2006. Field Investigation of Hydraulic Structures Facilitating Fish Abundance and Passage Through Bridges in Western Iowa Streams. Iowa DOT TR-521. University of Iowa: Iowa City, Iowa.

Rantz S.E., et al. 1982. Measurement and computation of streamflow, volume 2: computation of discharge—US Geological Survey, Water Supply Paper 2175. Available from http://water.usgs.gov/pubs/wsp/wsp2175/.

Schmidt, A.R. 2002. Analysis of Stage-Discharge Relations for Open-Channel Flow and their Associated Uncertainties. University of Illinois, Urbana.

Shahin, M., van Orschot, H.L., Delange, S.J. 1993. Statistical Analysis in Water Resources Engineering. A.A. Balkema, Rotterdam, The Netherlands.

Stevens, J.C., (1907). A method for estimating stream discharge from a limited number of gauging, Engineering News, 58(3):52-53, Jul 18.

Thomas, J.T., Papanicolaou, A.N., Wilson, C., Dermisis, D., and Elhakeem, M. 2009. Knickpoint migration in western Iowa. Published in the Proceedings of the 33rd Congress of IAHR on Water Engineering for a Sustainable Environment, Vancouver, British Columbia, August 9-14, 2009.

Welsh, K.E., Dearing, J.A., Chiverrell, R.C., and Coulthard, T.J. 2009. Testing a cellular modelling approach to simulating late-Holocene sediment and water transfer from catchment to lake in the French Alps since 1826. *The Holocene*. 19:785.

8. APPENDIX

Figure A1. LSPIV and total station set-up in Turkey Creek (Cass County). In the background is Mr. John Thomas of Hungry Canyons Alliance, Project Director and Fluvial Geomorphologist.

Figure A2. Survey in the Mosquito Creek (Shelby County).

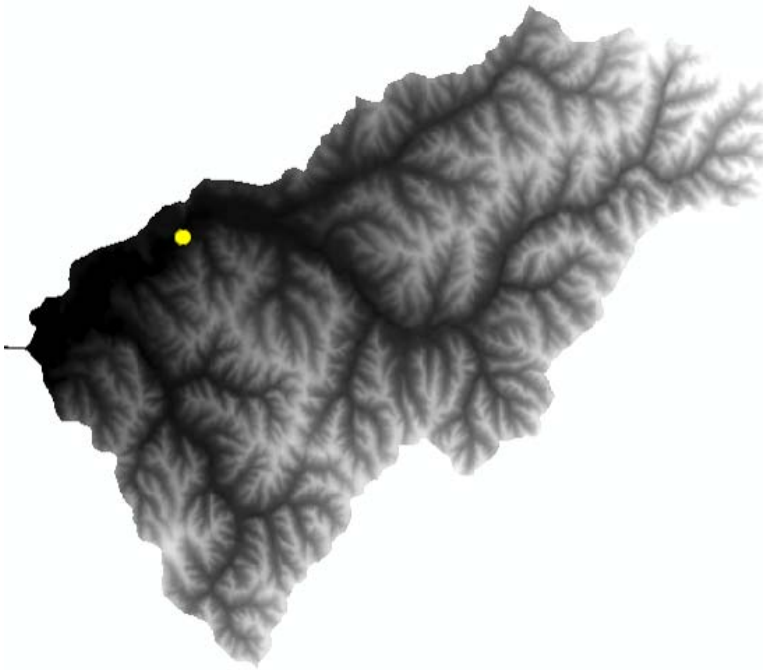

Figure A3. DEM of the watershed that drains to site 06_9_F (yellow dot) located in Harrison County.

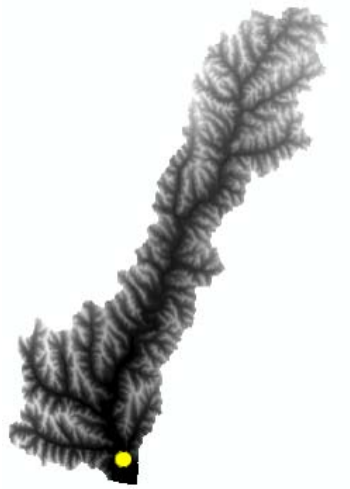

Figure A4. DEM of the watershed that drains to site 01_2 (yellow dot) located in Monona County.

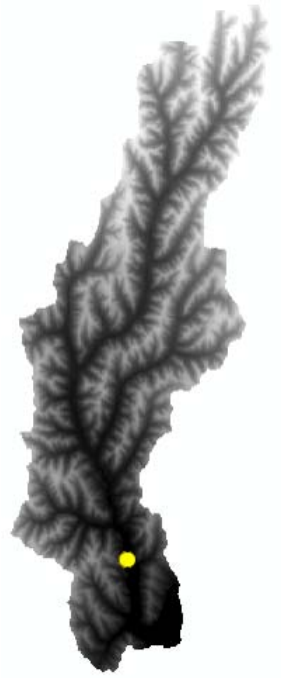

Figure A5. DEM of the watershed that drains to site EWP_309_104 (yellow dot) located in Mills County.

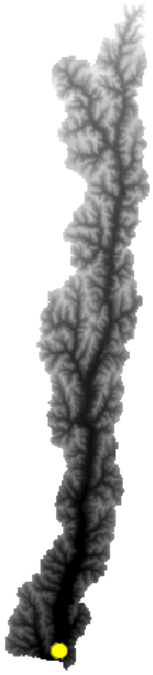

Figure A6. DEM of the watershed that drains to site 69_6114_1_23 (yellow dot) located in Page County.

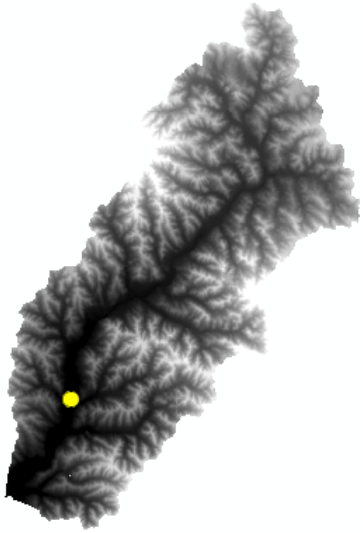

Figure A7. DEM of the watershed that drains to site 99_8 (yellow dot) located in Audubon County.

Figure A8. DEM of the watershed that drains to site L_EWP_22,23,24 (yellow dot) located in Woodbury County.

Figure A9. DEM of the watershed that drains to site 02_2_F (yellow dot) located in Shelby County.

Figure A10. DEM of the watershed that drains to site L_EWP_8339_26 (yellow dot) located in Pottawattamie County.

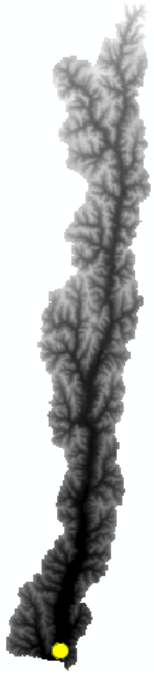

Figure A11. DEM of the watershed that drains to site 69_6114_9_6 & 05_9_F (yellow dot) located in Montgomery County.

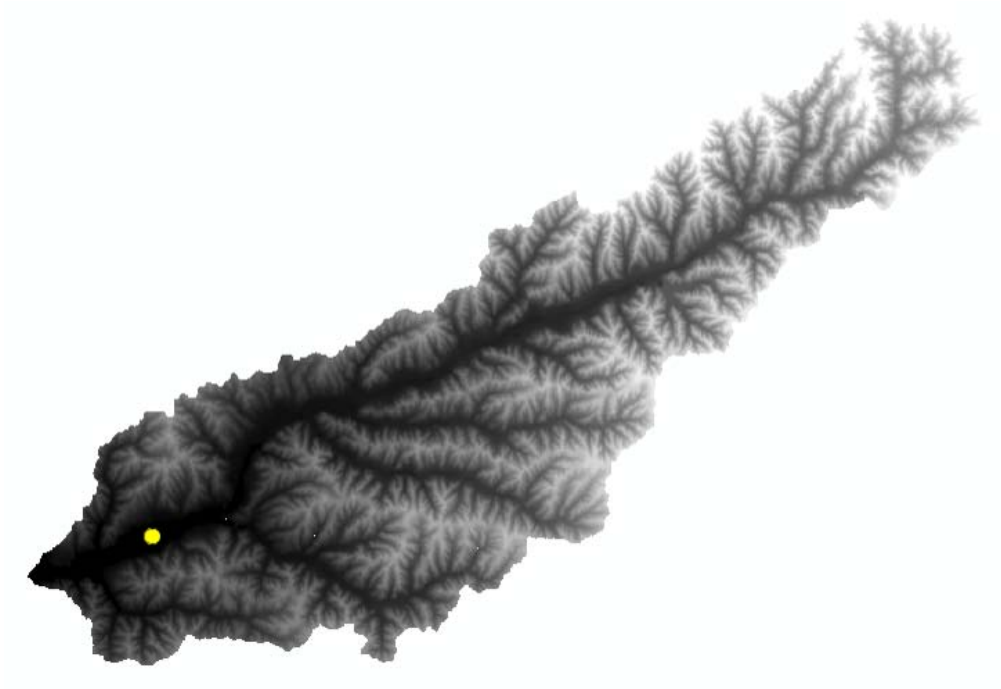

Figure A12. DEM of the watershed that drains to site 00_11 & 04_26 (yellow dot) located in Cass County.

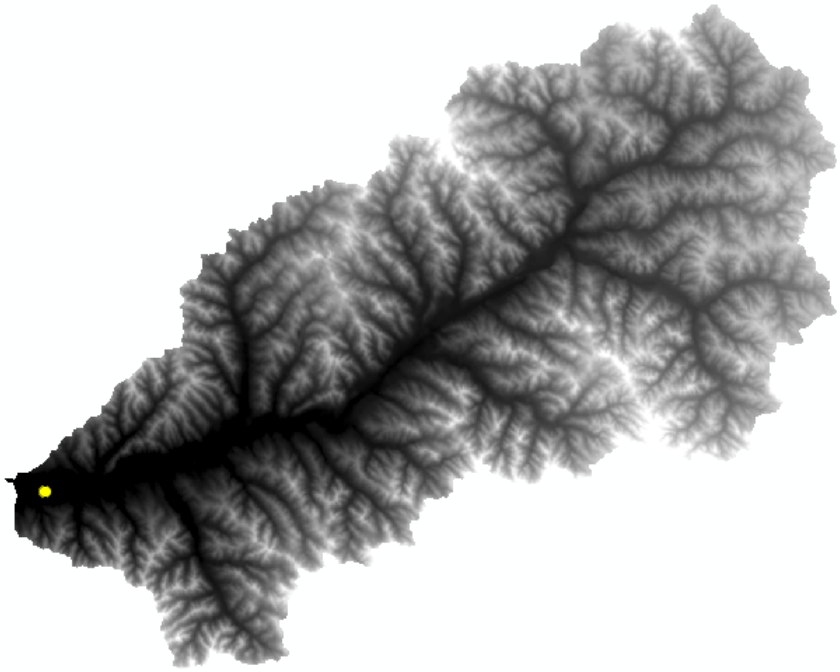

Figure A13. DEM of the watershed that drains to site 99_14 (yellow dot) located in Crawford County.