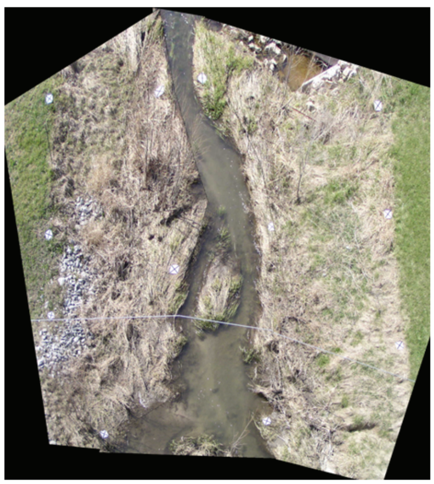
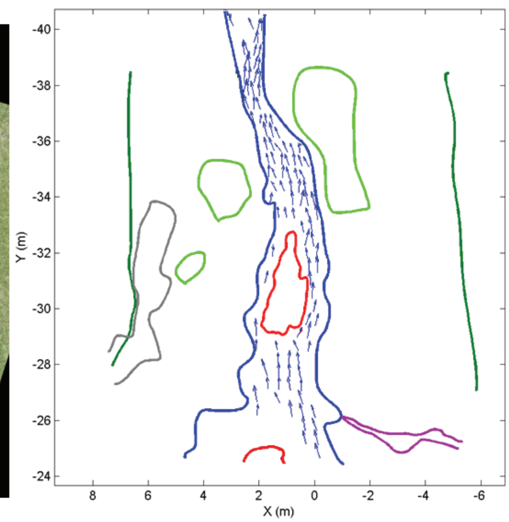
THE UNIVERSITY OF IOWA

FINAL REPORT FOR IHRB TR-569

QUANTITATIVE MAPPING OF WATERWAYS CHARACTERISTICS AT BRIDGE SITES





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The software and instruction manuals will be delivered to Mark Dunn, Research Engineer, Iowa DOT.

16. Abstract

Iowa state, county, and city engineering offices expend considerable effort monitoring the state's approximately 25,000 bridges, most of which span small waterways. In fact, the need for monitoring is actually greater for bridges over small waterways because scour processes are exacerbated by the close proximity of abutments, piers, channel banks, approach embankments, and other local obstructions. The bridges are customarily inspected biennially by the county's road department bridge inspectors. It is extremely time consuming and difficult to obtain consistent, reliable, and timely information on bridge-waterway conditions for so many bridges. Moreover, the current approaches to gather survey information is not uniform, complete, and quantitative.

The methodology and associated software (DIGIMAP) developed through the present project enable a non-intrusive means to conduct fast, efficient, and accurate inspection of the waterways in the vicinity of the bridges and culverts using one technique. The technique combines algorithms image of registration and velocimetry using images acquired with conventional devices at the inspection site.

The comparison of the current bridge inspection and monitoring methods with the DIGIMAP methodology enables to conclude that the new procedure assembles quantitative information on the waterway hydrodynamic and morphologic features with considerable reduced effort, time, and cost. It also improves the safety of the bridge and culvert inspections conducted during normal and extreme hydrologic events. The data and information are recorded in a digital format, enabling immediate and convenient tracking of the waterway changes over short or long time intervals.

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About the IIHR- Hydroscience & Engineering

IIHR, a unit of The University of Iowa's College of Engineering, is one of the nation's premier and oldest fluids research and engineering laboratories. Situated on the Iowa River in Iowa City, Iowa, IIHR seeks to educate students and to conduct research in the broad fields of hydraulics and fluid mechanics.

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SUMMARY

"The amount of infrastructure to inspect is enormous. The nation has 1,000,000 miles of water mains, 600,000 bridges, and 4,000,000 miles of public roadway. Public safety professionals and engineers responsible for this infrastructure strive to maintain these systems. They seek to prioritize repair schedules and to avoid premature replacement of infrastructure. Better technologies have the potential to provide invaluable input to these recommendations by making the monitoring of processes and conditions that affect structures more quantitative, more thorough, and more frequent. Technologies that achieve the goal of continuous monitoring of structural integrity with costs low enough to permit wide-scale, permanent deployment, require transformative research."

Technology Innovation Program, National Institute of Standards and Technology, June 2008

Counties in Iowa have many small bridges to monitor and maintain. For example, most of the counties surrounding Harrison County have 350 to 400 county bridges to maintain, and all these bridges must be inspected biennially by the county's road department bridge inspectors. It is extremely time consuming and difficult to obtain consistent, reliable information on bridge-waterway conditions for so many bridges. Moreover, the current approaches to gather survey information is fragmentary, incomplete, qualitative, and subjective.

This research introduces a new, innovative image-processing software, DIGIMAP, to easily quantify and document waterway features in the vicinity of bridges including the free-surface velocity in the stream. The proposed approach uses images acquired from close range with conventional photographic techniques. Given that in most of the cases the images are taken from an oblique angle with the horizontal plane, the close-range images are distorted due to perspective effect. Consequently, the raw images must be ortho-rectified before mapping the characteristic elements of the banks and floodplain. The image rectification is obtained with a geometric transformation that linearly relates the distorted geometry with a Cartesian coordinate system. Particle Image Velocimetry algorithms are used to estimate the free-surface velocity in the stream. This approach is highly versatile for conducting routine bridge inspections, providing quantitative information for a variety of geomorphic and hydraulic waterway parameters. Periodic inspections at bridges followed by processing of the acquired images allows to conveniently and accurate track in time changes that occur in the vicinity of the bridges.

ACKNOWLEDGEMENTS

The software development and the field work associated with the software implementation were funded by the Iowa Highway Research Board, as Research Project TR-569.

A Technical Advisory Committee, provided advice and recommendations as to the content and format of the software. The members of the Committee and their affiliations are listed below:

Paul Assman	Crawford County, Iowa
Greg Parker	Johnson County, Iowa
Lyle Brehm	Tama County, Iowa

Conduct of the project was coordinated with Mark Dunn, Iowa Department of Transportation.

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1. Problem Statement

Counties in western Iowa have many small bridges to monitor and maintain. For example, Crawford County has 280 county bridges to maintain, and all these bridges must be inspected biennially by the county's road department bridge inspectors. Shelby County, adjacent to Harrison County, has 430 bridges, and most of the counties surrounding Harrison County have 350 to 400 county bridges. It is extremely time consuming and difficult to obtain consistent, reliable information on bridge-waterway conditions for so many bridges. Currently, such information is fragmentary, incomplete, qualitative, and subjective.

Iowa state, county, and city engineering offices expend considerable effort monitoring the state's approximately 25,000 bridges, most of which span small waterways. In fact, the need for monitoring is actually greater for bridges over small waterways because scour processes are exacerbated by the close proximity of abutments, piers, channel banks, approach embankments, and other local obstructions. The hydrodynamic force driving the flow in rivers encounters the resistance of the flow boundaries to produce the velocity distribution in river cross-sections and along its streamline path. Documentation of these velocity distributions allows us to understand the equilibrium between the forces acting on the flow and estimation of the flow availability for multiple uses. Moreover, the spatial distribution of velocity influences the river habitat, pollutant dispersion and storage, and is key dynamic factor in shaping the waterway path, which in turn produces changes in the stream hydrodynamics. It is obvious from the above, that there are many reasons for which the monitoring of the dynamic interaction between the river flow and its boundary in space and time is important. The existing analytical, experimental, and computer predictions of scour, however, are still limited and often unreliable, bridge monitoring is of great importance to ensure that foundations and approach embankments are not imperiled by various and often rapidly-developing scour processes.

Generally speaking, a "bridge waterway" encompasses the bridged stream or river bed along with its banks, abutments, and any other local obstructions that significantly impact flow velocity, flow alignment, and scour depth. The length of a bridge waterway must include sufficient distance to capture all flow behavior that influences local scour depths. Accordingly, it is not sufficient to assess the condition of the channel only within the bridge waterway, but equally important is to do this for the channel farther upstream from the bridge opening as well as the channel immediately downstream from the bridge opening. Figure 1 depicts the common features of a bridge waterway and gives a quick sense of the flow field and the boundary-soil complexities potentially involved in a waterway.

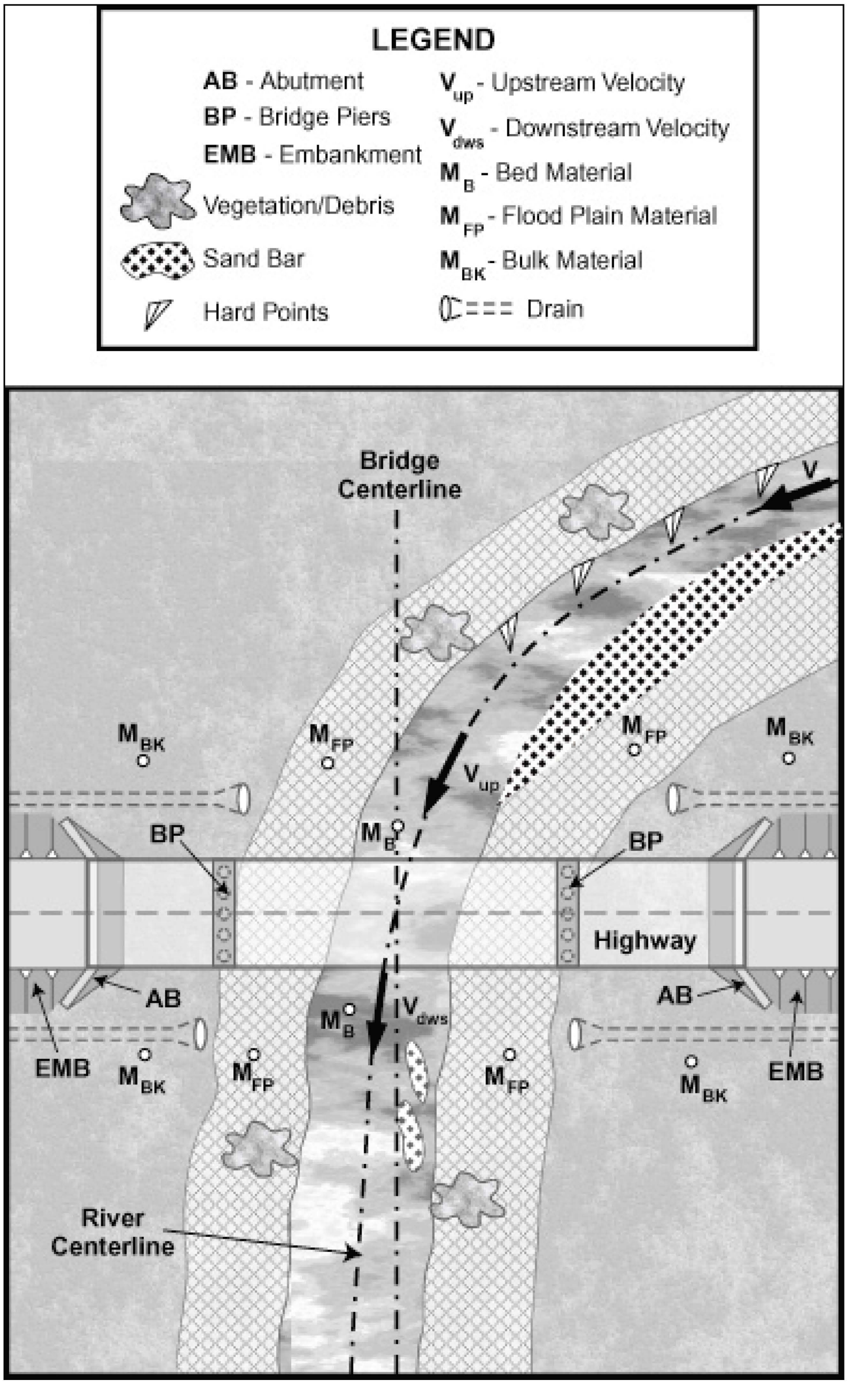


Figure 1. Plan-view sketch showing typical bridge components and surrounding features that potentially affect scour of a bridge waterway

Among the most important purposes of the bridge-site inspections are waterway monitoring (conducted to create a record of the existing channel conditions adjacent to a particular bridge) and checking for waterway changes (current waterway observations). These data should be compared to previous observations and data to identify channel changes. This "tracking" of temporal changes in channel conditions is a very important monitoring step for ensuring the safety of a bridge. The proposed research is aimed at developing an accurate, rapid, convenient, and economical methodology for monitoring bridge waterways using state-of-the-art digital imagery.

The river banks guiding the flow can be described by their shape (straight or sinuous reach), slopes, land coverage and roughness (grass, rocks, mud, vegetation). In addition, the flow can be influenced by lateral secondary channels (drain or erosion prevention ditches) and debris accumulated in the cross section. Also important are the flood plains geometry and roughness as they are critical players during flood flows. The techniques typically used to gather quantitative information about the river banks and floodplains include surveys using total stations, imagery, and written documents that attempt to capture the dynamics not revealed by the "static" snapshots of the survey and photographs usually taken from points with access. This approach is relatively expensive, time consuming, and limited in coverage given that total stations only provide point information that need to be subsequently assembled to describe continuous landscape features. Moreover, the needed information is stored in various formats (maps, photos, word documents). Another approach for mapping the river surroundings is photogrammetry, initiated in 1895 by Laussedat through the invention of the metrophotographic technique. The typical input for photogrammetry is photographic images (Wolf, 1974). The technique outputs are the object geometry and appearance. Images for photogrammetry are typically collected with airborne or satellite imagery. Photogrammetry requires perfect knowledge of the intrinsic parameters of the camera, multiple views of the surveyed area and extensive post-processing. As our goal is to apply the technique for quickly surveying different sites, this procedure involves extensive effort and time. Recently, landscape radar- or laser-based scanning tools have been developed. This combination of techniques acquires three-dimensional images by scanning the surface of an object with three different laser wavelengths (red, green and blue) in one focused beam (see for example http://www.faro.com/). The main drawback of this emerging technology is its high price.

Image-based methods can measure surface flow velocity provided that tracers such as solid particles, bubbles or turbulence patterns are visible at the free-surface and are advected by the river flow. The technique stems from the conventional Particle Image Velocimetry (PIV) which has been extensively used for almost three decades in laboratory experiments for investigating fluid dynamic problems [Adrian, 1991]. Image-based techniques have been also applied to quantify natural scale flows in areas such as shore oceanography by Holland et al. [1997] as well as in small or large scale river gauging by Bradley et al. [2002], Fujita et al. [1998], Creutin et al. [2003], Hauet et al. [2008, in press]. The later application is labeled Large Scale PIV (LSPIV) because large areas of flows are imaged from the river bank at an oblique angle. Consequently, an additional geometric transformation is needed compared with the conventional PIV to obtain free-of-distortion images that are then used to estimate the whole vector field at the river free surface. LSPIV is the only available instrument that can provide instantaneous velocity measurement at the free surface, over considerably large flow areas. The obtained velocities provide critical information for assessing streamlines, velocity gradients, recirculation eddies, or stagnant areas within waterways. Discharges can be obtained using the free surface velocity along river cross-sections and the associated river bathymetry obtained with alternative measurements.

This research introduces a new, innovative software to easily quantify and document waterway features in the vicinity of bridges including the free-surface velocity in the stream. The proposed software uses images acquired from close range with conventional photographic techniques. The image acquisition procedure takes advantage of the mobile imaging unit developed at IIHR-Hydroscience & Engineering, The University of Iowa, but the software can be applied to images obtained by other imaging recording approaches. Given that in most of the cases the images are taken from an oblique angle with the horizontal plane, the close-range images are distorted due to perspective effect. Consequently, the raw images must be ortho-rectified before mapping the characteristic elements of the banks and floodplain. The image rectification is obtained with a geometric transformation that linearly relates the distorted geometry with a Cartesian coordinate system. Particle Image velocimetry algorithms are used to estimate the free-surface velocity in the stream. This approach is highly versatile for conducting routine bridge inspections, providing quantitative information for a variety of geomorphic and hydraulic waterway parameters.

2. Objectives

The methodology proposed herein is applicable to waterway bridge monitoring in general, but is especially well suited for monitoring of “small” bridges (defined as those that cross waterways with watersheds encompassing less than 100 square miles) that are typical for Iowa and surrounding states. This proposed bridge monitoring methodology is focused on the following key points:

1. It would provide accurate quantitative mapping of the waterway characteristics (i.e., information about flow distribution and velocity magnitude, channel and bank characteristics, including vegetation presence) in the vicinity of the bridges using one measurement tool;
2. It would reduce the effort, time, and cost associated with current bridge monitoring methods;
3. It would improve the safety of bridge inspections conducted during normal and extreme hydrologic events; and
4. It would record waterway changes upstream and downstream of the bridge with an emphasis on quantifying changes in channel pattern, shape, and elevation. The data must be recorded in a digital format, readily available for tracking aforementioned changes over short or long time periods.

The proposed methodology for quantitative bridge waterway mapping is envision to be part of both a short and long term technologic development. The short term and immediately achievable purpose is to dramatically improve current capabilities for quantifying and monitoring bridge scour. Eventually this methodology can be refined to include additional equipment through a long term development of customized bridge monitoring platforms. These platforms would comprise multiple non-intrusive instruments (based on image, acoustic-, and laser-based principles proven through this proposal's research) which would allow cost-effective, information-rich, comprehensive measurements with improved accuracy and information detail at minimal effort and expense.

3. Background

The quantitative bridge waterway mapping method proposed herein is based on an imaging technique pioneered at IIHR in 1995 (Muste et al., 2004). The original technique and methodologies were developed for characterizing features derived from free-surface flow velocities in streams over large scale areas (Fujita et al., 1998). The method, dubbed Large-Scale Particle Image Velocimetry (LSPIV), was successfully used in laboratory and field conditions for mapping of the free-surface flow characteristics such as streamlines, large-scale vortices, and velocity gradients. It has been expanded to measure free-surface velocities in cross sections and channel discharges under field conditions (Muste et al., 2004). Currently, IIHR has assembled a mobile (truck-based) LSPIV unit, labeled the Mobile Large-Scale Image Velocimetry (MLSIV) to enable convenient measurements at field location of interest.

MLSPIV was developed for measuring stream's free-surfaces velocities. The unit, illustrated in Figure 2, essentially comprises an imaging device set on a telescopic mast. The light weight aluminum, hydraulically operated mast allows for setting the camera from 15 ft to 50 ft above the ground level to accommodate imaging of various stream widths. Camera positioning and panning control are remotely conducted using a notebook computer located in the truck cabin. The MLSPIV truck is equipped with a power generator, additional batteries, and an uninterrupted power supply (UPS) that provides power for all equipments, a notebook computer, a pan-tilt unit, and a digital camera (Figure 2). Three guy wires are used after positioning to secure the mast against wind-induced or accidental vibrations.

Images taken from a distance at and oblique angles are generally distorted, as illustrated in Figure 3a. This type of distortion is common in LSPIV applications because the images are usually recorded from oblique angles to cover large flow areas. IIHR's LSPIV team developed several algorithms for removal of the image distortion (see Figure 3b). The most common algorithm is based on a geometrical transformation applied to the recorded images based on an in-situ topographic survey. The topographic survey can be made using several approaches depending of the accuracy targeted by the survey.

a) b)

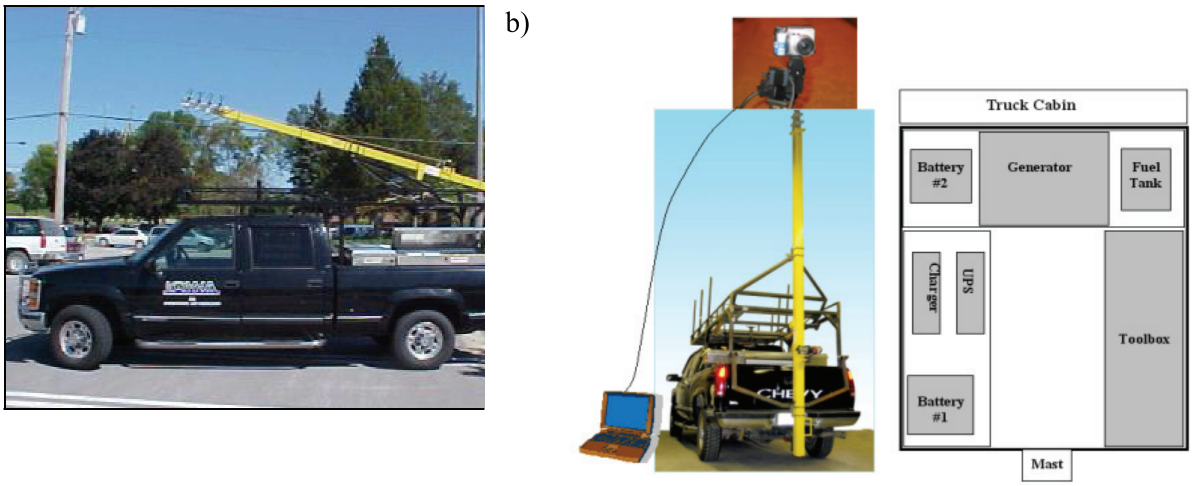
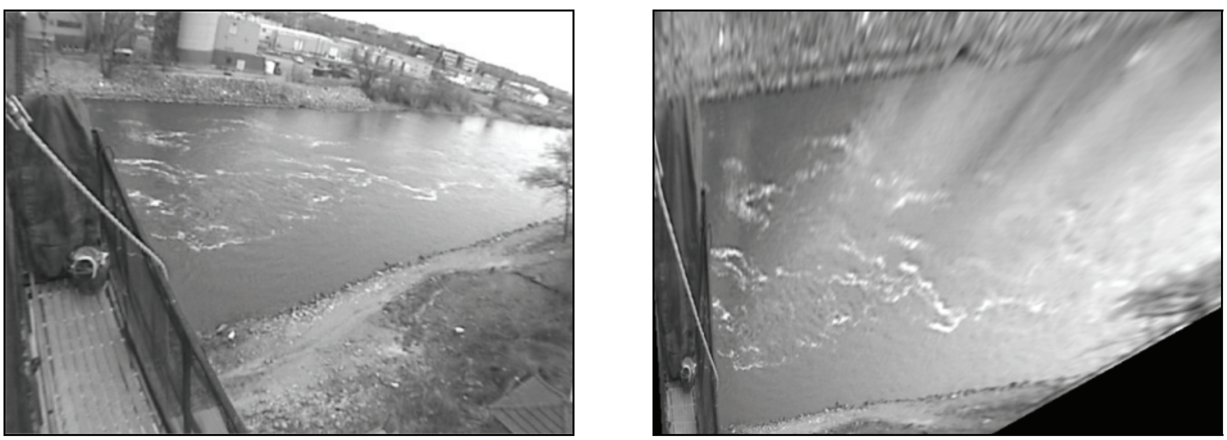


Figure 2. MLSPIV unit: a) general view; b) mast deployed and ancillary equipment



a) Distorted image. Image recorded with digital video camera under natural light

b) Undistorted image. Transformation from camera to real world coordinates obtained using 4 marker points. The software rescales flow boundaries, the size & shape of patterns in the image (note parallel river banks).

Figure 3. Removal of image distortion due to recording with an oblique angle and reconstruction of the image in real coordinates.

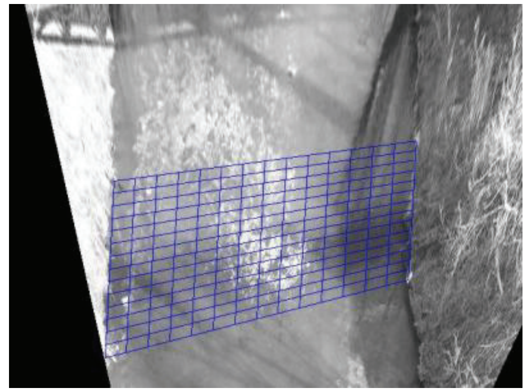
Estimation of free-surface velocities with LSPIV is based on the same concept as human vision. Specifically, the technique "guesses" using special pattern-recognition algorithms where small particles floating on the free-surface are recorded in consecutive images, separated at a known time interval. LSPIV is the only available instrument that can provide an instantaneous velocity measurement at the free surface over large flow areas. The obtained velocities provide critical information for assessing streamlines, velocity gradients, recirculation eddies, or stagnant areas within waterways. The LSIPV measurements are fast and can be obtained with minimum preparation.

If the bathymetry of the stream is known at the location of the LSPIV velocity measurements, the stream discharge can be also calculated. For the present application, use of the LSPIV system will rely on the assumption that free-surface velocities closely approximate mean-flow characteristics in waterways. This assumption is generally valid for small bridge waterways. For example, Figure 4 shows free-surface velocity measurements obtained with the MLSPIV for Clear Creek near Coralville, Iowa (Kim et al., 2007). Using the free-surface flow information, the MLSPIV discharge estimate was within five percent of the discharge reported by a nearby USGS stream gage.

Another relevant use of LSPIV for the present context is quantitative mapping of the free-surface velocity distribution around bridge structures (Ettema et al., 2005.a). The technique has been extensively used to analyze scour initiation and development for various channel and bridge geometries over a range of flow conditions. Figure 5 shows example LSPIV results from a recent study conducted in a large basin (the model basin is 15 ft wide and 75 ft long) at IIHR. The flow mapping around the bridge abutments provided by LSPIV was not only useful to gain insights into the flow field around the structures, but the measured velocities were further used in conjunction with analytical relationships or numerical models to assess scour condition and its evolution. The documentation of the flow field in the vicinity of the bridges is important for bridge inspections as it may indicates changes in the hydrodynamics of the approaching stream. The changes are usually related with stream the bank erosion (eventually leading to a change in the angle of incidence with the bridge) or with scour or deposition processes that can develop in time in the vicinity of the bridges.

a)

b)



c)

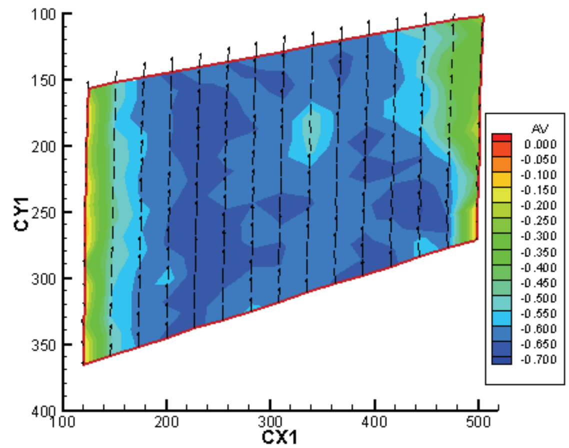


Figure 4. MLSPIV velocity measurements in Clear Creek, Coralville, IA: a) the truck deployed for measurements; b) distorted image of the Clear Creek; and c) velocity estimated by LSPIV at the free surface (velocities are computed for the grid overlaid over the channel shown in Figure 4b)

a) b)

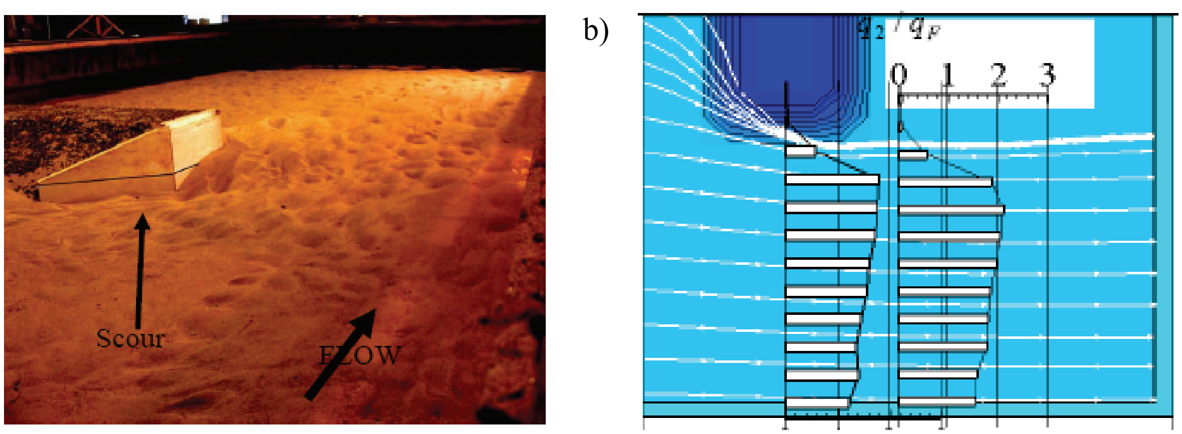


Figure 5. LSPIV flow mapping around a large bridge abutment hydraulic model (model width 15 ft): a) wing-wall abutment model; b) measured LSPIV velocity distribution in the channel contracted section of a spill-through abutment

4. Prototype Development

4.1. System Configuration

The MSLPIV prototype hardware used in this project is essentially the same as the original MLSPIV technique documented in Kim et al (2007). Therefore, the project benefits from a decade of LSPIV technique development. This continuous development process has entailed improvement of the software algorithms, processing procedures, and construction of the Mobile LSPIV unit, which can now be deployed at practically any site and operated real time. While all the above-mentioned MLSPIV features are useful, they are not necessary for acquiring images at bridge locations. The actual configuration for acquiring the images in the absence of the MLSPIV unit is not specified herein as imaging with conventional devices can be made in a variety of ways. The essential elements of a good bridge mapping are locating the camera to a vantage point (axis of the bridge, poles existing at the sites, trees in advantageous location) and following the recommended procedure to acquire the images

In addition to the image acquisition system, the software used for surveying the bridge sites requires an in-situ survey that can be conducted with various approaches (total station, Global Positioning System-based devices, Lidar technology, etc). A minimum of four Ground Reference Points (GRP) is needed to reconstruct the images. The survey s greatly improved if a minimum of six GRPs are used instead, that are located on along the four edges of the images.

4.2. Field Procedures

The aim of the field experiment is (i) to make an accurate survey of some points of the site and (ii) to imaging interesting areas upstream and downstream a bridge or culvert. Those data will be then used in the software for digital mapping DIGIMAP. The steps to be implemented at the bridge site described below are based on the use of the IIHR's MLSPIV. As mentioned above, the MLSPIV unit is not needed, but following the target of the described steps is essential. Data acquisition procedures would include the following steps:

1. Select two recording positions (on or near the bridge) with good visibility of the waterways upstream and downstream from the bridge. Position successively the

MLSIV truck at the selected positions and proceed with the next data acquisition sequence (Figure 6a).

2. Set the mast in a vertical position at a favorable height. This will be determined by the type of bridge, stream size, bridge height, area of coverage in the vicinity of the bridge, proximity to power lines, etc.
3. Record views of the bridge surroundings. The area of study should be decomposed in plans to be analyzed with digital mapping software. River plan decomposition is illustrated in Figure 6b. These recordings are repeated for the two pre-established truck positions.
4. Conduct a geodetic survey of Ground Reference Points (GRPs) for each plan for ortho-rectifying the images. The surveyed points have to be placed both in the near-field as well as in the far-field areas of the photo framing. Each of the plans should be defined by at least 6 spatially well-distributed GRPs to allow an accurate ortho-rectification (see Fujita, 1994).
5. LSPIV analysis required having a sequence of images of a flow where tracers are visible. From one of the recording locations take video images upstream and downstream along the waterway for 3-5 minutes for estimation of the free-surface hydrodynamic characteristics.

a) b)

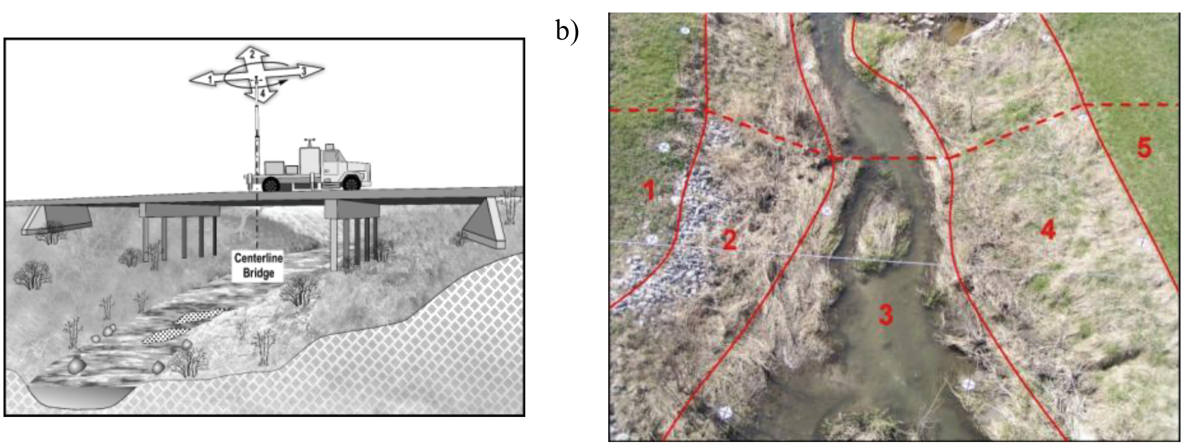


Figure 6. MLSPIV bridge monitoring prototype: a) site image registration; b) River reach plan decomposition. Numbers in the image indicate the quasi-planar surfaces: (1) and (5) floodplains; (2) and (4) sloping banks; (3) river water surface

4.3. Data processing

The methodology of digital mapping proposed herein is applicable to waterway bridge monitoring in general, but is especially well suited for monitoring of small bridges (defined as those that cross waterways with watersheds encompassing less than 100 square miles) that are typical for Iowa and surrounding states. The key ingredients of the proposed bridge monitoring methodology are:

I. to provide accurate quantitative mapping of the waterway characteristics (i.e., information about flow distribution and velocity magnitude, channel and bank characteristics, including vegetation presence) in the vicinity of the bridges using one measurement tool;
II. to record waterway changes upstream and downstream of the bridge with an emphasis on quantifying changes in channel pattern, shape, and elevation. The data must be recorded in a digital format, readily available for tracking aforementioned changes over short or long time periods
III. to reduce the effort, time, and cost associated with current bridge monitoring methods; and
IV. to improve the safety of bridge inspections conducted during normal and extreme hydro logical events.

The newly developed technique assembles innovative means to accomplish the above tasks. In essence, the technique is carried out in 3 steps:

1. Water vicinity mapping: Images of a river reach taken from several angles are ortho-rectified and assembled to obtain a panoramic distortion free image of the area;
2. Flow measurement: Image pairs of the river free-surface flow are analyzed using LSPIV to obtain the surface velocity field;
3. Assembling of flow and terrain data: The information obtained in steps 1 and 2 is assembled, stored and analyzed. Characteristics elements of the waterway are identified and localized in the ortho-rectified image, which leads to the creation of a digital map stored in electronic format.

In order to facilitate the understanding or the data processing steps, the procedure is described in conjunction with images acquired in-situ at a culvert site on Jordan Creek near Solon, Johnson County, Iowa.

4.3.1. Waterway vicinity mapping

The river vicinity characteristics can be broadly described using 5 quasi-planar surfaces (see Figure 6b):

- 2 flood-plains;
- 2 sloping banks;
- River water surface.

The images containing these planar surfaces need to be ortho-rectified, i.e. mapped into a new and free of distortion image where the image coordinate system (in pixel) is linearly related to the actual coordinate system (in meter for example). The ortho-rectification is carried out using an 8 parameters plan-to-plan transformation (Mikhail et al. [2001]) :

$$X = \frac{a_1 i + a_2 j + a_3}{a_7 i + a_8 j + 1} \quad (1)$$

$$X = \frac{a_4 i + a_5 j + a_6}{a_7 i + a_8 j + 1} \quad (2)$$

where [i, j] are the coordinates of a point in the image coordinates system (in pixels), [X, Y] are the coordinates of the same point in the actual coordinates system (in meters) and a_i are the projective transformation parameters. Determination of the transformation parameter is accomplished using an implicit method [Wei, 1994] based on a set of GRPs, i.e. points of known coordinates in the actual coordinate system and in the image coordinate system. At least 4 GRPs are needed to solve for the a_i parameters, and a least square fit is applied if more than 4 GRPs are available. The ortho-rectification of the waterway vicinity is accomplished with a graphical user interface and encompasses 5 steps, as illustrated in Figure 7:

1. Identification of the different planar surfaces on the images.y
2. Decomposition of the image planar surfaces onto Red, Green and Blue (RGB) channels
3. Ortho-rectification of the RGB channels using Equation 1
4. Summation of the RGB ortho-images to obtain a 24 bits color orthoimage of each planar surface
5. Assembling of the ortho-images of the planar surfaces to obtain the ortho-image of the waterway vicinity.

The result of the above processing steps is a color ortho-image of the area of interest that is a scaled replica of the actual vicinity of the waterway.

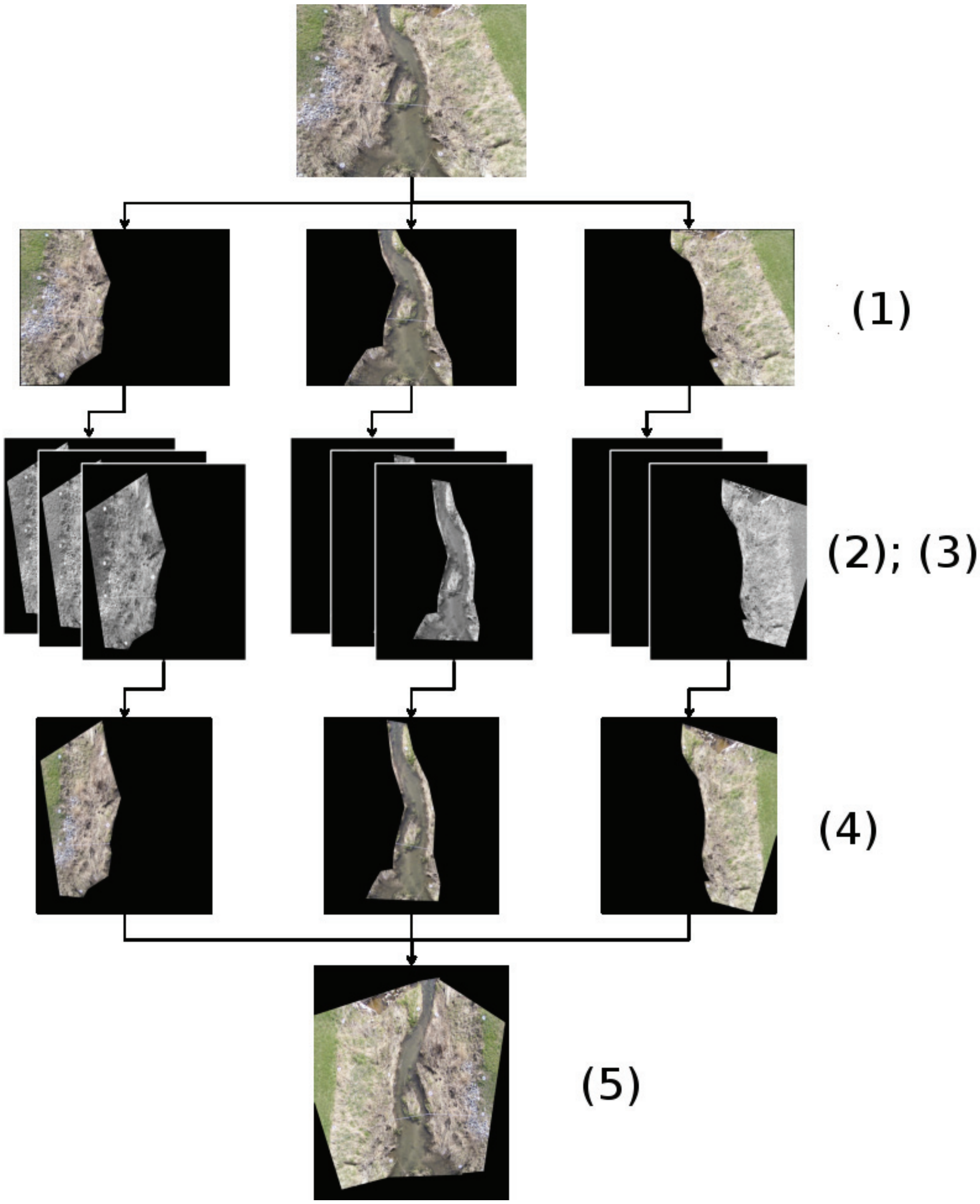


Figure 7. Waterway vicinity ortho-rectification protocol: (1) identification of the planar surfaces on the images; (2) decomposition of each planar surface onto RGB channels; (3) ortho-rectification of the RGB channels; (4) summation of the RGB ortho-images of each planar surfaces to obtain a color ortho-image of each planar surfaces and (5) assembling of the ortho-images of the planar surfaces to obtain the ortho-image of the landscape.

4.3.2. Flow measurement

LSPIV has been successfully implemented to measure free-surface velocities and discharges in various streams [Bradley et al., 2002, Creutin et al., 2003, Fujita, 1994, Fujita et al., 1998, Hauet et al., 2008, in press]). The technique is the extension of the conventional PIV applied in fluid mechanics [Adrian, 1991]. Estimation of free-surface velocities with LSPIV is based on the same concept as human vision. Specifically, the technique "guesses" using special pattern-recognition algorithms where small particles floating on the free-surface are moving in consecutive images, separated at a known time interval. A classical cross-correlation algorithm is used to determine the movement of flow tracers. In this study, a PIV algorithm for large scale applications with low resolution images, developed by Fincham and Spedding [1997], is used. The advantage of this algorithm is that it decreases the mean bias and root mean square errors [Piirto et al., 2005]. It calculates the correlation between the interrogation area (IA) centered on a point a_{ij} in the first image (image A) and the IA centered at point b_{ij} in the second image (image B) recorded with a time interval of δ_t seconds. The correlation coefficient R(aij , bij) is a similarity index for the gray-scale intensity of a group of pixels contained in the two compared IAs, expressed as:

$$R(a_{ij},b_{ij}) = \frac{\sum_{i=}^{Mi}\sum_{j=1}^{Mj}[(A_{ij}-\overline{A_{ij}})(B_{ij}-\overline{B_{ij}})]}{[\sum_{i=1}^{Mi}\sum_{j=1}^{Mj}(A_{ij}-\overline{A_{ij}})^2\sum_{i=1}^{Mi}\sum_{j=1}^{Mj}(B_{ij}-\overline{B_{ij}})^2]^{1/2}} \tag{3}$$

where M_i , M_j are the sizes of the interrogation areas (in pixels), and A_{ij} and B_{ij} are the distributions of the grey-level intensities in the two interrogation areas. Correlation coefficients are only computed for points within a pre-defined searching area (SA). The SA size is selected so that the displacement of tracer patterns from the first image is contained within the SA of the second image, commensurate with the expected range of velocities of the river. For rivers with small cross-stream velocities, the SA should be asymmetric, elongated in the direction of the flow. The algorithm assumes that the most probable displacement of the fluid from point a_{ij} during the period δ_t is the one corresponding to the maximum correlation coefficient. Sub-pixel displacement accuracy is reached using a parabolic fit [Fujita and Komura, 1992]. Velocity vectors are derived from these displacements by dividing them by δ_t. The process is iteratively conducted over the entire image using a computational grid. An example of LSPIV surface velocity field for the Jordan Creek site, downstream the culvert, is shown in Figure 8.

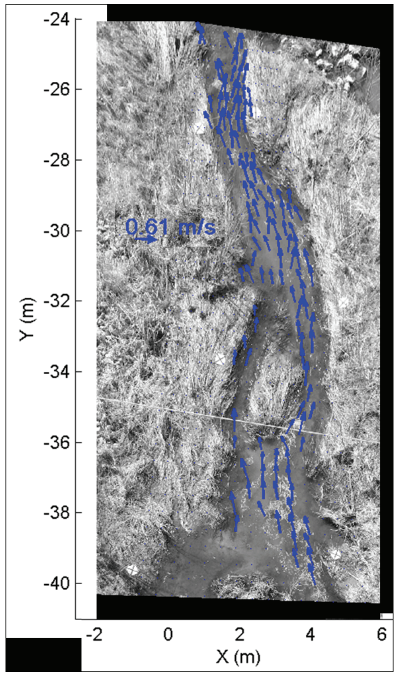


Figure 8. LSPIV time-averaged velocity field for the Jordan Creek site, downstream the culvert.

4.3.3. Assembling of flow and terrain data

In this step the ortho-rectified dry land in the vicinity of the water way and the velocity of free-surface are assembled in one map for further analysis. In general, the waterway encompasses the bridged stream or river bed along with its banks, abutments, and any other local obstructions that significantly impact flow velocity, flow alignment, and scour depth. software allows to identify, select and extract features of importance for customized analysis. These operations are conveniently carried out by scrawling the mouse over assembled ortho-rectified image of the site. Each feature is labeled with a code name and its coordinates are saved so that a map of the waterway characteristics can be created. For example, the colored ortho-image in Figure 9 allows easy identification of:

1. The intersection between the banks and the river surface waterline defining the shape and the angle of attack of the stream;
2. Islands, debris, deposits or other obstacle in the channel;
3. Floodplain characteristics, including land cover (rocks, mud, vegetation), the presence of side ditches, vegetation, debris or other obstacles.

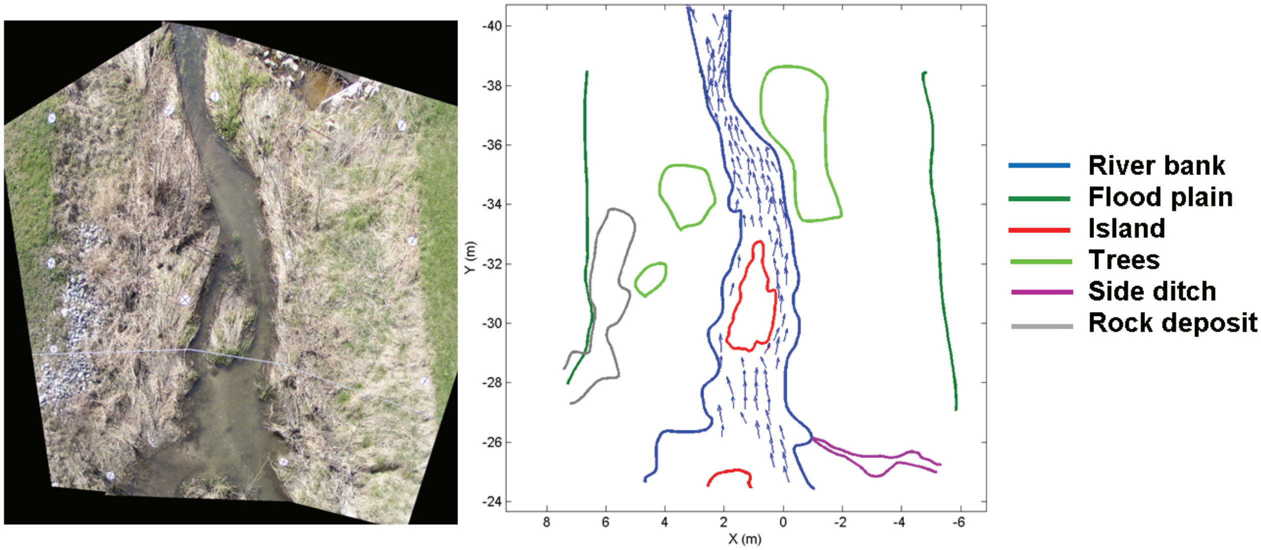


Figure 9. Example of mapping: Ortho-image of the studied area (left) and the corresponding digital map containing selected features of the waterway and its vicinity (right)

5. Case Study

As described in the preliminary part of the report, the main goal of the digital mapping is to quantify changes in bank positions and other morphological features (island, vegetation growth, debris, etc...) that can occur over time and lead to bridge threats. The implementation of DIGIMAP for a culvert site in Iowa is demonstrated in this section of the report.

5.1. Experimental site

The study area for the proof of concept experiment is the waterway in the vicinity of a culvert on Jordan Creek, Solon, Iowa, USA. At this location, Jordan Creek is about 3 m wide and flows westward (see Figure 10). The 3-box culvert is 20.6 m long.

Figure 10. Satellite view of the study site, from Google Earth. Gray arrow indicates flow direction

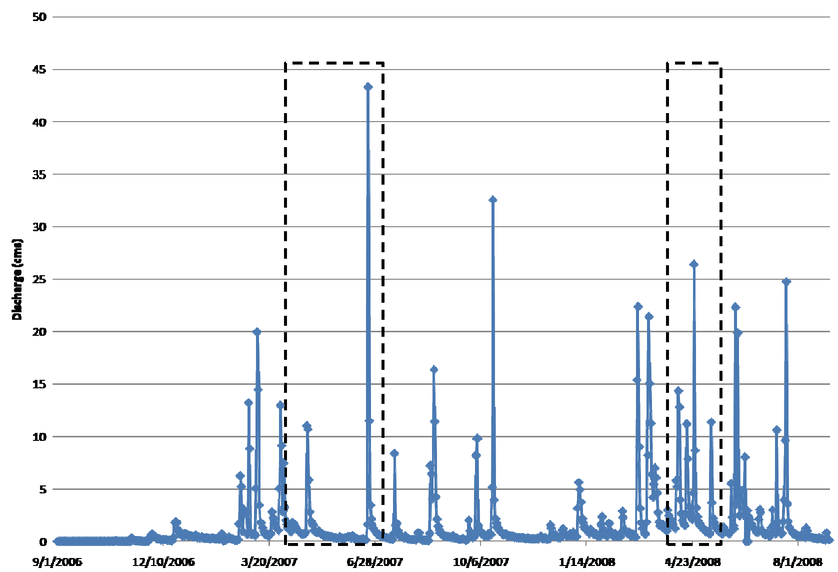
5.2. Digital Mappings

Four mappings of the site were carried out:

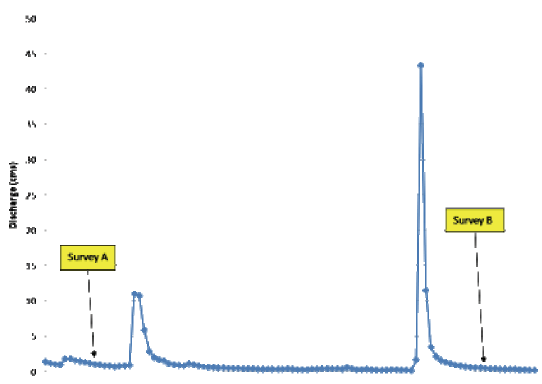
- Survey A: conducted on the 17th of April 2007 at a discharge of 0.7 m^3/s
- Survey B: conducted on the 5th of July 2007 at a discharge of 0.6 m^3/s
- Survey C: conducted on the 14th of April 2008 at a discharge of 2.03 m^3/s
- Survey D: conducted on the 28th of May 2008 at a discharge of 0.76 m^3/s

Between surveys A and B, the flood occurred on June 22th and reached a peak of 44.0 m^3/s; between survey C and D, the flood occurred on April 25th and reached a peak of 26 m^3/s, as illustrated by the hydrograph plotted in Figure 11.

a)



b)



c)

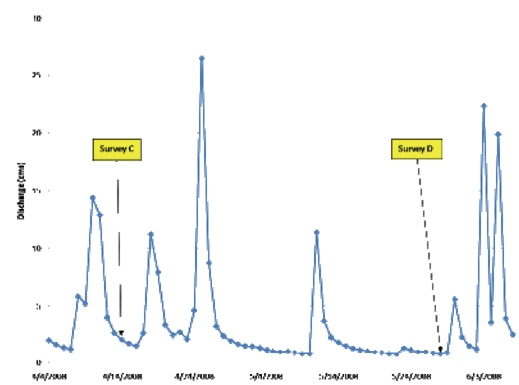


Figure 11. a) Two-year hydrograph for Jordan Creek and the timing for the mappings reported, b) Enlarged hydrograph from 04/07/2007~07/15/2007, c) Enlarged hydrograph from 04/04/2008~06/15/2007

5.2.1. Survey A

Survey A was carried out at a discharge of 0.7 m^3/s which corresponds to a normal flow condition. The images were recorded at noon to avoid shadows of trees. Two photos were taken for the mapping, one upstream taken from the east shoulder of the culvert and one downstream taken from the west shoulder of the culvert with a camera tilt angle of about 70^0. The upstream and downstream images were both partitioned into three planar surfaces: the two sloping banks and the river water surface. The flood plain was not mapped as the water did not reach it during the flood. 6 GRPs were used to define each planar surface. For the LSPIV analysis, series of 50 images with interval time of 1s were recorded upstream and downstream. The total area analyzed by LSPIV is about 100 m2 for both upstream and downstream. As few natural tracers were present on the free-surface, vegetation debris (e.g. grass and leaves) from surrounding area were added during the 1 minute of image recording. The size of the SA is 32×32 pixels which correspond to a physical size of around 0.1 m^2. The assembled ortho-rectified upstream and downstream image is shown in Figure 12. The relevant features for the mapping goal include:

- River banks positions;
- Flood plain edges;
- Deposition islands;
- Mud deposit;
- Different kinds of vegetation, grass, bushes or trees within the waterway or on the banks;
- Rocks on the banks;
- Erosion patterns (side ditches).

The mapping of the sediment deposition related features along with the velocity vectors obtained from LSPIV using the ortho-rectified images are shown in Figure 12. The map allows to identify very easily the different hydrodynamic and morphologic features of the study area. At the time of the survey A, the creek flowed mainly through the right box of the culvert, the middle and the left boxes being filled by mud upstream the culvert. Downstream the culvert, only the middle box was filled with mud which produced a slow velocity recirculation area in the left box. The formation of the sediment deposition in the central and left boxes of the culvert can be explained by the oblique angle of the waterway upstream the culvert. Those two boxes are located in the convex part of the bend where low velocities, hence sediment deposition, are expected (see also Figure 6).

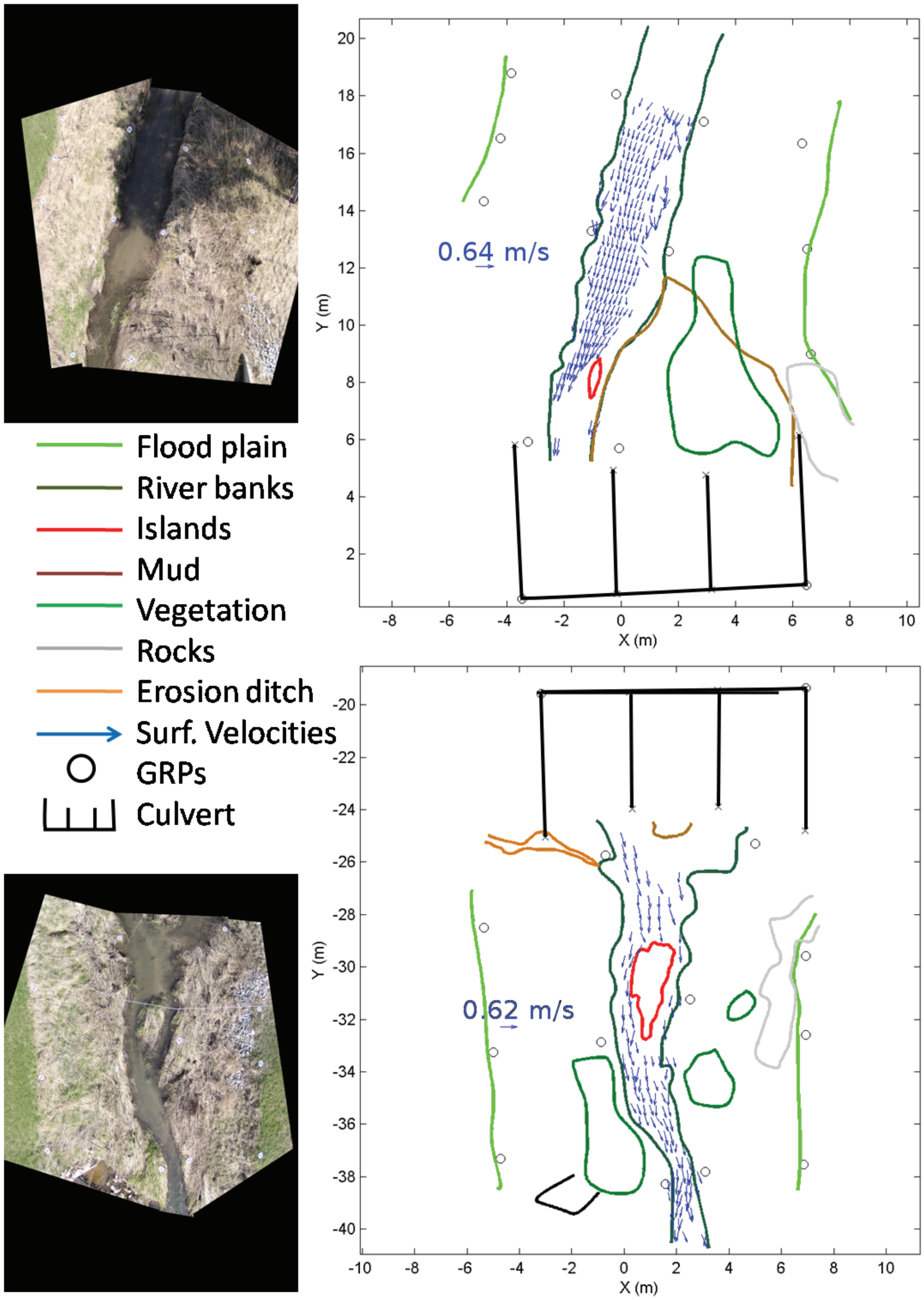


Figure 12. Mapping of survey A with the ortho-rectified image of the culvert site (left) and the mapping of the relevant features (right).

5.2.2. Survey B

Survey B was conducted at a discharge of 0.6 m^3/s, 10 days after the flood event of June 22th. In the absence of drastic changes in the stream bathymetry, it is expected that mapping the area of interest at same discharge will maintain the waterline position in the maps. Consequently, perfect features overlapping indicate lack of changes between surveys. Images were recorded at noon to get the best illumination. Mapping of the culvert area entailed four photos, two upstream photos taken from the east shoulder of the culvert and two downstream ones taken from the west shoulder of the culvert with tilted camera of about 80˚ and 60˚, respectively. This strategy of measurement allows covering a larger surface. The upstream and downstream images were both decomposed into three planar surfaces: the two sloping banks and the river water surface. 6 GRPs were used to define each planar surface. For the LSPIV analysis, we use the same parameter that in the Survey A. The assembled ortho-rectified image of the upstream and downstream areas and the features mapping for Survey B are shown in Figure 13. Most of the observations made for Survey A are valid for the new survey. A new feature is a wood weir upstream the culvert formed by wood debris accumulation. That weir generates a pool upstream the culvert that drastically reduce the flow. As a result, the LSPIV analysis was only conducted for the flow downstream this weir. As in Experiment A, the creek only flows in the right box of the culvert. In the downstream part of the culvert, the left and the middle boxes are filled by mud.

Using of more photos for the same area in Survey B leads to an increased image resolution. The higher resolution allows identification of finer vegetation such as the short grass cover. This short grass loaded with the fine sediment carried during the high flow acts as virtual flow tracers [Jegou, 2002]. A careful inspection of the short grass appearance indicated that they are orderly aligned with the downstream direction over the banks and floodplain area. This observation is valid for the entire area upstream the culvert, including the mid and left culvert cells, indicating that during the flood all 3 culvert boxes were carrying flow (see Figure 14). The type of inferences presented above calls for engineering judgments as the type of vegetation and its appearance in the image may lead to erroneous inferences (for example, tall vegetation will be affected by out-of-plan distortion and won't be a good tracer of the past flood). Nevertheless, use of high resolution images for the mapping is encouraged.

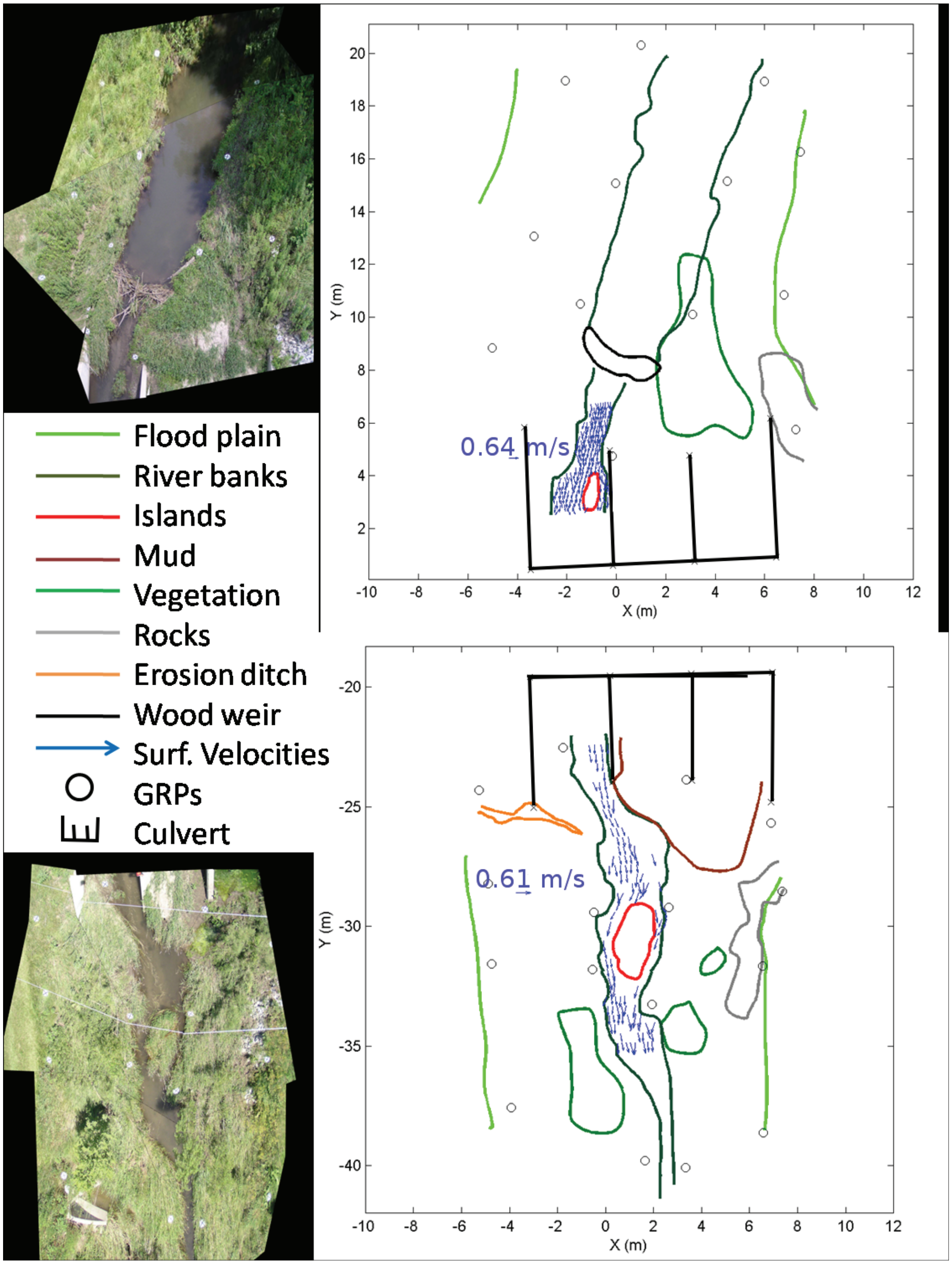


Figure 13. Mapping of survey B with the ortho-rectified image of the culvert site (left) and the mapping of the relevant features (right).

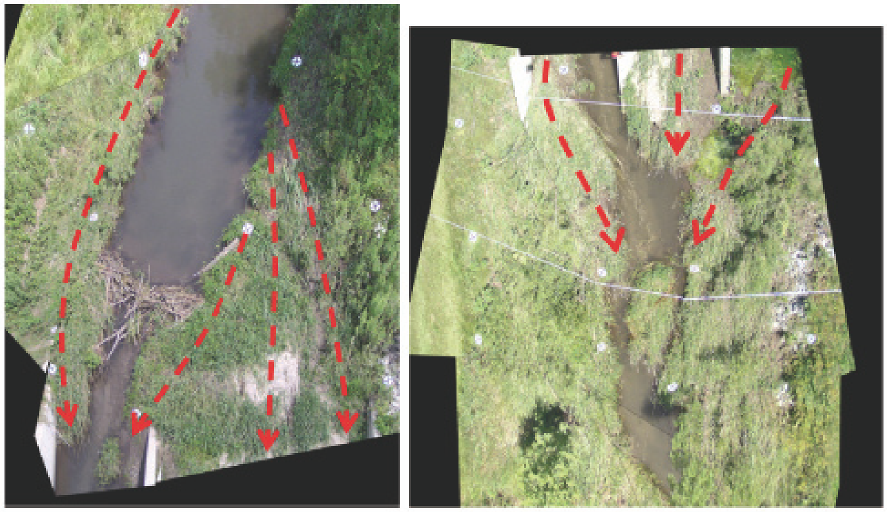


Figure 14. Flood flow identification using Survey B.

5.2.3. Survey C

Survey C was conducted at a discharge of 2.03 m^3/s, ten months after survey B. The mapping of the area of interest was made at a discharge considerably higher than the normal discharge. Several flood events occurred between Survey B and C (see Figure 11a). The images were recorded at noon to have the best illumination. Two photos were taken for the mapping, one upstream taken from the east shoulder of the culvert and one downstream taken from the west shoulder of the culvert. The upstream and downstream images were both decomposed into three planar surfaces as in the previous surveys. For the LSPIV analysis, the same parameters as in Survey A were used to process the images. The assembled ortho-rectified image of the upstream and downstream areas and the features mapping for Survey C are shown in Figure 15. Given the large difference of discharges at the time of the Surveys B and C, the comparison of the digital maps for the two surveys is not made, as the water lines are potentially very different. From Figure 15 it can be inferred that the discharge difference does not drastically change the flow downstream the culvert. The flow upstream the culvert however, shows considerable changes. It also can be noted from Figure 15 that the poor seeding for the downstream region of the flow precluded obtaining of good resolution for the velocity vectors at the free surface.

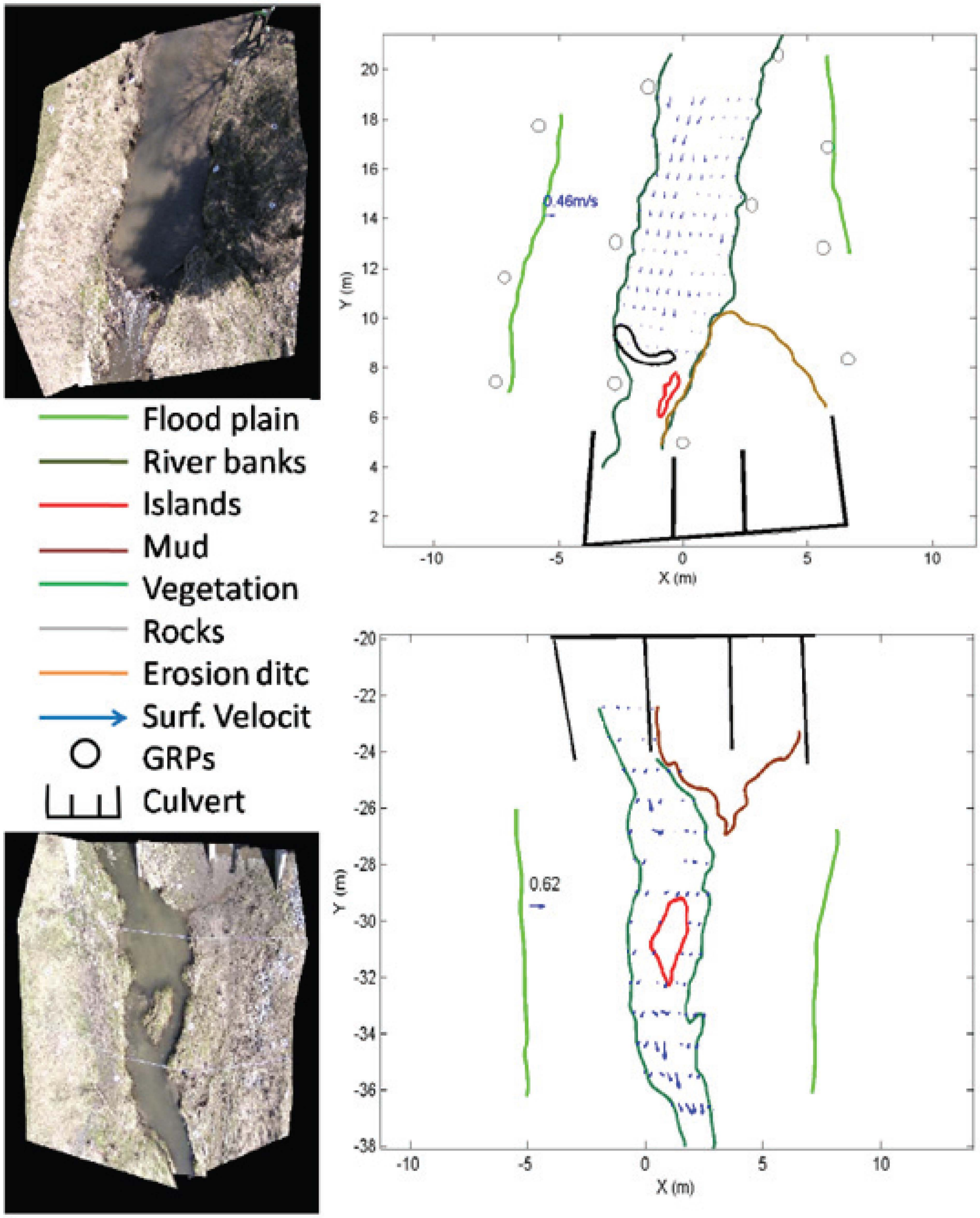


Figure 15. Mapping of Survey C with the ortho-rectified image of the culvert site (left) and the mapping of the relevant features (right).

5.2.4. Survey D

Survey D was conducted at a discharge of 0.76 m^3/s, one months after survey C. At the time of survey, the flow was closer to the normal flow conditions in the stream and also similar to Surveys A and B. Consequently, it is expected that mapping of the area of interest in the vicinity of the culvert for Surveys A, B, and C to be similar as the waterline position should have had the same position with respect to the stream bed. The upstream and downstream images were both decomposed into three planar surfaces as the previous surveys. For the LSPIV analysis, the same parameters in Survey A were used to process the images. The assembled ortho-rectified image of the upstream and downstream areas and the features mapping for Survey D are shown in Figure 16. All of the observations made for previous surveys are valid for the new survey.

5.3. Tracking feature changes over time

5.3.1. Comparison of the Surveys A and B

The comparison of the two Surveys A and B allows inferring the effect of the flood occurred between surveys. The comparison was conducted at the same discharge as confirmed by the LSPIV velocities (around 0.6 m/s) in Figure 11.

5.3.2. Upstream area

Figure 17 shows the overlaid maps of Surveys A and B for the culvert upstream area. One of the noticeable differences in this area is the presence of the wood weir created during the flood. The weir is located near an island existing prior to the flood event. It is obvious that this island obstructed the flow and has blocked more and more wood debris during the flood, facilitating the creation of the woody weir.

Another drastic change is the shift in the waterway approaching the culvert. The weir produced an upstream pool, with a wideness of the wet area but the channel was also shifted. The ortho-rectified images allow to actually quantify this shift. Specifically, the upstream waterway has shifted in the positive X direction with about 1 m throughout the mapped area. The new stream path encroached in the vegetated area and an important amount of fresh mud deposition was crowded, as can be seen from Figure 17.

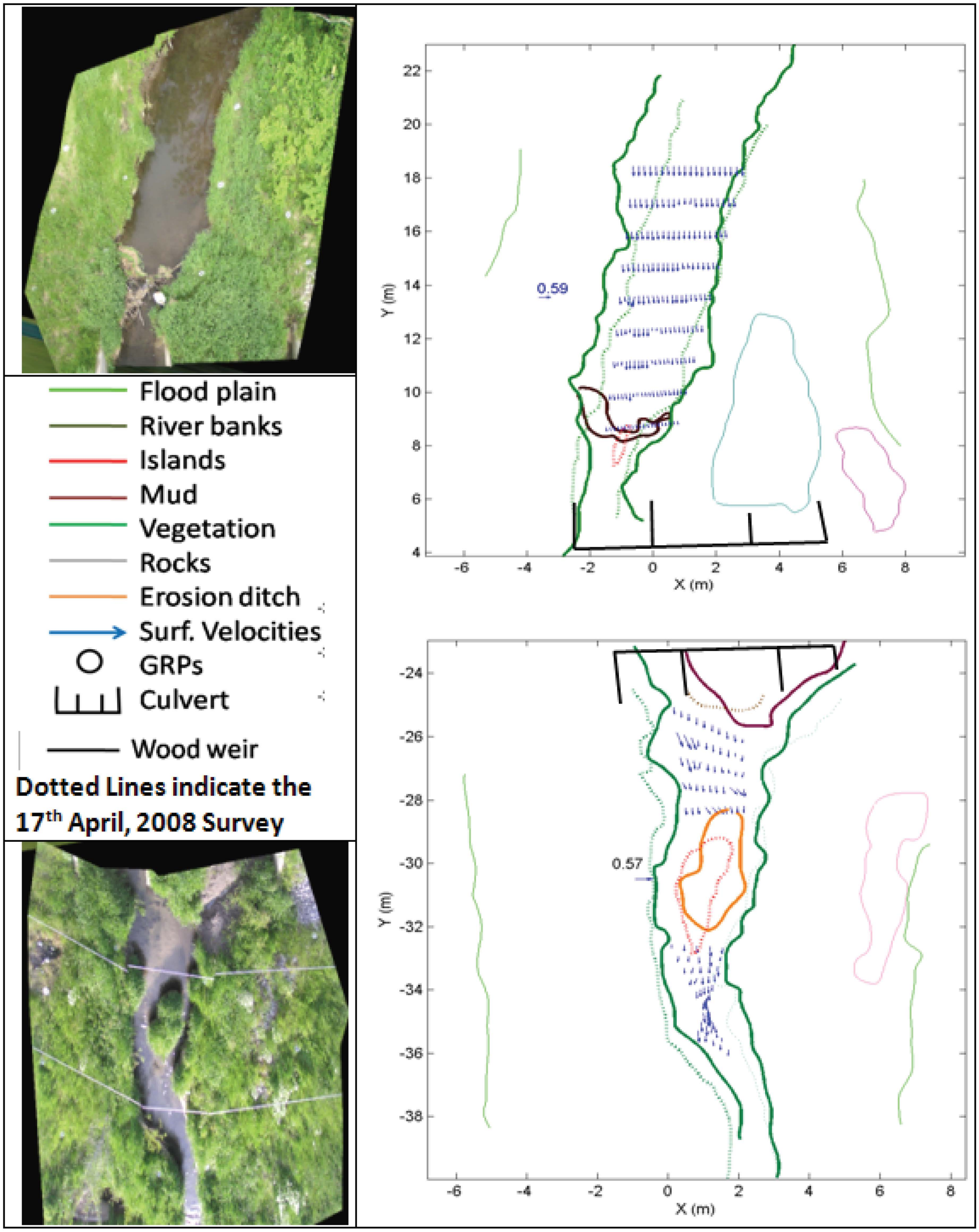


Figure 16. Mapping of Survey D with the ortho-rectified image of the culvert site (left) and the mapping of the relevant features (right).

5.3.3. Downstream area

Figure 18 compares the maps of Surveys A and B for the area downstream the culvert. The changes in this area are numerous. After the flood, the recirculation area existing prior to the flood downstream the left box has disappeared. The middle and left boxes are filled with fresh mud, constraining the flow only in the left box. Thanks to the flood flow direction identified in Section 3.4, one can think that this mud material, deposed during the fall of the flood, comes from the muddy area eroded in the upstream part and also from lateral contribution of the erosion ditches. A small sediment bar can be observed close to the confluence of the side ditch and the stream. This deposit can be explained by the presence of a slow recirculation flow formed in this confluence and favoring deposition. The large in-stream island, of about 4.5 m^2, has quite not changed between surveys. Its right side has been eroded and deposition of material occurred in the left side. This can be explained regarding the flow characteristics given by the LSPIV as the flow is faster in the right side of the island. This result is consistent with the meander shape of the creek at that location resulting in the erosion of the right bank (concave part of the meander) and the deposition of sediment on the left bank (convex part of the meander). The river banks have not changed considerably. Globally, the channel was shifted of about 0.4 m in the X positive direction. The trees and vegetated areas present downstream the culvert played an important role in maintaining the stream morpho-dynamics before and after the flood, reinforcing their positive role in controlling stream erosion processes (Figure 18).

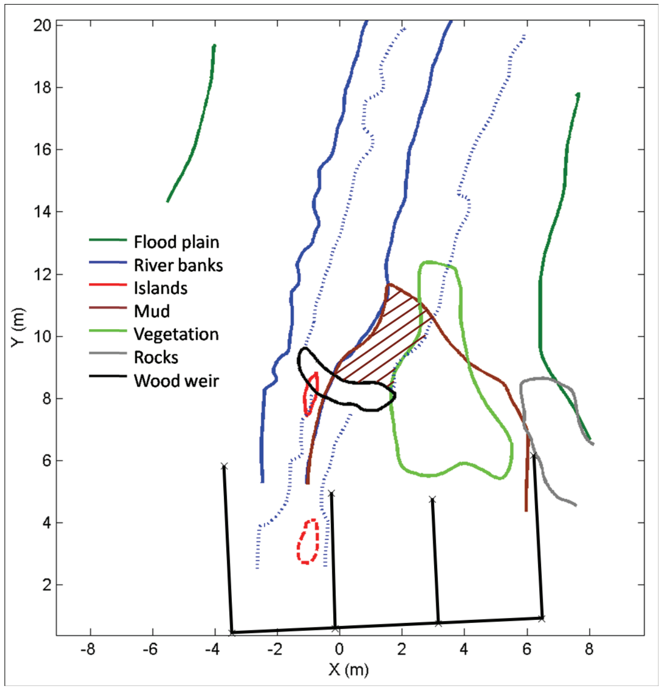


Figure 17. Overlap of the maps of Surveys A (solid lines) and B (dash lines) for the upstream area. The eroded mud area is represented by strips.

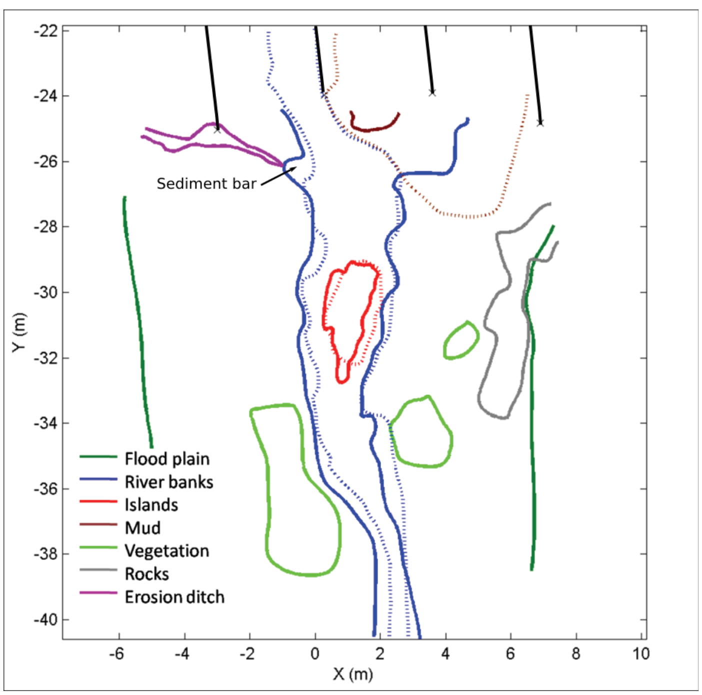


Figure 18. Overlap of the maps of Surveys A and B for the downstream area

6. Discussions

The proposed bridge waterway mapping represents an innovative methodology built on recent advances in imaging, computer, and data acquisition technologies and should provide bridge engineers and inspectors with hydrodynamic and geomorphic information critical to bridge monitoring activities. Existing bridge monitoring methods only provide sparse information and not uniformly substantiable. Rarely do existing bridge monitoring programs allow quantitative analyses of bridge waterway scour processes, primarily due to the amount of manual efforts involved and numerous bridge inspections necessary for such analyses. These documentation gaps hamper the timely recognition of the detrimental effect produced by local changes in bridge waterways and development of safety and prevention plans. A typical example of a local change is the upstream migration of a knickpoint, a process very common in west central Iowa in small tributary streams such as those along the Boyer River, particularly in Harrison, Crawford, and surrounding counties. Knickpoint migration causes severe damage to state and county bridges.

While most of the knowledge required for the development of LSPIV mapping technology is in place, the present research has several exploratory features that will require an intense intellectual contribution**.** These features stem from the complexity and novelty of the research issues involved including development of an easily implemented measurement method and understanding how to deal with difficult situations encountered during field measurements. However, this methodology has the potential to bring about substantial benefits to an area of Iowa transportation that currently requires considerable financial and time resources. Previous studies have mentioned the need to obtain quantitative information about waterways characteristics such as those summarized in Table 1 (Ettema et al, 2006). Using DIGIMAP that type of information is not available.

The repeated surveys encompass both quantitative as well as qualitative information. For example, the series of ortho-rectified images shown in Figure 19 show the quick and effective documentation of change in vegetation or soil deposition around interested area. The mapping method developed through this research has potential ability to provide a monitor system for professionals, such as foresters, ranchers, wildlife biologists, and nature enthusiasts, who are interested in changes of natural resource surrounding the streams.

Table 1. Characteristics that can be quantitatively mapped by the DIGIMAP software

Review of waterway developments/conditions influencing the bridge site
Channel head-cutting, or nick-point migration Channel straightening/ channelization Channel diversion Watershed-wide bank instability owing to channel migration/ widening Grade-control structure control of the hydraulic regime at the bridge site Upstream or downstream check dam/ storage reservoir Sediment bar control of the hydraulic regime at the bridge site Waterfall control of the hydraulic regime at the bridge site
Waterway adequacy
Significant blockage of the waterway (identify source: e.g. debris, bars, vegetation, foundations, guidebanks, scour countermeasures, other) Countermeasures present (identify: e.g. none, relief/ overflow bridges/ channels, other)
Lateral channel movement, channel widening, bridge approaches
Grading of waterway banks (identify: e.g. narrow, wide, unknown): Bank erosion/failure influencing the factors of safety for the bridge Flow concentration at a bridge approach Bridge approach fill movement Countermeasures present and their status (damaged/ineffective)

7. Suggestions for further work

The methodology presented in this research is considered as a first step in assembling a set of tools capable to remotely assess quantitatively and qualitatively the status of the bridges during normal flow conditions and extreme events. The remote measurements are mostly valued when the inspections are needed most: during floods. The LSPIV-based technology presented in this report is relatively cheap, easy and friendly to utilize for documenting the geometry and hydrodynamics of the waterway in the vicinity of the bridges. If the DIGIMAP software and procedures presented herein can be completed with similar convenient and non-intrusive means to quantify the flow and geometry under the stream free surface the current needs for monitoring bridge sites can be considerably enhanced. These developments are timely at a time when the need for the assessment of the nation’s aging infrastructure is continuously increasing. The proposed technological solutions for bridge monitoring are now possible due to the exponential growth of the modern digital-based advances in computer science, electronics, and communication.

a)
b)
c)

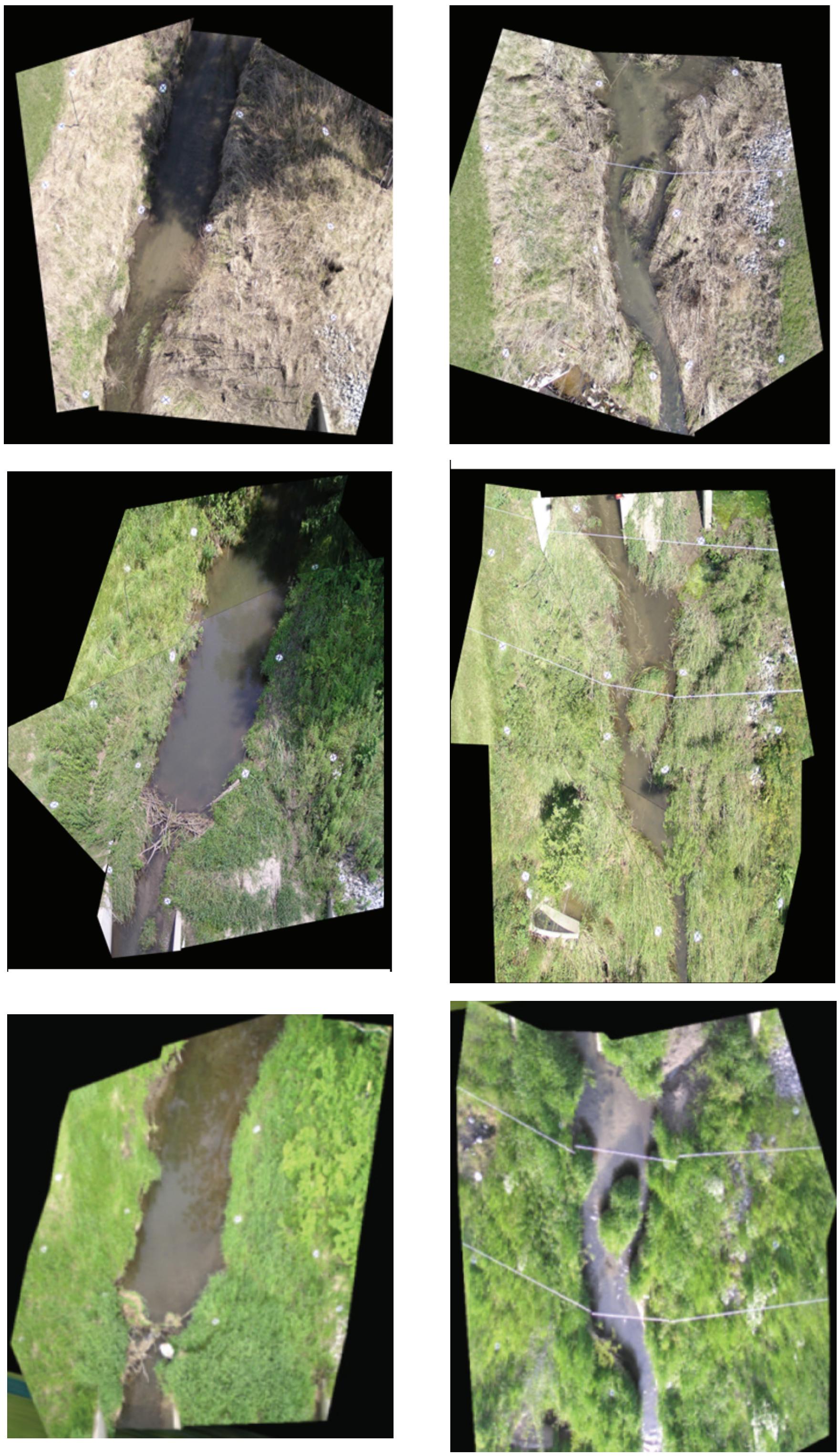


Figure 19. Ortho-rectified images of the Jordan Creek Survey, A, B, and C (Left is upstream, and right is downstream the culvert): a) Survey A: 17th April 2007, b) Survey B: 6th July 2007, and c) Survey D: 28th May 2008

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Appendix A. DIGIMAP USER GUIDE

DIGIMAP

User Guide

IIHR – Hydroscience & Engineering

The University of Iowa

Iowa City, IA 52242

USA

1. Introduction

The software DIGIMAP is a Matlab code allowing the study of waterways using digital images.

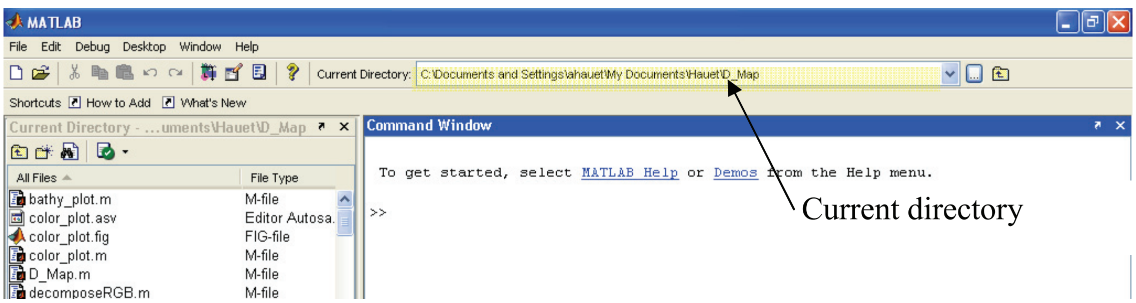
2. Input Data

The input data are the survey file and the images recorded in the field experiment (see Appendix B: Field Procedure manual).

3. Procedure

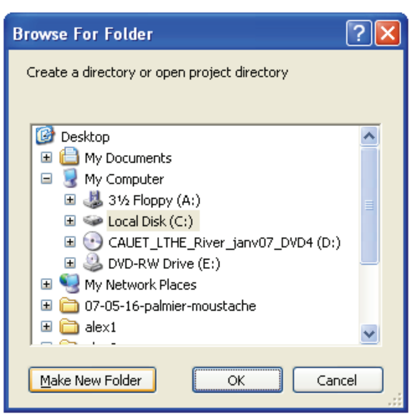
3.1. Launching the software

Launch Matlab and input the D_Map directory as the current directory.



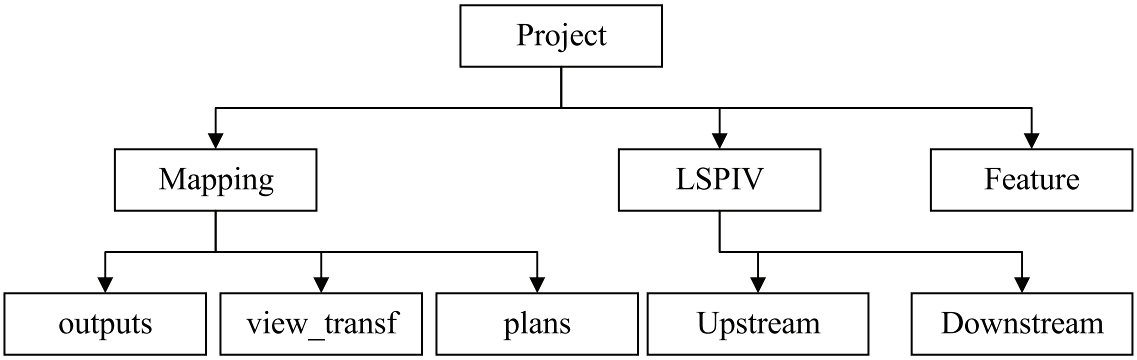
Run the software with the command:

>> D_Map

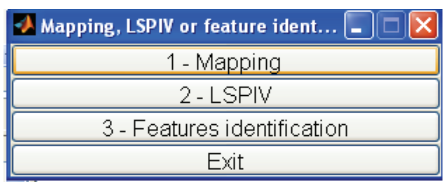


A pop-up window appears. If you want to create a new project, create a new folder (using the **Make New Folder** button) at the desired location. If you want to resume an old project, browse for the folder of the old project and click **OK**.

A project folder contains 3 folders: *Mapping*, *LSPIV* and *Features*, corresponding to the 3 main procedure steps. The architecture is described in the next figure:

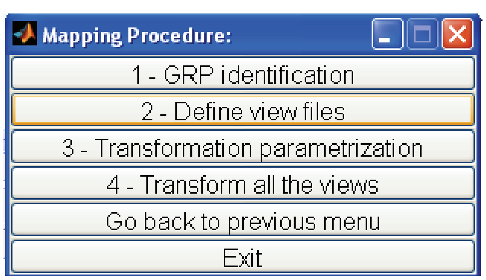


The Main procedure table pops up. It contains the 3 elemental steps for getting a digital map: (i) **Mapping**, (ii) **LSPIV** and (iii) **Features identification**.



First, click on **Mapping**.

3.2. Mapping



The Mapping Procedure table appears. The Mapping procedure contains 4 steps: (i) identification of the Ground Reference Points (GRPs) on the images (ii) Selection of the plans to be rectified, (iii) Parameterization of the geometric correction and (iv) Transformation of all the views.

3.2.1. GRP identification

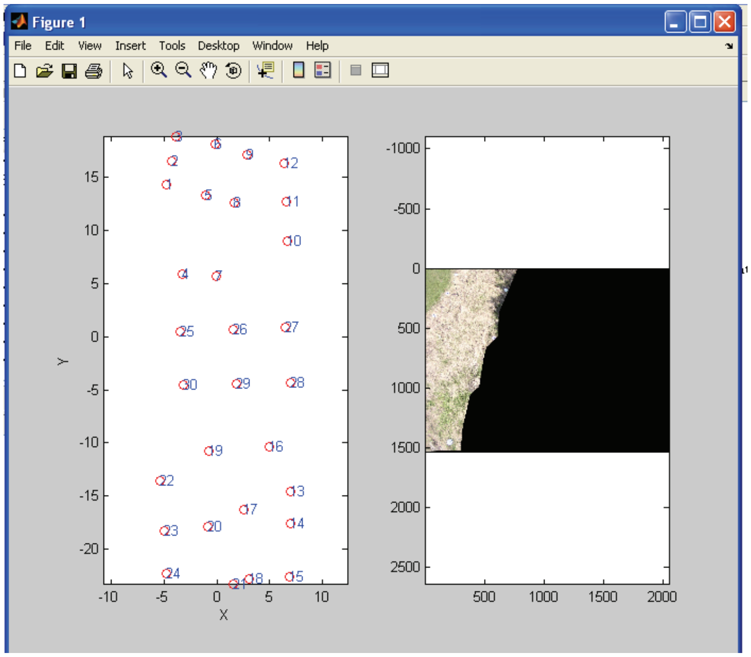
The GRP identification consists in localizing on the images the GRP that have been surveyed.

First, browse folders to input the survey file (see Input Files). Then, browse folders to get an image containing the GRP referred as #1 in the survey file. This image is stored in the folder “Map” of your field experiment project. Two windows pop up: Figure 1 shows a map of the points of the survey file, and Figure 2 shows the selected image. Use figure 1 as a reminder of the position of the GRP. Matlab asks for the first GRP (Ground Reference Point #: 1). On Figure 2, click on the GRP #1. Matlab asks then for the second GRP. Repeat those steps until you reach the last GRP that can be seen on the selected image. “***Click right on this last point.”*** If all the GRP listed in the survey file have been localized, this procedure ends. If not, browse for the image containing the next GRP. When all the GRP listed in the survey files have been localized, the Mapping procedure table appears. Click on step **2-Define view files**.

3.2.2. Define view files

In this step, the different plans (see Appendix B: Field Procedure Manual, section 2.1) are extracted from the images and the GRP corresponding to each plan to be rectified (see Input Files) are defined.

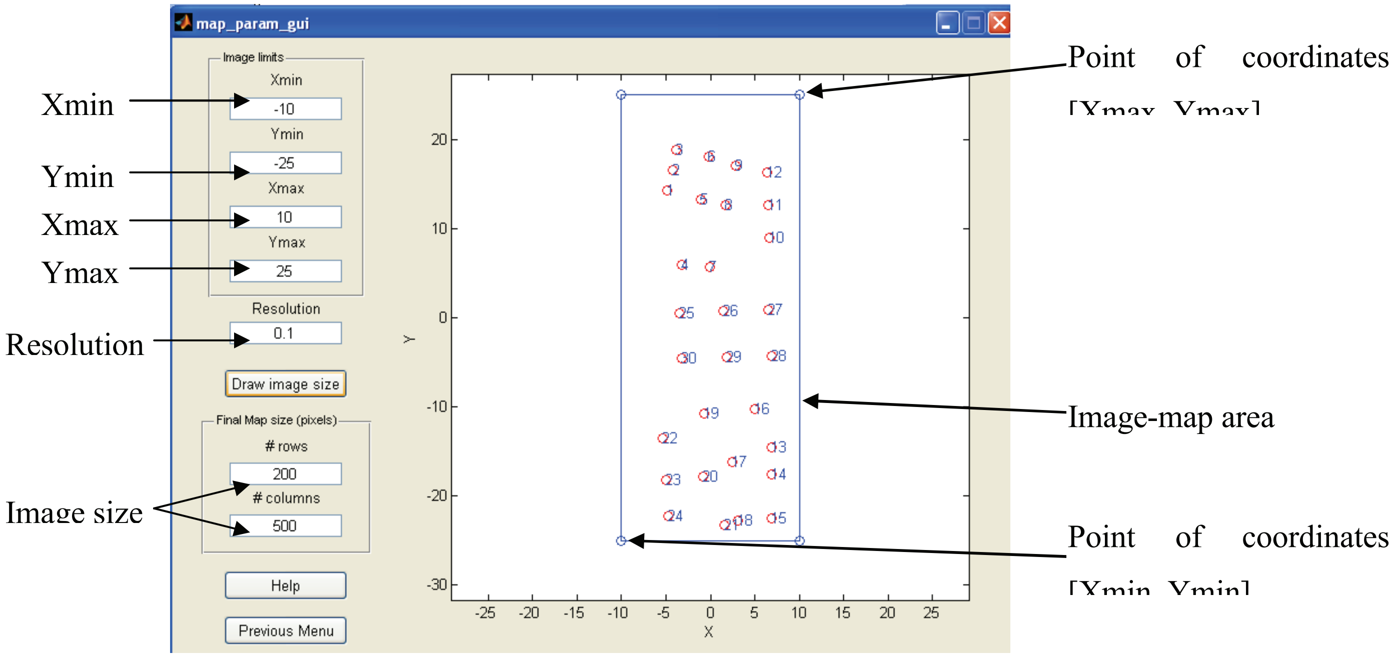
Browse folders to get an image containing a plan you want to extract. This image is stored in the folder *Map* of your field experiment project. The selected image is displayed on Figure 1. Draw the contour of the plan using the mouse and double click for the last inputted point. The software creates a masked image showing only the selected plan. The new window Figure 1 shows the map of surveyed points on the left and the selected plan image on the right.



Use Figure 1 to input the number of GRP to be used to rectify the view, and to input the reference of those GRP. Repeat this procedure for all the plans you want to extract. At the end, the Mapping Procedure table appears. Click on step **3-Transformation parameterization.**

3.2.3. Transformation parameterization

The parameterization consists in inputting the size of the final rectified images. This is defined by the physical area that the image-map should cover, and its resolution. The area that the image-map should cover is a rectangle defined by 2 opposite corners of coordinates: the corner of coordinates [Xmin, Ymin] and the corner of coordinates [Xmax, Ymax]. The map_param_gui window helps you for the parameterization. It shows a map of the surveyed points. Define the Xmin, Xmax, Ymin and Ymax coordinates so that all the points are included in the rectangle of the image-map. This rectangle can be seen by clicking on **Draw image size**. The coordinates units depend on the unit of the points in the survey file. For example, if the survey file is in meter, then the basic units for all the procedure is meter.



The resolution of the image represents the physical area that a pixel should cover. The unit is physical/pixel. For example, if the survey file is in meter, the resolution unit is meter/pixel. A large resolution (ex. 1 m/pix) will produce an image-map of small size (so the computational time will be short) but poorly detailed, and vice versa. The size of the image-map is shown in the **Final Map size** area of Figure map_param_gui. "***The resolution must be chosen depending on what needs to be seen on the final image-map.***" Once you feel OK with the parameterization, click on **Previous Menu**.

3.2.4. Transform all the views

During this step, the N views you inputted in the **Define view files** steps are geometrically corrected.

- First each view is decomposed into Red, Green and Blue channels.
- Then each channel is rectified using the relation:

$$X = \frac{a_1 i + a_2 j + a_3}{a_7 i + a_8 j + 1}$$
$$Y = \frac{a_4 i + a_5 j + a_6}{a_7 i + a_8 j + 1} \quad (1)$$

where *[i,j]* are the coordinates of a point in the image coordinate system (in pixels), *[X,Y]* are the coordinates of the same point in the space coordinate system (in meters for example) and a_i are the projective transformation parameters. Determination of the transformation parameter is accomplished using the set of GRP inputted in the step **Define view files**.

- The 3 corrected channels are combining to create the corrected color image
- Finally, the N corrected view are overlapped to create the image-map. The image-map is displayed, and you can check its quality.

The Mapping procedure is then finished. By clicking on **Previous Menu** in the Mapping procedure table, you access the Main procedure table. Click on the button **2 – LSPIV**.

3.3. LSPIV

The LSPIV procedure, consisting in analyzing the displacement of tracers of the flow, can be made for the bridge upstream and/or downstream areas. The LSPIV procedure table contains 7 steps.

3.3.1. GRPs

The GRP step allows inputting the GRP to be used for the river geometric correction. First, you need to browse the folders to get an image of the studied area (upstream or downstream). This image is stored in the folder *PIV_Upstream* or *PIV_downstream* of your field experiment project (see Appendix B: Field Procedure manual). Figure 1 pops up and shows the selected image (on the left) and the map of the surveyed points (on the right). This helps you finding which GRP are those defining the river plan. Input the number of GRP to be used for the correction of the river plans, and then, input the index of those GRP.

3.3.2. Image transformation parameterization

This step is similar to the step **Transformation parameterization** of the **Mapping procedure**. Click on **Display survey** and zoom in the interesting area. Input the coordinates Xmin, Ymin, Xmax, and Ymax so that the rectangle defined by those points includes the studied area. Set the resolution. Click on **Compute** to obtain a corrected view of the river. ***"When adjusting the corners of coordinates Xmin, Ymin, Xmax and Ymax, use a poor resolution which allows a short computational time. Then, when the corners of coordinates are OK, change the resolution."*** Once the parameterization is good, click on **Previous Menu**.

3.3.3. Transform all images

This step is similar to the step **Transform all the views** of the **Mapping procedure**. First, you need to input the sequence of images to be processed. Browse folders and select multiple image files. All the selected images are converted onto PGM ASCII format, and then corrected using Equation 1.

3.3.4. PIV parameterization

PIV algorithm calculates the correlation between the interrogation area (IA) centered at a point a_{ij} in the first image and the IA centered at a point b_{ij} in the second image taken with a time interval of δt seconds. The IA size defines the spatial resolution of the measurement. It must be small enough to preserve the scale of interest in the flow since any flow scales smaller than the size of the IA are lost through processing. However, it has to be large enough to include recognizable tracer patterns within it, i.e. to encompass one ore more "typical patterns" that are used to trace the flow free surface. The correlation coefficient $R(a_{ij},b_{ij})$ is a similarity index for the grey-scale intensity of a group of pixels contained in the two compared IAs, expressed as:

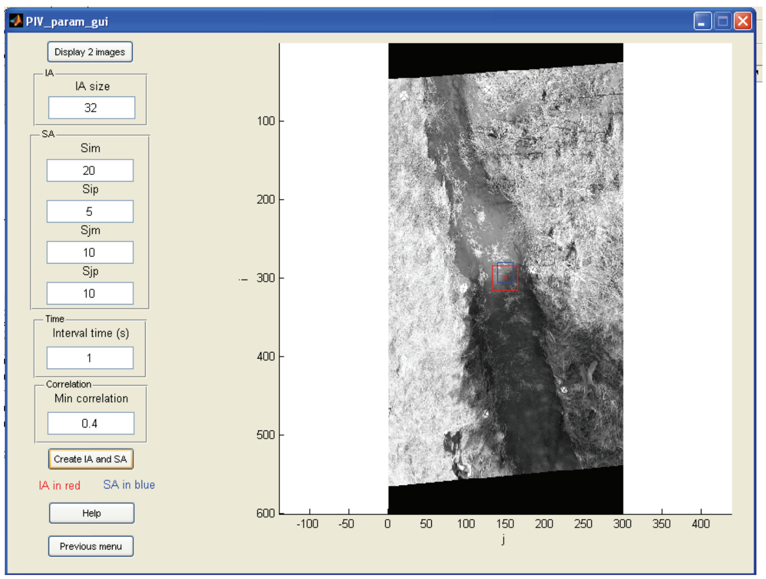
$$R(a_{ij},b_{ij}) = \frac{\sum_{i=1}^{Mi}\sum_{j=1}^{Mj}\left[\left(A_{ij}-\overline{A_{ij}}\right)\left(B_{ij}-\overline{B_{ij}}\right)\right]}{\left[\sum_{i=1}^{Mi}\sum_{j=1}^{Mj}\left(A_{ij}-\overline{A_{ij}}\right)^2\sum_{i=1}^{Mi}\sum_{j=1}^{Mj}\left(B_{ij}-\overline{B_{ij}}\right)^2\right]^{1/2}}$$

where Mi and Mj are the sizes of the interrogation areas (in pixels), and A_{ij} and B_{ij} are the distributions of the grey-level intensities in the two interrogation areas. Correlation coefficients are only computed for points within a searching area (SA). The SA size has to be selected so that the displacement of tracer patterns from the first image is contained within the SA of the second image. Consequently, the SA size is commensurate with the expected range of velocities of the river. *"**For rivers with small cross-stream velocities, the SA should be asymmetric, elongated in the direction of the flow**."* The PIV approach assumes that the most probable displacement of the fluid from point a_{ij} during interval time between 2 images of a pair, δt, is the one corresponding to the maximum correlation coefficient. Sub-pixel displacement accuracy can be reached using a parabolic fit (Forliti et al, 2000). Velocity vectors are derived from these displacements by dividing them by δt.

The figure PIV_param_gui helps in the PIV parameterization. Display 2 corrected images by clicking on **Display 2 images** and asses the size of the IA and of the SA regarding the flow and tracers properties. The IA shape is a square. Its size must be an even number. The SA is defined by 4 lengths: Sim, Sip, Sjm, Sjp, where i and j are the 2 axis of the image and m and p stands for minus and plus. Sim, for example, is the length of the SA from the center of the IA following the i axis in the negative direction.

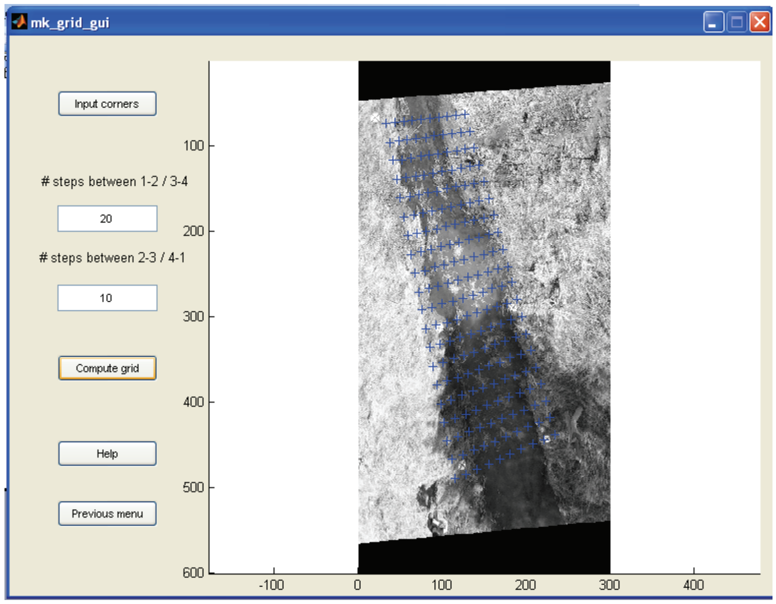
The **Min Correlation** edit zone allows inputting a threshold for the minimum value of the correlation coefficient that is used. If the maximum R is lower to that threshold, the vector is considered as spurious.

Clicking on **Create IA and SA** display a corrected images and an IA (in red) and a SA (in blue) localized in the center of the image. Check if the sizes of the IA and SA are OK.



3.3.5. Computational grid

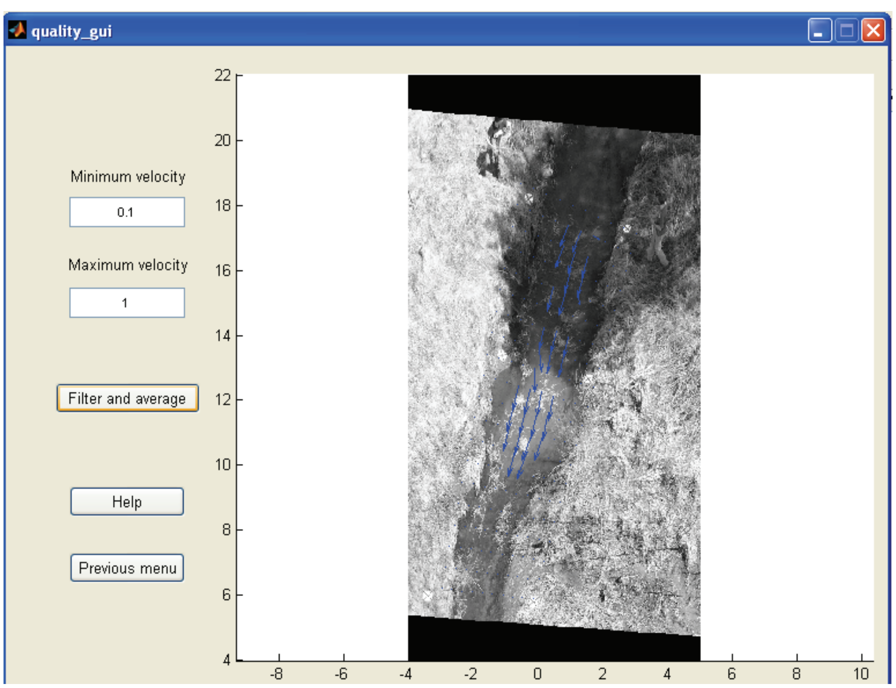
The computational grid defines the points in the image coordinate system where the IAs and the SAs are centered. The grid is defined by its 4 corners and the number of steps. Input the 4 corners localization by clicking on **Input corners**, and then by clicking on the image. The corners should be inputted clockwise or counterclockwise. Then input the number of steps between the points 1 and 2 and the points 3 and 4, and the number of steps between the points 2 and 3 and the points 4 and 1. The grid is displayed when the button **Create grid** is pressed.



3.3.6. PIV processing of all the images

Select if the images are a sequence or pairs (see Input Files). Then, the software analyses each pair of images with a PIV algorithm. The instantaneous velocity fields are stored in the folder *LSPIV/UpStream/displacements/* or *LSPIV/DownStream/displacements/*.

3.3.7. Quality check and averaging



The quality check interface allows putting a filter on the velocities computed with the PIV step. Input a minimum and a maximum expected velocity values. For each computed velocity field, the velocities that do not fit in the expected range are removed. Then, the instantaneous velocity fields are averaged and displayed over a corrected image. The filtered velocity fields are stored in the folder *LSPIV/UpStream/quality_vel/* or *LSPIV/DownStream/quality_vel*, and the averaged velocity field is stored in the folder *LSPIV/UpStream/outputs/average_vel.dat* or *LSPIV/DownStream/outputs/average_vel.dat*.

3.3. Features identification

The Features procedure includes 2 steps: Features identification and Mapping of features.

3.3.1. Features identification

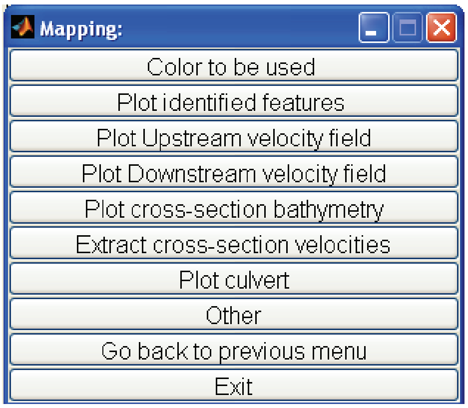
In this step, the user can define on the rectified images some interesting features of the waterways.

Figure 1 shows the ortho-map. Zoom on Figure 1 on the area where you want to identify a feature. When the view is adjusted, press Enter. Input a code name for the feature. Using the mouse, click on several points to define precisely the feature. Click right for inputting the last point. The coordinates of the identified features are stored in the folder *Features* in a [x,y] format.

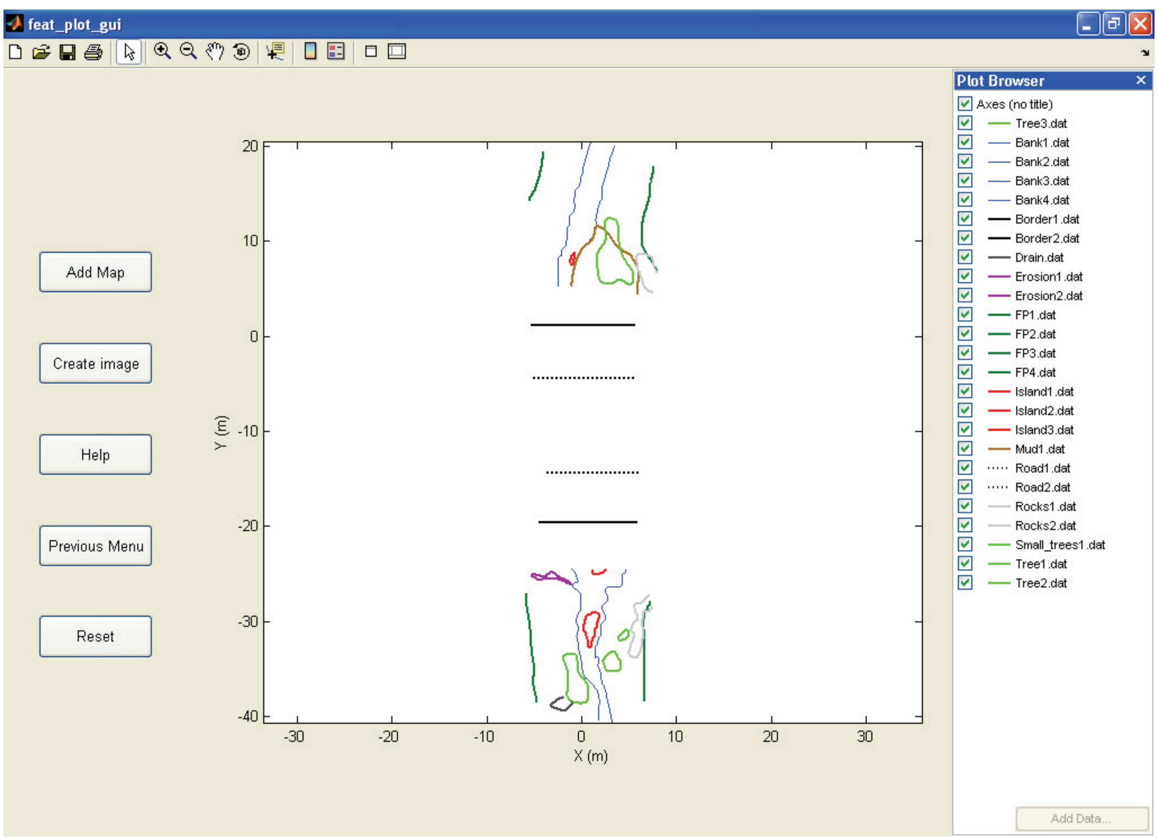
3.3.2. Mapping of features

3.3.2.1. Plot identified features

Click on **Add Map**. First, select the color for the map. Then, click on **Plot identified features**, go to the *Features* folder of your project and select the features you want to plot.



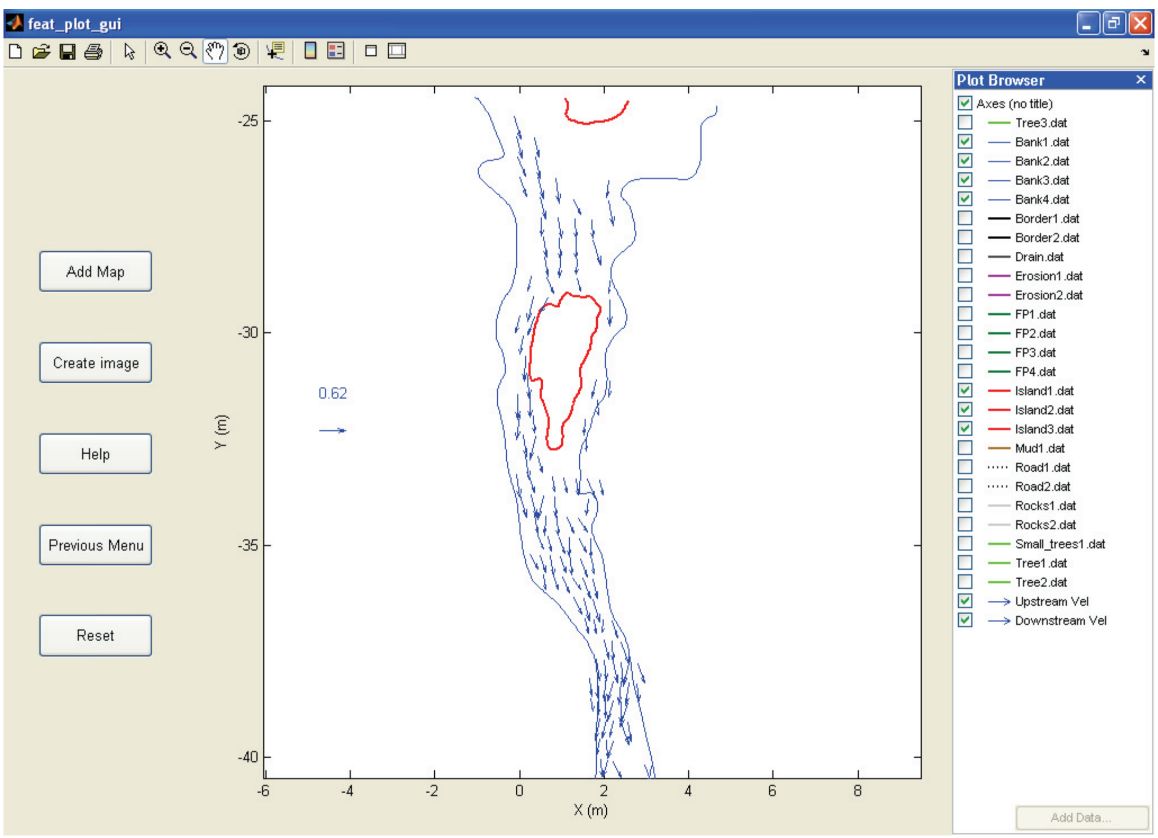
The features are displayed on the Graphical User Interface (GUI). The following figure shows an example of Mapping.



To make editorial changes (color, line style, etc..), click right on the feature you want to change or open the **show plot tool** by clicking on the last left button of the toolbar.
The plot browser window on the right part of the GUI displays the plotted features. You can hide or delete features by clicking right on the feature name in the browser window.

3.3.2.2. Plot velocity fields

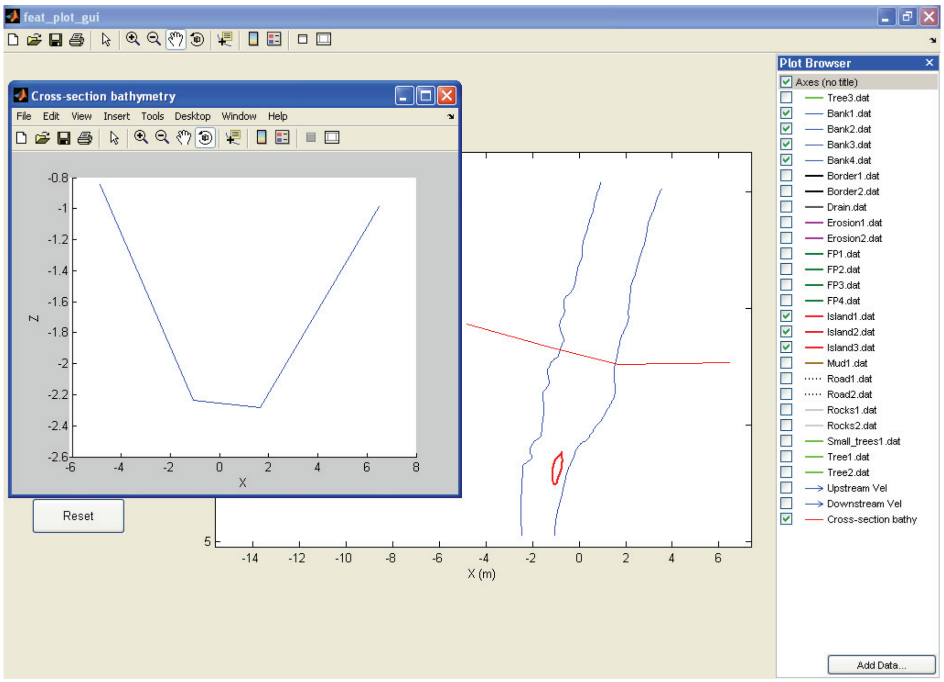
To add velocity fields computed during the LSPIV procedure, click on **Plot upstream velocity field** or **Plot downstream velocity field**. Then, select the velocity field you want to plot (LSPIV/UpStream/outputs/average_vel or LSPIV/DownStream/outputs/average_vel). The velocity field is displayed in the GUI with a reference vector.



3.3.2.3. Plot cross-section bathymetries

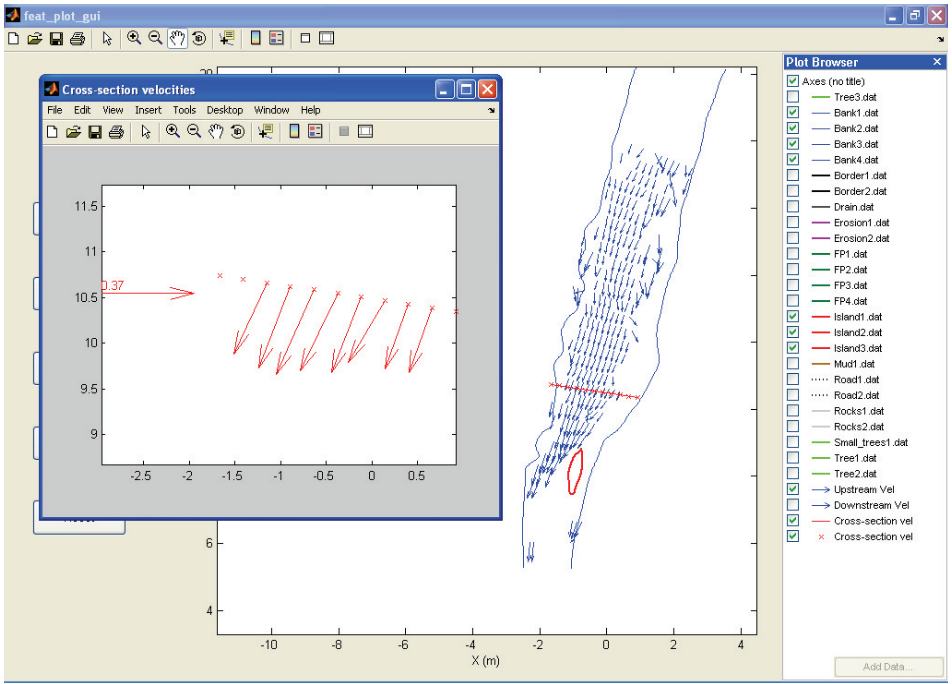
Cross-section bathymetries are defined by the GRPs. For displaying a bathymetry, select the survey file of the project (see Field procedure). Then, input the number of GRPs defining a cross-section and enter the labels of the GRPs defining the interesting cross-section. The cross-section is displayed on the GUI and the bathymetry is shown in a pop-up window (see next figure).

To remove the cross-section in the GUI, use the Plot browser.



3.3.2.4. Extract cross-section velocities

After plotting velocity fields, you can extract cross-section velocities. Select the project folder for which you want to extract velocities. Then, using the mouse in the GUI, define the beginning and ending points of the cross-section. Velocities are extracted on 11 points over the cross-section and are displayed with a reference vector in a pop-up window. The cross-section line and points are displayed in the GUI, as illustrated in the next figure. Use the Plot browser to remove or hide the cross-section information when it is not needed.



3.3.2.5. Plot bridge or culvert

Select the bridge survey file (see Appendix B: Field Procedure manual). The coordinates of the edges of the bridge or culvert are displayed in the GUI. Use the Plot browser to remove or hide the cross-section information when it is not needed.

3.3.2.6. Plot survey

Select the survey file (see Appendix B: Field Procedure manual). The GRPs are displayed in the GUI. Use the Plot browser to remove or hide the cross-section information when it is not needed.

Appendix B. DIGIMAP FIELD PROCEDURE

DIGIMAP FIELD PROCEDURE

1. Introduction

This guide for field experiment is based on the Mobile Large-Scale Particle Image Velocimetry unit (MLSPIV) developed at IIHR. For more information about the MLSPIV, readers could refer to Kim et al. (2007).

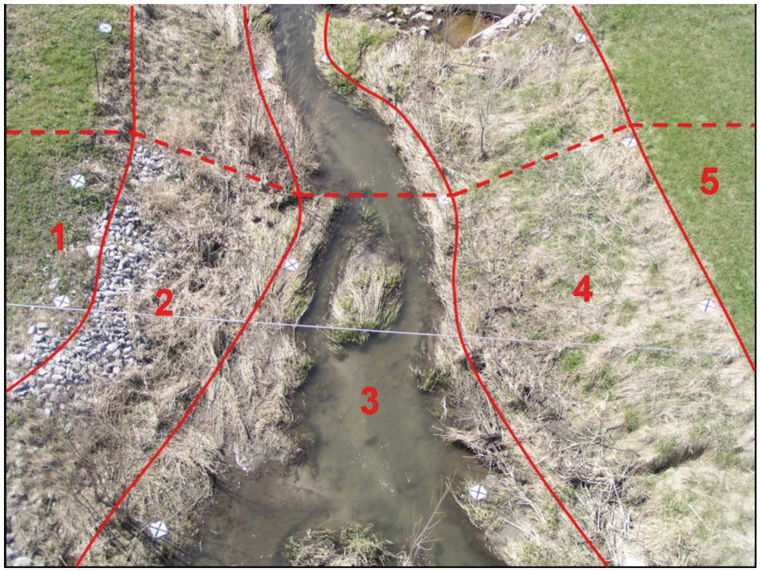
The aim of the field experiment is: (i) to make an accurate survey of some points of the site and (ii) to imaging interesting areas upstream and downstream a bridge or culvert. Those data will be then used in the software DIGIMAP.

Before getting the data, create a folder for your experiment. In this folder, create 3 folders called *Map*, *PIV_upstream,* and *PIV_downstream*.

2. Survey and imaging

2.1 Localization of the GRPs

On the study site, locate the MLSPIV on the shoulder upstream of the bridge. Set the elevation of the mast and the camera pan-tilt position so that the entire interesting area fits in the image.
The area of study should be decomposed in plans to be analyzed with DIGIMAP. This is illustrated in the following figure.



Dispose bench marks, also called Ground Reference Points (GRP), on the field. Each of the plans should be defined by at least 6 spatially well-distributed GRPs to allow an accurate orthorectification (see Fujita, 1994). Take a picture of the site and store this picture in the folder *Map*.

2.2 Survey

Use a survey tool (total station or GPS) to get the coordinates [X,Y,Z] of all the GRPs. Save this survey in the folder *Map* as a text file containing the survey of upstream and downstream GRPs on a 4 columns table like in the following example:

1	12.5244	36.5488	2.356
2	32.6788	78.21347	1.326

Where the first column is the reference, the 3 following columns are respectively X, Y and Z.

Make also a survey of the bridge or culvert edges. Store that survey as an X,Y,Z text file in the folder *Map*.

3. Imaging for LSPIV analysis

LSPIV analysis required having a sequence of images of a flow where tracers are visible. If natural tracers (bubbles, foam, turbulence patterns, debris, etc...) do not present on the river surface, you should add artificial tracers. Take a sequence of image pairs so that the final number of image pairs should be at least 20 and the total recorded time should be at least 40s. Store the images in the folder *PIV_upstream*.

Repeat the same protocol (step 2 and 3) for the downstream part using *PIV_downstream* as storage folder.

4. Reference

Fujita, I. and Komura, S. (1994). "Application of Video Image Analysis for Measurements of River-Surface Flows", *Annual Journal of Hydraulic Engineering*, Japan Society of Civil Engineering.